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Final Report for Period Beginning 30-Sep-2018 and Ending 29-Sep-2022

Title: Emerging Two Dimensional Van Der Waals Materials for Optical Information Transfer and Processing

Begin Performance Period: 30-Sep-2018

End Performance Period: 29-Sep-2022

Report Term: 0-Other

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Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: 10

STEM Participants: 18

Major Goals: The research performed under the grant W911NF1810433: Emerging Two Dimensional Van Der Waals Materials for Optical Information Transfer and Processing presents a systematic study directed toward understanding of the fundamental aspects for novel two-dimensional materials for optical information transfer and processing. These materials include graphene, transition-metal dichalcogenides (TMDC), Xenes (silicene, germanene, stanene), hexagonal $\sqrt{3}$ -T3 layer, phosphorene and transition-metal trichalcogenides' freestanding, supported and encapsulated by dielectrics monolayers, bilayers and van der Waals heterostructures (vdW) formed by monolayers of these materials separated by hexagonal boron nitride (hBN) monolayers. We are addressing the following topics:

1. Optical properties of excitons in buckled two-dimensional materials in an external electric field and optical properties of anisotropic excitons in phosphorene by focused on the dependence of the excitonic properties, the ground and excited state, optical absorption transition energies, and optical absorption coefficients for optical absorption transitions from the excitonic ground state to the excitonic excited states, Can freestanding Xene monolayers behave as excitonic insulators? The answer for this question can be used as an electric current switch, where the switch is "off" when the material is in the excitonic insulator phase, and the switch is "on" when the material is in the semiconducting phase.
2. Light-matter interactions and collective quantum dynamics by considering the quantum dynamics of coupled charges and photons and the interaction with phonons, to understand the charge and photon transport in novel two-dimensional materials. In particular, analyze the polariton flow induced by the spin flow due to spin Hall Effect for excitons in TMDC. Study the effects of a periodic potential on a superfluid of excitons and cavity polaritons, formed by excitons, and controlling an electron-hole superfluid in semiconductor coupled quantum wells and double layers of a 2D material by an external periodic field and the BCS-like superfluid an electron-hole plasma phase transition.
3. Examine the occurrence of Bose-Einstein condensation (BEC) and superfluidity of dipolar (indirect) excitons

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and polaritons in vdW heterostructures. Consideration includes both materials where excitons are formed by isotropic electron and hole masses and formed by anisotropic electron and hole masses. Studies of the superfluid density and the temperature of the phase transition as functions of the excitonic density, the magnetic field, electro and hole mass anisotropy and the interlayer separation.

4. Study possibility to use topological materials Weyl-semimetals that are characterized by broken time-reversal or inversion symmetry as the polarization filters for the electromagnetic waves propagation.
5. Study an exciton-dipolaritons as a platform for realizing working elements of a polaritronic transistor and optimizing room-temperature polaritonic circuit performance when dipolaritons propagation is guided by a Y-shaped channel. To introduce designs for optical routers at room-temperature based on exciton-dipolaritons, which are a three-way superposition of direct excitons, indirect excitons, and cavity photons, by considering the dipolariton propagation is guided by a Ψ -shaped channel.
6. Study an influence of the reduction of dimensionality on the binding energy of excitons, trions and the screening effects in 2D material. Analyze collective properties of interlayer trions and consider strongly correlated phases. Study the crystal phases of charged interlayer excitons a possibility of Wigner crystallization of trions in TMDC double-layered system.
7. Study the formation of magnetoexcitons in monolayers, bilayers and vdW heterostructures of novel 2D materials with isotropic and anisotropic electron and hole masses. Consider a tunability of excitonic properties in these systems by external magnetic and electric fields. Possibility to tailor of IX magnetoexcitons properties in vdW heterostructures by varying the number of hBN sheets between two layers of novel 2D materials.
8. Consider some problem of quantum entanglement and computations that support the quantum information transfer and processing.

Accomplishments: 1. We study of optical properties of direct (X) and indirect (IX) excitons in monolayers and double layer heterostructures of the buckled two-dimensional (2D) Xenes (silicene, germanene, and stanene) and phosphorene. Applying an external electric field (EF) to the Xenes changes a band gap and, thus, properties of excitons in these materials. We demonstrated the tunability by EF of excitonic properties: the ground and excited state energies, optical absorption transition energies, and optical absorption coefficients for optical absorption transitions from the ground state to the excitonic excited states.

2. We predicted a phase transition in freestanding monolayer Xenes from the semiconducting (SC) phase to the excitonic insulating (EI) phase that can be induced by EF below some critical value. We show the coexistence of SC phase of A excitons with EI phase of B excitons for a particular range of EF due to spin-orbit coupling. We proposed that suspended Xenes can be used as an electric current switch, where the switch is “off” when the material is in EI phase, and the switch is “on” when the material is in the SC phase.

3. Our study of excitons in phosphorene shows that excitonic optical absorption is strongly enhanced (suppressed) along the crystal axis with the lighter (heavier) charge carrier effective mass. Notably, due to the non-trivial relationship between the anisotropic effective masses and their effect on the optical properties of excitons, we proposed that in-situ modification of the effective carrier masses via e.g. mechanical strain could be used to great effect to manipulate the optical properties of X in phosphorene.

4. We studied collective properties of exciton-polaritons in Xene monolayers embedded in an optical microcavity as a function of EF. We show that encapsulated by hBN silicene monolayers exhibit stable polaritons at room-temperature with strong exciton-photon coupling and large Rabi splitting and are excellent candidates for stable room-temperature polariton superfluids.

5. We predict the BCS-like superfluid in an electron-hole plasma (EHP) phase transition can be controlled by an external periodic field and analyze its influence on Tc temperature of EHP-superfluid transitions of IXs in TMDC van der Waals (vdW) heterostructures. We propose controlling an electron-hole superfluid in semiconductor coupled quantum wells and vdW heterostructures by an external periodic field.

6. We predicted the spin Hall effect for polaritons in TMDC monolayer embedded in a microcavity. We show that two counterpropagating laser beams incident on a TMDC monolayer can deflect a superfluid polariton flow due to the generation of effective gauge vector and scalar potentials and polariton flows in the same valley are splitting: the superfluid components of A and B polariton propagate in opposite directions along the counterpropagating beams, while the normal components slightly deflect in opposite directions and propagate almost perpendicularly to the beams.

7. We examine BEC and superfluidity of IX for a quasi-2D spatially separated hexagonal α -T₃ layers. The superfluid density and phase transition Tc are probed as functions of the excitonic density, MF, and interlayer separation. We predict BEC and superfluidity for a two-component weakly interacting Bose gas of A and B IXs in α -T₃ model with a mass term.

8. We predict angle-dependent superfluidity in 2D transition metal trichalcogenides (TMTC) and suggest an experiment for its observation. We demonstrate the angle-dependent superfluidity temperature in vdWHs: for a given density a maximum and minimum Tc of superfluidity occurs along the chain and a directions, respectively.

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Our work can guide experimental search toward a realization of anisotropic superfluidity in TMTC vdWH.

9. We studied X and IX magnetoexcitons in the Rydberg states in 2D monolayers, bilayers and vdW of TMDC and Xenes in an external magnetic field (MF) and report MF energy contribution to BEs and diamagnetic coefficients (DMCs) for X and IX magnetoexcitons. The tunability of the energy contribution and DMCs of X and IX by MF is shown. For Xenes X and IX BEs and DMCs can be also tuned by EF. BEs and DMCs of IXs can be tuned by MF and EF and manipulated by the number of hBN layers. All these allowing the possibility of electronic devices design that can be controlled by EF and MF and a number of hBN layers.

10. We study X and IX magnetoexcitons in Rydberg states in mass anisotropic materials: phosphorene and TMTC. BEs and DMCs for X and IX strongly depend on the effective anisotropic masses of charge carriers and can be tuned by MF. Our studies raise the possibility of controlling BEs and DMCs of X and IX magnetoexcitons in anisotropic materials using MF and opens an additional degree of freedom to tailor BEs and DMCs for heterostructures by varying a number of hBN sheets in vdW heterostructures.

11. We predict the quantum Hall effect for X and IX pseudomagnetoexcitons in monolayers and heterostructures of gapped graphene under strain-induced gauge pseudomagnetic field. We show that using a circularly polarized laser field, electrons and holes can be excited only in one valley of the honeycomb lattice of gapped graphene and provides a possibility to observe various Quantum Hall phenomena in this pseudomagnetoexciton system.

12. We studied X⁻ and X⁺ trions in 3D, 2D and 1D SCs: bulk, TMDC and nanowires. We show that a decrease of degrees of freedom in a system, decreases the system kinetic energy and reduces a screening. The combinations of two effects leads to 2D and 1D bound trions because with the reduction of dimensionality the kinetic energy decreases faster than the potential energy while in 3D X⁻ is bound and X⁺ is unbound. Thus, lowering the dimensionality of the system makes the effects of interaction in trions more pronounced, resulting in an increase in BEs of trions.

13. We analyze collective properties of interlayer trions and predict strongly correlated phases—crystal and Wigner crystal—that can be selectively realized with TMDC bilayers of properly chosen electron-hole effective masses by varying their interlayer separation. Our results can be used for nonlinear coherent control, charge transport and spinoptronics application development with quantum vdW heterostructures.

14. Exciton-dipolaritons are investigated as a platform for realizing working elements of a polaritronic transistor. We suggested Dipolariton Transistors in Y-shaped Channels. Exciton-dipolaritons are three-way superposition of cavity photons, X and IX excitons in a bilayer SC system embedded in an optical microcavity. We demonstrate that polaritronic signals can be redistributed in channels by applying a driving voltage in optimal directions.

15. We simulate a propagation of dipolaritons present in a MoSe₂-WS₂ heterostructure, where the dipolariton propagation is guided by a Ψ -shaped channel. We introduce designs for optical routers at room-temperature and show how driving forces and electric field angles can optimize dipolaritons redistribution efficiencies in Ψ channel guide. Our findings open a route towards the design of an efficient room-temperature dipolariton-based optical transistors and optical routers based on TMDC materials.

16. We predicted that transmission of the normally incident polarized electromagnetic wave (EMW) through Weyl-semimetals strongly depends on the orientation of polarization with respect to a gyration vector and can be applied as the polarization filters. By changing the polarization the system undergoes the transition from the isotropic dielectric to the medium with Kerr or Faraday-like rotation of polarization and finally to the system with chiral selective EMW.

17. We studied the dynamics of qubits coupled to a harmonic oscillator system with time-periodic coupling within of Floquet theory that can be used to model nonadiabatic phenomena and support quantum information transfer and processing.

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Training Opportunities: The Grant supported nine Graduate students: Matthew Brunneti, Mirko Amiko, Anastasia Spiridonova, Gabriel Martins, Andrew Dublin, Patrick Serafin, Shaina Raklyar, Yamuna Paudel, Tom Brick. These students are mentored by Profs. Kezerashvili, Berman and Kolmakov.

The graduate students Matthew Brunneti, Mirko Amiko, and Patrick Serafin had defended of their PhD dissertation in 2020, 2021 and 2022, respectively.

The grad student Anastasia Spiridonova finalized her Ph.D. dissertation, and the expectation defense of her PhD thesis is early February 2023. The expectation defense of Gabriel Martins PhD dissertation is December 2023 - February 2024.

Seven undergraduate students STEM major Mubinjon Satymov, Patrice Prosper, Jorge Bermeo, Olga Privman, (Major Applied Computational Physics) and Shaina Raklyar (Major: Bioinformatics) Xu Lu, Li Alan (Major: Computer Science) had training in novel two dimensional materials and applications.

During the grant period we had 40 seminars given by experts from different USA universities and universities from Europe. Seminar were given for City Tech physics faculty, graduate students and undergraduate students. These seminars are given through the Center for Theoretical Physics and represented the excellent training for graduate and undergraduate students as well as professional development for faculty. Graduate students from other CUNY campuses and Faculty working in solid state physics from other CUNY campuses also joined our seminars. The seminars have held in person and online. During pandemic period all seminars were given via the ZOOM platform.

Since October 2018

1. Dr. Javad Shabani, Superconducting proximity effect in two-dimensional semiconductor-superconductor structures, New York University, New York, NY, USA
2. Dr. David C. McKay, Calibrating, Characterizing and Applying Quantum Circuits, IBM T.J. Watson Research Center, Yorktown Heights, NY, USA
3. Prof. Leonid Glazman, Quantum Many-Body Physics of Qubits, Yale University
4. New Haven, CT, USA
5. Dr. Sriram Ganeshan, Odd surface waves in two-dimensional incompressible fluids, City College, CUNY, New York, NY, USA
6. Prof. Christopher C. Gerry, Entanglement Enhanced Quantum Interferometry and Sensing, Lehman College, CUNY Bronx, NY, USA
7. Prof. Steven M. Girvin, Schrödinger's Cat meets Maxwell's Demon:
8. Quantum Error Correction (That Works), Yale University, New Haven, CT, USA

2019

9. Prof. Junichiro Kono, Ultrastrong Light-Matter Coupling: Dicke Phenomena in Condensed Matter, Rice University, Houston, Texas, USA
10. Prof. Klaus Ziegler, Quantum-Hall phases created by electron-phonon interaction, University of Augsburg, Germany.
11. Prof. Jacob Khurgin, Polaritonics in 2 and 3 Dimensions, Johns Hopkins University
12. Prof. Vinod Menon, Control of light-matter interaction in 2D materials, City College, CUNY.
13. Dr. Alexey Galda, "Exceptional points in non-Hermitian spin dynamics", James Franck Institute, University of Chicago,
14. Dr. Andrii Iurov, "Collective phenomena and transport for optically-induced electron dressed states in alpha - T3 materials", Medgar Evers College, CUNY, December 12, 2019.

2020

15. Dorri Halbertal, "Novel nano-imaging techniques for probing electronic properties in graphene devices", Columbia University, February 20, 2020.
16. Héctor Romillo, "Chiral optical response of moiré insulators", Columbia University, May 14, 2020.
17. Dr. Gabriele Grosso, "2D materials for optoelectronics and quantum applications", Graduate Center, CUNY, Thursday, May 21, 2020
18. Prof. Michael Schulz, Few-Body Dynamics and Coherence Effects in Simple Atomic Systems, Missouri University of Science and Technology, September 17, 2020.
19. Prof. David Snoke, A possible path to room temperature superconductivity via charged excitonic complexes in

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two-dimensional materials, University of Pittsburgh, September 24, 2020.

