CCMI 2026

Cold and Controlled Molecules and Ions

Book of Abstracts

Stony Brook University

August 17–21, 2026

Table of Contents

Roland Wester

Universität Innsbruck

Photodetachment spectroscopy and detachment reactions of cold trapped negative ions

Abstract

Negative molecular ions are interesting objects of study as fundamental building blocks of matter. Using cryogenic radiofrequency ion traps we study the spectroscopy, photodetachment and reactivity of negative ions and well-controlled conditions. Of particular interest are negative ions that have been observed in interstellar molecular clouds. Here, we recently studied vibrational spectroscopy of several negative ions in the far-infrared as well as associative detachment reactions with atomic hydrogen. Regarding the homonuclear negative ion C_2^-, we have recently measured the electron affinity of the carbon dimer using accurate photodetachment spectroscopy and we have determined several vibrational frequencies, the transitions of which are dipole forbidden, using optical excitation via Λ schemes. This work paves the way improved fluorescence detection of these anions and the search for direct Doppler cooling schemes.

David Patterson

UCSB

A general method for single molecule spectroscopy

Abstract

Single molecular ions present a highly attractive platform for high resolution and highly sensitive spectroscopy. These molecules can be held for many hours in a pristine environment, and can be motionally laser cooled into the millikelvin regime and below. Prior to this work, methods to study "generic" single molecules have not been demonstrated. Here, we demonstrate a novel single molecule action-spectroscopy technique that is compatible with high precision measurement, and present the first spectra ever recorded of single polyatomic gas-phase molecules. The method is generally applicable to a wide range of polyatomic molecular ions, and promises spectral resolution comparable to state of the art quantum logic methods, with significantly less stringent experimental overhead. Progress towards extending this technique to include chiral recognition of single molecules will be discussed. Adaptations of this technique will prove useful in a wide range of precision spectroscopy arenas including the search for parity violating effects in chiral molecules and searches for biological signatures in samples from beyond Earth.

Chris Johnson

Stony Brook University

Resolving the electronic effects of silver doping in atomically-precise $Au_{25}(SR)_{18}$— nanoclusters

Abstract

Atomically-precise nanoclusters are valued as nanoparticles that can be isolated with exact compositional purity and often crystallized to determine their exact structures. They are tunable by size, metal doping, or exchange of some or all ligands, giving them great flexibility to be tuned for various applications in catalysis, sensing, or photonics. Due to a lack of clear experimental benchmarks and the difficulty in accurately treating nanoclusters using quantum chemical approaches, the current understanding of their electronic structure and its synthetic manipulation is still relatively qualitative. This is exacerbated by the difficulty in isolating and characterizing doped or mixed-ligand clusters. Here we use a unique spectroscopic approach that allows us to unambiguously separate doped clusters from a mixture and record their electronic spectra with high resolution. Applying this technique to the ubiquitous $Au_{25}(SR)_{18}$— (R = hexanethiolate, phenylethanethiolate) nanocluster, we reveal for the first time the detailed changes in electronic structure induced by doping of individual Ag atoms. We show that the net blue shift of the main features of the spectrum, observed previously, masks the more complex evolution of the HOMO-LUMO gap, which alternates between red shifting and blue shifting as Ag atoms are exchanged. Decomposing the spectra into individual transitions, we propose an intuitive framework to describe the impact of Ag doping on the nanocluster orbital shapes and energies, and suggest the order in which specific Au sites exchange for Ag. This framework can guide hypothesis-driven optimization of nanoclusters for various applications.

G. Stephen Kocheril

JILA/University of Colorado, Boulder
Hot Topic

Unraveling the formation of aromatic molecules through sequential ion-molecules reactions in Coulomb crystals

Abstract

Aromatic molecules are believed to be highly relevant to the chemistry of the Interstellar Medium (ISM) due to their intrinsic high stability. Recent astronomical observations have clearly identified that the formation of large polycyclic aromatic hydrocarbon (PAH) molecules can readily occur throughout the ISM, however, the formation of these complex molecules remains unknown. To better understand possible formation mechanisms of these PAHs under astrophysical conditions, we have carried out a series of ion-molecule reactions using a Coulomb crystal to imitate the cold and diffuse environment of interstellar space. We find that aromatic molecular ions can be produced readily through sequential ion-molecule reactions beginning with small hydrocarbons. These results indicate that ion-molecule reactions should be considered as primary candidates for precursors to PAHs.

