From Quantum to Cosmology

QMCOSMOS 2024

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Book of abstracts

Guest speakers

Universal Matter-Wave Interferometry Across the Mass & Complexity Scales

Markus Arndt
University of Vienna, Faculty of Physics, Boltzmanngasse 5, A-1090 Vienna, Austria

We celebrate the centenary of Louis de Broglie conception of matter waves.
It inspired Erwin Schrödinger's wave equation and a century of studies on quantum foundations and technologies. Louis de Broglie still believed to have solved "probably … all problems related to quanta"[1], however, the very nature of the quantum wave has remained a matter of debate.
Our research group at the University of Vienna is running matter-wave interference experiments with atoms [2], hydrocarbons [3], organic clusters [4], biomolecules [5-8], macromolecules [8] in more than half a dozen of different matter-wave interferometers, searching for indications of violations of quantum linearity as well as applications in bio-physical chemistry. In all experiments quantum mechanics has been found to be the correct description of nature.
I will review these efforts and recent progress in matter-wave interferometry with nanoparticles – focusing on objects of high mass and on new materials [10,11].

[1] L. De Broglie, Nature **112**, 540-540 (1923).
[2] Y. Y. Fein, et al., Phys. Rev. X **10**, 011014 (2020).
[3] Y. Y. Fein, et al., Phys. Rev. Lett. **129**, 123001 (2022).
[4] P. Haslinger, et al., Nature Physics **9**, 144 (2013).
[5] L. Mairhofer, et al., Angew. Chem. Int. Ed. **56**, 10947 (2017).
[6] C. Brand, et al., Ann. Phys. **527**, 580 (2015).
[7] C. Brand, et al., Phys. Rev. Lett. **125**, 033604 (2020).
[8] A. Shayeghi, et al., Nat. Communs. **11**, 1447 (2020).
[9] Y. Y. Fein, et al., Nature Phys. **15**, 1242 (2019).
[10] S. Pedalino, et al., Phys. Rev. A **106**, 023312 (2022).
[11] F. Kiałka, et al., AVS Quant. Sci. **4**, 020502 (2022).

Bio: Markus Arndt is a Professor of Quantum Nanophysics at the University of Vienna. He got his PhD in 1994 working at LMU Munich / MPQ Garching with A.R. Weis and T.W. Hänsch on spectroscopy and spin coherence of metal atoms trapped in solid helium. As a postdoc at Ecole Normale Supérieure, Paris, he worked with Jean Dalibard on atom cooling, atom interferometry in the time domain. Together with A. Zeilinger he realized the first fullerene diffraction experiments in Vienna, in 1999. Arndt became Ao. Univ. Prof. (2002), V. Prof. (2004) and Univ. Prof. (2008) at the University of Vienna, where he has been leading the quantum nanophysics group for more than 20 years. They are developing universal matter-wave interferometers for atoms, tailored and biologically relevant molecules, as well as massive clusters composed of atoms of molecules. The team is interested in experimental tests of quantum decoherence and quantum macroscopicity, quantum tools for physical chemistry, new cooling and the coherent manipulation methods for biological nanoobjects, in quantum sensors based on superconducting nanowires and matter-waves as well as in rotational optomechanics.

Quantum Sensors: Beyond the Classical Limits of Precision

Luiz Davidovich
Federal University of Rio de Janeiro

Subtle properties of quantum physics, like coherent superpositions, squeezing, and entanglement may lead to substantial increase in the precision of estimation of important physical parameters, contributing to frontier research in several fields, from the interaction of biological cells with light [1] to the probing of general relativity at the millimeter scale [2]. Devices based on quantum physics have allowed the precise estimation of the gravitational field [3], the detailed imaging of the brain [4], the detection of gravitational-wave sources more than 400 million light years away [5], and an ever-increasing precision in the measurement of time [6]. Quantum metrology is the conceptual framework that encompasses all these devices, and quantum sensors allow the estimation of parameters with precision higher than that obtained with classical strategies. This talk reviews the basic concepts and some of the developments in quantum sensing, focusing on recent developments in this field that lead to precision bounds for noisy systems [7—12].