20. Prof. Klaus Ziegler, Pairing transition in interacting electronic double layers, Institut fuer Physik, Universitaet Augsburg, Augsburg, Germany, October 8, 2020.

21. Prof. Philip Phillips, Beyond BCS: An Exact Model for Superconductivity and Mottness, University of Illinois, Urbana Champaign, October 15, 2020.

2021

22. Prof. Alexey Chernikov, Mobile optical excitations in 2D materials, Department of Physics, Dresden University of Technology (TU Dresden), Germany

23. Dr. Marcin Szyniszewski, Entanglement transitions in random quantum circuits, ULC - University of London, UK

24. Dr. Mohammad Zarenia, Hydrodynamic Transport in Graphene Systems, Center for Imaging Research, Medical College of Wisconsin

25. Prof. Andrea Alù, Optical Metamaterials Based on Broken Symmetries, Photonics Initiative, Advanced Science Research Center, City University of New York.

26. Dr. Neil Drummond, Quantum Monte Carlo studies of excitonic charge-carrier complexes in two-dimensional transition-metal dichalcogenides, Lancaster University, Department of Physics, UK,

2022

27. Prof. Shaul Mukamel, Ultrafast nonlinear spectroscopy of elementary molecular events with quantum light and in optical cavities, University of California, Irvine

28. Prof. Steven Simon, Topologically Ordered Matter and Why You Should be Interested, Oxford University, UK

29. Prof. Michael Fogler, Polaritons in van der Waals nano-materials, University of California San Diego

30. Prof. Andrey Varlamov, Fluctuation spectroscopy: From Rayleigh-Jeans waves to Abrikosov vortex clusters, Institute of Superconductivity and Innovative Materials (SPIN-CNR), Rome, Italy

31. Prof. Federico Camia, From conformal field theory to Brownian loops... and back, New York University AD Campus and Courant Institute

32. Prof. Lev Deych, Effects of confinement and degeneracy on optomechanical interaction between whispering-gallery-modes and a nanoparticle: old results and new ideas, Department of Physics, Queens College CUNY.

33. Dr. Ipsita Mandal, Emergent Collective Phenomena in Many-Body Systems, Institute of Nuclear Physics, Polish Academy of Sciences, Poland.

34. Dr. Maxim Trushin, Optoelectronic and Biomimetic Properties of Layered Materials with Mutual Interactions, The Institute for Functional Intelligent Materials National University of Singapore.

35. Prof. Giovanni Vignale, Quantum continuum mechanics and quantum incompressibility of electron-hole bilayers, The Institute for Functional Intelligent Materials National University of Singapore.

36. Prof. Leonid V. Butov, Indirect Excitons, University of California at San Diego, November 10

37. Prof. Mark Dykman, Resonant time-symmetry breaking in classical and quantum oscillators, Michigan State University.

38. Prof. Yuri Lvov, Fermi Pasta Ulam Tsingou chain: Thermalization and anomalous conduction, Rensselaer Polytechnic Institute.

39. Prof. Irinel Chiorescu, Engineering quantum coherence and control in diluted spin systems, Florida State University and the National High Magnetic Field Laboratory.

1. Four undergraduate students STEM major, Olga Privman, Patrice Prosper, Jorge Bermeo, (Major Applied Computational Physics) and Shaina Raklyar (Major: Bioinformatics) had training in novel two denominational materials and applications.

2. We had 5 seminars given by experts from different universities. Seminar were given for physics faculty, graduate students and undergraduate students. These seminars are given through the Center for Theoretical Physics and represent the excellent training for graduate and undergraduate students and professional development for faculty.

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Results Dissemination: Publications

Results of Grant activities and accomplishments were published in 26 peer review articles and on book chapter in most prestigious journals:

Physical Review A – 2 articles. Impact Factor 2.971 (2021)

Physical Review B – 11 articles. Impact Factor 3.908 (2021)

Physical Review Research - 3 articles Impact Factor 3.9 (2021)

Physics Letters A – 4 articles Impact Factor 2.654 (2022)

Scientific report – 1 article Impact Factor 4.996 (2021)

Nanomaterials – 1 article Impact Factor 5.719 (2021)

Journal of Physics B Atomic, Molecular Optics – 1 article. Impact Factor 1.917 (2021)

International Journal of Modern Physics B – 1 article. Impact Factor 1.219 (2021)

Communication Physics – 1 article. Impact Factor 6.368 (2022)

Few Body System – 1 article. Impact Factor 1.362 (2022)

Physica E Low-dimensional Physics and Nanostructures – 1 article. Impact Factor 3.382 (2022)

The Presentations at International and National conferences

During the grant period Undergraduate, Graduate and Faculty made 30 presentations at American Physical Society March Meetings with published abstracts.

2019

A15.00008 The stable trion states in 2D WSe₂ monolayer

A26.00015 Quantum entanglement dynamics due to dynamical Lamb effect

C12.00005 Tunable Optical Absorption by Excitons in Xenes via an External Electric Field

G70.00278 Laplace transform approach for the dynamics of N qubits coupled to a resonator

S16.00007 Spin Hall effect for polaritons in a TMDC monolayer embedded in a microcavity

T70.00287 Are freestanding Xene monolayers excitonic insulators in their ground state?

V15.00012 Study of dipolar excitons in TiS₃ double layer

A27.00003 Optical manipulation of entanglement in plasmonically coupled quantum dot qubits

G70.00350 Emission of entangled photons via the biexciton formation and decay in core/shell nanoplatelets

2020

C71.00386 Floquet approach to the study of the dynamical Lamb effect

J62.00005 Can trions crystallize in TMDC monolayers?

J62.00007 Electron-hole superfluidity controlled by a periodic potential in double layers of two-dimensional material

M07.00014 Dynamical Lamb effect in a superconducting circuit

H71.00201 Dipolar Magnetoexcitons in α -T₃ double layers in a high magnetic field

M07.00014 Dynamical Lamb effect in a superconducting circuit

H71.00094 Polariton Optical Transistor based on a MoSe₂-WS₂ Heterogenous Bilayer embedded in an Optical Microcavity at Room Temperature

H71.00096 Polariton Formation and Propagation in an Optical Microcavity with Embedded Transition Metal Dichalcogenide with Disorder

2021

C55.00006 Strain induced quantum Hall phenomena of excitons in graphene

F41.00012 Magnetoexcitons in Transition-Metal Dichalcogenides Monolayers and Double-Layer Heterostructures

M56.00002 Crystal phases of charged interlayer excitons in van der Waals heterostructures.

M56.00006 Rydberg Excitons in buckled two-dimensional materials in presence of parallel magnetic and electric fields

F56.00010 Driven dipolariton transistors using van der Waals TMDC with channel guides

U71.00077 Dipolariton propagation in a van der Waals TMDC with π -shaped channel guides and buffered channel branches.

U71.00112 Multi-Layered Structures for Low-Temperature Low-Energy Optical Interconnects for Quantum Computers

U71.00063 Superfluidity of dipolar excitons in a double layer of α -T₃ with a mass term

U71.00094 Quantum entanglement between two excitons in graphene under strain

2022

F55.00001 Excitons and magnetoexcitons in transitional metal trichalcogenides and phosphorene

G66.00007 Magnetoexcitons in phosphorene monolayer, bilayer, and van der Waals heterostructure

M57.00003 Superfluidity of a two-component Bose gas of dipolar excitons in a double layer of gapped hexagonal α -T₃

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T00.00125 Polaritonic and Excitonic Bose Einstein Condensates in a Periodic Potential

- One oral and two poster presentations at the conference: Universal Themes of Bose-Einstein Condensation, UBEC 2019, April 1-5, 2019, to Pittsburgh, PA, USA. <https://www.pqi.org/events/universal-themes-bose-einstein-condensation-conference-ubec-2019>
- Poster and Oral presentations at Department of Defense MURI Review Meeting, Ann Harbor, MI, Oct 7-8, 2019.
- Four oral presentations at the International School and Workshop on Two-Dimensional Crystals and Photonics, September 9-14, 2019, Tbilisi Georgia. <https://events.mifp.eu/2dcp-2019/> Abstracts published.
- Invited oral talk at The Sixth Conference on MESOSCOPIC Physics (NMP22) that held at the at Michigan State University East Lansing, Michigan, USA, May 23-27, 2022. <https://indico.frib.msu.edu/event/17/> Abstracts published.
- Invited lecture and oral presentation at International School and Conference on Functional Materials for Modern Technologies ISCFMMT October 1-7, 2022, Batumi, Georgia October 1-7 2022, <https://iscfmmt2022.tsu.ge/> Abstracts published.
- Undergraduate and Graduate students presented poster report "Polariton Propagation and Exciton Phase Correlations in an Optical Microcavity with Embedded Topologically-Disconnected Transition Metal Dichalcogenide Microflakes" at the Materials Science Research Society Fall Meeting, MRS Fall-2019, Boston, MA, Dec 1-6, 2019 <https://www.mrs.org/meetings-events/fall-meetings-exhibits/past-fall-meetings/2019-mrs-fall-meeting> Abstracts published.

Seminars

Research group members gave 5 seminars: 3 seminars at different at City University of New York colleges and at North Carolina Central University and Florida State University.

Seminar at National High Magnetic Field Laboratory: Roman Kezerashvili, Magnetoexcitons in novel 2D monolayers and van der Waals heterostructures. <https://nationalmaglab.org/news-events/events/calendar/3327>

Dissemination on the local level. New York City College of Technology, City University of New York

1) Undergraduate and Graduate students and Faculty made 12 poster presentations at City Tech Annual Poster session for faculty and students research

<https://www.citytech.cuny.edu/annual-poster/>

2) Graduate students made 8 poster presentations at the Poster Sessions at the Graduate Center, City University of New York

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- Honors and Awards:**
1. Grad student Mirko Amico won the CUNY Graduate Center dissertation fellowship competition and obtained Doctoral Student Research Grant in 2019, \$10k.
 2. Anastasia Spiridonova won the award for the best poster at 18th Annual Poster Session of Faculty and Student Research at the New York City College of Technology.
 3. Grad student Anastasia Spiridonova won the CUNY Graduate Center dissertation fellowship competition and obtained Doctoral Student Research Grant in 2022, \$10k.
 4. PSC Grant Award. "Trion in Monolayer Transition Metal Dichalcogenides: Faddeev Equations and Hyperspherical Harmonics Approaches", PI Roman Ya. Kezerashvili, Award #61188-00 49, \$3.5k.
 5. PSC Grant Award. Properties of Microcavity Polaritons in Heterostructures, Formed by Novel Two-Dimensional Materials, PI Oleg L. Berman, Award # TRADB-52-130, \$6k.
 6. Advanced Science Research Center Seed Program grant award "Exciton polariton-mediated conversion of microwave radiation to optical pulses", PI Kolmakov, together with M. Begliarbekov and G. Grosso (ASRC), Research Foundation CUNY award #95663-00 01, August 1, 2021-July 31, 2022, \$20k.
 7. Matthew Brunetti got Ph.D. The defense of Ph.D. thesis "Optical and Collective Properties of Excitons in 2D Semiconductors" was on August 28, 2019.
 8. Mirko Amico got Ph.D. The defense of Ph.D. thesis "Generating entanglement with the dynamical Lamb effect" was on March 20, 2020.
 9. Patrick Serafin got Ph.D. The defense of Ph.D. thesis "Driven Dipolaritons in Van der Waals Transition Metal Dichalcogenide Heterostructures: Properties and Applications" was on June 24, 2022.

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: Community College Faculty

Participant: Shalva M. Tsiklaury

Person Months Worked: 6.00

Project Contribution:

National Academy Member: N

Funding Support:

Participant Type: Graduate Student (research assistant)

Participant: Matthew N Brunetti

Person Months Worked: 15.00

Project Contribution:

National Academy Member: N

Funding Support:

Participant Type: Graduate Student (research assistant)

Participant: Mirko Amico

Person Months Worked: 15.00

Project Contribution:

National Academy Member: N

Funding Support:

Participant Type: Graduate Student (research assistant)

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Participant: Patrick Serafin

Person Months Worked: 15.00

Project Contribution:

National Academy Member: N

Funding Support:

Participant Type: Graduate Student (research assistant)

Participant: Patrick Serafin

Person Months Worked: 15.00

Project Contribution:

National Academy Member: N

Funding Support:

Participant Type: Graduate Student (research assistant)

Participant: Anastasia Spiridonova

Person Months Worked: 15.00

Project Contribution:

National Academy Member: N

Funding Support:

Participant Type: Graduate Student (research assistant)

Participant: Anastasia Spiridonova

Person Months Worked: 15.00

Project Contribution:

National Academy Member: N

Funding Support:

Participant Type: Graduate Student (research assistant)

Participant: Andrew Dublin

Person Months Worked: 13.00

Project Contribution:

National Academy Member: N

Funding Support:

Participant Type: Graduate Student (research assistant)

Participant: Gabriel P. Martins

Person Months Worked: 14.00

Project Contribution:

National Academy Member: N

Funding Support:

Participant Type: Graduate Student (research assistant)

Participant: Yamuna Paudel

Person Months Worked: 10.00

Project Contribution:

National Academy Member: N

Funding Support:

Participant Type: Undergraduate Student

Participant: Shaina Raklyar

Person Months Worked: 5.00

Funding Support:

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Project Contribution:
National Academy Member: N

Participant Type: Undergraduate Student

Participant: Lu Xu

Person Months Worked: 6.00

Funding Support:

Project Contribution:

National Academy Member: N

Participant Type: Undergraduate Student

Participant: Alan Li

Person Months Worked: 6.00

Funding Support:

Project Contribution:

National Academy Member: N

Participant Type: Graduate Student (research assistant)

Participant: Tom Brick

Person Months Worked: 2.00

Funding Support:

Project Contribution:

National Academy Member: N

Participant Type: Undergraduate Student

Participant: Mubinjon Satymov

Person Months Worked: 5.00

Funding Support:

Project Contribution:

National Academy Member: N

Participant Type: Undergraduate Student

Participant: Patrice Prosper

Person Months Worked: 5.00

Funding Support:

Project Contribution:

National Academy Member: N

Participant Type: Undergraduate Student

Participant: Jorge Bermeo

Person Months Worked: 5.00

Funding Support:

Project Contribution:

National Academy Member: N

Participant Type: Undergraduate Student

Participant: Olga Privman

Person Months Worked: 5.00

Funding Support:

Project Contribution:

National Academy Member: N

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ARTICLES:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

Journal: Physical Review B

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Publication Identifier: 10.1103/PhysRevB.98.125406

Volume: 98

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Date Submitted: 9/17/19 12:00AM

Date Published: 9/1/18 8:00AM

Publication Location:

Article Title: Optical properties of excitons in buckled two-dimensional materials in an external electric field

Authors: Matthew N. Brunetti, Oleg L. Berman, Roman Ya. Kezerashvili

Keywords: Xenes, silicene, germanene, stanene, Rytova-Keldysh potential

Abstract: We study the binding energies and optical properties of direct and indirect excitons in monolayers and doublelayer heterostructures of Xenes: silicene, germanene, and stanene. It is demonstrated that an external electric field can be used to tune the eigenenergies and optical properties of excitons by changing the effective mass of charge carriers. Our calculations show that the existence of the excitonic insulator phase is plausible in freestanding Xenes at small electric fields. The Schrödinger equation with field-dependent exciton reduced mass is solved by using the Rytova-Keldysh (RK) potential for direct excitons, while both the RK and Coulomb potentials are used for indirect excitons. It is shown that for indirect excitons, the choice of interaction potential can cause huge differences in the eigenenergies at large electric fields and significant differences even at small electric fields. Furthermore, our calculations show that the choice of material parameters are significant

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Article Title: Spin Hall effect for polaritons in a transition metal dichalcogenide embedded in a microcavity

Authors: Oleg L. Berman, Roman Ya. Kezerashvili, Yurii E. Lozovik

Keywords: transition metal dichalcogenides, spin Hall effect, polaritons

Abstract: The spin Hall effect for polaritons (SHEP) in a transition metal dichalcogenides (TMDC) monolayer embedded in a microcavity is predicted. We demonstrate that two counterpropagating laser beams incident on a TMDC monolayer can deflect a superfluid polariton flow due to the generation of the effective gauge vector and scalar potentials. The components of polariton conductivity tensor for both noninteracting polaritons without Bose-Einstein condensation (BEC) and for weakly interacting Bose gas of polaritons in the presence of BEC and superfluidity are obtained. It is shown that the polariton flows in the same valley are splitting: the superfluid components of the A and B polariton flows propagate in opposite directions along the counterpropagating beams, while the normal components of the flows slightly deflect in opposite directions and propagate almost perpendicularly to the beams. The possible experimental observation of SHEP in a microcavity is proposed.

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Volume: 99 **Issue:** 19 **First Page #:**
Date Submitted: 9/17/19 12:00AM **Date Published:** 5/1/19 4:00AM
Publication Location:

Article Title: High-temperature tunable superfluidity of polaritons in

Authors: Matthew N. Brunetti, Oleg L. Berman, Roman Ya. Kezerashvili

Keywords: silicene, germanene, stanene, polaritons, binding energy

Abstract: We study tunable polaritons in monolayers of silicene, germanene, and stanene (Xenes) via an external electric field in an open optical microcavity whose length can be adjusted. An external electric field applied perpendicular to the plane of the Xene monolayer simultaneously changes the band gap and the exciton binding energy, while the variable length of the open microcavity allows one to keep the exciton and cavity photon modes in resonance. First, the Schrödinger equation for an electron and hole in an Xene monolayer is solved, yielding the eigenenergies and eigenfunctions of the exciton as a function of the external electric field. The dependence of the polaritonic properties, such as the Rabi splitting, on the external electric field and on the cavity length, is analyzed. The Berezinskii-Kosterlitz-Thouless (BKT) transition temperature of polaritons is calculated as a function of the external electric field.

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Journal: Physics Letters A
Publication Identifier Type: DOI **Publication Identifier:** 10.1016/j.physleta.2018.11.018
Volume: 383 **Issue:** 5 **First Page #:** 482
Date Submitted: 9/17/19 12:00AM **Date Published:** 1/1/19 5:00AM
Publication Location:

Article Title: Can freestanding Xene monolayers behave as excitonic insulators?

Authors: Matthew N. Brunetti, Oleg L. Berman, Roman Ya. Kezerashvili

Keywords: monolayer Xenes, excitonic insulator, binding energy

Abstract: We predict that a phase transition in freestanding monolayer Xenes from the semiconducting phase to the excitonic insulating (EI) phase can be induced by reducing an external electric field below some critical value which is unique to each material. The splitting of the conduction and valence bands due to spin-orbit coupling at non-zero electric fields leads to the formation of A and B excitons in the larger or smaller band gap, with correspondingly larger or smaller binding energies. Our calculations show the coexistence of the semiconducting phase of A excitons with the EI phase of B excitons for a particular range of electric field. The dielectric environment precludes the existence of the EI phase in supported or encapsulated monolayer Xenes.

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Journal: Physica E: Low-dimensional Systems and Nanostructures
Publication Identifier Type: DOI **Publication Identifier:** 10.1016/j.physe.2019.01.019
Volume: 109 **Issue:** **First Page #:** 228
Date Submitted: 9/17/19 12:00AM **Date Published:** 5/1/19 4:00AM
Publication Location:

Article Title: Trions and biexcitons in ZnO/ZnMgO, CdSe/ZnS and CdSe/CdS core/shell nanowires

Authors: R.Ya. Kezerashvili, Z.S. Machavariani, B. Beradze, T. Tchelidze

Keywords: nanowire, trion, biexciton. optical property

Abstract: A study of the trion and biexciton in a nanowire (NW) in the framework of the effective-mass model is presented. We consider the formation of trions and biexcitons under the action of both the lateral confinement and the localization potential. The analytical expressions for the binding energy and eigenfunctions of the trion and biexciton are obtained and expressed by means of matrix elements of the effective one-dimensional cusp-type Coulomb potentials whose parameters are determined self-consistently by employing eigenfunctions of the confined electron and hole states. Our calculations for the ZnO/ZnMgO, CdSe/ZnS and CdSe/CdS core/shell cylindrical shaped NWs show that the trion and biexciton binding energy in NWs are size-dependent and for the same input parameters the biexciton binding energy in NWs is always larger than the binding energy of the trion. The trion and biexciton remain stable in NW with the increase of the dielectric shell until it exceeds the critical values.

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Journal: Few-Body Systems
Publication Identifier Type: DOI **Publication Identifier:** 10.1007/s00601-019-1520-1
Volume: 60 **Issue:** 3 **First Page #:**
Date Submitted: 9/17/19 12:00AM **Date Published:** 7/1/19 4:00AM
Publication Location:

Article Title: Few-Body Systems in Condensed Matter Physics

Authors: Roman Ya. Kezerashvili

Keywords: excitons, trions, biexcitons, three-, two- and one-dimensional configuration spaces

Abstract: This review focuses on the studies and computations of few-body systems of electrons and holes in condensed matter physics. We analyze and illustrate the application of a variety of methods for description of two-, three- and four-body excitonic complexes such as an exciton, trion and biexciton in three-, two- and one-dimensional configuration spaces in various types of materials. We discuss and analyze the contributions made over the years to understanding how the reduction of dimensionality affects the binding energy of excitons, trions and biexcitons in bulk and low-dimensional semiconductors and address the challenges that still remain.

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Publication Type: Journal Article Peer Reviewed: N **Publication Status:** 1-Published
Journal: Physical Review B
Publication Identifier Type: Other **Publication Identifier:** arXiv:1907.11344v1 [cond-mat.mes-hall] 26
Volume: **Issue:** **First Page #:**
Date Submitted: 9/17/19 12:00AM **Date Published:** 7/26/19 8:00AM
Publication Location:
Article Title: Optical Properties of Anisotropic Excitons in Phosphorene
Authors: Matthew N. Brunetti, Oleg L. Berman, and Roman Ya. Kezerashvili
Keywords: phosphorene, direct exciton, indirect exciton, binding energy
Abstract: We study the eigenenergies and optical properties of both direct excitons in a phosphorene monolayer in different dielectric environments, and indirect excitons in heterostructures of phosphorene with hexagonal boron nitride. For these systems, we solve the 2D Schrodinger equation using the Rytova-Keldysh (RK) potential for direct, and both the RK and Coulomb potentials for indirect excitons. The results show that excitons formed from charge carriers with anisotropic effective mass exhibit enhanced (suppressed) optical absorption, compared to their 2D isotropic counterparts, under linearly polarized excitations along the crystal axis with relatively smaller (larger) effective carrier masses. This anisotropy leads to dramatically different excited states than the isotropic exciton. The direct exciton binding energy depends strongly on the dielectric environment, and shows good agreement with previously published data.
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Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review B
Publication Identifier Type: DOI **Publication Identifier:** 10.1103/PhysRevB.100.134514
Volume: 100 **Issue:** 13 **First Page #:** 134514
Date Submitted: 8/3/20 12:00AM **Date Published:** 10/1/19 4:00AM
Publication Location:
Article Title: Electron-hole superfluidity controlled by a periodic potential
Authors: Oleg L. Berman, Roman Ya. Kezerashvili, Yuri E. Lozovik, Klaus G. Ziegler
Keywords: coupled quantum wells, external periodic field, 2D material, second-order phase transition
Abstract: We propose controlling an electron-hole superfluid in semiconductor coupled quantum wells and double layers of a two-dimensional (2D) material by an external periodic field. This can be created either by the gates periodically located and attached to the quantum wells or double layers of the 2D material or by the moiré pattern of two twisted layers. The dependence of the electron-hole pairing order parameter on the temperature, the charge carrier density, and the gate parameters is obtained by minimization of the mean-field free energy. The second-order phase transition between superfluid and electron-hole plasma, controlled by the external periodic gate field, is analyzed for different parameters.
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Journal: PHYSICAL REVIEW B

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Volume: 100

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Date Submitted: 8/10/20 12:00AM

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Publication Location:

Article Title: Optical properties of anisotropic excitons in phosphorene

Authors: M. N. Brunetti, O. L. Berman, R. Ya. Kezerashvili

Keywords: Phosphorene, direct exciton, indirect exciton, anisotropic effective mass, optical properties

Abstract: We study the eigenenergies and optical properties of both direct excitons in a phosphorene monolayer in different dielectric environments and indirect excitons in heterostructures of phosphorene with hexagonal boron nitride. For these systems, we solve the 2D Schrödinger equation using the Rytova-Keldysh (RK) potential for direct and both the RK and Coulomb potentials for indirect excitons. The results show that excitons formed from charge carriers with anisotropic effective mass exhibit enhanced (suppressed) optical absorption, compared to their 2D isotropic counterparts, under linearly polarized excitations along the crystal axis with relatively smaller (larger) effective carrier masses. This anisotropy leads to dramatically different excited states than the isotropic exciton. The direct exciton binding energy depends strongly on the dielectric environment, and shows good agreement with previously published data.

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Journal: Physical Review B

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Date Submitted: 8/30/21 12:00AM

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Publication Location:

Article Title: Effects of parallel electric and magnetic fields on Rydberg excitons in buckled two-dimensional materials

Authors: Roman Ya. Kezerashvili, Anastasia Spiridonova

Keywords: Excitons, magnetic field, electric field, Xenes, binding energy, diamagnetic coefficients, Rydberg states, monolayer, bilayer, heterostructure

Abstract: We study direct and indirect magnetoexcitons in Rydberg states in monolayers and double-layer heterostructures of Xenes (silicene, germanene, and stanene) in external parallel electric and magnetic fields applied perpendicular to the monolayer and heterostructure. We calculate binding energies of magnetoexcitons for the Rydberg states, 1s, 2s, 3s, and 4s by numerical integration of the Schrödinger equation using the Rytova-Keldysh potential for direct and both the Rytova-Keldysh and Coulomb potentials for indirect magnetoexcitons, respectively. The latter allows understanding a role of screening in Xenes. We report the energy contribution from electric and magnetic fields to the binding energies and DMCs. The tunability of the energy contribution of direct and indirect magnetoexcitons by electric and magnetic fields is demonstrated.

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Journal: Physical Review Research
Publication Identifier Type: DOI **Publication Identifier:** 10.1103/PhysRevResearch.3.033078
Volume: 3 **Issue:** 3 **First Page #:** 033078-1
Date Submitted: 8/30/21 12:00AM **Date Published:** 7/1/21 8:00AM
Publication Location:

Article Title: Magnetoexcitons in transition metal dichalcogenides monolayers, bilayers, and van der Waals heterostructures

Authors: Roman Ya. Kezerashvili, Anastasia Spiridonova

Keywords: Magnetoexcitons, magnetic field, TMDCs, binding energy, diamagnetic coefficients, Rydberg states, monolayer, bilayer, heterostructure

Abstract: We study direct and indirect magnetoexcitons in Rydberg states in monolayers and heterostructures of transition metal dichalcogenides (TMDCs) in an external magnetic field, applied perpendicular to the monolayer or heterostructures in the framework of a Mott-Wannier model of excitons. We calculate binding energies of magnetoexcitons for the Rydberg states 1s, 2s, 3s, and 4s by numerical integration of the Schrödinger equation using the Rytova-Keldysh potential for direct magnetoexcitons and both the Rytova-Keldysh and Coulomb potentials for indirect magnetoexcitons. We report the magnetic field energy contribution to the binding energies and diamagnetic coefficients (DMCs) for direct and indirect magnetoexcitons. The tunability of the energy contribution of direct and indirect magnetoexcitons by the magnetic field is demonstrated. It is shown that binding energies and DMCs of indirect magnetoexcitons can be manipulated by the number of hBN layers.

