ICOLS 2023, Estes Park, Colorado

	Sunday	**Monday**	**Tuesday**	**Wednesday**	**Thursday**	**Friday**	
	6/25/23	**6/26/23**	**6/27/23**	**6/28/23**	**6/29/23**	**6/30/23**	
7:00 AM		Breakfast 7 am to 8:30 am	Breakfast	Breakfast	Breakfast	Breakfast	**7:00 AM**
8:30 AM		**Klaus Blaum**	**Stephen Leone**	**Mark Kasevich**	**Hidetoshi Katori**	**Eric Cornell**	**8:30 AM**
9:00 AM		**Kenneth Baldwin**	**Margaret Murnane**	**Dietrich Leibfried**	**Piet Schmidt**	**Zheng-Tian Lu**	**9:00 AM**
9:30 AM		**Dylan Yost**	**Marco Bellini**	**Philipp Schindler**	**Peter Thirolf**	**Saïda Guellati-Khélifa**	**9:30 AM**
10:00 AM		Coffe Break	Coffe Break	Coffe Break	Coffe Break	Coffe Break	**10:00 AM**
10:30 AM							**10:30 AM**
		Lawrence Cheuk	**John Doyle**	**Benjamin Lev**	**Magdalena Zych**	**Lee McCuller**	
11:00 AM							**11:00 AM**
		Tim Langen	**Xinyu Luo**	**Dan Blumenthal**	**Yevgeny Stadnik**	**Jeff Kimble & Carl Caves**	
11:30 AM							**11:30 AM**
		Lunch	Lunch	Lunch	Lunch	Lunch	
12:00 PM	**JILA/CU/NIST**			Box to go		Box to go	**12:00 PM**
	Open House and Lab Tours						
12:30 PM	Boulder, CO					Bus to Airport x2 12:30pm	**12:30 PM**
	12pm to 4pm			**Excursion / Free Time**			
1:00 PM				12:30 pm to 6:30pm			**1:00 PM**
		Monika Aidelsburger	**Kang-Kuen Ni**	Rocky Mountain Nat. Park	**Vladan Vuletić**		
1:30 PM				Sign up for bus tour			**1:30 PM**
		Jeff Thompson	**Ernst Rasel**	krista.beck@colorado.edu	**Tanya Zelevinsky**		
2:00 PM						Bus to Boulder x1 2pm	**2:00 PM**
		Poster Session	**Poster Session**		**Poster Session**		
2:30 PM						Bus to Airport x1 2:30pm	**2:30 PM**
						Colorado State University	
3:00 PM						**Open House and Lab Tours**	**3:00 PM**
						Fort Collins, CO	
3:30 PM	Bus Boulder to Estes Park x2					2:30pm to 4pm	**3:30 PM**
4:00 PM							**4:00 PM**
4:30 PM							**4:30 PM**
5:00 PM							**5:00 PM**
5:30 PM	**Welcome Reception**						**5:30 PM**
	Estes Park, CO						
6:00 PM	5:30 to 7:30						**6:00 PM**
6:30 PM	Bus Boulder to Estes Park x1						**6:30 PM**
7:00 PM				**Conference Dinner**			**7:00 PM**
				7pm to 9pm			
7:30 PM							**7:30 PM**
8:00 PM			**Movie Night**				**8:00 PM**
			8pm start				
8:30 PM							**8:30 PM**
9:00 PM	Bus Boulder to Estes Park x1						**9:00 PM**
9:30 PM							**9:30 PM**
10:00 PM							**10:00 PM**

***Limited number of seats on buses**
Reserve your seat on a bus by emailing krista.beck@colorado.edu

ICOLS Speakers

Monika Aidelsburger

Max-Planck-Institut für Quantenoptik
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State-dependent potentials for the 1S 0 and 3P 0 clock states of neutral ytterbium atoms

The ground and meta-stable clock state pair in ytterbium provides an excellent resource for quantum metrology, simulation and computation applications. Being capable of individually addressing the two optical clock qubit states in a state-selective manner enhances the controllability of such systems, allowing for novel methods for state preparation, read-out or simulation schemes. Utilizing high-resolution clock spectroscopy, we present the first measurements of the Yb ground-state tune-out wavelength and of two new magic wavelengths [1]. We further showcase how this will be used in our hybrid tweezer-lattice experiment to probe and engineer lattice gauge theories, using state-dependent potentials to robustly implement local gauge invariance [2].

[1] arXiv: 2305.20084
[2] PRX Quantum 4, 020330 (2023)

Professor Kenneth Baldwin
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The Australian National University
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Verifying QED through precision measurement of the metastable Helium tune-out frequency

Quantum electrodynamics is one of the most stringently tested theories underpinning modern physics, so it is important to challenge QED using novel, independent tests to uncover any potential new physics. Here we present a new test of QED [1] by measuring the "tune-out" frequency for metastable helium between transitions to the 2^3P and 3^3P manifolds, at which point the dynamic polarizability vanishes and the atom does not interact with applied laser light. The experimentally determined value of 725,736,700(260) MHz differs from our calculated theoretical value of 725,736,252(9) MHz by 1.7 times the measurement uncertainty (σ), and is able resolve both the QED contributions (~30σ) and retardation corrections (~2σ). It is notable that by ignoring the retardation correction term — proposed in [2] and included here in our tune-out frequency calculations — the difference between theory and experiment is $\sim$0.1σ.