[1] M. T. Cone, J. D. Mason, E. Figueroa, B. H. Hokr, J. N. Bixler, C. C. Castellanos, G. D. Noojin, J. C. Wigle, B. A. Rockwell, V. V. Yakovlev, and E. S. Fry, *Measuring the absorption coefficient of biological materials using integrating cavity ring-down spectroscopy*, Optica **2**, 162 (2015).
[2] T. Bothwell, C.J. Kennedy, A. Aeppli *et al.*, *Resolving the gravitational redshift across a millimetre-scale atomic sample*, Nature **6**02, 420–424 (2022).
[3] V. Ménoret *et al.*, *Gravity measurements below 10^{-9} g with a transportable absolute quantum gravimeter*, Sci. Rep. **8**, 12300 (2018).
[4] N. Aslam, H. Zhou, E. K. Urbach *et al.*, *Quantum sensors for biomedical applications*, Nat Rev Phys **5**, 157-169 (2023).
[5] R. Abbott *et al.*, *Observation of gravitational waves from two neutron star–black hole coalescences*, ApJL **915**, L5 (2021).
[6] Boulder Atomic Clock Optical Network (BACON) Collaboration, *Frequency ratio measurements at 18-digit accuracy using an optical clock network*, Nature (London) **591**, 564 (2021).
[7] B. M. Escher, R. L. de Matos Filho, and L. Davidovich, *General framework for estimating the ultimate precision limit in noisy quantum-enhanced metrology*, Nat. Phys. **7**, 406 (2011).
[8] B. M. Escher, L. Davidovich, N. Zagury, and R. L. de Matos Filho, *Quantum metrological limits via a variational approach*, Phys. Rev. Lett. **109**, 190404 (2012).
[9] M. M. Taddei, B. M. Escher, L. Davidovich, and R. L. de Matos Filho, *Quantum Speed Limit for Physical Processes*, Phys. Rev. Lett. **110**, 050402 (2013).
[10] C. L. Latune, B. M. Escher, R. L. de Matos Filho, and L. Davidovich, *Quantum limit for the measurement of a classical force coupled to a noisy quantum-mechanical oscillator*, Phys. Rev. A **88**, 042112 (2013).
[11] J. Wang, L. Davidovich, and G. S. Agarwal, *Quantum sensing of open systems: Estimation of damping constants and temperature*, Phys. Rev. Res. **2**, 033389 (2020).
[12] Jiaxuan Wang, Ruynet L. de Matos Filho, Girish S. Agarwal, and Luiz Davidovich, *Quantum advantage of time-reversed ancilla-based metrology of absorption parameters*, Phys. Rev. Research **6**, 013034 (2024).

Bio: The main thrust of Luiz Davidovich work has been on the dynamics of open systems, involving theoretical and experimental developments, with applications to cavity QED, entangled photon pairs, and quantum metrology. He has worked on the theory of cavity QED experiments carried out in Serge Haroche's group at Ecole Normale Supérieure in Paris, and on the resilience of entangled photon states, with experiments carried out at the Federal University of Rio de Janeiro. Lately, he has worked on the quantum metrology of open systems, cooperating with his group at the Federal University of Rio de Janeiro and with Girish Agarwal at Texas A&M University. He is member of the Brazilian Academy of Sciences, and Foreign Member of the National Academy of Sciences, the Chinese Academy of Sciences, and the European Academy of Sciences. He is Fellow of the American Physical Society and of the Optica Society.

Can Quantum Computing Enhance Machine Learning and, If Yes, How?

Roman Krems
University of British Columbia, Canada

I will begin by demonstrating that the answer to the first question in the title is yes [1], in principle. I will then discuss if the quantum advantage of quantum machine learning can be exploited in practice. To discuss how to build optimal quantum machine learning models, I will describe our recent work [2-3] on applications of classical Bayesian machine learning for quantum predictions by extrapolation. In particular, I will show that machine learning models can be designed to learn from observables in one quantum phase and make predictions of phase transitions as well as system properties in other phases. I will also show that machine learning models can be designed to learn from data in a lower-dimensional Hilbert space to make predictions for quantum systems living in higher-dimensional Hilbert spaces. I will then demonstrate that the same Bayesian algorithm can be extended to design gate sequences of a quantum computer that produce performant quantum kernels for data-starved classification tasks [4].

[1] J. Jäger and R. V. Krems, *Universal expressiveness of variational quantum classifiers and quantum kernels for support vector machines*, Nature Communications **14**, 576 (2023).
[2] R. A. Vargas-Hernandez, J. Sous, M. Berciu, and R. V. Krems, *Extrapolating quantum observables with machine learning: Inferring multiple phase transitions from properties of a single phase*, Physical Review Letters **121**, 255702 (2018).
[3] P. Kairon, J. Sous, M. Berciu and R. V. Krems, *Extrapolation of polaron properties to low phonon frequencies by Bayesian machine learning*, Phys. Rev. B **109**, 144523 (2024).
[4] E. Torabian and R. V. Krems, *Compositional optimization of quantum circuits for quantum kernels of support vector machines*, Physical Review Research **5**, 013211 (2023).

Bio: Roman Krems is a Professor of Chemistry and Distinguished University Scholar at the University of British Columbia. He is also a member of the computer science department at UBC and a principle investigator at the Stewart Blusson Quantum Matter Institute. His work is at the intersection of quantum physics, machine learning and chemistry on problems of relevance to quantum materials and quantum technologies. He is particularly excited about applications of machine learning for solving complex quantum problems and applications of quantum hardware for machine learning. He is Fellow of the American Physical Society and Member of the College of the Royal Society of Canada.

A Postquantum Theory of Classical Gravity

Jonathan Oppenheim
University College London, England

I will present a consistent theory of classical systems coupled to quantum ones via the path integral formulation. In the classical limit, this is the path integral for stochastic processes like Brownian motion. We then apply the formalism to general relativity, since it's reasonable to question whether spacetime should have a quantum nature given it's status within quantum field theory. In contrast to perturbative quantum gravity, the pure gravity theory is renormalisable. The theory introduces a dimensionless coupling constant which controls the degree of diffusion in the gravitational field and runs to zero at short distances. Because of the stochastic nature of the theory, we find a deviation from general relativity at low acceleration which results in anomalous behavior of the gravitational field. This allows for both tabletop experiments and astrophyscical tests of the nature of spacetime in comparison to quantum gravity and cold dark matter.