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Journal: Physical Review B
Publication Identifier Type: DOI **Publication Identifier:** 10.1103/PhysRevB.102.155408
Volume: 102 **Issue:** 15 **First Page #:** 155408-1
Date Submitted: 8/30/21 12:00AM **Date Published:** 10/1/20 4:00AM
Publication Location:

Article Title: Superfluidity of dipolar excitons in doped double-layered hexagonal lattice in a strong magnetic field

Authors: Yonatan Abranyos, Oleg L. Berman, Godfrey Gumbs

Keywords: Superfluidity, dipolar excitons, Kosterlitz-Thouless phase transition

Abstract: We examine the occurrence of Bose-Einstein condensation and superfluidity of dipolar excitons for a pair of quasi-two-dimensional spatially separated hexagonal γ -T3 layers. In the γ -T3 model, the AB-honeycomb lattice structure is supplemented with C atoms, located at the centers of the hexagonal lattice. We have solved a two-body problem for an electron and a hole for the model Hamiltonian for the γ -T3 double layer in a magnetic field. The exciton binding energy is changed due to the magnetic field, and magnetoexcitons are formed as excitons in a magnetic field. The energy dispersion of collective excitations, the spectrum of sound velocity, and the effective magnetic mass of magnetoexcitons are obtained in the integer quantum Hall regime for high magnetic fields. The superfluid density and the temperature of the Kosterlitz-Thouless phase transition are probed as functions of the excitonic density, the magnetic field, and the interlayer separation.

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Journal: Physics Letters A

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Volume: 384 Issue: 34

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Date Submitted: 8/30/21 12:00AM

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Publication Location:

Article Title: Driven dipolariton transistors in Y-shaped channels

Authors: Patrick Serafin, Tim Byrnes, German V. Kolmakov

Keywords: Dipolaritons Transition metal dichalcogenide Exciton-polaritons Forced diffusion equation Optical transistors

Abstract: Exciton-dipolaritons are investigated as a platform for realizing working elements of a polaritronic transistor. Exciton-dipolaritons are three-way superposition of cavity photons, direct and indirect excitons in a bilayer semiconducting system embedded in an optical microcavity. Using the forced diffusion equation for dipolaritons, we study the room-temperature dynamics of dipolaritons in a transition-metal dichalcogenide (TMD) heterogeneous bilayer. Specifically, we considered a MoSe₂-WS₂ heterostructure, where a Y-shaped channel guiding the dipolariton propagation is produced. We demonstrate that polaritronic signals can be redistributed in the channels by applying a driving voltage in an optimal direction. Our findings open a route towards the design of an efficient room-temperature dipolariton-based optical transistor.

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Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

Journal: Physics Letters A

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Volume: 384 Issue: 33

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Date Submitted: 8/30/21 12:00AM

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Publication Location:

Article Title: Magnetoexcitons in monolayer transition-metal dichalcogenides

Authors: Anastasia Spiridonova

Keywords: Binding energy Excited states Excitons Magnetoexcitons Diamagnetic shift Transition-metal dichalcogenides

Abstract: We study the magnetoexciton Rydberg states in MoS₂, MoSe₂, WS₂, and WSe₂ monolayers encapsulated by hexagonal boron nitride. Excitons in the magnetic field are described in the framework of the nonrelativistic potential model. We use the Rytova-Keldysh potential to calculate the energies of the magnetoexcitons. Our calculations use as inputs the effective masses of electron and hole obtained in the framework of the density functional theory. The binding energies of A and B magnetoexcitons are calculated by numerical integration of the Schrödinger equation. We report the energy contribution from the magnetic field to the binding energy and its dependence on the magnetic field. The diamagnetic coefficients are calculated. The reasonable agreement for diamagnetic coefficients and experimental data is obtained.

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Journal: Communications Physics
Publication Identifier Type: DOI **Publication Identifier:** 10.1038/s42005-021-00624-1
Volume: 4 **Issue:** 1 **First Page #:**
Date Submitted: 8/30/21 12:00AM **Date Published:** 6/1/21 4:00AM
Publication Location:

Article Title: Crystal phases of charged interlayer excitons in van der Waals heterostructures

Authors: Igor V. Bondarev, Oleg L. Berman, Roman Ya. Kezerashvili, Yuri E. Lozovik

Keywords: Trions, TMDC, Wigner crystalization, van der Waals heterostructures

Abstract: The dynamics of qubits coupled to a harmonic oscillator with time-periodic coupling is investigated in the framework of Floquet theory. This system can be used to model nonadiabatic phenomena that require a periodic modulation of the qubit/oscillator coupling. The case of a single qubit coupled to a resonator populated with $n = 0, 1$ photon is explicitly treated. The time-dependent Schrödinger equation describing the system's dynamics is solved within the Floquet formalism and compared to a solution obtained with perturbative approaches in the time- and Laplace-domain. Excellent quantitative agreement is found between the analytical and numerical calculations within the Floquet approach, demonstrating the effectiveness of the technique for the study of the dynamical Lamb effect.

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Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Journal of Physics B: Atomic, Molecular and Optical Physics
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Volume: 54 **Issue:** 1 **First Page #:** 015502
Date Submitted: 8/30/21 12:00AM **Date Published:** 1/1/20 5:00AM
Publication Location:

Article Title: Dynamics of a qubit-oscillator system with periodically varying coupling

Authors: Mirko Amico, Roman Ya Kezerashvili

Keywords: qubit, dynamical lamb effect, cavity

Abstract: The dynamics of qubits coupled to a harmonic oscillator with time-periodic coupling is investigated in the framework of Floquet theory. This system can be used to model nonadiabatic phenomena that require a periodic modulation of the qubit/oscillator coupling. The case of a single qubit coupled to a resonator populated with $n = 0, 1$ photon is explicitly treated. The time-dependent Schrödinger equation describing the system's dynamics is solved within the Floquet formalism and compared to a solution obtained with perturbative approaches in the time- and Laplace-domain. Excellent quantitative agreement is found between the analytical and numerical calculations within the Floquet approach, demonstrating the effectiveness of the technique for the study of the dynamical Lamb effect.

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Journal: Physics Letters A

Publication Identifier Type: DOI

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Volume: 399

Issue:

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Date Submitted: 8/30/21 12:00AM

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Publication Location:

Article Title: Chiral filtration of light by Weyl-semimetal medium

Authors: Nikolay M. Chtchelkatchev, Oleg L. Berman, Roman Ya. Kezerashvili, Yurii E. Lozovik

Keywords: Weyl-semimetal Topological protection High mobility Chiral reflection and transmission

Abstract: Recently discussed topological materials Weyl-semimetals (WSs) combine both: high electron mobility comparable with graphene and unique topological protection of Dirac points. We present novel results related to electromagnetic field propagation through WSs. It is predicted that transmission of the normally incident polarized electromagnetic wave (EMW) through the magnetic WS strongly depends on the orientation of polarization with respect to a gyration vector g . The latter is related to the vector-parameter b , which represents the separation between the Weyl nodes of opposite chirality in the first Brillouin zone. By changing the polarization of the incident EMW with respect to the gyration vector g the system undergoes the transition from the isotropic dielectric to the medium with Kerr-or Faraday-like rotation of polarization and finally to the system with chiral selective electromagnetic field. It is shown that WSs can be applied as the polarization filters.

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Journal: International Journal of Modern Physics B

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Publication Identifier: 10.1142/S0217979221502532

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Publication Location:

Article Title: Dipolariton propagation in a van der Waals TMDC with Ψ -shaped channel guides and buffered channel branches

Authors: Patrick C. Serafin, German V. Kolmakov

Keywords: Dipolaritons; TMDC; polariton guides.

Abstract: Using a computational approach based on the driven diffusion equation for dipolariton wave packets, we simulate the diffusive dynamics of dipolaritons in an optical micro-cavity embedded with a transition metal dichalcogenide (TMDC) heterogeneous bilayer encompassing a Ψ -shaped channel. By considering exciton-dipolaritons, which are a three-way superposition of direct excitons, indirect excitons and cavity photons, we are able to drive the dipolaritons in our system by the use of an electric voltage and investigate their diffusive properties. More precisely, we study the propagation of dipolaritons present in a MoSe₂-WS₂ heterostructure, where the dipolariton propagation is guided by a Ψ -shaped channel. We also consider the propagation of dipolaritons in the presence of a buffer in the Ψ -shaped channel and study resulting changes in efficiency. We introduce designs for optical routers at room-temperature.

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Journal: Scientific Reports

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Volume: 12

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Date Published: 2/1/22 10:00AM

Publication Location:

Article Title: Strain-induced quantum Hall phenomena of excitons in graphene

Authors: Oleg L. Berman, Roman Ya. Kezerashvili, Yurii E. Lozovik, Klaus G. Ziegler

Keywords: Direct and indirect pseudomagnetoexcitons, Strain-induced quantum Hall phenomena, graphene

Abstract: We study direct and indirect pseudomagnetoexcitons, formed by an electron and a hole in the layers of gapped graphene under strain-induced gauge pseudomagnetic field. Since the strain-induced pseudomagnetic field acts on electrons and holes the same way, it occurs that the properties of single pseudomagnetoexcitons, their collective effects and phase diagram are cardinally different from those of magnetoexcitons in a real magnetic field. We have derived wave functions and energy spectrum of direct in a monolayer and indirect pseudomagnetoexcitons in a double layer of gapped graphene. The quantum Hall effect for direct and indirect excitons was predicted in the monolayers and double layers of gapped graphene under strain-induced gauge pseudomagnetic field, correspondingly.

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Peer Reviewed: Y

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Publication Identifier: 10.3390/nano12091437

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Article Title: Superfluidity of Dipolar Excitons in a Double Layer of α -T₃ with a Mass Term

Authors: Oleg L. Berman, Godfrey Gumbs, Gabriel P. Martins, Paula Fekete

Keywords: Bose-Einstein condensation; dipolar excitons; superfluidity

Abstract: We predict Bose-Einstein condensation and superfluidity of dipolar excitons, formed by electron-hole pairs in spatially separated gapped hexagonal α -T₃ (GHAT₃) layers. We considered the α -T₃ model in the presence of a mass term which opens a gap in the energy-dispersive spectrum. The gap opening mass term, caused by a weak magnetic field, plays the role of Zeeman splitting at low magnetic fields for this pseudospin-1 system. We consider two types of dipolar excitons in double-layer GHAT₃: A and B excitons. The binding energy of A and B dipolar excitons is calculated. For a two-component weakly interacting Bose gas of dipolar excitons in a GHAT₃ double layer, we obtain the energy dispersion of collective excitations, the sound velocity, the superfluid density, and the mean-field critical temperature T_c for superfluidity.

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Publication Location:

Article Title: Charge-dipole and dipole-dipole interactions in two-dimensional materials

Authors: Roman Ya. Kezerashvili, Vladimir Ya. Kezerashvili

Keywords: Charge-dipole interaction in 2D; dipole-dipole interaction in 2D, analytical form for 2D interaction

Abstract: We derive the explicit analytical form for the charge-dipole and dipole-dipole interactions in two-dimensional (2D) configuration space. We demonstrate that the reduction of dimensionality can alter the charge-dipole and dipole-dipole interactions in the 2D case. The asymptotics of these interactions at long distances coincide to the charge-dipole and dipole-dipole interactions in three-dimensional configuration space. The obtained chargedipole and dipole-dipole interactions will find wide application and contribute to the advancement of research on novel two-dimensional materials.

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Article Title: Magnetoexcitons in phosphorene monolayers, bilayers, and van der Waals heterostructures

Authors: Roman Ya. Kezerashvili, Anastasia Spiridonova, Andrew Dublin

Keywords: Magnetoexcitons in phosphorene; magnetoexcitons monolayers, bilayers, and van der Waals heterostructure; diamagnetic coefficients; binding energies

Abstract: We study direct and indirect excitons in Rydberg states in phosphorene monolayers, bilayers, and van der Waals (vdW) heterostructure in an external magnetic field within the framework of the effective-mass approximation. Binding energies of magnetoexcitons are calculated using the Rytova-Keldysh (RK) potential for direct magnetoexcitons and both the RK and Coulomb potentials for indirect magnetoexcitons. We report the magnetic field energy contribution to the binding energies and diamagnetic coefficients (DMCs) for magnetoexcitons, which can be tuned by the external magnetic field. We demonstrate that the vdW phosphorene heterostructure is a novel category of two-dimensional semiconductors with magnetoexcitonic binding energies tunable by means of the external magnetic field. The binding energies and DMCs are controlled by the number of hexagonal boron nitride layers separating two phosphorene sheets. Such tunability is potentially useful for the device design.

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Publication Location:

Article Title: Quantum entanglement between excitons in two-dimensional materials

Authors: Gabriel P. Martins, Oleg L. Berman, Godfrey Gumbs, Yurii E. Lozovik

Keywords: Quantum entanglement between two excitons; three-qubit model,

Abstract: The quantum entanglement between two excitons in two-dimensional materials, embedded in an optical microcavity, was investigated. The energy eigenstates of a Jaynes-Cummings like Hamiltonian for two qubits coupled to a single cavity mode have been calculated. The quantum entanglement between such states was estimated by calculating the concurrence between two qubits in each of these eigenstates. The system is allowed to decay only through the emission of cavity photons at low temperatures, then there is a maximally entangled eigenstate, protected from decay. By briefly analyzing the three-qubit model, we have demonstrated that the probability for the entanglement to be preserved is enhanced when the number of qubits is increased. In addition, we calculated the time evolution of the concurrence between a pair of excitons in a strained graphene monolayer.

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Publication Location:

Article Title: Anisotropic magnetoexcitons in two-dimensional transition metal trichalcogenide semiconductors

Authors: Roman Ya. Kezerashvili, Anastasia Spiridonova

Keywords: Anisotropic magnetoexcitons; transition metal trichalcogenide; monolayers, bilayers, and van der Waals heterostructures.

