International Workshop on Ultracold Group II Atoms

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Book of Abstracts

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Strontium optical lattice clocks at LNE-SYRTE

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We report progress towards practical optical frequency standards by demonstrating that an OLC using strontium atoms, with an accuracy of 4.1×10^-17 can be reliably operated over time periods of several weeks, with a time coverage larger than 80%, which can be considered as nearly continuous, given the stability of local oscillators. We take advantage of these long integration times to compare one of our strontium clocks with two atomic fountains with a statistical uncertainty below 10^-16.

Poster session / 8

Perfect probe Light-shift elimination in Generalized Hyper-Ramsey quantum clocks

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We present a new generation of quantum clocks absolutely free from ac Stark-shift caused by laser probing fields themselves based on generalized hyper-Ramsey resonances.
Sequences of composite laser pulses with specific selection of phases, frequency detunings and durations are combined to generate a very efficient and robust frequency locking signal with a perfect elimination of the light-shift from off resonant states. Laser phase-step modulations during interactions with electromagnetic fields are applied in order to decouple the unperturbed frequency measurement from the laser's intensity. The frequency lock point is thus protected against laser pulse area fluctuations and errors in potentially applied frequency shift compensations.
Quantum clocks based on weakly allowed or completely forbidden optical transitions in atoms, ions, molecules and nuclei will benefit from these hyper-stable laser frequency stabilization schemes to reach relative accuracies well below the 10^{-18} level.

Session 3 / 10

Ultracold chemistry and asymptotic physics with diatomic strontium molecules

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Simple molecules at ultracold temperatures, combined with high-resolution optical spectroscopy tools, open the door to molecular and fundamental science that is difficult to access with other physical systems. Here we discuss the studies of ultracold chemistry enabled by photodissociation of diatomic strontium molecules, including the phenomena of resonant and nonresonant barrier tunneling, matter wave interference of reaction products, and forbidden reaction pathways. The weakly bound molecules reveal the peculiar physics of the asymptotic atom-molecule regime and enable new types of precision measurements.

Session 2 / 11

Collective atom counting and first lasing on a millihertz linewidth optical transition

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Is it possible to exploit atom-atom correlations and entanglement to advance the field of precision measurement beyond the current independent-atom paradigm? We have explored this question along two fronts that will be discussed: superradiant or bad-cavity lasers that could be 10,000 times less sensitive to thermal motion of the optical cavity's mirrors [1], and spin-squeezed states that can greatly surpass the standard quantum limit on phase estimation [2]. Our experimental system consists of laser cooled strontium atoms held inside of a finesse 30,000 cavity by a magic-wavelength lattice. My talk will describe strong collective coupling between the atoms and cavity, non-destructive atom counting [3], prospects for entangled clocks that surpass the standard quantum limit, lasing in the superradiant crossover regime on the 7.5 kHz linewidth transition $^1S_0$ to $^3P_1$ [4], and the first observation of pulsed lasing deep into the superradiant regime on the 1 mHz linewidth transition $^1S_0$ to $^3P_0$.

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[4] "A Cold-Strontium Laser in the Superradiant Crossover Regime," M. A. Norcia, J. K. Thompson, arXiv:1510.06733 (2015)

Session 4 / 12

Remote frequency comparison of cryogenic optical lattice clocks

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The accuracy of recent optical lattice clocks reaches to 10⁻¹⁸ level, which allows us to explore cm-level distortion of time and space. The remote comparison of such clocks is of great importance in fundamental physics, such as, gravitational measurement³, geodesy⁴, and dark matter search⁵. Here we report a remote frequency comparison of cryogenic Sr clocks, one of which is located at the University of Tokyo (UTokyo) while the other is located at RIKEN, which is 15 km apart from UTokyo. We connect them by a 30-km-long telecom fiber link with the stability of 1×10⁻¹⁷ at 1s. After 11 measurements carried out over 6 months, frequency difference between the clocks is determined to be 0.7095(24)Hz which translates into a height difference of 15.16 m with an uncertainty of 5 cm. This result is consistent with a height difference independently measured by employing a leveling scheme. Furthermore, we continuously operate these clocks for a period of 3 days and achieved an experimental running time of 73 %. We discuss the future prospect for such precision measurements.

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Session 2 / 13

Studies of Cold strontium atoms in an optical cavity

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Today's ultra-precise and accurate atomic clocks continue to make important contributions to fundamental physics as well as applied technology. Atomic clocks have imposed significant limits on the drift of fundamental constants, such as the fine structure constant and the ratio of electron to proton mass and may have the potential to enhance the sensitivity of gravitational wave detectors, or put general theory of relativity to the ultimate test. To further improve atomic clocks we propose alternative strategies on how to perform laser frequency stabilization by exploiting cavity QED with atoms having ultra-narrow optical transitions. Recently we have constructed a cavity QED system where cold 88-atrontium atoms are coupled to a single mode of the optical cavity. The atoms are interrogated on the 7.6 kHz narrow intercombination line 1S0 − 3P1 of strontium. Since the sample temperature is typically of a few mK it provides an interesting domain where the Doppler energy scale is several orders of magnitude larger compared to the narrow linewidth of the optical transition. This opens for non-linear phenomena where the cavity-atom system becomes sensitive to velocity dependent multi-photon scattering events the so-called Dopplerons that affect the cavity field transmission and phase. We have studied the cavity atom system and will discuss how this system may improve on future atomic clocks. We will also discuss the prospects of superradiant laser sources involving narrow optical transitions in thermal sample of atoms.