Pavol Jusko

Max Planck Institute for Extraterrestrial Physics

22 Pole Radio-Frequency Ion traps for Astrophysical Applications

Abstract

In this contribution cryogenic (down to 4 K) ion traps based on 22 poles (linear Paul traps) focused on astrophysical applications are going to be presented. The two main areas where the long storage time in UHV environment and well defined conditions can be explored are spectroscopy and reaction studies. For spectroscopy, as the number of ions in the trap is too small for conventional absorption/ emission techniques action spectroscopy schemes, like laser induced reactions (LIR), tagging/ pre-dissociation, e.g., (IR-PD), or leak out spectroscopy (LOS), have to be used. For reactivity studies, i.e., ion-molecule reactions, the main caveat is the neutral reactant, which tend to freeze at very low temperatures. The capabilities are going to be demonstrated on select systems from light molecules like $[H,C,N]^+$ isomers (spectroscopy and reactivity) up to smaller PAHs (spectroscopy).

Bryan Changala

University of Colorado, Boulder/JILA

Cavity-enhanced IR comb modulation spectroscopy of astrophysical ions

Abstract

UV photons that impinge on interstellar clouds initiate a chain of ion-molecule reactions that are believed to form complex organic molecules and new carbon-carbon bonds. Since the launch of the James Webb Space Telescope in 2021, the remarkable spatial-spectral resolution and detection sensitivity of its on-board infrared instruments have already begun to transform our understanding of this nascent organic chemistry through the detection of some of the most important small molecules in these networks, most notably CH_3^+. These early successes have made clear that continued progress will only be possible with new spectroscopic data on many other small carbocations (C_2H^+, c-$C_3H_3^+$, etc.) at LWIR wavelengths. In this talk, I describe a new laboratory instrument that addresses this need by combining cavity-enhanced direct infrared comb spectroscopy with ion modulation techniques, which together provide the necessary sensitivity, wavelength coverage, and frequency resolution needed to characterize the surprisingly complex IR signatures of these fundamental astrophysical ions.

Leah Dodson

University of Maryland

Symmetry-Controlled Nuclear Spin Conversion in Molecular Hydrogen

Abstract

Molecular hydrogen is the simplest neutral molecule, yet the microscopic mechanisms governing nuclear-spin conversion between its ortho and para forms remain incompletely understood. In this talk, I will present recent results demonstrating that the symmetry of a condensed-phase environment can directly control the allowed pathways for nuclear-spin conversion. Using cryogenic infrared spectroscopy, we monitor state-resolved ortho- and para-H_2 populations confined within crystalline CO_2 and N_2O solids, where anisotropic crystal fields lift the degeneracy of the ortho-H_2 rotational manifold and render H_2 infrared active. By directly resolving these crystal-field-split sublevels, we show that the symmetry of the host lattice imposes selection rules that determine which nuclear-spin conversion channels are allowed, with diamagnetic and paramagnetic hosts exhibiting fundamentally different relaxation pathways. These results establish molecular crystals as a platform for engineering quantum-state dynamics through symmetry alone, providing a condensed-phase analogue of symmetry-controlled state selection familiar from atomic and molecular physics and illustrating how tailored environments can be used to manipulate quantum relaxation without applied external fields.

Tijs Karman

Radbound University

Good Vibrations

Abstract

In my talk I will describe the ro-vibrational van der Waals interaction between ultracold polar molecules [1]. This interaction is strong, leading to fast elastic collisions and orders of magnitude suppression of collisional loss. This enables evaporative cooling of Fermi mixtures of molecules in different ro-vibrational states without active shielding by applying external fields. The scheme is compatible with microwave shielding, where it enables controlled state dependent interactions [2], opening up new opportunities for quantum simulation and impurity physics. The interaction can also be used to stabilize fermionic molecules in optical lattices, to control interactions in synthetic dimensions, for direct infrared shielding, and for deterministic tweezer loading [3].

[1] Feng et al. arXiv:2607.25774
[2] Jozwiak et al. arXiv:2607.25777
[3] Walraven et al. arXiv:2607.25783

Timur Tscherbul

University of Nevada, Reno

Entanglement and quantum information scrambling in low-temperature molecular collisions and chemical reactions

Abstract

Ultracold molecules provide controlled access to a largely unexplored intersection of chemical physics and quantum information science, where bimolecular collisions and chemical reactions generate and scramble quantum information. We present the first results on quantum information scrambling in low-temperature gas-phase chemical reactions. Scattering out-of-time-order correlators (OTOCs) for the one-dimensional model of the $F + H_2 \rightarrow HF + H$ reaction grow exponentially at early times, reflecting the dynamical instability of the reaction barrier. This growth saturates at late times without the oscillations or revivals characteristic of bound-state OTOCs due to the continuous spectrum of the scattering problem. We also show that coupling between the motional and internal degrees of freedom of the collision partners generates discrete-discrete, continuum-continuum, and hybrid discrete-continuum forms of product-state entanglement, and we introduce a general framework that quantifies each type directly in terms of scattering S-matrix elements. Near magnetic Feshbach resonances, this product-state entanglement can be efficiently controlled, establishing cold collisions as a tunable resource for entanglement generation.