Abstract: Direct and indirect excitons in Rydberg states in transition metal trichalcogenide (TMTC) monolayers, bilayers, and van der Waals (vdW) heterostructures in an external magnetic field are studied within the framework of the effective mass approximation. Binding energies (BEs) of magnetoexcitons are calculated using both the Rytova-Keldysh and Coulomb potentials for indirect magnetoexcitons. We report the magnetic field energy contribution to BEs and diamagnetic coefficients (DMCs) for magnetoexcitons that depend on a mass anisotropy of electrons and holes. In TiS₃, TiSe₃, and ZrSe₃ BEs and DMCs demonstrate the same kind of anisotropy as in phosphorene. In contrast, ZrS₃ has the opposite anisotropy to phosphorene. The tunability of BEs of direct and indirect magnetoexcitons by the external magnetic field and the possibility to control the binding energy of magnetoexcitons in vdW heterostructures by manipulation of numbers of hBN monolayers are shown.

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Publication Location:

Article Title: Superfluidity of indirect excitons in van der Waals heterostructures of transition metal trichalcogenides

Authors: Roman Ya. Kezerashvili, Anastasia Spiridonova

Keywords: angle-dependent superfluidity, anisotropic superfluidity, indirect excitons, 2D materials, transition metal trichalcogenides

Abstract: We predict angle-dependent superfluidity for a new class of two-dimensional materials: transition metal trichalcogenides (TMTC). Within a mean-field approach superfluidity of indirect excitons in TMTC van der Waals heterostructures (vdWHs) is studied. We use different potentials for charged carrier interaction to analyze the influence of the screening on the studied phenomena. Our study demonstrates the angle-dependent superfluidity temperature in TMTC vdWHs: for a given density a maximum and minimum T_c of superfluidity occurs along the chain and a directions, respectively. This work can guide experimental research toward the realization of anisotropic superfluidity in TMTC vdWH. We suggest an experiment for the observation of anisotropic superfluidity in TMTC vdWH.

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Publication Location:

Article Title: Dynamical Lamb effect in a superconducting circuit

Authors: Mirko Amico, Oleg L. Berman, Roman Ya. Kezerashvili

Keywords: superconducting circuits, dynamical Lamb effect, qubit

Abstract: The dynamical Lamb effect is predicted to arise in superconducting circuits when the coupling of a superconducting qubit with a resonator is periodically switched "on" and "off" nonadiabatically. We show that by using a superconducting circuit which allows one to switch between longitudinal and transverse coupling of a qubit to a resonator, it is possible to observe the dynamical Lamb effect. The switching between longitudinal and transverse coupling can be achieved by modulating the magnetic flux through the circuit loops. By solving the Schrödinger equation for a qubit coupled to a resonator, we calculate the time evolution of the number of excitations in the qubit and the resonator due to the dynamical Lamb effect. The number of excitations created in the system is maximum when the coupling is periodically switched between longitudinal and transverse using a square-wave or sinusoidal modulation of the magnetic flux.

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Date Submitted: 12/24/22 12:00AM **Date Published:** 3/1/19 10:00AM
Publication Location:

Article Title: Optical detection and storage of entanglement in plasmonically coupled quantum-dot qubits

Authors: M. Otten, S. K. Gray, G. V. Kolmakov

Keywords: Optical detection, quantum-dot qubits, entanglement, cavity photons

Abstract: Recent proposals and advances in quantum simulations, quantum cryptography, and quantum communications substantially rely on quantum entanglement formation. We consider a system composed of two quantum-dot qubits coupled with a common, damped surface plasmon mode; each quantum dot is also coupled to a separate photonic cavity mode. We also show that the degree of entanglement is conserved during the time evolution of the system. Furthermore, if coupling of the photonic cavity and quantum-dot modes is large enough, the quantum-dot entanglement can be transferred to the cavity modes to increase the overall entanglement lifetime. This latter phenomenon can be viewed as a signature of entangled, long-lived quantum-dot exciton-polariton formation. The preservation of total entanglement in the strong-coupling limit of the cavity-quantum-dot interactions suggests a novel means of entanglement storage and manipulation in high-quality optical cavities.

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Authors: Matthew N. Brunetti

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Description: The website gives an overview of the group's research focus, the projects the group will be working on, the research published by each member of the group, the conferences where the work was presented and the members of the group. By visiting the website, the public can see what is the general line of work pursued by each participant and have access to the published research.

Partners

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I certify that the information in the report is complete and accurate:

Signature: Roman Kezerashvili

Signature Date: 12/26/22 7:55AM

Final Report for the ARO Grant W911NF1810433

PI: Professor of Physics Roman Ya. Kezerashvili

Major Goals

The research performed under the grant W911NF1810433: Emerging Two Dimensional Van Der Waals Materials for Optical Information Transfer and Processing presents a systematic study directed toward understanding of the fundamental aspects for novel two-dimensional materials for optical information transfer and processing. These materials include graphene, transition-metal dichalcogenides (TMDC), Xenes (silicene, germanene, stanene), hexagonal α - T_3 layer, phosphorene and transition-metal trichalcogenides' freestanding, supported and encapsulated by dielectrics monolayers, bilayers and van der Waals heterostructures (vdW) formed by monolayers of these materials separated by hexagonal boron nitride (hBN) monolayers. We are addressing the following topics:

1. Optical properties of excitons in buckled two-dimensional materials in an external electric field and optical properties of anisotropic excitons in phosphorene by focused on the dependence of the excitonic properties, the ground and excited state, optical absorption transition energies, and optical absorption coefficients for optical absorption transitions from the excitonic ground state to the excitonic excited states, Can freestanding Xene monolayers behave as excitonic insulators? The answer for this question can be used as an electric current switch, where the switch is "off" when the material is in the excitonic insulator phase, and the switch is "on" when the material is in the semiconducting phase.
2. Light-matter interactions and collective quantum dynamics by considering the quantum dynamics of coupled charges and photons and the interaction with phonons, to understand the charge and photon transport in novel two-dimensional materials. In particular, analyze the polariton flow induced by the spin flow due to spin Hall Effect for excitons in TMDC. Study the effects of a periodic potential on a superfluid of excitons and cavity polaritons, formed by excitons, and controlling an electron-hole superfluid in semiconductor coupled quantum wells and double layers of a 2D material by an external periodic field and the BCS-like superfluid an electron-hole plasma phase transition.
3. Examine the occurrence of Bose-Einstein condensation (BEC) and superfluidity of dipolar (indirect) excitons and polaritons in vdW heterostructures. Consideration includes both materials where excitons are formed by isotropic electron and hole masses and formed by anisotropic electron and hole masses. Studies of the superfluid density and the temperature of the phase transition as functions of the excitonic density, the magnetic field, electro and hole mass anisotropy and the interlayer separation.
4. Study possibility to use topological materials Weyl-semimetals that are characterized by broken time-reversal or inversion symmetry as the polarization filters for the electromagnetic waves propagation.
5. Study an exciton-dipolaritons as a platform for realizing working elements of a polaritronic transistor and optimizing room-temperature polaritonic circuit performance when dipolaritons propagation is guided by a Y-shaped channel. To introduce designs for optical routers at room-temperature based on exciton-dipolaritons, which are a three-way superposition of direct excitons, indirect excitons, and cavity photons, by considering the dipolariton propagation is guided by a Ψ -shaped channel.

6. Study an influence of the reduction of dimensionality on the binding energy of excitons, trions and the screening effects in 2D material. Analyze collective properties of interlayer trions and consider strongly correlated phases. Study the crystal phases of charged interlayer excitons a possibility of Wigner crystalization of trions in TMDC double-layered system.
7. Study the formation of magnetoexcitons in monolayers, bilayers and vdW heterostructures of novel 2D materials with isotropic and anisotropic electron and hole masses. Consider a tunability of excitonic properties in these systems by external magnetic and electric fields. Possibility to tailor of IX magnetoexcitons properties in vdW heterostructures by varying the number of hBN sheets between two layers of novel 2D materials.
8. Consider some problems of quantum entanglement and computations that support the quantum information transfer and processing.

Accomplishment under the grant

1. We studied the optical properties of direct (X) and (IX) indirect excitons in monolayers and double layer heterostructures of the buckled two-dimensional (2D) allotropes of silicon (silicene), germanium (germanene), tin (stanene), and black phosphorus (phosphorene). The 2D forms of silicene, germanene, and stanene, known collectively as the Xenes, are noteworthy for the uniquely tunable nature of their electronic properties via the application of an external electric field (EF) oriented perpendicular to the monolayer(s). Applying an external EF to the Xenes changes the band gap of the material, in turn changing the effective masses of charge carriers and, therefore, the properties of excitons formed in these materials. We focused on the dependence of the excitonic properties, the ground and excited state eigenenergies, optical absorption transition energies, and optical absorption coefficients for optical absorption transitions from the excitonic ground state to the excitonic excited states, as a function of applied electric field. We started this research when our grant application was under review. The results of our comprehensive study were compiled and published in Ref. [1] when our group was awarded by the grant.
2. In Ref. [2] we predicted that a phase transition in freestanding monolayer Xenes from the semiconducting (SC) phase to the excitonic insulating (EI) phase can be induced by reducing an external EF below some critical value which is unique to each material. The splitting of the conduction and valence bands due to spin-orbit coupling at non-zero electric fields leads to the formation of A and B excitons in the larger or smaller band gap, with correspondingly larger or smaller binding energies. Our calculations show the coexistence of the semiconducting phase of A excitons with the EI phase of B excitons for a particular range of electric field. The dielectric environment precludes the existence of the EI phase in supported or encapsulated monolayer Xenes. As a consequence of this predicted behavior, we proposed that suspended Xenes can be used as an electric current switch, where the switch is “off” when the material is in the excitonic insulator phase, and the switch is “on” when the material is in the semiconducting phase. Our calculations also showed that the presence of a substrate such as SiO₂ or hexagonal boron nitride precludes the formation of the excitonic insulator state by reducing the exciton binding energy because of increased dielectric screening.
3. We studied the collective properties of exciton-polaritons in Xene monolayers embedded in an optical microcavity in Ref. [3]. In particular, we calculated the Rabi splitting and superfluid critical

temperature of the Berezinskii-Kosterlitz-Thouless (BKT) phase transition, and we focused on the dependence of these quantities as a function of the external EF, and considered the dependence of these quantities on other experimental and material parameters such as the polariton concentration and the linewidth of the excitonic transition. Our results showed that silicene monolayers encapsulated by *h*BN should exhibit stable polaritons at room-temperature with strong exciton-photon coupling and large Rabi splittings. Furthermore, for some combinations of moderately high 2D polariton concentrations and relatively small exciton optical transition linewidths, the critical temperature of the BKT superfluid phase transition should exceed room temperature, therefore indicating that polaritons in encapsulated silicene monolayers are excellent candidates for stable room-temperature polariton superfluids. These predictions are based on contemporary experiments of polaritons in TMDC monolayer in the same open microcavity setup, enabling relatively straightforward testing of our predictions.

4. We study the optical properties of both X excitons in a phosphorene monolayer in different dielectric environments and IX excitons in heterostructures of phosphorene with *h*BN [4]. The results show that excitons formed from charge carriers with anisotropic effective mass exhibit enhanced (suppressed) optical absorption, compared to their 2D isotropic counterparts, under linearly polarized excitations along the crystal axis with relatively smaller (larger) effective carrier masses. This anisotropy leads to dramatically different excited states than the isotropic exciton. The X exciton binding energy (BE) depends strongly on the dielectric environment and shows good agreement with previously published data. IX excitons, the oscillator strength and absorption coefficient increase as the interlayer separation increases. Notably, due to the non-trivial relationship between the anisotropic effective masses and their effect on the optical properties of excitons, we proposed that *in-situ* modification of the effective carrier masses via e.g. mechanical strain could be used to great effect to manipulate the optical properties of excitons in phosphorene.
5. We study how the BCS-like superfluid an electron-hole plasma (EHP) phase transition can be controlled by the external periodic field. The main goal of this research is to analyze the influence of the external periodic field on the critical temperature of the EHP-superfluid transition of indirect excitons formed in a double layer of TMDC.

We propose controlling an electron-hole superfluid in semiconductor coupled quantum wells and double layers of a 2D material by an external periodic field. This can be created either by the gates periodically located and attached to the quantum wells or double layers of the 2D material or by the moiré pattern of two twisted TMDC layers. In Figure a schematic electrode pattern in the *x*-*y* and *z*-*x* plane is presented. The dependence of the electron-hole pairing order parameter on the temperature, the charge carrier density, and the gate parameters is obtained by minimization of the mean-field free energy. The second-order phase transition between superfluid and

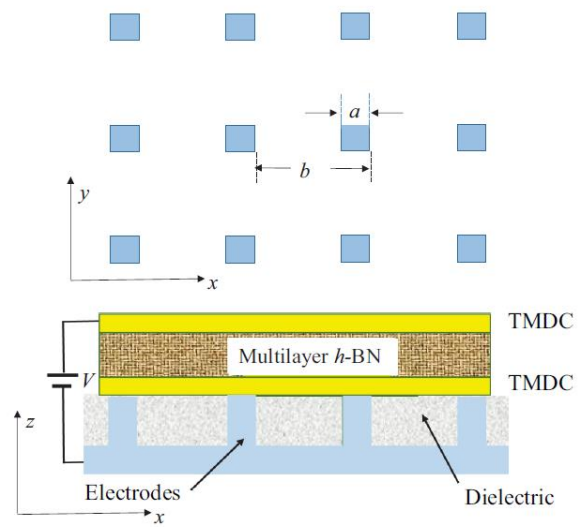


FIGURE Schematic electrode pattern in the *x*-*y* and *z*-*x* planes.

electron-hole plasma, controlled by the external periodic gate field, is analyzed for different parameters. This study was published in Ref. [5].