Session 3 / 14

Synthetic spin-orbit coupling in an optical lattice clock

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We discuss a proposal to implement spin-orbit coupling in a 1D optical lattice clock operated with spin polarized fermionic alkaline-earth-atoms. The resulting single-particle and many-body physics can be probed at current clock operating temperatures thanks to the exquisite precision and sensitivity of the JILA Sr optical lattice clock. The system can realize an effective two-leg ladder where the rungs correspond to the two clock states (synthetic dimension), and the legs to the 1D lattice sites. While the former are coupled by the probing laser, the latter are coupled by tunneling. A large flux per plaquette is naturally generated because the clock laser imprints a phase that varies significantly across lattice sites. We propose to use standard spectroscopic tools – Ramsey and Rabi spectroscopy – to probe the band structure and reveal signatures of the spin-orbit coupling, including chiral edge states and the modification of single-particle physics due to s-wave and p-wave interactions.

Session 4 / 15

Improved Sr clock total uncertainty and development of a degenerate, 3D lattice clock

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Abstract: We report on improvements to the accuracy and stability of the JILA Sr clock, reaching a total fractional clock uncertainty of 2e-18, primarily by reducing the uncertainties due to the optical lattice and blackbody radiation. The blackbody radiation shift was determined through accurate thermometry, with in vacuum thermometers traceable to the NIST ITS-90 temperature scale, and an improved determination of the atomic structure. We will also discuss progress of a new apparatus that traps quantum degenerate strontium in a three-dimensional magic-wavelength optical lattice. We have reached quantum degeneracy with ten spin states and will load the degenerate atoms into the lowest band of a 3D lattice. The apparatus will be used to explore spin-orbit coupling, quantum magnetism, and improve the performance of future lattice clocks.

Poster session / 16

Symmetry protected topological phases and ultracold alkaline-earth fermionic atoms in one dimension

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Alkaline-earth and ytterbium cold atomic gases make it possible to simulate SU(N)-symmetric fermionic systems in a very controlled fashion. Such a high symmetry is expected to give rise to a variety of novel phenomena in many-body quantum physics.
We describe the main exotic properties of alkaline-earth and ytterbium fermions loading into a one-dimensional optical lattice. In particular, a special emphasis will be laid on
the nature of one-dimensional symmetry-protected topological phases with
an SU(N) symmetry that one can stabilize with these fermions.

Session 3 / 17

High-resolution spectroscopy of ultracold Ytterbium atoms on the clock transition

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I will describe our experimental results on spectroscopy with quantum-degenerate bosonic gases. In the experiment, a gas of bosonic Ytterbium atoms is probed by exciting an ultra-narrow optical transition (the "clock transition") linking the ground state to a metastable excited state. I will preliminary spectroscopy experiments of Bose-Einstein condensates (BEC) and thermal gases, which allows to determine the scattering parameters; and the observation of coherent Rabi oscillations between a BEC in the ground state and in the excited state. Elastic and inelastic interaction result in a damping of these oscillations, in analogy with the basic problem in quantum optics of a discrete level coupled to a continuum.

Poster session / 18

The polarization potential as a probe in interstellar matter.

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It is established since a long time (1926) that one can model atomic structure of alkaline species adding to the Coulomb potential a potential called the polarization potential $V_p(r) = -\frac{e^2}{2}\alpha_D\frac{1}{r^4}$. (It acts same sign that the Coulomb potential. (Born 1960)

Our main purpose is to show that the effect of modification of the core structure of alkaline atoms in their neutral states, leads to energy transitions detectable in low temperature universe domain (as interstellar molecular clouds called GMC giant molecular clouds).
The emission of light due to atomic transitions with effective quantum numbers $n_* = n - \delta$ be found in interstellar clouds, or even in HI regions of space for $2 \geq n_* \geq 9$.
All subsequent calculations will use the
hydrogen ionization potential $I_H = 13.616 eV$ to measure the effect of the atom core on energy levels.
α_D is the static dipolar polarizability, estimates of that quantity exists for elements like : Mg, Na, Li, Cs, K, Ca

Session 1 / 19

Searching for Physics beyond the Standard Model with Laser-Cooled Radium Atoms

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Laser cooling and trapping techniques have long been used for precision tests of physics, but never before have they been used to measure the electric dipole moment (EDM) of an atomic species. Such an EDM would violate time-reversal, parity, and charge-parity (CP) symmetries, which makes them a sensitive probe of expected physics beyond the Standard Model. However, to date, no such EDM has been found using any technique. Due to its large nuclear octupole deformation and high atomic mass, the radioactive isotope Ra-225 is a favorable EDM case; it is particularly sensitive to CP-violating interactions in the nuclear medium. We have developed a cold-atom approach of measuring the EDM of Ra-225 atoms held in an optical dipole trap, and last year demonstrated the method by completing the first measurement of radium's EDM. We have since improved on our first result by a factor of 36, reaching an upper limit of |d(Ra-225)| < 1.4×10^{-23} e-cm (95% C.L.). This constitutes not only the first EDM measurement of any laser-cooled and trapped atom, but also the first such measurement on any species with an octupole deformed nucleus. Upcoming improvements are expected to dramatically increase our sensitivity, and significantly improve on the search for new physics in several sectors.
This work is supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, Contract No. DE-AC02-06CH11357.

Session 6 / 20

Atom interferometry with ultra-cold strontium atoms

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In this talk I'll present the most recent results on a large
momentum transfer (LMT) Mach-Zehnder atom interferometer with
ultra-cold strontium atoms [Mazzoni2015].

LMT Bragg diffraction pulses (up to eight photon recoils) are
applied to atoms in free fall, launched upward with an accelerated lattice. We then use the strontium interferometer as a gravimeter, demonstrating best sensitivity of dg/g=4×10^-8.

Thanks to the special characteristics of strontium atoms for precision measurements [Poli2011], this result introduces new possibilities for experiments in fundamental and applied physics, as high precision measurements of gravity and gravity gradients, and precision test of Einstein Equivalence principle [Tarallo2014].