Mateo Londono

Stony Brook University

Rovibrational dynamics of CaF/BaF ($X^2\Sigma^+$) in a buffer gas of ^{4}He

Abstract

Polar molecules at ultralow temperatures provide powerful opportunities for quantum science and emerging quantum technologies [1]. Among direct molecular cooling approaches, buffer-gas cooling is a crucial step toward enabling efficient laser cooling of dipolar species into the sub-microkelvin regime [2]. The performance of this technique is governed by the microscopic dynamics of atom–molecule collisions, which determine thermalization and energy transfer processes [3]. Of particular interest is the cooling of alkaline-earth monofluorides, such as CaF and BaF. Recent experiments have revealed a significant difference in the rovibrational relaxation rates of these two molecules when immersed in a cryogenic helium buffer gas at cold temperatures. In this work, we explain the origin of these differences by means of quantum mechanical scattering calculations. We compute accurate atom–molecule interaction potentials using high-level quantum chemistry methods and solve the multichannel Schrödinger equation to obtain rovibrational relaxation rates. Our results are in good agreement with experimental observations and show that the distinct sympathetic cooling behavior of CaF and BaF arises from differences in the anisotropy of the interaction potential and from the location of shape resonances in the scattering dynamics.

[1] J. L. Bohn, A. M. Rey, and J. Ye, Cold molecules: Progress in quantum engineering of chemistry and quantum matter, Science 357, 1002 (2017)
[2] S. L. Cornish, M. R. Tarbutt, and K. R. A. Hazzard, Quantum computation and quantum simulation with ultracold molecules, Nat. Phys. 20, 730–740 (2024)
[3] N. R. Hutzler, H.-I. Lu, and J. M. Doyle, The buffer gas beam: An intense, cold, and slow source for atoms and molecules, Chemical Reviews 112, 4803 (2012).

Stefan Truppe

Imperial College London

Towards a BEC of stable polar molecules

Abstract

We report recent progress toward producing a Bose–Einstein condensate of stable, deeply bound, and polar AlF molecules. AlF combines several favourable properties for reaching ultracold temperatures: its deep chemical bond makes molecule–molecule reactions endothermic, and long-lived collisional complexes are strongly suppressed, suggesting that direct evaporative cooling may be feasible without additional shielding. AlF also has an alkaline-earth-like electronic structure with a strong cycling transition in the deep ultraviolet. Using this transition, we have trapped and cooled AlF in a magneto-optical trap. We present progress toward increasing the phase-space density by implementing grey molasses cooling and by developing a Zeeman slower aimed at improving trap loading and accumulation. In addition, weak spin-forbidden transitions provide access to narrow-line cooling and accumulation in conservative traps, with potential applications in precision measurements.

Lan Cheng

Johns Hopkins

Quantum-chemical calculations of molecular properties pertinent to laser cooling

Abstract

Direct laser cooling of molecules necessitates precise knowledge about a variety of molecular parameters. In this presentation we discuss some recent efforts in quantum-chemical calculations of molecular properties pertinent to direct laser cooling, using RaF, RaOH, and $CaNH_2$ as examples, aiming to address the challenges in the construction of potential energy and property surfaces and accurate calculations of vibrational energies and wave functions.

John Doyle

Harvard University

Ultracold Laser Cooled Polyatomic Molecules for Quantum Science

Abstract

I will present an update on experiments with SrOH, CaOH and $CaNH_2$.

Javier Madronero

Universidad del Valle

Stable Dynamical Structures in Complex Quantum Systems: From the Stochastic Dynamics of Trapped Ions to Nondispersive Wave Packets in Helium

Abstract

Complex quantum systems often exhibit the coexistence of regular and chaotic dynamics, giving rise to robust structures that survive despite strong interactions, external driving, and environmental perturbations. In this talk, I will present a series of theoretical studies aimed at understanding, characterizing, and controlling such stable dynamical structures in atomic and hybrid quantum systems.

The first part of the presentation focuses on hybrid atom-ion systems, where the dynamics of trapped ions immersed in ultracold atomic gases are investigated using stochastic approaches based on the Langevin equation and event-driven molecular dynamics simulations. These methods provide insight into sympathetic cooling, energy relaxation processes, dynamical stability, and the role of micromotion in radio-frequency multipole traps.