6. In Ref. [6] we predicted the spin Hall effect for polaritons (SHEP) in a TMDC monolayer embedded in a microcavity. We demonstrate that two counterpropagating laser beams incident on a TMDC monolayer can deflect a superfluid polariton flow due to the generation the effective gauge vector and scalar potentials. The components of polariton conductivity tensor for both noninteracting polaritons without BEC and for weakly interacting Bose gas of polaritons in the presence of BEC and superfluidity are obtained. It is shown that the polariton flows in the same

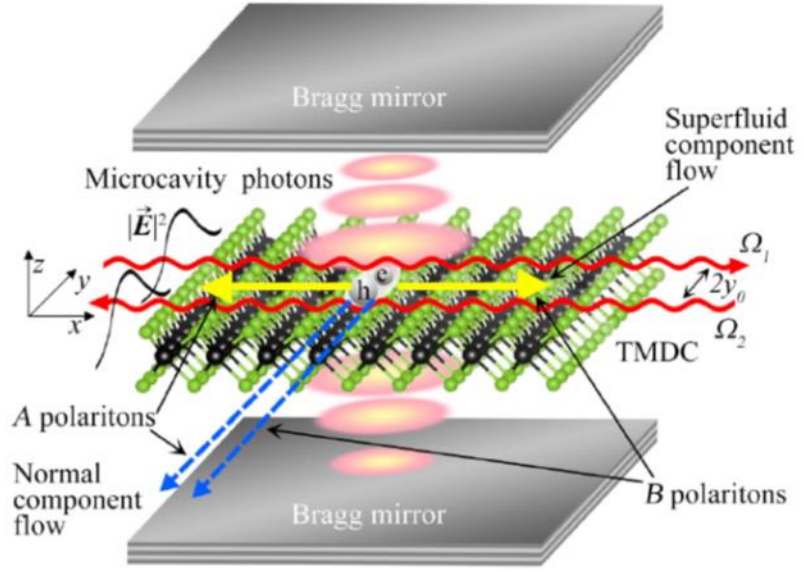


FIG. 1. Schematic representation of the light-induced spin Hall effect for polaritons in a TMDC monolayer embedded in a microcavity. The solid and dashed lines with arrows show the directions of deflected superfluid and normal flows of A and B polaritons, correspondingly. Two counterpropagating laser beams are shown by waved lines.

valley are splitting: the superfluid components of the A and B polariton flows propagate in opposite directions along the counterpropagating beams, while the normal components of the flows slightly deflect in opposite directions and propagate almost perpendicularly to the beams as shown in Fig. 1. The possible experimental observation of SHEP in a microcavity is proposed.

7. We examine the occurrence of Bose-Einstein condensation and superfluidity of dipolar excitons for a pair of quasi-two-dimensional spatially separated hexagonal α - T_3 layers. In the α - T_3 model, the AB-honeycomb lattice structure is supplemented with C atoms, located at the centers of the hexagonal lattice. We have solved a two-body problem for an electron and a hole for the model Hamiltonian for the α - T_3 double layer in a magnetic field. The exciton binding energy is changed due to the magnetic field, and magnetoexcitons are formed as excitons in a MF. The energy dispersion of collective excitations, the spectrum of sound velocity, and the effective magnetic mass of magnetoexcitons are obtained in the integer quantum Hall regime for high MFs. The superfluid density and the temperature of the Kosterlitz-Thouless phase transition are probed as functions of the excitonic density, the magnetic field, and the interlayer separation. This study was published in Ref. [7].
8. We predict BEC and superfluidity of dipolar excitons, formed by electron-hole pairs in spatially separated gapped hexagonal α - T_3 (GHAT3) layers in Ref. [8]. We considered the α - T_3 model in the presence of a mass term which opens a gap in the energy dispersive spectrum. The gap opening mass term, caused by a weak magnetic field, plays the role of Zeeman splitting at low magnetic fields for this pseudospin-1 system. The band structure of GHAT3 monolayers leads to the

formation of two distinct types of excitons in the GHAT3 double layer. We consider two types of dipolar excitons in double-layer GHAT3: (a) “A excitons”, which are bound states of electrons in the conduction band (CB) and holes in the intermediate band (IB) and (b) “B excitons”, which are bound states of electrons in the CB and holes in the valence band (VB). The BE of A and B dipolar excitons is calculated. For a two-component weakly interacting Bose gas of dipolar excitons in a GHAT3 double layer, we obtain the energy dispersion of collective excitations, the sound velocity, the superfluid density, and the mean-field critical temperature T_c for superfluidity.

9. In Ref. [9] predict angle-dependent superfluidity for a new class of 2D materials: transition metal trichalcogenides (TMTC). Within a mean-field approach superfluidity of indirect excitons in TMTC van der Waals heterostructures (vdWHs) is studied. We use different potentials for charged carrier interaction to analyze the influence of the screening on the studied phenomena. Our study demonstrates the angle-dependent superfluidity temperature in TMTC vdWHs: for a given density a maximum and minimum T_c of superfluidity occurs along the chain and a directions, respectively. This work can guide experimental research toward the realization of anisotropic superfluidity in TMTC vdWH. We suggest an experiment for the observation of anisotropic superfluidity in TMTC vdWH. The schematic plan view of experiment is shown in Fig. 2.
10. We study the effect of a uniform pseudomagnetic field, induced by a strain in a monolayer and double layer of gapped graphene, acting on excitons [10]. For our analysis it is crucial that the pseudomagnetic field acts on the charges of the constituent particles of the excitons, i.e., the electrons and holes, the same way in contrast to a magnetic field. Moreover, using a circularly polarized laser field, the electrons and the holes can be excited only in one valley of the honeycomb lattice of gapped graphene. This breaks the time-reversal symmetry and provides the possibility to observe the various Quantum Hall phenomena in this pseudomagnetoexciton system. Our study poses a fundamental problem of the quantum Hall effect for composite particles and paves the way for quantum Hall physics of pseudomagnetoexcitons.
11. Recently discussed topological materials Weyl-semimetals (WSs) are characterized by broken time-reversal or inversion symmetry and combine both: high

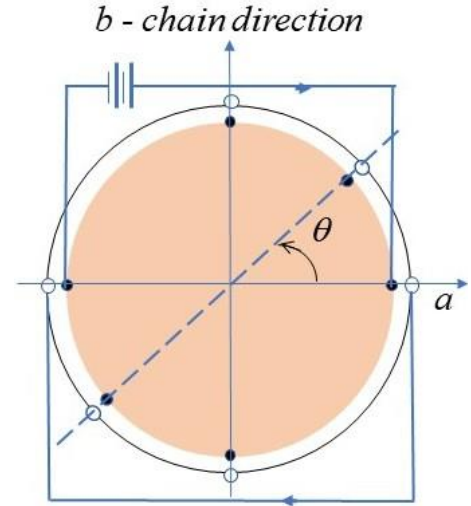


Fig. 2. A schematic plan view for a suggested experiment. The “active” and parallel “passive” layers are shown as shaded and white areas, respectively. Filled and open dots indicate contacts to the “active” and “passive” layers, respectively.

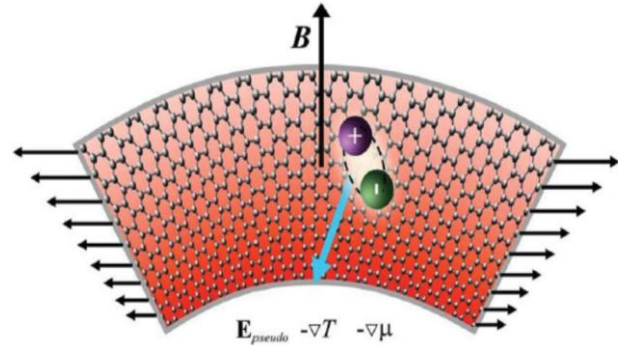


Fig. 3. Conceptual picture of the quantum Hall effect of PME in graphene. The QHE PME flow, shown by the blue arrow, is generated by the PMF $\mathbf{B}$, normal to the graphene layer, and a pseudoelectric field $\mathbf{E}_{\text{pseudo}}$ or $-\nabla T$, or $-\nabla \mu$, directed along the graphene layer. The QHE PME flow in the graphene layer is directed normal to $\mathbf{E}_{\text{pseudo}}$ or $-\nabla T$, or $-\nabla \mu$. The strain is created by the normal forces applied at two opposite boundaries and their magnitude is gradually decreased, which is indicated by the length of the plotted arrows.

electron mobility comparable with graphene and unique topological protection of Dirac points. We present novel results related to electromagnetic field propagation through WSs. It is predicted that transmission of the normally incident polarized electromagnetic wave (EMW) through the magnetic WS strongly depends on the orientation of polarization with respect to a gyration vector $\mathbf{g}$. The latter is related to the vector-parameter, which represents the separation between the Weyl nodes of opposite chirality in the first Brillouin zone. By changing the polarization of the incident EMW with respect to the gyration vector $\mathbf{g}$ the system undergoes the transition from the isotropic dielectric to the medium with Kerr-or Faraday-like rotation of polarization and finally to the system with chiral selective electromagnetic field. It is shown that WSs can be applied as the polarization filters. This research is published in [Ref. \[11\]](#).

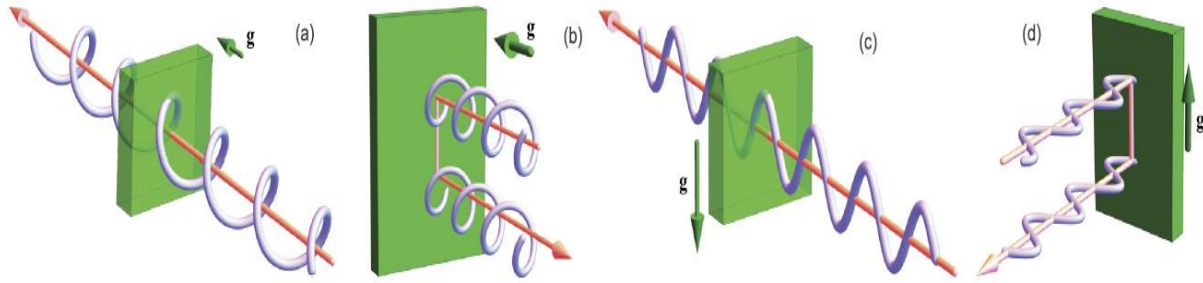


Fig. 4. (Color online.) The figure schematically shows the filtering of light by polarization by the Weyl semimetal depending on the direction of the gyration vector $\mathbf{g}$ (shown by green arrows). In (a) and (b) $\mathbf{g}$ and $\mathbf{k}$ are parallel. Then EMWs (a) transmit through WS for one chirality (type of circular polarization); (b) reflect for the other chirality (opposite circular polarization). In (c) and (d) $\mathbf{g}$ and $\mathbf{k}$ are perpendicular. Then EMWs (c) transmit for collinear with $\mathbf{g}$ linear polarization and (d) reflect otherwise.

12. We studied X^- and X^+ trions in 3D, 2D and 1D SCs: bulk, TMDC monolayers and nanowires (NW). We show that a decrease of degrees of freedom in a system, decreases the system kinetic energy and reduces a screening. The combinations of two effects leads to 2D and 1D bound trions because with the reduction of dimensionality the kinetic energy decreases faster than the potential energy while in 3D X^- is bound and X^+ is unbound. Thus, lowering the dimensionality of the system makes the effects of interaction in trions more pronounced, resulting in an increase in BEs of trions [12]. We consider the formation of trions and biexcitons in NW under the action of both the lateral confinement and the localization potential [13]. Our calculations for the ZnO/ZnMgO, CdSe/ZnS and CdSe/CdS core/shell cylindrical shaped NWs show that the trion and biexciton binding energy in NWs are size-dependent and for the same input parameters the biexciton binding energy in NWs is always larger than the binding energy of the trion. The trion and biexciton remain stable in CdSe/ZnS NW with the increase of the dielectric shell, while in ZnO/ZnMgO NW they become unstable when the surrounding dielectric shell exceeds 2.5 nm and 2 nm for each, respectively. Based on the results for size dependence of biexciton binding energy and probability associative ionization an optimal radius for optoelectronic application NW is suggested [13].
13. We published review article [14] that is focuses on the studies and computations of few-body systems of electrons and holes in condensed matter physics. We analyze and illustrate the application of a variety of methods for description of two- three- and four-body excitonic complexes such as an exciton, trion and biexciton in three-, two- and one-dimensional configuration spaces in various types of materials.

14. We analyze collective properties of interlayer trions and predict strongly correlated phases. Throughout the years, strongly correlated coherent states of excitons have been the subject of intense theoretical and experimental studies. This topic has recently boomed due to new emerging quantum materials such as van der Waals bound atomically thin layers of transition metal dichalcogenides. We analyze the collective properties of charged interlayer excitons shown in Fig. 5 and observed recently in bilayer TMDC heterostructures. We predict strongly correlated phases—crystal and Wigner crystal—that can be selectively realized with TMD bilayers of properly chosen electron-hole effective masses by just varying their interlayer separation distance. Our results can be used for nonlinear coherent control, charge transport and spinoptronics application development with quantum vdW heterostructures. The study is published in [15].
15. The prediction of supefluidity [9] was required the knowledge of IXs excitons interaction in 2D space. We derive the explicit analytical form for the charge-dipole and dipole-dipole interactions in 2D configuration space [16]. We demonstrate that the reduction of dimensionality can alter the charge-dipole and dipole-dipole interactions in the 2D case. The asymptotics of these interactions at long distances coincide to the charge-dipole and

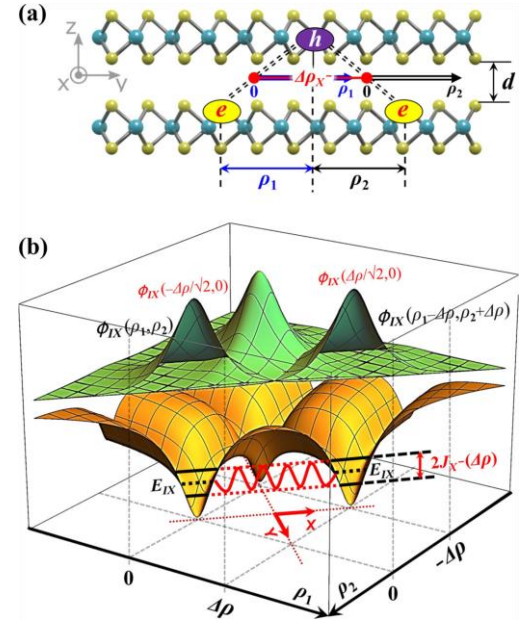


Fig. 5. Configuration space view. (a) The structure of a negatively charged IXs complex in a TMDC bilayer of the interlayer separation d . (b) The same structure in the orthogonal configuration space of the two equivalent independent IXs excitons separated by the center-of-mass-to-center-of-mass distance. From Ref. 15.