Ref.

[Poli2011] N. Poli, F.-Y. Wang, M. G. Tarallo, A. Alberti, M. Prevedelli, G. M. Tino "Precision measurement of gravity with cold atoms in an optical lattice and comparison with a classical gravimeter", Phys. Rev. Lett. 106, 038501 (2011)

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Session 4 / 21

Experiments with Sr lattice clocks at PTB

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I will report the ongoing activities and plans concerning our two strontium lattice clocks at PTB. In our stationary laboratory clock system we now can achieve clock instabilities of $1.6\times10^{-16}/(\tau/\mathrm{s})^{1/2}$. We deduce this from a noise model of our clock [1], which we compare with instabilities observed when measuring systematic frequency shifts in interleaved mode. Though we use a high quality interrogation laser [2], the instability is still limited by the Dick effect. Higher duty cycle achieved by e.g. longer interrogation would mitigate this effect. Along these lines I will discuss a demonstration of a compound clock that allows extending the interrogation time considerably beyond the coherence time of the laser. The scheme will actually provide better clock stability of the compound system compared to faster averaging of ratio measurements.

Our stationary clock was also involved in comparisons against optical clocks, in particular with a Sr clock from LNE-SYRTE. This comparison was enabled by a coherent fibre frequency link designed and built by the SYRTE, Laboratoire de Physique des Lasers, and PTB groups [3]. In this measurement we could confirm the agreement of both clocks on the level of 5×10^{-17}. With this performance of optical clocks, it is reasonable to think about an implementation of a timescale steered by an optical clock. We have demonstrated [4] that this is indeed feasible, and better performance than with the current primary standards could be achieved.

Our second Sr lattice clock is transportable. Its first evaluation yielded an uncertainty of 7×10^{-17}. The frequency difference between our two lattice clocks was found to be much smaller. The apparatus is now prepared for its first measurement campaign, a comparison with INRIM's clocks in Torino, Italy, via fibre link that involves a height difference of about 1000 m. This experiment will constitute a proof-of-principle experiment in relativistic geodesy.

This work was performed within the framework of the Centre of Quantum Engineering and Space-Time Research (QUEST). Funding from DFG (CRC 1128, RTG 1729) and EU FP7 (FACT) is acknowledged, as well as funding within the ITOC and QESOCAS projects in the European Metrology Research Programme EMRP. The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union.

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4. C. Grebing, A. Al-Masoudi, S. Dörscher, S. Häfner, V. Gerginov, S. Weyers, B. Lipphardt, F. Riehle, U. Sterr, C. Lisdat, arXiv:1511.03888

Poster session / 22

Strongly interacting ultracold quantum gases of fermionic Ytterbium-173

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In contrast to the more common alkali atoms, Ytterbium features a strong decoupling between the nuclear and the electronic spin degree of freedom and possesses a metastable excited state. In consequence, interactions cannot be enhanced with standard magnetic Feshbach resonances as in alkalis. We report on the discovery of a new orbital interaction-induced Feshbach resonance in Ytterbium-173. In a second experiment, we investigated the SU(N)-symmetric Fermi-Hubbard model, realized by loading Ytterbium-173 atoms into a threedimensional optical lattice. We prepared a low-temperature SU(N)-symmetric Mott insulator and characterized the Mott crossover by probing it locally, representing important steps towards probing predicted novel SU(N)-magnetic phases.

Session 1 / 23

Intermittent operation of a lattice clock toward the realization of a time scale

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With a reference to a ^{87}Sr lattice clock, we demonstrated a frequency evaluation of a hydrogen maser (HM) over a few months. The HM is a part of the Japan Standard Time (JST) system and is linked to the International Atomic Time (TAI). Therefore, the result obtained over a few months has enabled an accurate TAI-based frequency measurement with the smallest uncertainty [1]. This measurement may be utilized to calibrate the clock rate of the TAI since lots of frequency measurements reported by many laboratories have now determined the absolute frequency of the ^{87} Sr clock transition with an uncertainty of 5×10^{-16}. The results were also utilized for a feasibility study of steering HM frequency to generate a time scale. Referring the time differences recorded in the JST system, it was figured out that the intermittent operation of the lattice clock once in two weeks allows us to maintain the time scale in a few ns level.

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Session 3 / 24

Two-body and many-body physics in the ultracold regime: a quantum chemist's perspective

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State-of-the-art ab initio methods of quantum chemistry have found numerous applications in many areas of atomic, molecular, condensed matter, and nuclear physics. During the last decade they have been applied with success to interpret precision experiments on two-body and many-body processes in atomic gases in the ultracold regime. In this talk I will present recent examples of successful applications of the ab initio methods to describe two-body processes in atomic optical lattices leading to the formation of unusual chemical bonds and observations of exotic optical transitions and state-resolved photofragmentation processes in diatomic molecules, as well as to many-body processes in one-dimensional harmonic traps of identical fermionic spin-1/2 atoms. All reported theoretical results will be illustrated by an extensive comparison between theory and high-precision experiments.

Session 3 / 26

Ultracold Ytterbium Atoms in Dynamically Tunable Optical Lattices

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Dynamical controllability of the system parameters in ultracold atomic gases has made it possible to observe diverse kind of quantum dynamics. In this talk, we present the optical-lattice realization of a Lieb lattice [1], which plays an important role in quantum magnetism. Making full use of the tunability of the lattice potential, we load a Bose condensate of ^{174}Yb into the excited dispersionless band of the Lieb lattice. By exploiting a technique to measure the sublattice occupancies of atoms in the lattice, we observe the characteristic freezing of tunneling to adjacent lattice sites.
We also show the first demonstration of Thouless' topological pumping [2] of fermionic ^{171}Yb atoms

with an optical superlattice [3]. Here, the long-period lattice moving with respect to the short-period lattice realizes the Rice-Mele model with dynamically tunable parameters. Depending on the trajectory in the 2D parameter space, atoms show quantized transport which reflects the Chern number of the energy band.