Bio: Jonathan Oppenheim is a professor of physics at University College London. He is an expert in quantum information theory and quantum gravity. Oppenheim published a proposal in 2023 for a hybrid theory that couples classical general relativity with quantum field theory. According to this proposal, spacetime is not quantized but smooth and continuous, and is subject to random fluctuations.

Dynamically Assisted Tunnelling

Ralf Schützhold
Helmholtz-Zentrum Dresden-Rossendorf, Germany

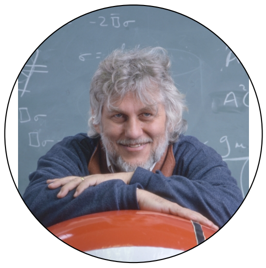
Although tunnelling is usually taught in the first lecture course on quantum mechanics, our understanding is still far from complete – especially in time-dependent scenarios. We consider the enhancement (or suppression) of tunnelling through a potential barrier by an additional time-dependent electric field. As a prominent example, we apply our findings to the enhancement of nuclear fusion by a x-ray free electron laser (XFEL) field.

Interaction of Gravitational Waves with Quantum Matter

We study the interaction between gravitational waves and quantum matter such as Bose-Einstein condensates, superfluid helium, or ultracold solids, explicitly taking into account the changes of the trapping potential induced by the gravitational wave. As a possible observable, we consider the change of energy due to the gravitational wave, for which we derive rigorous bounds in terms of kinetic energy and particle number. Finally, we discuss implications for possible experimental tests.

Bio: Ralf Schützhold is the director of the Department of Theoretical Physics at the Helmholtz-Zentrum Dresden-Rossendorf, Germany and full professor for Theoretical Physics at the Technische Universität Dresden, Germany. His research focuses on exploring analogies between disparate domains, including fundamental phenomena such as Hawking radiation, and experimental realms such as ion traps, cold atoms, graphene, and beyond.

Analog Black Holes



William G. Unruh
University of British Columbia, Canada

Using fluid analogs promise to a) allow us to test theories of quantum emission by black hole and quantum thermal effects of acceleration. I will review this field, and ideas for further experiments.

Bio: William Unruh is a Professor of Physics at the University of British Columbia who has made seminal contributions to our understanding of gravity, black holes, cosmology, quantum fields in curved spaces, and the foundations of quantum mechanics, including the discovery of the Unruh effect. His investigations into the effects of quantum mechanics of the earliest stages of the universe have yielded many insights, including the effects of quantum mechanics on computation. Dr. Unruh was the first Director of the Cosmology and Gravity Program at the Canadian Institute for Advanced Research (1985-1996). His many awards include the Rutherford Medal of the Royal Society of Canada (1982), the Herzberg Medal of the Canadian Association of Physicists (1983), the Steacie Prize from the National Research Council (1984), the Canadian Association of Physicists Medal of Achievement (1995), and the Canada Council Killam Prize. He is an elected Fellow of the Royal Society of Canada, a Fellow of the American Physical Society, a Fellow of the Royal Society of London, and a Foreign Honorary Member of the American Academy of Arts and Science.

Decoherence and Quantum Darwinism: From Quantum Foundations to Classical Reality

Wojciech H. Zurek
Theoretical Division, Los Alamos National Laboratory, USA

I will describe three insights into the transition from quantum to classical. After a brief discussion of decoherence I will give (i) a minimalist (and decoherence-free) derivation of preferred states. Quantum jumps to such pointer states define “events” (e.g., measurement outcomes). Enhanced role of information in quantum theory and its role in the wavepacket collapse will be noted. Probabilities and (ii) Born’s rule ($p_k = |\psi_k|^2$) can be then derived from the symmetries of entangled quantum states. With probabilities at hand one can analyze information flows from the system to the environment in course of decoherence. They explain how (iii) robust classical reality arises, via Quantum Darwinism, from the quantum substrate by accounting for the evidence of objective existence of the pointer states of quantum systems through the redundancy of their records in the environment. Taken together, and in the right order, these three advances (i)-(iii) elucidate quantum origins of the classical.

WHZ, Physics Today **67** (10), 44-50 (2014); Entropy **24** (11), 1520 (2022);
Decoherence and Quantum Darwinism: From Quantum Foundations to Classical Reality (Cambridge University Press, forthcoming).

Bio: Wojciech Hubert Zurek is a physicist with expertise in quantum theory. His research focuses on quantum-to-classical transitions including decoherence and quantum Darwinism, and non-equilibrium dynamics concerning symmetry breaking and the generation of defects during phase transitions (known as the Kibble-Zurek mechanism). Additionally, he made contributions to quantum information theory, particularly in formulating the no-cloning theorem (with Wootters).

Guest students speakers

INERTIAL QUANTUM SENSORS AT THE INTERFACE OF RELATIVITY

Daniel Derr
Technische Universität Darmstadt, Germany

Atom interferometry is an emerging high-precision tool for inertial sensing. Compared to optical interferometers, matter waves are manipulated by light to propagate in superposition of two trajectories through space-time. The enclosed space-time area determines the observed interference signal and allows to measure inertial forces like the gravitational acceleration. In addition, differential setups, for example, can be used to test the various facets of the Einstein equivalence principle [1] or detect gravitational waves. For the latter, the decihertz range is at the focus of current efforts and has initiated the construction of long baseline sites (such as MAGIS, AION, MIGA, ZAIGA) to complement conventional detection capabilities over the whole frequency range. Besides these applications, atom interferometers can be used to test physics beyond the Standard Model [2]. There are several possibilities, one of which is ultra-light dark matter coupled to the internal degrees of freedom of atoms. These applications make atom interferometry a testbed for the interface of relativity and quantum mechanics or the detection of ultralight dark-matter candidates [3, 4].