The asymptotics of these interactions at long distances coincide to the charge-dipole and

dipole-dipole interactions in three-dimensional configuration space. The obtained charge-dipole and dipole-dipole interactions will find wide application and contribute to the advancement of research on novel two-dimensional materials.

16. Exciton-dipolaritons are investigated as a platform for realizing working elements of a polaritonic transistor. Exciton-dipolaritons are three-way superposition of cavity photons, direct and indirect excitons in a bilayer semiconducting system embedded in an optical microcavity [17]. Using the forced diffusion equation for dipolaritons, we study the room-temperature dynamics of dipolaritons in a TMDC heterogeneous bilayer. Specifically, we considered a $\text{MoSe}_2\text{-WS}_2$ heterostructure, where a Y-shaped channel guiding the dipolariton propagation is produced. We demonstrate that polaritonic signals can be redistributed in the channels by applying a driving voltage in an optimal direction. Our findings open a route towards the design of an efficient room-temperature dipolariton-based optical transistor.
17. Using a computational approach based on the driven diffusion equation for dipolariton wave packets, we simulate the diffusive dynamics of dipolaritons in an optical micro-cavity embedded with a TMDC heterogeneous bilayer encompassing a Ψ -shaped channel. By considering exciton-dipolaritons, which are a three-way superposition of direct excitons, indirect excitons, and cavity photons, we are able to drive the dipolaritons in our system by the use of an electric voltage and investigate their diffusive properties.

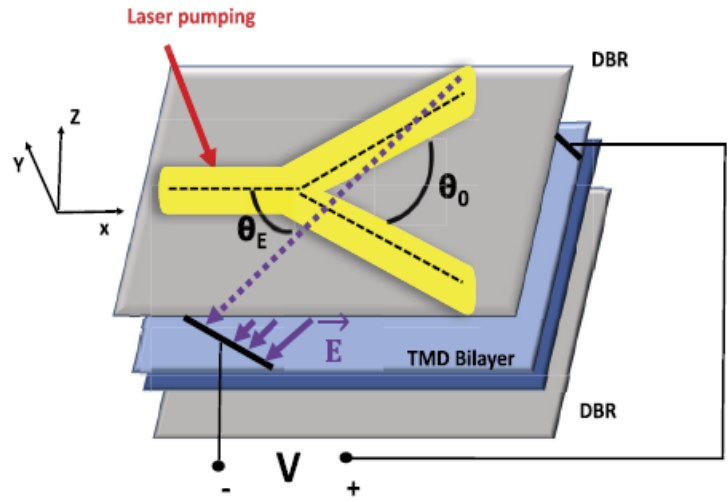


Fig. 6. Schematic of a TMD heterogeneous bilayer embedded inside an optical microcavity with a Y-shaped channel guiding the dipolaritons. The opening angle of the channel is $\theta_0 = 30$ and the direction of the field E generated by an external voltage applied to the bilayer is defined by an angle θ_E between the field vector and the direction of the stem of the Y-shaped channel. The direction of the electric driving force applied to the dipolaritons is opposite to the direction of the electric field. Distributed Bragg Reflectors (DBR) are placed between the TMD bilayer and laser pumping is applied to generate dipolaritons, at the beginning of the stem of the channel at which point they propagate along the x -axis towards the junction under the action of the electric field E .

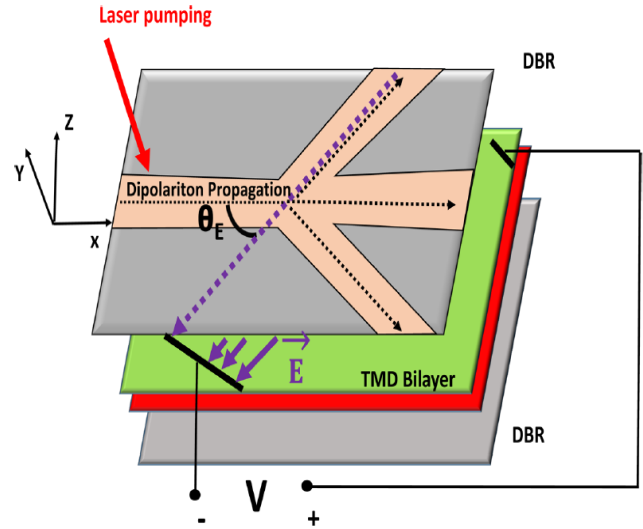


Fig. 7. (Color online) Schematic of a TMD heterogeneous bilayer embedded inside an optical microcavity with a Ψ -shaped channel guiding the dipolaritons. The opening angle of the channel relative to the middle branch is $\theta_0 = 30$ and the direction of the field E generated by an external voltage applied to the bilayer is defined by an angle θ_E between the field vector and the direction of the stem of the Ψ -shaped channel. The direction of the electric driving force applied to the dipolaritons is opposite to the direction of the electric field. Distributed Bragg Reflectors (DBR) are placed between the TMD bilayer and laser pumping is applied to generate dipolaritons, at the beginning of the stem of the channel at which point they propagate along the x -axis towards the junction under the action of the electric field E .

More precisely, we study the propagation of dipolaritons present in a MoSe₂-WS₂ heterostructure, where the dipolariton propagation is guided by a Ψ -shaped channel. We also consider the propagation of dipolaritons in the presence of a buffer in the Ψ -shaped channel and study resulting changes in efficiency. We introduce designs for optical routers at room-temperature as well as show that system parameters including driving forces of 2.0 eV/mm and electric field angles of 60° optimize the dipolariton redistribution efficiencies in our channel guide. This study is published in Ref. [18].

18. In the circle of the work [19-21], we studied the formation of magnetoexcitons in novel 2D monolayers, bilayers and van der Waals heterostructures (vdW). In particular, we investigated X and IX magnetoexcitons in Rydberg states in monolayers and vdW heterostructures of TMDC and Xenes in an external parallel electric and magnetic fields, applied perpendicular to the monolayer and heterostructure. We report the MF energy contribution to the binding energies and diamagnetic coefficients (DMCs) for X and IX magnetoexcitons for the Rydberg states, 1s, 2s, 3s, and 4s. The tunability of the BE of X and IX magnetoexcitons in TMDC by the magnetic field is demonstrated [19,21]. The calculations of the BEs and DMCs of indirect magnetoexcitons in TMDC heterostructures are novel and can be compared with the experimental results when they are available. We report the energy contribution from electric and magnetic fields to the BEs and DMCs in Xenes. The tunability of the energy contribution of X and IX magnetoexcitons by electric and magnetic fields in Xenes is demonstrated. Both the BEs and DMCs for TMDC and Xenes can be manipulated by the number of hBN layers. The calculations of the binding energies and DMCs of magnetoexcitons in Xenes monolayers and heterostructures are novel and can be compared with the experimental results when they will be available. Our studies demonstrated the possibility of electronic devices design that can be controlled by external electric and magnetic fields and the number of hBN layers.
19. In Refs. [22,23] our research was extended to the study of the formation of X and IX magnetoexcitons in Rydberg states in mass anisotropic materials such as phosphorene and transition metal trichalcogenide monolayers, bilayers, and vdW heterostructures in an external magnetic field within the framework of the effective mass approximation. The magnetic field is applied perpendicular to the monolayer or heterostructure and is varied between 0 and 60 T. The theoretical formalism for study of X and IX with anisotropic electron and hole masses was developed and BEs and DMCs of magnetoexcitons are calculated. We report the magnetic field energy contribution to the BEs and DMCs for X and IX magnetoexcitons, which depend strongly on the effective anisotropic masses of electrons and holes and can be tuned by the external magnetic field. The comparative study of TMTCs and phosphorene is given. In TiS₃, TiSe₃, and ZrSe₃ the excitonic binding energies and DMCs demonstrate the same kind of anisotropy as in phosphorene. In contrast, ZrS₃ has the opposite anisotropy to phosphorene. The tunability of the BEs of X and IX magnetoexcitons by the external magnetic field and the possibility to control the binding energy of magnetoexcitons in vdW heterostructures by manipulation of numbers of hBN monolayers are shown. Our calculations in Refs. [19-23] are performed using the Rytova-Keldysh (RK) potential for direct magnetoexciton and both the RK and Coulomb potentials for indirect excitons. The latter allows understanding the role of screening in TMDCs heterostructures. Our studies [19-23] raise the possibility of controlling the binding energies of X and IX magnetoexcitons in isotropic (TMDC, Xenes) and anisotropic (phosphorene and TMTC) monolayers, bilayers, and vdW heterostructures using magnetic field and opens an additional

degree of freedom to tailor the binding energies and DMCs for heterostructures by varying the number of hBN sheets between TMDC, Xenes, TMTC and phosphorene layers.

20. Within the grant funding we consider the problem of quantum entanglement and computations which is not directly related to the proposal of the grant but was motivate us to address this problem due to recent development in this field and applicability of our methods used in the grant. Therefore, the results of our theoretical research can support the quantum information transfer and processing. In Ref. [24] we consider a system composed of two quantum-dot qubits coupled with a common, damped surface plasmon mode; each quantum dot is also coupled to a separate photonic cavity mode. Cavity quantum electrodynamics calculations show that upon optical excitation by a femtosecond laser pulse, entanglement of the quantum-dot excitons occurs, and the time evolution of the pair correlation function of the cavity photons is an indicator of the entanglement. We also show that the degree of entanglement is conserved during the time evolution of the system. Furthermore, if coupling of the photonic cavity and quantum-dot modes is large enough, the quantum-dot entanglement can be transferred to the cavity modes to increase the overall entanglement lifetime. In Ref. [25] the dynamical Lamb effect is predicted to arise in superconducting circuits when the coupling of a superconducting qubit with a resonator is periodically switched “on” and “off” nonadiabatically. We show that by using a superconducting circuit which allows one to switch between longitudinal and transverse coupling of a qubit to a resonator, it is possible to observe the dynamical Lamb effect. The dynamics of qubits coupled to a harmonic oscillator with time-periodic coupling is investigated in the framework of Floquet theory [26]. Excellent quantitative agreement is found between the analytical and numerical calculations within the Floquet approach, demonstrating the effectiveness of the technique for the study of the dynamical Lamb effect. This system can be used to model nonadiabatic phenomena that require a periodic modulation of the qubit/oscillator coupling and to model nonadiabatic phenomena and support quantum information transfer and processing. In Ref. 27 the quantum entanglement between two excitons in two-dimensional materials, embedded in an optical microcavity, was investigated. The energy eigenstates of a Jaynes-Cummings like Hamiltonian for two qubits coupled to a single cavity mode have been calculated. According to the results of our calculations, if the system is allowed to decay only through the emission of cavity photons at low temperatures, then there is a maximally entangled eigenstate, protected from decay. We demonstrated that the existence of such a state results in the counterintuitive conclusion that, for some initial states of the system,

the fact that the cavity is leaky can actually lead to an increase in the average concurrence on the timescales of the average photonic lifetime.

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The references present the published paper with acknowledgement to the grant

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III Training

The Grant supported nine Graduate students: Matthew Brunneti, Mirko Amiko, Anastasia Spiridonova, Gabriel Martins, Andrew Dublin, Patrick Serafin, Shaina Raklyar, Yamuna Paudel, Tom Brick. These students are mentored by Profs. Kezerashvili, Berman and Kolmakov.

The graduate students Matthew Brunneti, Mirko Amiko, and Patrick Serafin had defended of their PhD dissertation is 2020, 2021 and 2022, respectively.

The grad student Anastasia Spiridonova finalized her Ph.D. dissertation, and the expectation defense of her PhD thesis is early February 2023. The expectation defense of Gabriel Martins PhD dissertation is December 2023 - February 2024.

Seven undergraduate students STEM major Mubinjon Satymov, Patrice Prosper, Jorge Bermeo, Olga Privman, (Major Applied Computational Physics) and Shaina Raklyar (Major: Bioinformatics) Xu Lu, Li Alan (Major: Computer Science) had training in novel two denominational materials and applications.

During the grant period we had 40 seminars given by experts from different USA universities and universities from Europe. Seminar were given for City Tech physics faculty, graduate students and undergraduate students. These seminars are given through the Center for Theoretical Physics and represented the excellent training for graduate and undergraduate students as well as professional development for faculty. Graduate students from other CUNY campuses and Faculty working in solid state physics from other CUNY campuses also joined our seminars. The seminars have held in person and online. During pandemic period all seminars were given via the ZOOM platform.

Since October 2018

1. Dr. Javad Shabani, Superconducting proximity effect in two-dimensional semiconductor-superconductor structures, New York University, New York, NY, USA
2. Dr. David C. McKay, Calibrating, Characterizing and Applying Quantum Circuits, IBM T.J. Watson Research Center, Yorktown Heights, NY, USA
3. Prof. Leonid Glazman, Quantum Many-Body Physics of Qubits, Yale University

4. New Haven, CT, USA
5. Dr. Sriram Ganeshan, Odd surface waves in two-dimensional incompressible fluids, City College, CUNY, New York, NY, USA
6. Prof. Christopher C. Gerry, Entanglement Enhanced Quantum Interferometry and Sensing, Lehman College, CUNY Bronx, NY, USA
7. Prof. Steven M. Girvin, Schrödinger's Cat meets Maxwell's Demon:
8. Quantum Error Correction (That Works), Yale University, New Haven, CT, USA

2019

9. Prof. Junichiro Kono, Ultrastrong Light-Matter Coupling: Dicke Phenomena in Condensed Matter, Rice University, Houston, Texas, USA
10. Prof. Klaus Ziegler, Quantum-Hall phases created by electron-phonon interaction, University of Augsburg, Germany.
11. Prof. Jacob Khurgin, Polaritonics in 2 and 3 Dimensions, Johns Hopkins University
12. Prof. Vinod Menon, Control of light-matter interaction in 2D materials, City College, CUNY.
13. Dr. Alexey Galda, "Exceptional points in non-Hermitian spin dynamics", James Franck Institute, University of Chicago,
14. Dr. Andrii Iurov, "Collective phenomena and transport for optically-induced electron dressed states in α - T_3 materials", Medgar Evers College, CUNY, December 12, 2019.