[1] B.M. Henson *et al.*, Science **376**, 199–203 (2022).

[2] K. Pachucki and M. Puchalski, Phys. Rev. A **99**, 041803 (2019).

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Manipulating the character and shape of ultrashort quantum light states

Gaining a full control of the state and mode of nonclassical light is among the major challenges in the path of future quantum technologies.

In recent years, quantum state engineering has quickly evolved, with new tools and techniques, such as photon addition and subtraction, which have demonstrated their extreme versatility for performing operations normally unavailable in the realm of Gaussian quantum optics [1,2]. While photon subtraction can enhance nonclassicality and entanglement in a quantum light state, photon addition has the unique capability of creating nonclassicality and entanglement from scratch, whatever the input [3,4].

However, engineering quantum light states in a single, well-defined, mode is rarely enough. In real experiments, states are often prepared in modes that do not coincide with those used for their processing and detection [5], or for the optimal coupling to matter systems [6]. Moreover, gaining access to the rich mode structure of quantum light would greatly increase the capacity of communicating, manipulating, and storing quantum information. Therefore, controlling the modes that host the quantum states is also of fundamental importance.

In this talk, I will briefly present some recent experimental results towards the controlled generation, manipulation, and characterization of the quantum state and of the mode structure of ultrashort light wavepackets.

[1] M. Bellini and A. Zavatta, Manipulating light states by single-photon addition and subtraction, *Progress in Optics* **55**, 41 (2010).
[2] N. Biagi, S. Francesconi, A. Zavatta, and M. Bellini, Photon-by-photon quantum light state engineering, *Progress in Quantum Electronics*, **84**, 100414 (2022).
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[4] N. Biagi, L.S. Costanzo, M. Bellini, and A. Zavatta, Entangling macroscopic light states by delocalized photon addition, *Physical Review Letters* **124**, 033604 (2020).
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[6] L.S. Costanzo, A.S. Coelho, D. Pellegrino, M.S. Mendes, L. Acioli, K.N. Cassemiro, D. Felinto, A. Zavatta, and M. Bellini, Zero-area single-photon pulses, *Physical Review Letters*, **116**, 023602 (2016)

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Precision Tests of Fundamental Interactions and Their Symmetries using Exotic Ions in Penning Traps

The four fundamental interactions and their symmetries, the fundamental constants as well as the properties of elementary particles like masses and moments, determine the basic structure of the universe and are the basis for our so well tested Standard Model (SM) of physics. Performing stringent tests on these interactions and symmetries in extreme conditions at lowest energies and with highest precision by comparing, e.g., the properties of particles and their counterpart, the antiparticles, will allow us to search for physics beyond the SM. Any improvement of these tests beyond their present limits requires novel experimental techniques.

An overview is given on recent mass and *g*-factor measurements with extreme precision on single or few cooled ions stored in Penning traps. Among others the most stringent test of CPT symmetry in the baryonic sector could be performed by mass comparison of the antiproton with the H^- ion. Furthermore, the development of a novel technique, based upon the coupling of two ions as an ion crystal, enabled the most precise determination of a *g*-factor difference to date. This difference, determined for the isotopes $^{20,22}Ne^{9+}$ with a relative precision of 5.6×10^{-13} with respect to the *g* factor, improved the precision for isotopic shifts of *g* factors by about two orders of magnitude. Our latest results on precision measurements with exotic ions in Penning traps will be presented.

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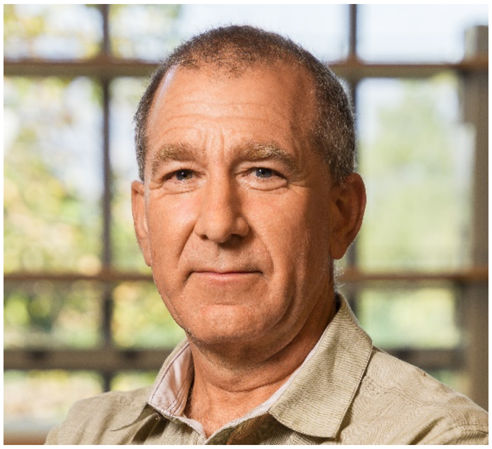

Visible Light Photonic Integration for Atom and Quantum Science

Visible light photonic integration will enable compact, low weight, and reliable quantum and atomic sensing systems. In this talk we will review the latest advances in the ultra-low loss silicon nitride integration platform and heterogeneous integration, that enable quantum systems on chip (QSOC). Various technologies supported include visible light and ultra-narrow linewidth lasers, modulators, laser noise measurement, frequency stabilization circuits and reference cavities, beat-note detection, spectroscopy locks, and atom trap and cooling beam emitters. We will also talk about current integration and QSOCs for cold atom 3D-MOTs, trapped ions, and the potential for future neutral atom trapping.