The second part is devoted to the dynamics of strongly correlated two-electron states in helium subjected to periodic and static electric fields. Using a spectral configuration-interaction approach based on Coulomb-Sturmian functions combined with Floquet theory and complex scaling, we identify long-lived Floquet resonances associated with frozen-planet configurations and demonstrate the existence of nondispersive wave packets in fully three-dimensional helium. Particular emphasis will be placed on the stabilization mechanisms induced by external fields and on the connection between quantum localization and classical phase-space structures.

Taken together, these studies illustrate how stochastic methods, nonlinear dynamics, and quantum-spectral approaches provide complementary perspectives on the emergence and control of stable dynamical structures in complex quantum systems.

Naduvalath Balakrishnan

University of Nevada

Quantum controlled collisions of cold molecules

Abstract

Advances in quantum state preparations combined with molecular cooling and trapping technologies have enabled unprecedented control of molecular collision dynamics. This progress, achieved over the last two decades, has dramatically improved our understanding of molecular phenomena in the extreme quantum regime characterized by translational temperatures well below a kelvin. In this regime, collision outcomes are dominated by isolated partial waves, quantum threshold and quantum statistics effects, tiny energy splitting at the spin and hyperfine levels, and long-range forces. Collision outcomes are influenced not only by the quantum state preparation of the initial molecular states but also by the polarization of their rotational angular momentum, i.e., stereodynamics of molecular collisions. In this talk, I will provide an overview of recent theoretical developments for the description of stereodynamics of cold molecular collisions and their implications to cold controlled chemistry. I will also discuss our recent studies of non-adiabatic effects in Li+LiNa and K+KRb chemical reactions and the role non-adiabatically driven quantum interference plays in state-to-state chemistry of these systems at ultracold temperatures.

Robert Forrey

Penn State University

Fine-structure resolved quasi-resonant transitions of OH due to cold collisions with He and H_2

Abstract

OH is a reliable tracer of water in photodissociation regions (PDRs) surrounding molecular clouds and protoplanetary disks. UV radiation from neighboring stars or a central protostar can photodissociate water via the 2nd absorption band into a rotationally hot distribution of OH. "Prompt emission" of the rotationally hot OH is then the spectral signature of the water exposed to the UV radiation field. Modulation of a prompt emission spectrum due to collisions has never been studied due to the high gas densities that would be required and the low densities that are typically found in molecular cloud PDRs. This talk instead considers the relatively high gas densities that may be found in a PDR near the protostar of a planet-forming disk. At elevations approaching the disk plane, the UV radiation from the protostar is shielded and the temperature drops, thereby providing an interesting regime to study collision physics. In this talk, I will describe fine-structure resolved rovibrational transitions of OH due to collisions with He and H_2. Highly specific and efficient quasi-resonant vibration-rotation (QRVR) transitions are found together with spin-orbit ladder changing and lambda-doublet symmetry changing transitions. Our full database of collision rate coefficients is included in several radiative transfer models and good agreement is found with observed data from the James Webb Space Telescope.

Ronald Garcia Ruiz

MIT

Radium-Containing Molecules for Fundamental Physics

Abstract

Rapid advances in the quantum control and precision interrogation of molecules are opening new avenues for exploring the properties of atomic nuclei and the fundamental particles and interactions that govern them. In particular, molecules containing heavy radioactive nuclei with reflection-asymmetric shapes, such as radium, offer exceptional sensitivity to phenomena beyond the Standard Model, including symmetry-violating interactions and electroweak nuclear properties that remain largely unexplored. In this talk, I will present recent progress in the production and study of both neutral and ionic radium-containing molecules. I will discuss recent results, the unique challenges associated with working with radioactive molecules, and the opportunities these systems offer for precision measurements.

Tanya Zelevinsky

Columbia University

Precision Measurements and Quantum Chemistry with Ultracold Molecules

Abstract

Advances in the production and control of ultracold molecules are creating new opportunities at the interface of precision measurement, quantum science, and chemistry. We exploit these systems both to realize molecular clocks based on ultracold Sr_2, enabling precision isotope-shift measurements, tests of ab initio molecular QED, and searches for physics beyond the Standard Model, and to develop new methods for preparing and probing laser-cooled molecules, including the first magneto-optical trap of CaH. The latter efforts could provide a route to optically trapped ultracold hydrogen via controlled molecular dissociation and to quantum-state-resolved studies of ultracold chemical dynamics. I will present recent experimental progress in ultracold molecules as a platform for precision metrology and quantum chemistry.

