

LEES 2016

International Conference on Low-Energy Electrodynamics in Solids

PROGRAM & ABSTRACTS



May 29 - June 3, 2016 Hotel LAFORET Biwako, Moriyama, Shiga, JAPAN

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Outline of LEES 2016

SCOPE

LEES 2016 will be a forum for the interdisciplinary discussion of the low-energy electrodynamics in solids, at both the theoretical and experimental methods of optical/photoemission spectroscopy, inelastic neutron/X-ray scattering, scanning tunneling microscopy/spectroscopy and so on, with specific emphasis on the electronic and magnetic properties of quantum materials. This conference will be the 12th LEES meeting and follows the highly successful workshops at Bad Honnef (1993), Trest (1995), Ascona (1997), Pecs (1999), Montauk (2002), Kloster Banz (2004), Tallinn (2006), Vancouver-Whistler (2008), Les Diablerets (2010), Napa Valley (2012), and Loire Valley (2014).

TOPICS

Cuprate & Iron-based superconductors Graphene & Dirac materials Weyl semimetals Topological effects Non-Fermi & Fermi liquids in metals Multiferroics & Ferroelectrics 2D electronic systems Heavy Fermions Novel superconductors Other strongly correlated systems Novel physical peroperties and new materials New methods and techniques

COMMITTEE MEMBERS

ORGANIZERS

TAJIMA, Setsuko, Osaka KIMURA, Shin-ichi, Osaka OKAMURA, Hidekazu, Tokushima

LOCAL ORGANIZING COMMITTEE

ASHIDA, Masaaki, Osaka FUJIMORI, Atsushi, Tokyo FUJITA, Masaki, Sendai HANAGURI, Tetsuo, Wako ISHII, Kenji, Hyogo MAEDA, Atsutaka, Tokyo TOHYAMA, Takami, Tokyo

PROGRAM COMMITTEE

BENFATTO, Lara, Italy GREVEN, Martin, USA HOMES, Chris, USA KAMBA, Stanislav, Czech Republic LOBO, Ricardo, France LUPI, Stefano, Italy MARTIN, Mike, USA NOH, Tae Won, Korea NORMAN, Mike, USA SHIMADA, Kenya, Japan SHIMANO, Ryo, Japan WANG, Nan Lin, China





Information

- Conference site
 - Large conference room on the 2nd floor (2F).
- Meal
 - All meals are provided at Dinning Espoir on the 1st floor (1F).
- Internet
 - Wifi will be available in the conference room, lobbies on 1F and 2F and rooms on 6F.
- Welcome reception on May 29th
 - Start at 19:00.
 - Banquet room on the basement floor (BF).
- Excursion on June 1st
 - Start at 14:00 from the entrance of Hotel Laforet.
 - Schedule: Visit to Sakamoto (www.biwako-visitors.jp/spot/detail/803 [in Japanese])
 → Mt. Hiei-zan Enryaku-ji temple (kyoto.travel/en/shrine temple/126)
 - \rightarrow Conference dinner restaurant in Kyoto (see the map).
- Conference dinner on June 1st
 - Place: Ganko Takasegawa Nijoen (http://www.gankofood.co.jp/en/)
 - Phone: +81-75-223-3456
 - Time: 18:30-
 - All participants can take buses to come back to Hotel Laforet Biwako after the dinner.



Poster session Oral session Vender exhibition 2F 10011 0000000000 11111 199999999999 181 No.2 No.1 No.3 88888 (11111111111111111 111111111111111 888888 No.4 No.1.N Lobby

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Interactive Materials Science Cadet Program, Osaka University



SPACTION



Program

| May 29 (Sun.) | May 30 (Mon.) | May 31 (Tue.) | June 1 (Wed.) | June 2 (Thu.) | June 3 (Fri.) |
|---------------|-------------------------------|-------------------------------|---------------------|-------------------------------|---------------------|
| | 8:45 | | 8:45 | | |
| | Opening Genzel Prize Ceremony | | | | |
| | 9:00-10:30 | 9:00-10:30 | 9:00-10:25 | 9:00-10:25 | 9:00-10:30 |
| | Cuprates (I) | Iron S.C. (I) | Topology (II) | Novel materials | Cuprate (III) |
| | (Tajima) | (Hanaguri) | (Dressel) | (Pimenov) | (Sacuto) |
| | I-1: Sacuto | I-10: Feng | I-19: Armitage | I-25: Rusydi | I-34: Van der Marel |
| | I-2: Greven | I-11: Borisenko | I-21: Murakami | I-26: Perucchi | I-35: Toda |
| | I-3: Kondo | I-12: Chubukov | C-17: Akrap | C'-21: Maeda | I-36: Seibold |
| | C-1: Ideta | C-9: Degiorgi | C'-18: Sohn | C-22: Skiadopoulou | C-29: Badoux |
| | | - | | | |
| | 11:00-12:25 | 11:00-12:30 | 11:00-12:25 | 11:00-12:25 | 11:00-12:30 |
| | Time-resolved (I) | 4f & 5d systems | Cuprates (II) | Time-resolved (II) | Topology (III) |
| | (Chubukov) | (Kimura) | (Greven) | (Tohyama) | (Armitage) |
| | I-4: Hu | I-13: Schemm | I-22: Le Tacon | I-27: Shimano | I-37: Chen |
| | I-5: Oka | I-14: Scheffler | I-24: Julien | I-28: Devereaux | I-38: Dai |
| | C'-2: Tohyama | I-15: Kim | C'-19: Ishii | C'-23: Cantaluppi | I-39: Pronin |
| | C-3: Morimoto | C-10: Zonno | C-20: Sakai | C-24: Crepaldi | C-30: Kohsaka |
| | | | | | 10.00 |
| | 12:30-14:00 | 12:30-14:00 | 12:30-14:00 | 12:30-14:00 | 12:30 |
| | Lunch & Discussion | Lunch & Discussion | Lunch | Lunch & Discussion | -14:00 Lunch |
| | 14:00-15:50 | 14:00-15:45 | 7 | 14:00-15:50 |] |
| | Topology (I) | Multiferroic | | Iron S.C.(II) | |
| | (Kim) | (Tokura) | | (Borisenko) | |
| | I-6: Tokura | I-16: Kezsmarki | Excursion 14:00- | I-29: Hanaguri | |
| | I-7: Orlita | I-17: Pimenov | Sakamoto, Mt. Hiei | I-30: Coldea | |
| | I-8: Moore | C'-11: Kamba | & Enryakuji temple | I-31: Gastiasoro | |
| | C'-4: Lupi | C'-12: Room | | C'-25: Blumberg | |
| | C-5: Lee | C-13(P-22): Wang | | C-26: Miyasaka | |
| | | | _ | | - |
| | 16:10-17:20 | 16:10-17:20 | | 16:10-17:30 | |
| | Space-resolved | Novel optics (I) | | Novel optics (II) | |
| | (Okamura) | (Rusydi) | | (van der Marel) | |
| | I-9: Kuzel | I-18: Shin | | I-32: Dressel | |
| | C-6: Boehmler | C-14: Bachar | | I-33: Gorshunov | |
| | C-7: Martin | C-15: Boris | | C-27: Burch | |
| | C-8: Hattori | C-16: Ito | | C-28: Chia |] |
| 17.00 10.00 | 17.00 10.00 | 17.00 10.00 | 7 | 17.20 10.10 | 7 |
| Desistration | 17.20-10.00 | 17.20-10.00 Dester Dreview | | 17.30-10.10 Dester Dreview | |
| Registration | (Maoda) | (Eulita) | | | |
| | (Maeua) | (rujita) | | (ISHII) | J |
| 19:00-21:00 | 18:00-19:30 | 18:00-19:30 | | 18:10-19:30 | |
| Welcome | Dinner | Dinner | Banquet 18:30- | Dinner | |
| party | | | Japanese Restaurant | | _ |
| | 19:30-21:00 | 19:30-21:00 | in Kyoto | 19:30-21:00 | |
| | Poster | Poster | | Poster | |
| | | | | | = |

I-**: invited talk (25 min.) C'-**: contributed talk (20 min.) C-**:contributed talk (15 min.) incl. discussion

May 30 (Mon.)

Cuprate I

Chair: S. Tajima (Osaka Univ.)

I-1 (9:00 ~ 9:25)

Pseudogap and its Interplay with the Superconducting Gap in Cuprates Superconductors

A. Sacuto (Université Paris Diderot, France)

I-2 $(9:25 \sim 9:50)$ New insight into the strange-metal and pseudogap behavior of the cuprates

M. Greven (University of Minnesota, USA)

I-3 (9:50 ~ 10:15) **Point nodes persisting far beyond** *T***c in Bi2212** T. Kondo (ISSP, University of Tokyo, Japan)

C-1 (10:15 ~ 10:30) Observation of triple-layer splitting in high- T_c cuprate Bi₂Sr₂Ca₂Cu₃O_{10+ δ} observed by ARPES

S. Ideta (UVSOR, Institute for Molecular Science, Japan)

Time-resolved I

Chair: A. V. Chubukov (Univ. of Minnesota)

I-4 (11:00 ~ 11:25)

Light control of correlated electron systems

W. Z. Hu (Max Planck Institute for the Structure and Dynamics of Matter, Germany)

I-5 (11:25 ~ 11:50)

Control of Topology in Quantum Materials by Laser

T. Oka (Max Planck Institute for Chemical Physics of Solids, Germany)

C'-2 (11:50 ~ 12:10)

Nonequilibrium Charge Dynamics in Strongly Correlated Electron Systems

T. Tohyama (Department of Applied Physics, Tokyo University of Science, Japan)

C-3 (12:10 ~ 12:25)

Topological aspects of nonlinear optical responses

T. Morimoto (Department of Physics, University of California, Berkeley, USA)

Topology I

Chair: C. Kim (Seoul Nat'l Univ.)

I-6 (14:00 ~ 14:25)

Magnetoelectric responses from topological magnets

Y. Tokura (RIKEN Center for Emergent Matter Science, Japan)

I-7 (14:25 ~ 14:50)

Magneto-optics of massless and massive electrons

M. Orlita (Laboratoire National des Champs Magnétiques Intenses – Grenoble, France)

I-8 (14:50 ~ 15:15)

Electromagnetic response of semimetals from wavefunction geometry and topology

J. E. Moore (University of California, Berkeley, USA)

C'-4 (15:15 ~ 15:35)

Non Linear Terahertz Behavior of Bi₂Se₃ Topological Insulator S. Lupi (INFN and Department of Physics, Sapienza University of Rome, Italy)

C-5 (15:35 ~ 15:50)

Direct measurement of proximity-induced magnetism at the buried interface between a topological insulator and a ferromagnet

C. Lee (Department of Physics, Massachusetts Institute of Technology, USA)

Space-resolved

Chair: H. Okamura (Tokushima Univ.)

I-9 (16:10 ~ 16:35)

Terahertz photoconductivity in semiconductor nanostructures: Effective medium theory aspects

P. Kužel (Institute of Physics, Academy of Sciences of the Czech Republic, Czech Republic)

C-6 (16:35 ~ 16:50) nano-FTIR: Imaging & Spectroscopy with 10 nm Spatial Resolution M. Boehmler (neaspec GmbH, Germany)

C-7 (16:50 ~ 17:05)

Nanospectral Imaging of Phonon Polaritons and Single Plasmonic Nanocrystals with Synchrotron Infrared Nano Spectroscopy (SINS) M. C. Martin (ALS, Lawrence Berkeley National Laboratory, USA)

C-8 (17:05 ~ 17:20)

Investigation of nanodomain properties in the phase-separated manganite by probing electron dynamics

A. N. Hattori (ISIR, Osaka University, Japan)

<u>May 31 (Tue.)</u>

Iron-based superconductors I

Chair: T. Hanaguri (RIKEN)

I-10 (9:00 ~ 9:25)

Exploration of superconductivity in FeSe films and electron doped Sr_2IrO_4

D. L. Feng (State Key Laboratory of Surface Physics, Department of Physics, Fudan University, China)

I-11 (9:25 ~ 9:50)

Spin-Orbit Coupling and Nematicity in Iron-Based Superconductors S. Borisenko (IFW Dresden, Germany)

I-12 (9:50 ~ 10:15)

Magnetism, superconductivity, and spontaneous orbital order in iron-based superconductors: who comes first and why?

A. V. Chubukov (School of Physics and Astronomy, University of Minnesota, USA)

C-9 (10:15 ~ 10:30)

Origin of the resistive anisotropy in the electronic nematic phase of BaFe₂As₂ revealed by optical spectroscopy

L. Degiorgi (Laboratorium für Festkörperphysik, ETH - Zürich, Switzerland)

4f & 5d systems

Chair: S. Kimura (Osaka Univ.)

I-13 (11:00 ~ 11:25)

Polar Kerr effect studies of heavy fermion superconductors

E. Schemm (Stanford Institute for Materials and Energy Sciences (SIMES), SLAC National Accelerator Laboratory, USA)

I-14 (11:25 ~ 11:50)

Non-Fermi-Liquid Behavior in the THz Response of CeCoIn₅

M. Scheffler (1. Physikalisches Institut, Universität Stuttgart, Germany)

I-15 (11:50 ~ 12:15)

Electric field control of octahedra rotation on the surface of Sr₂RuO₄ C. Kim (Center for Correlated Electron Systems, Institute for Basic Science and Department of Physics and Astronomy, Seoul National University, Korea)

C-10 (12:15 ~ 12:30)

The Spectral Function of Honeycomb Na2IrO3 by ARPES upon Li Substitution

M. Zonno (Department of Physics and Astronomy, UBC, Canada)

Multiferroic

Chair: Y. Tokura (RIKEN)

I-16 (14:00 ~ 14:25)

Magnetoelectric memory with optical readout

I. Kezsmarki (Budapest University of Technology and Economics, Hungary)

I-17 (14:25 ~ 14:50)

Directional anisotropy of light in multiferroics

A. Pimenov (Institute of Solid State Physics, Vienna University of Technology, Austria)

C'-11 (14:50 ~ 15:10)

Review of ferroelectric and magnetic soft modes in multiferroics S. Kamba (Institute of Physic, Czech Academy of Sciences, Czech Republic)

C'-12 (15:10 ~ 15:30)

Optical Diode Effect at Spin-Wave Excitations of the Room-Temperature Multiferroic BiFeO₃

T. Rõõm (National Institute of Chemical Physics and Biophysics, Estonia)

C-13 (15:30 ~ 15:45)

From confined spinons to emergent fermions: Evolution of elementary excitations in a transverse-field Ising chain

Z. Wang (Experimental Physics V, Center for Electronic Correlations and Magnetism, Institute of Physics, University of Augsburg, Germany)

Novel optics I

Chair: A. Rusydi (NUS)

I-18 (16:10 ~ 16:35)

Ultrahigh spatial resolution magnetic imaging of oxide surfaces and interfaces by the development of laser-PEEM

S. Shin (The Institute for Solid State Physics, The University of Tokyo, Japan)

C-14 (16:35 ~ 16:50)

Competition between enhanced Cooper pairing and suppressed phase coherence in coupled aluminum nanograins

N. Bachar (Laboratory for Superconductivity and Optical Spectroscopy, Ariel University, Israel)

C-15 (16:50 ~ 17:05)

Giant Exciton Fano Resonance in Ta₂NiSe₅

A. V. Boris (Max Planck Institute for Solid State Research, Germany)

C-16 (17:05 ~ 17:20)

Electronic structure of a quasi-one dimensional thermoelectric material Ba₃Co₂O₆(CO₃)_{0.7} studied by angle-resolved photoemission spectroscopy

T. Ito (Graduate School of Engineering, Nagoya University, Japan)

June 1 (Wed.)

Topology II

Chair: M. Dressel (Univ. of Stuttgart)

I-19 (9:00 ~ 9:25)

Low energy electrodynamics of topological insulators

N. P. Armitage (The Institute for Quantum Matter, Department of Physics and Astronomy, The Johns Hopkins University, USA)

I-21 (9:25 ~ 9:50)

Topological phase transitions and surface states in topological semimetals

S. Murakami (Tokyo Institute of Technology, Japan)

C-17 (9:50 ~ 10:05)

Kane electrons evidenced by magneto-optics of Cd_3As_2 in the quantum limit

A. Akrap (DPMC, University of Geneva, Switzerland)

C'-18 (10:05 ~ 10:25) Optical Spectroscopic Studies on the Lifshitz-Type Metal-Insulator Transition in Cd₂Os₂O₇

C. H. Sohn (Center for Correlated Electron Systems, Institute for Basic Science and Department of Physics and Astronomy, Seoul National University, Korea)

Cuprates II

Chair: M. Greven (Univ. of Minnesota)

I-22 (11:00 ~ 11:25)

Magnetic Excitations in doped Cuprates and Iridates from Raman Scattering and RIXS

M. Le Tacon (Institut für Festkörperphysik, Karlsruher Institut für Technologie, Germany)

I-24 (11:25 ~ 11:50)

NMR studies of charge order in YBa₂Cu₃O_y

Marc-Henri Julien (Laboratoire National des Champs Magnétiques Intenses (LNCMI), Grenoble, France)

C'-19 (11:50 ~ 12:10)

Momentum-resolved charge fluctuations proximate to the charge-order phase measured by resonant inelastic x-ray scattering

K. Ishii (SPring-8, Japan Atomic Energy Agency, Japan)

C-20 (12:10 ~ 12:25)

Hidden fermionic excitation as the origin of pseudogap and high-temperature superconductivity in cuprates

S. Sakai (Center for Emergent Matter Science, RIKEN, Japan)

<u>June 2 (Thu.)</u>

Novel materials

Chair: A. Pimenov (TU Wien)

I-25 (9:00 ~ 9:25)

High-energy optical conductivity and anomalous spectral weight transfers in strongly correlated electron systems

A. Rusydi (National University of Singapore, Singapore)

I-26 (9:25 ~ 9:50)

Optical properties of nickelate thin films and heterostructures

A. Perucchi (INSTM UdR Trieste-ST and Elettra - Sincrotrone Trieste S.C.p.A., Italy)

C'-21 (9:50 ~ 10:10)

Superconductivity fluctuation of $FeSe_{1-x}Te_x$ measured by microwave broadband technique

A. Maeda (Department of Basic Sciences, University of Tokyo, Japan)

C-22 (10:10 ~ 10:25)

Magnetoelectric spin excitations in multiferroic Ni₃TeO₆

S. Skiadopoulou (Institute of Physics, Academy of Sciences of the Czech Republic, Czech Republic)

Time-resolved II

Chair: T. Tohyama (Tokyo Univ. of Science)

I-27 (11:00 ~ 11:25)

Nonlinear THz spectroscopy of collective modes in superconductors R. Shimano (Cryogenic Research Center, The University of Tokyo, Japan)

I-28 (11:25 ~ 11:50) **On the theory for pump-probe spectroscopy in quantum materials** T. P. Devereaux (Stanford University, USA)

C'-23 (11:50 ~ 12:10)

Possible light-induced superconductivity in metallic K_3C_{60}

A. Cantaluppi (Max Planck Institute for the Structure and Dynamics of Matter, Germany)

C-24 (12:10 ~ 12:25) Ultrafast Optical Control of the Topologically Protected Electronic Properties of ZrTe5

A. Crepaldi (Elettra-Sincrotrone Trieste S. C. p. A., Italy)

Iron-based superconductors II

Chair: S. Borisenko (IFW Dresden)

I-29 $(14\!:\!00 \sim 14\!:\!25)$ Spectroscopic-imaging STM studies of the iron chalcogenide superconductor FeSe

T. Hanaguri (RIKEN Center for Emergent Matter Science, Japan)

I-30 (14:25 ~ 14:50)

Fermi surface evolution across the nematic phase in bulk $Fe(Se_{1-x}S_x)$ using ARPES and quantum oscillations

A. Coldea (Clarendon Laboratory, Oxford University, UK)

I-31 (14:50 ~ 15:15)

Emergent defect states as a source of resistivity anisotropy in iron pnictides

M. N. Gastiasoro (Niels Bohr Institute, University of Copenhagen, Denmark)

C'-25 (15:15 ~ 15:35)

Helicity preserving photoluminescence from the topological insulator Bi_2Se_3

G. Blumberg (Rutgers University, Department of Physics and Astronomy, USA)

C-26 (15:35 ~ 15:50)

Anomalous low-energy excitation induced by magnetic impurity in optical spectrum of iron-based superconductor

S. Miyasaka (Department of Physics, Osaka University, Japan)

Novel optics II

Chair: D. van der Marel (Univ. of Geneva)

I-32 (16:10 ~ 16:35) Time-Resolved FTIR Studies of Phase Transitions in Low-Dimensional Organic Crystals

M. Dressel (1. Physikalisches Institut, Universität Stuttgart, Germany)

I-33 (16:35 ~ 17:00) Incipient ferroelectricity of nanocaged water molecules B. Gorshunov (Moscow Institute of Physics and Technology, Russia)

C-27 (17:00 ~ 17:15) **Towards Fractional Excitations with Raman and Exfoliation** K. S. Burch (Department of Physics, Boston College, USA)

C-28 (17:15 ~ 17:30)

Role of disorder, free-carrier recombination kinetics and phonon modes in the performance of CH₃NH₃PbI₃ perovskite films

E. E. M. Chia (Division of Physics and Applied Physics, School of Physical and Mathematical Sciences, Nanyang Technological University, Singapore)

<u>June 3 (Fri.)</u>

Cuprate III

Chair: A. Sacuto (Univ. Paris Diderot)

I-34 (9:00 ~ 9:25)

The correlation energy in superconductors using optics as a probe D. van der Marel (University of Geneva, Switzerland)

I-35 (9:25 ~ 9:50)

Photoexcited quasiparticle dynamics in the pseudogap state of high-Tc superconductors

Y. Toda (Department of Applied Physics, Hokkaido University, Japan)

I-36 (9:50 ~ 10:15)

Low energy electrodynamics of strongly disordered superconductors G. Seibold (Fachbereich Computational Physics, BTU Cottbus Senftenberg,

G. Selboid (Fachbereich Computational Physics, BTO Cottbus Senitenberg, Germany)

C-29 (10:15 ~ 10:30)

Signature of the pseudogap critical point in cuprate superconductors S. Badoux (Département de physique & RQMP, Université de Sherbrooke, Canada)

Topology III

Chair: N. P. Armitage (Johns Hopkins Univ.)

I-37 (11:00 ~ 11:25)

Magnetoinfrared spectroscopy of Landau levels and Zeeman splitting of three-dimensional massless Dirac fermions in ZrTe₅

R. Y. Chen (International Center for Quantum Materials, School of Physics, Peking University, China)

I-38 (11:25 ~ 11:50)

Optical Properties of Weyl Semimetals

Y. M. Dai (Center for Integrated Nanotechnologies, Los Alamos National Laboratory, USA)

I-39 (11:50 ~ 12:15)

Optical conductivity of the 3D Dirac semimetals Cd_3As_2 , $CaMnBi_2$, and $SrMnBi_2$

A. V. Pronin (1. Physikalisches Institut, Universität Stuttgart, Germany)

C-30 (12:15 ~ 12:30)

Spectroscopic imaging scanning tunneling microscopy of spin-polarized two-dimensional states on a polar semiconductor BiTeI Y. Kohsaka (RIKEN Center for Emergent Matter Science, Japan)

<u>May 30 (Mon.)</u>

Poster I

Chair: A. Maeda (Univ. of Tokyo)

P-1

Electron-Hole Asymmetry in the Electron-phonon coupling in Top-gated Phosphorene Transistor

S. N. Gupta (Department of Physics, Indian Institute of Science, India)

P-2

Dimensionality-Induced Bandwidth control in $[(SrIrO_3)_m/(SrTiO_3)]$ (m=1, 2, and ∞) Superlattices

S. Y. Kim (Center for Correlated Electron Systems, Institute for Basic Science (IBS), Korea)

P-3

Negative Electronic Compressibility and Tunable Spin-Splitting in WSe₂

J. M. Riley (SUPA, University of St Andrews, UK)

P-4

Interaction-driven spin-nematicity and magnetic double-Q phases in iron pnictides

B. M. Andersen (Niels Bohr Institute, University of Copenhagen, Denmark)

P-5

The optical properties in superconducting optimally electron-doped $Ca_{8.5}La_{1.5}(Pt_3As_8)(Fe_2As_2)_5$

Y. S. Kwon (Department of Emerging Materials Science, DGIST, Korea)

P-6

Optical observations of SDW fluctuations cooperate with nematic order in Ba122 iron-based superconductors

B. Xu (Center for High Pressure Science and Technology Advanced Research, China)

P-7

Photoexcited nonequilibrium dynamics of *c*-axis Josephson plasma in La_{2-x}Sr_xCuO₄

K. Tomari (Department of Physics, The University of Tokyo, Japan)

P-9

Terahertz nonlinear response in an optimally-doped YBa₂Cu₃O₇ single crystal

Y. I. Hamada (Department of Physics, The University of Tokyo, Japan)

P-10

Theory of Inelastic X-Ray Scattering for Cuprates and Iron Arsenides

T. Tohyama (Department of Applied Physics, Tokyo University of Science, Japan)

P-11

The role of Hund's coupling in the correlations and the nematicity of iron superconductors

L. Fanfarillo (International School for Advanced Studies (SISSA/ISAS) and CNR-IOM Democritos, Italy)

P-12

Investigation of Precursor Superconducting State in YBCO through In-plane Infrared Optical Spectroscopy

K. Lee (Department of Physics, Osaka University, Japan)

P-13

Critical Charge Fluctuations in Iron Pnictide Superconductors

G. Blumberg (Rutgers University, Department of Physics and Astronomy, USA)

P-14

Chirality density wave of the "hidden order" phase in URu₂Si₂

G. Blumberg (Rutgers University, Department of Physics and Astronomy, USA)

P-15

Non-Trivial Metallic Surface State of a Kondo Semiconductor YbB₁₂

K. Hagiwara (Department of Physics, Osaka University, Japan)

P-16

Detailed optical spectroscopy of the hybridization gap and the hidden order transition in high quality URu₂Si₂ single crystals

N. Bachar (Department of Quantum Matter Physics, University of Geneva, Switzerland)

P-17

Study on electronic states of the mixed-valence compound SmS by resonance x-ray emission spectroscopy under high pressure

K. Imura (Graduate School of Science, Nagoya University, Japan)

P-18

Lattice and Magnetostrictive Contributions to the Internal Energy in Cobalt Oxide Observed by THz-TDS

M. Tatematsu (Graduate School of Science, Kobe University, Japan)

P-19

Observation of Negative Pulse Delay in Photo-Excited Silicon by THz-TDS

T. Moriyasu (Graduate School of Science, Kobe University, Japan)

P-20

Microwave Spectroscopy at mK Temperatures Using Planar Devices

M. Scheffler (1. Physikalisches Institut, Universität Stuttgart, Germany)

<u>May 31 (Tue.)</u>

Poster II

Chair: M. Fujita (Tohoku Univ.)