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Frequency-Dependent Squeezing: From There to Here

Jeff Kimble and Carl Caves

The talk, which will be styled as Carl Caves interviewing Jeff Kimble, will present a brief history of squeezed-light interferometry, with a focus on Jeff Kimble's contributions to the field and a particular emphasis on Kimble's invention of the filtration-cavity method for implementing frequency-dependent squeezing **.**

Professor Lawrence Cheuk
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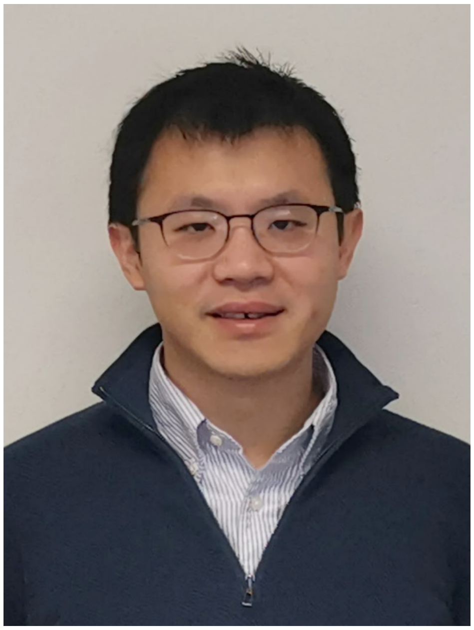

Optical Tweezer Arrays of Laser-Cooled Molecules as a New Quantum Science Platform

Polar molecules, with their rich internal structure and tunable long-range interactions, have long been proposed for quantum information processing and quantum simulation of a wide range of many-body Hamiltonians. For these applications, the abilities to detect and manipulate individual particles are often useful and sometimes necessary. By offering microscopic detection and control at the single-molecule level, optical tweezer arrays of polar molecules therefore promise to be a new versatile platform for quantum science. In this talk, I will report on several recent advances from our group on controlling individual laser-cooled molecules trapped in rearrangeable tweezer arrays. I will describe our work on creating defect-free arrays of CaF molecules in 1D and observing coherent dipolar interactions between molecular pairs, and discuss how these results establish the building blocks for quantum information processing and simulation of quantum spin models. I will also describe our recent results towards full quantum control of laser-cooled molecules including their motional degrees of freedom. Specifically, I will report on our work on demonstrating Raman sideband cooling for molecules, and discuss how it provides a new pathway towards low-entropy molecular ensembles through laser-cooling.

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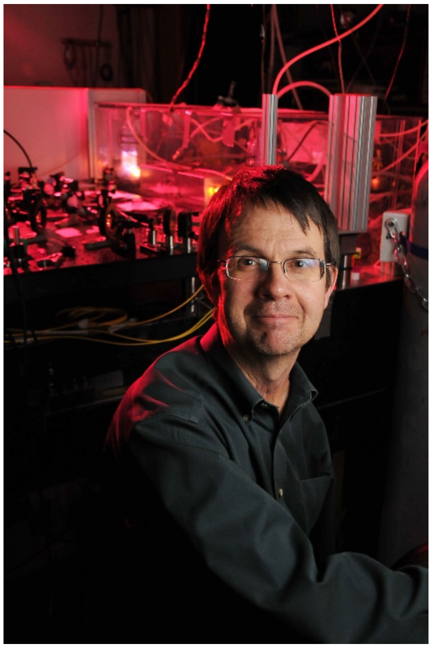

A New Limit on the Electron Electric Dipole Moment

At JILA we have completed a measurement on the electron electric dipole moment (eEDM) in HfF+ confined in a Paul trap. [Roussy, Caldwell, Wright, Cairncross, Shagam, Ng, Schlossberger, Park, Wang, Ye and Cornell, arXiv:2212.11841]. The new measurement, consistent with zero, yields a factor of two more stringent than the previous best result, from ACME [ACME Collaboration, Nature 562, 355 (2018).] Combining the two results yields tighter limits also on CP violating effects in the baryonic sector. I will describe the new result and also touch on efforts to realize an additional factor of ten improvement in sensitivity.

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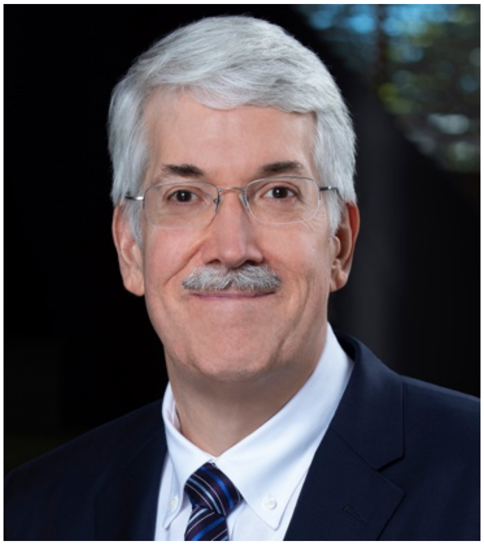