The talk gives an introduction into the main concepts of atom interferometry and the toolbox necessary to manipulate atoms. While we explain basic examples of atom interferometers, we also discuss current and ambitious proposals for high-precision tests of fundamental physics and current developments in the field aiming at large-scale quantum detectors of gravitational waves and dark matter.

[1] F. Di Pumpo, A. Friedrich, C. Ufrecht & E. Giese, *Universality-of-clock-rates test using atom interferometry with T^3 scaling.* Phys. Rev. D **107**, 064007 (2023).
[2] A. Bott, F. Di Pumpo & E. Giese, *Atomic diffraction from single-photon transitions in gravity and Standard-Model extensions.* AVS Quantum Sci. **5**, 044402 (2023).
[3] D. Derr & E. Giese, *Clock transitions versus Bragg diffraction in atom-interferometric dark-matter detection.* AVS Quantum Sci. **5**, 044404 (2023).
[4] F. Di Pumpo, A. Friedrich & E. Giese, *Optimal baseline exploitation in vertical dark-matter detectors based on atom interferometry.* AVS Quantum Sci. **6**, 014404 (2024).

Quantum Sensors Based on Tunneling

Patrik Schach
Technische Universität Darmstadt, Germany

Ultracold gases represent a unique and versatile platform for a wide range of sensing applications. Atom interferometers utilize large spatial separation of cold atomic clouds to facilitate precise measurements of accelerations and inertial forces. The inherent atomic structure serves as a fundamental element for precise timekeeping, utilizing atomic transitions for precise time measurements. By combining both external and internal degrees of freedom, novel applications and possibilities emerge.

The advent of ultracold clouds cooled below the Doppler limit enables coherent and precise manipulation of external degrees of freedom. These systems play a crucial role for the investigation of tunneling phenomena, relying on the manipulation and observation of the atomic motion. Furthermore, combining external and internal degrees of freedom provides insights into tunneling times and associated phenomena.

As promising application of quantum tunneling, we study the transmission spectrum of matter-wave Fabry-Pérot interferometers, present their sensitivity to accelerations and discuss their applicability to gravimetry [1]. Exploring the tunneling process, we investigate the phase difference of tunneled quantum clocks in various differential measurements. We identify relativistic contributions accumulated by a tunneled quantum clock due to time dilation and mass defect. In particular, we relate these contributions to a tunneling time and highlight the relations to conventional approaches [2].

[1] P. Schach, A. Friedrich, J. R. Williams, W. P. Schleich & E. Giese, *Tunneling gravimetry.* EPJ Quantum Technol. **9**, 20 (2022).
[2] P. Schach & E. Giese, *A unified theory of tunneling times promoted by Ramsey clocks.* Sci. Adv. **10**, eadl6078 (2024).

Local LANL speakers

The Dynamics and Capacity of Neuromorphic Neural Networks and Learning by Mistakes

Frank Barrows
Theoretical Division and Center for Nonlinear Studies, Los Alamos National Laboratory, USA

Understanding the emergent computational properties of the brain is challenging as we currently lack a theory of computation in the brain. Despite this, the current machine learning revolution has been loosely motivated by neuronal computation. Further computational gains are possible by developing computing hardware and algorithms that reproduce the emergent properties of the brain. Neuromorphic systems have properties akin to neurons; understanding the dynamical information processing properties of neuromorphic networks will aid in designing brain-like computers. In addition, deep insights into information processing in the brain are possible by studying neuromorphic networks.

In this talk, I will discuss recent work to bridge neuromorphic algorithms and hardware. Specifically, I will discuss recent theoretical and experimental work on training neuromorphic neural networks using the Chialvo-Bak model. Further, I will discuss a general formalism to understand neuromorphic circuits. Using circuit conservation laws we have developed a unifying formalism that relates the electrical transport properties to circuit topology. Specifically, I will discuss the capacity of neural networks, and the representations of rules in a trained neural network. Finally, I present work on ordering in neural networks and related scaling laws.

Bio: Frank Barrows is Director's Postdoctoral Fellow in The Physics of Condensed Matter and Complex Systems group at Los Alamos National Laboratory and a Center of Nonlinear Studies Fellow. He received his PhD in 2021 from Northwestern University, completing his graduate work at Argonne National Laboratory studying the emergent properties of neuromorphic and magnetic systems. He received his MD in 2023 from Northwestern University as part of the Medical Scientist Training Program. He is interested in emergent computation in unconventional computing systems, neuromorphic systems and algorithms, nonequilibrium classical and quantum systems, spin field theories, and consciousness.

