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T01

The dipolar supersolid: a self-induced Josephson junction

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The supersolid is a fundamental state of matter combining superfluidity with a crystalline structure, realized for the first time in a Bose-Einstein condensate (BEC) of strongly magnetic atoms in 2019 [1]. In my talk, I'll briefly present some important results obtained during my PhD: the measurement of the moment of inertia of the supersolid [2] and the characterization of the quantum phase transition from the superfluid (the BEC) to the supersolid [3]. I'll devote most of the talk to our more recent work, in preparation, where we characterize the Josephson dynamics between the clusters of the supersolid. I'll show that, remarkably, the supersolid can perform population and phase oscillations in analogy with a bosonic Josephson junction. We characterize such oscillations both experimentally and with numerical simulations. However, I'll show that the self-induced barrier introduces exciting new phenomena, such as a very low-energy Goldstone mode in competition with the Josephson mode, which makes the supersolid Josephson junction a completely new system where to study Josephson-related superfluid effects. I'll also discuss ideas to employ the novel supersolid junction as an innovative platform to study matter-wave interferometry and entanglement.

[1] L. Tanzi et al., PRL, **122**, 130405 (2019).
[2] L. Tanzi, J.G. Maloberti, G. Biagioni et al., Science, **374**, 6534 (2021).
[3] G. Biagioni et al., PRX **12**, 021019 (2022).

T02

Towards atomic diffraction through single-layer graphene

Christian Brand[1]

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We discuss the prospect of diffracting fast atomic matter waves through atomically thin membranes, such as graphene [1]. Using hydrogen atoms with a velocity of up to 120 000 m/s, we predict a high probability of coherently diffracting atoms through the natural lattice of the crystalline gratings. Nevertheless, the minimum distance between the matter wave and the grating is on the picometer scale, leading to significant couplings. As this interplay is encoded in the matter wave, it brings direct and dose-independent imaging of the interaction within reach. While investigations below the damage threshold ensure virtually infinite interrogation times, studies above the damage threshold give insights into dynamical processes in real-time. Such information is important to understand technologically-relevant atom-induced processes in 2D material, such as milling, defect-formation, and excitations.

[1] C. Brand, M. Debiossac, T. Susi, F. Aguillon, J. Kotakoski, P. Roncin, and M. Arndt, New J. Phys. **21**, 033004 (2019).

T03

Testing the foundation of quantum physics in space via Interferometric and non-interferometric experiments with mesoscopic nanoparticles

Quantum technologies are opening novel avenues for applied and fundamental science at an impressive pace. In this talk, I will focus on the promises coming from the combination of quantum technologies and space science to test the very foundations of quantum physics and, possibly, new physics. In particular, I will survey the field of mesoscopic superpositions of nanoparticles and the potential of interferometric and non-interferometric experiments in space for the investigation of the superposition principle of quantum mechanics and the quantum-to-classical transition. I will delve into the possibilities offered by the state-of-the-art of nanoparticle physics projected in the space environment and discuss the numerous challenges, and the corresponding potential advancements, that the space environment presents.

T04

Interference dynamics of matter-waves of SU(N) fermions

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We consider an atomtronic circuit comprised of strongly interacting SU(N) fermions, pierced by an effective magnetic flux. Inspired by the experimental know-how in the field, we perform an in-depth analysis of the matter-wave interference patterns of SU(N) fermions as a function of the operating conditions of the synthetic gauge field, particle numbers and in the interaction regimes ranging from attractive to repulsive. Through the so-called homodyne and self-heterodyne protocols, which are two protocols that are widely employed in the current experimental setups for interfering ultracold matter-waves, we highlight the different physics exhibited by the repulsive and attractive regimes. Furthermore, we show how the number of particles as well as the number of components of SU(N) fermions, two quantities that are notoriously hard to extract experimentally, can be detected through our analysis.

[1] W.J. Chetcuti, A. Osterloh, L. Amico and J. Polo ArXiv:2206.02807 (2022).

T05

Bow-tie two-photon recoil interactions and gray molasses in a ring cavity

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In our experiment, ultracold ^{87}Rb atoms are charged at the center of the cross–shaped cavity at 1560 nm, where a far off–resonant dipole trap (FORT) is created. High–finesse at 780 nm allows for collective strong atom-cavity coupling via frequency doubling of the 1560 nm source which is locked to the cavity resonance.