Ultracold molecules for quantum science and particle physics

Polar molecules, due to their intrinsic electric dipole moment and their controllable complexity, are a powerful platform for precision measurement searches for physics beyond the standard model (BSM) and, potentially, for quantum simulation/computation. This has led to many experimental efforts to cool and control molecules at the single quantum state level, including with CaF. I will present work demonstrating entanglement and iSWAP operations with individual CaF molecules in optical tweezers. Polyatomic molecules have attracted new focus as potential novel quantum resources with distinct advantages - and challenges - compared to both atoms and diatomic molecules. I will discuss features of polyatomic molecules that can be used in quantum simulation/computation, the search for BSM physics, and ultracold chemistry. I will discuss our results on the laser cooling of polyatomic molecules into the ultracold regime, including the laser cooling of the polyatomic molecules SrOH, YbOH, CaOH and $CaOCH_3$. Finally, if time permits, I will discuss recent measurements on spin precession in a metastable vibrational bending mode of CaOH, useful for future experiments searching for the electron electric dipole moment, a probe for BSM physics in the >10 TeV range.

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Matter-wave interferometry for testing fundamental physics

C. Debavelaere1, L. Morel1, Z. Yao1, C. Carrez1, C. Solaro1 P. Cladé and
S. Guellati-Khélifa1,2

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An atom interferometer is a quantum sensor that relies on the superposition of atomic wave packets and measures the difference in atomic phase between two interfering paths. Atom interferometry experiments have proved a remarkable ability to perform ultra-precise measurements of inertial acceleration, gravity and fundamental constants that can be used to test the Standard Model. They offer interesting perspectives for searches for new physics beyond the Standard Model or for the detection of gravitational waves in a frequency range

inaccessible to experiments using optical interferometry.

To fully exploit the potential of atom interferometers, efforts are currently focused on developing new methods to increase the length and separation of interfering paths, understanding and controlling systematic biases, implementing quantum entanglement protocols, with a view to significantly increasing both the sensitivity and the accuracy. Efforts are also underway to extend atom interferometry to a broader range of atomic species.

At the Laboratoire Kastler Brossel, we are working on two experiments. The first one concerns the measurement, by atom interferometry, of the recoil of a rubidium atom that absorbs a photon. From this measurement, we have determined the fine-structure constant α with a relative uncertainty of 8.1 × 10−11 [1]. This value enabled the calculation of the most accurate value of the electron magnetic moment predicted by the standard model [2], but it differs by 5 σ from the value of α deduced from the recoil of the caesium atom [3]. Resolving this discrepancy is crucial for the test of the Standard Model, which relies on the comparison between theoretical and experimental values of the electron's magnetic moment [4]. We are currently working on a thorough investigation of systematic effects. The second experiment deals with atom interferometry driven by frequency comb. Until recently, experiments had only used continuous-wave laser sources to split and recombine atomic wave-packets. We demonstrated an atom interferometer where the beam splitters are realized with pulsed lasers, more specifically a frequency-comb lasers [5]. This technique, which we have demonstrated in the visible spectrum on rubidium atoms, paves the way for extending light-pulse interferometry to other wavelengths (e.g. deep-UV to X-UV) and therefore to new species, since one can benefit from the high peak intensity of the ultrashort pulses which makes frequency conversion in nonlinear media efficient.

In my talk, I will present the latest results of both experiments.

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[2] T. Aoyama, T. Kinoshita, and M. Nio, "Theory of the Anomalous Magnetic Moment of the Electron," Atoms, vol. 7, p. 28, Feb. 2019.
[3] R. H. Parker, C. Yu, W. Zhong, B. Estey, and H. M˙uller, "Measurement of the fine-structure constant as a test of the Standard Model," Science, vol. 360, pp. 191–195, Apr. 2018.
[4] X. Fan, T. G. Myers, B. A. D. Sukra, and G. Gabrielse, "Measurement of the electron magnetic moment," Phys. Rev. Lett., vol. 130, p. 071801, Feb 2023.
[5] C. Solaro, C. Debavelaere, P. Clad́ e, and S. Guellati-Khelifa, "Atom interferometer driven by a picosecond frequency comb," Phys. Rev. Lett., vol. 129, p. 173204, Oct 2022.

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Distributed quantum sensing with networks of entangled atomic ensembles

Abstract: The noise performance of atomic sensor networks can improve with non-local entanglement protocols. Here we show how a modified quantum non-demolition spin squeezing protocol improves two node atomic clock and atomic interferometer networks. These protocols can be directly applied to recently demonstrated gravity gradient atomic interferometer configurations. Applications of such networks range from satellite geodesy to gravitational wave and ultra-light dark matter detection. We also show how these methods can be extended to larger networks.

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Development of transportable optical lattice clocks and applications

An “optical lattice clock” benefits from a low quantum-projection noise (QPN) by simultaneously interrogating many atoms trapped in an optical lattice [1]. The essence of the scheme is an engineered perturbation based on the “magic frequency” protocol, which has been proven successful up to 10^{-18} uncertainty [2-4]. About a thousand atoms enable such clocks to achieve 10^{-18} stability in a few hours. This superb stability is especially beneficial for chronometric leveling [5-7], which determines a centimeter-level height difference of the clocks located at remote sites by the gravitational redshift [8].