[1] S. Taie, *et al.*, Sci. Adv. **1**, e1500854 (2015).
[2] D. J. Thouless, PRB **27**, 6083 (1983).
[3] S. Nakajima, *et al.*, Nature Phys., published online (2016); see also M. Lohse *et al.*, *ibid* (2015).

Session 1 / 27

Element No. 12: Benefits and challenges of Mg in frequency metrology

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Among the alkaline earth(-like) elements, magnesium is considered to be an ideal candidate for optical lattice clocks: it features a very large transition Q-factor [1] and a naturally low sensitivity to blackbody radiation at the same time [2]. Moreover, as a consequence of its low mass and simple atomic structure, atomic models can be implemented with higher precision in Mg, than for Sr or Yb [3]. However, these advantages come at the expense of experimental challenges for creating ultra-cold atomic ensembles.

In this talk, we will give an overview of past and on-going works for applications in frequency metrology. We will consider the relevant level scheme of bosonic ^{24}Mg and highlight the technical challenges concerning laser cooling and trapping. Finally, we summarize the requirements to demonstrate an optical lattice clock with ^{24}Mg at 10^{-18} uncertainty.

Recently, we demonstrated the trapping of cold magnesium atoms in a magic-wavelength optical lattice and observed the strongly forbidden $^1S_0 - {}^3P_0$ clock transition in bosonic ^{24}Mg. We determined the magic wavelength of 468.46(21) nm and observed a magnetic polarizability of -206(2) MHz/T^2 [4].

References:

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Poster session / 30

Volume Holographic Grating Stabilized 780nm Diode Laser With an Output Power of 380mW

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Abstract : A ridge waveguide laser stabilized by a compact holographic grating-cavity with an output power of 380 mW, a short-term optical linewidth of 18 kHz and a nearly diffraction-limited beam for saturation spectroscopy of rubidium is presented

Conclusion :
* Compact and spectrally narrow VHG stabilized ECDL with high output power of 380 mW at 780 nm
* Excellent laser stability and wavelength tunability via current and temperature
* VHG period may easily be adapted to different wavelengths in the near infra-red

Session 1 / **31**

Making 10^{-18} fractional frequency measurements with ytterbium optical lattice clocks

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We describe the design and operation of an optical lattice clock based on ytterbium. Exploiting a combination of narrowline laser cooling on the 1S0-3P1 transition and quenched sideband cooling on the 1S0-3P0 clock transition, we realize lattice-trapped ytterbium with temperatures <=1 uK. By using large atom number ensembles to reduce quantum projection fluctuation in atomic state measurements, we measure clock stability levels at the 1 x 10^{-18} level over long timescales. By operating two atomic systems in an interleaved interrogation scheme to achieve a composite system with zero dead time, we explore similar levels of instability on faster timescales. Finally, we report on recent efforts towards a full evaluation of systematic shift uncertainties at the 10^{-18} level, including a detailed study of high-order lattice Stark effects.

Poster session / **32**

The role of the molecular hyperfine structure to control ultracold molecular formation

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High efficiency production as well as the confinement and manipulation of ultracold molecules with external fields require a precise knowledge of their level structure. The transfer of the initially weakly bound ultracold molecules to their absolute ground state, relies on the existence of suitable electronically excited states allowing an efficient stimulated Raman adiabatic transfer (STIRAP). Due to the complexity of the problem little is known about the hyperfine structure of molecu- lar states, especially in case of the electronically excited ones. We propose an asymptotic model where the molecular hyperfine interactions are determined by the atomic hyperfine interaction [1]. This assumption is strictly valid for large internuclear distances when the exchange energy be- tween the two atoms is negligible. At shorter distances, the variation of the electronic current is expected to be small enough to allow the model for catching the essential of the hyperfine split- ting of the

molecular levels. As a first step, we have determined potential energy surfaces (PES) for any internuclear distance considering the molecular spin-orbit and hyperfine interactions for a non-rotating molecule. I will present our results [2] on the hyperfine structure for the bosonic ^{39}K^{133}Cs and sermonic ^{40}K^{133}Cs molecules for excited molecular states which correlate to the K(4s ^{2}S$_{1/2}$)+Cs(6p ^{2}P$_{1/2,3/2}$) dissociation limits.

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Poster session / 33

Towards quantum many-body physics with Sr in optical lattices

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Within the last decade, fermionic alkaline earth atoms in optical lattices have become a platform for precision measurements, culminating in the realization of an atomic clock with the currently highest stability and accuracy at the 2×10^{-18} level. In the meantime, quantum degenerate gases of all bosonic and fermionic isotopes of Sr have been realized. With the extension of the quantum gas microscopy technique to fermionic alkali metal atoms, experiments with quantum degenerate gases in optical lattices have taken another step towards full control over the internal and external degrees of freedom of fermions in optical lattices.

Here, we report on the construction of a new experiment with quantum degenerate gases of Sr in optical lattices. Our experiment aims to combine the high spatial control over the atomic degrees of freedom from quantum gas microscopy with the precision control over the internal degrees of freedom enabled by optical lattice clock techniques.