Cooling of an atomic gas to ultracold temperatures requires a multistage process: laser cooling in a magneto–optical trap (MOT); sub–Doppler cooling; loading into a conservative magnetic or optical trap; and often evaporative cooling. Sub–Doppler cooling schemes involving dark states have emerged as a powerful technique: they are known as gray molasses. In this context, we show that dark state cooling in a hyperfine two–photon Raman condition can be used in combination with FORT when strong differential light shifts are present. Additionally, we utilize this technique to cool the atomic ensemble in the FORT by further detuning the Raman beams to the red.

In another set of experiments, we exploit the doubly resonant character of the cavity, both at 1560 and 780 nm, to explore the interaction between the atoms and the cavity. Experimentally, continuous 780 nm laser light injection has been obtained by improving the 1560 nm frequency lock to the cavity, where ultracold atoms loaded into the FORT can collectively interact with the 780 nm light. Interactions between counter-propagating modes and BECs could reveal the existence of different phases of matter which we would like to explore in the future.

[1] D. S. Naik and G. Kuyumjyan and D. Pandey and P. Bouyer and A. Bertoldi, Q. Sci. and Tech. **3**, 045009 (2018).
[2] D. S. Naik and H. Eneriz-Imaz and M. Carey and T. Freegarde and F. Minardi and B. Battelier and P. Bouyer and A. Bertoldi, Phys. Rev. Res. **2**, 013212 (2020).
[3] G. Condon and M. Rabault and B. Barrett and L. Chichet and R. Arguel and H. Eneriz–Imaz and D. Naik, A. Bertoldi and B. Battelier and P. Bouyer and A. Landragin, Phys. Rev. Lett. **123**, 240402 (2019).

T06

State-dependent potentials for trapped atom interferometry

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Atom interferometry does not necessarily require free propagation of matterwaves, be it in free-space or along a waveguide.
The example of Sagnac interferometry with fully trapped atoms in state-dependent trapping potentials [1] will be discussed, advantages and disadvantages, as well as our efforts for an implementation.
Recently, radio-frequency dressing allowed us to demonstrate state-dependent guiding of different rubidium hyperfine states in opposite directions around a closed loop on an atom chip. Spectroscopy in such potentials is rich in detail [2], and sharp microwave transitions can be used to prepare superpositions of atoms in different trappable states. Additional dressing fields and field modulations can be used to fine-tune the relevant potentials and enhance coherence between these states.

[1] R. Stevenson et al., Sagnac Interferometry with a Single Atomic Clock, Phys. Rev. Lett. **115**, 163001 (2015).
[2] G. A. Sinuco-Leon et al., Microwave spectroscopy of radio-frequency-dressed ^{87}Rb, Phys. Rev. A **100**, 053416 (2019)

T07

LaceNET — A machine learning approach for mask generations for matter-wave lithography

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[2] *Department of Informatics, University of Bergen, HIB - Thormøhlens gate 55, 5006 Bergen, Norway.*

Recent progress in matter-wave experiments led to technical applications, particularly for acceleration sensing, single-particle detectors, quantum microscopes or matter-wave lithography. Thus, they act on the nanometre length scale. Consequently, the quantised nature of the object is not neglectable. In particular, the quantum vacuum has to be taken into account. Hence, the interactions between the objects are dressed by the vacuum polarisability leading to dispersion forces.

The diffraction of matter waves is based on the wave-particle duality and has the advantage that waves with sub-nanometre wavelengths can be created and thus strongly increases the resolution compared to optical devices [1]. However, the additional interactions between the matter-wave particles and the diffraction object dramatically influence the propagation of the wave [2]. We will illustrate the impact of dispersion forces on the results of diffraction experiments and demonstrate possibilities for their manipulation to enhance the contrast for matter-wave lithography applications [3].

Photolithography is a commonly applied method to create, among others, semiconductor devices. The current use is extreme-ultraviolet (EUV) photolithography that uses electromagnetic radiation with a wavelength of 13.5 nm, corresponding to an energy of 92 eV.