In transportable clocks [9], the potential stability of the optical lattice clocks is severely limited by the Dick effect [10] caused by the frequency noise of a compact clock laser. We proposed a “longitudinal Ramsey spectroscopy” [11] to improve the clock stability by continuously interrogating the clock transition. Two key ingredients for the continuous clock, continuous loading of atoms into a moving lattice [12] and longitudinal excitation of the clock transition, are reported. In addition, we report our recent development of compact and accurate optical lattice clocks in collaboration with industry partners.

This work received support from JST-Mirai Program Grant Number JPMJMI18A1, Japan.

References

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[8] T. Takano et al., Geopotential measurements with synchronously linked optical lattice clocks, Nat. Photon. 10, 662 (2016).

[9] N. Ohmae et al., Transportable Strontium Optical Lattice Clocks Operated Outside Laboratory at the Level of 1018 Uncertainty, Advanced Quantum Technologies, 2100015 (2021).

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[11] H. Katori, Longitudinal Ramsey spectroscopy of atoms for continuous operation of optical clocks, Appl. Phys. Exp. 14, 072006 (2021).

[12] R. Takeuchi, H. Chiba, S. Okaba, M. Takamoto, S. Tsuji, and H. Katori, Continuous outcoupling of ultracold strontium atoms combining three different traps, Appl. Phys. Exp. 16, 042003 (2023).

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Frequency-Dependent Squeezing: From There to Here

Abstract: The talk, which will be styled as Carl Caves interviewing Jeff Kimble, will present a brief history of squeezed-light interferometry, with a focus on Jeff Kimble's contributions to the field and a particular emphasis on Kimble's invention of the filtration-cavity method for implementing frequency-dependent squeezing.

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Dipolar supersolids: From magnetic atoms to molecules

I will present a series of experiments with ultracold dysprosium atoms, which feature the strongest magnetic dipole moment in the periodic table. Such gases can form exotic droplets that are - counterintuitively - self-bound by quantum fluctuations [1]. These droplets are a 100 million times less dense than helium droplets, but exhibit similar liquid-like properties. Most notably, the gases can self-organize to form a supersolid state of matter [2]. Such a supersolid is a paradoxical state in which atoms assume a rigid periodic pattern, as in a crystal, and yet flow without friction, as in a superfluid. We characterize the coherence of this exotic state, its elementary excitations, fluctuations and superfluid properties [3-5]. In particular, we find a rich phase diagram with many different supersolid states characterized by different patterns [6]. Finally, I will briefly report on how further insights into the nature of supersolids can be explored using future molecular Bose-Einstein condensates [7].

[1] M. Schmitt et al., Nature 539, 259 (2016).
[2] F. Boettcher et al., Phys. Rev. X 9, 011051 (2019).
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[4] J.-N. Schmidt et al., Phys. Rev. Lett. 126, 193002 (2021)
[5] J. Hertkorn et al., Phys. Rev. X 11, 011037 (2021)
[6] J. Hertkorn et al., Phys. Rev. Research 3, 033125 (2021)
[7] M. Schmidt et al., Phys. Rev. Research 4, 013235 (2022)

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Addressing challenges in scaling of trapped ion quantum information processors at NIST

In this talk, possible pathways to fault-tolerant large-scale quantum information processors based on trapped ions are presented. The envisioned machines incorporate millions of qubits, feature operation errors on physical qubits of order 10-4 and memory coherence times on the order of hours. Qubit connectivity with sufficiently low crosstalk is achieved by moving ions around in a large array of traps and executing operations on small groups of ions that are sufficiently isolated from all other qubits and the environment. 1 Fault-tolerant execution of complex algorithms is facilitated by extensive use of "helper qubits" that serve to cool the motion, initialize internal states, and read out error syndromes without compromising computational qubits in the algorithm substantially.

While building a machine of this scale is currently out of reach, present efforts can inform this vision and the performance of many necessary components can be demonstrated in separate proof-of-principle experiments in dedicated, smaller scale setups. Relevant experiments in the Ion Storage Group at NIST and in other laboratories will be discussed.

1 D. J. Wineland et al., J. Res. Nat. Inst. Stand. Technol. 103, 259 (1998).

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Coherent Molecular Dynamics with X-rays

Ultrafast X-ray spectroscopic investigations use transitions from localized inner shells of specific atomic sites in molecules or solids to valence orbitals or bands. The X-ray spectroscopic approach obtains new information about coherent electronic and vibrational dynamics. The interpretation of such spectra involves a new regime of core-to-valence X-ray probing that depends on energy shifts due to surrounding electronic densities, bond elongation with vibrational excitation, and electronic coherences due to charge migration. Coherent vibrational superpositions reveal different slopes of several inner shell potentials with bond extension in sulfur hexafluoride as well as Fermi resonance coupling in carbon dioxide in the X-ray. Vibronic superpositions composed of both electronic and vibrational parts are in dynamic interplay in small molecules, revealing windows on detection of both electronic and vibrational superpositions. Phase information contained in complex transition dipole moments of coherent superpositions provides new insight into how charge alterations surrounding specific atoms on different sites of a molecule are manifested. Jahn-Teller distortion is observed on few-femtosecond timescales in methane as the molecule abruptly changes symmetry, with a few periods of ensuing coherent vibrational motion. Progress in revealing the full power of time-resolved X-ray spectroscopy for the investigation of novel features in molecular coherent dynamics is described.