Session 1 / 35

Group II atoms: atomic clocks, long-range interactions, and precision measurements

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I will report recent advances in the calculations of atomic properties of group II atoms and similar systems of interest to the development of optical atomic clocks, production of ultracold molecules, quantum information, and precision measurements. The calculations include magic wavelengths and

blackbody radiation shifts for Mg, Cd, Zn, Sr, Yb and Hg, magic-zero wavelengths in Sr, C₆ and C₈ van der Waals coefficients for Sr-Sr, Yb-Yb, and Yb-alkali dimers, and other transition properties and ac polarizabilities. We demonstrate that measurements of a sequence of Sr magic-zero wavelengths can serve as a global benchmark of the spectroscopic accuracy that is required for further development of high-precision predictive methods. These magic-zero wavelengths are also needed for states elective atom manipulation for implementation of quantum logic operations. Finally, I will report a theoretical prediction of ionization potential of No, Z=102, which is a heavier analog of Yb.

Session 3 / 36

News from the Amsterdam strontium quantum gas group

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I'll report on two research lines centered around ultracold strontium.

The first research line has the goal to produce a quantum gas of RbSr ground-state molecules. We have created a ^{84}Sr-^{87}Rb Mott insulator and investigated STIRAP molecule association on the $^1S_0$-$^3P_1$ intercombination line. We found only very weak transitions between free atoms and optically excited molecules, hindering us to coherently create molecules. Using mass-scaling, our spectroscopy data points to a much more promising STIRAP molecule association path in ^{87}Sr-^{87}Rb mixtures. Furthermore, we have developed a STIRAP light-shift compensation method that has allowed us to coherently create Sr_2 molecules with more than 80 % efficiency, up from 30 % reached previously.

The second research line has the goal to create a perpetual atom laser. I'll describe our approach and show first ultracold atom signals from a new machine dedicated to this research line.

Poster session / 37

Ultra-cold alkaline-earth atoms at half-filling in one dimension

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Fermionic ultra-cold alkaline-earth atomic gases have recently acquired a great interest both experimental and theoretical. Recent experiences have shown that at very low energy, interactions between such atoms hardly depend, except via the fermionic statistic, on their nuclear spin. This so particular structure provides very high degrees of symetries to these systems, in particular the realisation of a degenerate fermionic gas with an extended SU(N) symmetry, N being the number of nuclear-spin states. In this work, we study, by low-energy approach and by numerical methods,the nature of Mott-insulating phases of these ultra-cold atoms trapped on unidimensional-optical lattices.

Session 2 / 38

Cooperative transmission in an optically dense medium on the strontium intercombination line

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The coherent transmission of a wave, through scattering medium, results of interference between the incident field and the forward scattering field. This basic and well established process was experimentally observed in the case of an electromagnetic wave transmitted through a resonant strontium cold cloud [1]. Since the forward scattering field is build up on the incident field, one may state that the amplitude of the former cannot be larger than the latter. We demonstrate that this intuitive picture is incorrect [2]. Moreover, cooperative response of the system allows to drive it faster than the excited state lifetime [3]. This regime shares interesting similarity with Dicke superradiance. We take advantage of the slow response time of the strontium intercombination line to clearly observe those effects.

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Poster session / 39

Bragg interferometry with strontium atoms for gravity measurements

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We report on the first atom interferometer based on large-momentum-transfer Bragg diffraction with strontium atoms in a fountain. We measured gravity acceleration of ^{88}Sr isotope with a sensitivity $\delta g/g = 4 \times 10^{-8}$ at 2000 s integration time [1]. This isotope has powerful coherence properties such as zero total spin in the ground state, narrow optical transitions, and low scattering cross section. Thanks to these properties and applications of new interferometric schemes, unprecedented sensitivities are foreseen.

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Poster session / 40

Rydberg atoms of Ytterbium

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Physical properties of Rydberg atoms pave the way to experimental control of the quantum state of mesoscopic ensemble of particles. Interactions between Rydberg atoms are large for interparticle distances in the micrometer range. They can be used to induce Rydberg blockade and generate entanglement between two[1,2] or even larger ensemble [3] of atoms. Nevertheless, Rydberg atoms lack some of the resources used with ground state atoms, especially optical techniques such as imaging and optical dipole traps.

In this poster I will describe the experimental scheme under development and present the status of the experiment. Ytterbium atoms have two valence electrons which should allow applying optical manipulation on the Rydberg states. The idea is first to promote one electron to a long lived Rydberg state. The system can then be approximated as a free electron orbiting around an ionic core. The latter has still a valence electron that can be used for optical manipulation (i.e. imaging or trapping).

We are currently able to have Ytterbium atoms held inside a magneto-optical trap on the intercombinaison transition between 1S0 and 3P1 around 556nm. We performed the spectroscopy of the ns and nd Rydberg states from n=35 to n=80, increasing by two orders of magnitude the precision of their energy levels. By means of a Multi-Channel Quantum Defect Theory (MQDT) analysis we are able to fit the levels and deduce a new value of the ionisation energy. The next step will be to complete the spectroscopy of the Rydberg levels (with p and f series), enabling us to compute the Stark map.

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Poster session / 41

Exploring Collective Physics in a Strontium Optical Lattice Clock

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We investigate collective emission from coherently driven ultracold ^{88}Sr atoms. We perform two sets of experiments, using a strong and weak transition that are insensitive and sensitive, respectively, to atomic motion at one microKelvin. We observe highly directional forward emission with a peak intensity that is enhanced, for the strong transition, by 10^3 compared to that in the transverse direction. This is accompanied by substantial broadening of spectral lines. For the weak transition, the forward enhancement is substantially reduced due to motion. Meanwhile, a density-dependent frequency shift of the weak transition ($\sim$ 10% of the natural linewidth) is observed. In contrast, this shift is suppressed to <1% of the natural linewidth for the strong transition. Along the transverse direction, we observe strong polarization dependences of the fluorescence intensity and line broadening for both transitions. The measurements are reproduced with a theoretical model treating the atoms as coherent, interacting, radiating dipoles. In addition we will present our latest results on spin-orbit coupling (SOC) measurements where the SOC emerges naturally during the clock interrogation when atoms are allowed to tunnel and accumulate a phase set by the ratio of the "magic" lattice wavelength to the clock transition wavelength.

