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ABSTRACTS

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INVITED LECTURES

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INVITED LECTURES

Research on atomic frequency standard and time-frequency transmission in NTSC

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Abstract: The National Time Service Center (NTSC), Chinese Academy of Sciences is responsible for generating and transmission the Chinese standard time. NTSC has developed different types of atomic frequency standards, including optically pumped cesium beam clock, cold atomic rubidium fountain clock, cold atomic cesium fountain clock, and cold atomic strontium optical clock and so on. In the field of the high-precision time-frequency transmission, NTSC has developed the optical fiber time-frequency transmission technology and the quantum time synchronization technology. And also the report will give the development of the high-precision ground timing system, national major science and technology infrastructure project, as well as the time and frequency experimental system of China space station, which includes a space optical clock.

Key words: atomic frequency standards; atomic clock; optical fiber time-frequency transmission; quantum time synchronization; China pace station; space optical clock

Assembling optical tweezer arrays of fully quantum-state controlled polar molecules

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Abstract: Ultracold polar molecules, compared to their atom counterparts, possess rich internal structures and exhibit long-range dipole-dipole interactions that render them useful for many applications such as quantum simulation, quantum computation and precision measurements. At the heart of many of these proposals is the ability to trap and control ultracold molecules at the individual particle level. In this talk, I will discuss our demonstration of this capability, achieved by assembling single rovibrational ground state NaCs molecules (4.6 D) in optical tweezers starting from single ultracold atoms. This bottom-up approach utilizes laser cooling and trapping techniques of ultracold atoms and has enabled us to achieve full quantum state control, including all the internal and external degrees of freedom, on individually trapped molecules in an array. Furthermore, I will present our recent characterization of the rotational transition and coherence of the ground state molecules, which is a crucial step towards generating dipolar interactions, and thus entanglement, between molecules. With these tools in hand, this platform provides new opportunities for quantum science applications harnessing the rich features of ultracold molecules.

Probing *T*-symmetry violating interactions with cold Thorium Monoxide (ThO) molecules

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Abstract: Measurements of the electron electric dipole moment (EDM) using atoms and molecules set very powerful constraints on *T*-symmetry violating new physics beyond the Standard Model. The best upper limit on the electron EDM was recently set by the ACME collaboration: $|d_e|<1.1\times10^{-29}$ e·cm[1], using a cold beam of thorium monoxide (ThO) molecules. This represents an order of magnitude improvement compared to the previous best results set by the same collaboration[2] and by other systems[3]. Here, we report both this recent electron EDM result[1] and new upgrades[4] which pave the way for another order of magnitude improvement in the electron EDM sensitivity in the upcoming ACME measurement.

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Searching for exotic spin-dependent interactions via single-spin quantum sensors

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Abstract: The dynamics of the spin system can be well controlled by quantum technologies. Thus spin systems can be utilized as promising platforms for quantum sensing. Here, I would like to introduce our recent progress in a novel application of spin system. We proposed that single-spin qubit, such as NV-centers in the diamond, can be utilized as quantum senor for dark matter searching. By observing and analyzing of the dynamics of the spin system, we have experimentally conducted laboratory searches for exotic spin-dependent interactions mediated by axion-like particles. Our results provide new limits on exotic spin-dependent interactions with micrometer scale.

Key words: NV-center; quantum sensor; dark matter

A mass-energy united test of the equivalence principle at 10^{-10} level using mass and internal energy specified atoms①

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Abstract: We use both mass and internal energy specified rubidium atoms to jointly test the equivalence principle (EP). We improve the Four-Wave Double-diffraction Raman transition method we proposed before to select atoms with certain mass and angular momentum state, and perform dual-species atom interferometer. By combining ^{85}Rb and ^{87}Rb atoms with different angular momenta, we measure the differential gravitational acceleration of them, and determine the value of Eötvös parameter, η, which measures the strength of the violation of EP. The Eötvös parameters of the four paired combinations ($^{87}\mathrm{Rb}|F=1\rangle$-$^{85}\mathrm{Rb}|F=2\rangle$, $^{87}\mathrm{Rb}|F=2\rangle$-$^{85}\mathrm{Rb}|F=2\rangle$, $^{87}\mathrm{Rb}|F=1\rangle$-$^{85}\mathrm{Rb}|F=3\rangle$ and $^{87}\mathrm{Rb}|F=2\rangle$-$^{85}\mathrm{Rb}|F=3\rangle$) were measured to be $\eta_1=(1.5 \pm 3.2) \times 10^{-10}$, $\eta_2=(-0.6 \pm 3.7) \times 10^{-10}$, $\eta_3=(-2.5 \pm 4.1) \times 10^{-10}$ and $\eta_4=(-2.7 \pm 3.6) \times 10^{-10}$, respectively. The violation parameter of mass and internal energy is constrained to $\eta_0 = (-0.8 \pm 1.4) \times 10^{-10}$, and the violation parameter of internal energy is constrained to $\eta_E = (0.0 \pm 0.4) \times 10^{-10}$ for reduced energy ratio ($h\nu_0/m_i^{85}c^2$, where m_i^{85} is the inertial mass of ^{85}Rb atoms, $\nu_0=10^9$ Hz). This work opens a door for mass and internal energy united tests of EP with quantum systems.

Key words: atom interferometry; equivalence principle; mass; internal energy; united test

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A multi-photon momentum transfer atom interferometer for gravity measurements

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Abstract: The matter wave interferometer was enlightened by the wave-particle duality. Atom interferometers (AI) based on cold atoms were demonstrated and are involved both in fundamental research and practical applications. Many precision cold atom interferometers are constructed for gravity measurements, gyroscopes, magnetic field sensors, determination of the fundamental constant and other applications. Further improving the sensitivity of the atom interferometer is becoming more and more necessary for testing gravity and finding new physics. Large momentum transfer AIs, such as Bragg type AI, are proposed and being demonstrated to have better performance. In this talk, we will present how to realize a sensitive Bragg atom interferometer and show its capability in gravity measurements and testing new physics. The Raman sideband cooling is employed to further cool the atoms to sub μK. In order to avoiding the cross-couplings due to the space overlapping of atomic states, a momentum-resolved detection technique was first demonstrated for measuring atoms populated in different momentum states. The coupling efficiency for the first and second Bragg diffraction can reach 99% and 95% respectively. We found that a shot term sensitivity better than $4\times10^{-9}g/Hz^{1/2}$ has achieved with our Bragg AI for absolute gravity measurements, which will help us to improve the performance of the atom gravimeter and the precision on testing spin gravity coupling.

Probing gravity by holding atoms for 20 seconds

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Abstract: Atom interferometers are powerful tools for both measurements in fundamental physics and inertial sensing applications. Their performance, however, has been limited by the available interrogation time of atoms freely falling in a gravitational field. I will present our realization of an intra-cavity trapped atom interferometer with 20 seconds of coherence, which extends the coherent interrogation time of spatially-separated quantum superpositions of massive objects by nearly an order of magnitude. After seconds of hold time, gravitational potential energy differences from as little as microns of vertical separation can generate megaradians of interferometer phase. Furthermore, this trapped geometry suppresses the phase sensitivity to vibrations by 3-4 orders of magnitude, addressing the dominant noise source in atom-interferometric gravimeters. In this talk, I will discuss our realization of a trapped atom interferometer, and how it differs from traditional free-fall atom interferometers by allowing potentials to be measured by holding, rather than dropping, atoms.

Key words: atom interferometry; precision measurement; quantum metrology and sensing; gravimetry

Quantum droplet and quantum bubble in ultracold Bose-Bose mixtures

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Abstract: The two-species Bose-Einstein condensate (BEC) of ultracold dilute atomic gases has been a quantum system with long-lasting interests. In recent years, many previously unexplored phenomena in this system have been observed by manipulating the interplay between the inter- and intra-species interactions. In this talk, I will present two experiments carried out in the double BEC of sodium and rubidium atoms. With the help of a Feshbach resonance, we tune the inter-species interaction to attractive enough so that the system should collapse in the mean-field regime. Instead, we observe the formation of a stable liquid droplet of the two species due to the beyond mean-field Lee-Huang-Yang correction. On the other hand, the large positive inter-species interaction near zero magnetic fields drives the system into the phase-separated phase. In this case, the Na BEC forms a closed shell surrounding the Rb BEC. After removing the rubidium atoms, we obtain a hollow bubble BEC which interferes with itself during free expansion. Several other studies of the quantum droplet and the quantum bubble will also be discussed.

The manipulation of ultracold atoms of high orbitals in optical lattices

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Abstract: Ultracold atoms in optical lattices are a powerful tool for quantum simulation, precise measurement and quantum computation. A fundamental problem in applying this quantum system is how to manipulate the higher bands or orbitals in Bloch states effectively. Here we mainly introduce our methods for manipulating high orbital ultracold atoms in optical lattices with different configurations. Based on these methods, we load the ultracold atoms into the P or D bands of the hexagonal optical lattice and the triangular lattice, and then observe the novel quantum phases and study the dynamical evolution of the atoms in the high bands. Furthermore, we investigate the collisional scattering channels for atoms in the excited bands of a triangular optical lattice and demonstrate a dominant scattering channel in the experiment. Finally, we construct the atom-orbital qubit under nonadiabatic holonomic quantum control. These effective manipulation of the high orbitals provides strong support for applying ultracold atoms in the optical lattice in many fields.

Atomic chiral superfluid in the second band of a hexagonal optical lattice

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Abstract: Topological superfluidity is an important concept in electronic materials as well as ultracold atomic gases. However, although progress has been made by hybridizing superconductors with topological substrates, the search for a material that intrinsically exhibits topological superfluidity has been ongoing since the discovery of the superfluid ^{3}He-A phase. Here, I will report our experimental evidence for a globally chiral atomic superfluid, induced by interaction-driven time-reversal symmetry breaking in the second Bloch band of an optical lattice with hexagonal boron nitride geometry. A phenomenological effective model is used to capture the dynamics of Bogoliubov quasi-particle excitations above the ground state, which are shown to exhibit a topological band structure. The observed bosonic phase is expected to exhibit phenomena that are conceptually distinct from, but related to, the quantum anomalous Hall effect in electronic condensed matter.

Superfluid transition in disordered dipolar Fermi gases

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Abstract: I will consider two-component ultracold Fermi gases of dipolar particles (magnetic atoms or polar molecules) in the two-dimensional geometry in the presence of weak disorder. According to the Anderson theorem in the weakly interacting regime such a disorder does not change the superfluid transition temperature in the case of short-range (contact) fermion-fermion interaction. However, the dipole-dipole interaction is long-range and the related interaction amplitude is momentum dependent, which violates the Anderson theorem. I will show that in the weakly interacting regime the weak disorder can increase the transition temperature by a factor of 2 for realistic parameters. This opens a remarkable possibility for the observation of superfluidity in weakly interacting Fermi gases. An increase of the fermion-fermion interaction reduces the influence of disorder on the superfluid transition temperature, and in the strongly interacting regime it practically remains the same as in the absence oif disorder.

Opticlock – a transportable and easy-to-operate optical single-ion clock

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Abstract: Today's most precise clocks are research prototypes based on optical reference transitions of neutral atoms or single ions. Their precision and accuracy on the order of 10^{-18} open up numerous applications, e.g. improved network synchronization or navigation as well as geodetic height easurements or tests of fundamental physics. Up to now, however, such optical clocks are operated by scientists in highly specialized laboratories restricting the use to basic research. In order to make wider use of their application potential, it is essential to demonstrate improvements in the robustness and the usability of these clocks.

The industry-led opticlock consortium (www.opticlock.de) has developed an easy-to-use optical clock with the aim to achieve accuracies and fractional instabilities below 10^{-16}. The opticlock is based on the E2 ($^2S_{1/2}$-$^2D_{3/2}$) transition of a single $^{171}Yb^+$ ion at 436 nm wavelength (688 THz) that has been selected as one of the secondary representations of the second. The opticlock consist of two specifically designed mobile 19" rack assemblies. It comes with a length-stabilized fiber-coupled optical output at 344 THz such that it can be easily compared to other optical clocks. The opticlock integrates a fully autonomous control system and is designed for reliable operation in environments outside scientific laboratories, i.e. "office space".

In our presentation, we will describe the detailed system engineering setup of the opticlock and show the results of the opticlock evaluation at the German national metrology institute PTB.

First tests allowed for low-maintenance continuous operation with 99.8 % availability over 14 days. The opticlock shows a fractional instability of about 6×10^{-15}/sqrt(t), where t is the averaging time in seconds, and averages down to 2×10^{-17}. A first analysis of the systematic uncertainties reveals that the absolute accuracy is predominantly limited by the 2×10^{-17} contribution of the differential polarizability[1] entering via the black-body radiation shift.

The key technologies developed within this project extend the portfolio of commercially available components for quantum technologies. Future extensions of opticlock may include using the E3 transition in order to aim at higher accuracies or the integration of a multi-ion reference to achieve comparable accuracies and instabilities in much shorter averaging times. As first step into that direction, a physics package using a string of ions stored in a linear trap[2] was developed and investigated within the opticlock project[3].

Key words: optical clock; frequency standard; quantum technologies; Yb ion

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Toward coherent formation of ultracold single molecule arrays

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Abstract: Compared with ultracold atoms, ultracold molecules possess richer internal structure that lend themselves useful for a variety of applications, such as ultracold chemistry, precision measurements, quantum simulation, and quantum computation and so on. A key ingredient in many of above proposed applications is the realization of such a single molecule array, where not only the quantum internal and external degrees of freedom of the individual molecules, but also the molecular interaction, and the numbers and species of molecules can be all controlled over. The relative research has been becoming an important frontier and hot topic in the worldwide[1]. To realize single molecule arrays, one can assemble molecules one by one from their constituent atoms individually trapped in the optical tweezers[2]. In this presentation, we will present the our recently experimental advances[3-7] towards assembly of single molecules arrays.

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Higher orbital optical lattices

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Abstract: Orbital is a fascinating degree of freedom independent of charge and spin. In condensed matter physics, it is traditionally known for playing important and rich roles in magnetism, superconductivity, and transport in electronic materials like transition metal oxides. Advanced spatiotemporal control of cold atoms provides new opportunities to explore orbital physics in physical conditions complementary to what natural materials usually offer. Higher orbital bands, realized with optical lattices, are found not only able to simulate some outstanding condensed matter orbital-related problems but also to bring forward conceptually novel phenomena that seem to have no prior analogue. In this talk, I will introduce the basics of orbital optical lattices and highlight unique aspects emerging from the interplay of novel lattice geometry, spatial and orbital symmetries, and topology beyond standard natural conditions in such artificial quantum systems. Great examples that have been discovered include p+ip-wave fermionic pairing across odd-even parity orbital bands, chiral atomic Bose-Einstein condensate with topological excitations, and topological sp-orbital ladder reminiscent of material topological insulators.

Novel probes of quantum many-body correlations with cold atoms

ZHAI Hui

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Abstract: I will discuss two novel methods to probe quantum correlations in many-body systems. One method uses the controlled dissipation as a probe tool and the other method utilizes the non-adiabatic response during ramping dynamics. I will talk about both theoretical framework and the experimental measurements in cold atom systems about these two methods. I will show that both methods can distinguish whether the quantum state possesses well-defined quasi-particle or not.

Synthesize topological structure with spin-orbit coupled quantum gas

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Abstract: The central role of quantum simulation via ultracold quantum gases is to synthesize an effective target Hamiltonian and studies the evolution of the atoms in such a system. The topological quantum matter attracted many of the researchers in recent years. Here, we report the technique of optical Raman lattices by which the 2D and 3D Spin-Orbit coupling with ultracold quantum gases are realized[1-3]. Besides, with observing the quantum quench dynamics[4-5] and the Floquet engineering, new approaches to study the topology has been developed and a series of novel topological structures are synthesized. Our techniques of operating ultracold quantum gases provide simple and powerful tools to explore novel topological physics.

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Realization of Qi-Wu-Zhang model in spin-orbit-coupled ultracold fermions

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Abstract: Based on the optical Raman lattice technique, we experimentally realize the Qi-Wu-Zhang model for quantum anomalous Hall phase in ultracold fermions with two-dimensional (2D) spin-orbit (SO) coupling. We develop a novel protocol of pump-probe quench measurement to probe, with minimal heating, the resonant spin flipping on particular quasi-momentum subspace called band-inversion surfaces. With this protocol we demonstrate a continuous crossover between 1D and 2D SO couplings by tuning the relative phase between two coherent Raman couplings, and detect the non-trivial topological band structures by varying the two-photon detuning. The non-trivial band topology is also observed by slowly loading the atoms into optical Raman lattices and measuring the spin textures. Our results show solid evidence for the realization of the minimal SO-coupled quantum anomalous Hall model, which can provide a feasible platform to investigate novel topological physics including the correlation effects with SO-coupled ultracold fermions.

Key words: spin-orbit coupling; cold gases in optical lattices; Fermi gases; quantum simulation; topological phases of matter

Precise spectroscopy of the trapped and cold calcium ion

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Abstract: The systematic uncertainty of the clock has been improved to below 3.0×10^{-18} was achieved under a cryogenic (liquid nitrogen temperature) environment[1]. Meanwhile, the stability of the $^{40}Ca^{+}$ optical clock has been improved to 6.3×10^{-18} in an averaging time of 524 000 s[2]. A robust and transportable clock installed in an air-conditioned car trailer has achieved performance almost as good as that of the laboratory clocks[3]. The absolute frequency of the $^{40}Ca^{+}$ optical clock transition was remeasured as 411 042 129 776 400.41(23) Hz, with a fractional uncertainty of 5.6×10^{-16} referenced to the SI second via satellite frequency transfer links. This radiation is now endorsed as a secondary representation of the second by the Consultative Committee for Time and Frequency (CCTF) at its 22nd session in 2020 and 2021[4].

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Sr optical lattice clocks toward E-18

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Abstract: In order to promote the accuracy of time and frequency metrology and prepare for the redefinition of the SI second, two Sr optical clocks are being built at National Institute of Metrology(NIM). Sr1 made its first systematic shifts evaluation in 2015, and was improved on the lattice laser locking, density shift control,etc, from then on. The total systematic uncertainty is evaluated to be 2.9E-17 in 2020. A campaign of absolute frequency measurement was made with reference to the ensemble of primary and secondary frequency standards published in the Circular T bulletin by BIPM through a satellite link. Sr2 was designed with many improvements on black body radiation control, clock laser stability, lattice laser control, fiber noise cancellation, etc. The total systematic uncertainty enters E-18 in the latest evaluation.

Key words: strontium; optical lattice clock; systematic shift; uncertainty budget

Floquet engineering in optical lattice clock

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Abstract: Optical lattice clocks (OLC) are the most accurate time-frequency measurement devices and even considered as a candidate for defining the unit of time. On the other hand, Floquet engineering is a powerful tool for quantum simulating the exotic Hamiltonian via time-periodic driving. Recent works in NSTC demonstrate the strong advantages of combining the Floquet methods and OLC, such as interference of Floquet modes via double modulation[1] and realization of Hz-Level Rabi spectra in shallow optical lattice clock[2] and so on[3-4].

Key words: optical lattice clock; floquet engineering; Rabi spectrum; interference

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Novel nonequilibium dynamics of the interacting quantum gases

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Abstract: The understanding the nonequilibium dynamics of strongly coupled quantum systems is an open problem at the frontiers of physics with widespread applications, including the expansion of the early universe, heavy ion collisions and quark-gluon plasmas. An ultracold quantum gas, owing to its great controllability on the interaction and external potential(dimensions), provides an ideal platform to study such important many-body physics. In the talk, we will present our recent progress of manipulating the short-range and long-range interaction of the ultracold quantum gases(Boson and Fermi gases). The novel dynamics expansion, quantum phase transition and the relaxation dynamics will be reported.