Catalytic Enhancement in the Performance of the Microscopic Two-Stroke Heat Engine

Tanmoy Biswas
Theoretical Division, Los Alamos National Laboratory, USA

We consider a model of a heat engine operating in the microscopic regime: the two-stroke engine. It produces work and exchanges heat in two discrete strokes that are separated in time. The engine consists of two d -level systems initialized in thermal states at two distinct temperatures. Additionally, an auxiliary non-equilibrium system called catalyst may be incorporated into the engine, provided the state of the catalyst remains unchanged after the completion of a thermodynamic cycle. This ensures that the work produced arises solely from the temperature difference, Upon establishing the rigorous thermodynamic framework, we characterize two-fold improvement stemming from the inclusion of a catalyst. Firstly, we show that the presence of a catalyst allows for surpassing the optimal efficiency of two-stroke heat engines which are not assisted by a catalyst. In particular, we prove that the optimal efficiency for two-stroke heat engine consisting of two-level systems is given by the Otto efficiency, and that it can be surpassed via incorporating a catalyst. Secondly, we show that incorporating a catalyst allows the engine to operate in frequency and temperature regimes that are not accessible for non-catalytic two-stroke engines.

Ref: arXiv:2402.10384

Bio: Tanmoy Biswas is currently a post-doctoral researcher at theoretical division of Los Alamos National Laboratory under the mentorship of Luis Pedro Garcia Pintos. Before joining to LANL, he obtained his Ph.D under supervision of Prof. Michal Horodecki at International Centre for theory of quantum technologies, University of Gdansk. His main research includes different topics of information theory and thermodynamics.

Honey, I Shrunk the Heat Uncertainty Relationship!

Francesco Caravelli
Theoretical Division, Los Alamos National Laboratory, USA

Heat, work, power and energy storage are important concepts in classical and quantum thermodynamics. In the present talk, we discuss recent results on quantum batteries and quantum thermodynamics, and in particular the observation that there exist not only bounds to power and energy, and energy and heat, but also uncertainty relationships emerging from the observation that heat and energy, and energy and power, are operators in quantum thermodynamics (a fact that we think to be surprisingly overlooked). We will then discuss the effect of having an open quantum system in simple models, and in particular the continuous measurement due to a Markovian bath, effectively shrinking these quantum uncertainties.

Resilience-Runtime Tradeoff Relations in Quantum Algorithms

Luis Pedro García-Pintos
Theoretical Division, Los Alamos National Laboratory, USA

A leading approach to algorithm design aims to minimize the number of operations in an algorithm's compilation. One intuitively expects that reducing the number of operations may decrease the chance of errors. This paradigm is particularly prevalent in quantum computing, where gates are hard to implement and noise rapidly decreases a quantum computer's potential to outperform classical computers.
We have found that minimizing the number of operations in a quantum algorithm can be counterproductive, leading to a noise sensitivity that induces errors when running the algorithm in non-ideal conditions. To show this, we developed a framework to characterize the resilience of an algorithm to perturbative noises (including coherent errors, dephasing, and depolarizing noise). Some compilations of an algorithm can be resilient against certain noise sources while being unstable against other noises. These results are condensed by a tradeoff relation between an algorithm's number of operations and its noise resilience.

Bio: Luis Pedro Garcia-Pintos is a Staff Scientist at the Theoretical Division (T4) of Los Alamos National Laboratory. Before joining LANL, he was an Assistant Research Scientist at the University of Maryland College Park and had positions at the University of Massachusetts Boston, Chapman University, and the University of Bristol. Luis Pedro's work focuses on describing the dynamics of physical systems from first principles. This work includes studying equilibration processes, quantum thermodynamics, open quantum systems, and quantum computing.

Quantum Metrology with non-Hermitian Rydberg Atoms

Andrew Harter
MPA-Q, Los Alamos National Laboratory, USA

Non-Hermitian quantum physics models dissipation in open quantum systems by using non- conserving imaginary potentials. The corresponding Hamiltonian is manifestly non-Hermitian, leading to many rich phenomena not seen in traditional systems with Hermitian Hamiltonians, including the presence of exceptional points where a pair of eigenvectors become parallel, non-unitary evolution with time-irreversible dynamics, and complex energies with unique classes of antilinear symmetries which grant a completely real spectrum. Experiments have realized many of these properties in single-particle settings; however it remains challenging to realize fully quantum interacting systems which can also produce these non-Hermitian phenomena. We study a possible implementation using an ultracold neutral atom platform with controlled dissipation and postselection to generate the required dynamics. Motivated by this possibility, we discuss applications to quantum metrology, including proposed exceptional-point based enhancements enabled by non-Hermitian Hamiltonians.

Ab initio Design of Quantum Materials for Quantum Sensing and sub-GeV Dark Matter Detection

Elizabeth A. Peterson
Theoretical Division, Los Alamos National Laboratory, USA

Quantum sensing of meV-scale scattering and absorption of impinging particles with electrons in solid state detectors has important and wide-ranging applications such as the detection of cosmological particles and single photon detection for quantum key distribution. In the search for sub-GeV dark matter specifically there is an increasing interest in detection via dark matter-electron scattering and absorption in crystalline materials. However, current sensing and detection schemes for meV-scale phenomena struggle to differentiate between signals that come from impinging particles and those from inherent quasiparticles, such as phonons and magnons. The state-of-the-art involves experiments using highly pristine, well-studied target materials (e.g. silicon) and operation at extreme cryogenic temperatures. As experiments push towards probing the largely unexplored sub-MeV dark matter regime there is an urgent need to identify novel detector target materials that host meV-scale excitations and crystalline anisotropy.