2020

15. Dorri Halbertal, "Novel nano-imaging techniques for probing electronic properties in graphene devices", Columbia University, February 20, 2020.
16. Héctor Romillo, "Chiral optical response of moiré insulators", Columbia University, May 14, 2020.
17. Dr. Gabriele Grosso, "2D materials for optoelectronics and quantum applications", Graduate Center, CUNY, Thursday, May 21, 2020
18. Prof. Michael Schulz, Few-Body Dynamics and Coherence Effects in Simple Atomic Systems, Missouri University of Science and Technology, September 17, 2020.
19. Prof. David Snoke, A possible path to room temperature superconductivity via charged excitonic complexes in two-dimensional materials, University of Pittsburgh, September 24, 2020.
20. Prof. Klaus Ziegler, Pairing transition in interacting electronic double layers, Institut fuer Physik, Universitaet Augsburg, Augsburg, Germany, October 8, 2020.
21. Prof. Philip Phillips, Beyond BCS: An Exact Model for Superconductivity and Mottness, University of Illinois, Urbana Champaign, October 15, 2020.

2021

22. Prof. Alexey Chernikov, Mobile optical excitations in 2D materials, Department of Physics, Dresden University of Technology (TU Dresden), Germany
23. Dr. Marcin Szyniszewski, Entanglement transitions in random quantum circuits, ULC - University of London, UK
24. Dr. Mohammad Zarenia, Hydrodynamic Transport in Graphene Systems, Center for Imaging Research, Medical College of Wisconsin
25. Prof. Andrea Alù, Optical Metamaterials Based on Broken Symmetries, Photonics Initiative, Advanced Science Research Center, City University of New York.
26. Dr. Neil Drummond, Quantum Monte Carlo studies of excitonic charge-carrier complexes in two-dimensional transition-metal dichalcogenides, Lancaster University, Department of Physics, UK,

2022

27. Prof. Shaul Mukamel, Ultrafast nonlinear spectroscopy of elementary molecular events with quantum light and in optical cavities, University of California, Irvine
 28. Prof. Steven Simon, Topologically Ordered Matter and Why You Should be Interested, Oxford University, UK
 29. Prof. Michael Fogler, Polaritons in van der Waals nano-materials, University of California San Diego
 30. Prof. Andrey Varlamov, Fluctuation spectroscopy: From Rayleigh-Jeans waves to Abrikosov vortex clusters, Institute of Superconductivity and Innovative Materials (SPIN-CNR), Rome, Italy
 31. Prof. Federico Camia, From conformal field theory to Brownian loops... and back, New York University AD Campus and Courant Institute
 32. Prof. Lev Deych, Effects of confinement and degeneracy on optomechanical interaction between whispering-gallery-modes and a nanoparticle: old results and new ideas, Department of Physics, Queens College CUNY.
 33. Dr. Ipsita Mandal, Emergent Collective Phenomena in Many-Body Systems, Institute of Nuclear Physics, Polish Academy of Sciences, Poland.
 34. Dr. Maxim Trushin, Optoelectronic and Biomimetic Properties of Layered Materials with Mutual Interactions, The Institute for Functional Intelligent Materials National University of Singapore.
 35. Prof. Giovanni Vignale, Quantum continuum mechanics and quantum incompressibility of electron-hole bilayers, The Institute for Functional Intelligent Materials National University of Singapore.
 36. Prof. Leonid V. Butov, Indirect Excitons, University of California at San Diego, November 10
 37. Prof. Mark Dykman, Resonant time-symmetry breaking in classical and quantum oscillators, Michigan State University.
 38. Prof. Yuri Lvov, Fermi Pasta Ulam Tsingou chain: Thermalization and anomalous conduction, Rensselaer Polytechnic Institute.
 39. Prof. Irinel Chiorescu, Engineering quantum coherence and control in diluted spin systems, Florida State University and the National High Magnetic Field Laboratory.
-
1. Four undergraduate students STEM major, Olga Privman, Patrice Prosper, Jorge Bermeo, (Major Applied Computational Physics) and Shaina Raklyar (Major: Bioinformatics) had training in novel two denominational materials and applications.
 2. We had 5 seminars given by experts from different universities. Seminar were given for physics faculty, graduate students and undergraduate students. These seminars are given through the Center for Theoretical Physics and represent the excellent training for graduate and undergraduate students and professional development for faculty.

IV Dissemination

Publications

Results of Grant activities and accomplishments were published in 26 peer review articles and on book chapter in most prestigious journals:

Physical Review A – 2 articles. *Impact Factor 2.971 (2021)*

Physical Review B – 11 articles. *Impact Factor 3.908 (2021)*

Physical Review Research - 3 articles *Impact Factor 3.9 (2021)*

Physics Letters A – 4 articles *Impact Factor 2.654 (2022)*

Scientific report – 1 article *Impact Factor 4.996 (2021)*

Nanomaterials – 1 article *Impact Factor 5.719 (2021)*

Journal of Physics B Atomic, Molecular Optics – 1 article. *Impact Factor 1.917 (2021)*

International Journal of Modern Physics B – 1 article. *Impact Factor 1.219 (2021)*

Communication Physics – 1 article. *Impact Factor 6.368 (2022)*

Few Body System – 1 article. *Impact Factor 1.362 (2022)*

Physica E Low-dimensional Physics and Nanostructures – 1 article. *Impact Factor 3.382 (2022)*

The Presentations at International and National conferences

During the grant period Undergraduate, Graduate and Faculty made 30 presentations at **American Physical Society March Meetings** with published abstracts.

2019

A15.00008 [The stable trion states in 2D WSe₂ monolayer](#)

A26.00015 [Quantum entanglement dynamics due to dynamical Lamb effect](#)

C12.00005 [Tunable Optical Absorption by Excitons in Xenon via an External Electric Field](#)

G70.00278 [Laplace transform approach for the dynamics of \$N\$ qubits coupled to a resonator](#)

S16.00007 [Spin Hall effect for polaritons in a TMDC monolayer embedded in a microcavity](#)

T70.00287 [Are freestanding Xenon monolayers excitonic insulators in their ground state?](#)

V15.00012 [Study of dipolar excitons in TiS₃ double layer](#)

A27.00003 [Optical manipulation of entanglement in plasmonically coupled quantum dot qubits](#)

G70.00350 [Emission of entangled photons via the biexciton formation and decay in core/shell nanoplatelets](#)

2020

C71.00386 [Floquet approach to the study of the dynamical Lamb effect](#)

J62.00005 [Can trions crystallize in TMDC monolayers?](#)

J62.00007 [Electron-hole superfluidity controlled by a periodic potential in double layers of two-dimensional material](#)

M07.00014 [Dynamical Lamb effect in a superconducting circuit](#)

H71.00201 [Dipolar Magnetoexcitons in \$\alpha\$ -T₃ double layers in a high magnetic field](#)

M07.00014 [Dynamical Lamb effect in a superconducting circuit](#)

H71.00094 [Polariton Optical Transistor based on a MoSe₂-WS₂ Heterogeneous Bilayer embedded in an Optical Microcavity at Room Temperature](#)

H71.00096 [Polariton Formation and Propagation in an Optical Microcavity with Embedded Transition Metal Dichalcogenide with Disorder](#)

2021

- C55.00006 [Strain induced quantum Hall phenomena of excitons in graphene](#)
- F41.00012 [Magnetoexcitons in Transition-Metal Dichalcogenides Monolayers and Double-Layer Heterostructures](#)
- M56.00002 [Crystal phases of charged interlayer excitons in van der Waals heterostructures.](#)
- M56.00006 [Rydberg Excitons in buckled two-dimensional materials in presence of parallel magnetic and electric fields](#)
- F56.00010 [Driven dipolariton transistors using van der Waals TMDC with channel guides](#)
- U71.00077 [Dipolariton propagation in a van der Waals TMDC with \$\Psi\$ -shaped channel guides and buffered channel branches.](#)
- U71.00112 [Multi-Layered Structures for Low-Temperature Low-Energy Optical Interconnects for Quantum Computers](#)
- U71.00063 [Superfluidity of dipolar excitons in a double layer of alpha-T3 with a mass term](#)
- U71.00094 [Quantum entanglement between two excitons in graphene under strain](#)

2022

- F55.00001 [Excitons and magnetoexcitons in transitional metal trichalcogenides and phosphorene](#)
- G66.00007 [Magnetoexcitons in phosphorene monolayer, bilayer, and van der Waals heterostructure](#)
- M57.00003 [Superfluidity of a two-component Bose gas of dipolar excitons in a double layer of gapped hexagonal alpha-T3](#)
- T00.00125 [Polaritonic and Excitonic Bose Einstein Condensates in a Periodic Potential](#)

- One oral and two poster presentations at the conference: Universal Themes of Bose-Einstein Condensation, UBEC 2019, April 1-5, 2019, to Pittsburgh, PA, USA. <https://www.pgi.org/events/universal-themes-bose-einstein-condensation-conference-ubec-2019>
- Poster and Oral presentations at Department of Defense MURI Review Meeting, Ann Harbor, MI, Oct 7-8, 2019.
- Four oral presentations at the International School and Workshop on Two-Dimensional Crystals and Photonics, September 9-14, 2019, Tbilisi Georgia. <https://events.mifp.eu/2dcp-2019/> Abstracts published.
- Invited oral talk at The Sixth Conference on MESOSCOPIC Physics (NMP22) that held at the at [Michigan State University East Lansing](#), Michigan, USA, May 23-27, 2022. <https://indico.frib.msu.edu/event/17/> Abstracts published.
- Invited lecture and oral presentation at International School and Conference on Functional Materials for Modern Technologies ISCFMMT October 1-7, 2022, Batumi, Georgia October 1-7 2022, <https://iscfmmt2022.tsu.ge/> Abstracts published.
- Undergraduate and Graduate students presented poster report “Polariton Propagation and Exciton Phase Correlations in an Optical Microcavity with Embedded Topologically-

Disconnected Transition Metal Dichalcogenide Microflakes” at the Materials Science Research Society Fall Meeting, MRS Fall-2019, Boston, MA, Dec 1-6, 2019
<https://www.mrs.org/meetings-events/fall-meetings-exhibits/past-fall-meetings/2019-mrs-fall-meeting> Abstracts published.

Seminars

Research group members gave 5 seminars: 3 seminars at different at City University of New York colleges and at North Carolina Central University and Florida State University.

Seminar at National High Magnetic Field Laboratory: Roman Kezerashvili, Magnetoexcitons in novel 2D monolayers and van der Waals heterostructures. <https://nationalmaglab.org/news-events/events/calendar/3327>

Dissemination on the local level. New York City College of Technology, City University of New York

- 1) Undergraduate and Graduate students and Faculty made 12 poster presentations at **City Tech Annual Poster session for faculty and students research**
<https://www.citytech.cuny.edu/annual-poster/>
- 2) Graduate students made 8 poster presentations at the **Poster Sessions at the Graduate Center, City University of New York**

V. Honors and Awards

1. Grad student Mirko Amico won the CUNY Graduate Center dissertation fellowship competition and obtained Doctoral Student Research Grant in 2019, \$10k.
2. Anastasia Spiridonova won the award for the best poster at 18th Annual Poster Session of Faculty and Student Research at the New York City College of Technology.
3. Grad student Anastasia Spiridonova won the CUNY Graduate Center dissertation fellowship competition and obtained Doctoral Student Research Grant in 2022, \$10k.
4. PSC Grant Award. “Trion in Monolayer Transition Metal Dichalcogenides: Faddeev Equations and Hyperspherical Harmonics Approaches”, PI Roman Ya. Kezerashvili, Award #61188-00 49, \$3.5k
5. PSC Grant Award. Properties of Microcavity Polaritons in Heterostructures, Formed by Novel Two-Dimensional Materials, PI Oleg L. Berman, Award # TRADB-52-130, \$6k
6. Advanced Science Research Center Seed Program grant award “Exciton polariton-mediated conversion of microwave radiation to optical pulses”, PI Kolmakov, together with M. Begliarbekov and G. Grosso (ASRC), Research Foundation CUNY award #95663-00 01, August 1, 2021-July 31, 2022, \$20k.
7. Matthew Brunetti got Ph.D. The defense of Ph.D. thesis "Optical and Collective Properties of Excitons in 2D Semiconductors" was on August 28, 2019.
8. Mirko Amico got Ph.D. The defense of Ph.D. thesis "Generating entanglement with the dynamical Lamb effect" was on March 20, 2020.
9. Patrick Serafin got Ph.D. The defense of Ph.D. thesis "Driven Dipolaritons in Van der Waals Transition Metal Dichalcogenide Heterostructures: Properties and Applications" was on June 24, 2022.

VI. Travel which was supported by the grant

- All travels within USA for Graduate students and faculty were supported by the Grant. Particularly travel for participation on American Physical Society March Meetings, the MURI Review Meeting, Ann Arbor, MI, Oct. 7-8, 2019, the Materials Science Research Society Fall Meeting, MRS Fall-2019, Boston, MA, Dec 1-6, 2019 and the Sixth Conference on MESOSCOPIC Physics (NMP22) that held at the at Michigan State University East Lansing, Michigan, USA, May 23-27, 2022. Grand supported the trips to Pittsburgh, PA, for the conference: Universal Themes of Bose-Einstein Condensation, UBEC 2019, April 1-5, 2019, Department of Defense MURI Review Meeting, Ann Harbor, MI, Oct 7-8, 2019.
- Due to the COVID 19 pandemic we did not spend all allocated funds for 2020-2021 Academic Year. Grant supported participation at APS March 2021 meeting through the payments of registration fees.
- Grant supported participation of the graduate students and key personal at APS March 2022 meeting through the payments of registration fees and travel at the Meeting site.

VII Website

The website gives an overview of the group's research focus, the projects the group will be working on, the research published by each member of the group, the conferences where the work was presented and the members of the group. By visiting the website, the public can see what the general line of work is pursued by each participant and have access to the published research.

Website: <https://2dphotonics.github.io/index.html>

VIII Outreach activity

The first two year of the grant activity the research team made presentations and meeting with high school students. Due to the COVID 19 pandemic and restrictions to meeting high school students as well as undergraduate students the team of professors and graduate students did not have any outreach activities. [Pictorial presentation of previous outreach activity is presented on the website.](#)