Optical manipulation of the vortex states in ultracold quantum gases

JIANG Kai-jun

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Abstract: Ultracold quantum gas has a high tunability which affords potential applications in quantum simulation and precision measurement. Different techniques have been explored to manipulate the quantum gases. In this talk, we will report how to create vortex states in ultracold atoms and manipulate them by using Laguerre-Gaussian (LG) laser beams. We experimentally observe the ground-state phase diagram of the spin-orbital-angular-momentum (SOAM) coupled Bose-Einstein condensate. The phase transitions are classified as the first order and the role of interatomic interaction on the phase transition is elucidated. We also show how to build up a vortex matter-wave interferometer and realize the superposition of orbital-angular-momentum (OAM) states in quantum gases.

Microscopic study of strongly correlated synthetic quantum materials

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Abstract: We study strongly correlated synthetic quantum material with microscopic techniques for solving formidable tasks to the state-of-the-art supercomputers. Such tasks include quantum phase transition of strongly correlated quantum systems, the topological structure of multipartite entangled state and lattice gauge theories. We developed unique techniques of spin-dependent superlattices, microscopic absorption imaging, and number resolved detection. A new method of deep cooling in optical lattice is realized and a defect-free system is achieved for creating 1250 pairs of entangled atoms. Thanks to these advances, we implemented the Schwinger model with a Hubbard model in deep lattice regime of a 71-site quantum simulator. We observed the interaction and conversion between matter fields and gauge fields and verified Gauss's law. The quantum simulator may be also used to study non-equilibrium lattice gauge systems, false vacuum decay, dynamical transitions related to the topological θ-angle, and thermal signatures of gauge theories under extreme conditions.

Prediction and measurement of tune-out wavelength in helium: a new way for QED test

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Abstract: Despite quantum electrodynamics (QED) being one of the most stringently tested theories underpinning modern physics, recent precision atomic spectroscopy measurements have uncovered several small discrepancies between experiment and theory, which calls for further QED test. Different from the traditional energy level measurement to test QED theory, we proposed a new way that tests QED independently is measurement of the tune-out wavelength, where the dynamic polarizability vanishes and the atom does not interact with applied laser light. This new proposal motivated international cooperation between theory and experiment. Recently, we have realized the measurement of the tune-out wavelength of helium with an precision of 0.35 ppm, and the new theoretical calculations have reached an precision of 12 ppb. The experimentally determined value of 725,736,700(260) MHz differs from theory [725,736,252(9) MHz] by 1.7σ. The comparisons between theory and experiment have verified the sensitivity of the tune-out wavelength to the QED and retardation effects, which also confirms our original theoretical prediction.

Key words: QED test; dynamic dipole polarizability; tune-out wavelength; helium; retardation effects

Precision measurements on small molecules

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Abstract: Precision measurements of small molecules such as hydrogen molecules can be used to test molecular theory involving quantum electrodynamics (QED) and fundamental constants, and to search for new physics. In the past few years, a series of advanced spectroscopy techniques have been developed to improve the accuracy of molecular transitions. The dissociation energies of H_2 and D_2 have been improved to 10 digits, resulting in a stringent test of *ab initio* theory of the two-electron molecular system. In the HD vibrational transition measurement, a dispersion-like line profile has been observed, exhibiting that the two-level approximation is no longer applicable to the weak transition. The uncertainty is studied and the HD vibrational transition frequency of R(0) (2-0) is improved. This result provides a test of quantum electrodynamics in the molecular domain, paving an alternative way for the determination of the proton-to-electron mass ratio.

Key words: precision measurement; fundamental physics; molecular spectroscopy

Sympathetic laser cooling and precision measurement of highly charged ions in penning traps

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Abstract: Penning traps have been proven as a versatile tool for fundamental physics. A multitude of high-precision measurements have been performed at Penning trap facilities, such as measurements of atomic masses and magnetic moments or *g*-factors of elementary particles. Recently, by confining highly charged ions (HCIs) in Penning traps it provides a unique system to probe atomic properties and to test Quantum electrodynamics (QED) in strong electric field. In a cryogenic penning trap, the motional temperature of ions is thermalized with a cryogenic superconducting tank circuit at 4.2 K. Owing to the particle oscillation amplitude, the accuracy of frequency determinations is limited by systematic uncertainties caused by anharmonicities arising from field imperfections and eventually special relativity. In *g*-factor measurements, a lower particle temperature furthermore decreases axial frequency fluctuations and thus helps to achieve higher fidelity of the spin state determination, which is specifically crucial for heavy ions with a comparably small magnetic moment. To reduce the ion temperature into the millikelvin regime, sympathetic cooling is a common method in rf traps. However, the co-trapping of different ions leads to drastic modifications of the motion of the ion of interest via the Coulomb interaction in penning traps. To solve the Coulomb disturbance, a cooling technique proposed by Heinzen and Wineland in 1990 is based on the coupling of two species in separate traps that share a common endcap electrode. This way, the ions can interact via their image charges induced into the shared endcap electrode. However, with realistic trap parameters the coupling strength is too small to achieve highly efficient sympathetic cooling.

Here, we present a new coupling technique for two ion species in separate traps via a common superconducting tank circuit which can significantly enhance the coupling strength. At ALPHATRAP this tank-circuit assisted coupling of two HCIs are investigated by observing the resulting avoided crossing of the coupled frequencies. The determined coupling strength is a factor of 760 larger than the method of common endcap coupling. Furthermore, we propose an intermittent laser cooling method for highly efficient sympathetic cooling. The numerical simulations show the possibilities of sympathetic cooling of arbitrary types of ions to the millikelvin regime within reasonable cooling times.

Key words: penning trap; sympathetic laser cooling; highly charged ions trapping and cooling

How spin and charge of fermionic atoms move at different speeds in 1D

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Abstract: Low-energy excitations of one dimensional (1D) interacting fermions typically split into two independent Tomonaga-Luttinger liquid (TLLs), each of which carries either spin or charge. This phenomenon is called spin-charge separation--a hallmark of 1D many-body physics. Although there have been more than 40 years of research in this field and evidence for spin-charge separation has been reported in 1D solid state materials, so far, conclusive experimental observation of this phenomenon is lacking.

In this talk I will report on our recent precise observation of the TLL theory of spin-charge separation in the trapped 1D ultracold Fermi gas. We used Bragg beams to excite spin and charge density waves separately and measure the corresponding spin and charge Bragg spectra at different interacting strengths. Peaks of the Bragg spectra give the corresponding spin and charge sound velocities. Theoretically, density distributions in 1D tubes were obtained from complicated 3D particle number distributions. Exact spin and charge dynamical structure factors were calculated through the Yang-Gaudin model of 1D interacting Fermi gases and TLL theory. By taking into account the curvature correction to the linear charge excitation spectrum and the nonlinear effect of the spin backward scattering in the spin sector, theoretical and experimental results are in good agreement. This work, for the first time, experimentally verifies the TLL theory of the spin-charge separation and provides strong evidence for nonlinear TLL effects, beyond the TLL model. It is a paradigmatic example of quantum many-body physics, offers new insight into quantum physics.

Emergent chaotic structures in the ground state of Rydberg p-wave interacting atoms

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Abstract: There has been tremendous research progress in controlling Rydberg excitations of Alkali atoms in the last several years, bringing new opportunities for quantum simulations and quantum computing. Recent preparation of topological ordered quantum states with Rydberg blockade effects is provoking much research interest in exotic quantum states. In this talk, I will present our theoretical study on the ground state of Rydberg p-wave dressed atoms, where we find an exotic phase transition characterized by bulk-to-surface response. To understand the nature of this phase transition, we construct a frustration free model that shares a similar bulk-to-surface response. With the frustration free model, the ground state phase transition is mapped to a dynamical order-to-chaos transition. Our theory construction also implies that the study of non-equilibrium phases would inspire unconventional ground-state phases.

Efficient quantum memory of single photon in cold atoms and its quantum state characterization

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Abstract: A quantum memory of single photon qubits with high storage fidelity, efficiency and long storage time is well known to be indispensable towards practical quantum information applications. In this report, we develop an efficient quantum memory for single photon qubits in cold atomic ensembles via the electro-magnetic induced transparency (EIT) effect. By optimizing the temporal shape of single photons with a lossless method, optimizing the optical depth of atomic ensemble and suppressing the atomic dephasing effect caused by both atom thermal motion and ambient stray magnetic field, etc., we achieved an overall storage efficiency of single photon qubits as high as 86% with fidelity higher than 99%, which is, as far as we know, still the best efficiency has been reported. Utilizing the intrinsic coherence of EIT process, by modulating the phase of control laser, we further developed a single photon phase modulator that is built-in the quantum memory. Fast phase modulation is verified using the Hong-Ou-Mandel interference between two single photons that are synchronized by storing and retrieve one photon using our quantum memory.

Besides storing the quantum state of single photon, measuring quantum wavefunction of single photons always attracts much attention of the research fields. Conventional quantum wavefunction measurement such as quantum state tomography becomes complicated when the dimension of quantum state Hilbert space increases. In order to explore more efficient quantum wavefunction measurement technique, we theoretically develop and experimentally demonstrate a new δ-quench method based on the quantum weak-value to measure the temporal wavefunction of photons, where the required measurements increase linearly with the quantum state dimension. Our δ-quench method is thus potentially useful in high dimensional quantum information applications.

Key words: cold atoms; quantum memory; single photons; quantum wavefunction measurement

Nonlinear interferometry beyond classical limit enabled by cyclic dynamics

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Abstract: Time reversed dynamics can support entanglement-enhanced measurements without the requirement of low-noise detection. Despite of the broad interest, it remains challenging to reverse the dynamics of a quantum many-body system through time-forward evolution, except when an (effective) sign-flip of the system Hamiltonian is easily accomplished. As a cost of engineering ‘effective’ time reversal for nonlinear interferometry, essentially all experiments demonstrated so far are constrained to ‘short-time’ evolutions, where ‘effective’ time-reversed dynamics kick in before the probe states become too deeply entangled to be disentangled [Oberthaler group, PRL 117, 013001 (2016); Kasevich group, Science 352, 1552 (2016); Wineland group, Science 364, 1163 (2019)], hence sacrificing potentially higher metrological gains.

We point out two complementary parts of a cyclic evolution loop behave as time-reversed evolutions of each other, as a system returns to its starting point in the end. This suggests a nonlinear interferometry implementation without invoking time-reversed dynamics. Specifically, a ‘closed-loop’ nonlinear interferometer in a three-mode ^{87}Rb atom spinor condensate is realized based on its quasi-periodic spin mixing dynamics which in the semiclassical mean-field theory is described by a nonlinear pendulum. By timing the system’s return to initial state (or its immediate vicinity), the complete ‘closed-loop’ time-forward evolution behave as the consecutive actions of two nonlinear ‘beam-splitters’, with the second one being the reverse (or complementary) of the first. We confirm such an implemented nonlinear interferometer by observing precisions beating SQL, a phase precision of over 5 dB below the SQL ($\sim1/\sqrt{N}$) for a total of N=26 500 atoms. Our interferometric protocol allows the dynamics (for nonlinear ‘beam-splitter’) to extend into the deep nonlinear regime, which gives rise to much more entangled probe state (non-Gaussian state). Furthermore, the performance of our interferometer deteriorates hardly with detection noise, which represents an inherent advantage of nonlinear interferometers over linear ones traditionally employed.

Ultracold atoms in high-cooperativity cavity and creation of GHz states with a few thousand atoms

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Abstract: In the first part of the presentation, I will give an introduction to the experimental development of the field of ultracold atoms in cavity in the past ten years, both technically and scientifically. In the second part, I will talk about the progress in my lab, including efforts to build an ultra-high-cooperativity cavity system and a proposal to create Greenberger-Horne-Zeilinger (GHZ) states with a large number of qubits in the atom-cavity system. The scheme starts with a multi-atom ensemble initialized in a coherent spin state. By shifting the energy of a particular Dicke state, we break the Hilbert space of the ensemble into two isolated subspaces to tear the coherent spin state into two components so that entanglement is introduced. After that, we utilize the isolated subspaces to further enhance the entanglement by coherently separating the two components. By single-particle Rabi drivings on atoms in a high-finesse optical cavity illuminated by a single-frequency light, 2000-atom GHZ states can be created with a fidelity above 80% in an experimentally achievable system, making resources of ensembles at Heisenberg limit practically available for quantum metrology.

Key words: Greenberger-Horne-Zeilinger state; metrological gain; cavity QED; high-cooperativity cavity

Manipulation of a few atoms and its interaction with optical cavity

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Abstract: Due to its long coherence time, neutral atom is an important system to demonstrate quantum control and the related quantum technology. Manipulation of cold atoms and its strong interaction with optical cavity have provided a nice experimental platform to study the decoherence and various quantum effects. We will show in this talk some recent experimental progress in single and few-atom manipulation, atom array control and few-atom cavity QED, such as the single atom in optical microtrap, optical nonreciprocity on single photon level and nonclassical statistics of nonreciprocity in the cavity QED system with a few atoms.


POSTERS

The formation of high-density cold molecules via an electromagnetic trap

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Abstract: The preparation and control of cold molecules is advancing rapidly, motivated by wide exciting applications from tests of fundamental physics to quantum information processing[1-2]. Here we proposed a trapping scheme to creating high density cold molecular samples by using a combination of electric and magnetic fields. In our theoretical analysis and numerical calculations, a typical alkaline-earth monofluorides molecule, MgF, is used to test the possibility of our proposal. A cold MgF molecular beam is firstly produced via an electrostatic Stark decelerator and then is loaded into our designed electromagnetic trap, which is composed of an anti-Helmholtz coil, an octupole and two disk electrodes as shown in figure 1 (a). Following that a huge magnetic force is applied to the molecular sample at an appropriate time, which enables further compressing the spatial distribution of the cold sample. Our numerical calculations show that the loading efficiency (η) in our trap can be increased by 40% compared to that containing only an electric field, as shown in Fig. 1 (b). This approach offers a good start for further cold molecular studies, such as laser cooling[3], cold collision, high-resolution spectroscopy and so on.

Key words: Stark effect; Zeeman effect; cold molecules

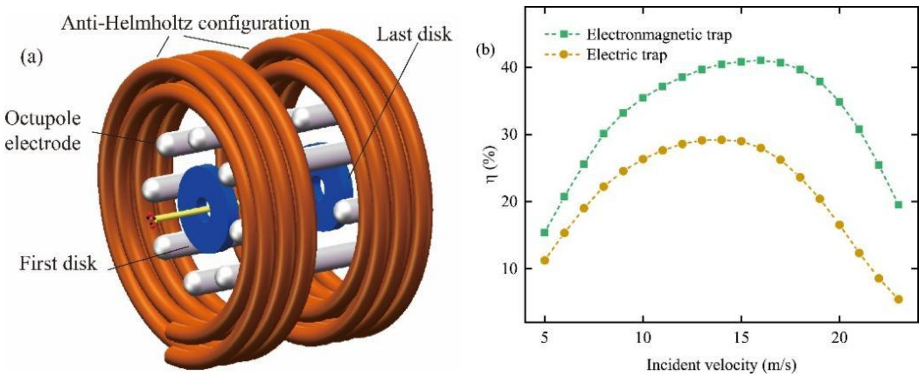

Fig 1. (a) Schematic diagram of the setup for loading, bunch, and compress slow-down molecular beam. (b) The calculated loading efficiencies of the scheme as a function of incident velocity in the electric trap (yellow) and electromagnetic trap (green).

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Fast laser cooling using optimal quantum control

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Abstract: State-of-the-art cooling schemes often work under a set of optimal cooling conditions derived analytically using a perturbative approach, in which the cooling rate is severely limited. Here we propose to use a quantum control technique powered with automatic differentiation to speed up the classical cooling schemes. We demonstrate the efficacy of our approach by applying it to find the optimal cooling conditions for classical sideband cooling and electromagnetically induced transparency cooling schemes, which are in general beyond the weak-sideband-coupling regime. Based on those numerically found optimal cooling conditions, we show that faster cooling can be achieved while at the same time a low average phonon occupation can be retained.

Key words: laser cooling; quantum control; optimal

Experimental study of quantum phenomena in Kr*-Rb cold collisions

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Abstract: The collision between atoms and molecules is one of the major research fields in atomic and molecular physics. The advancement of laser cooling, Stark deceleration and other manipulation methods has enabled study of the atomic (molecular) collision at very low temperature (<1 K). As the number of partial waves that participate the collision process decrease with the temperature, the quantum phenomena start to emerge, for example shape resonance etc. People have made significant progress toward this direction recently. Shape resonance has been observed in Ar-He* collision employing the "merged beam" method. Collisions within a MOT has also been studied.

Here we report on a different approach. By combining the MOT with a velocity mapping imaging (VMI) system. This configuration allows us to study the cold collision process between Rb and the metastable Kr atom. The internal energy of the Kr* atom is high enough so that both Penning ionization and Associative ionization process can occur. The center of the Rb MOT is overlapped with the VMI system. The Kr* atoms are first loaded in a MOT below the Rb MOT and then pushed toward the Rb atoms with a moving molassess with a controlled collision energy. With the VMI system both the differential cross-section and the dependence of the total cross-section with the collision energy between Rb and Kr* can be studied. The internal spin state and the its orientation can also be controlled with lasers. With this setup we are planning to explore the quantum phenomena in the Rb-Kr* cold collisions between 10 mK to 10 K, including the shape resonance, stereo-dynamics in the reaction, etc. A more accurate interaction potential energy surface for the Rb-Kr* collision, especially the behavior at large separations can be obtained.

Key words: cold collision; velocity mapping imaging (VMI)

Quantum sensing with space-borne ultracold atom platform

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Abstract: Recently, the successful operations of cold atom clock and BEC in space labs have opened the door to an exciting future of studying cold atom physics in space. In particular, these progress have made it possible to explore applications of the space-borne ultracold atom platform in the area of quantum sensing. Here, we will discuss several imminent projects in this area with the emphasis on their special advantages compared with other types of platforms. Due to the micro-gravity environment, they typically behave in a different manner compared with their ground counterparts. We will also discuss some of the main obstacles that must be overcome in realizing quantum sensing with space-borne ultracold atom platform.

Key words: quantum sensing; ultracold atom

One-dimensional isotropic laser cooling of atoms

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Abstract: We experimentally describe the configuration of one-dimensional gases of ^{87}Rb cooled by isotropic laser light. Different from the conventional spherical setups of isotropic laser cooling (ILC), a horizontal slender tube, with diameter 2 cm and length 105 cm, is employed in our experiment. With a total cooling light power of 250 mW, repumping light power of 20 mW and the cooling time of 0.17 s, we obtain an evenly distributed meter-long cold ^{87}Rb atom cloud whose atomic OD is more than 4 and atomic temperature is around 25 μk, the lifetime of the stable maximum cold atoms is about 0.03 s. The measured atomic density along the longitudinal direction of the tube is uniformly distributed. The configuration can also be used for ILC of other alkali metal atoms. The meter-long cold atom ensemble is appropriate for cold atom based quantum optics applications, such as electromagnetically induced transparency (EIT) and electronically highly excited (Rydberg) atoms. Here we emphasize that this method can easily generate km-long one dimensional continuous cold atoms in any shape with appropriate laser configuration. The cavity is easily scalable for different designs. This method can be extended to applications of quantum precision measurements.