Quantum materials have emerged as a promising class of materials for next-generation dark matter detectors. Broadly, these are materials that exhibit emergent quantum phenomena at the macroscopic scale; exemplar varieties include low-dimensional materials, f-electron materials, and Dirac materials. Heterostructures of layered massive Dirac materials offer a novel pathway to selective detection of impinging particles. By engineering interfacial orbital hybridization in van der Waals heterostructures of Dirac materials, interlayer charge transfer can be promoted only for pre-selected types of impinging particles based on their dispersion relations, mitigating existing challenges in differentiating meV-scale excitations from dark matter and from intrinsic quasiparticles. In this talk I will describe a proof-of-principle study of this novel quantum sensing scheme leveraging first-principles density functional theory calculations on heterostructures of the layered Dirac materials ZrTe5 and HfTe5. I will discuss the effects of strain and layer number for tuning hybridization in the electronic structure and the type of impinging particle that may be detected. These results will suggest that by exploiting hybridization in heterostructures of Dirac materials, it is possible to construct "dispersion filters" for next-generation quantum sensors.

Funding: This work was supported by the U.S. DOE NNSA under Contract No. 89233218CNA000001. It was supported by the LANL LDRD Program, and in part by the Center for Integrated Nanotechnologies, a DOE BES user facility, in partnership with the LANL Institutional Computing Program for computational resources. Additional computations were performed at the National Energy Research Scientific Computing Center (NERSC), a U.S. Department of Energy Office of Science User Facility located at Lawrence Berkeley National Laboratory, operated under Contract No. DE-AC02-05CH11231 using NERSC award ERCAP0020494. LA-UR-24-24253

Bio: Elizabeth A. Peterson is a staff scientist in Theoretical Division at Los Alamos National Laboratory in the Physics of Condensed Matter and Complex Systems (T-4) group. She completed her undergraduate studies at UCLA in 2013, earning a B.S. in Chemistry and a B.S. in Applied Mathematics. From 2014-2016 she worked as a Research Scientist at a tech startup in San Francisco. In 2022 she completed her PhD in Physics at UC Berkeley, under the supervision of Prof. Jeffrey B. Neaton, with a focus on ab initio electronic structure calculations of oxides and low-dimensional materials for applications in photocatalysis and quantum information. In 2022 she began a postdoctoral position in T-4 at LANL and converted to a staff position in 2023. Her research interests, broadly, include ab initio studies of defects and interfaces of quantum materials and oxides for applications in next-generation applied energy and quantum information technology.

Harnessing Quantum Light: Probing Cavity Polaritons with Entangled Photon Pairs

Andrei Piryatinski
Theoretical Division, Los Alamos National Laboratory, USA

Recent theoretical and experimental reports have shown that quantum light can be a highly sensitive tool for probing material system electronic and vibrational properties. This tool takes advantage of the unique properties of quantum photon states, e.g., entanglement, and further detects changes in the photon statistics introduced by the material response. Our theoretical study is inspired by several experimental findings that show how changes in the photon entanglement of frequency-entangled photons induced by material systems can be extracted using photon interferometry techniques. Moreover, optical microcavities provide a new platform for nonlinear quantum photon spectroscopes by facilitating strong light-matter interactions, leading to the emergence of hybrid light-matter states known as polaritons. In this talk, we explore the influence of cavity polariton states on the quantum state of the frequency-entangled photon pair as it propagates through the cavity. Utilizing the input-output formalism, we compute the biphoton scattering matrix corresponding to the Tavis-Cummings model describing the polaritons states. Setting the input state as a frequency-entangled photon pair generated via the spontaneous parametric down-conversion (SPDC) process, we examine the changes in its joint spectral amplitude (JSA). Specifically, we look at the features within the JSA of output photons arising from resonances of the biphoton scattering amplitude. Additionally, we conduct the Schmidt decomposition of both the input and output JSA, enabling us to calculate and compare the entanglement entropy of the input and scattered photon pair. The physical mechanisms underlining the computed entropy variations will be discussed.

Kibble-Zurek Mechanism for Nonequilibrium Phase Transitions

Charles Reichhardt and Cynthia Reichhardt
Theoretical Division, Los Alamos National Laboratory, USA

The Kibble-Zurek (KZ) mechanism describes the density of defects as a system is quenched through an equilibrium phase transition. The KZ scenario predicts a universal power law scaling and has implications for continuum phase transitions in the early universe, materials science, and condensed matter systems [1,2]. An open question is whether the KZ scenario also holds for nonequilibrium phase transitions. We show that the Kibble-Zurek mechanism applies to nonequilibrium phase transitions found in driven assemblies of superconducting vortices and colloidal particles moving over quenched disorder where a transition occurs from a plastic disordered flowing state to a moving anisotropic crystal. We measure the density of topological defects as a function of quench rate through the nonequilibrium phase transition, and find that on the ordered side of the transition, the topological defect density ρ_d scales as a power law with t_q, the quench time duration, consistent with the Kibble-Zurek mechanism. We show that scaling with the same exponent holds for varied strengths of quenched disorder and that the exponents fall in the directed percolation (DP) universality class [3]. Our results suggest that the Kibble-Zurek mechanism can be applied to the broader class of systems that exhibit absorbing phase transitions. We also examine a system of skyrmions with a strong Magnus force component that are driven over random disorder and exhibit a dynamic transition from a fluid to a two-dimensional crystal. In this case we find a different set of exponents and we argue that the the critical behavior is associated with coarsening since the defects can both climb and glide [4]. We discuss how systems with non-equilibrium phase transitions such as glasses, turbulence, time crystals, or systems exhibiting a reversible-irreversible transition could also be interesting places to look for Kibble-Zurek type dynamics.