P-21

Strain effect on the visible emission in ferroelectric nanotubes: template and wall-thickness effect

Y. S. Lee (Department of Physics, Soongsil University, Korea)

P-22 (same as C-13)

From confined spinons to emergent fermions: Evolution of elementary excitations in a transverse-field Ising chain

Z. Wang (Experimental Physics V, Center for Electronic Correlations and Magnetism, Institute of Physics, University of Augsburg, Germany)

P-23

Electric-Field Induced Magnetization in Antiferromagnetic Chromium Oxide

T. Shinkai (Graduate School of Science, Kobe University, Japan)

P-24

Non-reciprocal directional dichroism in the canted AFM phase of BiFeO₃ at THz frequencies

U. Nagel (National Institute of Chemical Physics and Biophysics, Estonia)

P-25

Ultrafast Lattice Dynamics in Multiferroic Cupric Oxide

T. Kohmoto (Graduate School of Science, Kobe University, Japan)

P-26

Photo-induced phase transition of SmS

Y. Takeno (Department of Physics, Osaka University, Japan)

P-27

Universalities of dielectric response in biological materials

B. P. Gorshunov (Moscow Institute of Physics and Technology, Russia)

P-28

Anomalous quasi-two dimensional electronic state in $Co_3Sn_{2-x}In_xS_2$ shandites

M. A. Kassem (Department of Materials Science and Engineering, Kyoto University, Japan)

P-29

Low energy electronic structure of the semimetal LaSb₂

M. Michiardi (Department of Physics and Astronomy, Aarhus University, Denmark)

P-33

Optical probe of spin correlations in the Kitaev magnet RuCl₃

L. Sandilands (IBS CCES & Dept. of Physics, Seoul National University, Korea)

P-34

THz magneto-optic study of Ni(Cl_{1-x}Br_x)₂·4SC(NH₂)₂ with x=0 and x=0.13

D. Hüvonen (National Institute of Chemical Physics and Biophysics, Estonia)

P-35

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Neutron-scattering and muon spin rotation/relaxation studies on the spin correlations in $Pr_{1.4-x}La_{0.6}Ce_xCuO_4$

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Optical Conductivity of Excitonic Insulator Ta2NiSe5 under High Pressure

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Rotating dipoles encapsulated in C₆₀

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NbN-Based Terahertz Superconducting Metamaterials

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Electronic structure of $Sr_{1-x}Ca_xFe_2(As_{1-y}P_y)_2$ (x = 0.08, y = 0.25) revealed by angle resolved photoemission spectroscopy

T. Adachi (Department of Physics, Osaka University, Japan)



Oral session abstract

Pseudogap and its Interplay with the Superconducting Gap in Cuprates Superconductors

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Much of the current research on the pseudogap phase of high-temperature cuprate superconductors is dominated by the quest to understand its microscopic origin and how it is related to the superconducting gap. Here we report electronic Raman scattering measurements on cuprates both in the normal and superconducting states.

We reveal in the first part how the pseudogap manifests itself in the normal state Raman response [1,2] and why it disappears at high doping level in the cuprate phase diagram. More precisely we show that the pseudogap is sensitive to the Fermi surface topology [3].

In the second part our study focuses on the superconducting state. Our main finding is that the superconducting pair-breaking peak is associated with a dip on its higher-energy side, disappearing together at T_c . We are able to interpret this observation as a new interplay between the pseudogap and the superconducting gap coexisting below T_c . The pseudogap and the superconducting gap share the same electronic states below the Fermi level but compete for the same electrons above the Fermi level. This non trivial scenario sheds new light on the long-standing debate about the role of the pseudogap in the unconventional pairing mechanism of cuprate superconductors [4].

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New insight into the strange-metal and pseudogap behavior of the cuprates

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The discovery of high-temperature superconductivity in the cuprates three decades ago triggered a tremendous amount of scientific activity, yet it remains a challenge to understand the metallic "normal" state of these fascinating materials [1]. I will review neutron scattering [2], X-ray scattering [3] and charge transport [4] results for the simple tetragonal compound HgBa₂CuO_{4+ δ} that reveal an unusual magnetic response, charge-density-wave correlations and Fermi-liquid behavior below optimal hole doping. Comparison with the properties of compounds that exhibit a higher degree of disorder and/or lower structural symmetry gives significant new insight into the normal-state of the cuprates.

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Point nodes persisting far beyond T_c in Bi2212

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In cuprates, the energy gap (pseudogap) starts opening at a temperature much higher than T_c , in some cases above the room temperature. Many experimental evidences point to a competing-order origin, rather than the preformed pair, for the pseudogap observed around the antinode. On the other hand, the energy gap near the node is expected to open due to the electron pairing as it is free from a contamination by the competing order establishing around the antinode. Unveiling the nature of the spectral gap near the node is therefore crucial to elucidate the superconducting mechanism in cuprates. A difficulty however is the small magnitude of the gap, which has been challenging the experimentalists to investigate.

It has been proposed that the pairing-gap evolution with temperature simply follows the conventional BCS function, and Fermi arcs emerge at T_c , marking momentum borders between the superconducting and the competing pseudogap regions [1]. In contrast, a contrasting view was recently proposed [2,3]; its underlying idea is that one should discard the notion of electron quasiparticles, instead pay attention to the density of states, which is an effective way of judging the existence of energy gap. Accordingly a momentum integration of angle-resolved photoemission spectroscopy (ARPES) spectra has been performed over a selected part of the momentum space. This quantity contributed from the nodal region was found to have a gap-like structure even above T_c . To address the controversial issue, we use a laser ARPES capable of an ultra-high energy resolution and a bulk-sensitivity, and provide a missing evidence for a single-particle gap near the node (fig.1), signifying the point-node gap persistent far above T_c in Bi₂Sr₂CaCu₂O_{8+d} [4].



Fig.1: (a) Dispersion maps at T_c (color lines in the inset of (d)). Each map is divided by the Fermi function. (b) Symmetrized EDCs at $k_{\rm F}$ over a wide range of ϕ (circles in the inset of (d)) at 10K and T_c (=92K), respectively. (d) Fermi angle ϕ dependence of spectral peak energies at 10K and T_c , determined from the peak positions of spectra in (b) and (c), respectively. The inset indicates surface the Fermi with measured momentum points. (e) Schematic behavior of the energy gap summarized based on our ARPES data. Temperature evolution of the point-node gap with a BCS-type gap function (inset curve) is depicted. (f,g) The point-node state, persisting beyond $T_{\rm c}$ up to the temperature of pair formation (T_{pair}) . (h) Emergence of the gapless Fermi arc around the node.

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Observation of triple-layer splitting in high-*T*_c cuprate Bi₂Sr₂Ca₂Cu₃O_{10+δ} observed by ARPES

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Effects of intra-multilayer interaction between the CuO₂ planes, which may contribute to the enhancement of critical temperature (T_c) in the multi-layer high- T_c cuprate superconductors (HTSCs) have been investigated to elucidate the mechanism of superconductivity [1]. The Bi-based HTSC can be classified by the number of the neighboring CuO₂ layers (n): single-layer (n = 1) Bi₂Sr₂CuO_{6+ δ} (Bi2201), double-layer (n = 2) Bi₂Sr₂CaCu₂O_{8+ δ} (Bi2212), and triple-layer (n = 3) Bi₂Cr₂Ca₂Cu₃O_{10+ δ} (Bi2223). The T_c of optimally doped Bi2223, ~ 110 K, which is the highest T_c in the Bi-family cuprates. In spite of both extensive experimental and theoretical studies [2-6], the microscopic origin of the T_c enhancement in the triple-layer HTSCs still remains unclear.

In recent ARPES studies, we have reported two bands originating from the outer and inner CuO_2 planes in Bi2223 [7-9]. In this study, we have performed an ARPES to reveal the polarization dependence of the electronic structure using low-energy photons with linear polarization along the Cu-O and Cu-Cu bond directions, and we observed three bands and three Fermi surfaces resulting from interaction between the three CuO_2 planes. Based on the observation, we will discuss the origin of the triple-layer splitting in Bi2223.



Fig. 1. Energy-momentum intensity plots in the Cu-O bond direction taken with $h\nu = 8$ and 8.5 eV at T = 12 K. ARPES intensity plots [(b)-(e)] correspond to cuts in panel (a). IP, BOP, and AOP denote the inner-plane, bonding outer-plane, and antibonding outer-plane bands, and SS is the superstructures.

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Light control of correlated electron systems

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Driving infrared-active modes to large amplitude will deform the lattice along selected coordinate via non-linear coupling. It has been shown as a powerful tool to achieve highly unconventional states inaccessible under equilibrium conditions. Combing with ultra-broadband transient optical spectroscopy, the time-dependent electrodynamics over the whole far-infrared region can be probed. In this talk, I will show two examples: the light-induced transient superconductivity in bilayer cuprate superconductors, and the phonon-driven insulator to metal transition in nickelate heterostructures.

(1) <u>Light-induced transient superconductivity</u>: excitation of the apical oxygen phonon in the cuprate superconductor $YBa_2Cu_3O_{6+d}$ promotes a transient superconducting state.[1] The total interlayer coherence is conserved, that the inter-bilayer coherence is enhanced at the expense of the intra-bilayer coupling.[2]

(2) <u>Light-induced insulator-metal transition</u>: by driving the infrared-active phonon in the LaAlO₃ substrate, we discovered a long-lived, five-order-of-magnitude increase in the low-frequency conductivity in the NdNiO₃ film.[3] I will present our recent ultra-broadband transient spectroscopy studies on NdNiO₃/LaAlO₃ and SmNiO₃/LaAlO₃ heterostructures, which revealed the mechanism of the light-induced insulator-metal transition. [4]

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Control of Topology in Quantum Materials by Laser

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The effect of strong laser on the topology of many body systems is becoming a hot topic [1,2,3]. A theoretical proposal was made in two dimensional Dirac systems where an application of circularly polarized light was shown to turn the system into a quantum Hall state [1,2]. One can see this as a dynamical realization of the Haldane model of a quantum Hall state without Landau levels [4]. This effect can be understood with the help of the Floquet theory for driven quantum systems, where the circularly polarized light plays the role similar to the "next nearest hopping with a nontrivial phase factor" in the Haldane model.

Floquet theory can be applied to other many-body systems as well. We have been studying the effect of laser on quantum magnets, multiferroics, and two dimensional gas [5]. In my talk, I will report our recent progresses.

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Nonequilibrium Charge Dynamics in Strongly Correlated Electron Systems

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A numerical method to calculate optical conductivity based on a pump-probe setup is discussed [1]. Its validity and limits are demonstrated via the numerical simulations on the half-filled one-dimensional extended Hubbard model both in equilibrium and out of equilibrium. By employing either a step-like or a Gaussian-like probing vector potential, it is found that in nonequilibrium, the method can be related to the linear response theory [2] or a different generalized Kubo formula [3], respectively. The observation reveals the probe-pulse dependence of the optical conductivity in nonequilibrium, which may have its applications in the theoretical analysis of ultrafast spectroscopy measurements.

The numerical method is applied to investing nonequilibrium charge dynamics in the various phases [spin-density wave (SDW), charge-density wave (CDW), and single-superconducting (sSC) phases] of the hall-filled one-dimensional extended Hubbard model [4,5]. In the SDW, the origin of a low-energy in-gap excitation appearing after pumping is attributed to the even-odd parity of the photoexcited states, while in the CDW an in-gap state is due to confined photogenerated carriers. The signature of the in-gap excitations can be identified as a characteristic oscillation in the time evolution of physical quantities. Quenching parameters from CDW region to sSC region produces a signature of pairing of electrons in the optical conductivity, giving an implication to recent reports on a signature of enhanced superconductivity by photoexcitations.

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Topological aspects of nonlinear optical responses

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There are a variety of nonlinear optical effects including higher harmonic generations, photovoltaic effects, and nonlinear Kerr rotations. A recent remarkable progress in the photovoltaic effect is the high efficiency solar cell action in perovskite oxides without inversion symmetry. In this case, the noncentrosymmetric crystal structure replaces the role of artificial structures such as p-n junctions in conventional solar cells. One of the proposed mechanisms for this phenomenon is so called "shift-current" which is supported by a band structure lacking inversion symmetry and is related to the Berry connection of Bloch wavefunctions.

Motivated by these, we explore topological aspects of the nonlinear optical responses [1]. To this end, we employ the Keldysh method combined with the Floquet formalism. In this formalism, effective band structures are defined under an electric field periodic in time, which provides a concise description of nonequilibrium steady states. This enables us to describe the shift-current, nonlinear Kerr rotation, and the photo-induced change in the order parameters in a unified fashion. We connect these nonlinear optical responses to topological quantities involving the Berry connection and the Berry curvature. It is found that vector fields defined with the Berry connections in the space of momentum and/or parameters govern the nonlinear responses. We also discuss how the shift current is affected by the electron-electron interaction, including the formation of excitons [2].

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Magnetoelectric responses from topological magnets

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Intriguing mangetoelectric responses can be anticipated to emerge from topological magnets characterized by topological indexes either in real space or in momentum space. One such example is magnetic skyrmions in noncentrosymmetric, e.g. chiral-lattice, mangets as protected by skyrmion number and endowed with real-space emergent magnetic flux. Dynamical responses of skyrmions coupled with electron transport and dielectric characteristics are investigated in terms of Lorentz transmission electron mcicroscopy/holography, small-angle neutron scattering, microwave spectroscopy, and ultrafast pump-probe spectroscopy.

One other important example of topological magnets is magnetic topological insulators, in which the spin-momentum locking as well as the magnetization-induced mass-gap shows up to form the ideal 2D Weyl fermion system at surface. With control of the magnetizations on the top and bottom surfaces of the thin film, quantum anomalous Hall state and quantum magnetoelectric state can be formed and the topological magneto-optical effects also show up therein.

New results on the magnetoelectric responses from these topological magnets are presented.



Magneto-optics of massless and massive electrons

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Intriguing analogies to relativistic systems have largely helped to understand the electronic properties of various solid-state systems. These include, for instance, 2D graphene, surfaces of topological insulators as well as novel 3D Dirac/Weyl semimetals, as well as certain narrow gap semiconductors. In this talk, I will discuss how the relativistic-like dispersion of electrons in solids impacts the basic magneto-optical properties of such materials [1]. The attention will be in particular paid to two specific systems: bismuth selenide (Bi_2Se_3) and cadmium arsenide (Cd_3As_2).

 Bi_2Se_3 is a representative 3D topological insulator with well-known surface states, but also, as deduced from recent Landau level spectroscopy experiments [2], with interesting electronic states in bulk. These may be described by a simple Dirac-type Hamiltonian for massive relativistic particles, which implies that electrons and holes in bulk Bi_2Se_3 are in a close analogy to massive relativistic spin-1/2 fermions in quantum electrodynamics (e.g., electrons in vacuum).

 Cd_3As_2 has been recently identified as a 3D topological Dirac semimetal – the first discovered to be stable under ambient conditions – which hosts a pair of Dirac nodes in the vicinity of the Brillouin center. Recent high-field magneto-reflectivity experiments performed on this material will be discussed [3]. These imply that this material hosts also another kind of massless charge carriers – massless Kane electrons. These particles appear at an energy scale that is significantly larger as compared to Dirac electrons and they are dominantly responsible for the optical and magneto-optical response observed in the infrared spectral range.

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Electromagnetic response of semimetals from wavefunction geometry and topology

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Many topological phases have been discovered recently that do not depend on strong correlations but can be well described at the independent-electron level using concepts such as Berry's phase and topological invariants. The next step was to figure out measurable responses generated by these wavefunction properties, and surprisingly many of the same mathematical objects that determine responses in topological phases are useful more broadly. An example in insulators is the orbital magnetoelectric polarizability. This talk focuses on (semi-)metals, where we show how a number of linear and nonlinear electromagnetic responses at low frequency, including the chiral/gyrotropic magnetic effects and some pieces of secondharmonic generation, are determined by Berry phases and orbital moments of Bloch electrons.



Non Linear Terahertz Behavior of Bi₂Se₃ Topological Insulator

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In this talk, we will discuss the non-linear optical response in the Terahertz (THz) range of the Dirac electron gas at the surface of Bi_2Se_3 topological Insulator. Here, we demonstrate that in Bi_2Se_3 films, an Electromagnetic Induced Transparency is achieved under the application of a strong terahertz (THz) electric field. This effect, concomitantly determined by harmonic generation and charge-mobility reduction, is exclusively related to the presence of Dirac electron in Bi_2Se_3 , and opens the road towards tunable THz nonlinear optical devices based on Topological Insulator materials.



Direct measurement of proximity-induced magnetism at the buried interface between a topological insulator and a ferromagnet

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When a topological insulator (TI) is in contact with a ferromagnet, both time reversal and inversion symmetries are broken at the interface^{1,2}. An energy gap is formed at the TI surface, and its electrons gain a net magnetic moment through short-range exchange interactions. Magnetic TIs can host various exotic quantum phenomena, such as massive Dirac fermions³, Majorana fermions⁴, the quantum anomalous Hall effect (QAHE)^{5,6} and chiral edge currents along the domain boundaries^{1,2}. However, selective measurement of induced magnetism at the buried interface has remained a challenge. Using magnetic second harmonic generation (MSHG), we directly probe both the in-plane and out-of-plane magnetizations induced at the interface between the ferromagnetic insulator (FMI) EuS and the three-dimensional TI Bi₂Se₃. Our findings not only allow characterizing magnetism at the TI-FMI interface but also lay the groundwork for imaging magnetic domains and domain boundaries at the magnetic TI surfaces⁷.



Fig. 1. The second harmonic generation (SHG) experiment. a, Schematic of the experimental setup. Magnitude of SHG was measured as a function of input polarization angle while an in-plane or an out-of-plane magnetic field was applied to the sample. PBS: polarizing beam splitter, PMT: photomultiplier tube. b, In EuS-Bi₂Se₃ heterostructures, surface SHG is generated from the EuS-Bi₂Se₃ and Bi₂Se₃-sapphire interfaces. c, SHG Intensity as a function of input polarization angle from a 7 nm (EuS)-7 QL (Bi₂Se₃) sample. A change in the anisotropy pattern is observed when an in-plane magnetic field of +300 Oe (orange) or -300 Oe (purple) was applied to the sample at 4 K. Interface ferromagnetism was measured using this SHG setup.

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Terahertz photoconductivity in semiconductor nanostructures: Effective medium theory aspects

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Ultrafast photoconductivity and charge carrier transport in nanostructured semiconductors is poorly understood on the microscopic level in many systems. The THz spectroscopy constitutes a suitable method to probe on ultrafast time scale the nanoscopic motion of conduction band charges confined within nanostructures without the need to deposit electrical contacts.

Straightforward fitting of the raw terahertz conductivity spectra by the Drude-Smith model, which was abundantly used in the literature, did not lead to a significant advance in an in-depth understanding of these phenomena [1]. This is mainly because of the depolarization fields which build up in any inhomogeneous system. On the one hand, these fields reflect the sample morphology and their understanding in each particular system may provide new information about the nanostructure connectivity. On the other hand, the effect of unknown depolarization fields can hide or distort fingerprints of the nanoscopic transport.

We developed a general analytical description of the THz photoconductivity transmission spectra where the effects of depolarization fields are systematically disentangled from the local carrier response function both for non-percolated samples and for samples with complex percolation pathways [1]. We show that the key parameter to be systematically varied in the measurements is the photoexcited carrier density in nanocrystals (controlled e.g. by the pump pulse fluence in optical pump – THz probe experiments).

We carry out ultrafast terahertz photoconductivity measurements in silicon nanocrystal superlattices [2]. Silicon nanocrystals are prepared by thermal decomposition of Si-rich 2–5 nm thick SiO_x layers with $0.64 \le x \le 1$ [3]. The control of the layer thickness and composition allows us to tune independently the NC size and concentration. Moreover, nanometer thick SiO_x layers are sandwiched between isolating SiO₂ barriers, which makes the arrangement of the nanocrystals truly two-dimensional. We capture and describe both intra-nanocrystal charge transport and charge transport within aggregates of nanocrystals in samples with various compositions close to the percolation threshold. We assess the morphology, namely the degree of percolation of the photoconducting component and the connectivity of individual nanocrystals.

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nano-FTIR: Imaging & Spectroscopy with 10 nm Spatial Resolution

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Scattering-type scanning near-field optical microscopy (s-SNOM) has evolved as one of the key techniques to study characteristic properties of materials with a spatial resolution of 10 nm, thus overcoming the diffraction limit of conventional optical microscopy and spectroscopy [1]. Accepting a broad spectral range including visible, near-IR, mid-IR and even far-IR (THz) frequencies, s-SNOM has a high application potential in many research fields such as semiconductor technology, graphene plasmonics, photonics, and correlated electron systems.

nano-FTIR spectroscopy and nanoscale plasmon interferometry imaging of graphene and other 2D materials like h-BN as well as their van der Waals hetero-structures is now possible routinely with the development of Fourier transform infrared spectroscopy on the nanoscale ("nano-FTIR") [2,3]. As example, Fig. 1 (left) shows a near-field image, where double fringes caused by plasmon interference reveal the grain boundaries in graphene. In addition, a nano-FTIR spectrum is shown in Fig. 1 (right), featuring the graphene-enhanced phonon resonance of SiO₂ in amplitude and phase spectrum.

This presentation will show that s-SNOM provides contact-free direct access to the plasmonic properties, local conductivity, electron mobility and intrinsic doping.

Further, an overview and outlook to the near future of new technical developments of the nano-FTIR microcopy will be given, including nano-THz imaging and time-domain spectroscopy, ultra-fast experiments, photocurrent nanoscopy, and the extension of the technology to cryogenic temperatures (cryo-sSNOM).



Fig. 1. s-SNOM: nano-FTIR image (left) and nano-FTIR spectrum (right) measured on graphene on SiO_2 substrate. Grain bounderies are reaveled by the plasmon interference fringes, and the amplitude and phase resolved spectra provide access to the doping level of the graphene.

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Low-Energy Electrodynamics in Solids

Nanospectral Imaging of Phonon Polaritons and Single Plasmonic Nanocrystals with Synchrotron Infrared Nano Spectroscopy (SINS)

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By combining scattering-type-scanning near-field optical microscopy (s-SNOM) with infrared light from a synchrotron source, synchrotron infrared nano-spectroscopy (SINS) enables sensitive vibrational chemical imaging, spanning the mid- and far-infrared regions $(300-5000 \text{ cm}^{-1})$ with < 25 nm spatial resolution [1]. The spatial field localization at the tip apex results in a large near-field momentum sufficient to optically excite phonon polaritons (PhPs), which are quasiparticles resulting from the strong coupling of photons with optical phonons. Here, we use SINS to image the PhP spectral response in thin hexagonal boron nitride (hBN) crystals. The large spectral bandwidth of the synchrotron source enables the simultaneous measurement of both the out-of-plane (780 cm⁻¹) and in-plane (1370 cm⁻¹) hBN phonon modes. In contrast to the strong and dispersive in-plane mode, the out-of-plane mode PhP response is weak. Measurements of the PhP wavelength reveal a proportional dependence on sample thickness for thin hBN flakes [2]..

Wide bandgap semiconductors such as metal oxides can be rendered plasmonic by doping to introduce exogenous free carriers. In the past few years, a number of doped metal oxides (i.e. transparent conducting oxides) have been prepared as colloidal nanocrystals. These nanocrystals have synthetically tunable doping levels, shapes, and sizes, giving rise to a broad range of localized surface plasmon resonance (LSPR) phenomena. Single nanocrystal mid-IR absorption measurements allow us to rationally compare the LSPR characteristics of different types of plasmonic semiconductor nanocrystals and to predict their suitability for emerging applications.



Fig. 1. (left) Synchrotron IR light illuminates the conductive AFM tip, which launches polariton waves that propagate radially outward from the tip along the hBN surface and reflect off the edges. (right) SINS amplitude spatio-spectral linescan obtained perpendicular to the edge of a 147 nm-thick hBN flake.

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Investigation of nanodomain properties in the phase-separated manganite by probing electron dynamics

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The 3d transition metal oxides have emerged as exotic materials with various functionalities such as the colossal magnetoresistivity (CMR) in manganites. In a typical perovskite manganites (La,Pr,Ca)MnO₃ (LPCMO), the observed CMR is associated to the huge order-of-magnitude insulator-metal transition (IMT) [1] from an insulator behavior at a high temperature to a metallic behavior at a low temperature through a critical transition temperature T_{IM} . Since the phase-separated metal and insulator domains coexist around T_{IM} , the CMR in manganites are considered to be dominated by competing nanoscale electronic phases. Therefore, understanding the electrical transport property: the quantitative evaluation of change of metal (or insulator) phase ratio and their microscopic and macroscopic conductivity is required. To realize simultaneous investigation of the metal population $P_M(T)$ and the dc conductivity $\sigma_{dc}(T)$, THz time domain spectroscopy (THz-TDS) has been employed.

The temperature-dependent conductivities at THz frequency range from 0.5 THz to 2.4 THz, $\sigma_{THz}(\omega,T)$, have been obtained for LPCMO film and nanostructured samples in the temperature region from 10 K to 250 K. The conductivity increased with decreasing temperature, which corresponds to the IMT in LPCMO. To describe the $\sigma_{THz}(\omega,T)$ behavior corresponding to the coexistence regime and estimate THz conductivity in the vicinity of 0 THz, $\sigma_0(T)$, and $P_M(T)$ concurrently, we have proposed an insulator-metal composite model [2] by incorporating the Austin-Mott model, which characterizes the hopping of localized electrons and the Drude model, which explains the behavior of free electrons:

$$\sigma_{\text{THz}}(\omega, T) = (1 - P_M(T))(\sigma_0^{\text{I}}(T) + A\omega^{0.5}) + P_M(T)\frac{\sigma_0^{\text{M}}(T)}{1 + \tau^2 \omega^2},$$
(1)

where $\sigma_0^{I}(T)$ and $\sigma_0^{M}(T)$ are the THz conductivity at 0 THz for the insulator and metal phases, respectively. Equation (1) showed the good agreement with the observed $\sigma_{THz}(\omega,T)$ curves at all temperatures. The $\sigma_0(T)$ was numerically determined by extrapolating $\sigma_{THz}(\omega,T)$ curve to 0 THz. The obtained $\sigma_0(T)$ changed by about five orders of magnitude through the T_{IM} , approximately 130 K during the cooling process, closely reproducing the $\sigma_{dc}(T)$ curve. Simultaneously, the evaluated $P_M(T)$ revealed the phase condition.