Session 6 / 43

Atom Interferometry with Group II Atoms for Gravitational Wave Detection

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The advent of gravitational wave astronomy promises to provide a new window into the universe. Low frequency gravitational waves below 10 Hz are expected to offer rich science opportunities both in astrophysics and cosmology, complementary to signals in LIGO's band. Detector designs based on atom interferometry have a number of advantages over traditional approaches in this band, including the possibility of substantially reduced antenna baseline length in space and high isolation from seismic noise for a terrestrial detector. In particular, atom interferometry based on the clock transition in group II atoms offers tantalizing new possibilities. Such an approach is expected to be highly immune to laser frequency noise because the signal arises strictly from the light propagation time between two ensembles of atoms. This would allow for a gravitational wave detector with a single linear baseline, potentially offering advantages in cost and design flexibility.

Poster session / 45

The 87Sr optical lattice clock at PTB

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We report on the implementation of a cryogenic optical lattice clock based on the $^1S_0 \leftrightarrow {}^3P_0$ transition of ^{87}Sr at PTB. While the atomic response to the blackbody radiation (BBR) field experienced by the atoms has been well characterized [1], our existing lattice clock is now limited to a total systematic uncertainty of 2×10^{-17} [2] by our knowledge of the effective BBR field itself. Several groups [3-5] have already demonstrated approaches to control the BBR-induced frequency shifts to the level of few parts in 1018 and below, near room temperature or at cryogenic temperatures.

The lattice clock at PTB is successively being upgraded to a fully cryogenic lattice clock. In a first step, we have implemented a cryogenic environment into which the atoms are transport-ed for interrogation. This has allowed us to achieve similar control of the BBR-induced fre-quency shifts and is expected to enable a total systematic uncertainty below 1×10^{-17}. A sub-sequent upgrade to a new physics package will remove the need for transporting the atoms and provide generally improved control of systematic effects to enable operation of the lattice clock at systematic uncertainties of few parts in 10^{-18} and better.

The instability of our optical lattice clock is $1.6 \times 10^{-16}/\sqrt{\tau/\mathrm{s}}$ [6], which is limited by Dick effect. We present a novel interrogation scheme to minimize the Dick effect by interrogating the atoms longer than the coherent time of the clock laser.

This work is supported by QUEST, by DFG within CRC 1128 (geo-Q) and RTG 1729, and by EMRP within ITOC and QESOCAS. The EMRP is jointly funded by the EMRP-participating countries within EURAMET and the European Union.

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Poster session / 46

One-dimensional two-orbital SU(N) ultracold fermionic quantum gases at incommensurate filling for a low-energy approach

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We investigate the zero-temperature phase diagram of two-orbital SU(N) fermionic models at incommensurate filling which are directly relevant to strontium and ytterbium ultracold atoms loading into a one-dimensional optical lattice.
Using a low-energy approach that takes into account explicitly the SU(N) symmetry, we find that a spectral gap for the nuclear-spin degrees of freedom is formed for generic interactions. Several phases with one or two gapless modes are then stabilized which describe the competition between different density instabilities.

Poster session / 47

Two-colour photoassociation spectroscopy in ultracold ensembles of ^{40}Ca near the ^{3}P$_1$ - ^{1}S$_0$ asymptote

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Compared to the intensively investigated two valence electron systems strontium and ytterbium, calcium offers by far the narrowest ^{1}S$_0$ - ^{3}P$_1$ intercombination line with a natural linewidth of 375 Hz at a wavelength of 657 nm. Using this transition for spectroscopy allows for highly precise measurements and might enable the application of optical Feshbach resonances with low atomic losses.

We have measured the three most weakly bound ground state vibrational levels in the $X^1\Sigma_g^+$ potential of ^{40}Ca$_2$, using two-colour photoassociation. We previously measured [1] molecular states corrected for quadratic magnetic shifts [2] in the a$^3\Sigma_u^+$, $c^3\Pi_g$ exited state potential that served as intermediate levels. Cold ensembles of about 10^5 calcium atoms trapped in a crossed dipole trap at temperatures of approximately 1 μK have been interrogated in both Raman and Autler-Townes configuration. The field free binding energies have been derived with kHz accuracy benefiting from offset-locked tunable lasers with few Hertz linewidth and from a detailed lineshape analysis.

The interaction potential at large internuclear separations for these weakly bound levels is dominated by the long-range coefficients C_6, C_8 which have been derived using a full quantum computation including variation of the inner potential range [3]. Based on the three ground state binding energies measured so far we obtain a preliminary value for the s-wave scattering length $a = 308(10)a_0$.

This work is funded by the DFG through the Research Training Group 1729

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Poster session / 48

Quantum chaos in ultracold collisions between Yb (1S0) and Yb (3P2)

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Dense Feshbach spectra in ultracold collisions that are chaotic cannot be analyzed in the same way as has been done for alkali metals. In

particular, good quantum numbers cannot be assigned to individual resonances in chaotic systems, such as ultracold Er+Er and Dy+Dy. Instead, a statistical approach must be taken.

We have calculated and statistically analyzed the Feshbach spectrum of ultracold collisions between Yb($^1S_0$) and Yb($^3P_2$) atoms. The strongly anisotropic potential of this system leads to chaotic signatures when a magnetic field is applied. We probe these chaotic signatures by examining Feshbach resonances as functions of both external magnetic field and an interatomic potential scaling factor λ. We find that the statistics of the Feshbach resonances with respect to λ show a transition from random behaviour at zero magnetic field to chaotic behaviour at finite field. Feshbach resonances as a function of magnetic field also show strong signs of chaos.