[1Y]. Kobayashi and S. R. Leone, " Characterizing coherences in chemical dynamics with attosecond time-resolved X-ray absorption spectroscopy," J. Chem. Phys. 157, 180901 (2022).
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Replica symmetry breaking in an open quantum spin glass

Optical cavity QED provides a versatile platform with which to explore quantum many-body physics in driven-dissipative systems [1]. Confocal cavities host both local and all-to-all, sign-changing, photon-mediated spin interactions [2]. The latter enable the study of spin glasses in a quantum optical setting [3]. We experimentally program fully connected interaction graphs between multiple BECs located inside the cavity [4]. This realizes an anisotropic XY-model. By using the confocal cavity as an active quantum gas microscope, where light simultaneously mediates the interaction and images the spin state, we microscopically study the model's magnetic phases. We observe two low-temperature ferromagnetic phases, and a spin glass phase that hosts vector RSB. These results enable further microscopic study of associative memories [5] and the influence of entanglement in spin glass physics [6].

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Microwave-shielded molecular Fermi gases and ultracold field-linked tetratomic molecules

Stable molecular Fermi gases with strong dipolar interactions provide unique opportunities for studying exotic quantum matter such as p-wave superfluidity and extended Fermi-Hubbard models. I will first show our endeavors in understanding and controlling collisions of ultracold molecules, which eventually allow us to stabilize the molecular gas by microwave shielding. This technique enables the evaporation of polar molecules to temperatures well below the Fermi temperature [1]. The intermolecular potential can be flexibly tuned by the microwave field, allowing us to observe field-linked resonances in collisions of polar molecules. It provides a universal tuning knob to independently control the dipolar interaction and contact interaction [2]. In the end, I will present the creation of ultracold field-linked tetratomic molecules by electroassociation in a degenerate Fermi gas of microwave-shielded polar molecules [3]. Additionally, I will discuss several exciting new possibilities associated with these field-linked molecules.

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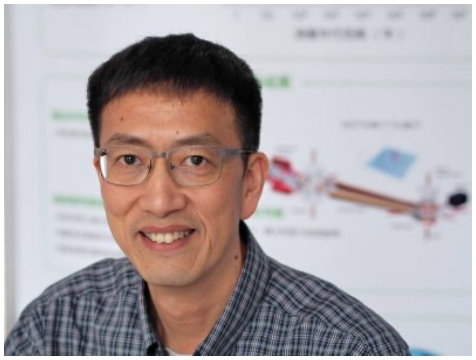

An atom-trap method for analyzing ^{41}Ca/Ca in bones and rocks at the 10^{-16} level

Calcium is a major element in the biosphere and lithosphere. Its rare isotope ^{41}Ca, with a half-life of 99 thousand years and isotopic abundances in the range of 10^{-16} – 10^{-15}, can trace environmental processes at an age scale beyond the reach of ^{14}C. We present an Atom Trap Trace Analysis (ATTA) method for ^{41}Ca/Ca analysis, realizing a precision of 10% at the level of 10^{-16} with samples of bones, rocks and seawater, and achieving a detection limit at the 10^{-17} level, well below the distribution of natural abundances. This table-top method is poised for studies of calcium-containing samples of Middle- and Late-Pleistocene in geoscience and archeology.

ATTA is also used to analyze the environmental radioactive isotopes ^{85}Kr, ^{39}Ar, and ^{81}Kr. In collaboration with earth scientists, we are dating groundwater and mapping its flow in major aquifers around the world, and dating old ice from the deep ice cores of Antarctica, Greenland, and the Tibetan Plateau. For an update on this worldwide effort, please google "ATTA Primer".

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Wielding Frequency Dependent Squeezing against Quantum Back-Action in the LIGO Gravitational Wave Observatories

Optical interferometer observatories such as LIGO have begun a new era of astrophysics by measuring the length of their vast arms to such precision that gravitational waves from distant collisions of black holes and neutron stars are now regularly observed. This past run, the global gravitational wave network itself entered a new era, whereby every detector has enhanced sensitivity using quantum squeezed states of light, limited by measurement back-action and optical loss. LIGO is now operating its "Frequency-dependent squeezing" upgrade as it starts the next observing run. This technique suppresses back-action in the form of quantum radiation pressure, seemingly bypassing trade-offs from Heisenberg uncertainty. This talk will overview quantum enhancements to enhance astrophysics, including how squeezed light works, what limits it, and how to use it to avoid back-action. Future, proposed observatories such as Cosmic Explorer will push quantum technologies even further and can potentially benefit from techniques beyond squeezing.

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Attosecond Quantum Technologies for Advanced Materials Science and Metrology

Next-generation nano and quantum devices have increasingly complex 3D structure. As the dimensions of these devices shrink to the nanoscale, their performance is often governed by interface quality or precise chemical, interfacial or dopant composition. Characterizing their structural and functional properties is challenging, requiring real-time, high-fidelity probes that can nondestructively probe large areas.