Our composite model for THz-TDS illustrates the potential for the investigation of dc transport dynamics for phase-separated materials in a contact-free manner. Additionally, we successfully observed how the insulator/metal phases behave at a scale of 10 nm order using the cathode luminescence measurement combined with scanning electron microscopy. Since the luminescence intensity difference originates from the different luminescent efficiency of a fluorescent layer on metal/insulator due to the interface energy transfer effect, the arrangement of metal and insulator domains with 70-200 nm in size were seen [3].

In the presentation, our detail analyses and results will be shown.

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Exploration of superconductivity in FeSe films and electron doped Sr₂IrO₄

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Interface and surface become important playgrounds for unconventional superconductivity, since they bring broken symmetry, competing orders, charge transfer, strain and other factors into the problem. Recently, interfacial superconductivity up to 75K has been discovered in FeSe/STO and FeSe/BTO interfaces [1,2]. In this talk, I will demonstrate that the combination of angle resolved photoemission spectroscopy (ARPES), scanning tunneling microscopy (STM) and molecular beam epitaxy (MBE) is a powerful tool to study the superconductivity at interfaces and surfaces. Specifically, I will present: 1. our recent efforts in the understanding of the pairing symmetry of FeSe/STO [3]; 2. the anomalous phase diagram of FeSe films upon surface electron doping [4,5]; 3. the discovery of signatures of high temperature superconductivity in electron doped Sr_2IrO_4 [6].

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Spin-Orbit Coupling and Nematicity in Iron-Based Supercondutors

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Spin-orbit coupling is a fundamental interaction in solids that can induce a broad range of unusual physical properties, from topologically non-trivial insulating states to unconventional pairing in superconductors. In iron-based superconductors its role has, so far, not been considered of primary importance, with models based on spin- or orbital fluctuations pairing being used most widely. Using angle-resolved photoemission spectroscopy, we directly observe a sizeable spin-orbit splitting in all the main members of the iron-based superconductors. We demonstrate that its impact on the low-energy electronic structure and details of the Fermi surface topology is stronger than that of possible nematic ordering. The largest pairing gap is supported exactly by spin-orbit-coupling-induced Fermi surfaces, implying a direct relation between this interaction and the mechanism of high-temperature superconductivity.



Fig. 1. a–c, Results of the band-structure calculations of FeSe excluding SOC (grey lines) and including SOC (blue lines) along the high-symmetry directions. d–f, Corresponding experimental data, shown as second derivatives of the raw data. Note that in c two single features are observed at the M-point, contrary to the expected two double features in the nematic scenario. g–i, Same for 122 materials. Dashed lines in h show the expected dispersions in the unoccupied part of the spectrum. j,k, Same for Co-SmFeAsO. l, Comparison of the experimental values for SOC obtained by reading the peak positions from the corresponding EDCs shown in Supplementary Fig. 3, with the theoretical values. 'el' means electron pocket.

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Magnetism, superconductivity, and spontaneous orbital order in iron-based superconductors: who comes first and why?

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Magnetism and nematic order are the two non-superconducting orders observed in iron-based superconductors. To elucidate the interplay between them and ultimately unveil the pairing mechanism, several models have been investigated. In models with quenched orbital degrees of freedom, magnetic fluctuations promote stripe magnetism which induces orbital order. In models with quenched spin degrees of freedom, charge fluctuations promote spontaneous orbital order which induces stripe magnetism. We develop an unbiased approach, in which we treat magnetic and orbital fluctuations on equal footing. Key to our approach is the inclusion of the orbital character of the low-energy electronic states into renormalization group analysis. Our results show that in systems with large Fermi energies, such as BaFe2As2, LaFeAsO, and NaFeAs, orbital order is induced by stripe magnetism. However, in systems with small Fermi energies, such as FeSe, the system develops a spontaneous orbital order, while magnetic order does not develop. Our results provide a unifying description of different iron-based materials.

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Origin of the resistive anisotropy in the electronic nematic phase of BaFe₂As₂ revealed by optical spectroscopy

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The ferroprictides harbor a structural tetragonal-to-orthorhombic transition at T_s that may either coincides or precedes a transition into a long-range antiferromagnetic order at T_{N_1} usually ascribed to a spin-density-wave state. There is an ongoing debate as to whether the dc anisotropy (both in the nematic phase $(T_N < T < T_s)$ or in the tetragonal phase above T_s in the presence of an external symmetry breaking field) is primarily determined by the Fermi surface or scattering rate anisotropy. We measure the in-plane optical reflectivity of BaFe₂As₂ over a broad spectral range, covering the energy interval from the far infrared to the ultraviolet, at several combinations of uniaxial pressure, used to detwin the specimen, and temperature. Our goal is to probe the anisotropic response in the real part $\sigma_1(\omega)$ of the optical conductivity, extracted from the reflectivity data via Kramers-Kronig transformations. We thus elucidate how the anisotropic optical metallic response evolves as a function of stress, considered as an external symmetry breaking field, and across the ferro-elastic structural transition at $T_s = T_N =$ 135 K. The infrared response reveals that the dc transport anisotropy in the orthorhombic antiferromagnetic state is determined by the interplay between the Drude spectral weight and scattering rate, but that the dominant effect is clearly associated with the metallic spectral weight (Fig. 1). In the paramagnetic tetragonal phase, though, the dc resistivity anisotropy of strained samples is almost exclusively due to stress-induced changes in the Drude weight rather (Fig. 1) than anisotropy in the scattering rate. This result definitively establishes that the primary effect driving the resistivity anisotropy in the paramagnetic orthorhombic phase (i.e., the electronic nematic state) is the anisotropy of the Fermi surface [1].

Drude weight anisotropy



Fig. 1: Temperature and stress dependence of the Drude weight anisotropy

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Polar Kerr effect studies of heavy fermion superconductors

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Heavy fermion materials have proven to be a rich platform for the study of (1) magnetic, charge, and superconducting orders; and (2) the interactions between these ordered states. In particular, a wide variety of unconventional superconductors have been identified within this family. A full characterization of these order parameters requires knowledge of which symmetries are broken relative to the (strongly correlated) normal state.

In this talk we focus specifically on the role of broken time-reversal symmetry (TRS) in identifying the order parameter symmetry of heavy fermion superconductors. In terms of experiment, broken TRS can be difficult to directly detect. However, one approach is to look for polar Kerr effect (PKE), which arises from differences between the right- and left-circular indices of refraction in a TRS-breaking medium when probed by normally incident light. Due to this geometry, PKE is sensitive only to broken TRS, generally of the type resulting in a net moment along the direction of the incident beam. Although the amount of optical rotation due to PKE from a TRS-breaking superconducting order parameter is on the order of 1 µrad or less, such weak signals can been resolved with an appropriately designed experimental apparatus [1].

We present the results of high-sensitivity PKE measurements on several heavy fermion materials with 4*f* and/or 5*d* electronic character: UPt₃ [2], CeCoIn₅ [3], and PrOs₄Sb₁₂ [3]. An absence of PKE in CeCoIn₅ is consistent with the (TRS-preserving) d_{x2-y2} gap symmetry proposed by measurements sensitive to the nodal structure of the gap. In contrast, UPt₃ and PrOs₄Sb₁₂, in addition to Sr₂RuO₄ [4] and URu₂Si₂ [5], show evidence of broken TRS in at least one superconducting phase, indicating that superconductivity in these systems is described by a complex two-component order parameter.

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Non-Fermi-Liquid Behavior in the THz Response of CeCoIn₅

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Quantum criticality can lead to exotic states in metals that are often classified by their temperature-dependent charge transport. Their frequency-dependent response can feature equally fascinating properties, including unconventional power-law behavior. Here, heavy-fermion metals are a prime material class of interest: for several compounds, including CeCoIn₅, non-Fermi liquid behavior has been established from dc transport, whereas their charge dynamics have been studied much less. This is mostly due to the severe experimental difficulties involved, namely optical spectroscopy on highly reflective metals at very low frequencies and temperatures.[1] We overcome these difficulties by THz transmission measurements (detecting amplitude and phase of the THz signal) [2,3] on high-quality thin films of CeCoIn₅.[4,5] We are particularly interested in the extended temperature range (above the superconducting transition) where the dc resistivity of CeCoIn₅ exhibits a linear temperature dependence, which is a signature of non-Fermi-liquid behavior.

We have measured the optical response of $CeCoIn_5$ at temperatures down to 3 K and at frequencies between 0.2 and 1.1 THz, i.e. at matching energy scales of the non-Fermi-liquid regime. We find characteristic metallic behavior in the THz response, and in particular we can follow the transport relaxation rate move through our spectral range upon cooling. Using the extended Drude formalism, we deduce the frequency dependence of relaxation rate and effective mass of the charge carriers. Here we find a strong increase of the relaxation rate with increasing frequency that demonstrates optical non-Fermi-liquid behavior and which even surpasses the temperature dependence at zero frequency. The effective mass also exhibits a strong temperature dependence, which allows us to observe the evolution of the heavy-fermion state upon cooling.

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Electric field control of octahedra rotation on the surface of Sr₂RuO₄.

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 MO_6 octahedron is the building block of many transition metal oxides and contributes to the electronic states near the Fermi energy. As a result, MO_6 dominantly determines the electronic properties. MO_6 octahedra in these materials are quite often rotated. The octahedra rotation was found to greatly affect the electronic structure, causing exotic phenomena such as metal insulator transition. Therefore, controlling the octahedra rotation would be interesting in both fundamental science and application point of views.

The RuO₆ octahedra in the surface layer of Sr_2RuO_4 are known to be rotated. By using alkali metal dosing method and angle resolved photoemission, we show that we can control the rotation of the surface RuO₆ octahedra. We find the RuO₆ octahedra rotation angle decreases as K is dosed on the surface of Sr_2RuO_4 , resulting in disappearance of the folded bands. We also investigated the phenomenon by using the low energy electron diffraction and provide a direct evidence for the reduction in the rotation angle. The origin of the reduced octahedra rotation will be discussed in conjunction with density functional calculation study.



The Spectral Function of Honeycomb Na₂IrO₃ by ARPES upon Li Substitution

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In recent years iridium oxides have received the attention of the scientific community owing to the strong interplay between spin-orbit coupling, one-electron hopping, and Coulomb repulsion. This unique combination of several comparable energy scales makes this class of compound extraordinarily interesting for studying correlated electronic phenomena. Particularly noteworthy is the small-gap antiferromagnetic insulator Na2IrO3, consisting of honeycomb NaIr2O6 layers stacked along the monoclinic c-axis, separated by hexagonal Na3 layers [1]. A description of the electronic structure of this system has been proposed in terms of the splitting of the Ir-t2g manifold – due to spin-orbit interaction – into a doublet with effective angular moment Jeff = $\frac{1}{2}$ and a quartet with Jeff = $\frac{3}{2}$. The half-filled Jeff = $\frac{1}{2}$ band at the chemical potential is further split into lower (LHB) and upper (UHB) Hubbard bands by electronic correlations (U), resulting in the so-called relativistic Mott insulating behavior. This scenario is validated by the observation of a 340meV conductivity gap open well above the long-range AFM ordering temperature $T_N=15K$ [2]. Given the correlated nature of this system, further insights on the electronic properties might be obtained studying by ARPES the evolution of the low-energy spectral function upon substitution at the Na site with Li. This will be complemented by in situ alkali-adatom deposition to disentangle the evolution of microscopic interactions from simple charger-carrier doping effects.

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Magnetoelectric memory with optical readout

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In conventional media light propagation is reciprocal, that is counter-propagating beams experience the same refractive index. However, reciprocity can be violated in magnetoelectric materials, where the refractive index depends not only on the polarization of light but also on the $\pm \mathbf{k}$ direction of the propagation [1]. Such unidirectional transmission is the consequence of the dynamic magnetoelectric effect emerging in materials with simultaneously broken time reversal and spatial inversion symmetries. This phenomenon, which has been exclusively observed in non-centrosymmetric (polar or chiral) materials with finite magnetization [2-5], may allow the development of optical diodes transmitting unpolarized light in one, but not in the opposite, direction [5].

Here, we demonstrate that LiCoPO₄ with a fully compensated antiferromagnetic ground state, i.e. with zero net magnetization, can also exhibit unidirectional transmission [6]. Following an appropriate magnetoelectric poling in crossed electric and magnetic fields, we succeeded to realize the unidirectional transmission as a remnant effect in this compound. The unidirectional transmission likely originates from a ferrotoroidic order which can be viewed as the cross-product of antiferroelectricity and antiferromagnetism coexisting in LiCoPO₄. The sign of the magnetoelectric effect can be set by the poling electric and magnetic fields via the establishment of mono-domain ferrotoroidic states, and can be read via the optical-diode effect.

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Directional anisotropy of light in multiferroics

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Multiferroics are materials which exhibit electric and magnetic order simultaneously. Due to the coupling of electric and magnetic effects, these materials show a strong potential to control electricity and magnetism and, more generally, the properties and propagation of light. One of the most fascinating and counter-intuitive recent results in multiferroics is directional anisotropy, the asymmetry of light propagation with respect to the direction of propagation. The absorption in the material can be different for forward and backward propagation of light, which in extreme case may lead to complete suppression of absorption in one direction.

Another remarkable effect in multiferroics is directional birefringence, i.e. different velocities of light for different directions of propagation. As an example, in the multiferroic samarium ferroborate giant directional birefringence can be realized. The effect is easily observed for linear polarization of light in the range of millimeter-wavelengths, and survives down to very low frequencies. The dispersion and absorption close to the electromagnon resonance can be controlled and fully suppressed in one direction.



Fig. 1. In multiferroic samarium ferroborate the electromagnon reveals strong directional anisotropy.

[1] *In collaboration with:* A. Shuvaev, W. Dziom, Anna Pimenov, M. Schiebl, A. V. Kuzmenko, V. Yu. Ivanov, A. A. Mukhin, I. A. Gudim, and L. N. Bezmaternykh



Review of ferroelectric and magnetic soft modes in multiferroics

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In proper ferroelectrics, the large dielectric anomaly in permittivity $\varepsilon'(T)$ occurring at the Curie temperature $T_{\rm C}$ is caused by softening of a polar optical phonon or by slowing down of a microwave dielectric relaxation. Such soft modes drive ferroelectric phase transitions in the type-I multiferroics like BiFeO₃, PbFe_{0.5}Nb_{0.5}O₃ or strained EuTiO₃. In the spin-order induced ferroelectrics (i.e. type-II multiferroelectrics), only small dielectric anomalies are observed at ferroelectric T_c, because these materials belong to improper or pseudoproper ferroelectrics (i.e., the order parameter is some other quantity than polarization). For the type-II multiferroics with noncollinear magnetic structure, Katsura, Balatsky and Nagaosa predicted already in 2007 that soft spin waves hybridized with the electric polarization should drive the ferroelectric phase transitions.[1] These spin waves can be called *electromagnons*, because they contribute to both dielectric permittivity and magnetic permeability. Only last year, Niermann et al.[2] confirmed this prediction, having discovered a critical slowing down of a Drude-like dielectric relaxation near the multiferroic phase transition in MnWO₄. The relaxation was observed in the microwave dielectric spectra only within 0.2 K above $T_{\rm C}$, because at higher temperatures the relaxation frequency hardens above 10 GHz and its dielectric strength becomes negligible. This excitation was interpreted as the soft electromagnon which drives the ferroelectric phase transition.²

Similar small and narrow dielectric peaks at $T_{\rm C}$ are known from most spin-induced ferroelectrics, but they were never investigated using microwave dielectric spectroscopy in the vicinity of $T_{\rm C}$. Nevertheless, electromagnons were observed for most multiferroics with spiral magnetic structures in their THz spectra. Thus, their frequencies are two or three orders of magnitude higher and we propose, based on analogy with phonons in structurally modulated crystals,[3] that they correspond to the amplitudon component of the spin wave, whereas the soft microwave component is a phason component of the electromagnon activated by the inverse Dzyaloshinskii-Moriya interaction. The frequencies of THz electromagnons harden upon cooling below $T_{\rm C}$ and their dielectric strengths increase due to the spin-phonon coupling, therefore they are responsible for the corresponding increases in permittivity. We will demonstrate this behaviour in TbMnO₃ and BiFeO₃ [4] perovskites as well as in (Ba_xSr_{1-x})₃Co₂Fe₂₄O₄₁ crystallizing in the Z-type hexaferrite structure. In the last case, we will also discuss the magnetic-field dependence of the magnon and electromagnon spectra.

Another type of multiferroics with improper ferroelectric phase transitions is represented by orbital-order driven ferroelectrics with the Jahn-Teller transitions. GaV_4S_8 belong to this family and it undergoes the ferroelectric and magnetic phase transitions at 44 K and 12.7 K. In its paraelectric phase, an overdamped soft mode arising from coupled orbital and polar fluctuations was detected in the THz region and its relaxation frequency drops by five orders of magnitude at the first order ferroelectric phase transition.[5] Another small hardening was detected at the magnetic phase transition, when Skyrmion lattice appears.[5]

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Low-Energy Electrodynamics in Solids

Optical Diode Effect at Spin-Wave Excitations of the Room-Temperature Multiferroic BiFeO₃

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The mutual coupling between magnetism and electricity present in many multiferroic materials changes the low energy electrodynamics of these materials in unprecedented way. A spin wave mode in the presence of magnetoelectric coupling is excited simultaneously by electric and magnetic component of electromagnetic radiation rendering the transmission of radiation unidirectional under favorable conditions[1]. The transparent direction can be switched with dc magnetic or electric field, thus opening up new possibilities to manipulate the propagation of electromagnetic waves.

We studied the unidirectional transmission of THz radiation in BiFeO₃ crystals, the unique multiferroic compound offering a real potential for room temperature applications. The electrodynamics of BiFeO₃ at 1THz and below is dominated by the spin wave modes of cycloidal spin order[2]. We found that the optical magnetoelectric effect generated by spin waves in BiFeO₃ is robust enough to cause considerable nonreciprocal directional dichroism in the GHz-THz range even at room temperature[3]. The optical magnetoelectric effect in BiFeO₃ is dominated by two types of spin-current induced polarizations, while the exchange-striction and single-ion polarization terms do not significantly contribute to it. Our work demonstrates that the nonreciprocal directional dichroism spectra of low energy excitations and their theoretical analysis provide microscopic model of the magnetoelectric couplings in multiferroic materials[4].

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From confined spinons to emergent fermions: Evolution of elementary excitations in a transverse-field Ising chain

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Emergent states of matter in quantum magnets are characterized by their elementary excitations that can be induced and tuned in an external magnetic field. Rigorous theoretical approaches are available for paradigmatic one-dimensional spin models which provide quantitative understandings of the elementary excitations and predictions for experimental realizations of novel quantum phenomena. We report on a spectroscopy study of elementary excitations in an Ising-like antiferromagnetic chain compound $SrCo_2V_2O_8$ as a function of temperature and applied transverse magnetic field up to 25 T [1,2]. An optical as well as an acoustic branch of confined spinons, the elementary excitations at zero field, are identified in the antiferromagnetic phase below the N kel temperature and described by a one-dimensional Schrödinger equation. The confinement can be suppressed by the applied transverse field and an order-disorder phase transition is induced at 7 T. In the disordered paramagnetic phase, three emergent fermionic excitations are observed with different transverse-field dependencies, which are consistent with dynamic structure factor calculated by the method of infinite time evolving block decimation (iTEBD). Our work reveals emergent quantum phenomena and provides a concrete system for testifying theoretical predications in one dimension.

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Ultrahigh spatial resolution magnetic imaging of oxide surfaces and interfaces by the development of laser-PEEM

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We report the first experiments carried out on a new chemical and magnetic imaging system, which combines the high spatial resolution of a photoemission electron microscope (PEEM) with a continuous wave deep ultraviolet laser. Threshold photoemission is sensitive to the chemical and magnetic structures of the surface of materials. The spatial resolution of PEEM is limited by space charging in use of pulsed photon sources as well as aberrations in the electron optics. We show that the use of continuous wave laser enables us to overcome such a limit suppressing the charge effect. We space achieved the resolution around This is the highest 2.6 nm. resolution of the world as the PEEM.



Fig.1 Feromagnetic domain structures of SrTiO3 surface

We would like to report the Feromagnetic domain structures of SrTiO3 perovskite oxide surfaces and interfaces of LaAlO3/SrTiO3. Oxide interface and surface have fruitful properties.



Competition between enhanced Cooper pairing and suppressed phase coherence in coupled aluminum nanograins

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Deterministic enhancement of the superconducting (SC) critical temperature Tc is a long-standing goal in solid-state physics. In a large variety of SC systems, the initial enhancement via tuning of a control parameter is followed by a suppression of Tc, shaping a superconducting dome in the phase diagram. This dome was postulated to be shaped by a competition between two energy scales: the superconducting energy gap Δ and the superfluid phase stiffness J [1]. One of the first evidence for such dome-like phase diagram was shown for granular Al, i.e. thin films composed of nano-scaled grains separated by thin insulating barriers, where grain-coupling acts as control parameter [2].

In this work, we used DC transport measurements and optical THz spectroscopy in order to study the development of Tc and the energy scales Δ and J as a function of the grain coupling and explain the phase diagram of granular Al [3]. Starting from well-coupled grains, Δ grows as the grains are progressively decoupled, causing the unconventional increase of Tc with sample resistivity. When the grain-coupling is suppressed further, Δ saturates while the critical temperature Tc decreases, concomitantly with a sharp decline of J, delimiting a SC dome in the phase diagram. The crossover to a phase driven SC transition is accompanied by a pseudogap observed in the normal state above Tc. Overall, we demonstrate that granular Al is an ideal testbed to understand the interplay between quantum confinement and global superconducting phase coherence due to nano-inhomogeneity.

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Giant Exciton Fano Resonance in Ta₂NiSe₅

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The challenging suggestion of electron-hole pair condensation in thermal equilibrium into the excitonic insulator ground state [1] has been experimentally tested only in a handful of cases. Very recently the excitonic insulator state is proposed as the ground state in a direct-gap semiconductor Ta₂NiSe₅, where Ta 5*d* conduction band hybridizes by the Coulomb interaction with the valence Ni 3d – Se 4p band. The spontaneous hybridization stabilizes the monoclinic lattice distortion with the orthorhombic-to-monoclinic phase transition at T_c = 328 K and concomitant flattening of the valence band top observed by ARPES [2,3].

Motivated by the desire to explore the exciton states, we have used wide-band spectroscopic ellipsometry to accurately determine the optical conductivity and permittivity of the closely related ternary chalcogenides Ta₂NiS₅ and Ta₂NiSe₅. For photon polarization along the Ta-Ni-Ta chains, the exciton doublet was unambiguously identified in both the compounds at low temperatures. Many-body interactions in these systems manifest themselves as a Fano interference of the discrete exciton states with a band continuum. The oscillator strength of the exciton Fano resonances in Ta_2NiSe_5 is found to be of giant magnitude. The lowest energy absorption band underlying the resonances is assigned to have the flat valence band probed by photoemission as the initial state for its associated interband transition. Quantum interference of the band continuum states with the embedded discrete exciton states is the compelling argument, complementary to ARPES, for the excitonic ground state. The optical absorption spectra above the energy scale of the exciton Fano resonances are dominated by a series of sharp interband transitions. Their steep temperature dependence corroborates strong electron-phonon interaction with a modification of the peak energies and widths proportional to the filling factor of optical phonon modes. This finding, along with the high Ta-Ni bond polarizability, implies that phonons in quasi-1D Ta_2NiSe_5 can effectively serve to reduce dynamically the effect of the local Coulomb attraction and to stabilize the exciton condensation.

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Electronic structure of a quasi-one dimensional thermoelectric material Ba₃Co₂O₆(CO₃)_{0.7} studied by angle-resolved photoemission spectroscopy

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Cobalt oxides have attracted attention due to their anomalous electric/magnetic properties such as a large thermoelectric power [1]. Among the cobalt oxides, a quasi-one-dimensional cobaltate $Ba_3Co_2O_6(CO_3)_{0.7}$ has fairly large thermoelectric power, comparable to that of Na_xCoO_2 and electrical resistivity with metallic behavior above 300 K [2] and the magnetic susceptibility increases below ~100 K along the face-sharing CoO₆ chains [3, 4]. In order to clarify the relationship of its thermoelectric properties to the electronic states, we have investigated the electronic structure of $Ba_3Co_2O_6(CO_3)_{0.7}$ by using three-dimensional angle-resolved photoemission spectroscopy.

We found clear band dispersions around 2 eV and 1 eV along the CoO₆ chain (//*c* axis). From the comparison with the other cobaltates [1], the former is originating from Co 3*d* t_{2g} bonding band, while the latter from anti-bonding one, respectively. The observed Co 3*d* bands dominate with the dispersive feature with $2\pi/c$ symmetry (dashed lines in Fig. 1) possibly originating from the symmetry of the CoO₆ chain [3]. In addition, we found that the Co 3*d* bands form two-dimensional gap feature around 650 meV and the narrow band dispersion around the valence-band maximum (solid line in Fig. 1) due to the π/c symmetry originating from the interaction between CoO₆ and CO₃ chain.

From the temperature dependence, we found the spectral weight of Co 3d bands near $E_{\rm F}$ increases below 90 K, while one of CO₃ states decreases (Fig. 2). The results suggest that the thermodynamic properties of Ba₃Co₂O₆(CO₃)_{0.7} originate from strong CoO₆ – CO₃ inter-chain interaction.

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Fig. 1. Band structure along ΓA line of Ba₃Co₂O₆(CO₃)_{0.7}. Dashed and solid lines are guide for Co 3*d* band dispersions with $2\pi/c$ and π/c symmetry, respectively.



Fig. 2. Temperature-dependence of PES spectra of $Ba_3Co_2O_6(CO_3)_{0.7}$ obtained from ARPES spectra summed along ΓA line.