Key words: isotropic laser cooling; one-dimensional gases; meter-long cold atom ensemble; quantum precision measurements

Characterization of charged particle-neutral atom collisions in an ion-neutral hybrid trap for the element ^{87}Rb

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Abstract: The quantum properties exhibited by low-temperature matter are crucial to the development of many fields of physics and quantum technology. Since the magneto-optical trap and ion trap were invented and combined, the cold ion-atom hybrid systems have paved the way for the study of reaction dynamics of neutral atoms and atomic ions, as well as of neutral atoms and molecular ions. When the trapped atoms and ions overlap in space, the ions will attract the atoms through their electrostatic electric field, and inelastic collisions may occur, such as two-body collision. In this work, the two-body collision reaction between cold rubidium atoms ^{87}Rb and cold rubidium ions $^{87}Rb^+$ was studied in a cold ion-atom hybrid trap, and the reaction product rubidium molecular ions $^{87}Rb_2^+$ were measured by time-of-flight mass spectrometry.

We investigated the effects of the MOT cooling light on $^{87}Rb_2^+$ molecular ions created in our ion-neutral hybrid trap. Particularly, after the period that MOT, ionization laser, and LPT worked together for 350 ms, during which $^{87}Rb_2^+$ molecular ions were formed, the ionization laser, gradient magnetic field, and re-pump light were turned off, and the ions were trapped in the LPT for a controlled time, either in the presence or absence of the MOT cooling light. Then, ions were pushed to the MCP and ion counts extracted from TOF spectra. In this work, The MOT cooling light had little effect on the dissociation of $^{87}Rb_2^+$ molecular ions. Moreover, the lifetime of the $^{87}Rb_2^+$ molecular ions owing to dissociation was approximately 1.5 s. Our measured lifetime of $^{87}Rb_2^+$ molecular ions is significantly different from lifetime of $^{85}Rb_2^+$ molecular ions reported by Jyothi et al[1].

Key words: ion-neutral hybrid trap; two-body collision; molecular ions; lifetime

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Preparation of ^{85}Rb-^{87}Rb dual-species ultra-cold sources for atom interferometers

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Abstract: Atom interferometers have important applications in the measurement of inertial physical quantities, fundamental physical constants and the testing of fundamental physical laws. However, as the evolution time *T* increases, the expansion of atomic cloud becomes a major source of systematic errors. Achieving atom sources with lower temperatures and higher atom numbers is therefore one of the challenges for long-baseline atom interferometers. We design and implement a modular assembled laser system[1] and realized an ^{85}Rb-^{87}Rb dual-species ultracold atom source for high-precision equivalence principle test and the Zhaoshan long-baseline atom interferometer gravitation antenna[2]. Initial evaporative cooling of the atom cloud was achieved, reaching temperatures of 350 nK for ^{87}Rb and 2 μK for the dual-species mixture.

Key words: ultra-cold sources; atom interferometer

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Nearly nondestructive thermometry of labeled cold atoms and application to isotropic laser cooling

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Abstract: We develop a form of nondestructive optical thermometry to deterministically measure the temperature of the selected segment of a cold-atom ensemble. The essence is to monitor the thermal expansion of the targeted cold atoms after their labeling through manipulation of the internal states, and the nondestructive property relies on nearly lossless detection via the driving of a cycling transition. The temperature information is extracted from the change of densities via a bucket detector without the necessity of a complicated imaging setup. We also focus on the application of this method to isotropic laser cooling, and it has the capability of addressing only the atoms on the optical detection axis within the enclosure, which is readily compatible with typical configurations of atomic clocks or quantum sensing. Our results confirm the sub-Doppler-cooling features of isotropic laser cooling, and we further investigate the relevant cooling properties. Furthermore, we demonstrate the recently developed optical configuration with injection of cooling-laser light in the form of hollow beams, which helps to enhance the cooling performance and accumulate more cold atoms in the central regions.

Key words: isotropic laser cooling; cold atom; nearly nondestructive thermometry

Microwave-optical conversion with cold Rydberg atoms

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Abstract: Long-distance quantum communications between solid-state superconducting quantum processors require microwave-optical conversion with near-unit efficiency. We aim to demonstrate that efficient bidirectional conversion can be realized with frequency mixing in cold atoms sitting on top of a coplanar microwave resonators. Rydberg energy levels offer a quasi-continuum of transitions available in the microwave and terahertz range of frequencies which makes this technique promising for a broad range of applications. In the quantum domain in particular, coherent microwave-optical conversion with Rydberg atoms could enable interfacing superconducting qubits and optical fibers for carrying quantum information over long distances using photons. This technology could also be used to generate bright terahertz beams with important application prospects in the fields of medicine, safety inspection and avionics. The planned work includes the realization of the cold atom source based on a magneto-optical trap, the coupling of the atoms to the waveguide.

Key words: Rydberg atom; cold atom; microwave-optical conversion; quantum communication

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Ion-neutral atom reactive collisions in an ion-atom hybrid trap for the element ^{87}Rb

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Abstract: The formation of cold molecular ions in cold hybrid ion-atom systems is important for the understanding of fundamental physical and chemical processes as well as future quantum technologies, e.g., such chemical reactions provide platforms for simulating and understanding evolution of astronomical objects, since both interstellar medium and cold ion-atom mixtures have cold and dilute environments. Our ion-atom hybrid trap comprises of two separated but spatially concentric a magneto-optical trap (MOT) for ^{87}Rb and a linear Pauli trap (LPT). Rb^+ ions are produced by two-step cw-laser photoionization of ^{87}Rb. Two peaks are observed in the time-of-flight mass spectrometry, and the peak at much later time is identified as Rb_2^+ due to its larger mass. Moreover, Rb_2^+ ions are verified by kinematic effects in the LPT, which are studied by varying the Mathieu parameter, which determines the ions' stability, micromotion amplitude , etc., and depends on the mass and charge of an ion.

Key words: ion-neutral hybrid trap; molecular ion; time-of-flight mass spectrometry

Pre-cooling of magneto-optical trap via isotropic laser cooling

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Abstract: Laser cooling of atoms has been rapidly developing since the late 20th century. There exist many different techniques of laser cooling and trapping, such as optical molasses, VSCPT, magnetic trap, magneto-optical trap (MOT) and evaporative cooling. Besides these methods, isotropic laser cooling (ILC) has been extensively used in cold atomic clocks. Its advantages include the simple all-optical physical package, and not requiring careful collimation of laser beams, either position or polarization. However, ILC cannot trap the atoms, thereby the density of the cold atoms is low, on the other hand, the pre-cooling device such as Zeeman slower or two-dimensional MOT is generally complex because it requires the magnetic field and the strict polarization of the laser. Here, we propose a new solution to obtain the ^{87}Rb MOT, it simplifies the pre-cooling stage via isotropic laser cooling and it is likely to increase the density of atoms compared with that obtained using the MOT cooling directly. Furthermore, this may improve the number of atoms and cooling efficiently of cold atom clock.

Key words: Rb atom; isotropic laser cooling; pre-cooling of magneto-optical trap

Doppler cooling of buffer-gas-cooled Barium monofluoride molecules

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Abstract: We demonstrate one-dimensional Doppler cooling of a beam of buffer-gas cooled Barium monofluoride (BaF) molecules. The beam of buffer-gas cooled BaF molecules is produced by a BaF_2 target fixed in a buffer gas cell which is Ablated by a pulse laser. The buffer gas is 4K He. Then the beam of BaF is cooled by the laser containing 860 nm (for cooling) and 736 nm (for repumping). In the end, we use a CCD to detect the shape of the molecular beam, which indicates its transverse temperature by a probe laser. The dependences of the cooling efficiency with the laser detuning, the bias field, and the laser intensity are carefully measured. We also study the influence of the laser power and the magnetic field in Doppler cooling. We numerical simulate our experiment with a Monte Carlo method and find the theoretical predictions consisting of our experimental data. This result represents a key step toward further cooling and trapping of BaF molecules.

Key words: BaF; doppler cooling; laser detuning

Coherently forming a single molecule in an optical tweezer

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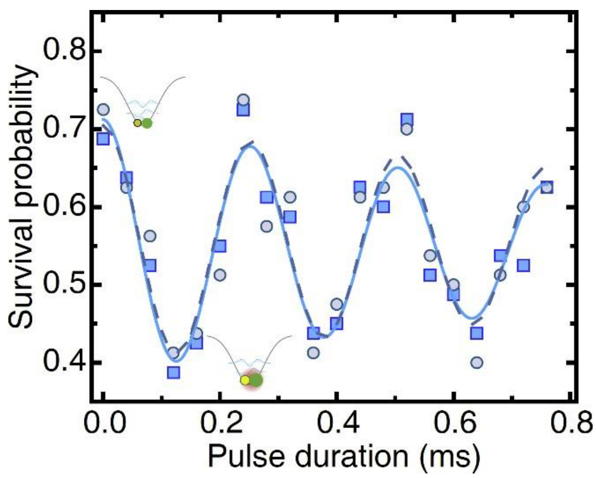
Abstract: Ultracold single molecules have wide-ranging potential applications, such as ultracold chemistry, precision measurement, quantum simulation and quantum computation. However, given the difficulty of achieving full control of a complex atom-molecule system, the coherent formation of single molecules remains a challenge. We achieved this goal by preparing an ultracold two-atom system in an optical tweezer trap. Two heteronuclear rubidium atoms (^{87}Rb and ^{85}Rb) are prepared in the motional ground state with Raman side cooling and species-dependent transport[1]. High-fidelity manipulation of the quantized motion is achieved with spin-motion coupling (SMC) mediated by the inherent polarization gradients in strongly focused tweezer beams[2]. By coupling atomic spins to the two-atom relative motion, we demonstrated coherently forming of a weakly bound single molecule (^{87}Rb^{85}Rb) [3]. The coherent nature is demonstrated by long-lived atom-molecule Rabi oscillations. We further manipulate the motional levels of the molecules. In future work, we will extend to the study of single dipolar molecule of RbCs in the ground rovibrational state.

Key words: ultracold atom; single molecule; optical tweezer



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Multi-type solitons in spin-orbit coupled spin-1 Bose-Einstein condensates

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Abstract: we derived exact analytical soliton solutions of Gross-Pitaevskii equations describing spin-orbit coupled spin-1 Bose-Einstein condensates. We also obtained the analytical relation between different types of one-dimensional spin-orbit coupling and Zeeman effect and found a transformation that can simplify the three-component Gross- Pitaevskii equations with spin-orbit coupling into the nonlinear Schrödinger equation. Further,The abundant stripe phase and dynamic characteristics of the system are investigated.

Key words: Bose-Einstein condensate; spin-orbit coupling; soliton

Controllable production of degenerate Fermi gases of Li-6 atoms in the 2D-3D crossover

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Abstract: The many-body physics in the dimensional crossover regime attracts much attention in cold atom experiments but is yet to explore systematically. One of the technical difficulties in the experiments is the lack of an experimental technique to quantitatively tune the atom occupation ratio of the different lattice bands. Here, we have developed such techniques in transferring a 3D Fermi gas into a 1D optical lattice, where the capability of tuning the occupation of the energy band is realized by varying the trapping potentials of the optical dipole trap and the lattice, respectively. By varying the lattice depth, we could prepare a Fermi gas with the occupation in the lowest band from unity to 80%. For the tuning of the optical dipole trap depth, we could produce Fermi gases with the occupation in the lowest band from 80% to 50%. Together, these methods could quantitatively control the ultracold Fermi gas in the 2D-3D crossover and promote further research on the relationship between many-body interaction and the system's dimensionality.

Key words: Fermi gases; 2D-3D crossover; 1D optical lattice; quantitatively control

Quantum-state exclusion induces anti-inertia and antigravity

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Abstract: The law of inertia in classical physics states that an object will continue to be in the state of rest or in a state of motion at constant velocity unless an external force acts on it. However, it is still unclear whether and how the law applies to quantum systems. In the nonrelativistic case, we prove that an accelerating quantum system is equivalent to a resting system in a gravitational field. We find that the inertial effects rely on the state of the quantum system. In contrast to the ground state which obeys the law of inertia, the excitations may violate the law when the system is gradually accelerated. This means that the excitations could be anti-gravitational when the gravitational field is turned on adiabatically. We demonstrate that the phenomena of antigravity result from a new mechanism we name as "quantum-state exclusion". In addition, we show that weak gravitational fields could effectively lead to and accelerate the expansion of quantum systems. We propose to observe these phenomena in topological excitations of Bose-Einstein condensate in ultracold atomic experiments. Our findings may shed new light on explaining the accelerating expansion of the universe.

Key words: anti-inertia; antigravity; Bose-Einstein condensate

Atomic cooling scheme and ground experimental verification towards Chinese space station

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Abstract: The Cold Atom Physics Rack (CAPR) of Chinese space station will be launched at the end of 2022. The important goal of CAPR is to achieve BEC at 100 pk. In order to obtain ultracold atoms in microgravity of space station, we propose a two-stage cooling scheme using all-optical trap with different waist beams. The cold atom cloud obtained by this scheme is composed of condensate and thermal atoms around condensate. The design of our two-stage cooling scheme will effectively reduce the temperature of the thermal atom cloud and the effective temperature generated by the interaction energy of the condensate. The atomic temperature of 2 nk is obtained from the ground test experiment, and the corresponding temperature under the microgravity condition of the space station is theoretically predicted to be less than 100 pk. Taking the advantages of ultracold temperature and long-time detection, many scientific experiments will be arranged.

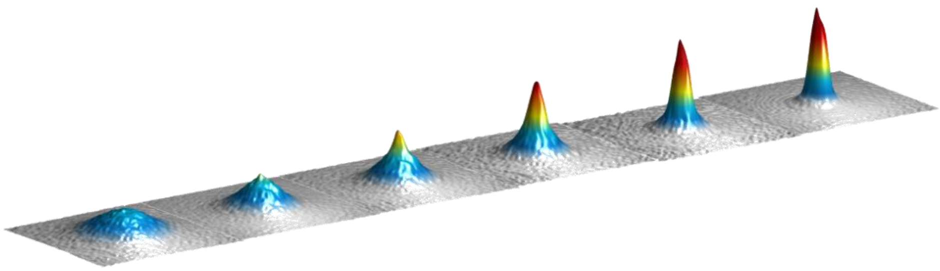

Fig.1 Ground experimental results for CAPR, from thermal gas to Bose-Einstein Condensation, the final temperature is 2 nK.

Key technologies for preparing Bose-Einstein condensation in CAPR on Chinese space station

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Abstract: Low temperature is the goal that mankind is constantly pursuing. From the preparation of liquid helium to cold atomic gases, the level of low temperature continued to improve from K (liquid helium) to 1e-3 K (magneto-optical trap), 1e-6 K (molasses), 1e-9 K (quantum degenerate gas), and possibly even 1e-12 K (deeply cooled quantum gas). Further cooling is a key area of competition. It has been widely recognized in the international physics community that ultra-cold atomic experiments in microgravity can achieve this goal. One of the purpose of the Cold Atom Physics Rack (CAPR) on Chinese space station is to achieve ultra-low temperature Bose-Einstein Condensation (BEC) on the scale of pico-Kelvin (pK). There are three advantages for the quantum gas in space: (1) ultralow temperature (pK), three order lower than on the earth (nK); (2) longer observation time (20 s), three order longer than on the earth (20 ms); (3) space uniform, no gravity gradient potential.

Our ground-based verification system for CAPR is a Rb-K Quantum gas mixture system for physical experiments in space microgravity. In order to achieve the goal of miniaturization and low power consumption in the space station, there are several key techniques in the process of preparing Bose-Einstein condensation (BEC). High frequency laser phase lock technology is used to produce a tunable frequency-stabilized laser to cool atoms. The line width of beat frequency signal is 10 MHz and the tuning range is ±12 GHz (dynamic range 500 MHz). Optical phase lock loop (OPLL) avoids the larger volume and high power consumption of the traditional AOM complex optical path. Complex programmable logic device (CPLD) takes the place of LabVIEW which needs board card to realize the control of system time sequence. It's just a 10 cm × 10 cm circuit board programmed through a computer, which realize the switch control of shutter driver, AOM driver, magnetic coil driver, laser power variation curve of optical dipole trap, camera trigger and so on. And high current magnetic trap control technology enables a high-current coil to have a current of 500 A and a magnetic field of. At present, 100 nK BEC has been realized on our experimental platform. Next we will use two step cross beam cooling (TSCBC) method to further cool down. In the first stage, atoms undergo the runaway evaporation cooling process in an optical trap formed by two crossed laser beams with narrow beam diameter and high power. In the second stage, low temperatures atoms are loaded into the other optical trap formed by two crossed laser beams with wide waist and weak power. After decompression cooling process, the temperature of atoms below 1e-10 K is expected to be achieved.

Key words: BEC; Chinese space station; miniaturization; key technologies

Realization of Qi-Wu-Zhang model in spin-orbit-coupled ultracold fermions

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Abstract: Based on the optical Raman lattice technique, we experimentally realize the Qi-Wu-Zhang model for quantum anomalous Hall phase in ultracold fermions with two-dimensional (2D) spin-orbit (SO) coupling. We develop a novel protocol of pump-probe quench measurement to probe, with minimal heating, the resonant spin flipping on particular quasi-momentum subspace called band-inversion surfaces. With this protocol we demonstrate a continuous crossover between 1D and 2D SO couplings by tuning the relative phase between two coherent Raman couplings, and detect the non-trivial topological band structures by varying the two-photon detuning. The non-trivial band topology is also observed by slowly loading the atoms into optical Raman lattices and measuring the spin textures.

Key words: Sr atom; optical Raman lattice; spin-orbit coupling; Qi-Wu-Zhang model

Universal physics with narrow Feshbach resonance

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Abstract: We explore the universal physics associated with the narrow Feshbach resonance using a degenerate Fermi gas of Li-6 atoms, in which three-body recombination dominates the behavior of the gas. The dependences of the three-body recombination on the collisional strength and the temperature are precisely measured, and several universal physics are verified experimentally for the first time. First, we find that three-atom recombination through a narrow resonance follows a universal behavior determined by the long-range van der Waals potential and can be described by a set of rate equations in which three-body recombination proceeds via successive pairwise interactions. It had been verified that the underlying physical picture to be applicable not only to narrow s wave resonances, but also to resonances in nonzero partial waves, and not only at ultracold temperatures, but also at much higher temperatures. Second, we demonstrate a novel technique of collisional cooling with the three-body recombination in which the threshold energy of the quasi-bounded Feshbach molecule acts as the knife of cooling, expelling the hot atoms with selective kinetic energy from the trap. By precisely tuning the threshold energy with a magnetic field, we find that the three-body loss results in cooling, instead of heating, if the collision threshold energy is larger than 3/2 k_BT. The maximum phase space density during a cooling process has been located to be around at the threshold energy of 9/2 k_BT, predicted by a general kinematic theory. Third, we examine that the scaling law of the three-body loss rate when the s-wave scattering length is larger than the range of the interatomic potential. The experimental result identifies the theoretical predictions with zero-range two-body interactions and displays the suppression effect from the Efimov-like physics. In the weakly interacting regime, where s-wave scattering length goes vanish, the scattering length dependence will be modified by considering the finite-range interaction associated with the narrow Feshbach resonance. We expect that the universal physics of three-body process could promote the development of the few-body and many-body physics with the finite-range interaction.