The ability to pattern materials at ever-smaller sizes using photolithography is driving advances in nanotechnology. When the feature size of materials is reduced to the nanoscale, individual atoms and molecules can be manipulated to dramatically alter material properties. However, the secondary electron blurring from extreme-ultraviolet photons hinders the creation patterns with a resolution below around 8 nm. An alternative approach is the use of matter waves which reaches much smaller wavelengths with a lower amount of kinetic energy. Lithography with metastable atoms has been suggested as a cost-effective, less-complex alternative to EUV lithography. In binary holography, a pattern of holes is used to approximate a Fourier transform of the desired target pattern [4]. This simple approach cannot be applied to matter-wave lithography with dielectric masks due to the additional dispersion forces. To overcome this issue, we will introduce a machine learning approach trained on the relation between mask design and interference pattern allowing an efficient estimation of a mask for a given target pattern [5]. This is of particular relevance for metastable atom lithography with binary holography masks, currently pursued in the FET-Open project Nanolace [6].

[1] C. Brand, *et al.* Ann. Phys. (Berlin) **527**, 580–591 (2015).
[2] N. Gack, *et al.* Phys. Rev. Lett. **125**, 050401 (2020).
[3] J. Fiedler, B. Holst, J. Phys. B: At. Mol. Opt. Phys. **55**, 025401 (2022).
[4] T. Nesse, I. Simonsen, B. Holst, Phys. Rev. Applied **11**, 024009 (2019).
[5] J. Fiedler, *et al.* in preparation.
[6] https://www.nanolace.eu/

T08

Composite pulses for atom interferometry

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The fidelity of atom interferometers that use laser pulses as their mirrors and beam-splitters can be severely limited by experimental realities. Doppler shifts, intensity inhomogeneities and stray fields can affect the Rabi frequency experienced by each atom and/or detune it from resonance. The resulting reduction in fringe visibility can limit read-out precision and prevent the use of extended pulse sequences for large momentum transfer. Happily, analogous problems have been solved by NMR spectroscopists through the use of composite pulses [1] and optimal control [2].

We have explored the design of a variety of high fidelity pulses for atom interferometry, and experimentally validated them using an atom interferometer based upon Raman transitions between the ground hyperfine states in ^{85}Rb. We have used gradient-based techniques to optimize π (mirror) and $\pi/2$ (beam-splitter) pulses for transfer efficiency and phase fidelity [3, 4]; designed pulses that track the separated velocity classes during large momentum transfer [5]; explored optimization of complete interferometer sequences for best fringe visibility and scale-factor stability [4, 6]; and investigated the dependence of the optimal solutions upon the target and optimization parameters. We have developed a perturbation theory method that links optimization to the interferometer's sensitivity function [7]; and shown that mirrors and beam-splitters can be optimized for interferometers in which the two 'arms' share the same electronic state [8]. For a 35 μK cloud, we have experimentally demonstrated a transfer efficiency increase from 75% to 99.8%, and shown that an efficiency of 90% can be achieved for detunings at which the conventional π-pulse transfers only 20%. The close agreement between experimental and simulated results has also allowed us to identify, characterize and correct modulation nonlinearities within our apparatus [9].

Our results, like some for NMR, show some intriguing features. Strong symmetry or anti-symmetry often emerges during optimization (such symmetries also allow certain errors to be corrected within sequences), and solutions sometimes show distinct phases reminiscent of early, simple composite pulses that were designed by hand. Investigation will involve parameterization of evolving ensemble distributions during the interferometer pulses, and holds the tantalizing prospect that computational optimizations could provide further insights into the mechanisms of quantum control.

[1] M H Levitt and R Freeman, J Magn Reson (1969) **43**, 502 (1981).
[2] N Khaneja *et al.*, J Magn Reson **172**, 296 (2005)
[3] J C Saywell *et al.*, Phys Rev A **98**, 023625 (2018).
[4] J C Saywell *et al.*, J Phys B **53** (8), 085006 (2020).
[5] J C Saywell *et al.*, Phys Rev A **101**, 063625 (2020).
[6] J C Saywell *et al.*, Proc SPIE **11881**, 83-92 (2021).
[7] N Dedes *et al.*, *in preparation* (2022).
[8] J C Saywell *et al.*, *submitted for publication* (2022).
[9] M Carey *et al.*, *in preparation* (2022).

T09

Towards a large spatial separation atom interferometer for geometrical phase measurements.

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Seminal experiments with electrons [1], neutrons [2] and atoms [3] have shown that matter wave interferometers provide remarkable tools for exploring geometric phases which are of great significance for the consistency of quantum physics. Recent experiments performed with ultra-cold atoms allow a macroscopic (cm-scale) spatial separation between the interferometer's arms. This specificity allows to shape electromagnetic and gravitational potentials, opening the way to new measurements in fundamental physics based on geometrical phase shifts.