[1] T.W.B. Kibble, "Topology of cosmic domains and strings." J. Phys. A: Math. Gen. **9**, 1387 (1976).
[2] W.H. Zurek, "Cosmological experiments in superfluid helium." Nature (London) **317**, 505 (1985).
[3] C.J.O. Reichhardt, A. del Campo, and C. Reichhardt, "Kibble-Zurek mechanism for nonequilibrium phase transitions in driven systems with quenched disorder." Commun. Phys. **5**, 173 (2022).
[4] S. Maegochi, K. Lenaga, and S. Okuma, "Kibble-Zurek mechnanisim for dynamical ordering in driven vortex systems." Phys. Rev. Lett. **129**, 227001 (2022).
[5] C. Reichhardt, I. Regev, K. Dahmen, S. Okuma, and C.J.O. Reichhardt Phys. Rev. Research **5**, 021001 (2023).

Non-Hermitian Quantum Mechanics and its Physical Implications

Avadh Saxena
Theoretical Division, Los Alamos National Laboratory, USA

The focus of this talk will be on significant recent efforts devoted to non-Hermitian quantum phenomena in the context of photonics and related fields. Just over 25 years ago it was shown by Bender and Boettcher that a non-Hermitian system with balanced gain and loss, or parity-time reversal (PT) symmetry, could still possess all eigenvalues as real below a threshold value of gain/loss. Subsequently, this prediction was experimentally verified in photonic waveguides and several other physical settings. After a brief pedagogical introduction to the subject, I will provide several examples that illustrate a variety of unusual properties of non-Hermitian systems such as exceptional points and coalescence of eigenfunctions. Specifically, I will consider decoherence, entanglement entropy and Fisher information for both PT-symmetric and anti-PT-symmetric qubits and compare these properties with the corresponding attributes of a Hermitian qubit. I will also consider a discrete system, that of a PT-symmetric Kagome photonic lattice, in which dispersionless flat bands emerge. The latter are responsible for long-lived chiral structures and localization in the lattice. Such photonic lattices are beginning to find applications in optical beam engineering, image processing and active metamaterials. Additionally, I will discuss a few other examples including the stability of driven non-Hermitian Hamiltonians with different periodicities using Floquet theory, dynamics of non-Hermitian many-body Landau-Zener models, etc.

Nonlinear Optics with Metal Nano-particles

Syed Shah
Theoretical Division and Center for Nonlinear Studies, Los Alamos National Laboratory, USA

Optical nano-structures hosting localized surface plasmon resonances have been used in multiple applications from chemical sensing to optical lasing. These structures and their lattices also promise applications as optical meta-surfaces. This talk will introduce the diverse applications and properties of surface plasmons in nano-structures, especially focusing on the linear and non-linear optical properties. Our recent numerical and theoretical treatments of the nonlinear optical processes exhibited and enabled by the metal nano-particles will be presented. Particularly, I will focus on their potential for spontaneous parametric down conversion, a well established process for entangled phonon generation.

Ref: Opt. Lett. **49**, 1680-1683 (2024).

Bio: Shah did his bachelors in physics and computer sciences. He then received PhD Chemistry from University of Houston in experimental spectroscopy and imaging for surface chemistry. Afterwards, he switched to theory, working as a postdoc on computational and stochastic methods for quantum simulations of nonlinear optical response from chemical systems. He now works on nonlinear optics and molecular qubits at Center for Nonlinear Studies, Los Alamos National Lab.

Corrections to Hawking Radiation from Primordial Black Holes as Dark Matter Probes

Makana Silva
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Primordial black holes (PBHs) within the mass range $10^{17} - 10^{22}$ g are a favorable candidate for describing the all of the dark matter content. Towards the lower end of this mass range, the Hawking temperature, T_H, of these PBHs is $T_H \gtrsim 100$ keV, allowing for the creation of electron – positron pairs; thus, making their Hawking radiation a useful constraint for most current and future MeV surveys. This motivates the need for realistic and rigorous accounts of the distribution and dynamics of emitted particles from Hawking radiation in order to properly model detected signals from high energy observations. This is the first in a series of papers to account for the O(α) correction to the Hawking radiation spectrum. We begin by the usual canonical quantization of the photon and spinor (electron/positron) fields on the Schwarzschild geometry. Then we compute the correction to the rate of emission by standard time dependent perturbation theory from the interaction Hamiltonian. We conclude with the analytic expression for the dissipative correction, i.e. corrections due to the creation and annihilation of electron/positrons in the plasma and future works.