Key words: degenerate Fermi gas; Feshbach resonance; collisional cooling; three-body recombination

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Spin Faraday waves in two-component Bose-Einstein condensate

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Abstract: We investigate the modulation instability of a binary Bose-Einstein condensate (BEC) in an elongated harmonic trap. By periodically modulating the scattering lengths of the two components, a spin Faraday wave can be generated where the two components exhibit an out-of-phase oscillation. Our systematic numerical results reveal that the pattern of the spin Faraday wave is related to the spin healing length and spin sound velocity. We also develop a Floquet theory to obtain the modulation stability phase diagram of the driven BECs. Our results may stimulate further theoretical and experimental research on the rich non-equilibrium dynamics of the periodical modulated Bose-Einstein condensates.

Key words: spin Faraday waves; modulation instability; periodical modulation

Long-range interactions and critical behavior in Bose-Einstein condensates

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Abstract: This talk will present several results on pattern-formation in long-range interacting ultracold atomic systems. The first part will focus on cold atomic gas with inherent long-range interactions, i.e., dipolar Bose-Einstein condensates, for which the possibility of obtaining quantum states with self-organized long-range ordering can be facilitated by quantum fluctuations which suppress collapse and pave the way for supersolids. We find that quantum fluctuations can alter the order of the phase transition from first- to second order. Furthermore, apart from the usual triangular lattice of density droplets, quantum fluctuations can give rise to a novel quantum state whose density distribution displays a honeycomb structure. The second part will present photon-mediated effective atom-atom interactions via retro-reflecting mirrors. These lead to a rich variety of patterns of self-bound droplet clusters of ultracold matter waves.

Key words: dipolar BECs; quantum fluctuations; supersolids; long-range interactions

Machine-designed nonlinear interferometer surpassing classical sensing limit

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Abstract: Engineering quantum dynamics is a demanding task for systems with large degrees of freedom. The empirical or intuition-based approaches often fail to find optimal solutions. Here we employ reinforcement learning to search for optimal designs of "path" splitter and recombiner in a nonlinear interferometer by tailoring the system dynamics through the control of a linear field. Remarkably, the learnt strategy is found to drive the system towards the initial state before detection, reminiscent of the paradigm time-reversal protocol while with a totally different traveling path which is optimized to compromise the effect of noise and loss. By using the optimized protocol, we achieve a metrological gain of $6.97^{+1.30}_{-1.38}$ dB beyond the classical precision limit for a condensate of 10 900 ^{87}Rb atoms. Our work highlights the power of reinforcement learning in optimal metrology and quantum dynamics engineering.

Key words: quantum metrology; nonlinear interferometer; machine-learning

Suppression of Coriolis error in weak equivalence principle test using ^{85}Rb-^{87}Rb dual-species atom interferometer

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Abstract: When testing the weak equivalence principle (WEP) with atom interferometers, the Coriolis effect is an important error source, so we study the problem of Coriolis error in the WEP test theoretically and experimentally. We analyze the Coriolis effect by establishing an error model and find out its relationship with experimental parameters, such as horizontal-velocity difference and horizontal-position difference of atomic clouds, horizontal-position difference of detectors, and rotation compensation of Raman laser's mirror are calculated. In the experimental investigation, the position difference between ^{85}Rb and ^{87}Rb atomic clouds is reduced to 0.1 mm by optimizing the experimental parameters, an alternating detection method is used to suppress the error caused by the detection position difference, thus the Coriolis error related to the atomic clouds and detectors is reduced to 1.1×10^{-9}. This Coriolis error is further corrected by compensating for the rotation of Raman laser's mirror, and the total uncertainty of η measurement related to the Coriolis effect is reduced as $\delta\eta = 4.4 \times 10^{-11}$.

Key words: equivalence principle test; atom interferometer; Coriolis effect

The experimental progress of 10-m atom interferometer

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Abstract: The equivalence principle (EP) is one of the basic assumptions of general relativity. Almost all new theories that attempt to unify gravity with the standard model require the EP to be broken. We have long been engaged in the experimental research of the weak equivalence principle test with a simultaneous ^{85}Rb-^{87}Rb dual-species atom interferometer. In 2021, we achieve a joint mass-and-energy test of the equivalence principle at the 10^{-10} level using atoms with specified mass and internal energy[1]. Recently, we accomplish upgrades to systems such as lasers[2], magnetic shielding[3], and detection. Firstly, we design and implement a laser system for ^{85}Rb and ^{87}Rb dual-species atom interferometers based on acousto-optical frequency shift and tapered amplifier laser technologies. Therefore, a height of atom fountain up to 12 m, the time-of-flight signal is 5 times larger than before. Secondly, we design and develop a high-performance magnetic shielding system for a long baseline fountain-type atom interferometer. The shielding system is achieved by a combination of passive shielding using permalloy and active compensation with coils. The active compensations compress the residual magnetic field to 8.0 nT max-to-min and the corresponding gradient below 30 nT/m over 10 m along the axial direction in which external compensation, internal compensation, and constant magnetic field (C-field) compensation reduce the inhomogeneities to 25.0, 12.6, and 1.7 nT (standard deviation) sequentially. We estimate that this system could reduce the systematic error of the quadratic Zeeman shift to the 10^{-13} level for the weak equivalence principle test with a simultaneous ^{85}Rb-^{87}Rb dual-species atom interferometer. Finally, we develop a method for directly imaging to get the phase and contrast of a single shot of an atom interferometer. Introducing a phase shear across the atom ensemble yields a spatially varying fringe pattern at each output port[4]. Thanks to the above methods, we can obtain a resolution of to 4.5×10^{-11} g per shot with a free evolution time of up to $2T = 2.6$ s.

Key words: equivalence principle; atom interferometer; ^{85}Rb-^{87}Rb dual-species

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Shipborne absolute gravity measurement based on atomic interference

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Abstract: The gravity field is one of the basic physical fields of the Earth. Dynamic gravity measurements could improve the efficiency of gravity surveying, and have important applications in the fields of geologic, geophysics, resource exploration, inertial navigation, and so on. Currently, dynamic gravity measurements are mostly based on relative gravimeters, which have the problem of zero drift. Dynamic absolute gravimeters can provide synchronous and co-site calibration for relative gravimeters and solve the problem of long drift.

A system of absolute gravity dynamic measurement was built based on a homemade atomic gravimeter and an inertial stable platform. The dynamic absolute gravity measurement under the state of shipborne mooring was carried out recently. Based on the dynamic absolute gravity measurement system, a series of measurement in South China Sea was carried out. According to the physical model of the measurement system, a data processing method was proposed based on the extended Kalman filter algorithm. The accuracy of shipborne mooring measurement reached the order of mGal, and the sensitivity of absolute gravity measurement was 136.8 mGal/Hz$^{-1/2}$ with extended Kalman filter algorithm method. Comparing the processed data with the data calculated with the earth gravity model (XGM2019), it is found that both of the data are in good agreement.

Key words: atomic interference; cold atom; absolute gravity; dynamic measurement

Precision spectroscopy of the pionic helium-4

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Abstract: Pionic helum is an exotic three-body atomic system that consists of a helium nucleus, an electron and a negatively charged pion meson. This system can formed by a negative pion that is stopped and then replaced one of the electrons in a helium atom. If it occupies a nearly circular orbit n~l+1 with n~16, it forms a long-lived stat that can be studies by methods of precision laser spectroscopy. Since the sensitivity coefficient of a tansitio frequency to the charged pion mass is 1.88 for the transition (n,l)=(17,16)->(16,15), one derive a value of charged pion mass to an accuracy of ppb level if this frequency can be both measured and calculated to ppb level.

Pionic helium-4 transtion (17,16)->(17,15) was firstly measured by Paul Scherrer Insitute (PSI) in 2020 [M. Hori et al., Nature 581, 37 (2020)]. The difference between theory and measurement is understood as collisional shift between pionic helium and helium. Meanwhile, the experiment of transition (17,16)->(17,16) frequency is measuring at PSI aiming a precision of 10 ppb. We caulcated resonance energies and widths for metastable states of ponic helium-4 by using the complex coordinate rotation method based on the gradient optimization (CCR-GO) [Z.-D. Bai et al., Chin. Phys. B 30(2), 023101 (2020)]. The relativistic and radiative corrections up to $R_\infty\alpha^5$ order are calculated for pionic helium-4 which let us estimate the (17,16)->(16,15) frequency to a precision of 4 ppb (parts per billion). Once the measurement at PSI achieve a precision of ppb level, our theory will improve the accuracy of charged pion mass by 2-3 orders of magnitude, and we may study the nutrino mass puzzle by using the pion decay process. Our results have been published at Physical Review Letters vol. 128, 183001 (2022).

Key words: exotic atom; pionic helium; pion mass; precision spectroscopy; relativistic and radiative corrections

Precision remote time and frequency traceability based on NIMDO

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Abstract: High-precision time-frequency transmission is a bridge connecting our country's time reference to all levels of time and frequency users, and plays an extremely important role. Using the remote time traceability device developed by the China Institute of Metrology—NIMDO (UTC(NIM)Disciplined Oscillator), and carrying out satellite common-view data comparison through NIMDO to achieve real-time traceability and real-time synchronization of time standards to benchmarks. The results of validation and analysis showed that 78.17% of the time offset between NIMDO and UTC(NIM) maintained within ±5 ns, 89.11% of the time offset between NIMDO and UTC(NIM) maintained within ±10 ns and 99.39% of the relative frequency deviation (one-day average) within ±2e-13. The results showed that the system solved the problem of time traceability and synchronization, and can provide reference for time synchronization in other fields.

Key words: UTC(NIM) disciplined oscillator; time synchronization; traceability system; time and frequency transfer

Systematic shifts of an $^{27}Al^{+}$ ion optical clock co-trapped with $^{40}Ca^{+}$

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Abstract: Optical clocks based on a single $^{27}Al^{+}$ ion have reached the best accuracy to date. Limited by the lack of suitable cooling and detecting laser, $^{27}Al^{+}$ ions require sympathetic cooling and quantum logic detection provided by another co-trapped auxiliary ion species. Due to the minimum mass difference, $^{24}Mg^{+}$ ion is the typical choice for this task. Here we report another approach using $^{40}Ca^{+}$ as the auxiliary ion. Benefit from its lower Doppler cooling limit, the time dilation shifts due to the secular motion of the clock ion is smaller than that of the $^{24}Mg^{+}$-$^{27}Al^{+}$ clock under the same cooling condition. The total systematic uncertainty of the $^{40}Ca^{+}$-$^{27}Al^{+}$ quantum logic clock is estimated to be 7.9×10^{-18}, limited by the uncertainty of the quadratic Zeeman shift. By comparing the frequency of two counter-propagating interrogation beams on the same ion, we measured the stability of the clock to be $3.7\times 10^{-14}/\sqrt{\tau}$.

Key words: optical clock; ion trap; quantum logic spectroscopy; sympathetic cooling

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Temperature measurement of expanding strongly coupled ultracold neutral plasmas

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Abstract: We have newly built a system combining of a magneto-optical trap and a velocity map imaging equipment (MOT-VMI) to measure the ion velocity distribution during the early evolution of an ultracold neutral plasma (UNP). The thermal velocity distribution and the radial expansion velocity of the ions in the expanding strongly coupled UNP are obtained and compared with the numerical simulations. The experimental results show that the Coulomb coupling parameter of the ions after the disorder-induced heating (DIH) is about 2.5, which is in good agreement with the theoretical results. Moreover, the radial expansion velocity of ions observed experimentally is equivalent to the plasma expansion velocity predicted by molecular dynamics (MD) simulation, which means that the collision-free model can be used to simulate the early UNP evolution process.

Key words: MOT-VMI; ultracold neutral plasma (UNP); strongly coupled plasma; molecular dynamics

Experimental study on a new stark decelerator: taking ND_3 molecules as an example

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Abstract: In recent years, cold atomic and molecular physics has played unique roles in many diverse areas of fundamentals interest, such as quantum reaction dynamics, condensed-matter physics, and even astrophysics[1]. Recently, we proposed a novel electrostatic Stark decelerator with true three-dimensional electric potential wells that allows preparing more cold molecules than that of a traditional one[2]. It is formed by a series of horizontally-oriented, U-shaped electrodes and two guiding electrodes. Most recently, we have carried out some preliminary experiments on this device by employing ND_3 molecules as an example. With the U-shaped electrodes of ± 5 kv and the guiding electrodes of -10 kv, a molecular beam with an initial velocity of 310 m/s is efficiently decelerated to 215 m/s with 166 slowing stages (S=3 mode), as shown in Figure 1. With the improvement of instrument performance, especially the available voltages, better results can then be achieved.

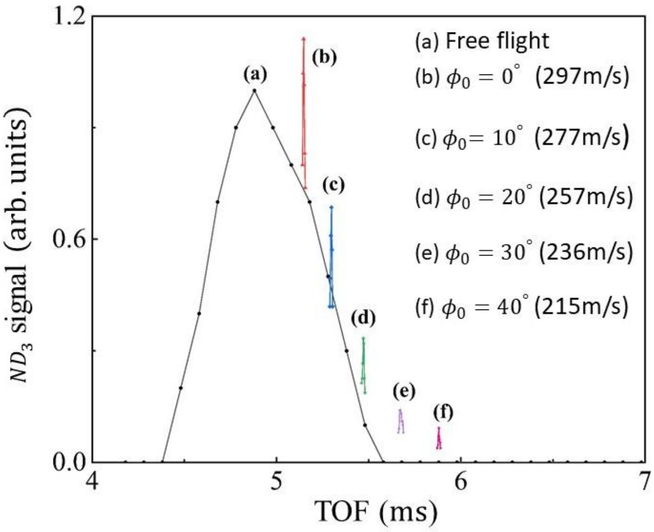

Figure1. Observed ND_3 signals as a function of flight time for different phase angels

Key words: Stark decelerator; polar molecules; inhomogeneous electric fields

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Isotope shift factors for Cd^+ 5s $^2S_{1/2}$ − 5p $^2P_{3/2}$ transition and Cd nuclear charge radii determination

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Abstract: The accuracy of atomic isotope shift factors limits the extraction of nuclear charge radii from isotope shift measurements since determining the atomic isotope shift factors is challenging both experimentally and theoretically. Here, the isotope shifts of the Cd^+ 5s $^2S_{1/2}$ − 5p $^2P_{3/2}$ transition is measured precisely by using the laser-induced fluorescence from a sympathetically-cooled large Cd^+ ion crystal. A King-plot analysis is performed based on the new measurement to obtain the accurate atomic field shift F and mass shift K factors, cross-checked by state-of-the-art configuration interaction and many-body perturbation calculations. The nuclear charge radii (R_{ch}) of $^{100-130}$Cd extracted by using such F and K values demonstrate a precision increase being nearly five times in the neutron-rich region. This work provides accurate extraction of R_{ch} from isotope shifts. New R_{ch} values reveal hidden discrepancies with previous density functional predictions in the neutron-rich region and pose a strict challenge for the advancement of nuclear models.

Key words: isotope shift; sympathetic cooling; nuclear charge radii

The scale factor measurement of a four-pulse atom interferometric gyroscope

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Abstract: Cold-atom interferometric gyroscopes have showed high sensitivity and excellent long-term stability and are expected to apply in inertial navigation and precision measurements. In order to determine the numerical relationship between the atomic interference phase shift measurements and the rotation information of carrier, the scale factor of the atomic interferometric gyroscope must be calibrated. We designed a gyroscope experiment that based on four-pulse interference technique. We obtain the interference phase shifts at different horizontal Earth azimuth angles by controlling the rotation of the gyroscope sensor around the vertical axis, and the scaling factor is obtained by fitting the measured rotation phase shifts with the horizontal Earth azimuth angle, which differs from the theoretical value by 4‰.

Key words: atomic gyroscope; scale factor

Multi-pass acousto-optic frequency shift laser system

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Abstract: We design and implement a laser system for ^{85}Rb and ^{87}Rb dual-species atom interferometers based on acousto-optic frequency shift and tapered amplifier laser technologies. This laser system uses only two seed lasers to provide the various frequencies required by ^{85}Rb and ^{87}Rb dual-species atom interferometers, which greatly improves laser usage. We use 8-pass acousto-optic frequency shift system to generate repumping lasers for ^{85}Rb and ^{87}Rb atoms. The maximum frequency shift of the laser is 2.8 GHz, and the diffraction efficiency is higher than 20%. Even more, through technical improvement, we design and implement a 12-pass acousto-optic frequency shift system. The frequency of the incident laser beam is shifted by 4.2 GHz with the total diffraction efficiency as high as 11%, and the maximum frequency shift is 5 GHz. Combining the ±1st order diffraction, laser signals with up to 10 GHz frequency difference can be obtained, which fulfill most frequency shift requirements of laser cooling and coherent manipulation experiments with alkali metal atoms.

Key words: acousto-optic frequency shift; atom interferometer

Compensation of low-frequency noise induced by power line in trapped-ion system

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Abstract: The low-frequency magnetic field noise resulting from the laboratory power supply is one of the main decoherence sources of trapped-ion qubits. Synchronizing the experimental sequence to the phase of the power line is widely used to mitigate this problem, but it will greatly reduce the experimental efficiency. We experimentally demonstrate a simple active compensation method to reduce the observed 50 Hz and 150 Hz strong magnetic noise in an ion trap induced by the power line. In our method, a single $^{40}Ca^{+}$ ion is used as the noise probe and a reverse compensation signal is generated by a programmable arbitrary waveform generator (AWG). After compensation, an 86% reduction of the periodic magnetic field fluctuation and over 35-fold extension of the coherence time from 70 μs to 2 500 μs were observed. This method can also be applied to compensate other spectral components of the magnetic field noise related to the power line, and it is also useful for other atomic systems such as neutral atoms.

Key words: low-frequency noise; power line; atomic systems

Estimating gravity acceleration from atomic gravimeter more precisely

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Abstract: The measurement precision of the static atomic gravimetry is limited by white phase noise in short term, which costs previous works an inevitable integration to reach the precision demanded. Here, we present the construction of the statistical model of the atomic gravimeter and the estimation algorithm to estimate gravity acceleration from atomic gravimeter more precisely. During 200 hours of static measurement of gravity, the atomic gravimeter demonstrates a sensitivity as good as 0.6 $nm/s^2/\sqrt{s}$, and highlights a precision of 1.7 nm/s^2 at the measuring time of a single sample. The measurement noise achieved is also lower than the quantum projection limit below ~ 30 s.

Key words: atom interferometry; atomic gravimeter; estimation of gravity acceleration

Close loop performance of Sr-1 optical lattice clock in USTC

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Abstract: Optical atomic clocks have demonstrated unprecedented stability and accuracy, and promised significant advances in various applications such as geodesy, definition of the second and test of fundamental physics. In this presentation, I will describe our apparatus of a ^{87}Sr optical lattice clock and the experimental study of Dick effect in optical atomic clock. After red MOT, cold Sr atoms are loaded into a magic-wavelength one-dimensional optical lattice with temperature of about 3 μK and lifetime of about 20 s. Narrow Rabi spectrum with linewidth as low as 0.6 Hz can be obtained. The Dick noise is carefully analyzed in the interleaved self-comparison stability measurements with the calibrated clock laser noise spectrum, indicating the dominant contribution of Dick effect to the clock stability in a wide range of parameters. By applying proper clock pulse length and dead time, the stability of the optical lattice clock system can be improved to $4.7 \times 10^{-16}/\sqrt{\tau}$.