High harmonic quantum light sources provide an exquisite source of short wavelength light, with unprecedented control over the spectral, temporal, polarization and orbital angular momentum of the emitted waveforms, from the UV to the keV photon energy regions.[1,2] These advances are providing powerful new tools for near-perfect x-ray imaging, for coherently manipulating quantum materials using light, and for extracting the functional transport, electronic, magnetic and mechanical properties of ultrathin films and nanosystems.[3-5]

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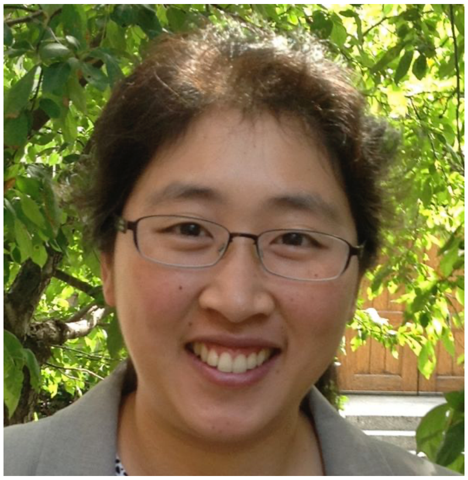

Programmable tweezer arrays of molecules for quantum science

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Quantum Gas Interferometry

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Quantum information processing with trapped ions - from two-level atoms to molecules?

Quantum operations in trapped-ion quantum processors can be interpreted as precise laser spectroscopy techniques. In such devices, the information is stored in a two-level system embedded in a trapped atomic ion. This encoding in a two-dimensional Hilbert space is known as a qubit. It is well known that information can be stored in a higher dimensional space, so called qudits. I will discuss our recent experiments where multiple qudits are encoded in multiple electronic levels of a single atom. Furthermore, molecules provide an even richer level structure than atoms with the potential to encode even more information. I will discuss the prospects and challenges of using molecular ions for quantum information processing. In particular, I will focus on the robust encoding of information in a single molecule using quantum error correction.

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Highly Charged Ion Optical Clocks to Test Fundamental Physics

Optical atomic clocks are the most precise and accurate measurement devices ever constructed, reaching fractional systematic uncertainties below one part in 10^{18} [1]. Their exceptional performance opens up a wide range of applications in fundamental science and technology. The extreme properties of highly charged ions (HCI) make them highly sensitive probes for tests of fundamental physical theories [2, 3]. Furthermore, these properties make them significantly less sensitive to some of the leading systematic perturbations that affect state-of-the-art optical clocks, making them exciting candidates for next-generation clocks [4, 2]. The technical challenges that hindered the development of such clocks have now all been overcome, starting with their extraction from a hot plasma and sympathetic cooling in a linear Paul trap [5], readout of their internal state via quantum logic spectroscopy [6], and finally the preparation of the HCI in the ground state of motion of the trap [7], which allows levels of measurement accuracy to be reached that were previously limited to singly-charged and neutral atoms. Here, we present the first operation of an atomic clock based on an HCI (Ar^{13+} in our case) and a full evaluation of systematic frequency shifts [8]. The achieved uncertainty is almost eight orders of magnitude lower than any previous frequency measurements using HCI. Measurements of some key atomic parameters confirm the theoretical predictions of the favorable properties of HCIs for use in clocks. The comparison to the $^{171}Yb^{+}$ E3 optical clock [9] places the frequency of this transition among the most accurately measured of all time. Furthermore, by comparing the isotope shift between $^{36}Ar^{13+}$ and $^{40}Ar^{13+}$ to improved atomic structure calculations, we were able for the first time to resolve the largely unexplored QED nuclear recoil effects. Finally, prospects for 5th force tests based on isotope shift spectroscopy of Ca^{+}/Ca^{14+} isotopes and the high-sensitivity search for a variation of the fine-structure constant using HCI will be presented. This demonstrates the suitability of HCI as references for high-accuracy optical clocks and to probe for physics beyond the standard model.

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Searching for dark matter with atoms and lasers: Varying fundamental “constants”

Ultra-low-mass bosonic particles produced non-thermally in the early Universe may subsequently form an oscillating classical field that can comprise the observed cold dark matter. The very high number density of such dark-matter particles can give rise to characteristic wave-like signatures that are distinct from the traditional particle-like signatures considered in searches for WIMP dark matter. In particular, ultra-low-mass scalar dark matter may induce apparent variations of the fundamental “constants” of Nature. I discuss the basic principles of and recent results in searches for ultra-low-mass scalar dark matter using precision low-energy experiments, including atomic clock spectroscopy, optical cavities and laser interferometry.

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Towards a ^{229m}Th Nuclear Clock: Status and Perspectives

Today's most precise timekeeping is based on optical atomic clocks. However, those could potentially be outperformed by a nuclear clock, based on a nuclear transition instead of an atomic shell transition. Such a nuclear clock promises intriguing applications in applied as well as fundamental physics, ranging from geodesy and seismology to the investigation of possible time variations of fundamental constants and the search for Dark Matter [1,2].