The results are a step towards characterizing the conditions required for the emergence of chaos, and demonstrate that a complicated electronic structure is not a prerequisite for chaos.

Poster session / 50

Novel Neodymium MOPA fiber laser for Strontium atom cooling

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We present the first step in the development of a stable fibered laser system operating at 461 nm for the laser cooling of Strontium atoms on the 1S0-1P1 line. This project fits in a long-term activity towards the development of a new generation of highly sensitive atom interferometers based on single photon transitions. This new development will particularly benefit to large-scale instruments based on atom interferometry, such as the Matter-wave laser Interferometry Gravitation Antenna (MIGA project).

The first stage of the laser consists in a 3W source at 922nm by using a MOPA configuration. For this purpose we use a special neodymium doped fiber, which strongly suppresses the 1060 nm amplification. We already demonstrated a non-single frequency laser output power of 2.5W, and are now focused on the generation of the 922nm radiation in in single frequency operation. The second stage of the laser system consists in the frequency doubling to obtain the 461 nm wavelength. For this propose we aim to develop a resonant doubling cavity in collaboration with industrial partners.

Poster session / 51

Multiple photon scattering and blockade in a dense dissipative Sr Rydberg gas

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Cooperative quantum optics has been one of the main research topics to emerge in the field of cold Rydberg gases. The first observations of optical nonlinearity at the single-photon level, and more recent demonstrations of single-photon transistors use a resonant two-photon excitation scheme. A key figure of merit is the optical depth per blockade sphere, which must be very high to ensure that all unwanted photons are scattered. Using a cold ($\sim 10\ \mu$K), dense (up to $\sim 10^{12}$ cm^{-3}) gas of strontium atoms we show that in this regime, a significant Rydberg population can be created by photons that are multiply scattered before leaving the cloud. The re-scattered field is density-dependent and has quite different spectral properties from the incident laser light. A careful analysis reveals that multiple scattering co-exists with signatures of the Rydberg blockade in this strongly dissipative regime. Our technique also provides a probe of the spectral distribution of the re-scattered light within the cloud, which may be qualitatively different from that of the transmitted light.

Session 3 / 52

Engineering new quantum systems with ultracold ^{173}Yb fermions

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I will report on new directions for quantum simulation with ultracold Fermi gases of two-electron ^{173}Yb atoms. Manipulation of their electronic state on the ultranarrow clock transition allowed us to engineer a new kind of magnetic interaction [1] and to produce strongly interacting Fermi gases with orbital degree of freedom at a newly discovered orbital Feshbach resonance [2]. By manipulating their nuclear spin we realized systems of fermions with tunable SU(N) symmetry [3] and demonstrated a new concept for atomic physics experiments based on the realization of a "synthetic dimension", that we have used to produce gauge fields and directly observe the propagation of chiral edge states in a quantum Hall system [4].

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Poster session / 53

Laser sources for trapping atoms in Sr optical lattice clock

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Sr Opical Lattice Clocks (OLCs) are promising candidates for a compact, transportable and even potentially space optical lattice clock. The space or transport applications need a compact and reliable apparatus. One of the largest problem is a miniaturization of lattice source at 813 nm. Due to the fact that the lattice light is countinously on during a clock cycle, in major cases Titanium-Sapphire (TiSa) laser is used to generate the lattice because guarantees spectral purity at 10-18 level. Unfortunately TiSa laser occupies a lot of space (to compare with another components), hence it is not an excellent candidate for mobile OLCs. In the other hand tests carried out with compact semi-conductor sources (like laser diode and tapered amplifiers) have shown discrepancies as high as several 10-15 (for 1 Er) between several clocks. Therefore, in order to reach uncertainties in the 10-17 range, a detailed study of the different possible laser sources is necessary. Firstly we perform differential measurements on one clock, alternating between a configuration in which the lattice light is generated by the Titanium-Sapphire laser and a configuration in which the light is generated by a tapered amplifier (TA) or slave diode laser. Second we determine spectral distributions of available sources in our lab using optical spectral analyzer. These measurements allow us to determine systematic effects for all sources and test if the TA is a reliable lattice light source.

Session 1 / 56

Comparing a mercury optical lattice clock with microwave and optical frequency standard

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Neutral mercury is a promising candidate to build an optical lattice clock thanks to several favorable atomic properties. Its high vapor pressure at room temperature suppresses the need for an oven and thus reduces temperature gradients on the experimental setup. Furthermore, the ${}^1S_0 - {}^3P_0$ ultranarrow clock transition is very weakly coupled to static and thermal radiation fields easing the efforts needed to control the blackbody radiation shift, one of the limiting factors in almost all the other optical clocks.

Additionally, ^{199}Hg has a simple structure with spin ½ for which tensor component of light shift is null and vector component can be exactly canceled when alternatively interrogating the two spin states. Finally, the ${}^3P_1$ state used for laser cooling has a 1.3 MHz linewidth yielding Doppler limited temperatures as low as 30μK. This allows for direct loading in the magic wavelength optical lattice from a single stage MOT.
In spite of these advantages, a big challenge lies in the need for adequate (narrow-linewidth, tunable…) cw laser sources in the UV region of the spectrum at 254, 362 and 266 nm respectively for cooling, trapping and probing the mercury atoms.