Key words: Sr atom; optical lattice clock; the stability; Dick effect

Spin-squeezing in alkaline-earth-like atoms

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Abstract: Optical lattice clocks with alkaline-earth like atoms have been used to realize the highest precision for time and frequency measurements. One of the typical way to improve the accuracy of an atomic clock is to average over a many-particle ensemble. If the atomic states are independent of each other, the precision of the averaging is limited by the standard quantum limit (SQL). Multi-particle entanglement in an atomic ensemble can be used to achieve precision beyond the SQL. With the state-of-art ultra-stable laser technology, the local oscillator noise in an alkaline-earth-like optical lattice clock has been significantly reduced. Therefore, the accuracy of the clock starts to be limited by the SQL. We are designing an experimental apparatus with alkaline-earth-like Ytterbium atoms coupled to an optical cavity and developing theoretical proposals for spin-squeezing generation in such an atom-cavity system. The entanglement between atoms can be generated by coupling the atoms with the quantized cavity field. By applying quantum non-demolition measurement of the collective atomic spin via the cavity photon field, entanglement between atomic spins can be generated. Furthermore, in the scenario of a strongly driven atom-cavity system, long-range spin-spin interactions can be generated by a feedback mechanism between the collective atomic spin and the population of cavity photons.

Key words: spin-squeezing; optical lattice clock; cavity quantum electrodynamics

Characterization of $^{130}Te_2$ transition lines around 444.4 nm

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Abstract: Molecular tellurium ($^{130}Te_2$) has been long regarded as a promising candidate for a variety of spectroscopic applications as a frequency reference. Its spectroscopic atlas of absorption lines was released a few decades ago; however, the spectral resolution there was not sufficiently high to be considered a precision spectroscopic reference. Here, electronic transition lines and associated absolute frequencies were measured by a wavemeter (calibrated via Cs D_1 lines[1]) via the saturated absorption spectroscopy (SAS) method. 187 lines were found in ~ 400 GHz frequency range, among which 22 lines were matched with previous atlas[2]. A new method was developed to assign lines for multiple bands in the B_1 ($^3\Sigma_u^+$) $0_u^+ \leftarrow X_1$ ($^3\Sigma_g^+$) 0_g^+ transition, and spectroscopic constants of the excited state B_1 were updated to a new level. The Toptica TA-SHG Pro laser was then locked to a single absorption line via a P-I servo around 444.4 nm to 10^{-8} $\Delta f/f$, thus providing the frequency reference for an eEDM (electron's Electric Dipole Moment) sensitive transition[3] for further spectroscopic detection proposal via PbF molecules .

Key words: tellurium spectrum; saturated absorption spectroscopy; frequency reference; *e*EDM

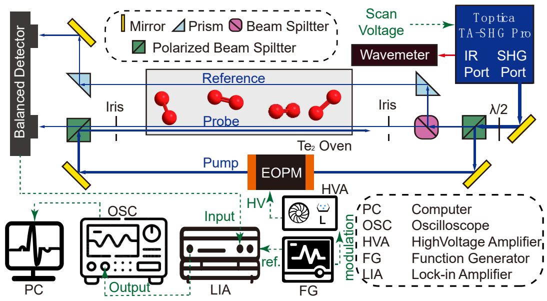

Figure1. Experimental setup for the saturated absorption spectroscopy of $^{130}Te_2$

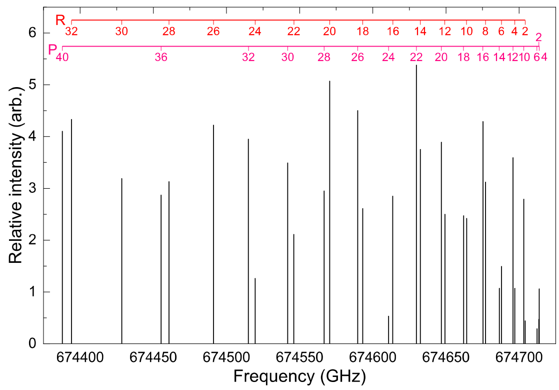

Figure2. Experimental result of $^{130}Te_2$ $X_1(^3\Sigma_g^-)0_g^+$-B_1 $(^3\Sigma_u^-)0_u^+$ 5-10 transition lines & labeling results

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Self-oscillating nuclear magnetic resonance gyroscope

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Abstract: In nuclear magnetic resonance gyroscope (NMRG), measuring precisely the Larmor frequency is a key step for improving the precision of inertial measurement. Two major factors affect the measuring precision of Larmor frequency, i.e. the signal to noise ratio (SNR) of Larmor precession signal and relaxation lifetime of nuclear spins. In practice, various parametric modulation and demodulation techniques are implemented to improve the SNR, as well as anti-relaxation coating and buffer gas techniques are used to prolong the spin relaxation times.

Theoretical analysis indicates that the inherent trispin dynamics of NMRG set a limit on the maximum response signal of the NMRG[1]. A close-loop NMRG may improve the Larmor signal, as has been proved by applying an external oscillating magnetic field with frequency close to the intrinsic Larmor frequency of nuclear spins to drive them resonantly[2]. Alternative close-loop NMRG uses a lock-in amplifier to improve the SNR, while increase the complexity of the whole system[3].

Inspired by the self-oscillating atomic magnetometer[4], here we propose a new scheme for close-loop NMRG, which use homemade electronics such as preamplifier, low pass filter and phase shifter to amplify and purify the original photodetection Larmor signal, and the feed it back to the driving magnetic field coils. We hope this scheme can improve the SNR and dynamic range of the close-loop NMRG.

Key words: NMRG; close-loop; self-oscillating

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Recent progress of mercury optical lattice clock in SIOM

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Abstract: To realize a neutral mercury lattice clock, an experimental setup is in developing in SIOM. For better the performance of the clock, an enhanced cold mercury atom source has been demonstrated based on two-dimensional (2D) magneto-optical trap (MOT). Two stable frequency-quadrupled DUV lasers at 253.7 nm are used for the 2D-MOT and 3D-MOT respectively, and a hybrid frequency stabilization method is developed for saving the DUV laser power and tuning the frequency of DUV laser conveniently. With this cooling laser system, we optimize the parameters of 2D-MOT and 3D-MOT, and it results in almost one order of magnitude on the loading rate of the 3D-MOT. Finally, about 1.3×10^6 atoms are loaded into the 3D-MOT for ^{202}Hg with a loading rate of 1.0×10^6 atoms per second.

An injection-locked Ti: sapphire laser with narrow line-width is developed for lattice laser of neutral mercury clock. A long-pass-filtering cavity mirror is used to suppress the mode competition from the long wavelength side. 1 W output power of the injection-locked Ti: sapphire laser at 725 nm is achieved with a slope efficiency of 27%, which is the shortest wavelength for the watt-level injection-locked continuous-wave Ti: sapphire laser. After a frequency doubling stage, 210 mW lattice laser at 362.5 nm is obtained.

In the future, the enhanced cold Hg atom source and the lattice laser will be used in a mercury optical lattice clock.

Key words: Hg atom; optical lattice clock; laser cooling; DUV laser

Towards cold atoms coherent population trapping clock based on grating magneto-optical trap

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Abstract: Herein, we present an ongoing laser-cooled ^{87}Rb atoms coherent population trapping clock based on a grating magneto-optical trap. The clock system mainly consists of a frequency-stabilized CPT interrogation laser and a cooling laser, a magneto-optical trap, a low phase noise microwave synthesizer. The magneto-optical trap is based on a high diffraction rate grating chip, which enables a single-beam atoms cooling scheme. The $\sigma_+ - \sigma_-$ interrogation scheme is performed in the clock system, which prevents atoms from being trapped in the extreme end Zeeman sublevels and significantly enhances the resonance signal contrast. The absorption contrast of the Rabi-type resonance signal achieves ~ 40%. The high contrast coherent population trapping resonance signal validates the potential of developing a miniature/compact high-performance cold atoms clock based on a grating magneto-optical trap.

Key words: coherent population trapping; cold atoms; grating; magneto-optical trap

A single-atom level mechano-optical transducer for ultrasensitive force sensing

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Abstract: Using light as a probe to detect a mechanical motion is one of the most successful experimental approaches in physics. The history of mechanical sensing based on the reflection, refraction and scattering of light dates back to the 16th century, where in the Cavendish experiment, the angle of rotation induced by the gravitational force is measured by the deflection of a light beam reflected from a mirror attached to the suspension. In modern science, mechano-optical transducers are such devices that could detect, measure and convert a force or dis-placement signal to an optical one, and are widely used for force detection. Especially, ultraweak force sensor with ultrahigh spatial resolution is highly demanded for detecting force anomaly in surface science, biomolecule imaging, and atomtronics. Here we show a novel scheme using a single trapped ion as a mechano-optical transduction. This method utilizes the force-induced micromotion, converting the micromotion to a time-resolved fluorescence signal, in which the ion's excess micromotion coupled to the Doppler shift of the scattered photons. We demonstrate the measurement sensitivity about 600 $\mathrm{zN}/\sqrt{\mathrm{Hz}}$ (1 zN $=10^{-21}$N). By alternating the detection laser beam in all three dimensions, the amplitude and the direction of a vector force can be precisely determined, constituting a 3D force sensor. This mechano-optical transducer provides high sensitivity with spatial resolution in single-atom level, enabling the applications in material industry and the search for possible exotic spin-dependent interactions that beyond the standard model.

Key words: force sensing; mechano-optical transducer

Spectroscopic studies of the X, A, and B states of PbF toward the EDM measurement

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Abstract: PbF, a relativistic, paramagnetic molecule with a single unpaired electron in the ground X^2 state, has been pointed out that it is an avenue for determining the electrostatic T, P violating electric dipole moment (EDM). As the EDM case, the molecular properties, especially, the fine and hyperfine energy level structures of PbF molecule are experimentally advantageous. Here, we report a detailed analysis of the fine and hyperfine structures of the $X^2\Pi_{1/2}$, $A^2\Sigma$, and $B^2\Sigma$ states and discussion the related spectroscopic parameters of EDM candidates, ^{207}PbF and ^{208}PbF, based on our experimental and theoretical results, respectively. Also, the measured lifetimes of $A^2\Sigma$, and $B^2\Sigma$states, the calculated potential energy curves of the X, A, and B states were analyzed and discussed.

Key words: PbF molecule; fine and Hyperfine structure; EDM measurement

The research was supported by a grant from the National Natural Science Foundation of China (Grants No. 11674096, and 11834003)

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[2] "Fine and hyperfine structures and spectrum study of PbF based on the eEDM measurement", under review.

Towards non-destructive detection of coherent delocalization effects in driven optical lattice

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Abstract: In this paper, we propose a method used for detection of delocalization-enhanced Bloch oscillations and driven resonant in optical lattices. When atomic wave packets loaded into an amplitude-modulated vertical optical-lattice potential, intraband transitions occurs among Wannier-Stark levels. These phenomena give rise to coherent delocalization effects, which we observe through a coherent ballistic expansion of cold atomic cloud. Using these techniques to develop a force sensor for precision measurements of the gravitational acceleration g based on an accurate determination of Bloch frequency which measured by direct observation of the modulation frequency at which resonant tunneling occurs. Coherent intraband resonant tunneling turns out to be quite practical for increasing the sensitivity of force measurements with submillimeter spatial resolution. We have realized coherent delocalization effects in alkali-metal atomic gases(^{87}Rb) and alkaline-earth-metal atomic gases(^{88}Sr) respectively, and measured the Bloch frequency in optical lattices. Here, we propose a feasible scheme which called simultaneous phase-shifting digital holographic microscopic imaging (SPSDHM) to realize the imaging of the atomic coherent expansion in optical lattices. Owing to the special structure of the interferometer, it can realize nearly nondestructive detection of atomic spatial distribution in optical lattice in real time, which is expected to improve the frequency of gravity measurement.

Key words: optical lattices; delocalization-enhanced Bloch oscillations; simultaneous phase-shifting digital holographic microscopic imaging

Spectroscopic progress of diatomic lead monofluoride (PbF) molecule toward the measurement of the electron's electric dipole moment (*e*EDM)

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Abstract: The diatomic lead monofluoride (PbF) molecule has many features that make it an attractive candidate for the measurement of the electron's electric dipole moment (*e*EDM). Recently the PbF B←X_1 transition was obtained via a buffer-gas cooling technique that can produce a molecular beam with small translational velocity and largely enriched population of the lowest vibrational level. Parameters like the flow rate of Helium, type of fluoride-donor gases, laser power and time delay had been modified to optimize the signal. The simulated spectrum was calculated, fitted with Lorentz line shape and compared with the experimental result. We also propose an *e*EDM sensitive Stark detection via the design of an ultra-sensitive continuous ionization detection scheme and the construction of *e*EDM measurement machine in an optical approach, which paves the way to measure the *e*EDM at the statistical sensitivity of 10^{-27} *e*·cm.

Key words: buffer-gas cooling; laser-induced fluorescence; resonance-enhanced multi-photon ionization; electron's electric dipole moment (*e*EDM)

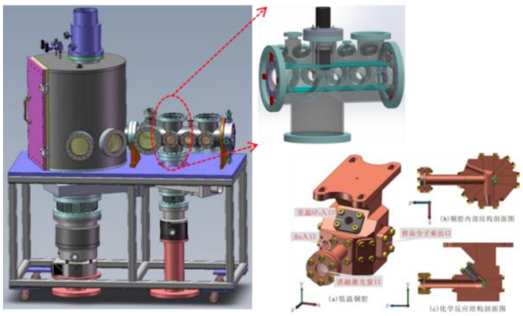

Figure1. Experimental design of the *e*EDM measurement using buffer-gas cooling of PbF molecules

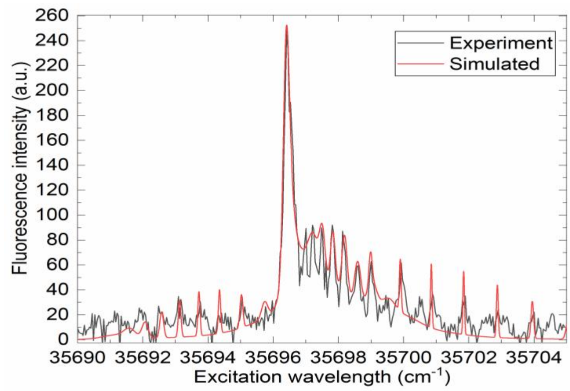

Figure2. Experimental result of PbF B←X_1 transition lines and fitted lines

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Observation of the dipolar splitting in an ultracold Li-6 gas near its p-wave Feshbach resonance

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Abstract: We report on an observation of the dipolar splitting in a p-wave Feshbach resonance of the two lowest hyperfine ground states mixed 6Li cold gases. Due to the dipole-dipole interactions, it has a p-wave Feshach resonance around 185 G. As shown in the previous experiment and theory studies, this dipole-induced splitting is about 4 mG, which is extremely narrow and becomes difficult to observe in many experiment systems. We built an ultra-precision magnetic field in our lab, and with the help of the three-body cooling model, the tiny splitting is measured. Furthermore, we investigate the temperature dependence of such doublet structures in terms of width, interval, and resonant point. We find this splitting also agrees well with coupled-channel calculations. We believe our experimental result will provide a more clear recognition for the studies near the p-wave Feshbach resonance.

Key words: p-wave; Feshbach resonance; dipolar splitting

Measurement of frequency sensitivity coefficients and evaluation of uncertainty based on statistical correlation of noise

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Abstract: We have proposed and demonstrated on a ^{87}Rb atomic fountain clock a method based on statistical correlation of noise to measure frequency sensitivity coefficients(FSCs) and evaluate uncertainty of atomic frequency standards(AFSs). This method processes environmental noises affecting the output of atomic clock as natural modulation, and measures FSC by projecting the environmental noises sequences to the sequence of fractional frequency of AFS. Then we evaluation the uncertainty of some effect by a complete statistical method, that is type-A method, which can be evaluated by type-B method. Since time parameter is introduced, the method can give more detailed and clear picture of how does environmental noises affect the output of AFS. The theoretical and experimental results show that the synchronization is one of the most important factors of uncertainty evaluation, which is neglected in the previous standard method. And the experiments show that the relative deviation of the two methods is less than 10%. Compared with the standard method, noise statistical correlation can solve the contradiction between uncertainty evaluation and continuous operation of the device, test the effectiveness of noise parameter monitoring, and parallelly evaluate the uncertainties of multiple noises. The method will not only be effective of uncertainty evaluation and suppression for frequency standard, but also be applied to other fields of precision measurement.

Key words: atomic frequency standards; uncertainty evaluation; frequency sensitivity coefficients; atomic fountain

High-performance microwave frequency standard based on sympathetically cooled $^{113}Cd^{+}$

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Abstract: Microwave frequency standard based on trapped ions is a candidate for the next generation of microwave frequency standard with high-performance and potential for very wide applications. The introduction of sympathetic cooling technology can suppress the Dick effect and second-order Doppler frequency shift and improve the stability and accuracy of the frequency standard. However, the sympathetically-cooled ion microwave frequency standard has seldom been studied before. This paper reports the first sympathetically-cooled ion microwave frequency standard in a Paul trap. Using laser-cooled $^{40}Ca^{+}$ as coolant ions, $^{113}Cd^{+}$ ion crystal is cooled to below 100 mK and has a coherence lifetime of over 40 s. The short-term frequency stability of the closed-loop measurement reached $3.48\times10^{-13}/\tau^{1/2}$ with Ramsey free evolution time of 5 s duration, which is comparable to that of the laser-cooled mercury ion frequency standard. The uncertainty is 1.5×10^{-14}, which is better than that of directly laser-cooled cadmium ion frequency standard. Compared with a hydrogen maser, the short-term stability of the clock signal is measured to be $1.36\times10^{-13}/\tau^{1/2}$ obtained because of the ultra-long Ramsey free evolution time of 50 s, which ensures future improvements in performance.

Key words: laser cooling; sympathetic cooling; ion trap; frequency standard

Precision magnetic field for the narrow Feshbach resonance of ultracold Li-6 gases

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Abstract: A precision magnetic field is important for ultracold atomic experiments. For example, the interaction strength of the atom-atom interaction can be easily tuned by an external magnetic field near a Feshbach resonance. In the two-lowest hyperfine ground states mixed ultracold Li-6 Fermi gases, there is an ultra-narrow s-wave Feshbach resonance at 543.3 G with a resonant width of 0.1 G. Thus, it often requires an ultra-precision magnetic field has a resolution of mG to study the rich phenomenon across the narrow Feshbach resonance.

Here, we are going to present an important technique to characterize the response of our magnetic field and introduce a useful method to improve its stability. Because of the eddy effect from the environment, which surrounds the magnetic coils, we need to measure the response time of the magnetic field in a fast and precise manner to better characterize the field changing during each sweep. With the help of the sub-hundred mG width of the three-body loss near the narrow Feshbach resonance, we successfully determine the responding time, which requires about 50 ms to reach a 1 ppm resolution.

Furthermore, we develop a method to compensate for heating-induced slow temperature drifting of the magnetic coils and increase the magnetic field stability from 4 mG to about 1 mG. In summary, we expect the practical methods of correcting the eddy effect error of the magnetic field and controlling the experimental sequence to improve the temperature stability of the coils can be further applied to future studies of quantum few- and many-body physics near a narrow Feshbach resonance.

Key words: narrow Feshbach resonance; three-body loss; precision magnetic field

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

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Abstract: On earth, ^{41}Ca is produced as a cosmogenic isotope via neutron capture process, leaving a natural isotopic abundance of 10^{-15} on earth surface. Calcium is also of vital importance for the metabolism of biological organisms. Consequently, analysis of the long lived radioactive isotope ^{41}Ca is of great importance in geoscience, archeology and life sciences. The half-life of ^{41}Ca is 1.03×10^5 years.