We are developing a new atom interferometer using rubidium Bose-Einstein condensates manipulated with a vertical optical lattice. The presentation will focus on a characterization of the Large Momentum Transfert (LMT) Beam splitters based on sequential quasi-Bragg diffraction [4]. The apparatus will explore the potential of geometrical phases for metrology, in particular to push further the limit of the electrical neutrality of matter with Aharonov-Bohm effect. This setup will also contribute to the metrology of the new LMT-interferometers proposed in many tests of fundamental physics.

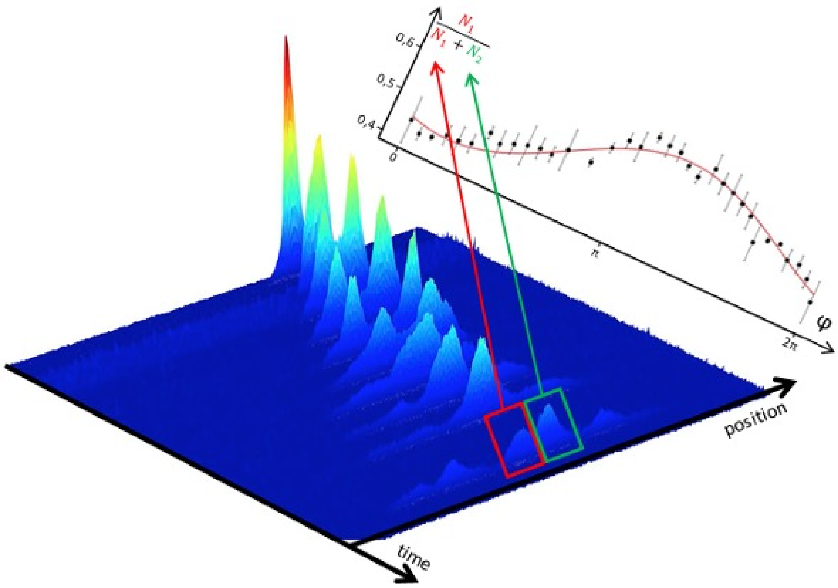

Figure 1: Fringes obtained with a 104 $\hbar k$ LMT-interferometer.

[1] M. Peshkin and A. Tonomura, Lecture Note in Physics **340**. Springer (1989).
[2] H. Rauch and S. A. Werner, Oxford university press (2000).
[3] S. Lepoutre, A. Gauguet, G. Trénec, M. Buchner, and J. Vigué, Phys. rev. Lett. **109**, 120404 (2012).
[4] A. Béguin, T. Rodzinka, J. Vigué, B. Allard, A. Gauguet, Phys. Rev. A **105**, 033302 (2022).

T10

Internal (Phonon) Decoherence and Interferometry with Nanoparticles

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Coherent splitting of massive objects has been a long sought-after goal of science. It is important not only for confirming quantum theory in extreme regimes, but also to gain insight at the interface of quantum mechanics and gravity, as well as to test exotic theories beyond the standard model [1, 2]. Here we discuss a new decoherence channel putting limits on the feasibility of such experiments. This type of decoherence may be called internal and arises when degrees of freedom internal to the object (phonons) are excited and may provide *Welcher Weg* information that precludes interference. As a specific example, we discuss the coherent splitting and recombining of a nanoparticle in a mesoscopic "closed-loop" Stern–Gerlach interferometer in which the observable is the spin of a single impurity embedded in the particle. This spin, when interacting with a pulsed magnetic gradient, generates the force on the particle and excites phonons in the lattice. We find that for a wide range of masses, forces, and temperatures, phonons do not inhibit Stern–Gerlach interferometry with micro-scale objects [3]. However, they do constitute a fundamental limit on the splitting of larger macroscopic objects, irrespective of the type of splitting, if the applied force induces phonons.

[1] C. Wan, M. Scala, G. Morley, A. Rahman, H. Ulbricht, J. Bateman, P. Barker, S. Bose, and M. Kim, Phys. Rev. Lett. **117**, 143003 (2016).
[2] C. Marletto and V. Vedral, Phys. Rev. Lett. **119**, 240402 (2017).
[3] C. Henkel, R. Folman, AVS Quant. Sci. **4**, 025602 (2022).