Xing Wu

Michigan State University/FRIB

Towards quantum control and sensing with ^{227}ThO and other radioactive molecules for fundamental symmetry test

Abstract

The Standard Model of particle physics accurately describes all fundamental particles discovered so far. However, it is unable to address two great mysteries in physics, the nature of dark matter and why matter dominates over antimatter throughout the Universe. Novel theories beyond the Standard Model may explain these phenomena. These models predict very massive particles whose interactions violate time-reversal (T) symmetry and would give rise to an electric dipole moment (EDM) along the spin of electron and nucleon. Thus, searching for EDM provides a powerful probe to these new physics and sheds light on the mystery of the matter-antimatter asymmetry of the Universe. This talk outlines the roadmap to establish a new generation EDM measurement at Michigan State that can outperform the current generation of precision measurements testing hadronic T-violations. We report our ongoing effort at Facility for Rare Isotope Beams (FRIB) to perform quantum control and sensing of ^{227}ThO and other radioactive molecules. These pave the way for quantum-enhanced test of fundamental symmetry, projecting to constrain T-violating new physics in 10$\sim$100 TeV energy range, exceeding what the Large Hadron Collider and its future upgrade could probe.

Katrin Dulitz

University of Innsbruck

Towards the production of sub-Kelvin-cold negative molecular ions

Abstract

Cold quantum state-selected negative ions are relevant to various fields, ranging from mass spectrometry to astrochemistry. The ability to cool them to sub-Kelvin temperatures would open up exciting new research avenues in cold chemistry, precision measurements, and quantum science. Beyond ongoing work on the Doppler laser cooling of C_2^-, including efforts in Innsbruck [1], BN^- has recently emerged as a possible candidate ion for optical cycling and laser cooling. In this talk, I will present the results of our investigations into optical cycling schemes for cooling trapped, cryogenically cooled, trapped $^{11}B^{14}N^-$ ions using excitation from the $X^2\Sigma^+$ ground state to the $B^2\Sigma^+$ excited state [2]. These findings also provide broader insights into the fundamental limits of laser cooling negative ions, specifically concerning the consequences of transitions into intermediate electronic states, such as the $A^2\Pi$ state in BN^-. Furthermore, I will outline our progress towards the production and spectroscopic characterization of this ion. In addition, I will discuss alternative cooling strategies we are investigating for negative ions beyond direct Doppler laser cooling.

[1] M. Nötzold, R. Wild, C. Lochmann, T. Rahim, S. Purushu Melath, K. Dulitz, B. Mant, J. Franz, F. A. Gianturco and R. Wester, Phys. Rev. Lett. 131, 183002 (2023)
[2] K. Dulitz, S. V. Jerosimić, P. del Mazo-Sevillano, J. Alonso de la Fuente, C. Sanz-Sanz, L. González-Sánchez, F. A. Gianturco, Phys. Scr. 100, 055411 (2025)

Michael Drewsen

Aarhus University

Rotational excitation in sympathetic cooling of diatomic molecular ions by laser-cooled atomic ions

Abstract

Sympathetic cooling of molecular ions through Coulomb interaction with laser-cooled atomic ions is an efficient tool to prepare translationally cold molecules without, ideally, affecting the internal state of the molecular ions. However, the electric field due to the Coulomb interaction may induce rotational transitions that change the purity of initially quantum state prepared molecules.

Based on rotational state changes in single collisions of diatomic ions with atomic ions [1], in the talk, I will discuss how to estimate the overall rotational excitation accumulated over the full sympathetic cooling process in two different experimental scenarios: that of a molecular ion co-trapped with a single atomic ion and that of a molecular ion interacting with a large Coulomb crystal of atomic ions [2].

[1] J. M. Berglund, M. Drewsen, and C. P. Koch, Phys. Rev. A 113, 042816 (2026)
[2] J. M. Berglund, M. Drewsen, and C. P. Koch, Phys. Rev. A 113, 042817 (2026)

Heather Lewandowski

University of Colorado, Boulder/JILA

Quantum-state controlled single molecule catalysis using Coulomb crystals

Abstract

Sympathetically cooled molecular ions in Coulomb crystals represent a highly controlled environment to probe and control chemical reactions. These cold ion–molecule reactions are often relevant to astrochemistry and molecular physics more broadly. We build a simple catalytic cycle using Ca^+, C_2H_2, and C_3H_4, where we first produce $CaCCH^+$ through a quantum-state-controlled reaction and then, in the next step of the cycle, break the Ca–C bond through a dissociative bimolecular reaction. This produces a larger neutral hydrocarbon as the catalytic product and recycles the Ca^+, allowing the process to be repeated. This study demonstrates the possibility of controlling a complete catalytic cycle at the single-molecule level using Coulomb crystals.