Low energy electrodynamics of topological insulators

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Topological insulators (TIs) are a recently discovered state of matter characterized by an "inverted" band structure driven by strong spin-orbit coupling. One of their most touted properties is the existence of robust "topologically protected" surface states. I will discuss what topological protection means for transport experiments and how it can be probed using the technique of time-domain THz spectroscopy applied to thin films of Bi₂Se₃. By measuring the low frequency optical response, we can follow their transport lifetimes as we drive these materials via chemical substitution through a quantum phase transition into a topologically trivial regime. I will then discuss our work following the evolution of the response as a function of magnetic field from the classical transport regime to the quantum regime. In the highest quality samples, we observe a continuous crossover from a low field regime where the response is given by semi-classical transport and observed in the form of cyclotron resonance to a higher field quantum regime. In the latter case, we find evidence for Faraday and Kerr rotation angles quantized in units of the fine structure constant. This quantized rotation angle can be seen as evidence for a novel magneto-electric of the TI's surface e.g. the much heralded axion electrodynamics of topological insulators. Among other aspects this gives a purely solid-state measure of fine structure constant.



Topological phase transitions and surface states in topological semimetals

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In this presentation we show our recent results on topological semimetals, such as Weyl semimetals and nodal-line semimetals. In such topological semimetals, the band gap closes at generic points or lines, due to topological reasons.

Weyl semimetals are semimetals with nondegenerate 3D Dirac cones in the bulk. Motivated by our previous works [1-3], in our presentation we show that if the gap of any inversion-asymmetric system is closed by a change of an external parameter, the system runs either into (i) a Weyl semimetal phase (Fig. 1(a)) or (ii) a nodal-line semimetal (Fig.1(b)) [4]. In particular, we find that insulator-to-insulator transition never happens in inversion asymmetric systems. This transition is realized for example in tellurium (Te) [5]. Tellurium has a unique lattice structure, consisting of helical chains, and therefore lacks inversion and mirror symmetries. At high pressure the band gap of Te decreases and finally it runs into a Weyl semimetal phase, as confirmed by our ab initio calculation. We also theoretically propose chiral transport in systems with such helical structures [6].

In our presentation we also discuss nodal-line semimetals and their surface band structures. We first show that the fcc alkaline earth metals such as Ca and Sr have nodal lines near the Fermi surface when the spin-orbit coupling is neglected [7]. At higher pressure they become nodal-line semimetals. We also show that across the nodal lines the Zak phase for each surface momentum jumps by π , meaning that there will be a large charge imbalance at the surfaces of

such nodal-line semimetals. Subsequently, this charge imbalance is screened, leaving behind a large Rashba splitting if adatoms with large spin-orbit coupling are adsorbed [7].



Fig. 1. Schematic band dispersion for (a) Weyl semimetal and (b) nodal-line semimetal

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Low-Energy Electrodynamics in Solids

Kane electrons evidenced by magneto-optics of Cd₃As₂ in the quantum limit

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Cadmium arsenide has recently been identified as a 3D Dirac semimetal in which two Dirac nodes are topologically protected and located near the Gamma point. While the available ARPES data show the Dirac cones over several hundreds meV, other experiments such as STM imply that the energy range of Dirac cones is an order of magnitude smaller.

We report the optical reflectivity data taken on cadmium arsenide in a broad range of photon energies and magnetic fields up to 33 T. The observed response, in particular the square root of field dependence of cyclotron resonance absorption in high magnetic fields, clearly indicates the presence of massless charge carriers. However, a closer analysis of our data and their comparison with a model developed for this compound in the past reveals that we observe topologically trivial massless Kane electrons rather than topologically protected 3D Dirac particles.

While Dirac particles likely appear in cadmium arsenide, their energy scale is significantly smaller than probed in our far and mid infrared experiments.



Optical Spectroscopic Studies on the Lifshitz-Type Metal-Insulator Transition in Cd₂Os₂O₇

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We studied the metal-insulator transition (MIT) induced by all-in/all-out (AIAO) magnetic ordering in 5*d* pyrochlore $Cd_2Os_2O_7$ using optical spectroscopy [1]. The temperature evolutions in the band gap edge illustrated a Lifshitz-type MIT where a rigid band shift near the Fermi level gradually annihilates the Fermi surface. The delicate relationship between free carrier density and band gap provides experimental evidence for the existence of an AIAO metal, the inevitable intermediate state in the Lifshitz-type MIT. This transition was further supported by spectral-weight analysis of the interband transition using first-principle calculations. Our data indicate that MIT driven by AIAO ordering in $Cd_2Os_2O_7$ is close to a Lifshitz type, providing the groundwork for exotic phenomena in 5*d* pyrochlores.



Fig. 1. Schematic diagram of Lifshitz-type MIT induced by AIAO ordering in Cd₂Os₂O₇.
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Magnetic Excitations in doped Cuprates and Iridates from Raman Scattering and RIXS

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Superconductivity in high temperature superconducting cuprates arises upon doping of half-filed insulating and antiferromagnetically ordered CuO_2 planes. We report on the details of the evolution of the magnetic excitation spectra from the undoped to the overdoped regime using resonant inelastic x-ray scattering (RIXS) at the Cu L₃-edge [1,2]. We observe a cross-over in the nature of these excitations, which are collective, magnon-like excitations at low doping and evolve into incoherent particle-hole excitations in the Fermi-liquid state. We have also studied the doping dependence of the magnetic excitations in electron-doped Sr_{2-x}La_xIrO₄ using Raman scattering and Ir L₃-edge RIXS [3,4]. The long range magnetic order is rapidly lost with increasing doping, but two-dimensional short-range order (SRO) and dispersive magnon excitations with nearly undiminished spectral weight persist up to x = 0:10. The magnons in the SRO phase are heavily damped and exhibit anisotropic softening. Similarities to the case of cuprates are discussed.

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NMR studies of charge order in YBa₂Cu₃O_v

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In 2011, the NMR discovery that superconductivity competes, and coexists, with charge-density-wave (CDW) order in $YBa_2Cu_3O_y$ was argued to strongly support the, hitherto controversial, view that underdoped cuprates are generically unstable towards CDW formation [1]. While this affirmation is now unanimously accepted, the exact nature of the CDW is not. In this talk, I will discuss insights into charge order from our NMR studies [1-3] in both the normal and superconducting states of $YBa_2Cu_3O_y$.

Work performed with R. Zhou, T. Wu, M. Hirata, I. Vinograd, H. Mayaffre, S. Krämer, M. Horvatić, C. Berthier (LNCMI Grenoble), P.L. Kuhns, A.P. Reyes (NHMFL, Tallahassee, USA), W.N. Hardy, R. Liang, D. A. Bonn (University of British Columbia, Vancouver, Canada), T. Loew, J. Porras, B. Keimer (MPI Stuttgart, Germany).

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Momentum-resolved charge fluctuations proximate to the charge-order phase measured by resonant inelastic x-ray scattering

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In strongly correlated electron systems, enhanced fluctuations in the proximity of the ordered states of electronic degrees of freedom often induce anomalous electronic properties such as unconventional superconductivity. Spin fluctuations in the energy-momentum space have been studied widely using inelastic neutron scattering, and resonant inelastic x-ray scattering (RIXS) at the transition metal L-edge has become a complementary technique in measuring spin-flip magnetic excitations recently [1,2]. In contrast, other degrees of freedom, i.e., charge and orbital, have hardly been explored so far.

We applied the K-edge RIXS technique to two systems that show a charge order and observed the momentum-resolved charge fluctuations proximate to the charge-ordered phase in strongly correlated transition metal oxides [3]. In the two-leg ladder of $Sr_{14-x}Ca_xCu_{24}O_{41}$, charge fluctuations are enhanced at the propagation vector of the charge order (\mathbf{q}_{CO}) when the order is melted by raising the temperature or by doping holes. In contrast, charge fluctuations are observed not only at \mathbf{q}_{CO} but also at other momenta in a geometrically frustrated triangular bilayer lattice of $LuFe_2O_4$. The observed charge fluctuations have high energy (~ 1 eV), suggesting that Coulomb repulsion between electrons is the principal interaction of the charge order.

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Hidden fermionic excitation as the origin of pseudogap and high-temperature superconductivity in cuprates

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The dynamics of quasiparticles reflects the pairing mechanism of superconductivity. In fact, in conventional superconductors, studies on the quasiparticle dynamics played an essential role in establishing the phonon-mediated pairing mechanism [1]. We study the quasiparticle dynamics in cuprate high-temperature superconductors, for which the pairing mechanism is still unknown.

As their simple microscopic model, we take the Hubbard model on a square lattice, and study its *d*-wave superconducting state with a cluster extension of the dynamical mean-field theory. Exploring the frequency-dependent structure of the electronic self-energy, we find that

- 1) Below the critical temperature (T_c) , the normal and anomalous components of the self-energy are peaked at the same frequency.
- 2) The peak of the normal self-energy persists above T_c , generating the pseudogap.
- 3) Below T_c , the contributions of the self-energy peaks to Green's function cancel out between the normal and anomalous parts while the superconducting gap is generated by another zero of Green's function.

The properties 2) and 3) suggest a novel relationship between the pseudogap and superconducting gap: They involve different singularities while closely related with each other. The property 3) at the same time explains how the self-energy peak has eluded a detection by spectroscopic experiments. The self-energy peaks of the property 1) in general indicate a coupling of the quasiparticle with some other excitations. We reveal that the property 3) suggests that the excitation is *fermionic*, in contrast to a bosonic excitation in many preexisting theories. Namely, the self-energy peaks are generated by a hybridization of the quasiparticle with the hidden fermionic excitation. Since the peak of the anomalous self-energy enhances the superconducting gap a lot, this result suggests that the hidden fermion is a key ingredient of high- T_c superconductivity. [2]

Fig. Quasiparticle (c) hybridizes with a hidden fermionic excitation (f) through V. D_c and D_f represent the static part of the superconducting gap for c and f, respectively.



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Low-Energy Electrodynamics in Solids

High-energy optical conductivity and anomalous spectral weight transfers in strongly correlated electron systems

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In this talk we will demonstrate potency of a combination of spectroscopy ellipsometry, synchrotron-based vacuum ultraviolet reflectivity and dc conductivity, to probe spectral weight transfers in correlated electron systems. Such a combination experimental method leads to a stabilized Kramers-Kronig transformation in a broad energy range and is powerful to reveal electronic and magnetic structures in complex systems [1,2].

We, first, discuss the observed high-energy spectral weight transfers associated with a sharp insulator-metal transition in LaAlO₃/SrTiO₃. Different mechanisms of charge transfer and redistribution are observed in LaAlO₃/SrTiO₃ as a function of LaAlO₃-film-thickness and most of charges are localized [3,4]. In fact, in case of SrTiO₃, we observe electron-electron (*e-e*) and electron-hole (*e-h*) interactions yielding to different type of excitons, resonant excitons and bound Wannier-like exciton with an unexpectedly higher level of delocalization [5]. Such as surprisingly strong *e-e* and *e-h* in SrTiO₃, perhaps, is one of main reasons for rich physical phenomena in SrTiO₃ based systems, including LaAlO₃/SrTiO₃ heterostructures.

In the second part of the talk, if time permits, we present our study on the first observation of the coexistence of a distinct midgap state and a Mott state in undoped and their evolution in electron and hole-doped ambipolar $Y_{0.38}La_{0.62}(Ba_{0.82}La_{0.18})_2Cu_3O_y$ films using spectroscopic ellipsometry and X-ray absorption spectroscopies at the O K and Cu $L_{3,2}$ edges [6]. Supported by theoretical calculations, the midgap state originates from the antiferromagnetic correlation. Surprisingly, while the magnetic state collapses and its correlation strength weakens with dopings, in contrast the Mott state moves toward a higher energy and its correlation strength increases. Our result provides important clues to the mechanism of electronic correlation strengths and superconductivity in cuprates.

The methodology presented here is valuable for the study of other strongly correlated systems.

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Optical properties of nickelate thin films and heterostructures

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Lanthanum nickelate is certainly one of the most studied oxide materials in condensed matter physics. Within the rare-earth nickelates family it is the only member not undergoing a metal-to-insulator transition in its bulk form at low temperatures. On the other hand, stress and dimensionality [1] strongly affect the electronic properties of LaNiO₃, eventually leading to a metal-to-insulator transition. Recent progresses in the growth of correlated oxide heterostructures has sparked interest in understanding and exploiting the novel electronic and magnetic properties that emerge at the interfaces between lanthanum nickelates and other oxides. Infrared spectroscopy [2] allows to evaluate the differences in terms of spectral weight between pristine bulk LaNiO₃ and the resulting bilayers or superlattice compounds, thus shedding new light on the mechanisms underlying the electronic properties of the resulting heterostructures.



Fig. 1. Artwork representation of a LaNiO₃/LaMnO₃ superlattice

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Superconductivity fluctuation of FeSe_{1-x}Te_x measured by microwave broadband technique

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The iron chalcogenides, $FeSe_{1-x}Te_x$, are superconductors with a maximum T_c of about 15 K at ambient pressure. However, the application of pressure and the intercalation raise T_c of these materials up to 30-45 K. In addition, ultrathin films of FeSe were reported to have T_c of 60-80 These suggest that Fe-chalcogenides have the potential as high $-T_c$ superconductors. In K. particular, the increase of T_c under high pressure and that by the intercalation suggest that the introduction of strain by thin film synthesis is another effective route to the increase of $T_{\rm c}$ in iron-chalcogenide superconductors. We have studied thin film synthesis of $FeSe_{1-x}Te_x$ by the PLD technique[1,2], and showed that T_c increased 1.5 times as bulk crystals, indeed[3]. Furthermore, by this technique, we succeeded in obtaining a series of $FeSe_{1-x}Te_x$ samples with all x values between 0 and 1, which was never achieved in bulk crystals because of the phase separation[4]. Once a complete series of FeSe_{1-x}Te_x samples were obtained, it is of great interest how the nature of superconductivity changes as a function of x, since the presence of a very small Fermi surface has been shown by various spectroscopic techniques, such as ARPES In that situation, it is theoretically expected that and STM etc., in these materials. superconductivity exhibits the nature of Bose Einstein condensation (BEC), rather than an ordinary BCS superconductivity. To discuss the nature of superconductivity, we showed that the measurement of superconductivity fluctuation shown up in complex ac conductivity was extremely effective, in case of cuprate superconductors[5,6,7].

We measure microwave complex conductivity by a broadband technique[8], where the frequency is swept in some frequency range, in a series of samples of $\text{FeSe}_{1-x}\text{Te}_x$. For x=0.5, our tentative result shows that fluctuation data are expressed by a 2 dimensional formula. However, no BKT feature is observed. It is also suggested that the superconductivity fluctuation starts from a rather higher temperature than is expected in an ordinary theory of superconductivity fluctuation. Together with a detailed interpretation of these results, data of films with other values of x will also be presented, and we will discuss how the nature of superconductivity changes as a function of x, particularly in terms of BEC vs BCS pictures.

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Magnetoelectric spin excitations in multiferroic Ni₃TeO₆

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 Ni_3TeO_6 presents a collinear antiferromagnetic order below 52 K, giving rise to spin-induced-ferroelectricity. Among the spin-order driven multiferroics, only Ni_3TeO_6 exhibits non-hysteretic colossal magnetoelectric effect near 8.5 T and 52 T, where spin-flop and metamagnetic phase transitions occur, respectively.^{1,2} The lack of hysteretic behavior in the magnetic field dependence of magnetization and dielectric constant precludes losses for a series of magnetoelectric applications.

In the current work, we investigated the spin and lattice excitations of Ni_3TeO_6 ceramics and single crystals. Infrared, time-domain THz and Raman spectroscopy experiments were conducted for a temperature range of 5 to 300 K. Time-domain THz spectroscopy at external magnetic field was carried out at selected temperatures below and close to the antiferromagnetic phase transition. The THz spectra revealed dynamic magnetoelectric coupling, i.e. tuning of THz spectra with magnetic field. Simultaneous infrared and Raman active spin excitations correspond to electromagnons, highly sensitive on magnetic field (Fig. 1).



Figure 1: (a) Raman and (b) THz spectra of Ni_3TeO_6 ceramics revealing two simultaneously detected spin excitations.

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Nonlinear THz spectroscopy of collective modes in superconductors

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Ultrafast nonequilibrium dynamics of superconductors after the photoexcitation has gained continuing interest over decades from the viewpoints of elucidation of pairing mechanisms, competing orders, collective modes, and toward the optical manipulation of superconductivity. The collective amplitude mode of the order parameter, recently referred to as Higgs mode, has long been studied theoretically [1], whereas the experimental observation has been limited to a special case where the superconductivity coexists with charge density wave that makes the Higgs mode Raman-active [2,3,4]. However, with the advance of ultrafast terahertz (THz) spectroscopy technique, the Higgs mode has been recently observed in a s-wave superconductor NbN by THz-pump THz-probe measurements [5,6]. It was also shown that the Higgs mode couples with the electromagnetic field in a nonlinear regime, giving rise to third harmonic generation(THG) of incident radiation tuned below the superconducting gap [6,7]. It is therefore highly intriguing to study how such a collective mode appear in other conventional/unconventional superconductors.

In this presentation, after a brief review on the experiments of Higgs mode in particular in NbN, we report our recent results on the THz nonlinear spectroscopy of multiband superconductor MgB₂. In MgB₂, two superconducting gaps exist in the THz frequency range corresponding to two kinds of Fermi surface termed as π - and σ -band, respectively [8]. The optical conductivity spectrum shows only one gap structure associated with the lower energy π -band reflecting its dirty limit character. Like the case of NbN, THz-THG was clearly observed below T_c , while the signal was dominated by the resonance with σ -band. The results will be discussed in terms of Higgs mode in multiband superconductors.

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On the theory for pump-probe spectroscopy in quantum materials

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The evolution of driven systems involves a broad class of phenomena that crosses many scientific disciplines, as the world around us is far from being in static equilibrium. The goal of ultrafast materials science studies is to understand and potentially control emergent phenomena at their natural time and length scales, under equilibrium and/or extreme conditions. It is clear that in order to describe non-equilibrium behavior and the path towards emergence in complex materials, a more precise and correct vocabulary is needed. In this talk I will discuss a few examples on the theory of pump-probe spectroscopies drawn from problems related to collective modes in superconductors, driving transitions between entwined spin and charge order in correlated oxides, and manipulating Berry's phase in materials with non-trivial quantum geometries, for example. It is shown that a common language for different related phenomena can be formulated to allow for refinement of important questions to be addressed.



Possible light-induced superconductivity in metallic K₃C₆₀

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Coherent excitation of anharmonically coupled lattice modes has introduced, in the last decade, the possibility to induce transient structural deformations in complex solids. In cuprates, strong resonant midinfrared (MIR) excitation was shown to induce a transient superconducting-like state at a temperature far above the equilibrium T_c [1, 2].

In the present experiment [3] a local vibrational driving force has been applied to a very different material: Potassium-doped fulleride (K_3C_{60}), where structural modes are known to be directly responsible for superconducting pairing.

 K_3C_{60} belongs to the class of alkali-doped fullerides, organic BCS-like superconductors in which superconductivity is mediated by high-energy (100-200 meV) intramolecular vibrations with Jahn-Teller character. These favor Cooper pair formation in a superconducting state with s-wave symmetry [4].

We excited metallic K_3C_{60} with MIR pulses tuned to be resonant to a local vibrational mode of the C_{60} molecule and monitored the induced changes in the transient optical response with time-resolved terahertz spectroscopy. A non-equilibrium state with the optical properties of a superconductor emerged, having a lifetime of a few picoseconds. Such state was found to persist up to base temperatures of 100 K, namely five times higher than the equilibrium T_c of 20 K.

As expected in a superconductor, the directly measured pump-induced increase in the sample reflectivity corresponded to the opening of a gap in the real part of the optical conductivity and to a $1/\omega$ -like divergence in its imaginary part. A quantitative comparison with the response measured at equilibrium below T_c allowed to identify an increase in the optical gap by a factor of two [3].

A possible interpretation of the data relies on the high intensity of the MIR pump pulses used in the experiment. These are expected to induce a strong distortion of the C-C bonds resulting in a local deformation the C_{60} molecule. Because local vibrational modes are thought to assist pairing at equilibrium, such deformation may play a role in enhancing superconductivity. Independent of the specific mechanism, our results suggest the possibility of a new type of superconductivity which is directly stimulated by the laser field and indicate novel emergent physics away from equilibrium.

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Ultrafast Optical Control of the Topologically Protected Electronic Properties of ZrTe₅

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 $ZrTe_5$ has recently attracted considerable interest owing to some unique, albeit only partially understood, properties. The electrical resistivity exhibits a peak at a temperature where the nature of the charge carriers changes from holes to electrons [1]. The observed magneto-resistance, with both positive and negative sign, has been attributed to the presence of Dirac particles, either three-dimensional [2, 3] or two-dimensional and spin-polarized [4, 5, 6].

Our study addresses both the anomalous transport properties and the nature of the Dirac particles in the band structure of $ZrTe_5$. As first thing, angle-resolved photoelectron spectroscopy (ARPES) studies reveal a peculiar temperature-dependent energy shift of the band structure, which we interpret as origin of the resistivity peak [7]. Secondly, by combining ARPES, both in the UV and soft X-ray energy ranges, with scanning tunneling microscopy and spectroscopy (STM/STS), we succeed in disentangling the 2D-surface and 3D-bulk contributions to the electronic properties of $ZrTe_5$. Our experimental data are well supported by *ab-initio* fully relativistic calculations, which also show that the 3D topological character of $ZrTe_5$ strongly depends on the interlayer lattice distance, whose precise value has been experimentally determined in our study by means of x-ray diffraction (XRD) [8]. Finally, we have performed time-resolved ARPES experiments on $ZrTe_5$, showing that an external optical excitation is capable to manipulate its electrical transport properties at the ultra-short timescale, by affecting both the band binding energy and the scattering rate [7].

All together, our observations shed light on the ground state electronic properties of $ZrTe_5$. Furthermore, they open the way to the exploitation of the topologically protected states of $ZrTe_5$ as a unique platform for magneto-optical switches and for ultrafast opto-spintronics.

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Spectroscopic-imaging STM studies of the iron chalcogenide superconductor FeSe

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In spite of its simple crystal structure, the electronic properties of the iron chalcogenide superconductor FeSe ($T_c \sim 9$ K) is rich and attractive. FeSe is one of the few iron-based superconductors that have nodes in the superconducting gap [1,2]. The superconductivity occurs in the non-magnetic orthorhombic phase that is associated with the orbital ordering [3-5]. Among other things, it should be noted that Fermi energy of FeSe is as small as the superconducting gap size. In accord with this, Fermi wave length is very long, being comparable to the coherence length. This is an unprecedented situation in a superconductor, indicating that FeSe is in the BCS-BEC crossover regime [1].

We performed low-temperature spectroscopic-imaging STM on high-quality single crystals of FeSe to visualize the electronic-state variations. We observed unidirectional quasiparticle interference patterns that reflect the orbital ordering [1]. Moreover, we have found that the apparent superconducting gap amplitude defined by the energy separation between the quasi-particle coherence peaks exhibits spatial periodic oscillations. The wavelength of the oscillations agrees with the wavelength of the normal-state quasiparticle interference pattern at the Fermi energy (Fig. 1). Such Friedel oscillations of the superconducting gap may be a characteristic of a superconductor in the BCS-BEC crossover regime.

This work has been done in collaboration with the groups of Prof. Y. Matsuda (Kyoto), Prof. T. Shibauchi (Tokyo), Prof. H. Kontani (Nagoya), Prof. C. Meingast (Karlsruhe) and Prof. H. v. Löhneysen (Karlsruhe).



Fig. 1. Superconducting gap map (left) and quasiparticle interference pattern in the tunneling conductance map at Fermi energy (right). Both images were taken in the same field of view.

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Fermi surface evolution across the nematic phase in bulk $Fe(Se_{1-x}S_x)$ using ARPES and quantum oscillations

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FeSe is a unique and intriguing superconductor which can be tuned into a high temperature superconducting state using applied pressure, chemical intercalation and surface doping. In the absence of magnetism, the structural transition in FeSe is believed to be electronically driven, with the orbital degrees of freedom playing an important part [1]. This scenario supports the stabilization of a nematic state in FeSe, which manifests as a Fermi surface deformation in the presence of strong interactions, as detected by ARPES [1]. Another manifestation of the nematicity is the enhanced nematic susceptibility determined from elastoresistance measurements under applied strain [1]. Isovalent Sulphur substitution onto the Selenium site constitutes a chemical pressure, which subtly modifies the electronic structure of FeSe, suppressing the structural transition without inducing high temperature superconductivity [3]. I will present the evolution of the electronic structure with chemical pressure in FeSe, as determined from quantum oscillations [1,2] and ARPES studies [3]. I will also discuss the suppression of the nematic electronic state, the electronic changes across the nematic phase boundaries as well as the role of electronic correlations in $Fe(Se_{1-x}S_x)$. This work is mainly supported by EPSRC, UK (EP/I004475/1, EP/I017836/1) and I acknowledge my collaborators from Refs. [1-3].



Fig.1. a) ARPES studies (after Ref.[1]), b) calculated and shifted Fermi surface and c) quantum oscillations in $Fe(Se_{1-x}S_x)$.

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Emergent defect states as a source of resistivity anisotropy in iron pnictides

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We discuss an impurity-driven scenario for the transport anisotropy in iron pnictides. In the paramagnetic nematic phase, the anisotropic spin fluctuations can be frozen by disorder, to create elongated magnetic droplets whose anisotropy grows as the magnetic transition is approached. Such states act as strong anisotropic defect potentials which scatter with much higher probability perpendicular to their length than parallel, although the actual crystal symmetry breaking is tiny. We calculate the scattering potentials, relaxation rates, and conductivity in this region, and show that such emergent defect states can explain all essential features of the transport anisotropy observed in experiments. New challenges to the elastic scattering mechanism from elastoresistivity measurements are discussed.

Finally, we extend the impurity-induced emergent states theory to the spin density wave phase. Stable unidirectional nematogens are formed locally, directed along the a-axis, and have typical length of 10 lattice constants. Interestingly, these cigarlike impurity-states exhibit a dimer structure in the electronic density, in excellent agreement with STM experiments. The temperature dependence of the observed resistivity anisotropy in this phase is captured within a simple model of a dirty SDW metal with nematic defect structures.

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Helicity preserving photoluminescence from the topological insulator Bi₂Se₃

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An ecxciton – in-band-gap bound state of an electron and hole – is one of the fundamental excitations in insulators. Conventionally, the exciton emission is unpolarized due to rapid phase and energy relaxation of the photo-excited electron-hole pairs during formation of an excitonic bound state. In a few rare examples partially polarized exciton emission has been demonstrated by engineering structures in which electron band and/or spin degeneracies are lifted.