In this talk, after briefly presenting a new evaluation of the systematics of our Hg clock down to 1.6×10^{-16} of relative uncertainty, we will report the first direct measurement of the Hg/Rb frequency ratio, and, to our knowledge, the best absolute frequency measurement of the Hg clock transition via comparison with FO2-Cs down to an uncertainty of 4×10^{-16}, close to the limit of the fountain and about 30 times better than the last measurement reported by our group [1]. Finally, we will report a direct optical to optical measurement of the Hg/Sr frequency ratio with an uncertainty of 1.8×10^{-16}. Our value is in good agreement, within the stated 1σ uncertainties, with the value reported in [2]. To the best of our knowledge, no other frequency ratio has been measured in different labs with an uncertainty below that of the SI second. These kinds of comparisons are essential in assessing the reliability of optical frequency standards as candidates for a redefinition of the SI second, as well as for tests of the variation of fundamental constants.

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Poster session / 57

Magnetically tunable Feshbach resonances in Li+Er

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Ultracold species make it possible to build state-selected quantum systems with controllable interactions, which open the door to exploring fascinating phenomena. Among their many applications, ultracold systems can be used as quantum simulators, to study condensed-matter physics and quantum-controlled chemistry, to develop quantum information devices, and for ultraprecise spectroscopy. Tunable Feshbach resonances are powerful tools to control the interaction and scattering properties of ultracold species, and make many of these applications possible. Having the possibility to address and tune across selected Feshbach resonances is thus key in ultracold experiments.

In this poster, I will discuss our recent work on magnetic s-wave Feshbach resonances in binary mixtures of ground-state Li atoms and bosonic Er isotopes [1]. Our study provides compelling and robust theoretical evidence that low-field resonances exist for Li+Er, with widths well within current experimental resolution. The Li+Er system may be especially appealing for experiments in optical lattices: Dipolar species with tunable interactions are key to studying the effects of long-range anisotropies, quantum magnetism, disorder, and quantum collective behaviour. Very importantly, such Feshbach resonances may be used for magnetoassociation of LiEr molecules, starting from ground-state atoms in order to avoid limiting background losses [2]. In addition, Er is a heavy atom, thus ultracold LiEr may be used to study the time variation of fundamental constants, while the extreme mass imbalance in the system makes it specially well suited for exploring Efimov physics. We predict Li+Er spectra to have strikingly different statistical properties than those of other systems involving highly-magnetic atoms such as Er+Er, Dy+Dy, etc. In particular, the spectra are much less congested and exhibit non-chaotic properties. I will hence discuss a simple model to predict resonance positions for different isotopologues from measurements on a reference system, which would greatly simplify designing experiments with various Er bosonic isotopes.

[1] M. L. González-Martínez and P. S. 379;uchowski, *Phys. Rev. A* **92**, 022708 (2015)
[2] M. L. González-Martínez and J. M. Hutson, *Phys. Rev. A* **88**, 020701(R) (2013)

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171Yb lattice clock at INRIM

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BIPM has recognized the 1S0-3P0 forbidden transition in neutral Ytterbium as a secondary representation of the second.

At INRIM, an optical lattice clock based on neutral 171Yb is under operation and currently the metrological characterization of the standard is ongoing.
The dipole trap at the magic wavelength of 759 nm collects up to 10^4 atoms in about 200 ms, starting from a double stage MOT at 399 nm and 556 nm.
The clock transition 1S0-3P0 at 578 nm is probed by a laser stabilized to an ultra-stable cavity.
The cycle duration sums up to about 250 ms.
We present the first characterization of the clock and the absolute frequency measurements towards the INRIM cryogenic cesium fountain ITCsF2 (accuracy 2×10^-16).
Moreover, we describe the ongoing activities involving the Yb clock, in particular a relativistic geodesy experiment within the European project International Timescale with Optical Clocks.

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Magnetically tunable Feshbach resonances in Li + Yb(³P_J)

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Many groups have now succeeded in producing alkali-metal dimers in high-lying vibrational states by either magneto- or photoassociation, and a few of these species have already been transferred to their absolute ground states. The alkali-metal dimers all have singlet ground states and there is considerable interest in extending molecule formation to molecules with doublet ground states, such as those formed from an alkali-metal or other closed-shell atom and an alkaline-earth atom. Żuchowski *et al.* [1] have shown that such systems can have magnetically tunable Feshbach resonances due to very weak couplings caused by the distance dependence of the hyperfine coupling. The resulting Feshbach resonances are very narrow [2, 3], but have nevertheless attracted the attention of several experimental groups worldwide.

The Li+Yb system has particularly narrow resonances when the atoms are in their ground states, with widths predicted to vary from a few microgauss to a few milligauss depending on the Yb isotope [2]. However, ultracold Yb can also be prepared in its metastable ³P₂ state which has a radiative lifetime of over 15 s [4]. Atoms in P states are anisotropic, so the interaction of Yb(³P₂) with Li(²S) introduces additional couplings that are expected to produce broader resonances that can be used for molecule formation (as originally suggested by Hansen *et al.* [5]). In this poster, I will discuss our efforts [6] in understanding the feasibility of this approach.

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[5] A. H. Hansen *et al.* *Phys. Rev. A* **87**, 013615 (2013)

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Session 6 / 60

Ultracold fermionic ytterbium with strong interactions in optical lattices

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Using both internal degrees of freedeom of ytterbium, the nuclear spin as well as the electronic spin quantum number, allows to implement novel many-body systems in optical lattices. The interaction properties of yetterbium-173 have proven to be particularly intriguing, with a Feshbach resonance between the singlet and triplet states of the electronic degree of freedom, which we characterize based on the recent predictions by Zhang et al. [1]. Here, the optical lattices allow for detailed quantitative studies of the interaction channels of individual pairs of atoms.
Another aspect of many-body physics with ytterbium is the large spin degree of freedom with the associated strong decoupling of nuclear to electronic degrees of freedom. This allows for very faithful realization of extended-symmetry Fermi-Hubbard systems. We will present the characterization of a strongly interacting SU(N)-symmetric gas of ytterbium in the metal to Mott crossover regime of an optical lattice using in-situ measurements of the equation of state.