We develop an atom trap trace analysis (ATTA) apparatus to analyze ^{41}Ca abundance in the range of $10^{-16} \sim 10^{-13}$, which is beyond the accelerator mass-spectrometry AMS capacity due to the interference of ^{41}K. ATTA is based on laser interaction with neutral atoms to selectively cool, load, and detect individual atoms in the magneto optical trap (MOT) of the desired isotope. It achieves high sensitivity of low abundance by employing a variety of techniques in atom optics, including transverse cooling, two-dimensional MOT, Zeeman slowing. We count ^{41}Ca atoms with our Calcium ATTA over a period of time, comparing the counting rate with that of ^{43}Ca (^{43}Ca/Ca = 0.135%), to derive the abundance of ^{41}Ca. It takes 60 hours to measure a calcium sample of ^{41}Ca/Ca abundance $\sim 3\times10^{-16}$ with uncertainty of 10%. This method is calibrated against AMS, showing good agreement between the two methods.

Key words: Ca atom; atom trap trace analysis; loading rate; single atom detection; isotopic abundance

Loophole-free test of Kochen-Specker contextuality using two species of atomic-ions

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Abstract: We report the first experimental observation of contextual correlations between the outcomes of repeatable and nondisturbing measurements which is free of the detection and compatibility/sharpness loopholes simultaneously. We encode one qubit in a $^{171}Yb^+$ ion and a second qubit in a separated $^{138}Ba^+$ ion. The detection loophole is closed by the high efficiency of the single-shot fluorescence detection. The compatibility/sharpness loophole is closed by testing that the measurements on each ion are repeatable and by targeting a noncontextuality inequality in which contexts have two measurements and each of them is performed on a different ion. Compatibility is assured by spatial separation and enforced by the adoption of ions of different species. Measurements on each species use different operation laser wavelengths, fluorescence wavelengths, and detectors. The $^{171}Yb^+$ is manipulated with 355 nm Raman laser and the $^{138}Ba^+$ with a 532 nm Raman laser. In the $^{138}Ba^+$ a shelving laser of 1762 nm is also used for high-fidelity detection. The experimental results show a measurement repeatability of 98.4 ± 0.3% and a violation of the noncontextuality inequality by 15 standard deviations.

Our experiment demonstrates that the persistency of a result when an ideal quantum measurement is repeated on a physical system cannot be taken as an indication that the system has a predefined property, as the correlations between the outcomes of these measurements violate a noncontextuality inequality. In addition, our experiment demonstrates a new technique to manipulate at the same time two different species of ions. In particular, it allows for preparing entangled states, ground state cooling, and individual readout. This technique has direct applications in ion-trap-based quantum computing and quantum networking.

Key words: contextuality; ion trap; loophole-free; two species

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Preliminary results of miniaturized Rubidium 87 atomic fountain clock

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Abstract: The atomic fountain clock is an important tool for implementing second definitions and UTC. Classical atomic fountain clocks are often deployed in large timekeeping or metrology laboratories due to their large size and complex systems. The highest precision time-frequency signals can only be used by enterprises through time-frequency transmission， which may degrade the signal. Therefore, the development of miniaturized portable atomic fountain clock is an effective way to meet the needs of local use of high-precision time-frequency signals.We have recently demonstrated short-term stability of 7×10^{-13} at 1 second and 8×10^{-15} at 10000 seconds in our first rubidium 87 atomic fountain clock, whose physical system size is 0.4m×0.4m×1.2m. Later, we will make plans to optimize the stability and reliability of the system, so as to improve the cost performance of the high precision atomic fountain clock as much as possible.

Key words: Rb atom; fountain clock; the stability

Transportable optical clock based on a single $^{171}Yb^+$ ion

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Abstract: We report recent results on the development of a transportable optical clock based on the $^{171}Yb^+$ ion. A single $^{171}Yb^+$ ion is loaded by laser ablation with a metal target and then confined in a linear Paul trap. All the lasers are simultaneously stabilized to a multi-channel ultra-stable cavity for better integration and portability. The 435.5 nm clock laser is locked to the $^2S_{1/2}\rightarrow{}^2D_{3/2}$ quadrupole (E2) transition and the frequency stability is being tested. In the next step, the $^2S_{1/2}\rightarrow{}^2F_{7/2}$ octupole (E3) transition at 467 nm will be employed for a compact and transportable optical clock with both systematic uncertainty and daily instability at the low level of 10^{-18}.

Key words: optical clock; ion trap; laser frequency stabilization

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FADOF at ^{87}Rb D2 line for modulated Raman laser beams

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Abstract: Atom interferometers are precision tools for measuring gravity, gravity gradient, rotation and for testing fundamental laws of physics. The inherent accuracy of atom interferometers is very high, but the actual accuracy of them built in laboratory is limited by vibration noises. An EOM is usually adopted in miniaturized atom interferometers for generating the Raman laser beams. They immune to common noises, especially vibration noises, introduced through optical paths before the mirror, because all frequencies components of them are originated from the same laser and then their initial phase noises are same. However, the modulated Raman laser beams not only include two frequencies for composing the Raman laser beams, but also include the other bandsides which introduce a phase bias error in measurement, and consequently limit accuracy of atom interferometers. Faraday anomalous dispersion optical filters (FADOFs) at ^{87}Rb D2 line are ultra-narrow bandwidth optical filters with high background rejection, mechanical robustness and high transmission. Optimizing parameters of FADOFs make the two frequencies of the Raman laser beams for ^{87}Rb atoms transmitted and the other bandsides rejected, thus the Raman laser beams with high performance are obtained, which will help the miniaturized atom interferometers work in mobile platforms with vibration noises.

Key words: atom interferometer; Raman laser beams; FADOF

Energy level structure and hyperfine branching ratios for the $A^2\Sigma_{1/2}(\upsilon=0) \leftarrow X^2\Pi_{1/2}(\upsilon=0)$ transition of $^{208}Pb^{19}F$ molecule as a promising candidate to measure the electron's Electric Dipole Moment

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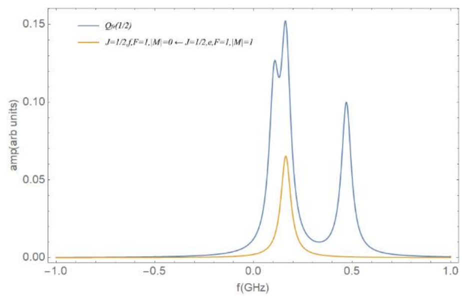
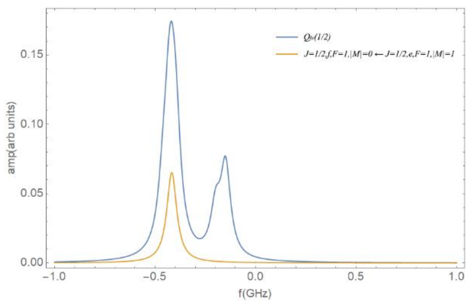
Abstract: In order to realize more sensitive measurement of the electron's Electric Dipole Moment (*e*EDM), it would be worthwhile to shed more lights on the molecular properties including the large internal effective electric field (E_{eff}), small magnetic *g* factor, long coherence time, the *e*EDM sensitive state and so forth. Here we demonstrate the theoretical analysis of the lead monofluoride ($^{208}Pb^{19}F$, $X^2\Pi_{1/2}$) in its energy level structure and associated hyperfine branching ratios, as well as the implications in the *e*EDM measurement using PbF. The hyperfine manifolds of the $X^2\Pi_{1/2}(\upsilon=0)$ and $A^2\Sigma_{1/2}(\upsilon=0)$ states were examined via the effective Hamiltonian approach, followed by the characterization of the Stark energy level structure upon the change of the externally applied electric field. Subsequently, the *J*-mixing of the ground state and the relevant branching ratios for the Π-Σ transition were also studied, thus paving the way for a possible *e*EDM phase measurement in a fully optical approach.

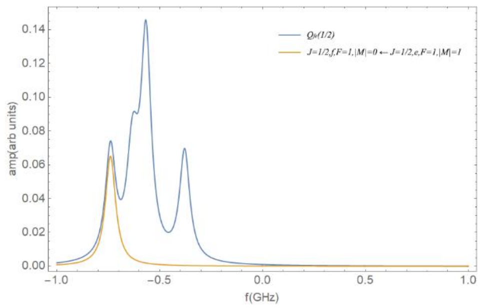
Key words: electron's Electric Dipole Moment (*e*EDM); effective Hamiltonian; Stark effect



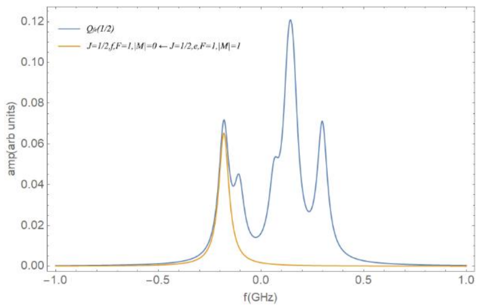
(a) $E_z = 0$ kV/cm



(b) $E_z = 4$ kV/cm



(c) $E_z = 9$ kV/cm



(d) $E_z = 12$ kV/cm

Figure caption: The simulation of the Stark dependent spectra with the external electric field varying from 0 to 12 kV/cm ($f = 674595.69$ GHz). The blue line indicates all the $Q_{fe}(1/2)$ transitions, while the yellow line denotes the specific transition of $A(\upsilon=0, |J=\frac{1}{2}, f, F=1, |M_F|=0\rangle) \leftarrow X_1(\upsilon=0, |J=\frac{1}{2}, e, F=1, |M_F|=1\rangle)$ that is sensitive to an *e*EDM measurement using PbF molecules.

Radiative force from optical cycling on magnesium monofluoride

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Abstract: We demonstrate radiative force deflection by using an optical cycling of the $X^2\Sigma^+_{1/2}-A^2\Pi_{1/2}$ electronic transition in diatomic molecule magnesium monofluoride (MgF). For the (0,0) and (0,1) bands of the electronic transition, the Franck-Condon factors—obtained by the dispersed laser-induced fluorescence spectrum—are f00 = 0.972 and f01 = 0.028, which suggests that the vibrational branching is quasiclosed. Furthermore, the dark Zeeman sublevels are destabilized by applying an external magnetic field. The cycling fluorescence is clearly observed to reveal that the molecular beam is deflected by 4.9 mm via scattering ~ 200 photons per molecule. This work is encouraging toward laser cooling and magneto-optical trapping of MgF molecules.

Key words: laser cooling and trapping; MgF molecule; Franck-Condon factors; rovibrational transitions; radiative force

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On-board testing of a compact horizontal atom gravity gradiometer

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Abstract: Taking transportation to perform mobile measurements is of great significance for a gravimetry instrument in the fields of geophysics research, resource exploration and autonomous navigation. We have developed a compact horizontal gravity gradiometer for Γ_{xx} and Γ_{yy} measurements based on Rb-85 atom interferometers and performed a test on a truck. A baseline L=44.5 cm and an interrogation time T=101 ms are realized in a sensor head with the dimension of only 70×43×36 cm. In laboratory environment, a resolution of 4.0 E (1 E=1×10^{-9} /s^2) is achieved after a averaging time of 4 300 s. In on-board condition, the small volume of 108 L and the weight of 83 kg bring great convenience in carrying and attitude controlling. An automatic leveling system is developed based on a 3-dof platform and achieves a precision of <0.01 degree, as a overall temperature control system is fabricated based on semiconductor TECs and achieves a stability of < 0.01℃. Consequently, a resolution of 11.8 E is achieved on the truck after a averaging time of 840 s. This work lays a foundation for carrying out mobile gravity gradient measurements over large areas with atom gravity gradiometers.

Key words: atom interferometer; gravity gradiometer; on-board testing

Simulation of EOM-based frequency-chirped laser slowing of MgF radicals

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Abstract: To date, all molecular MOT experiments have used frequency-chirped or frequency-broadened laser to slow the longitudinal velocity of the molecule beam. However, an appropriate slowing scheme of large chirp rate for molecules with large recoil velocity and small mass has not been studied as much, as well as the discussion of the relationship between the magnetic field applied to remix dark Zeeman sublevels in type-II transition with slowing efficiency. Here we propose a scheme to slow MgF molecules by using EOM-based frequency-chirped radiation pressure slowing. Two EOMs are used to compensate the quickly varying Doppler shift arised from the forward velocity of molecules, and to cover the hyperfine energy structure of MgF, respectively. Based on the scattering rate maps calculated from an optical Bloch equation model, molecule trajectories are simulated by using a semi-classical three-dimensional Monte-Carlo approach. We show that how the modulation configuration of EOM and the magnetic field influence the slowing results. The study shows that a cryogenic buffer gas-cooled MgF beam source is possible to be slowed down to satisfy a typical MOT-loading metric with a number of ~ 2×10^6 - 10^7, and an initial longitudinal temperature of 9.4 K is cooled down to 8.9 mK, which is promising to a better implementation of MOT.

Key words: laser slowing, frequency-chirped; MgF molecule; type-II transition; optical Bloch equation; Monte-Carlo simulation.

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Laser phase-noise to amplitude-noise conversion in compact cold atom clock

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Abstract: We have investigated theoretically the intensity noise induced by the phase fluctuations of laser as the weak resonant laser pass through the cold atomic gas. In this study, the noisy laser is characterized by the phase-diffusing model. The mean atomic absorption cross section and its autocorrelation function as well as the noise power spectral density have been derived analytically based on the Stratonovich differential equation. Then the intensity noise of the transmitted laser can be evaluated directly. Our results provide an effective method to estimate the amplitude noise transferred by phase noise, which can be used for estimation the contribution of laser frequency noise to clock stability in an integrating sphere cold atomic clock.

Key words: cold atom; phase noise; amplitude noise; clock stability

Progress on a compact and high-performance coherent population trapping clock

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Abstract: Coherent population trapping (CPT) based chip-scale atomic clock (CSAC) is the world's smallest atomic clock available at present, which has been already applied to various fields, e.g., compact satellite mission, unmanned aerial vehicle, underwater sensor, etc. The high-performance CPT atomic clock is also continuously investigated in recent years to meet higher requirements of frequency stability under the condition of maintaining a compact clock system. In this progress report, we implement a compact CPT clock by directly modulating a distributed Bragg reflector (DBR) laser diode to generate a narrow linewidth and high coherent bichromatic laser, and apply it to a differential detection configuration, in which the common-mode noise of light and atomic ensemble is highly suppressed, such as AM-AM, FM-AM conversion noises. With this method, we can further explore the limit for the frequency stability of CPT clocks.

Key words: atomic clock; coherent population trapping; high-performance; differential detection

An ytterbium optical lattice clock with instability of order 10^{-18}

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Abstract: We have built an ytterbium optical lattice clock with improvements over our previous version. An in-vacuum blackbody radiation (BBR) shield is employed to provide a well-characterized BBR environment. The effective temperature felt by the atoms can be determined at an accuracy level of 13 mK, leading to a total BBR stark shift uncertainty of 9.5×10^{-19}. The clock laser is stabilized to a 30-cm-long ULE optical cavity system, achieving a flicker frequency instability of 3×10^{-16}. A single-scan Rabi spectroscopy with 0.47 Hz linewidth is obtained at the interrogation time of 2 s. Two ytterbium clocks have been compared in an anti-synchronized configuration, with real-time BBR-Stark-shift corrections applied to both of them. A single-clock instability of $4.6\times10^{-16}/\sqrt{\tau}$ is demonstrated using total Allan deviation, and averages down to 5.4×10^{-18} in 4 500 s.

Key words: optical atomic clock; ytterbium atoms; instability

Low frequency drift of cold ^{87}Rb fountain clock

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Abstract: Low frequency drift ^{87}Rb atomic fountain clocks are used as continuous clocks in manner of commercial cesium beams and hydrogen masers for improving local time scale TA(K) performance. This paper reports the progress of building the clock including physical package, optical system, microwave-frequency synthesizer and preliminary operation results. The ^{87}Rb fountain clock exhibits frequency stability of $1.96\times10^{-13}\ \tau^{-1/2}$ within 90 days comparing to hydrogen maser 5 085 (BIPM code) and frequency drift of 5.77×10^{-18}/d relative to TT. The 5 MHz/1 PPS signal of the clock is generated by steering the maser through phase and frequency offset generator. These show ^{87}Rb atomic fountain clock has great potential to improve the local time scale.

Key words: cold ^{87}Rb fountain clock; frequency stability; frequency drift; time scale

Proposal for suppressing the ac Stark shift in the He(2^3S_1-3^3S_1) two-photon transition using magic wavelengths

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Abstract: Motivated by recent direct measurement of the forbidden 2^3S_1-3^3S_1 transition in helium [Thomas et al., Phys. Rev. Lett. 125, 013002 (2020)], where the ac Stark shift is one of the main systematic uncertainties, we propose a dichroic two-photon transition measurement for 2^3S_1-3^3S_1, which could effectively suppress the ac Stark shift by utilizing magic wavelengths: one magic wavelength is used to realize state-insensitive optical trapping; the other magic wavelength is used as one of the two lasers driving the two-photon transition. Carrying out calculations based on the no-pair Dirac-Coulomb-Breit Hamiltonian with mass shift operator included, we report the magic wavelength of 1 265.615 9(4) nm for ^{4}He [or 1265.683 9(2) nm for ^{3}He] can be used to design an optical dipole trap; the magic wavelength of 934.234 5(2) nm for ^{4}He [or 934.255 4(4) nm for ^{3}He] can be as one excitation laser in the two-photon process and the ac Stark shift can be reduced to less than 100 kHz, as long as the intensity of the other excitation laser does not exceed 1×10^4 W/cm^2. Alternatively, by selecting detuning frequencies relative to the 2^3P state in the region of 82-103 THz, as well as adjusting the intensity ratios of the two lasers, the ac Stark shift in the 2^3S_1-3^3S_1 two-photon transition can be canceled.

Key words: helium; ac Stark shift; magic wavelength; Dirac-Coulomb-Breit Hamiltonian

Improvement of average magnetic field measurement based on magnetic-sensitive ramsey fringes

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Abstract: Accurate magnetic field measurement is the key to evaluating the second-order Zeeman effect. The conventional method is to deduce the magnetic field by determining the center frequency of the magnetic-sensitive Ramsey fringes. In this letter, we present a more rigorous theory of this method and demonstrate that the current peak-searching method has a non-negligible sub-Hertz or even larger deviation. We introduce an improved method that considers more parameters and a strict formula, which can correct the deviation and suppress it below 0.1 Hz. The corresponding experiments on the ^{85}Rb atomic fountain demonstrate that this improved method is expected to enhance the precision of magnetic field measurement to improve the atomic fountain clock.

Key words: magnetic field measurement; second-order Zeeman effect; ^{85}Rb atomic fountain

Extension of the rotation-rate measurement range with no sensitivity loss in a cold-atom gyroscope

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Abstract: A cold-atom gyroscope as an intrinsic high-precision sensor has, however, one inevitable limitation for its dynamic application lying in the vanishing fringe contrast beyond the rotation-rate limit. Here, we realize the measurement beyond the rotation-rate limit via the tip-tilt mirror compensation technique in a three-pulse cold-atom gyroscope. The contrasts of both fringes at an external rotation rate of 15°/s or below are fully recovered to about 35%, nearly the same as that in the static condition. We elucidate theoretically that intact rotation information can still be extracted from the phase output even though the mirror completely counteracts its rotation. Before reaching 50% contrast loss, detailed numerical verification shows a two-orders-of-magnitude extension in the dynamic range for the compensated case compared with that without compensation. Further analysis shows that no reduction of sensitivity up to 60°/s is found for our scheme, whereas other schemes have a trade-off between sensitivity and dynamic range. These features are especially of major relevance in applications such as inertial sensing and navigation.