In this work we report a surprising discovery of polarization preserving photoluminescence (PL) from Bi₂Se₃ topological insulator (TI). High degree of PL polarization is consistently demonstrated in both bulk and thin film samples at low and even at room temperature. To explain the polarization preserving PL we propose that the emission occurs from a photo excited bound state of a topologically protected relativistic gapless surface band hole orbiting a massive bulk band electron. Two degenerate such relativistic excitons carrying opposite orbital momenta can be constructed. Depending on the helicity of the photo-excitation, one of these two bound states is selectively excited. The interchange between the two states is *topologically protected*, hence, the reported inhere temperature independent high degree of emission polarization.

This discovery of helicity preserving PL offers novel fast characterization tool for detecting the topological surface states, which is essential for developing optoelectronic and spintronic devices making use of TIs. As such, the discovery is fundamental both for understanding the matter of the TIs, the study of relativistic quantum effects, and for the applications using topological protection.

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Anomalous low-energy excitation induced by magnetic impurity in optical spectrum of iron-based superconductor

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In the iron pnictide systems, the end member such as BaFe₂As₂ undergoes the magnetic and structural phase transition to low-temperature antiferromagnetic-orthorhombic (AFO) state. The AFO phase is suppressed by various elemental substitutions and the superconductivity (SC) appears. The Co-doped BaFe₂As₂ (Co-Ba122), which is one of most investigated systems, shows the above-mentioned behavior. In Cr- and Mn-doped BaFe₂As₂ (Cr- and Mn-Ba122), however, the electronic phase diagrams are quite different from that of Co-Ba122. In these systems, the AFO phase is suppressed by Cr and Mn doping, but new magnetic order appears above a critical concentration instead of SC. [1,2] In order to understand the superconducting mechanism of iron pnictides, it is important to clarify the origin of the different behaviors among these systems. In this work, we have investigated the optical conductivity to elucidate the different substitution effects on the electronic structure and charge dynamics in Cr-, Mn- and Co-Ba122 systems.

Figure shows the optical conductivity spectra for single crystals of Ba122, Cr- and Mn-Ba122.

In Ba122, the coherent part has been observed in the whole temperature region, and the clear peak structure due to SDW gap appears below the AFO transition temperature (T_{AFO}). The coherent part is robust against Co doping. [3] In contrast, the coherent component of optical conductivity is strongly suppressed by Cr and Mn doping below and above T_{AFO} . (Please see Figs. (b) and (c).) In Ba122, the doped Cr and Mn are magnetic impurities, while Co is nonmagnetic one. The present results indicate that the coherent carriers are strongly scattered by magnetic impurities but not by the nonmagnetic one in iron pnictides.

In addition, the new peak structures, indicated by triangles in Figs. (b) and (c), appear in the low energy region above T_{AFO} , suggesting the carrier localization. This localized carrier feature is not observed in Ba122 and Co-Ba122. Below T_{AFO} , other peak structure due to SDW gap appears at different energy position. The existence of this anomalous low energy peak of optical conductivity above T_{AFO} indicates that the strong interplay between the doped magnetic impurity and carrier causes the carrier localization even in the paramagnetic state. This interaction strongly suppresses the coherent carrier transport in the normal state, and resultantly destabilizes SC in Cr- and Mn-Ba122.



Figure : Optical conductivity spectra at 5 K and 150 K for Ba122, Cr- and Mn-Ba122 single crystals. Triangles indicate anomalous peaks induced by magnetic impurity at 150 K.



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Time-Resolved FTIR Studies of Phase Transitions in Low-Dimensional Organic Crystals

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The dynamics near correlation-driven phase transitions in organic charge-transfer salts is investigated using Fourier-transform spectroscopy to measure time-dependent optical response in the infrared spectral range after the electron system is perturbed by a voltage or optical pulse. This rarely used method allows us to investigate the dynamics of the electron system and lattice in the millisecond and microsecond range. After some tests using liquid crystals and vanadium oxide, we present two examples on electronically driven phase transitions.

First we measure the charge and lattice dynamics at the neutral-ionic phase transition in the organic mixed-stack compound TTF-CA in the microsecond time range. We find that neutral, non-dimerized metastable domains are created after photoexcitation. The time evolution of the reflectivity reveals a stretched exponential decay. The change in reflectivity depends linearly on the laser intensity for all temperatures, but decreases with temperature in a nonlinear fashion. The observed time profile can be explained by a random-walk annihilation process of the generated neutral-ionic domain walls. Close to the phase transition, large domains are formed (panels a and b) due to the valence instability. We also assert that the merger and interaction of the

induced domains play an important role for the formation of the macroscopic domains and deduce from the model with decreasing laser intensity, the average domain size decreases. At lower temperatures the ionic phase is more robust; the average domain size is much smaller and changes less with laser intensity (panels c and d). We conclude that the random walk of the neutralionic domain walls is the dominant factor for the relaxation of the metastable domains in the temperature range considered [1].



As a second example we investigated the metal-insulator transition in α -(BEDT-TTF)₂I₃ at $T_{CO} = 135$ K which is known to be due to electronic charge-order. Previously we could establish that the local charge per molecule can be quantitatively determined by vibrational spectroscopy and a gap opens in the optical spectra around 600 cm⁻¹ [2]. Applying voltage pulses of 10 ms in the insulating regime $T < T_{CO}$, the system switches into a high-conducting state after a certain delay time which is a nonlinear function of the electric field strength. The particular time-response of the infrared reflectivity evidences that the charge order does not melt, but hot charge carriers are excited. Eventually they dissipate their energy to the lattice [3].

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Incipient ferroelectricity of nanocaged water molecules

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An outstanding characteristic of the water molecule is its extremely large electrical dipole moment. Despite the enormous electrical polarizability, however, neither water nor ice is ferroelectric since short-range hydrogen bonds screen the long-range intermolecular dipole-dipole coupling. The situation changes drastically when water is confined to nanochannels, nanopores or very thin layers. In these cases, among other exotic effects, an ordering of the molecular dipoles can occur. This kind of confined water ferroelectricity is thought to play a key role in functioning of biosystems and in forming properties of different natural and artificial objects. Though predicted theoretically and modelled by computer simulations, the phenomenon has never been clearly observed experimentally. We have placed water molecules in the matrix of a beryl crystal lattice so that separate H₂O molecules are located far enough from each other to avoid hydrogen bonding, but close enough to keep the dipole-dipole interaction. Using broad-band dielectric spectroscopy we demonstrate incipient ferroelectricity within the ensemble of interacting water molecules: on cooling, the static permittivity increases according to the Curie-Weiss law as a ferroelectric soft mode develops in the terahertz frequency range. At temperatures below 10 K, quantum fluctuations eventually suppress the ferroelectric phase transition and lead to a saturation of the soft mode parameters and of the static permittivity. Our results are in full agreement with the theoretical models developed to describe ferroelectric orientational phase transitions. The discovered effect will help to get deeper insight into fundamental properties of confined water and it may also find applications in fuel and memory cells and other nanoscale electronic devices.



Towards Fractional Excitations with Raman and Exfoliation

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The combination of electronic correlation and spin-orbit coupling is thought to precipitate a variety of highly unusual electronic phases in solids, including topological and quantum spin liquid states. In this talk I will outline our efforts to pursue such a state and its associated excitations in RuCl₃ (see Fig. 1a). The Combination of IR and Raman spectroscopy provides direct access to all the energy scales, which are well separated and easily identifiable in this strongly correlated material (Fig 1b). Raman not only reveals the sharpest spin-orbit exciton, but a continuum indicative of fractional excitations (Fig 1c). However the material reveals low temperature magnetic order, as such I will also discuss our efforts to search for a true spin liquid in this material via mechanical exfoliation.



Fig. 1. (a) Honeycomb structure of a single plane of $RuCl_3$. (b) Spin-Orbit excitations expected from a Ru atom in the Jeff = $\frac{1}{2}$ state and their observation with Raman and IR spectroscopy. (c) The broad continuum observed in Raman indicating the fractional excitations in this potential Kitaev spin liquid.



Role of disorder, free-carrier recombination kinetics and phonon modes in the performance of CH₃NH₃PbI₃ perovskite films

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Apart from broadband absorption of solar radiation, the performance of photovoltaic devices is governed by the density and mobility of photogenerated charge carriers. The latter parameters indicate how many free carriers move away from their origin, and how fast, before loss mechanisms such as carrier recombination occur. However, only lower bounds of these parameters are usually obtained. Here we independently determine both density and mobility of charge carriers in the organometallic halide perovskite film CH₃NH₃PbI₃ by use of time-resolved terahertz (THz) spectroscopy (TRTS). Our data reveal the modification of the free carrier response by strong backscattering expected from these heavily disordered perovskite films. The results for different phases and different temperatures show a change of kinetics from two-body recombination at room temperature to three-body recombination at low temperatures as long as the three-body recombination has not become predominant [1].

We also studied the temperature-dependent phonon modes of these films across the THz (0.5 - 3 THz) and temperature (20 - 300 K) ranges, using THz time-domain spectroscopy (THz-TDS). These modes are related to the vibration of the Pb–I bonds. We found that two phonon modes in the room-temperature tetragonal phase split into four modes in the low-temperature orthorhombic phase. The carrier mobility values calculated from the low-temperature phonon mode frequencies, via two theoretical approaches, are found to agree reasonably with the experimental value from our TRTS work. Thus we have established a possible link between THz phonon modes and the transport properties of perovskite-based solar cells [2].

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The correlation energy in superconductors using optics as a probe

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Photoexcited quasiparticle dynamics in the pseudogap state of high-Tc superconductors

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The pseudogap is one of the remarkable features of high-Tc superconductors and its elucidation is believed to be a key to understanding the mechanism of the high- T_c superconductivity. Various spectroscopic measurements have been carried out and revealed that a pseudogap exists in the electronic energy spectrum and has a unique temperature and carrier doping dependence. However its detailed properties are still controversial. Optical time-resolved spectroscopy using femtosecond pulse laser has been shown to be a powerful tool for the investigation of the quasiparticle (QP) dynamics in the pseudogap and superconducting (SC) gap states, and provided complementary information to the well-established spectroscopy. In addition, the excitation dynamics on ultrafast time scale can provide a way to resolve the formation dynamics of the energy gaps, offering new and improved insights into the high- T_c superconductivity.

In this work, we will present a systematic study of the nonequilibrium dynamics in Bi-based high-T_c cuprates (Bi2212) by means of femtosecond optical pump-probe (UV-NIR pulses with 100 fs durations) spectroscopy. Temperature dependence study of photoexcited QP dynamics has revealed relaxation components associated with SC gap (BCS-like T-dependence below T_c , appeared together with a critical slowing down), pseudogap (T-independent gap below T^*), and electron-phonon relaxation through the continuum [1]. The results of the hole-doping dependence, including the systematic variations of the gap energies, agreed well with those obtained from other spectroscopies [2, 3]. The polarization analysis has addressed the rotational symmetry breakings of the dynamics, which are suppressed at room temperature and appears below T^* , implying that the anisotropic QPs are coherently excited because the underlying rotational symmetry is spontaneously broken below T^* [3]. While the anisotropic SC component (B_{1g}) extends to T^* , the anisotropic pseudogap component (B_{2g}) does not show any measurable change at $T_{\rm c}$. On the other hand, the fluence dependence study above the photodestruction condition of the SC has revealed coexisting SC and pseudogap QP dynamics below T_c , allowing more precise analysis of the correlation dynamics in the SC gap formation. The results including a doping dependence have indicated a correlation between the pseudogap QPs and SC pairing time. The coherent quench experiment of the pseudogap (pump-probe experiment with a photodestruction prepulse of the pseudogap) has indicated an absence of long-range electronic order beyond a few coherence lengths on short timescales [4]. These results lead to a physical picture of the pseudogap with short-range correlated localized carriers, pairs or very small clusters, which have a locally breaking rotational symmetry and partly contribute the SC gap formation.

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Low energy electrodynamics of strongly disordered superconductors

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In the last decades the failure of the BCS paradigm of superconductivity in several correlated materials led to a profound modification of the description of the superconducting phenomenon itself. A case in point is the occurrence of Cooper pairing and phase coherence at distinct temperatures, associated respectively with the appearance of a single-particle gap and a non-zero superfluid stiffness. This particular behavior is observed in several materials, which range from high-temperature cuprate superconductors to strongly-disordered films of conventional superconductors. For the latter system scanning tunneling microscopy measurements have revealed that the superconducting state becomes inhomogeneous, segregating into domains of large and suppressed superconducting order parameter. In this contribution we will discuss the static and dynamical response of such systems based on studies of the attractive Hubbard model with strong on-site disorder and by including fluctuations beyond the Bogoljubov-de Gennes approach. We find a decoupling of charge and amplitude correlations with increasing disorder due to the formation of superconducting islands. This emergent granularity also induces an enhancement of the charge correlations on the SC islands whereas amplitude fluctuations are most pronounced in the 'insulating' regions. While charge and amplitude correlations are short-ranged at strong disorder we show that current correlations have a long-range tail due to the formation of percolative current paths. Moreover we show that for strongly disordered superconductors phase modes acquire a dipole moment and appear as a subgap spectral feature in the optical conductivity which even survives long-range Coulomb interactions.

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Signature of the pseudogap critical point in cuprate superconductors

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Since the discovery of the cuprates 30 years ago, the mechanism of the superconductivity in these materials is still an open question. The phase diagram of hole-doped cuprates is composed of different phases. The link between these phases is not yet clear. The most studied and the less understood of these phases is the pseudogap phase. In order to study this phase at low temperature, high magnetic fields are required to suppress superconductivity.

I will present measurements of the Hall and Seebeck coefficients on two cuprate materials, YBCO [1] and LSCO [2], performed in magnetic fields large enough to suppress superconductivity at low temperature. We arrive at two main findings. First, with decreased doping, the pseudogap critical doping p^* occurs well before the onset of the charge-density-wave order that develops in these materials. So the two phenomena are separate. Secondly, the carrier density n is observed to drop sharply at p^* , going from n = 1 + p above p^* to n = p below p^* . This signature imposes strong constraints on the possible nature of the pseudogap phase.

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Magnetoinfrared spectroscopy of Landau levels and Zeeman splitting of three-dimensional massless Dirac fermions in ZrTe₅

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Three-dimensional (3D) Dirac/Weyl materials have been under intensive study recently. In this talk, I will present our optical spectroscopy study on $ZrTe_5$ single crystals. The measurement at zero field revealed a linear energy dependence of optical conductivity over a relatively broad frequency range, which provides optical spectroscopic proof of 3D Dirac fermions. When magnetic field is applied, we observe clear transitions between Landau levels and their further splitting. Both the sequence of transitions and their field dependence follow quantitatively the relation expected for 3D massless Dirac fermions. The measurement also reveals an exceptionally low magnetic field needed to drive the compound into its quantum limit, demonstrating that $ZrTe_5$ is an extremely clean system and ideal platform for studying 3D Dirac fermions. The splitting of the Landau levels provides direct, bulk spectroscopic evidence that a relatively weak magnetic field can produce a sizable Zeeman effect on the 3D Dirac fermions, which lifts the spin degeneracy of Landau levels. Our theoretical analysis indicates that the compound can be transformed from a Dirac semimetal to a line-node/Weyl semimetal by magnetic field along the crystalline *b*-/*c*- axis.



Optical Properties of Weyl Semimetals

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Weyl semimetals (WSMs) are materials with two non-degenerate bands linearly crossing at the Fermi level in three-dimensional (3D) momentum space. The band crossing points are called Weyl points. This class of materials, a 3D analogue of graphene, provide a platform for a condensed-matter realization of the Weyl fermions. Recently, transition-metal monoarsenides and monophosphides (TaAs, TaP, NbAs, and NbP) have been theoretically predicted and experimentally confirmed to be natural WSMs with 12 pairs of Weyl points, paving the way for further investigations into the WSM state.

Here, we use Fourier Transform Infrared Spectroscopy (FTIR) to study the charge and lattice dynamics in WSMs. Figure 1 displays the far-infrared optical conductivity at different temperatures for TaAs. Our study reveals that the optical conductivity of TaAs is characterized by a narrow Drude response alongside a pronounced linear dependence on the photon energy. The spectral weight of the Drude response vanishes as T^2 , in good agreement with theoretical predictions for a WSM. The low-temperature optical conductivity features two linear components with distinct slopes. By comparing the experimental results with first-principles calculations, we found that the linear conductivity below 230 cm⁻¹ arises purely from the interband transitions in proximity to 4 pairs of Weyl points lying very close to the Fermi energy. These interband transitions contain rich information about the the WSM state in TaAs. In addition, an infrared-active lattice vibration mode was observed at ~250 cm⁻¹ in the optical conductivity spectra. This mode exhibits a Fano-like lineshape, indicating strong coupling with the continuum of transitions near the Weyl points.



Fig. 1. Waterfall plot of the optical conductivity at different temperatures for TaAs.

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Optical conductivity of the 3D Dirac semimetals Cd₃As₂, CaMnBi₂, and SrMnBi₂

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In a broad frequency range $(50 - 22\ 000\ \text{cm}^{-1})$ and for temperatures from 10 to 300 K, we measured the complex optical conductivity of three different 3D Dirac semimetals: Cd₃As₂, CaMnBi₂, and SrMnBi₂.

In Cd₃As₂, the real part of the optical conductivity follows a power law, $\sigma_1(\omega) \propto \omega^{1.65}$, in a broad frequency range, 2000 to 8000 cm⁻¹. We interpret this behavior as a manifestation of interband transitions between two Dirac bands which are effectively described by a sublinear dispersion relation, E(k) $\propto |k|^{0.6}$. The momentum-averaged Fermi velocity v_F of the carriers in these bands is energy dependent and ranges from 1.2×10^5 to 3×10^5 m/s, depending on the distance from the Dirac points. At 160 meV, we observe a diminishing conductivity, consistent with observations of an "optical gap" made in the 1960s [1]. However, we hesitate to follow the traditional interpretation of this feature and to straightforwardly relate it to a gap in the density of states. Applying recent models for the optical response of Dirac/Weyl semimetals [2, 3], we instead relate this feature to the Fermi level, which is positioned around 100 meV above the Dirac points, and which is consistent with the carrier concentration.

In CaMnBi₂ and SrMnBi₂, where the Dirac bands are believed to be gapped (but still conical) and highly anisotropic, the infrared optical conductivity is dominated by the intraband transitions, which mask the interband contributions. If we fit the intraband conductivity by a Drude term, $\sigma_1(\omega) \propto v_F^{-1}$, [2] and subtract this contribution from the experimental spectra, the remaining optical conductivity will demonstrate a linear in frequency increase. Applying a model for gapped conical bands [3], we derive the Fermi velocity from the slope of the interband $\sigma_1(\omega)$. We find the Fermi velocities derived from the intra- and interband contributions to be identical [$v_F = 1.5 \times 10^4$ m/s for CaMnBi₂ and 6×10^4 m/s for SrMnBi₂] proving the consistency of our analysis. These values of v_F coincide with the low limit of the ARPES data, thus indicating that the optical conductivity effectively probes the smallest Fermi velocity in the case of anisotropic cones.

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Spectroscopic imaging scanning tunneling microscopy of spin-polarized two-dimensional states on a polar semiconductor BiTeI

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Two-dimensional (2D) electronic states on the surface of a polar material is subject to the spontaneous electric polarization in the bulk, forming distinct contrasts between 2D electronic states at one side and at the other side. A polar semiconductor BiTeI among others provides a unique platform to examine spectroscopically such 2D electronic states under influence of the bulk polarization as well as strong spin-orbit interaction because of its layered structure composed of heavy atoms [1,2]. Angle-resolved photoemission spectroscopy has uncovered that 2D electronic states at the surface of BiTeI possess momentum-dependent (Rashba-type) spin splitting larger than ever reported [3] and an ambipolar nature sometimes coexisting on a single surface [4,5].

Here we present a comprehensive study of the ambipolar 2D states on the surface of BiTeI with spectroscopic imaging scanning tunneling microscopy [6]. We identify by thoroughly examining topographic images that submicron-scale domains of this material are comprised of opposite stacking orders. By imaging electron standing waves (Fig. 1), we find that positive or negative carriers with Rashba-type spin splitting appear correspondingly to the polar directions of the domains. The electron densities at the surface stay constant independently of those in the bulk, providing a compelling experimental evidence that the 2D carriers are induced by the spontaneous electric polarization. By closely analyzing electron standing waves, we uncover that electron spin is not preserved but rotated by non-magnetic impurity, indicating strong influence of spin orbit interaction to the scattering process. Our study demonstrates that the surface of polar materials provides 2D systems consisting of non-volatile, spin-polarized, and ambipolar carriers suitable for spectroscopy

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Fig. 1 A differential conductance image of BiTeI showing electron standing waves.





Poster session abstract

Electron-Hole Asymmetry in the Electron-phonon coupling in Top-gated Phosphorene Transistor

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Using in-situ Raman scattering from phosphorene channel in an electrochemically top-gated field effect transistor, we show that its phonons with A_g symmetry depend much more strongly on concentration of electrons than that of holes, while the phonons with B_g symmetry are insensitive to doping. With first-principles theoretical analysis, we show that the observed electron-hole asymmetry arises from the radically different constitution of its conduction and valence bands involving π and σ bonding states respectively, whose symmetry permits coupling with only the phonons that preserve the lattice symmetry. Thus, Raman spectroscopy is a non-invasive tool for measuring electron concentration in phosphorene-based nanoelectronic devices.

[1] Biswanath Chakraborty^{*}, Satyendra Nath Gupta^{*}, Anjali Singh, Manabendra Kuiri, Chandan Kumar, D. V. S. Muthu, Anindya Das, U. V. Waghmare and A. K. Sood, 2*D* materials 2016 (just accepted).

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Dimensionality-Induced Bandwidth control in $[(SrIrO_3)_m/(SrTiO_3)]$ (m=1, 2, and ∞) Superlattices.

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We investigate the electronic structure of the $[(SrIrO_3)_m/(SrTiO_3)]$ on $SrTiO_3$ (001) superlattice (SL) (m=1, 2, ∞) using optical spectroscopy and first-principles calculation. The preceding research on temperature dependent transport and magnetism along with first-principle calculation was reported [1]. Similar to Ruddlesden-Popper (RP) series $Sr_{n+1}Ir_nO_{3n+1}$ [2], our SLs shows metallic to insulating phase and blue shift of α -peak position in $\sigma_1(\omega)$ by decreasing dimensionality. However unlike RPs, SLs show finite carrier still remain even at SL m=1. Also broadening feature of RPs and SLs by the dimensionality show opposite trend. For m= ∞ , or SrIrO₃, we observe very sharp bandwidth which is consistent with recent ARPES data [3]. We study the discrepancies in RPs and SLs with first-principle calculation. Possible origins will be discussed.

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Negative Electronic Compressibility and Tunable Spin-Splitting in WSe₂

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Recently, semiconducting transition metal dichalcogenides have garnered attention for their extraordinarily large exciton-binding energies [1,2] and locking of the spin with valley and layer pseudospins [3,4]. Through sub-monolayer deposition of alkali metals onto the vacuum-cleaved surface of bulk WSe₂, analogous to electrical gating in a field-effect transistor, we create a 2D electron gas at the sample surface with tuneable carrier concentration (Fig. 1b,c) [5]. Counter-intuitively, we find that the surface electron doping induces a reduction of the chemical potential in the near-surface. We attribute this to a pronounced negative electronic compressibility [6] where strong electron-electron interactions lead to the lowering of the chemical potential with band filling, which we find persists to remarkably high electron densities. Simultaneously, we show that this is accompanied by a giant tuneable spin-splitting of the valence band states, Fig. 1d, and a reduction of the quasiparticle band gap, the most fundamental property of a semiconductor.



Fig. 1. ARPES measurements of a) pristine bulk WSe2 and b) surface-dosed bulk WSe2. Deposition of alkali metal at sample surface c) forms a multi-valley 2DEG and d) simultaneously induces tunable spin-splitting of valence bands states at the Brillouin zone corners.

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Interaction-driven spin-nematicity and magnetic double-Q phases in iron pnictides

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The role of Coulomb interactions and their specific influence on the ordered phases in the iron pnictides remains a topic of great current controversy. Resolving e.g. the detailed nature of the magnetic exchange couplings and the nematic correlations in these itinerant systems may pave the way to enhanced understanding of unconventional superconductivity.

In the first part of the presentation, I will discuss the nematic susceptibility obtained by including fluctuations beyond RPA of the on-site five-orbital Hubbard model. A main result is the existence of a (preemptive) purely nematic phase originating only from Coulomb interactions, as shown in Fig. 1(a). Application of this formalism to iron-based superconductors reveals a key role of the d_{XY} orbital to drive the nematic instability. Comparison with the ferro-orbital order susceptibility shows that the latter does not diverge. This work provides a promising framework to search for new materials displaying nematic order.

In the second part of the presentation, I will discuss the origin of the recently experimentally discovered double-Q (C4 symmetric) magnetic phases in the iron-based superconductors within a fully self-consistent microscopic approach that includes a realistic band structure and Hubbard-Hund correlations. The general phase diagram displays prominent regions of stability of these unusual magnetic structures as shown in Fig. 1(b). I will discuss their properties, and propose further new experiments to test for their existence in real materials.



Fig. 1. (a) Doping (n)-temperature (T) phase diagram of iron pnictides. (b) n-T phase diagram of the nature of the magnetically ordered phases: (OM ortho-magnetic, MS magnetic stripe, SCO spin-charge ordered) also displayed in top panel of (b).

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The optical properties in superconducting optimally electron-doped Ca_{8.5}La_{1.5}(Pt₃As₈)(Fe₂As₂)₅

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Recently, two more complex superconductors in the Ca-Pt-Fe-As chemical system have been found and synthesized.[1] $Ca_{10}(Pt_3As_8)(Fe_2As_2)_5$ (the 10-3-8 phase), has triclinic crystal structure, while the other, Ca₁₀(Pt₄As₈)(Fe₂As₂)₅ 5 (the 10-4-8 phase), possesses higher, tetragonal symmetry. In both compounds, the skutterudite spacer layer (Pt–As) is sandwiched by Ca ions. The undoped 10-3-8 material shows a semiconductor with the magnetic transition around 100 K, while the undoped or lightly-doped 10-4-8 shows a superconductivity around 25 K. However the hole or electron doped 10-3-8 materials shows a superconductivity dome according to the doping quantity, 38 K optimal doped sample. We focus the optimally La-doped 10-3-8 sample $(Ca_{8.5}La_{1.5}(Pt_3As_8)(Fe_2As_2)_5)$ with $T_c=35$ K and have measured FIR and IR spectroscopy in various temperatures below and above T_c. We have observed the reflectivity due to Drude response and infrared absorption in low frequency region and the reflectivity due to interband transition in high frequency region in normal state. However, in superconducting state we found a flat reflectivity with 1 below 80 cm⁻¹, which may be due to s-wave superconductivity. To understand these behaviors in detail, we calculate the optical conductivity via Kramers-Kronig relation. In this conference we will report the interesting results.