T11

Experimental observation of the Pendellösung effect for neutrons under low-coherence conditions

I. V. Masiello[1,2], **M. Fally**[2], **P. Geltenbort**[3], **C. Pruner**[4], **Y. Tomita**[5], **and J. Klepp** [2]

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We report on experimental observation of the Pendellösung interference effect for first and second order diffraction, using a low-coherence beam of slow neutrons (wavelength around 3.5 nm) and optically thin diffraction gratings (holographic nanoparticle-polymer composite gratings [1]) with 500 nm period.

We demonstrate the dependence of the effect on the grating thickness and confirm its wavelength-dependence qualitatively. In contrast to typical single-crystal diffraction experiments, multiple diffraction orders are observed for a given angle of incidence, so that a rigorous coupled-wave theory [2] is employed for the analysis. The latter theory allows access to the full information (amplitudes and phases) of the Fourier components of the grating profile as a by-product [3]. We give a short overview of potential applications in neutron interferometry and imaging.

[1] Y. Tomita, E. Hata, K. Momose, S. Takayama, X. Liu, K. Chikama, J. Klepp, C. Pruner, and M. Fally, Journal of Modern Optics **63**, 63(sup3):S1–S31 (2016).

[2] M. Moharam and T. Gaylord, JOSA **71**, 7:811–818 (1981).

[3] Martin Fally, Yasuo Tomita, Antonio Fimia, Roque F. Madrigal, Jinxin Guo, Joachim Kohlbrecher, and Jürgen Klepp, Opt. Express **29**, 16153-16163 (2021).

T12

Efficient atomic lensing of quantum gas mixtures

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Mixtures of ultracold quantum gases are at the heart of currently planned high-precision quantum tests of the weak equivalence principle, where dual-species Bose-Einstein condensates are probed with atom interferometry techniques. An important challenge for such experiments is to reach very low expansion velocities by means of time-dependent potentials acting as matter-wave lenses while ensuring the co-location of the two atomic species and matching their expansion rates during the whole free evolution. To achieve the required control, one lensing pulse is needed for each independent spatial direction and atomic species, which makes a full 3D implementation rather impractical.

Here we propose to overcome these challenges by taking advantage of special magic wavelengths for optical dipole traps where the ratio of the optical potentials is given by the ratio of the masses of the different species. In this case the center-of-mass dynamics is identical for all species, resulting in a perfect co-location of the mixture even in an Earth-based laboratory. Most importantly, optical dipole traps with such a magic laser wavelength give rise to a common expansion dynamics for both species and therefore guarantee that the relative shape of the mixture is conserved during the entire evolution, including when the lensing potentials are applied. Hence, our approach enables an efficient collimation of mixtures of ultracold atoms in order to reach the very low expansion rates that are necessary for high-precision measurements while cutting in half the number of required lensing pulses compared to standard approaches.

T13

Fractional angular momentum quantization in Atomtronic circuits

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Bosonic systems guided in a ring-shaped atomtronic circuit present quantized values of the winding number. In this talk, I will show cases for which fractional values of winding number quantization occurs. First I will consider attracting bosonic systems [1, 2, 3]. Then, I will discuss fermionic systems with N components that present SU(N) symmetry [4, 5, 6]. For repulsive interactions a specific emerging phenomenon of attraction from repulsion appears, providing a quantization with similar properties to the attracting boson case. For attractive interactions, the quantization is determined by the number of components N.

[1] P. Naldesi, J. Polo, V. Dunjko, H. Perrin, M. Olshanii, L. Amico, and A. Minguzzi, SciPost Physics 12, 138 (2022).
[2] J. Polo, P. Naldesi, A. Minguzzi, and L. Amico, Physical Review A 101, 043418 (2020).
[3] J. Polo, P. Naldesi, A. Minguzzi, and L. Amico, Quantum Science and Technology 7, 015015 (2021).
[4] W. J. Chetcuti, T. Haug, L.-C. Kwek, and L. Amico, SciPost Physics 12, 33 (2022).
[5] W. J. Chetcuti, J. Polo, A. Osterloh, P. Castorina, and L. Amico, arXiv:2112.06950 (2021).
[6] W. J. Chetcuti, A. Osterloh, L. Amico, J. Polo arXiv:2206.02807 (2022).