Key words: measurement beyond rotation-rate limit; no contrast loss; tip-tilt mirror compensation; cold-atom gyroscope; inertial sensing

Measurement of the electric dipole moment of ^{171}Yb atoms in an optical dipole trap

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Abstract: The permanent electric dipole moment (EDM) of the ^{171}Yb ($I = 1/2$) atom is measured with atoms held in an optical dipole trap (ODT). By enabling a cycling transition that is simultaneously spin-selective and spin-preserving, a quantum non-demolition measurement with a spin-detection efficiency of 50% is realized. A systematic effect due to parity mixing induced by a static E field is observed, and is suppressed by averaging between measurements with ODTs in opposite directions. The coherent spin precession time is found to be much longer than 180 s. The EDM is determined to be $d(^{171}\mathrm{Yb}) = (-1.21 \pm 0.72_{stat} \pm 0.20_{syst}) \times 10^{-26}$ e cm, leading to an upper limit of $|d(^{171}\mathrm{Yb})| < 2.4 \times 10^{-26}$ e cm (95% C.L.). These measurement techniques can be adapted to search for the EDM of ^{225}Ra.

Key words: permanent electric dipole moment; optical dipole trap; quantum non-demolition; parity mixing; ^{171}Yb atoms

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Fine and hyperfine structures and spectra study of PbF based on the eEDM measurement

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Abstract: PbF, a relativistic, paramagnetic molecule with a single unpaired electron in the ground X^2 state, has been pointed out that it is an avenue for determining the electrostatic T, P violating electron electric dipole moment (eEDM). As the eEDM case, the molecular properties, especially, the fine and hyperfine structures of PbF molecule are experimentally advantageous. Here, we report a detailed analysis of the fine and hyperfine structures of the X $^2\Pi_{1/2}$, A $^2\Sigma$, and B $^2\Sigma$ states based on our experimental laser-induced fluorescence spectra of the A $^2\Sigma$ - X $^2\Pi_{1/2}$ and B $^2\Sigma$ - X $^2\Pi_{1/2}$ transitions of four $^{204, 206, 207, 208}$PbF. Resulting fine and hyperfine structures will be discussed and compared with recent theories and experiments. Also, the lifetimes of A $^2\Sigma$, and B $^2\Sigma$ states are measured and discussed.

Key words: PbF molecule; fine and hyperfine structure; Λ-doubling; eEDM

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Research on the mobile high-precision $^{85}Rb/^{87}Rb$ cold atom absolute gravimeter WAG-H57-1

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Abstract: Gravimeters have important applications in the fields of geophysics, geodesy and metrology. Compared with the traditional laser interferometric absolute gravimeter (such as FG5), the cold atom gravimeter has the advantages of high sensitivity, long-term stability, and low maintenance cost. Here we report a $^{85}Rb/^{87}Rb$ mobile high-precision cold atom absolute gravimeter named WAG-H57-1. In order to reveal the potential systematic errors in the current atom gravimeters, we adopt ^{85}Rb and ^{87}Rb atom interferometers working in the same physical device at different time. With the shared apparatus and environment, some systematic errors could be suppressed in self-comparison, such as wave-front aberration and self-attraction. In order to meet the requirements of integration and high precision of the gravimeter, we design and implement a compact titanium ultra-high vacuum system, optical system and electronics system, with a total volume of 0.9 m^3. We obtain over 2×10^8 atoms with 0.3 s MOT loading after launch. Using active vibration isolation and Coriolis effect compensation technique, atom interferometer with 0.2 s free evolution time is realized. On the third floor of laboratory building, the sensitivity of the gravimeter reaches 74 μGal/$Hz^{1/2}$, and the long-term stability is below 1 μGal (> 4 000 s).

Key words: atom interferometer; absolute gravimeter; systematic error

Feedback control of atom trajectories in a horizontal atom gravity gradiometer

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Abstract: The coincidence between the atom trajectory and the Raman pulse sequence is very important for an intersection type atom interferometer. Here we present a feedback control technique for the atom trajectories in our horizontal gravity gradiometer, which improves the stabilities of the trajectories by about 2 orders of magnitude. Through the further study of the dependence of the interferometer contrasts on the atom trajectories, we lock the trajectories at optimal positions. And by this technique, the sensitivity of the gravity gradiometer is improved from 982 E/Hz$^{1/2}$ to 763 E/Hz$^{1/2}$, while the long-term stability is enhanced more significantly and reaches 8.9 E after an integration time of 6 000 s. This work may provide hints to other experiments based on intersection type atom interferometers.

Key words: intersection type; stabilities of atom trajectories; interferometer contrasts.

Angiographic video blood vessel segmentation and frame interpolation method

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Abstract: The mainstream method of medical image segmentation is the two-dimensional U-shaped convolutional neural network, that has a symmetric structure of an image scale compression path and an expansion path (encoder-decoder), and skip connections between the encoder and the decoder through which the same level of image feature informations are transferred, ie., 2D U-Net①. However, the network structure is still insufficient in the fusion ability of image features at different levels. In work[1], in the skip connections of U-Net, multi-scale dilated convolution branches and pooling modules with various window sizes are introduced to effectively extract and fuse image features at different encoder-decoder levels, thereby improving the cardiovascular vessel segmentation accuracy of X-ray contrast images and videos.

Angiography videos contain more temporal domain information than images. Making full use of the temporal domain information helps to improve the accuracy of blood vessel segmentation. Work[2] introduces a dimension conversion module in the input layer of a 2D U-Net network, to extract the spatial and temporal domain correlations of multi-frame input images, and to fuse and convert the 3D temporal domain features into a 2D feature map. As a result, using a 2D network achieves more accurate medical image vessel segmentation.

The 3D U-Net network has a larger amount of network parameters and higher performance. In order to better utilize 3D time domain information to complete the task of cardiovascular angiography video segmentation, work[3] designs an asymmetric 3D encoder-2D decoder network. Multiple space-time dimension conversion modules are embedded between the encoder and decoder to effectively fuse temporal domain information. Therefore, with only half the amount of parameters and computational complexity of the 3D U-Net, the blood vessel segmentation performance consistent with the latter can be achieved.

In order to obtain contrast images with high signal-to-noise ratio, doctors need to increase the frequency and intensity of X-ray irradiation during the surgery, which inevitably increases radiation damage to doctors and patients. Work[4] establishes a novel coronary angiography image sequence dataset, and applies several mainstream deep learning video frame interpolation methods with the dataset. Experimental results show that the video frame interpolation technology based on bidirectional optical flow estimation can effectively reduce the frame rate of angiographic video acquisition, thus reducing the exposure of doctors and patients to X-rays.

Optical flow is widely used in medical image processing, however, high-precision optical flow training datasets for medical images are difficult to generate. Work[5] proposes a

semi-supervised learning paradigm to estimate the optical flow of coronary angiography. A new optical flow estimation model suitable for medical images can be trained with only the original medical image, the segmentation results of the target of interest, and a pre-trained model based on general optical flow datasets. Test results on the dataset proposed in [4] show that this semi-supervised learning method can significantly improve the optical flow estimation accuracy for coronary angiography image sequences.

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① Remarks: U-Net proposed by Olaf Ronneberger et al. in 2015 is one of the early algorithms for semantic segmentation using fully convolutional networks, which has profoundly affected the design of subsequent image segmentation networks.

Protection of quantum evolutions under parity-time symmetric non-Hermitian Hamiltonians by dynamical decoupling

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Abstract: Parity-time (PT) symmetric non-Hermitian Hamiltonians bring about many novel features and interesting applications such as quantum gates faster than those in Hermitian systems, and topological state transfer. The performance of evolutions under PT-symmetric Hamiltonians is degraded by the inevitable noise and errors due to system-environment interaction and experimental imperfections. In contrast to Hermitian Hamiltonians, the errors in dissipative beams that are utilized to generate non-Hermitian contributions in the PT-symmetric Hamiltonians cause additional errors. Here we achieve the protection of PT-symmetric Hamiltonians against noise acting along the qubit's quantization axis by combining quantum evolutions with dynamical decoupling sequences. We demonstrate the performance of our method by numerical simulations. We also experimentally implemented the DD-protected PT-symmetric Hamiltonian in the trapped ion setup. The fidelities of the protected evolutions are well above the unprotected ones. Our work paves the way for further studies and applications of non-Hermitian PT-symmetric physics in noisy quantum systems, it also sheds light on Hamiltonian engineering in open quantum systems.

Phonon tomography with vibrational modes of trapped ions

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Abstract: Boson network, which consists of a number of bosons evolving through beam-splitters and phase shifters between different modes, has been proposed to demonstrate a quantum advantages as the size of the network grows. While the network has been implemented mostly in linear optical systems with photons, alternative realizations have been pursued due to limitations of photonic systems such as photon loss, probabilistic nature of creation and detection of photons. Phonons of trapped ions, the quantized excitations of collective vibrational modes, can be considered as a good candidate to realize boson network. Here, for the first time, we experimentally demonstrate all the necessary requirements for the scalable and programmable network of phonons, where the preparation and detection of phonons are deterministic without loss mechanism. We apply the network to perform the full tomography of arbitrary multimode states with a definite number of phonons proposed by Banchi et al. (PRL 121, 250402 (2018)). Our experiment demonstrates a new way to realize boson tomography with minimal resources for a trapped ion system which can be generalized to other physical systems.

Key words: boson network; trapped ions; phonons; vibrational modes; quantum state tomography

Rotation sensing with a compact penning trapped calcium ion crystal system

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Abstract: In traditional mechanics, harmonic oscillators could be utilized for force, acceleration or rotation measurement. The traditional harmonic oscillators usually composed of a mass block. Here we describe a quantum harmonic oscillator based on trapped ion crystal. These trapped ions are trapped in a penning trap and they can form a 2D ion crystal. The calcium ions are cooled through lasers and driven by RF electronic magnetic field. The spins of the ions and the harmonic motion are coupled through a laser. Just like the traditional oscillators, we try to figure out if the trapped ions could form a rotation sensor. We also will show the compact penning trap design in our lab. In the penning trap, the super conducting magnet will be replaced by permanent magnet. The cost and the volume of the trap are greatly reduced.

Key words: ion crystal; quantum harmonic oscillator, penning trap; quantum gyroscope

Super-resolved imaging of a trapped ion at nanosecond timescale

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Abstract: In cold atomic systems, fast and high-resolution microscopy of individual atoms is crucial since it can provide direct information on the dynamics and correlations of the system. In this presentation, we show a demonstration of nanosecond two-dimensional stroboscopic pictures of a single trapped ion beyond the optical diffraction limit, by combining the main idea of ground state depletion microscope with the quantum state transition control in cold atoms. We achieve a spatial resolution up to 175 nm and a time resolution up to 50 ns simultaneously under a NA=0.1 objective in the experiment, which is improved over ten times compared to direct fluorescence imaging. To show the potential of this method, we applied it to record the motion of the trapped ion and observe one cycle of the secular motion of the ion with a displacement detection sensitivity of 10 nm. In the outlook section of the talk, we will prospect our method with different specified cold atom systems, to show using this method as a powerful tool for probing particles' positions, momenta and correlations, as well as their dynamics in cold atomic systems.

Key words: quantum state manipulation; cold trapped ions; super-resolution imaging; atom dynamics detection; quantum chemistry

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Measurement of critical parameters of cold atom optical lattice by means of Kibble Zurek mechanism

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Abstract: Nonequilibrium physics and dynamic behavior is an important and challenging direction in modern physics. For the dynamic behavior of phase transition, people qualitatively discuss it based on the nature of spontaneous breaking of symmetry, and obtain the universal scale invariant rate of phase transition dynamic behavior, namely kibble Zurek mechanism. Using the cold atom optical lattice system, this paper starts from a symmetry broken quantum state and enters a symmetry conserved quantum state. In this experiment, through the independent observation of the excitation number and relaxation time of topological defects, we found that the dynamic phase critical parameters obtained different values in the same system. The core reason is that the opening approach of the energy gap changes from the initial square root relationship to the linear relationship, which makes two different phase transition dynamic mechanisms compete in the same quantum multi-body system. At the same time, the opening of the energy gap protects the early topological defects. This result goes beyond the kibble Zurek mechanism, it provides new possibilities for further study of the dynamic behavior of quantum phase transition.

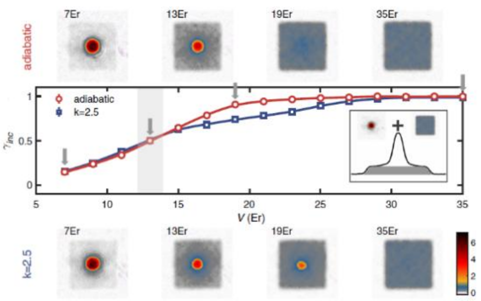

Fig 1. Experiment results for Measurement of critical parameters of cold atom optical lattice by means of Kibble Zurek mechanism, red curve: adiabatic ramp, blue curve: ramp rate k=2.5.

Key words: optical lattice; kibble Zurek mechanism; critical parameters

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Many-body dynamical quantum phase transitions in optical lattice

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Abstract: Nonequilibrium physics and many-body dynamic behavior is an important and challenging question in modern physics. We using the cold atomic inhomogeneous optical lattice system investigate dynamic quantum phase transition from superfluid to Mott insulator. We use a new method to measure the quasi-momentum distribution and define the observable physical quantities based on it. According Kibble-Zurek mechanism which is used to explain some universal scaling law in dynamic phase transitions and our observations, by obtaining the relaxation time and defect density respectively, we get two sets of critical parameters. Also, different regions with different scaling behaviors are observed by different ramp rates. These provide new possibilities for further study of the many-body and dynamic behavior of quantum phase transition.

Key words: dynamical quantum phase transition; critical parameters; superfluid-Mott insulator

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High-fidelity entanglement of neutral atoms via a Rydberg-mediated single-modulated-pulse controlled-PHASE gate

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Abstract: The neutral atom platform has become a promising candidate to study the science of quantum simulation and quantum computation. A two-qubit controlled-PHASE gate via Rydberg blockade is one of the most fundamental elements, and intense efforts have been devoted to improving the fidelity of two-qubit gates[1-2]. Recent theoretical studies have suggested the advantages of introducing nontrivial waveform modulation into the gate protocol, which is anticipated to improve its performance towards the next stage[3]. Here, we demonstrate our recent experimental results in realizing the two-qubit controlled-PHASE (CZ) gate via single-modulated-pulse off-resonant modulated driving embedded in a two-photon transition for Rb atoms[4]. It relies on a global driving laser pulse with a specially tailored smooth waveform to gain the appropriate phase accumulations required by CZ gate. Combining this CZ gate with global microwave pulses, two-atom entanglement is generated with the raw fidelity of 0.945(6). After accounting for state preparation and measurement errors, we extract the entanglement operation fidelity to be 0.980(7). Our work features completing the CZ gate operation within a single pulse to avoid shelved population in the Rydberg levels, thus demonstrating another promising route for realizing a high-fidelity two-qubit gate for the neutral atom platform.

Key words: high-fidelity entanglement; controlled-phase gate; Rydberg blockade

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Quantum simulation of an exact 1D transverse Ising model in an optical lattice

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Abstract: A spinless Bose-Hubbard model in a one-dimensional (1D) double-chain tilted lattice is numerically studied at unit filling per cell. When each atom is localized in a two-site cell, the low-energy effective model gives rise to an exact textbook model of the 1D transverse Ising model via superexchange interaction. To validate the effective transverse Ising model, we calculate the energy spectrum and the nearest-neighbor correlation functions of the states in a subspace of the Bose-Hubbard model which is equivalent to the Hilbert space of a spin-1/2 magnetic model. The results show good consistency with the effective transverse Ising model, and we show that it is possible to simulate the dynamical quantum phase transition of the 1D transverse Ising model exactly with such a double-chain Bose-Hubbard model. Our results may provide some inspirations for realizing and exploring an exact 1D transverse Ising model in ultracold neutral atom systems.

Key words: quantum simulation; transverse Ising model; optical lattice

Probe equilibrium correlations in cold atomic optical lattice by path-independent ramping dynamics

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Abstract: Quantum correlations are the central features characterizing many-body physics, which become one of the most important observables in many experiments. Here we present an alternate scheme both theoretically and experimentally, probing the equilibrium correlations by ramping dynamics which can tell a strong correlated system has well-defined quasi-particle descriptions or not. By ramping a physical parameter non-adiabatically with finite speeds, we find the leading deviation of any measured observable to the adiabatical value is linearly proportional to the ramping speed, path-independent and only depending on the final states' equilibrium correlations. The slope of linearity reflects the equilibrium correlations and is significant while the system does not have a well-defined quasi-particle description. We demonstrate and experimentally prove our theory in Bose-Hubbard models with degenerate cold gas.

Experimentally, we first ramp our system from four different initial lattice depths to the same final one at 15Er(recoil energy). After each ramp, we extract our observable, the central quasi-momentum distribution in 1D by means of our developed band-mapping method. Through the four sets of measurements, we find that the strength of our observable is only linearly dependent on the ramping speed and we obtain the same slope of linearity reflecting the same equilibrium correlations for the same final state. Then we change the final lattice depths to 11, 13, 17, 19, 21Er to obtain the slopes of linearity for different final states. We find the slopes of linearity are apparently larger in quantum critical region , reflecting the significant equilibrium correlations.

Ideally, by comparing our measurements with theoretical results, we can determine the critical exponent by studying the temperature dependence of this correlation. Our scheme can be directly applied to probe correlations in other ultracold atomic gases systems, such as unitary Fermi gas and quantum simulation of various spin models. Our method can also be applied to other systems beyond ultracold atomic gases, such as trapped ions, NV centers, and condensed matter systems. As shown in the example of studying the Bose-Hubbard model, our method accesses a different aspect of quantum many-body correlation compared with many existing measurement tools. Thus, our protocol provides a new direction to study correlations in quantum matters.

Key words: quantum correlation; path-independent; linear response; quantum simulation

Observation of non-Hermitian skin effect and topology in ultracold atoms

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Abstract: The non-Hermitian skin effect (NHSE), the accumulation of eigen wavefunctions at boundaries of open systems, underlies a variety of exotic properties that defy conventional wisdom. While NHSE and its intriguing impact on band topology and dynamics have been observed in classical or photonic systems, their demonstration in a quantum gas system remains elusive. Here we report the experimental realization of a dissipative Aharonov-Bohm chain—a non-Hermitian topological model with NHSE—in the momentum space of a two-component Bose-Einstein condensate. We identify unique signatures of NHSE in the condensate dynamics, and perform Bragg spectroscopy to resolve topological edge states against a background of localized bulk states. Our work sets the stage for further investigation on the interplay of many-body statistics and interactions with NHSE, and is a significant step forward in the quantum control and simulation of non-Hermitian physics.

Key words: ultracold atoms; non-Hermitian skin effect; non-Hermitian topology; non-Bloch theory

Comprehensive calculations of energies for the light helium-like ions with 3≤Z≤12

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Abstract: As the simplest multi-electron system, atomic helium and helium-like ions possessing two bound electrons have long been attractive subjects for both theorists and experimentalists. At present, energies of helium-like ions with high precision have been achieved in the relevant calculations and measurements. The high-accuracy calculations need to take quantum electrodynamic (QED) effects into account strictly. For light atomic systems, QED effect usually can be calculated perturbatively by using the nonrelativistic quantum electrodynamics (NRQED) approach, which only calculate energies of states one by one. Different from the NRQED approach, we developed our previous relativistic configuration interaction (RCI) method by adding directly the radiative potential operators into the Dirac-Coulomb-Breit (DCB) Hamiltonian. Using this improved method, energies including QED correction for all the states with the same angular momentum number can be obtained from only one diagonalization of the total Hamiltonian. In our work, a series of energies of helium-like ions for the n^3S_1, $n^3P_{0,1,2}$, and $n^3D_{1,2,3}$ states with the main quantum number n up to 7 and the nuclear charge number Z up to 12 are presented. Our final results, which include relativistic, finite-nuclear-mass, relativistic nuclear recoil, and QED corrections, are in good agreement with other available results.