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Optical observations of SDW fluctuations cooperate with nematic order in Ba122 iron-based superconductors

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Using infrared spectroscopy, we report detailed optical measurements of the K-, Co-, and P-doped BaFe₂As₂ single crystals. At low dopings, we found that the reflectivity and optical conductivity in all the three series show a small additional suppression preceded by the substantial suppression of the spin-density-wave (SDW) order. In the optimal doping or even beyond it, where the SDW order is absolutely suppressed, this additional suppressed effect becomes weaker in the Co and P dopings but completely disappears in the case of K doping. Almost the same energy scale and similar behavior on the optical spectrums as the SDW order can easily make one attributes this effect to a consequence of the magnetic fluctuations. Nevertheless, it cannot well explain the absent suppression of the optimally K-doped compound in which the magnetic fluctuations are also strong. From the doping evolution of the onset suppressed temperature, we found it is well consistent with the nematic fluctuations. Therefore, our optical observations are most likely related to the electronic nematic fluctuations.



Photoexcited nonequilibrium dynamics of *c*-axis Josephson plasma in La_{2-x}Sr_xCuO₄

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A high- T_c cuprate superconductor La_{2-x}Sr_xCuO₄ consists of stacks of two-dimensional superconducting CuO₂ planes capacitively coupled by insulating block layers, and its optical properties are well described as a SIS Josephson junction arrays. Below T_c the Josephson plasma resonance (JPR) arises at THz frequency region due to coherent charge transport of the tunneling superconducting carries across the CuO₂ planes. Because the JPR directly reflects the strength of the coupling between CuO₂ layers, the properties of the JPR have been intensively studied in equilibrium [1] and also in nonequilibrium for the study of ultrafast dynamics [2] and for photo-induced coherence above T_c [3]. Here, using time-resolved optical pump-THz probe spectroscopy, we investigate nonequilibrium behaviors of *c*-axis JPR in La_{2-x}Sr_xCuO₄.

We used an optimally-doped La_{1.85}Sr_{0.15}CuO₄ single crystal with $T_c = 35$ K. Figure 1 shows reflectivity spectra at 5 K along the *c*-axis. The black curve shows the spectrum in equilibrium, exhibiting JPR at around 7 meV. The other curves show transient spectra measured 3 ps after the optical pump with 100-fs pulse duration, 1.55-eV photon energy, and *c*-axis polarization. In the weak pump regime the plasma toward edge shifts low frequencies. Under the intense excitation regime (> 1 mJ/cm^2), however, a new reflectivity peak



Fig. 1. Pump intensity dependence of transient c-axis reflectivity spectra 3 ps after the optical excitation at 5 K.

appears with higher frequency, and gradually redshifts as the pump intensity increases. This new peak is reminiscent of the transverse optical JPR mode observed in $YBa_2Cu_3O_{6.6}$ under parallel magnetic fields [4]. In the presentation we will discuss the origin of the new peak in the transient spectra based on the "multilayer model" [5].

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Terahertz nonlinear response in an optimally-doped YBa₂Cu₃O₇ single crystal

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Recently, the amplitude Higgs mode has been observed in *s*-wave superconductors(SCs) by using terahertz (THz) pump-probe spectroscopy [1]. It has also been reported that the order parameter oscillates under the irradiation of sub-gap pump pulse at the twice of the pump frequency which gives rise to an efficient third harmonic oscillation(THG)[2], whereas the contribution from charge density fluctuation to THG has also been pointed recently in a 2D square-lattice model[3]. How such a collective amplitude mode emerges in high- T_c SCs is an intriguing problem, as the theory predicts the existence of multiple Higgs mode in *d*-wave SCs [4]. In this research, we studied the nonlinear response of a high- T_c SCs YBa₂Cu₃O₇ induced by an intense THz pulse in order to investigate the Higgs modes.

We used an optimally-doped (001) YBa₂Cu₃O₇ detwinned single crystal ($T_c = 90$ K) as a

sample. The THz pump pulse with the peak electric field of 500 kV/cm was generated by optical rectification in а LiNbO₃ crystal with the tilted-pulse-front scheme. Ultrafast dynamics induced by the THz pump pulse (E_{pump}/b) was probed by the near infrared (1.55 eV) optical pulse in a reflection geometry. Figure 1 shows pump-probe delay dynamics of the reflectivity change, $\Delta R/R$, at 84 K with different probe polarizations. Instantaneous signal was observed that follows the squared waveform of the pump electric field. This signal appears only below T_c , indicating coherent nonlinear response of the superconducting state. The signal has strong anisotropy for the polarization of the probe pulse. The origin of the nonlinear responses will be discussed in our poster in detail.



Fig. 1. The pump-probe delay dynamics of reflectivity change for different probe polarizatios, $E_{\text{probe}}//a$ and b-axis.

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Theory of Inelastic X-Ray Scattering for Cuprates and Iron Arsenides

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Resonant inelastic x-ray scattering (RIXS) tuned for Cu L edge is a possible tool to detect momentum-dependent intra-orbital charge excitations in cuprate superconductors [1]. We theoretically investigate the possibility for observing the low-energy charge excitation with the same energy scale as spin excitation by RIXS [2]. We find that the core-hole Coulomb potential enhances the spectral weight of the charge excitation in electron-doped systems. Furthermore, from a large scale density-matrix renormalization group (DMRG) calculation, we find that the electron-doped system enhances small-momentum low-energy dynamical charge structure factor, whose energy is lower than that of spin excitation. This indicates a nontrivial mechanism of charge-spin coupling and superconductivity in electron-doped cuprates.

In contrast to cuprates, the orbital degrees of freedom are crucial for understanding the electronic excitations in iron-based superconductors. For this purpose, we propose nonresonant inelastic x-ray scattering (NIXS) to detect orbital-selective electronic excitations in the iron-based superconductors. As a theoretical example, we choose the antiferromagnetic state of iron arsenides and demonstrate that the orbital-selective excitations are detectable by choosing appropriate momentum transfer in NIXS [3]. We propose that both NIXS and resonant RIXS are complementary to each other for fully understanding the nature of orbital excitations in multiorbital itinerant electron systems.

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The role of Hund's coupling in the correlations and the nematicity of iron superconductors

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Understanding the nature and strength of correlations in iron superconductors is key to unveil the nature of the superconducting, nematic and magnetic instabilities that appear in the phase diagram of these systems. Due to their multi-orbital character, correlations in iron superconductors are strongly affected by Hund's coupling.

For a long time there has been a strong controversy on the nature of correlations induced by Hund's coupling and its relation to Mott physics. While some authors describe Hund metals as strongly correlated systems which are not in proximity to a Mott insulating state, others have described iron superconductors as doped Mott insulators. We show [1] that the atomic spin polarization, promoted by Hund's coupling, induces strong correlations, without necessary leading to an increase in the localization of total charge. Indeed, in some cases the polarization may even promote itineracy.

Then I will discuss our recent results [2] about the role of Hund's coupling in the nematicity of iron superconductors, with special emphasis on the case of FeSe. In particular, we find that the Hund's coupling induces anisotropies at the symmetry points in the electronic band structure via strong nematic responses in the quasiparticle weights. These results, in agreement with photoemission and optical experiments, suggest a new mechanism that could explain the origin of the anisotropic properties of iron superconductors.

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Investigation of Precursor Superconducting State in YBCO through In-plane Infrared Optical Spectroscopy

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The c-axis optical studies^[1] of YBa₂Cu₃O_y(YBCO) revealed the existence of a precursor temperature T_p that is much higher than the superconducting transition temperature T_c . In the superconducting (SC) state, $\sigma_1(\omega, T) = \sigma_{1,n}(\omega, T) + \delta(\omega)\sigma_{1,s}(0, T)$ where the SC carriers are condensed into a Dirac delta peak which is not accessible in optical data. The superfluid density ω_{ps}^2 is then estimated using the difference in $\sigma_1(\omega)$ spectral area i.e. $\omega_{ps}^2 = 8 \int_0^{\omega_{cut}} [\sigma_1(\omega, T = 293K) - \sigma_1(\omega, T < 293K)]$. Besides this indirect approach, performing Kramers-Kronig transformation on $\sigma_{1,n}(\omega, T)$ produces the normal component of the imaginary conductivity $\sigma_{2,n}(\omega, T)$. Subtracting this from the original $\sigma_2(\omega)$ we can obtain the superconducting component $\sigma_{2,s}(\omega, T)$ which must satisfy the relationship $\omega_{ps}^2 = \omega \sigma_{2,s}(\omega, T) = \omega [\sigma_2(\omega, T) - \sigma_{2,n}(\omega, T)]$. In ref. [1], a finite superfluid density was observed at temperatures above T_c from both approaches.

In this research, we sought the same optical response in the ab-plane of two underdoped YBCO samples (T_c =63K, p=0.11 and T_c =77K, p=0.136 respectively) using the abovementioned procedure. Our results are in very good agreement with the c-axis studies' results, indicating the presence of a precursor of superconductivity above T_c .



- Fig. 1. Phase diagram showing doping level dependence of the pseudogap temperature T^* , precursor temperature T_p and superconducting transition temperature T_c .
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Critical Charge Fluctuations in Iron Pnictide Superconductors

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The multiband nature of iron pnictides gives rise to a rich temperature-doping phase diagram of competing orders and a plethora of collective phenomena. At low dopings, the tetragonal-to-orthorhombic structural transition is closely followed by a concomitant spin density wave transition both being in close proximity to the superconducting phase. A key question is the microscopic mechanism of high- T_c superconductivity and its relation to orbital ordering and magnetism.

Here we study the 111 and 122 families of iron superconductors using low energy polarization resolved Raman spectroscopy. The Raman susceptibility shows critical non-symmetric charge fluctuations across the entire phase diagram. The charge fluctuations are interpreted in terms of plasma waves of quadrupole intra-orbital excitations in which the



electron and hole Fermi surfaces breath in-phase. We demonstrate that above the structural phase transition the quadrupolar fluctuations with long correlation times are precursor to the discrete four-fold symmetry breaking transition. This is manifested in the critical slowing down of XY-symmetry collective fluctuations observed in dynamical Raman susceptibility and strong enhancement of the static Raman susceptibility. Below superconducting transition, these collective excitations undergo a metamorphosis into a coherent ingap collective mode of extraordinary strength and at the same time serve as a glue for non-conventional superconducting pairing.

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Chirality density wave of the "hidden order" phase in URu₂Si₂

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Many novel electronic ground states have been found to emerge from the hybridization between localized *d*- or *f*-electron states and conduction electron states in correlated electron materials. The heavy fermion (HF) compound URu₂Si₂ exhibits the coexistence of two such ground states: so-called "hidden order" (HO) below T_{HO} =17.5 K and superconductivity below T_c =1.5 K. Despite 30 years of research the symmetry of the order parameter associated with HO phase below 17.5 K has remained ambiguous.

Here we report results of low energy polarization resolved Raman spectroscopy study aimed to specify the symmetry of the low energy excitations above and below the HO transition. These excitations involve transitions between interacting heavy uranium 5f orbitals, responsible for the broken symmetry in the HO phase. From the symmetry analysis of the collective mode, we determine that the HO parameter breaks local vertical and diagonal reflection symmetries at the uranium sites, resulting in crystal field states with distinct chiral properties, which order to a commensurate *chirality density wave* ground state (Fig. 1) [1]. We further explore the competition between the HO phase and large moment antiferromagnetic (LMAFM) phase and the connection between the HO chirality density wave and the unconventional superconductivity in URu₂Si₂, which has recently been proposed to be of a chiral *d*-wave type.

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Fig. 1: Schematics of the chirality density wave in the HO phase. The uranium sites are occupied by left-and right-handed *5f* orbital states



Non-Trivial Metallic Surface State of a Kondo Semiconductor YbB₁₂

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Ytterbium dodecaboride YbB₁₂ is one of Kondo insulators/semiconductors (KIs), which have a tiny energy gap owing to the hybridization between conduction and localized 4*f* electrons, namely *c-f* hybridization, renormalized by the strong correlation [1]. Although the bulk energy gap is fully opened [2], the electrical resistivity is saturated at lower temperature than 10 K. The origin of the saturation has been unrevealed for a long time. However, it is recently speculated to originate from a topologically protected surface metallic state, namely YbB₁₂ is a candidate of "topological Kondo insulators" [3]. To elucidate the origin of the metallic conduction at the surface, we performed angle-resolved photoemission spectroscopy (ARPES) of a well-defined clean surface of YbB₁₂(001).

Figure 1 shows an ARPES image along the [100] axis near the $\overline{\Gamma}$ point of the surface Brillouin zone. The band from *S* to F_{dn} can be assigned as a *c*-*f* hybridization band explained by a bulk band calculation [4]. At the binding energy below the *c*-*f* hybridization band, surface states (*F* and F_{up})

and metallic bands across the Fermi level have been observed. The band dispersion of the metallic state can be assigned to be a topological state owing to the c-f hybridization. Similar metallic state has been recently expected by a theoretical calculation [5].

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surface.



Detailed optical spectroscopy of the hybridization gap and the hidden order transition in high quality URu₂Si₂ single crystals

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We measured the optical reflectivity of ac and ab -plane of high quality URu_2Si_2 single crystals. We demonstrate that the optical properties are very sensitive to strain in the sample surface, which may result from e.g. polishing. We obtained strain-free and stoichiometric acplanes by vacuum annealing at 950°C, which allows measurement of the *a*-axis and *c*-axis optical conductivity. When the temperature is lowered below 75 K we observe a gradual reduction of the a-axis and c-axis optical conductivity in the frequency range from 10 to 50 meV, and a gradual emergence of interband transitions at 20 meV, which we interpret as a crossover to a state where the narrow 5f bands become coherent. This temperature is higher than 30 K reported previously [1], as a result of aforementioned surface conditions. Below the hidden order transition at 17 K the low frequency optical conductivity shows two main components, namely a narrow (less than 1 meV) zero-frequency mode, and a fully gapped (6 meV) component. The spectral weight removed from the gapped region is transferred to the range just above the gap, which is reminiscent of a charge density wave. The gap size diminishes as a function of increasing temperature, and falls below the measured range as the hidden order temperature is approached from below. In contrast to recent reports [2,3] the optical conductivity just above the gap has a single-gap structure and the gap-feature is stronger, possibly due to higher homogeneity or cleaner surface conditions.

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Study on electronic states of the mixed-valence compound SmS by resonance x-ray emission spectroscopy under high pressure

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Samarium mono sulfide (SmS) is a typical compound that exhibits successive phase transitions under high pressure. At a first critical pressure P_{c1} (~ 0.6 GPa at room temperature), SmS shows a phase transition from an insulator to a mixed-valence "metal" accompanied by a color change from black to golden-yellow^[1]. At pressures above a second critical pressure P_{c2} (~ 1.8 GPa at low temperature), the system shows an antiferromagnetic transition at a low temperature. In the mixed-valence phase of SmS above P_{c1} , namely golden phase, we observed anomalous physical properties at low temperature, such as a non-metallic temperature dependence of electrical resistivity, a drastic decrease of carrier density and a large negative linear thermal expansion coefficient ^[2]. From these results, we proposed that the pseudogap is formed at low temperatures associated with the (exciton-like) local bound state formation of Sm³⁺ hole and conduction electrons ^[3]. The main objective of the present study is to clarify a role of the mixed-valence in the local bound state formation.

Using high-quality bulk single crystals of SmS we performed the Sm- L_{III} edge x-ray absorption spectroscopy in the high-resolution partial fluorescence yield mode (PFY-XAS) under pressure and at low temperatures. All experiments were carried out at the inelastic x-ray scattering beamline BL12XU installed at SPring-8. Focused beam was obtained by using the Kirkpatrick-Baez mirror. Silicon (440) crystal was used for analyzing the Sm $L_{\alpha 1}$ emission line.

Figure 1 shows the temperature dependence of the PFY-XAS spectrum of golden SmS at 0.8 GPa. Data are normalized by total intensities. As the temperature is decreased, the Sm^{2+} peak

observed at the incident energy of 6715 eV monotonically grows, which suggests that the Sm mean valence decreases with lowering temperature. In the presentation, we will show the detailed results and discuss the relationship between the mean valence change and the anomalous transport thermodynamic properties and observed at low temperature.

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Fig. 1. Temperature dependence of the PFY-XAS spectrum of SmS at 0.8 GPa.



Lattice and Magnetostrictive Contributions to the Internal Energy in Cobalt Oxide Observed by THz-TDS

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In the previous study, on an antiferromagnet manganese oxide (MnO), we showed that the lattice and magnetostrictive contributions to the internal energy can be observed by terahertz time domain spectroscopy (THz-TDS) [1]. In the present study, the refractive index in the terahertz region of an antiferromagnet cobalt oxide (CoO) is obtained from the peak shift of the transmitted THz electric field. We discuss that the lattice and the magnetostrictive contributions to the internal energy appear on the temperature dependence of the refractive index.

At room temperature, CoO has a rock-salt type cubic crystal structure and is paramagnetic, while, below the Néel temperature, it has a tetragonal crystal structure and is antiferromagnetic [2]. The Néel temperature T_N is reported to be about 290K. We generated the THz wave from air plasma induced by two-color laser pulses. To detect the THz wave, we used a 1-mm thick ZnTe crystal for the electro-optical (EO) sampling.

The temperature dependence of the transmitted THz electric field is shown in Fig. 1. As the temperature increases, the shift of the peak time of the transmitted THz electric field increases. It is considered that the refractive index in CoO increases and the speed of the THz wave decreases. We can derive the change Δn in averaged refractive index from the peak time shift, and the result is shown in Fig. 2. The change Δn in averaged refractive index reflects the internal energy in the system. Above T_N , it is considered that the lattice contribution is dominant to the internal energy. The solid curve in Fig. 2 shows the lattice contribution calculated by the Einstein model. On the other hand, below T_N , the magnetstriction is considered to be also dominant in addition to the lattice contribution.



Fig. 1. Temperature dependence of the transmitted THz electric field.

Fig. 2. Temperature dependence of the change Δn in averaged refractive index.

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Observation of Negative Pulse Delay in Photo-Excited Silicon by THz-TDS

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By using terahertz time domain spectroscopy (THz-TDS), transient spectra can be observed with femtosecond time resolution. Recently, in the photo-excited Si, the formation dynamics of excitons and electron-hole droplets (EHDs) [1], the exciton Mott transition [2], and the carrier dynamics [3] have been investigated using the optical-pump/terahertz-probe spectroscopy.

In the present study, we investigate the carrier dynamics of photo-excited Si at room temperature by using THz-TDS. Negative delay of the transmitted terahertz pulse was observed under the photo-excitation.

The optical pulses for the THz generation, the THz detection, and the photo-excitation are provided by a Ti: sapphire regenerative amplifier. Their wavelength, pulse width, pulse energy, and repetition rate are 810 nm, 0.15 ps, 700 μ J, and 1 kHz, respectively. The THz pulse is emitted from ambient air irradiated by a symmetry-broken laser field composed of the fundamental and its second harmonic laser pulses [4], and detected by the EO sampling using a 1-mm thick ZnTe <110> crystal [5]. The sample of Si is photo-excited ~10 ps before the THz pulse.

The typical electric field of the THz pulse observed after its transmission through the photo-excited Si is shown in Fig. 1(a). The transmitted terahertz pulse has a negative delay under the photo-excitation. The fluence dependence of the peak shift is shown in Fig. 1(b). As is seen, the THz peak shift has negative value; namely the THz pulse propagates faster in the photo-excited Si than in no excited Si. The absolute value of the THz pulse peak shift increases as the fluence increases in the low fluence region (< \sim 170 µJ/cm²), and then it decreases in the higher fluence region above \sim 170 µJ/cm². The gray curve in Fig. 1(b) shows a calculated fluence dependence of the peak shift, which is estimated from the group velocity.



Fig. 1. (a) Transmitted THz electric field in the photo-excited Si. The gray curve shows that without photo-excitation. (b) The fluence dependence of the peak shift.

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Microwave Spectroscopy at mK Temperatures Using Planar Devices

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The techniques that are employed in spectroscopic studies of solids are matched to the different energy scales that characterize the phenomena of interest. If these are on the order of just a few K or even in the mK range, as is the case for several unconventional metals and superconductors, then microwave experiments at GHz frequencies are the appropriate way to extend optical spectroscopy to these extremely low energies, on the μ eV scale.[1] Performing microwave spectroscopy on highly conductive samples at mK temperatures is an experimental challenge and only few approaches have been demonstrated so far.[2,3]

Main objectives in our work are a compact probe geometry that can easily be implemented in dilution refrigerators and a convenient access to the frequency-dependent response of the sample, i.e. either a broadband or a multiresonant approach, at frequencies spanning the range from 1 GHz to 20 GHz or even higher. Therefore, we have developed different microwave planar devices with chip dimensions of a few mm. These devices can easily be fabricated according to the particular requirements, including sample size and shape.

For quantitative measurements of the microwave surface impedance on metals and superconductors, we use superconducting stripline resonators. Based on our previous experience at ⁴He temperatures,[4] we now study both conventional and unconventional superconductors with critical temperatures well below 1 K. From the surface impedance, we determine further electrodynamic quantities of interest: e.g., the temperature dependence of the penetration depth can yield information about the presence of nodes in the energy gaps of superconductors.

Coplanar resonators can be even more compact in size, allowing the study of smaller samples at comparably low frequency. Superconducting coplanar resonators allow high quality factors and high sensitivity [5] whereas metallic coplanar resonators and metallic broadband coplanar lines can be operated in high magnetic fields,[6] as needed in studies of magnetic resonance. While regular magnetic resonance operates at temperatures that are much higher than the Zeeman energy, our approach allows magnetic resonance studies where the temperature can be similar to or even considerably lower than the Zeeman energy.

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Strain effect on the visible emission in ferroelectric nanotubes: template and wall-thickness effect

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We investigated the strain effect on temperature-dependent photoluminescence property in the clamped (with template) and free-standing (without template) $PbTiO_3$ (PTO) nanotubes. The wall-thickness of nanotubes was varied from 25 to 80 nm with the outer diameter fixed to 420 nm. While all nanotubes show sizable green/yellow emission, the temperature dependent shift of the emission energy is significantly suppressed in the clamped PTO nanotubes, which is attributed to the lattice strain driven by the template clamping. This clamping effect is more significant for thinner nanotubes. Even in the free-standing PTO nanotubes the temperature-dependence of emission is affected by the wall-thickness. The similar behavior is identified in the $Pb(Zr,Ti)O_3$ nanotubes. Our finding is the clear manifestation of the template and geometrical shape effect on the optical property of the nanotubes [1].

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From confined spinons to emergent fermions: Evolution of elementary excitations in a transverse-field Ising chain

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This presentation is the same as C-13.



Electric-Field Induced Magnetization in Antiferromagnetic Chromium Oxide

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In recent years, various type of multiferroic materials, in which ferroelectric and magnetic orders coexist, have been found. Many of them are antiferromagnets which have spin structures of spiral type. Chromium(III) oxide (Cr_2O_3) is not multiferroic, but has been interested in for a long time by its magnetoelectric effect.

In the present study, we pay attention to the magnetization induced by the electric field in the magnetoelectric effect. We observed the dynamics of the electric-field induced magnetization by a Faraday rotation measurement using a pulsed electric field and a delayed probe light pulse (800nm, 0.2 ps). The critical behaviors of the amplitude and the time response around the Néel temperature are investigated.

Before the Faraday rotation measurement, the temperature of Cr_2O_3 is increased above the Néel temperature ($T_N = 307K$), and then is decreased across T_N under the magnetic field of 1 T and the electric field of 1 kV along the c-axis (ME field cooling). The electric-field induced Faraday rotation is measured in no magnetic field. To improve the signal-to-noise ratio, the sign of the applied electric field is switched with each shot of the probe pulse ($\pm 1 \text{ kV}$). The output from the polarimeter is lock-in detected.

Fig. 1 shows the Faraday rotation signals observed at 285 and 309 K, where the electric field applied along the c-axis, and the electric-field pulse rises at t = 0. In our experiment, very small Faraday rotation angle less than 10^{-6} rad can be detected. The rise time of the Faraday rotation signal at 309 K becomes longer than that at 285 K. The temperature dependence of the Faraday rotation angle is shown in Fig. 2. The observed Faraday rotation angle decreases toward the Néel temperature. This fact means the observed Faraday rotation signal arises from the electric-field induced magnetization.



Fig. 1. Faraday rotation signals observed at (a) 285 and (b) 309 K.



Fig. 2. Temperature dependence of the Faraday rotation angle.



Low-Energy Electrodynamics in Solids

Non-reciprocal directional dichroism in the canted AFM phase of BiFeO₃ at THz frequencies

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BiFeO₃ is a room temperature multiferroic material where, because of the low symmetry, the magnetic ordering can induce local electric polarization via three mechanisms – the spin-current, exchange-striction, and single-ion mechanisms. However, only the spin-current mechanism causes the observed large directional dichroism (DD) of absorbance at THz frequencies in the cycloidal state [1]. By strong magnetic fields the cycloidal order is transformed into a canted antiferromagnetic order and the cycloidal modes are replaced by excitations of the canted AFM structure [2]. However, the static magneto-electric effect persists even in the canted AFM state [3]. Therefore, studies of DD in the canted AFM phase, with simple spin structure as compared to the cycloidal state, could clarify the origin of magneto-electric coupling.

We have measured THz absorption spectra of BiFeO₃ single crystals in magnetic fields above 18T in the canted AFM phase, in the Voigt geometry at 1.6K. We see strong DD of the absorption of the magnon mode for one direction of light propagation, along the direction of the ferroelectric polarization, in pseudocubic notation, $\mathbf{k} \parallel \mathbf{P} \parallel [111]$. In addition, the DD is observed only if $\mathbf{e}^{\omega} \parallel \mathbf{B}_0 \parallel [1-10]$ and $\mathbf{b}^{\omega} \parallel [-1-12]$, where \mathbf{e}^{ω} and \mathbf{b}^{ω} are the electric and magnetic field components of THz radiation. The sign of DD can be reversed (i) by reversing the direction of applied field \mathbf{B}_0 or (ii) by reversing the propagation direction of light.