Dan McCarron

University of Connecticut

Magneto-Optical Forces in AlCl

Abstract

Ultracold molecules promise new opportunities in quantum information science, quantum simulation, precision measurement, and controlled chemistry, but scalable preparation remains a key challenge. Here, I present experimental results demonstrating one dimensional magneto optical forces on AlCl molecules, a promising platform for scalable molecular qubits. We observe both damping and restoring force components and use these measurements to estimate the trap capture velocity. These results inform ongoing molecular beam slowing efforts aimed at realizing a three-dimensional magneto-optical trap. I will conclude with an outlook on complementary efforts with CH radicals, including studies of cold chemistry and simulations of Stark deceleration prior to loading a CH MOT.

Tim Langen

Technical University of Vienna

Laser Cooling of Complex Molecules

Abstract

Molecules are emerging as powerful platforms for precision measurement science, offering unique sensitivity for high-resolution spectroscopy and tests of fundamental symmetries. These experiments can probe energy scales and interactions that complement searches at high-energy collider facilities, opening new avenues for discovering physics beyond the Standard Model in previously unexplored regimes.

Achieving the required level of control over molecules demands precise manipulation of both internal quantum states and external motion, as well as long coherence times. Laser cooling provides a versatile route to meet these requirements.

While well-established techniques enable control over molecular vibrational and rotational degrees of freedom, extending laser cooling to heavy species remains challenging. In particular, complex hyperfine structures arising from multiple nuclear spins significantly complicate the realization of efficient optical cycling. Yet it is precisely these heavy, complex molecules that are especially promising candidates for searches for nuclear parity and time-reversal violation.

In this talk, I will introduce novel laser-cooling strategies designed to address these challenges. I will present experimental implementations of these techniques and their application to several isotopologues of barium monofluoride (BaF), and discuss their scalability and prospects for cooling other molecular species - including radioactive ones - relevant to precision tests of fundamental symmetries.

Finally, I will outline a new experiment based on laser-cooled BaF molecules aimed at probing nuclear-spin-dependent parity violation and the weak interaction.

Sid Wright

Fritz Haber Institut

Magneto-optical trapping and novel molecular sources with aluminum monofluoride

Abstract

Aluminum monofluoride (AlF) is the first spin-singlet molecule that has been directly laser-cooled and captured in a magneto-optical trap (MOT). A number of properties combine to make AlF a unique species: laser cooling and efficient UV-fluorescence detection are possible for any excited rotational level, via closed Q(J) lines; its lowest (metastable) spin-triplet state decays exclusively to the electronic ground state, via an extremely narrow but vibrationally diagonal transition; it can be produced in a high-brightness continuous molecular beam using conventional effusive ovens or dispensers. These features position AlF as an attractive system for experiments in the ultracold regime, despite the challenges of producing deep ultraviolet light for a MOT.

In this talk, I will give a status update on the experiments in Berlin and our plans for the future. After trapping AlF in different rotational levels, we subsequently have found that it collides with certain coated surfaces with near-zero sticking probability at room temperature. I will discuss our observations, experimental measurements of the sticking probability and consequences for future work with AlF. I believe several exciting avenues are now open: compact, inexpensive and portable sources for molecular MOTs, vapour cell experiments akin to those routinely used with alkali atoms, and the possibility to laser cool molecules in highly excited rotational levels.

Michal Tomza

University of Warsaw

Ultracold highly magnetic and polar molecules for new physics search

Abstract

I will present new classes of highly magnetic and polar diatomic molecules, which can be produced at ultralow temperatures from laser-cooled ultracold atoms. I will show a new mechanism of useful Feshbach resonances in Cr+Yb mixtures. Next, I present how high-spin Σ-state polar molecules assembled from ultracold atoms can be used to probe charge-parity violating physics beyond the Standard Model. We identified YbCr as a prime candidate to search for the electric dipole moment of the electron. We showed that the combination of relativistic ytterbium and high-spin chromium, amenable to magneto-association, leads to molecules with easy-to-polarize parity doublets and large intramolecular electric fields. Based on ab initio results for molecular constants, we predicted a sensitivity of $\delta de = (6 \times 10^{-31}/(\mathrm{nday})^{1/2})$ e.cm via standard spin-precession measurements, assessed the experimental feasibility, and discussed potential extensions to more advanced quantum control as well as searches of the nuclear magnetic quadrupole moment. This work paves the way to next-generation searches for new physics with ultracold molecules in both the leptonic and hadronic sectors.