T14

Very Long Baseline Atom Interferometry

Vishu Gupta[1] , Ali Lezeik[1] , Christian Meiners[1] , Constantin Stojkovic[1] , Dorothee Tell [2] , Klaus Zipfel[1] , Christian Schubert[1,2] , Ernst M. Rasel[1] , Dennis Schlippert[1]

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Very Long Baseline Atom Interferometry (VLBAI) enables ground-based atomic matter-wave interferometry on large scales in space and time. By letting atomic wave functions interfere after free evolution times of several seconds or wave packet separation at the scale of meters, these devices benefit from significantly enhanced sensitivity to inertial forces thanks to the quadratic scaling of the leading order phase shift with the free evolution time.

With shot noise-limited instabilities better than 10^{-9} m/s^2 at 1 s at the horizon [1], the Hannover VLBAI facility may compete with state-of-the-art superconducting gravimeters, while providing absolute instead of relative gravity measurements. Operated with rubidium and ytterbium simultaneously, tests of the universality of free fall at a level of parts in 10^{13} and beyond are in reach [2]. Finally, the large spatial extent of the interferometer allows one to probe the limits of coherence at macroscopic scales [3,4] as well as the interplay of quantum mechanics and gravity [5]. We report on the status of the VLBAI facility and its key features - the high-flux atomic sources for Rb and Yb and small-scale interferometry, the 10 m magnetic shield, and the low-noise seismic attenuation system. We discuss the prospects of tests of fundamental physics in the VLBAI facility.

[1] D. Schlippert, C. Meiners, R.J. Rengelink, C. Schubert, D. Tell, E. Wodey, K.H. Zipfel, W. Ertmer, and E. M. Rasel, Presented at the Eighth Meeting on CPT and Lorentz Symmetry, Bloomington, Indiana, May 12-16, 2019 (2020).

[2] J. Hartwig, S. Abend, C. Schubert, D. Schlippert, H. Ahlers, K. Posso-Trujillo, N. Gaaloul, W. Ertmer, and E. M. Rasel, , New J. Phys. **17**, 035011 (2015).

[3] T. Kovachy, P. Asenbaum, C. Overstreet, C. A. Donnelly, S. M. Dickerson, A. Sugarbaker, J. M. Hogan, and M. A. Kasevich, Nature **528**, 530–533 (2015).

[4] Björn Schrinski, Klaus Hornberger, Stefan Nimmrichter, arXiv:2008.13580 (2020).

[5] A. Roura, C. Schubert, D. Schlippert, and E. M. Rasel, Phys. Rev. D **104**, 084001 (2021).

T15

Conformer selection and enantiomer superpositions from matter-wave interference

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Molecular matter-wave interferometry enables novel strategies for manipulating the mechanical motion of complex molecules [1]. In this presentation, I will argue how chiral molecules can be prepared in a quantum superposition of two enantiomers by far-field matter-wave diffraction and how the resulting tunnelling dynamics can be observed [2]. I will discuss the impact of ro-vibrational phase averaging and propose a setup for sensing enantiomer-dependent forces and environment-induced superselection of handedness.

[1] C. Brand, B. A. Stickler, C. Knobloch, A. Shayeghi, K. Hornberger, and M. Arndt, Conformer-selection by matter-wave interference, Phys. Rev. Lett. **121**, 173002 (2018).
[2] B. A. Stickler, M. Diekmann, R. Berger, D. Wang, Enantiomer superpositions from matter-wave interference of chiral molecules, Phys. Rev. X **11**, 031056 (2021).

T16

Observation of the Einstein-Podolsky-Rosen paradox between two Bose-Einstein condensates

We experimentally demonstrate the famous paradox of Einstein, Podolsky, and Rosen with two spatially separated BECs. We first prepare a single two-component BEC of about 1400 ^{87}Rb atoms whose spin degree of freedom is entangled by collisional interactions in a collective spin squeezed state. Using coherent spin manipulation we split this entangled many-particle state into two halves in spin space and magnetic field gradients allow us to separate the two two-component BECs spatially by more than 15 μm. Our technique allows us to individually address the collective spin of the two BECs thereby realizing arbitrary spin measurements on the two systems. Their correlations allow to infer measurement results of non-commuting spin observables in one system from measurements on the other, with an inferred uncertainty product below the Heisenberg bound. This realizes the paradox envisioned by EPR for two massive many-particle systems. Our experiments pave the way for investigations in quantum technologies which are explicitly based on EPR entanglement such as quantum key distribution and quantum teleportation and for applications such as quantum metrology with these systems.