Only one nuclear state is known so far that could drive a nuclear clock: the 'Thorium Isomer ^{229m}Th', i.e. the isomeric first excited state of ^{229}Th, representing the lowest nuclear excitation so far reported in the whole landscape of nuclear isotopes. Since its first direct detection in 2016 [3], considerable progress could be achieved in characterizing the properties and decay parameters of this elusive nuclear excitation: the half-life of the neutral isomer was determined [4], the hyperfine structure was measured via collinear laser spectroscopy, providing information on nuclear moments and the nuclear charge radius [5] and also the excitation energy of the isomer could be directly determined 8.28(17) eV [6].

In a recent experiment at CERN's ISOLDE facility, the long-sought radiative decay of the Thorium isomer could be observed for the first time via implantation of (⍰ decaying) ^{229}Ac into a VUV transparent crystal and subsequent fluorescence detection in a VUV spectrometer. Thus, the excitation energy of ^{229m}Th could be determined with unprecedented precision to 8.338(24) eV, corresponding to a wavelength of 148.71(42) nm [7]. This recent breakthrough opens the door towards a laser-driven control of the isomeric transition and thus to the development of an ultra-precise nuclear frequency standard and quantum sensor.

The talk will review recently completed, ongoing and planned activities towards this goal.

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Quantum computing with Yb Rydberg atoms

Neutral atom quantum computing is a rapidly developing field. Exploring new atomic species, such as alkaline earth atoms, provides additional opportunities for cooling and trapping, measurement, qubit manipulation, high-fidelity gates and quantum error correction. In this talk, I will present recent results from our group on implementing high-fidelity gates on nuclear spins encoded in metastable 171Yb atoms [1], including mid-circuit detection of gate errors that give rise to leakage out of the qubit space, using erasure conversion [2]. I will also discuss ongoing spectroscopy of Yb Rydberg states, motivated by a new experiment to use circular Rydberg states to achieve even longer Rydberg lifetimes [3].

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Atom-atom interactions for quantum metrology and quantum computing

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Abstract

Strong controlled interactions between atoms can be used to create entanglement for a variety of purposes. I will discuss two applications, quantum interferometry beyond the Standard Quantum Limit (SQL), and quantum computing. For atomic clocks, we generate entangled atomic states by inducing an effective atom-atom interaction via the coupling to an optical cavity. We then use an effective time-reversal protocol to achieve performance beyond the SQL, and experimentally investigate the relation between quantum information scrambling, out-of-time-order correlators and metrological gain. For quantum computing with ultracold neutral atoms, the interaction between Rydberg states is used to induce two-qubit quantum gates with errors below 1%, the threshold for surface code error correction. I will also discuss prospects for future optical quantum connections between locally error-corrected modules.

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Molecular lattice clocks

The ability to create and manipulate small molecules at ultracold temperatures [1] presents an opportunity to apply them to metrology and precise measurements. Observations of very narrow optical and terahertz transitions in highly controlled environments [2,3] enable molecular clocks that feature quantum states with very long natural lifetimes and low sensitivities to external fields. Molecular clocks are complementary to atomic clocks in terms of sensitivity to new physics. For example, isotope shifts of clocks based on pure vibrations allow probes of interatomic forces at the nanometer scale. In this talk I will discuss the current precision limit of molecular metrology [4] and possible paths forward.

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Composite quantum particles at the interface with general relativity

A major goal of modern physics is to understand and test the regime where quantum mechanics and general relativity both play a role. Until recently, new effects of this regime were thought to be relevant only at high energies or in strong gravitational fields. However, rapid progress in experimental techniques allows for quantum experiments over increasing time and distance scales and with staggering precision [1].

I will discuss why and how looking at composite quantum particles opens new avenues for both theoretical insights and laboratory tests of quantum and general relativistic effects. The key insights is that composite quantum particles can serve as ideal clocks [2], quantum test and source masses [3], or thermometers or fundamental-particle detectors [4]. I will show some of the new insights that arise from studying such composite particles and how the resulting effects could be tested. In particular, I will argue that even very weak relativistic effects associates with such particles will become relevant for next-generation high-precision quantum technologies with trapped particles [5].

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Precision spectroscopy of atomic hydrogen at Colorado State University

Because of atomic hydrogen's simplicity, its energy levels can be precisely described by theory. This has made hydrogen an important atom in the development of quantum mechanics and quantum electrodynamics (QED). While one can use hydrogen spectroscopy to determine the Rydberg constant and the proton charge radius, a discrepancy of these constants determined through different transitions, or in different species, can indicate new physics. Such discrepancies currently persist between different measurements in hydrogen and muonic hydrogen. With this motivation in mind, I will discuss several precision spectroscopy measurements of hydrogen as Colorado State University including a relatively recent measurement of the hydrogen 2S-8D two-photon transition, a measurement of the hydrogen 2S hyperfine splitting, and our future plans to measure several relatively narrow 2S-nS transitions in hydrogen. If these latter measurements are successful, they could provide some of the most precise measurements of the Rydberg constant along with insight into the experimental discrepancies.