Piotr Wcislo

Nicolaus Copernicus University, Torun, Poland
Hot Topic

Trapping cold hydrogen molecules

Abstract

Due to its simplicity, H_2 constitutes a perfect tool for testing fundamental physics: testing quantum electrodynamics, determining fundamental constants, or searching for new physics beyond the Standard Model. H_2 has a huge advantage over the other simple calculable systems of having a set of a few hundred ultralong living rovibrational states, which implies the ultimate limit for testing fundamental physics with H_2 at a relative accuracy level of 10^{-24}. The present experiments are far from this limit. I will present our so far results of an ongoing project aimed at trapping cold H_2 [1]. We develop an ultra-strong optical dipole trap. The time-dependent potential is going to recapture the coldest fraction of the cryogenic H_2 cloud. We develop a new type of cryogenic effusive valve to prepare a cryogenic H_2 sample. I will also discuss our preliminary results obtained with cryogenic cavity [2] and our recent results on 1D-trapping spectroscopy of H_2 obtained in the group of Wim Ubachs in Amsterdam [3].

[1] H2TRAP ERC Starting grant
[2] K. Stankiewicz, et al., Cavity-enhanced spectroscopy in the deep cryogenic regime for quantum sensing and metrology, Nature Physics (2026)
[3] W. Ubachs, F. M. J. Cozjin, M. L. Diouf, C. Lauzin, H. Jóźwiak and P. Wcisło Letokhov-Chebotayev Intracavity Trapping Spectroscopy of H_2. Physical Review Letters 135, 223201 (2025)

Ferruccio Castellini

Imperial College London
Hot Topic

Measuring the eEDM with Ultracold YbF Molecules

Abstract

The standard model predicts a value for the bound electron's electric dipole moment (eEDM, d_e), $d_e \approx 10^{-35}$ e.cm, far smaller than what is predicted by theories beyond the standard model, typically $d_e \approx 10^{-31} - 10^{-24}$ e.cm. To date, the current experimental upper limit is set at $d_e < 4.1 \times 10^{-30}$ e.cm. Further improvements in experimental precision are likely to discover new physics or rule out much of the parameter space of popular theories. The eEDM can be measured through the precession of the electron spin in an applied electric field. The precision is enhanced enormously when the electron is bound into a heavy polar molecule. The statistical precision depends on the spin precession time so a slow, ultracold beam of molecules has the potential to measure the eEDM to greater precision than the current limit. We use a beam of collimated ultracold YbF molecules produced by a cryogenic buffer gas source and then laser cooled to 100 µK in the two transverse axes. Such cooling increases beam brightness and spin-precession time, leading to a projected statistical uncertainty below 10^{-30} e.cm. However, magnetic field noise can severely limit the precision of our phase sensitive measurement of d_e. To overcome this source of noise, we have developed and characterized a novel spin precession region, including ceramic electric field plates, a glass vacuum chamber, magnetometry, and a four-layer magnetic shield with a shielding factor $> 10^5$. We prepare the eEDM-sensitive state using a Raman transition and detect the molecules with near unit efficiency. We are currently working to reach the shot noise limit of statistical sensitivity and understanding the possible sources of systematics.

Jutta Toscano

University of Basel

Orchestrating astrochemistry: Do dancing molecules live longer in Space?

Abstract

The combined use of electric fields, magnetic fields and laser light affords us an ever-increasing level of control over the properties of atoms and molecules, enabling reactivity to be probed as a function of their various degrees of freedom [1, 2]. Here, we discuss how these tools can be harnessed to investigate whether the addition of single quanta of rotational excitation makes molecules react slower in interstellar environments such as diffuse and dense interstellar clouds [3]. Additionally, we present preliminary results on the reactivity of water towards CO^+ ions.

[1] Cold and controlled chemical reaction dynamics, J. Toscano, H. J. Lewandowski and B. R. Heazlewood, Phys. Chem. Chem. Phys. 22, 9180 (2020)
[2] Control of chemical reactions in radiofrequency ion traps, P. Paliwal, J. Toscano and S. Willitsch, Annu. Rev. Phys. Chem. 77, 465 (2026)
[3] Rotational-state-selected carbon astrochemistry, J. Toscano, Chimia 78, 40 (2024)

Leon Karpa

Hannover University

Mesoscopic molecules in ultracold ion-polar molecule systems

Abstract

The rapidly evolving fields of ultracold polar molecules and mixtures of ions and neutral quantum gases offer exciting avenues in various interdisciplinary domains, including quantum chemistry, many-body physics, quantum simulation, and information processing [1,2]. These largely complementary research areas have both experienced substantial advancements in recent years, such as the demonstration of molecular quantum degenerate gases [3,4] and the observation of quantum effects in ion-atom collisions [5,6].

In this presentation, I will discuss methodologies for preparing mixtures of ultracold ions and quantum gases composed of polar molecules. This novel hybrid system offers access to a diverse hierarchy of simultaneously active and adjustable interactions. As an application, this enables the alignment and attraction of molecules through charge-dipole interactions, while simultaneously inducing anisotropic dipole-dipole repulsion to prevent collapse [7]. I will present first theoretical studies of the ground-state structure and stability of a single ion immersed in a two-dimensional ultracold gas of polar molecules. These findings suggest that the interplay of ion-molecule and molecule-molecule interactions enables the formation of robust mesoscopic molecular ions. This hybrid approach opens the way to the exploration of charged impurities in quantum baths with anisotropic interactions.