Bio: Makana Silva is a Native Hawaiian astrophysicist born and raised on the island of O'ahu. He graduated with his B.S in physics from the University of Hawaii at Manoa and his Ph.D in physics from The Ohio State University with his advisor Christopher Hirata. He is now a Director's Fellow at LANL studying gravity on various physical scales: from gravitational waves from the dynamics around supermassive black holes, to understanding how radiative processes on curved spacetimes could change emission profiles of Hawking radiation from primordial black holes. He plans on applying these analyses to current/future observatories (LIGO, LISA, Fermi LAT, AMEGO, etc.) in order to address astrophysical/fundamental physics questions. In parallel to his research, he is also a member of the Board of Directors and Director of Mentorship for the Native Hawaiian non-profit organization 'Ohana Kilo Hōkū (OKH) aiding in the development of community-based events where people can learn about the science of the stars from a Hawaiian culture and scientific perspective. When he is not working, he enjoys lifting stones, logs, kegs, and other heavy objects that one would see in a strongman competition.

Asymmetry in Production of Nearly Identical Particles: Lessons from Exactly Solvable Models

Nikolai Sinitsyn
Theoretical Division, Los Alamos National Laboratory, USA

How to separate very similar particles from their mixture is an important technological and scientific problem. An example is the isotope separation, e.g. of plutonium in a nuclear waste. There is also as famous and not fully answered question about the origin of the asymmetry between the matter and anti-matter abundance in our universe. Here, we discuss this problem from the point of view of fully solvable explicitly time-dependent quantum models. Such models generally predict that, despite the same initial conditions for almost identical particles, an evolution can lead to a highly asymmetric their final distribution.

Extending the Kibble-Zurek Mechanism to Weakly First-Order Phase Transitions

Fumika Suzuki
Theoretical Division and Center for Nonlinear Studies, Los Alamos National Laboratory, USA

Just as water freezes into ice, the theories of high energy physics predict that the universe has experienced phase transitions following the Big Bang, as it expanded and cooled. Signals stemming from such phase transitions would have influenced its evolution and may persist to this day, offering valuable insights into the early universe. W. H. Zurek has proposed that this mechanism can be tested in a laboratory using liquid crystals and developed a theory to predict the density of the signals (i.e., defects). It is called the Kibble-Zurek mechanism (KZM). KZM has found applications in fields such as cosmology and condensed matter physics. However, it is generally not suitable for describing first-order phase transitions. It has been demonstrated that transitions in systems like superconductors or charged superfluids, typically classified as second-order, can exhibit weakly first-order characteristics when the influence of fluctuations is taken into account. In our research, we extended the applicability of the KZM to cover weakly first-order phase transitions by combining it with nucleation theory. This result may not only deepen our understanding of diverse phase transitions in material science and condensed matter physics but also open doors to exploring various cosmological models.

Ref: Fumika Suzuki, and W. H. Zurek, *Topological defect formation in a phase transition with tunable order*, arXiv:2312.01259 (2024) (to appear in Phys. Rev. Lett)

Bio: Fumika Suzuki is a postdoctoral researcher under the mentorship of Nikolai Sinitsyn and W. H. Zurek at the Center for Nonlinear Studies and Theoretical Division, Los Alamos National Laboratory. Originally from Japan, she earned her Ph.D. at the University of British Columbia, Canada, under the supervision of W. G. Unruh, Roman Krems and Taka Momose. Her research interest includes quantum physics, condensed matter physics, optics and field theories.

Emergence of Consensus About Classical Reality in a Quantum Universe

Akram Touil
Theoretical Division, Los Alamos National Laboratory, USA

In my talk, I will explore how the classical world we experience emerges from the quantum universe, focusing on the concept of Quantum Darwinism. This framework extends beyond decoherence theory by considering the environment as a communication channel that informs us about the state of quantum systems. I propose a new, information-theoretic measure to quantify consensus among observers within this framework. By examining branching states within a quantum universe, I demonstrate how this consensus, on our shared objective reality, forms. Using a many-qubit model, I will illustrate these concepts, offering a comprehensive yet approachable view on the emergence of the classical reality we all experience. This talk aims to bridge the gap between complex quantum phenomena and our everyday understanding of reality.

Bio: Akram is currently a Director-funded postdoc at Los Alamos National Laboratory. He completed his Ph.D. at the University of Maryland Baltimore County, where he worked on quantum thermodynamics and quantum foundations. His research lies at the intersection of quantum thermodynamics and quantum information theory. His current work includes quantifying quantum-to-classical transitions within the Quantum Darwinism framework, identifying mechanisms that lead to wave function branching in the universe, studying quantum probabilities and the Born rule, exploring thermalization processes in quantum mechanics, and applying machine learning to open systems.

Correlations between Alice and Bob: From Classical to Super-Quantum

Bin Yan
Theoretical Division, Los Alamos National Laboratory, USA

Quantum mechanics is renowned for supporting stronger-than-classical correlations, notably the non-local correlation between distant parties (commonly referred to as "Alice and Bob") illustrated by violations of Bell inequalities. However, quantum mechanics represents just one layer of the correlation landscape. There exist a class of (hypothetical) theories that exhibit even stronger correlations (super-quantum). In this presentation, I will provide a brief historical account of the studies of quantum correlations and discuss several key results on the possibilities and consequences of super-quantum correlations.