The strong DD in the collinear AFM phase can be explained assuming that due to magneto-electric coupling both e^{ω} and b^{ω} excite the same magnon mode simultaneously. Further theoretical studies are needed to clarify the magneto-electric coupling mechanism in the AFM phase of BiFeO₃.

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Ultrafast Lattice Dynamics in Multiferroic Cupric Oxide

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The optically induced ultrafast lattice dynamics in a multiferroics CuO was studied by a transient birefringence measurement with the pump-probe technique, and the character of the ferroelectric phase transitions is discussed.

Cupric oxide CuO undergoes two successive magnetic phase transitions at $T_{N1} = 213$ K and $T_{N2} = 230$ K. In the low-temperature phase ($T < T_{N1}$), the magnetic moments are aligned collinearly and order antiferromagnetically. This material has a multiferroic phase in the temperature range between T_{N1} and T_{N2} . In this phase ($T_{N1} < T < T_{N2}$), a noncollinear spiral antiferromagnetic order [1] and a ferroelectric polarization appear [2]. The temperature of the multiferroic phase is higher in CuO compared with other multiferroic materials [2].

The pump pulse (800 nm, 0.2 ps) is provided by a Ti:sapphire regenerative amplifier and the probe pulse (400 nm, 0.2 ps) by the second harmonic generation. The transient birefringence of the relaxational lattice mode generated by the linearly polarized pump pulse is detected by a polarimeter as the change in polarization of the reflected probe pulse.

The observed transient birefringence signal of the relaxational lattice modes is shown in Fig. 1. The vertical axis represents the ellipticity in the electric-field amplitude of the reflected probe pulse. The observed relaxation curve is a sum of two or three relaxation components, whose relaxation times distribute from subpicoseconds to over nanoseconds. The temperature dependence of the relaxation time τ is shown in Fig. 2. Two different type of lattice relaxation modes are seen in the figure. In the temperature region below the phase transition temperature T_{N2} , the temperature dependence can be fit by $\tau = \tau_0 T_{N2}/(T_{N2}-T)$, which suggests a ferroelctric phase transition of the order-disorder type. In the temperature region above the phase transition temperature T_{N1} , the temperature dependence can be fit by $\tau = a (T - T_{N1})^{1/2} + b$, which may suggest a ferroelctric phase transition of the displacive type.



Fig. 1. Transient birefringence signal of the relaxational modes; (a) short-time and (b) longer-time components observed at 205 K.

Fig. 2. Temperature dependence of the relaxation time of the relaxational lattice modes.

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Photo-induced phase transition of SmS

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SmS is known to have a pressure-induced isostructural first-order insulator-to-metal transition that accompanies a color change from black to golden-yellow, namely B-G transition [1]. However in thin films, the B-G transition occurs by the irradiation of strong light [2], so the origin of the B-G transition is not clear. Then to get the information of the effect of the pure electron excitation, we measured a transient reflectivity change after photo-excitation of a single crystalline SmS using a Ti:Sapphire laser (1 kHz, 800 nm, 60 fs) as both pump and probe lights.

Figure 1 shows the temporal development of the change of reflectivity ($\Delta R/R$) after light irradiation of the power of 300 mW. The reflectivity suddenly drops down to 14 % just after the irradiation. During to return the ground state, two relaxation times were observed, fast-one ($\tau_{\text{fast}} \sim 1.43 \text{ ps}$) and slow-one ($\tau_{\text{slow}} \sim 400 \text{ ps}$) with 20 GHz oscillation. The inset of Fig. 1 shows the excitation power dependence of the oscillation amplitude, which has threshold at the laser power of 100 mW. The oscillation frequency became about double when we used a probing light of 400-nm wavelength. This result implies that the oscillation originates from the interference between reflections of the sample surface and a bottom of the photo-induced phase

domains that expands in the crystal like a domino effect as depicted in Fig. 2.

Fig. 1. The time dependence of the reflectivity change $(\Delta R/R)$ at the wavelength of 800 nm $(hv \sim 1.5 \text{ eV})$ after the irradiation of pulse light of 800nm wavelength (blue line) and fitting curve (red line). The inset shows the pump power dependence of the amplitude of the oscillation.



- Fig. 2. Image of the domain expansion created at SmS surface.
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Low-Energy Electrodynamics in Solids

Universalities of dielectric response in biological materials

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A remarkable feature of the high-frequency dielectric response of disordered materials is the universal temperature-frequency behavior of the dynamical conductivity $\sigma_{ac}(v,T)$. In the presence of quasi-free charge carriers, $\sigma_{ac}(v,T)$ demonstrates the Universal Dielectric Response (UDR) $\sigma_{ac}=\sigma_{dc}[1+(v/v_{co})^s]$ [1] (v_{co} is the frequency, where the frequency-independent Drude regime changes to the hopping regime $\sigma_{ac}\sim v^s$, s<1). Another universality is observed at low



Fig. 1 Scaled [3] ac conductivity of pili.

temperatures and high frequencies, where the imaginary dielectric constant is nearly frequency independent ε "≈const (the nearly constant loss, NCL) [2]. We combine spectroscopic techniques and experience in developing models of dielectric universalities in inorganic solids in order to study the molecular and charge dynamics in biological compounds. We have measured broad-band (1 Hz - 1 THz) dielectric response of extracellular filaments of *Shewanella oneidensis* MR-1 (pili), bovine heart cytochrome C (CytC) and bovine serum albumin (BSA), at T = 5 K-300 K. The

spectra of pili reveal both, UDR and NCL universalities. We associate the high-temperature Drude-type conductivity with the ionic transport through liquid bound water; it obeys the scaling relation $\sigma(v)/\sigma_{dc}=F(v\sigma_{dc}^{-1}T^{-1})$ [3] (Fig.1). At helium temperatures and at THz frequencies, we detect signs of the boson peak - excitation typical of disordered systems. The data on the heat capacity of pili and of CytC also reveal signs of the boson peak and, below 2 K, signs of a glass phase. The spectra of CytC and BSA show NCL regimes within the range of room temperatures down to liquid helium temperatures. The results are analyzed from the viewpoint of microscopic models of dynamical response developed for inorganic materials.

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Anomalous quasi-two dimensional electronic state in $Co_3Sn_{2-x}In_xS_2$ shandites.

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Among layered shandite compounds of the general formula $T_3M_2X_2$ (*T* is Ni or Co; *M* is In, Sn , Pb or Tl and *X* is a chalcogen element S or Se), solid solutions of Co₃Sn_{2-x}In_xS₂ show a wide variety of exotic electronic and magnetic properties making them recently of great interest. Co₃Sn₂S₂ has been reported as a type I_A half metal ferromagnet. On the other hand, Co₃In₂S₂ is expected be a nonmagnetic metal and at the edge of magnetic instability based on electronic structure calculations [1]. Furthermore, low gap semiconducting behavior and large thermoelectronic effect have been reported in Co₃SnInS₂ [2-4].

Recently, we have succeeded to synthesis single crystals of the solid solutions $\text{Co}_3\text{Sn}_{2-x}\text{In}_x\text{S}_2$ ($0 \le x \le 2$) out of Sn and Pb fluxs [5]. Here we report the electronic transport properties and heat capacity results of $\text{Co}_3\text{Sn}_{2-x}\text{In}_x\text{S}_2$ using our grown single crystals. A drastic increasing of the resistivity ρ around $x \sim 1$ is found. The semimetallic, not semiconducting, temperature dependence of ρ and strong reduction of the electronic specific heat coefficient γ indicate an unconventional electronic state with anomalously small Fermi surface. The metallic electronic state is restored again for higher indium concentrations. Moreover, a large enhancement of the anisotropy of the electrical resistivity, ρ_c/ρ_{ab} , upon In-substitution is observed which indicate an enhanced quasi-two-dimensional (Q2D) electronic state and consists with the reported trigonal distortion caused by In-substitution [1,2,5]. Additional enhancement of the anisotropy around x ~ 1 , in the anomalous semimetallic region, is also found. Enhancements of γ are observed as approaching $x \rightarrow 0.8$ and 2. The former is due to the strong spin fluctuations in the vicinity of the ferromagnetic-nonmagnetic quantum critical point. The latter may be the enhanced effective mass of electrons associated with the enhanced Q2D state and/or may be related to the expected weak magnetic instability.

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Low energy electronic structure of the semimetal LaSb₂

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Light rare earth diantimonides have been found to exhibit intriguing electronic properties; in particular few of them are characterized by a strongly anisotropic linear and non-saturating magnetoresistance [1]. Within this class of materials the simplest case is represented by $LaSb_2$ which, contrarily to the others, lacks magnetic transitions. LaSb₂ is not only considered for applications in magnetoresistive devices but it is also found to be superconducting at low temperatures and it is investigated as candidate material to host charge density wave phases [2,3]. Despite the several studies on its transport properties, the electronic structure of LaSb₂ is still largely unknown and conjectures on the magnetoresistive properties were mostly based on assumptions [4]. Here we present an angle-resolved photoemission spectroscopy and ab-initio calculation study of LaSb₂ (001). The observed band structure is found to be in very good agreement with the theoretical predictions. Our results reveal that LaSb₂ is a semimetal with a strongly nested two-dimensional Fermi surface, as shown in Fig. 1. The low energy spectrum is characterized by four massive hole-pockets and by four shallow, strongly directional, electron-pockets that exhibit anisotropic Dirac-like dispersion. We discuss the role that this peculiar electronic structure can play on the magnetoresistance, possibly driving it down to its quantum limit, explaining its unconventional behavior.



Fig. 1. (a) Fermi Surface of $LaSb_2$ (001) obtained by Angle Resolved Photoemission Spectroscopy (ARPES). The projected Brillouin zone is marked by dashed lines. (b) Calculated Fermi surface of $LaSb_2$ in the first Brillouin zone.

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Optical probe of spin correlations in the Kitaev magnet RuCl₃

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Identifying and understanding quantum spin liquid states is a central goal of condensed matter physics. Experimental progress has, however, been hindered by a scarcity of real materials displaying QSL behaviour. One possible avenue to realize such QSL states is in honeycomb lattice Mott insulators with strong spin-orbit coupling. In these systems, the entanglement of spin and orbital degrees of freedom can lead to highly anisotropic, bond-directional interactions best described by an extended Heisenberg-Kitaev (HK) model. For sufficiently strong Kitaev coupling K, a QSL ground state with fractionalized spin excitations is anticipated. The charge degrees of freedom are expected to be similarly peculiar in a QSL, as the quantum fluctuating local moments strongly affect the coherent propagation of electrons/holes. In the specific case of the Kitaev QSL, various exotica have been proposed theoretically: 'hidden' quasiparticles and non-Fermi liquid behaviour, as well as doping-induced d- and topological p-wave superconducting states.

Many of the ingredients needed for Kitaev magnetism have in fact been identified in various iridates and, more recently, α -RuCl₃ (hereafter RuCl₃). Several experimental and theoretical studies have established that RuCl₃ is a Mott insulator with a spin-orbit coupled electronic structure and provided evidence for Kitaev-type interactions in this material, although the material orders magnetically at low temperatures. Despite these studies, the finite temperature properties of the HK and related models remain poorly understood and are a matter of significant theoretical interest. In particular, how are the Kitaev QSL or magnetically ordered states, present at low temperature, connected with the high-temperature, paramagnetic phase? The expected coupling between charge and spin degrees of freedom, which underlies many of the predictions for the doped HK magnet, has also not been rigorously explored in RuCl₃ or any other candidate Kitaev magnet.

With these issues in mind, we studied the optical properties of RuCl₃ over a broad temperature range using spectroscopic ellipsometry. By monitoring the intensity of intersite *dd* transitions, we track the evolution of the nearest neighbour spin-spin correlations as a function of temperature. Surprisingly, we find evidence for spin-spin correlations that evolve over a broad temperature range (> 10 T_N) in a manner suggestive of the 'thermal fractionalization' of spins predicted for the pure Kitaev model. We also identify a quasibound excitonic state, rarely observed in Mott insulators, and show that this excitation is clearly affected by magnetic long range order. Our measurements demonstrate that the novel spin textures present in RuCl₃ affect the charge dynamics and that, at temperatures above T_N, this system shares some features with the nearby Kitaev QSL.



THz magneto-optic study of Ni(Cl_{1-x}Br_x)₂·4SC(NH₂)₂ with x=0 and x=0.13

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We report THz absorption spectroscopy results for a well-known spin-1 quantum magnet NiCl₂·4SC(NH₂)₂ (DTN) and its magnetic bond disordered derivate Ni(Cl_{0.87}Br_{0.13})₂·4SC(NH₂)₂ (DTNX) at 0.3K, 0.8K and 1.3K in magnetic field range from 0 to 12T. In zero field the single optically active mode at 9 cm⁻¹ in DTN corresponds to the top of the magnon band excitation at wavevector Q = (0,0,0). In DTNX an additional broad feature is observed at about 1.5cm⁻¹ above the 9 cm⁻¹ mode in agreement with inelastic neutron scattering data on the x=0.06 sample [1]. Both modes undergo Zeeman splitting in magnetic field with similar g-factors, but the weak mode loses intensity as the systems order antiferromagnetically at ~2T at T=0.3K. Above ordering field a new mode emerges just below the Zeeman split mode with increasing energy at about 10 cm⁻¹. An additional weak mode with similar field dependence can be resolved at about 1.5 cm⁻¹ above the latter up to 7T. As DTNX nears the second critical field of the induced ferromagnetic transition at \sim 11.5T at 0.3K, an additional mode emerges at ~14 cm⁻¹ which is not present in DTN. Linewidths of the observed resonances remain resolution limited at low magnetic fields (below 2T) for both samples, whereas small systematic broadening is observed deep in the ordered phase with increasing field. This is in contrast to the magnon excitation at the bottom of the band where notable broadening was observed in the x=0.06 bond disordered sample with inelastic neutron scattering [1]. Current results complement the available low temperature ESR spectroscopy data below 150 GHz [2] and assist in constructing a detailed Hamiltonian essential for understanding the complicated physics [3,4] in DTN and DTNX.



Fig. 1. THz absorption spectra of DTN (left) and DTNX (right) from 3 to 22 cm⁻¹ (~0.4 to 2.7meV) at T = 0.3K in magnetic fields up to 12T (spectra are vertically offset for clarity).

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Low-Energy Electrodynamics in Solids

Studies of the Mott Insulator-Metal transition on BaCo_{1-x}Ni_xS₂ by optical conductivity

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Understanding the metal-insulator transition (MIT) driven by electronic correlations (Mott transition) remains a challenge in many-body physics. One difficulty is that, in most real systems, the electronic degrees of freedom are coupled to those of the lattice or to disorder.

The 2D Mott system $BaCo_{1-x}Ni_xS_2$ shares a similar electronic phase diagram with superconducting cuprates and heavy fermions. This phase diagram, reported on Fig 1, is characterized by a metal-insulator transition (MIT) controlled by pressure or chemical substitution, *x*, concomitant to an antiferromagnetic (AFM) to paramagnetic (PM) transition [1]. By virtue of the high symmetry of its crystal structure, no structural distortions occur at the MIT controlled by the substitution level, x [2]. Thus, this system is an ideal playground for studying the MIT as a function of electronic doping for an ideal square lattice in the regime of moderately ionic *d-p* bonds.



Fig. 1. Electronic phase diagram T vs x of BaCo_{1-x}Ni_xS₂.

Previous optical studies on BaCo_{1-x}Ni_xS₂, for x between 0 and 0.28. BaCoS₂ suggest a charge transfer-type Mott insulator and a more pronounced 2D electronic character than predicted by electronic structure calculations [3]. However, in the metallic phase (x= 0.28) no Drude-like peak has been confirmed. Recent ARPES data on high-quality single crystals of BaNiS₂ and band structure calculations suggest a moderate renormalization effect due to weak electron-electron correlations and an unexpected large Rashba coupling amplified by a huge staggered crystal field [4]. Magnetotransport measurements are consistent with a compensated semi-metal where electron-phonon scattering dominates the transport of charge [5].

We measured the optical conductivity on the ab-plane of the Mott insulator $BaCoS_2$ and the highly conducting $BaNiS_2$ extremes of the phase diagram. We find that the Mott insulator $BaCoS_2$ has actually an almost incoherent conductivity with little temperature dependence. The highly conducting $BaNiS_2$ shows a large thermal evolution with a redistribution of spectral weight correlated to a dielectric induced spin-orbit coupling. We will discuss these data in the frame work of the strength of electron-electron correlations.

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Low-energy electrodynamic of quantum spin liquid candidate YbMgGaO₄

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We report a direct measurement of the low-energy optical conductivity of large-area single crystal YbMgGaO₄, a newly found spin-liquid candidate material, by means of time domain terahertz spectroscopy. Below the lowest infrared active phonon (~2Thz), real part of optical conductivity is close to zero indicating trivial insulating state. There is no detective in-gap absorption arising from spinon Fermi surface of gapless U(1) Dirac spin liquid. No magnetic resonance absorption was observed in polarization dependent measurement down to 1.5K indicating absence of magnetic order. From magneto-terahertz measurement up to 7T within Faraday geometry, we observed an absorption feature which is linearly proportional to the applied magnetic field, yielding evidence for a Zeeman splitting of magnetic moment, from which we extract the value of in-plane g-factors $g \parallel \sim 4.2$. Furthermore, we measure reflectivity and transmittance spectra between $10000cm^{-1}$ and $20000cm^{-1}$ using FTIR, our measurement reveal that the fine structure spectrum of YbMgGaO₄ is similar to a single ion Yb^{3+} absorption features arising from ground state ${}^{2}F_{7/2}$ to ${}^{2}F_{5/2}$ excitations in trigonal CEF. From optical measurement, we suggest that YbMgGaO₄ is a nonmagnetic insulator and long range order do not develop down to 1.5K.



Superconducting States of Topological Surface States in β-PdBi₂ investigated by STM/STS

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 β -PdBi₂($T_c = 5.4$ K [1]) is known to possess topologically-protected surface states with in-plane spin-polarization at the Fermi level in the normal state [2]. In this situation, various unconventional superconducting (SC) states such as a mixing of spin-singlet and triplet Cooper pairing [3] and the possibility of Majorana zero modes in vortex cores [4] are theoretically expected. However, experimental investigation of such SC states originated from topological surface states has remained elusive. In this study, we perform low temperature scanning tunneling microscopy/spectroscopy (STM/STS) measurements to investigate the superconducting states of β -PdBi₂, particularly paying attention to the symmetry of the SC gap and the existence of zero-bias conductance peak in a vortex core. We observed characteristic quasiparticle interference patterns that strongly support the existence of the spin-polarized surface states. Fully-opened SC gap ($\Delta = 0.8 \text{ meV}$) described by the conventional BCS model was observed at the spin-polarized Fermi surfaces. Considering a possible mixing of odd- and even parity orbital functions in C_{4v} group symmetry reduced from D_{4h} near the surface, we suggest that the SC gap consists of the mixture of s- and p-wave SC gap functions in the two-dimensional state. No clear zero-bias conductance peak was observed in a vortex core, indicating that the sample (residual resistivity ratio of 15) is in a dirty limit. In the case of Rashba-type spin-orbit coupling as realized in β -PdBi₂, radially-textured magnetic moment density around the vortex is theoretically predicted [5]. Spin-polarized STM may enable us to detect such unusual magnetic textures originated from the spin-polarized surface state.

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Terahertz properties of Dirac charge carriers in HgTe films

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We present and discuss magneto-optical properties of mercury telluride (HgTe) films in the terahertz frequency range. Density of charge carriers is controlled, using contact-free optical gating by visible light and in experiments with gated samples. Transmission measurements in applied magnetic field demonstrate presence of several types of charge carriers (electron-like and hole-like) with significantly different properties which may be controlled experimentally. Magneto-optics at terahertz frequencies allows to measure Faraday rotation angle with precision high enough to resolve quantum steps in magnetic field. These steps are present in a wide voltage range and their periodicity changes along with charge density. Possibility to observe universal Faraday rotation angle is analyzed and discussed.



Probing of the dispersion of the phonon that couples with the Dirac electrons in graphene: an ARPES study

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The electron-phonon coupling rules many properties of solids, and have been extensively studied. However, it has been difficult to probe its elemental process, i.e., electron-phonon scattering, in a way of resolving the momentum by using any spectroscopies. Recently, we proposed a new experimental method which enables us to probe the electron-phonon scattering in HOPG graphite with resolving the momentum and energy of both the electron and the phonon by using the angle-resolved photoelectron spectroscopy (ARPES)[1]. Here, we report an investigation using the same method for the epitaxial graphene on SiC.

The experiments were performed at BL-7U of the UVSOR at the Institute for Molecular Science, Okasaki, Japan. We measured the ARPES spectra of graphene as a function of the photon energy, and found that a step-like structure around 155meV in the binding energy near the Γ -point, where no electron emissions are expected from the valence bands of graphene in this energy region, when taken at hv=10.8eV. This strep-like structure is, in fact, the Fermi edge of the Dirac-cone electron which is scattered from near the K-point due to the electron-phonon scattering. The energy shift from the Fermi level, which matches the energy of the transverse –optical (TO) phonon mode of graphene, is due to the energy conservation rule during the phonon-emission in the electron-phonon scattering process. The fact that only one branch is observed at the particular photon energy indicates that the ejected free-electrons are not scattered but it is a result of the coupling between specific electronic bands of the graphene, and that a matrix elements of the electron-phonon scattering is particularly high in this set of the phonon and the bands.

Thanks to the momentum conservation rule, it is possible to probe the phonon dispersion that

couples the electron by measuring the step-energy as a function of the electron-emission angle. The momentum of the initial state (of the electron-phonon scattering) has some uncertainty around the K-point, since the Dirac point is located below 0.4 eV in the graphene layer on the SiC substrate, and then the phonon energy is not strictly determined. Thus, we compare the simulation including the convolution of the phonons and the energy broadening due to the instrumental resolution (upper panel) to the experimental results (lower panel), where the step is converted into the peak by taking differential with respect to the binding energy. The dispersion is along the G-M line for the emitted electron, which corresponds to the K-K line for the phonon. The phonon dispersion curve assumed in the simulation is the result of the DFT-GW calculation[2]. The agreement between the simulation and the experimental results is good.

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Pressure-dependent optical studies of α -(BEDT-TTF)₂I₃: tuning charge order and narrow gap towards a Dirac metal

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A piston pressure cell has been designed and tested ranging up to approximately 11 kbar that allows for optical reflection measurements in the infrared spectral range from 100 to 8000 cm⁻¹

down to temperatures as low as 6 K. The mechanical alignment and vacuum considerations are discussed and details of the sample preparation are given, with particular emphasis on small and fragile single crystals, mosaics and pressed powder. The performance of the setup is illustrated on several examples for organic crystals [1].





In particular, we have performed Infrared optical investigations of α -(BEDT-TTF)₂I₃ in the spectral range from 80 to 8000 cm⁻¹ down to temperatures as low as 10 K by applying hydrostatic pressure up to 11 kbar. Band-structure calculations [2] evidence that the system develops a zero-gap state under high pressure. In contrast to graphene, the Dirac point does not occur at high-symmetry points but at finite k-values. The Dirac points are anisotropic and exhibit different velocities for the first and second band, as illustrated in the figure to the left. In the metallic state, *T* > 135 K, we observe an increase in spectral weight of the Drude contribution as well as the mid-infrared band due to the growing

intermolecular orbital overlap. We extract how in the ordered state the electronic charge per molecule varies with temperature $T < T_{\rm CO}$ and pressure: The chargeorder transition temperature $T_{\rm CO}$ shifts linearly by -9 K/kbar, the charge disproportionation $\Delta \rho$ diminishes by 0.017 *e*/kbar, and the optical gap Δ decreases with pressure by -40 cm⁻¹/kbar. In our high-pressure and low-temperature experiments, we do observe contributions from the massive charge carriers as well as from massless Dirac electrons to the low-frequency optical conductivity, however, without being able to disentangle them unambiguously [3].



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Low-Energy Electrodynamics in Solids

Synthesis, doping control and Raman study of cuprate HgBa₂Ca₂Cu₃O_{8+δ}

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Although high Tc superconductivity has been discovered more than 29 years, the mechanism of superconductivity is not yet understood and raises fundamental questions. How critical temperature T_c can be 10 to 100 times higher than conventional superconductors ? Why does T_c describe a dome like shape with doping ? What is the order which competes with the superconducting state ? Why does Tc increase so much with pressure ? HgBa₂Ca₂Cu₃O_{8+δ} (Hg-1223) might be a good candidate to meet this challenge, given it high tetragonal symmetry and it record T_c value T_c=135K which increases under pressure (165K at 30 GPa). Unfortunately very few studies have been done on this compound because no crystal was available.

Here we report our recent progress [1] to grow single crystals of Hg-1223 cuprate with a new self-flux growth technique. The crystals thus synthesized are submilimetric, slightly underdoped and show high surface quality for spectroscopic measurements. Magnetometry, X-Ray diffraction and micro-Raman have been performed. We show for the first time that with adequate heat treatment, we can largely under-dope the Hg-1223 compound and control its doping level.

We also study the temperature-dependent electronic Raman response of a slightly underdoped single crystal [2]. Our main finding is that the superconducting pair-breaking peak is associated with a dip on its higher-energy side, disappearing together at T_c . This result reveals a key aspect of the unconventional pairing mechanism: spectral weight lost in the dip is transferred to the pair-breaking peak at lower energies. This conclusion is supported by cellular dynamical mean-field theory on the Hubbard model [3], which is able to reproduce all the main features of the Raman response and explain the peak-dip behavior in terms of a nontrivial relationship between the superconducting and the pseudo gaps. We confirmed this results on others compounds revealing his universality.

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Angle-resolved photoemission study of electronic structure of BaFe₂As₂ in the electronic "nematic" phase

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BaFe₂As₂, a parent compound of iron-based superconductors, has the tetragonal structure and is paramagnetic at room temperature. A tetragonal-to-orthorhombic structural transition occurs at the structural-transition temperature of $T_{\rm S}$ = 142 K, accompanied by stripe-type antiferromagnetic (AFM) transition. In the AFM phase, an electronic nematic state, in which the rotational C_4 symmetry of electronic structure is broken, has been observed by angle-resolved photoemission spectroscopy (ARPES) [1] and resistivity measurements [2]. Recently, it has been reported that the electronic nematic phase persists up to T^* well above $T_{\rm S}$ for the parent ($T^* \sim 170$ K) and P-doped compounds [3]. The investigation of the properties in the electronic nematic phase is expected to give clues to the mechanism of the superconductivity because the electronic nematic phase is contiguous to the superconducting dome in phase diagram.