[1] Bohn et al., Science 357, 1002 (2017)
[2] Tomza et al., Rev. Mod. Phys. 91, 1–57 (2019)
[3] Schindewolf et al., Nature 607, 677 (2022)
[4] Bigagli et al., Nature 631, 289 (2024)
[5] Weckesser et al., Nature 600, 429 (2021)
[6] Feldker et al., Nat. Phys. 16, 413 (2020)
[7] Karpa and Dulieu, Phys. Rev. Research 7, 021002 (2025)

Prerna Paliwal

University of Basel
Hot Topic

Cold Chemistry with Single Polyatomic Molecular Ions

Abstract

Polyatomic molecular ions offer new opportunities for precision spectroscopy and quantum control due to their rich internal structure. At the same time, their complex energy levels and lack of cycling transitions makes their state-preparation and readout challenging. I will present a cryogenic trapped-ion experiment which we recently developed and our first results demonstrating chemistry with single molecular ions, enabling control and detection at the level of individual reaction events. We will also discuss how this single-ion methodology opens a new route to studying cold ion-neutral collisions, pushing into the cold regime where quantum effects can influence reaction dynamics. I will also outline our efforts toward quantum logic spectroscopy of polyatomics in which a co-trapped atomic ion serves as a coolant and messenger for the internal state of the molecular ion, enabling non-destructive internal-state identification by mapping molecular information onto an atomic ion for state-resolved reaction control.

Lawrence Cheuk

Princeton University

Magnon Dynamics and Spin-Squeezing with Molecular Tweezer Arrays

Abstract

Optical tweezer arrays of polar molecules are a new platform for quantum science that combines the richness of molecules with the microscopic control of tweezer arrays. In this talk, I will present recent work investigating interacting spin physics with mesoscopic molecular arrays. First, I will report quantum simulation experiments studying many-body spin dynamics in 1D interacting spin models realized with interacting molecules. Specifically, we explore a variety of non-equilibrium many-body dynamics in $1/r^3$ XXZ/XYZ spin chains, including coherent quantum walks of single spin excitations, emergence of two-magnon bound states, and creation and annihilation of magnon pairs. Second, I will describe work using 1D XXZ models to create and probe metrologically useful many-body entangled states of molecules for the first time. I will describe how we create spin-squeezed states, demonstrate their metrological advantage, and transduce them in non-interacting molecular states. In addition, I will discuss investigations of the spin correlations of the squeezed states, which reveal the emergence of extended correlations near the Heisenberg point, bipartite entanglement, and EPR steering.

Kaden Hazzard

Rice University

Hubbard models with ultracold shielded molecules in optical lattices

Abstract

While electromagnetic shielding dramatically suppresses losses in ultracold molecules, it also alters the interactions governing their many-body physics. It produces a strong repulsive core extending to ∼100 nm, raising doubts that shielded molecules can simulate Hubbard models beyond the hard-core limit [effectively infinite (U/t)]. The strong, long-range interactions also preclude the perturbative techniques used to calculate atomic Hubbard parameters.

In this talk, I will show through nonperturbative calculations that shielded molecules are flexible simulators of extended Hubbard models. Standard shielding schemes yield widely tunable (U/t) of either sign, including near zero, with independent control of on- and off-site interactions. An application enabled is an "interaction microscope" that probes otherwise-inaccessible inter-hole interaction potentials in a doped Mott insulator.

These models also possess SU(N) nuclear-spin symmetry with capabilities unavailable in other SU(N) platforms: N = 36 or larger, tunable interactions – including attraction, and both bosonic and fermionic particles. I will discuss opportunities ranging from attractive SU(N) many-body physics to novel spin textures.

Ian Stevenson

University of Virginia

Dipolar Quantum Matter with Polar Molecules

Abstract

Recently, the first BEC of polar molecules was realized at Columbia. By eliminating two- and three-body collisional losses via double microwave shielding, gases of sodium-cesium molecules are evaporatively cooled to quantum degeneracy. Dipolar interactions can be induced by unbalancing the two microwave fields or by inducing ellipticity in one of the fields. As the dipolar interactions increase, the gas transitions to either self-bound droplets or droplet arrays. For very strong dipolar interactions we estimate that their characteristic length scale can exceed the interparticle separation. In totality, polar molecules offer a new paradigm for quantum gases with strong and flexible long-range interactions.