Key words: energies; helium-like ions; relativistic configuration interaction; radiative potential; QED correction

Manipulating non-Hermitian skin effect via electric fields

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Abstract: In non-Hermitian systems, the phenomenon that the bulk-band eigenstates are accumulated at the boundaries of the systems under open boundary conditions is called non-Hermitian skin effect (NHSE), which is one of the most iconic and important features of a non-Hermitian system. In this work, we investigate the fate of NHSE in the presence of electric fields by analytically calculating the dynamical evolution of an initial bulk state and numerically computing the spectral winding number, the distributions of eigenstates, as well as the dynamical evolutions. We show the abundant manipulation effects of dc and ac fields on the NHSE, and the physical mechanism behind is the interplay between the Stark localization, dynamic localization and the NHSE. In addition, the finite size analysis of the non-Hermitian system with a pure dc field shows the phenomenon of size-dependent NHSE. The results will help to deepen the understanding of NHSE and its manipulation.

Key words: skin effect; localization; 1-dimensional systems

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arXiv:2201.10318

Homogeneous linear ion crystal in a hybrid potential

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Abstract: We investigate the properties of a linear ion crystal in a combination of quadratic and quartic potentials. Both the discrete and the continuous models are employed to explore the homogeneity of a linear ion crystal by tuning the proportional parameter between the quadratic and quartic components. It is found that the size of the uniform region is significantly larger than that in either a purely quadratic or a quartic potential. The zigzag transition is also investigated in the hybrid potential, and its critical condition and phase diagram are determined numerically, which agrees well with previous theoretical and experimental results. Our results pave the way for experimental investigation of superlarge inear ion crystals in the combination of quadratic and quartic potentials.

Key words: homogeneous ion crystal; hybrid potential

Defect-free arbitrary-geometry assembly of mixed-species atom arrays

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Abstract: Neutral atom arrays have emerged as a promising quantum platform for the good scalability and long coherence time. Recently, the operations of hundreds of atoms and the demonstration of high-fidelity quantum gates have built a solid base for quantum error correction (QEC). To realize QEC, the mixed-species single atom arrays with low crosstalk will provide several advantages, as demonstrated in the platforms of superconducting circuits and trapped ions. However, efficient preparation of defect-free mix-species atom arrays is still challenging. Here, we present the first assembly of defect-free two-dimensional dual-isotope atom (^{85}Rb and ^{87}Rb) arrays with arbitrary geometries. A sorting algorithm (heuristic heteronuclear algorithm) is designed to rearrange initially randomly distributed atoms with both customizable geometries and two-species atom number ratios. The measured filling fraction of 6×4 atom assembly of ^{87}Rb (^{85}Rb) atoms is 0.89 (0.88). Furthermore, we introduce the concept of articulation points in an undirected graph to improve the success rate of the algorithm, thus to ensure it can be used in large-scale dual-species arrays. This versatile scheme also opens promising paths for ultracold single molecule arrays with high filling fractions and quantum many-body simulations with site-specific manipulations.

Key words: Rb atom; atom arrays; mixed-species;sorting algorithm

A compact and stable apparatus for producing ultra-cold Fermi mixture to address high energy physics problems

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Abstract: With almost all experimental parameters can be precisely tuned, cold atoms is widely welcomed as simulators for addressing key problems in diverse research area, from condensed matter physics to few-body physics[1]. Of particular interest for this project, we are more interested in simulating hot topics in high energy physics with cold atoms, for example, dynamics of the strong interacting quark-gluon plasma[2] and manifestations of the Heisenberg's uncertainty principle.

We've accomplished building a new experimental apparatus producing Ultra-cold Fermionic ^{6}Li atoms. It can routinely load more than 5×10^8 lithium-6 atoms per spin state into a magneto-optic trap (MOT) in 5 s, then cool them down to below 300 micro-Kelvin and raise the density to ~ 10^{11} per cm^{-3} in less than 5 ms by conducting the compressed MOT technique. After that, we manage to transfer ~ 2×10^6 atoms in total into an optical dipole trap with a moderate depth of ~ 1 mK, and conduct forced evaporative cooling to produce weak interacting ultra-cold Fermi gas, as well as Bose-Einstein condensates of bosonic dimers composing of atoms with opposite spins. Further, anisotropic expansion was also demonstrated with strongly interacting Ultra-cold Fermi mixture. We also observed the narrow p-wave resonances and pinned down the magnetic field precisely with RF-spectrum, which confirmed the electro-magnets is very stable and has a resolution of ~ 10 mG.

In future work, we will focus on simulating the origin of elliptic flow of quark-gluon plasma that produced by colliding heavy ions. More attention will be put into the relation between elliptic flow and anisotropy of the cold atom system, as well as making the size of cold atom system more comparable to the colliding heavy-ion system, in hope to observe elliptic flow in the regime beyond hydrodynamic limit[3].

Keywords: ^{6}Li atoms; Fermi gas; elliptic flow; quark-gluon plasma

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Observation of topological phase with critical localization in a quasi-periodic lattice

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Abstract: Disorder and localization have dramatic influence on the topological properties of a quantum system. While strong disorder can close the band gap thus depriving topological materials of topological features, disorder may also induce topology from trivial band structures, wherein topological invariants are shared by completely localized states. Here we experimentally investigate a fundamentally distinct scenario where topology is identified in a critically localized regime, with eigenstates neither fully extended nor completely localized. Adopting the technique of momentum-lattice engineering for ultracold atoms, we implement a one-dimensional, generalized Aubry-Andr\'e model with both diagonal and off-diagonal quasi-periodic disorders in momentum space, and characterize its localization and topological properties through dynamic observables. We then demonstrate the impact of interactions on the critically localized topological state, as a first experimental endeavor toward the clarification of many-body critical phase, the critical analogue of the many-body localized state.

Key words: momentum lattice; quantum simulation; critical localization phase; topological phase

Non-Hermitian quantum interface between photons and magnons

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Abstract: We realize a tunable non-Hermitian beam-splitter for the interference between traveling photonic and localized magnonic modes. The localized magnonic modes are collective atomic coherence, widely used in quantum storage, probabilistic entanglement between atomic sources, atomic sensor, etc. Here we for the first time demonstrate a flying photon and a localized “photon” stored as collective atomic spin excitation in an ensemble of laser cooled atoms. The interference is occurred between the two channels shared by photon-magnon and magnon-photon conversion, which is initiated by a short coupling pulse applying onto the atomic ensemble. The first-order interference shows an unconventional correlated interference pattern is observed at the photon and magnon output ports of a hybrid interferometer. Further, the second-order interference, i.e., Hong-Ou-Mandel interference between a photon and a quanta of atomic excitation is observed. The Hong-Ou-Mandel interference between photons and quanta of atomic coherence reveals bunching or anti-bunching depending on the far-detuned or resonance excitation.

Our work is based on a three-level atomic system prepared in a magneto-optical trap, applicable to realize interference between a single photon and magnon. Our recent results demonstrate that Hong-Ou-Mandel interference between photons and the stored single quanta of magnons, and the coalescence of the photons and magnons is altered through the beam-splitter-type quantum interface. These results implie a new type of non-Hermitian quantum physics based on atom-light interface, and a potential mechanism to manipulate the quantum information.

Key words: non-Hermitian physics; quantum storage; cold atomic ensembles; atom-light interface

Generation of large-scale two-dimensional defect-free atom arrays

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Abstract: Large-scale physical qubit arrays are key ingredients toward building a platform for quantum simulation of many-body physics[1-9], quantum computation[10-19] and precise measurements[20-21]. Neutral atom array trapped in strongly confined optical tweezers is one of the most promising platforms that have the potential to scale up to more than one hundred physical qubits. Previously, our group[22] have prepared the two-dimensional 6×4 dual-species atom assembly with a filling fraction of 0.88(0.89) for ^{85}Rb (^{87}Rb) atoms and a group has realized a quantum spin model with tunable interactions with 256 qubits. In this work, we demonstrate a large-scale atom array with alkali Rubidium atoms. Firstly, an atom reservoir is loaded randomly into a static optical tweezers array that is generated from a spatial light modulator (SLM). By moving an auxiliary optical tweezer with newly designed algorithm for rearrangement, geometry-programmable and defect-free atom array is assembled. A two-dimensional defect-free 7×7 atom array is generated with a high probability of 98(3)% for one rearrangement cycle. Next we will generrate the two-dimension 32×32 dual-species defect-free atom array with ^{85}Rb-^{87}Rb atoms which will be a two-dimensional dual-species defect-free atom array with the largest number of atoms. Combined with high-fidelity single atom control and Rydberg mediated entanglement, this paves the way towards quantum simulation and computation with neutral atoms.

Key words: neutral atoms; optical tweezers; quantum simulation; quantum computation

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Realization of single Sr atoms in an optical tweezer

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Abstract: Neutral atom arrays provide a versatile platform for quantum simulation and quantum computing. In comparison with alkali species, alkaline-earth (-like) atoms offer important features, e.g., narrow and ultra-narrow optical transitions, the ability to stably trap Rydberg atoms by the same red-detuned optical tweezer. In recent years, microscopic manipulations of strontium and ytterbium atoms in an optical tweezer array have been demonstrated. In this poster, we report the experimental realization of single Sr atoms in an optical tweezer in Shenzhen.

Key words: single atoms; alkaline-earth (-like) atoms; quantum computing

Quantum state transfer via topological pumping of edge states in the Su-Schrieffer-Heeger model

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Abstract: Robust quantum state transfer (QST) is an important building block for scalable quantum information processing. Taking advantage of the topological properties will improve the performance of QST in disordered systems. Here we present an experimental robust QST in Su-Schrieffer-Heeger (SSH) chains, simulated by a momentum lattice of Bose-Einstein condensate (BEC). By dynamically modulating the couplings between the momentum states in the synthetic lattice, we efficiently transfer the edge state from one end to the other of the chain with different lengths. Then, we implement a topological beam splitter through the topological chains. The input state in the central site is equally transferred into the two end sites and interfered at the center again. Furthermore, we additionally introduce disorders in the coupling strengths, allowing us to explore the robustness of the transfer protocol. Compared to a trivial method based on ballistic transfer, the QST via topological chain is more robust. Our experiments demonstrate the flexibility for performing robust QST in cold atoms and provide a new way for implementing robust QST in large-scale quantum processors and networks.

Key words: ultracold atoms; quantum state transfer; topological pumping; momentum space lattice

Parity-time-symmetry phase transition in an optical lattice with an open boundary condition

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Abstract: Lattice models, including tight-binding chains, have been a cornerstone of theoretical explorations due to their analytical and numerical tractability. Open physical systems with balanced loss and gain, described by non-Hermitian parity-time (PT) Hamiltonians, exhibit a lot of novel phenomenas, such as phase transition, toplogical properties and coherent absorption behaviors. In this work, we study the phase diagram of the PT-symmetry in a tight-binding chain with N sites and hopping energy J in the presence of two impurities with imaginary potentials located at arbitrary (P-symmetric) positions. It turns out that there are some special cases in which the PT-symmetric region is algebraically robust and fragile. Further, we numerically analyze the system with pure loss and obtain the reduced atom loss and the phase diagram. Particularly, we find an open boundary case with atoms being not die out to zero, this is much different from periodic boundary conditions. To explain it, we plot the visualizing matter waves and find the difference between the two cases.

Key words: non-Hermitian; PT-symmetry; optical lattice; cold-atoms

Observing quantum synchronization of a single trapped-ion qubit

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Abstract: Synchronizing a few-level quantum system is of fundamental importance to understanding synchronization in deep quantum regime. Whether a two-level system, the smallest quantum system, can be synchronized has been theoretically debated for the past several years. Here, for the first time, we demonstrate that a qubit can indeed be synchronized to an external driving signal by using a trapped-ion system. By engineering fully controllable gain and damping processes, an ion qubit is locked to the driving signal and oscillates at the same frequency. Moreover, upon tuning the parameters of the driving signal, we observe characteristic features of the Arnold tongue as well. Our measurements agree remarkably well with numerical simulations based on recent theory on qubit synchronization. By synchronizing the basic unit of quantum information, our research unlocks potential applications of quantum synchronization in large-scale quantum computing, quantum networking, and quantum sensing.

Key words: quantum synchronization; two-level system; trapped ion

Towards high-fidelity ion-photon entanglement

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Abstract: In a quantum network, flying qubits can transmit information between stationary nodes. Photons that travels at the speed of light are ideal information transmitters. Repeater-based communication schemes therefore require entanglement between storage medium and communication photons. We employ trapped Ca^+ ions as storage medium in the repeater protocol. Compared with other quantum systems, repeater nodes implemented with trapped ions have in particular the advantage of realizing high-fidelity and deterministic logical operations on multiple qubits in a single node. In order to generate entanglement between trapped ions and single photons, the ion trap is spatially overlaid with a low-loss, high-finesse Fabry-Perot cavity. The presence of the cavity can significantly improve the collection efficiency of single photons due to the Purcell effect, thereby improving the performance of quantum repeaters. Using bichromatic cavity-mediated Raman transition, calcium ions in the electronic ground state are excited to two different Zeeman levels, and these two paths generate photons with different polarization states, respectively. This way, entanglement between the internal state of the ion and the polarization state of the photon can be established with high fidelity and high efficiency. The main factor limiting our entanglement distance is the photon propagation loss in the fiber, where optimal wavelengths of photon propagation lie between 1 300 nm and 1 600 nm. The 854 nm photons emitted by our Ca^+ ion can be converted to the communication band 1550 nm with high efficiency and low noise. Duplicating the protocol above to multiple repeater nodes will potentially extend the communication distance to more than 1 000 km.

Key words: Ca^+ ion; quantum repeater; entanglement distribution; high fidelity

Quantum simulation of a general anti-PT-symmetric Hamiltonian with a trapped ion qubit

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Abstract: Non-Hermitian systems satisfying parity-time (PT) symmetry have aroused considerable interest owing to their exotic features. Anti-PT symmetry is an important counterpart of the PT symmetry, and has been studied in various classical systems. Although a Hamiltonian with anti-PT symmetry only differs from its PT-symmetric counterpart in a global ±i phase, the information and energy exchange between systems and environment are different under them. It is also suggested theoretically that anti-PT symmetry is a useful concept in the context of quantum information storage with qubits coupled to a bosonic bath. So far, the observation of anti-PT symmetry in individual quantum systems remains elusive. Here, we implement an anti-PT-symmetric Hamiltonian of a single qubit in a single trapped ion by a designed microwave and optical control-pulse sequence. We characterize the anti-PT phase transition by mapping out the eigenvalues at different ratios between coupling strengths and dissipation rates. The full information of the quantum state is also obtained by quantum state tomography. Our work allows quantum simulation of genuine open-system feature of an anti-PT-symmetric system, which paves the way for utilizing non-Hermitian properties for quantum information processing.

Key words: open quantum system; non-Hermitian quantum mechanics; parity-time symmetry; anti-parity-time symmetry; quantum simulation

Realizing quantum speed limit in open system with a PT-symmetric trapped-ion qubit

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Abstract: Evolution time of a qubit under a Hamiltonian operation is one of the key issues in quantum control, quantum information processing and quantum computing. It has a lower bound in Hermitian system, which is limited by the coupling between two states of the qubit, while it is proposed that in a non-Hermitian system it can be made much smaller without violating the time-energy uncertainty principle. Here we have experimentally confirmed the proposal in a single dissipative qubit system and demonstrate that the evolution time of a qubit from an initial state to an arbitrary state can be controlled by tuning the dissipation intensity in a non-Hermitian Parity-Time-Symmetric (PT-symmetric) quantum system. It decreases with increasing dissipation intensity and also gives a tighter bound for quantum speed limit (QSL). We also find that the evolution time of its reversal operation increases with the increasing dissipation intensity. These findings give us a well-controlled knob for speeding up the qubit operation, and pave the way towards fast and practical quantum computation, opening the door for solving sophisticated problems with only a few qubits.

Key words: non-Hermitian; parity-time symmetry; quantum speed limit; quantum computation

A compact high-resolution absolute gravity gradiometer based on atom interferometers

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Abstract: Gravimetry technology play significant roles in the fields of metrology, geology, geophysics, seismology and industrial-related applications such as resource exploration and autonomous navigation. Here we present a compact high-resolution absolute gravity gradiometer based on dual Rb-85 atom interferometers using stimulated Raman transitions. A baseline L= 44.5 cm and an interrogation time T=130 ms are realized in a sensor head with the volume of only 95 liters. Many experimental parameters are optimized to improve the short-term sensitivity as interleaving measurements by reversing the direction of the Raman wave vector are implemented to improve the long-term stability. After an averaging time of 17000 s, a phase resolution of 104 μrad is achieved, which corresponds to a gravity gradient resolution of 0.86 E (1 E=1×10^{-9} /s^2). To our knowledge, this is the sub-E atom gravity gradiometer with the highest level of compactness to date. After the evaluation and correction of systematic errors induced by light shift, residual Zeeman shift, Coriolis effect and self-attraction effect, etc., the instrument serves as an absolute gravity gradiometer and with it the local vertical gravity gradient (Γ_{zz}) is measured to be 3114 (53) E.

Key words: atom interferometer; gravity gradiometer; stimulated Raman transition

Cold atom interferometer for onboard gravity gradient measurement

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Abstract: A high precision mobile gravity gradiometer is essential in the resource exploration, matching navigation, concealed massive target detection, geophysics and etc. Here we present the research progress of our group on onboard gravity gradient measurement with a mobile cold atom interferometer-based gravity gradiometer. The key technologies such as Raman pulse power stabilization, ultra-low noise atoms detection and optomechanical systems integration have been solved, and the first mobile cold atom gravity gradiometer in China has been demonstrated. A static measurement sensitivity of 105 $E/\sqrt{Hz}$ is obtained with a data-rate of 3 Hz. By alternate placing a source mass between two positions, a deviation of gravity gradient variation of -1.8±7.3 E between the experimental value and the theoretical value is achieved. Finally, the gravity gradient distribution near a wall was measured by our mobile atomic gravity gradiometer. The deviation between the mobile measurement value and the static calibration value is 17.2±57.1 E.

Key words: atom interferometer; mobile cold atom gravity gradiometer; onboard gravity gradient measurement

Investigation of the effect of quantum measurement on parity-time symmetry

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Abstract: Symmetry, including the parity-time(PT)-symmetry, is a striking topic, widely discussed and employed in many fields. It is well known that quantum measurement can destroy or disturb quantum systems. However, can and how does quantum measurement destroy the symmetry of the measured system? To answer the pertinent question, we establish the correlation between the quantum measurement and Floquet PT-symmetry and investigate for the first time how the measurement frequency and measurement strength affect the PT-symmetry of the measured system using the $^{40}Ca^{+}$ ion. It is already shown that the measurement at high frequencies would break the PT symmetry. Notably, even for an inadequately fast measurement frequency, if the measurement strength is sufficiently strong, the PT symmetry breaking can occur. The current work can enhance our knowledge of quantum measurement and symmetry and may inspire further research on the effect of quantum measurement on symmetry.

Key words: quantum measurement; PT-symmetry; ion trap