In order to study the band folding caused by antiferro-orbital order predicted for the electronic nematic phase of BaFe₂As₂, we have performed ARPES measurements on the temperature dependence of the band dispersion over a temperature range from 100 K to 200 K on detwinned BaFe₂As₂. From comparison of the peak intensity of momentum dispersion curves (MDSs) across apices of the Dirac cone which is feature of reconstructed band structure due to the band folding between different temperatures, one can see the intensity persists above T_S up to ~170 K that consistent with T^* defined in Ref. [3]. These results indicate the existence of an antiferro order which has the same periodicity as the stripe-type AFM ordering in the electronic nematic phase.



Figure 1. (a) MDC spectra at the binding energy of 20 meV corresponding to the Dirac cone at various temperatures. (b) Temperature dependence of the peak intensity of the Dirac cone obtained by integrating MDC curves shown in (a).

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Low-Energy Electrodynamics in Solids

Optical spectroscopy of FeSe thin film

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For most iron-based superconductors, the superconducting phase emerges in the vicinity of the antiferromagnetic-orthorhombic (AFO) phase. However, FeSe exhibits the tetragonal-to-orthorhombic structural phase transition at $T_s \sim 90$ K without accompanying the magnetic phase transition. Below T_s , the orbital ordering was observed, suggesting the electronic origin of the structural transition. Although the band structure above and below T_s has been intensively studied, the effect of the orbital ordering on the charge dynamics remains unclear. Investigation of commonalities and differences of the charge dynamics between the AFO and the orbital ordered phase has been highly required.

In this work, we performed optical spectroscopy on the FeSe thin film on CaF₂ substrates grown by the pulsed laser deposition method [1]. Figure 1 shows the temperature dependence of the optical conductivity spectrum of FeSe in the low-energy region below 800 cm⁻¹, after removing the contribution of the substrate. At room temperature, the spectrum is essentially flat, indicative of incoherent charge dynamics. With decreasing temperature, a peak at $\omega = 0$, corresponding to the free-carrier response, becomes appreciable, which suggests a Drude component with a small spectral weight on the large incoherent background. Interestingly, no abrupt spectral change was observed across $T_s \sim 90$ K, in contrast with the case of iron pnictides showing the AFO phase, in which a clear gap feature is observed. Below T_s , the weight of the Drude component gradually decreases with decreasing temperature. This would be associated with the presence of the small Fermi surface at the Brillouin- zone corner in the orbital ordered

We phase. found the anomalous behavior of the optical phonon mode at ~ 248 cm⁻¹, involving displacements of Fe and Se atoms, which shows distinct temperature dependences of frequency above and below T_s . This indicates the change in the nature of the bonding between Fe and Se atoms driven by the orbital ordering and thus the relation intimate between lattice and orbital degrees of freedom. Our results seem to support the orbital degree of freedom as a driving force of the structural transition in FeSe.



Fig. 1. Temperature dependence of the optical conductivity spectrum of FeSe.

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Neutron-scattering and muon spin rotation/relaxation studies on the spin correlations in Pr_{1.4-x}La_{0.6}Ce_xCuO₄

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Magnetism in the carrier doped Mott insulator one of fascinating issue in a search of strongly correlated electron system. In the lamellar cuprate oxides, the magnetism is recognized to play a key role in the mechanism of superconductivity and the relationship has been intensively studied. It was well know that in the bulk sample the superconductivity in the electron-doped cuprate oxide emerges after the suppression of long-ranged antiferromagnetic order by a cation substitution and an oxygen reduction treatment. However, Naito's group claimed that the superconducting state can be realized even in the updoped thin film, when the sample is annealed under the adequate conditions. Therefore, the mechanism of superconductivity as well as the role of Ce substitution and the oxygen reduction by annealing is still unclear.

In order to extract these two effects on the magnetism, we carried out systematic inelastic neutron scattering and muon rotation/relaxation (μ SR) measurements on the as-grown and the Ar-annealed Pr_{1.40-x}La_{0.60}Ce_xCuO_{4-y}. We have successfully observed the dynamical spin response below ~300 meV throughout the first Brillouin zone for the as-grown *x*=0, 008 and 0.18 samples, and the annealed *x*=0 sample. The dispersion relation in as-grown and annealed Pr_{1.40}La_{0.60}CuO_{4-y} is found to be almost identical and it was well reproduced by the two-dimensional spin-wave relation with the nearest neighbor exchange coupling J of ~140 meV. However, the absolute value of dynamical susceptibility is much weaker in the annealed sample. Therefore, the magnetic moment is drastically suppressed by the reduction annealing. On the other hand, in a series of as-grown samples, the zone boundary energy increases upon Ce-substitution, suggesting that the magnetic excitation becomes steeper with the electron-doping, and the total intensity does not change so much by Ce-substitution. These experimental facts suggest the distinct effect of oxygen reduction and Ce-substitution. The origin of the anomalous reduction of intensity after annealing will be discussed in terms of change in the spin density cloud in the real space, combined with the results of μ SR measurements.

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Quantized Faraday and Kerr rotation and axion electrodynamics of the surface states of three-dimensional topological insulators

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Topological insulators have been proposed to be best characterized as bulk magnetoelectric materials which show response functions quantized in terms of fundamental physical constants. It has been predicted that this manifests as Faraday and Kerr rotations that are quantized in units of the fine structure constant. In our work we use a charge-transfer-doping preparation to lower the chemical potential of Bi_2Se_3 films into the bulk gap and as low as ~ 30 meV above the Dirac point, and then probe their low-energy electrodynamic response with high-precision time-domain terahertz polarimetry. As a function of field, a crossover from semi-classical cyclotron resonance to a quantum regime was observed. We find quantized Faraday and Kerr rotations the size of which is set by the fine structure constant, which provides evidence for the long-sought axion electrodynamics and the topological magnetoelectric effect of the topological insulator's surface states. Among other aspects, the unique time structure used in such measurements allow us a direct measure of the fine structure constant based on a topological invariant of a solid-state system for the first time.



Electron Dynamics in n- and p-doped Topological Insulators

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Topological insulators (TIs) represent a new quantum state of matter that is attracting growing attention thanks to its unique electrical transport properties. Particularly relevant to TIs is their characteristic spin texture [1], making these materials ideal candidates for future spintronics devices and a playground for new theoretical models [2,3].

The first observation of a persistent electron population in the photo-excited surface state (SS) of TIs was obtained by studying the out-of-equilibrium electronic properties of these materials [4,5]. The major goal in the field is to improve the spin transport properties at the surface, hence circumventing the limitations of the transport in the semiconducting bulk. In this respect a detailed knowledge of the dynamical response of TIs after optical excitation is needed, and a deeper understanding of the scattering mechanisms between the surface and bulk states of TIs is important. The most relevant mechanism initially proposed as responsible for the relaxation dynamics of the photo-excited electrons is the electron-phonon scattering.

Recent experimental reports have shown that Time and Angle Resolved Photoelectron Spectroscopy (tr-ARPES) plays a major role in the study of these materials, thanks to the ability to map the k-space resolved electronic states and their evolution after an optical perturbation.

Here we report tr-ARPES experiments performed on a wide set of TIs in order to provide a comprehensive picture of their relaxation dynamics. We analyzed in particular the n-doped $GeBi_2Te_4$ and $GeBi_3Te_7$, the p-doped Sb_2Te_3 and Sb_6Te_3 and the intrinsic Bi_2Te_3 and $GeBi_2Te_4$ TIs. We observed different dynamics in the bulk and surface states of p-doped Bi_2Te_3 and $GeBi_2Te_4$. Comparing dynamics of p-doped Bi_2Te_3 and heavily p-doped Sb_6Te_3 came out that the surface and bulk states behaviors are comparable thus indicating a strong coupling between the two.

These findings suggest that charge diffusion is playing a major role in determining the relaxation dynamics. We argue that the observed asymmetry in the electron-hole dynamics in n-and p-doped TIs is determined by the sub-surface charge diffusion, constituting the primary mechanism responsible for the energy dissipation in TIs [6].

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Antiferroelectric like state in BiFeO₃/LaFeO₃ superlattices

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Bismuth ferrite (BiFeO₃ or BFO) is the most studied multiferroic due to its robust ferroelectric state ($T_c = 1100K$) coexisting at room temperature with an antiferromagnetic order ($T_N=640K$) [1]. Such coexistence and the possible cross coupling between both ferroic orders pave the way to so-called MagnetoElectric RAM combining advantages of the ferroelectric and the antiferromagnetic state [2]. Similarly to the relaxor-ferroelectric systems (PbMg_{1/3}Nb_{2/3}O₃-PbTiO₃) a morphotropic phase boundary has been observed in La doped BFO (Bi,La)FeO₃ solid solution with peculiar nanoscale mixture (incommensurate and antiferroelectric ordering). Emergence of such MPB is believed to arise from the competition between antiferrodistortive and ferroelectric instabilities. Our approach to investigate the structural interaction between BFO and LFO is based on superlattices. Superlattices are ideal platforms for studying and exploring antagonistic interactions at the origin of many exotic systems. For instance Cuprates combined with Manganites in superlattices were investigated to better understand the competition between magnetic and superconducting orders [3]. Similarly to this strategy we grew series of SLs made of BiFeO3 and LaFeO3. Structural characterizations and Raman spectroscopy indicate an anti-polar structure in the BFO layers of the SLs that is strongly dependent on the BFO thickness and temperature [4]. This antiferroelectric like structure very similar to the PbZrO₃ system cannot be explained by the nature of the induced strain (compressive vs tensile) but by the symmetry mismatch at the interfaces of the SLs. Compatibility of the octahedral tilt system seems to be the main driving force for this induced anti-polar state. Phonon mode reminiscent to the PbZrO3 soft mode, resonant like excitation and electron-phonon interactions are detected in the SLs. Electromagnon and magnetic excitations were investigated using Raman scattering in the SLs and will be discussed.

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Low-Energy Electrodynamics in Solids

Raman scattering investigation of

YMnO₃ and YbMnO₃ structural phase transition

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The exact mechanism responsible of the ferroelectricity in hexagonal manganite has been the subject of intense debate. Whether ferroelectricity and ferroelastic order appear at the same temperature and what is the role of covalency in the ferroelectric order is still discussed [1]. High temperature phase transitions are here investigated through the prism of lattice dynamics evolution with temperature. Comparison is made between the YMnO₃ and YbMnO₃ behaviour using polarized Raman spectroscopy. While YMnO₃ shows two phase transitions (isosymetric at about 900 K and ferroelastic at 1200 K) YbMnO₃ presents no lattice instability up to 1350 K. Phonons involved in the lattice instability and the zone tripling transition are identified. Moreover peculiar hardening on heating of some YbMnO₃ phonons is revealed and discussed that further highlight the dynamical difference between these two hexagonal manganites [2].

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Topological Phase Transitions in Topological Insulators Driven by Dimensional Reduction and Substrate Control

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Topological insulators exhibit novel quantum states known as topological surface states originating from strong spin-orbit interaction and time-reversal symmetry of the bulk. We show that dimensional reduction realized in ultrathin, few-quintuple layer films leads to a number of topological phase transitions from three-dimensional topological insulators (3DTI) to two-dimensional hybrid topological insulators (2DHTI) and finally to two-dimensional trivial insulators. Along with these transitions, there follows a series of quantized conductances and concomitant changes in the electron-phonon interaction as evidenced by a Fano effect. Substrate potentials can also be incorporated into topological insulators to hybridize the topological surfaces states with substrate electronic states, leading to decoupled two-dimensional topological insulators (2DTI). Our experiment demonstrates the feasibility to control and utilize the topological surfaces states for practical electronic and photonic applications.



Fig. 1. Band diagram for the various phases of Bi₂Se₃ ultrathin films.

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Topological heterodyne in a two dimensional electron gas

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We report an extension of the concept of topological index for a two dimensional electron gas with an applied electric field, subject to a periodically driven orthogonal magnetic field. The magnetic field acts as a heterodyne on the electric field, i.e. it mixes the frequency of the input electric field with its driving frequency in a non linear process. Focusing on the electric field-current response, we show that this system presents a quantized heterodyning Hall response.



Intertwined Charge Density Wave and Superconductivity in 2H-TaS₂ under Pressure

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In the transition metal dichalcogenides (MX₂, with M=Nb,Ta and X=S,Se), superconductivity and charge density waves often coexist. The interplay between the two phases is the main focus of interest and as discussed recently in the High-Tc Cuprates, whether or not the charge density wave order plays a role on the nature of the superconducting (SC) state is still debated. In 2H-TaS₂, at ambient pressure an Incommensurate Charge Density Wave (ICDW) appears below 78 K [1] and a SC state below 0.8 K. When high pressure is applied, the critical temperature of the SC transition increases up to 8 K at about 8 GPa [2].

We have studied the ICDW and SC in 2H-TaS₂ using Raman spectroscopy under high pressures (up to 9.5 GPa), down to low energies (10 cm^{-1}) and low temperature (down to 3.5 K). By following the excitations of both phases, we have drawn the phase diagram up to the critical pressure where the ICDW collapses (Fig. 1). We will discuss the relationship between the two phases, notably their critical temperatures. We will also discuss the possible observation of a fundamental excitation of the SC state, the amplitude "Higgs" mode [3], most probably observed in a neighbor compound 2H-NbSe₂ [4,5].



Fig. 1. (T-P) Phase diagram of 2H-TaS₂ obtained by Raman spectroscopy

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Low-Energy Electrodynamics in Solids

One-Dimensional Surface States on Bi/InSb(001)

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The Fermi liquid theory of ordinal three-dimensional (3D) metals breaks down in one-dimensional (1D) systems to produce various exotic quantum phases. Tomonaga-Luttinger liquid (TLL) [1] is an exactly solvable model of a gapless 1D quantum system, characterized by power-law scaling and spin-charge separation for low-energy excitation spectra [2]. So far, only a few 1D systems such as carbon nanotubes [3] have shown metallic states with power-law spectral features and they are regarded as TLL. The surface of semiconductors is known to show various self-assembled 1D atomic structures that are regarded as suitable systems for studying 1D metallic states [4]. However, most of them do not behave as TLLs at low temperature.

In this paper, we report on the case of a new surface TLL candidate discovered with angle-resolved photoelectron spectroscopy (ARPES) on a Bi-induced anisotropic structure on InSb(001) (Bi/InSb(001)). As shown in Figure 1, the Bi/InSb(001) surface state showed a 1D Fermi contour (FC) with almost no undulation and stayed metallic down to 35 K. The photoelectron spectra around the Fermi level obey power-law scaling as a function of the binding energy and sample temperature with the same power index $\alpha = 0.7\pm0.1$. These results strongly suggest that the 1D surface structure of Bi/InSb(001) hosts a surface TLL[5].



Fig. 1. ARPES results. (a) Constant energy contour around the Fermi level. Dashed lines indicate boundaries of the surface Brillouin zone. (b) Band dispersion along the horizontal direction in (a). (c) Angle-integrated photoelectron spectra at various temperatures using a *T*-normalized energy scale.

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Optical spectroscopy and pump-probe studies on charge density wave orders in LaAgSb₂

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The layered lanthanum silver antimonide LaAgSb₂ exhibits many interesting physical properties. The compound was known to experience two charge density wave (CDW) phase transitions at 207 and 186 K, respectively. Recent transport measurement revealed a large linear magnetoresistance, suggesting possible contribution from Dirac fermions. Presence of linear Sb 5px,y band dispersion and the Dirac-cone-like structure was indeed observed by ARPES experiment. We present optical spectroscopy and pump-probe measurement on the compound. We observe clear energy gap formation below the CDW phase transition temperatures in optical conductivity, which removes most part of the free carrier spectral weight. The time resolved pump probe measurement indicates that the photoinduced reflectivity can be well described by a single exponential decay for the whole measurement temperature range, except for the emergence of strong oscillations upon entering the CDW states. The oscillations come from the collective excitation of CDW condensate (i.e. the amplitude mode). The frequencies of the two amplitude modes extracted from the oscillations are 0.12 THz for the CDW order with higher transition temperature and 0.34 THz for the lower one. The surprisingly low energy scale of the CDW amplitude mode implies a very low frequency of associated acoustic phonon mode that experiences a softening to zero frequency and triggers the CDW transition.



Optical Conductivity of Excitonic Insulator Ta₂NiSe₅ under High Pressure

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An "excitonic insulator" (EI) refers to an exotic insulating state caused by strong excitonic correlation between electrons and holes. The EI was predicted theoretically in the 1960s [1], but the identification of an actual material as EI was not established for a long time. Recently, the layered chalcogenide Ta₂NiSe₅ has been strongly suggested to be an EI, on the basis of unusually flat valence band dispersion found in ARPES data [2]. It is expected that an external pressure is an important parameter to control the properties of an EI [1], and Ta₂NiSe₅ has actually shown strongly pressure-dependent electrical resistivity [3]. Therefore, we have studied the pressure evolution of optical conductivity $\sigma(\omega)$ for Ta₂NiSe₅. In our experiment, high pressure was applied on Ta_2NiSe_5 single crystals using a diamond anvil cell (DAC), and the IR studies in the mid- and far IR ranges were made with IR synchrotron radiation at SPring-8 [4,5]. The measured $\sigma(\omega)$ data show that Ta₂NiSe₅ at ambient pressure is an insulator with an energy gap of about 0.1 eV at 300 K. With cooling, a sharp peak centered near 0.3 eV grows in $\sigma(\omega)$, which is likely due to a flat dispersion caused by strong excitonic correlation. With increasing pressure, the energy gap in $\sigma(\omega)$ is suppressed, and is not observed any more at 3.5 GPa. With further increasing the pressure, a Drude component due to free carriers grows in $\sigma(\omega)$. The IR peak, on the other hand, becomes weaker with pressure, suggesting that the excitonic correlation becomes weaker with increasing pressure. We will discuss the pressure evolution of the electronic structures in Ta₂NiSe₅ based on the $\sigma(\omega)$ data.

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Rotating dipoles encapsulated in C₆₀

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Buckminsterfullerene C_{60} has a cavity large enough to hold a small molecule. A technique to insert a small molecules into molecular cage of C_{60} , called molecular surgery, was pioneered by Murata and Komatsu in 2005 when they made first molecular endofullerene H₂@C₆₀[1]. The H₂O@C₆₀ followed in 2011[2] and HF in 2014[3]. These small molecules behave like quantum rotors in a spherical potential and they do not stop rotating even at temperatures of few Kelvin[4-8]. This opens a unique possibility to study isolated molecules at cryogenic temperatures. Our technique was THz and infrared spectroscopy. We will discuss the effect of C₆₀ on the vibration, translation, and rotation motion of H₂O[8] and HF[3], deviations from the icosahedral symmetry[9], the screening of the molecule dipole moment by the fullerene cage[8,10], and the ortho-para conversion of spin isotopologs[11].

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NbN-Based Terahertz Superconducting Metamaterials

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We performed intaglio lithography on 20-nm thick NbN film grown on Si, a prototype BCS superconductor, and then conducted terahertz time-domain spectroscopy. We studied the low-temperature electrodynamics of DSRR (Double Split Ring Resonator) structures [1], which exhibited open and closed resonance modes emerging from the low frequency region. The open mode yields a quality factor of 30 at 3.8 K. The observed resonance mode reradiates at 0.8 THz. Our results demonstrate that traditional BCS superconductors provide useful frameworks for terahertz metamaterials.



Fig. 1. Optical real conductivity of patterned NbN film in terahertz region

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Electronic structure of $Sr_{1-x}Ca_xFe_2(As_{1-y}P_y)_2$ (x = 0.08, y = 0.25) revealed by angle resolved photoemission spectroscopy

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Essential key to elucidate the material dependence of the superconducting (SC) transition temperature (T_c) in the iron based superconductor is to clarify how the electronic structure changes with the lattice parameters. Recent studies of angle-resolved photoemission spectroscopy (ARPES) have reported that since c/a (the ratio of *a*- and *c*-axes lattice constants) in SrFe₂(As_{0.65}P_{0.35})₂ (Sr122P) is smaller than that in BaFe₂(As_{0.62}P_{0.38})₂ (Ba122P), the innermost d_{xy} hole Fermi surface (FS) shows the strong three dimensionality (3D) and disappears around the Γ point while all hole Fermi surfaces remaining in the entire k_z Brillouin zone in Ba122P [1, 2]. These results indicate that the strong 3D in Sr122P originates from the enhanced interlayer hopping matrix elements due to the smaller c/a than that in Ba122P. Despite the difference of c/a, their T_c values are almost the same. Namely, T_c is insensitive to c/a.

In the present study, we have carried out ARPES to study the electronic state of $Sr_{0.92}Ca_{0.08}Fe_2(As_{0.75}P_{0.25})_2$ (SrCa122P, $T_{cmax}=32K$) which has smaller c/a than Sr122P. It was observed that the inner hole band near the Γ point assigned as the d_{xy} orbital is located below the Fermi level (E_F), consistent with the ARPES result of Sr122P [2]. Figure 1 shows SC gaps plotted as a function of the FS angle (θ_{FS}) around the Γ and X points in SrCa122P. The SC gap of the hole FS near the Γ point shows isotropic within the error bar. On the other hand, the SC gap for the outer α electron FS decreases rapidly toward $\theta_{FS} \sim 40$ deg, indicating that nodes or the SC gap minimum is present. The SC gap anisotropy is different from that of Ba122P [3] and the present study suggests that there is a relationship between the SC gap anisotropy and the electronic structure which strongly depends on the structural anisotropy (c/a).



Fig. 1. (a), (c) SC gaps near the Γ and X points as a function of θ_{FS} (b), (d) Markers on the FSs show the Fermi momentum. The Fermi angle is defined as the Γ -X line is $\theta_{FS} = 0$ deg.

- [1] T. Yoshida et al., Phys. Rev. B 106, 117001 (2011)
- [2] H. Suzuki et al., Phys. Rev. B 89, 184513 (2014)
- [3] T. Yoshida et al., Sci. Rep. 4, 7292 (2014)





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| May 29 (Sun. |) May 30 (Mon.) | May 31 (Tue.) | June 1 (Wed.) | June 2 (Thu.) | June 3 (Fri.) |
|--------------|--------------------|--------------------|---------------------|--------------------|---------------------|
| | 8:45 | | 8:45 | | |
| | Opening | | Genzel Prize Ceremo | ny | |
| | 9:00-10:30 | 9:00-10:30 | 9:00-10:25 | 9:00-10:25 | 9:00-10:30 |
| | Cuprates (I) | Iron S.C. (I) | Topology (II) | Novel materials | Cuprate (III) |
| | (Tajima) | (Hanaguri) | (Dressel) | (Pimenov) | (Sacuto) |
| | I-1: Sacuto | I-10: Feng | I-19: Armitage | I-25: Rusydi | I-34: Van der Marel |
| | I-2: Greven | I-11: Borisenko | I-21: Murakami | I-26: Perucchi | I-35: Toda |
| | I-3: Kondo | I-12: Chubukov | C-17: Akrap | C'-21: Maeda | I-36: Seibold |
| | C-1: Ideta | C-9: Degiorgi | C'-18: Sohn | C-22: Skiadopoulou | C-29: Badoux |
| | | • | | | |
| | 11:00-12:25 | 11:00-12:30 | 11:00-12:25 | 11:00-12:25 | 11:00-12:30 |
| | Time-resolved (I) | 4f & 5d systems | Cuprates (II) | Time-resolved (II) | Topology (III) |
| | (Chubukov) | (Kimura) | (Greven) | (Tohyama) | (Armitage) |
| | I-4: Hu | I-13: Schemm | I-22: Le Tacon | I-27: Shimano | I-37: Chen |
| | I-5: Oka | I-14: Scheffler | I-24: Julien | I-28: Devereaux | I-38: Dai |
| | C'-2: Tohyama | I-15: Kim | C'-19: Ishii | C'-23: Cantaluppi | I-39: Pronin |
| | C-3: Morimoto | C-10: Zonno | C-20: Sakai | C-24: Crepaldi | C-30: Kohsaka |
| | | | | | |
| | 12:30-14:00 | 12:30-14:00 | 12:30-14:00 | 12:30-14:00 | 12:30 |
| | Lunch & Discussion | Lunch & Discussion | Lunch | Lunch & Discussion | Closing |
| | | - | - | | -14:00 Lunch |
| | 14:00-15:50 | 14:00-15:45 | | 14:00-15:50 | |
| | Topology (I) | Multiferroic | | Iron S.C.(II) | |
| | (Kim) | (Tokura) | | (Borisenko) | |
| | I-6: Tokura | I-16: Kezsmarki | Excursion 14:00- | I-29: Hanaguri | |
| | I-7: Orlita | I-17: Pimenov | Sakamoto, Mt. Hiei | I-30: Coldea | |
| | I-8: Moore | C'-11: Kamba | & Enryakuji temple | I-31: Gastiasoro | |
| | C'-4: Lupi | C'-12: Room | | C'-25: Blumberg | |
| | C-5: Lee | C-13(P-22): Wang | | C-26: Miyasaka | |
| | | | | | |
| | 16:10-17:20 | 16:10-17:20 | | 16:10-17:30 | |
| | Space-resolved | Novel optics (I) | | Novel optics (II) | |
| | (Okamura) | (Rusydi) | | (van der Marel) | |
| | I-9: Kuzel | I-18: Shin | | I-32: Dressel | |
| | C-6: Boehmler | C-14: Bachar | | I-33: Gorshunov | |
| | C-7: Martin | C-15: Boris | | C-27: Burch | |
| | C-8: Hattori | C-16: Ito | | C-28: Chia | |
| | | | | | |
| 17:00-19:00 | 17:20-18:00 | 17:20-18:00 | | 17:30-18:10 | |
| Registration | Poster Preview | Poster Preview | | Poster Preview | |
| | (Maeda) | (Fujita) | | (Ishii) | |
| | | | | | |
| 19:00-21:00 | 18:00-19:30 | 18:00-19:30 | | 18:10-19:30 | |
| Welcome | Dinner | Dinner | Banquet 18:30- | Dinner | |
| party | | | Japanese Restaurant | | |
| | 19:30-21:00 | 19:30-21:00 | in Kyoto | 19:30-21:00 | |
| | Poster | Poster | | Poster | |
| | | | | | • |

I-**: invited talk (25 min.) C'-**: contributed talk (20 min.) C-**:contributed talk (15 min.) incl. discussion