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Exploring quantum gases for space-borne interferometry

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ABSTRACT

Ultra-cold quantum gases in space promise to boost the sensitivity of matter-wave interferometers. Applications of the latter extend from fundamental physics over the use in navigation to interdisciplinary applications such as geodesy, e.g. satellite gravimetry [1, 2]. Exploiting quantum gases for high-precision interferometry places high demands on their control and manipulation. We take benefit of various microgravity platforms such as the Bremen drop tower [3], the Einstein elevator in Hannover [4], sounding rockets [5,6] and the international space station [7] to advance the necessary methods. The DLR-mission MAIUS-1 demonstrated Bose-Einstein condensation and performed first interferometry experiments [4]. NASA's Cold Atom Laboratory continues this research in orbit on the ISS [7]. In addition, atom interferometry is pursued in highly dynamic environments such as parabolic flights [8].

Starting from a rubidium Bose-Einstein condensate, recently lowest expansion energies have been achieved by us in the Bremen drop tower as required for extending atom interferometry over several seconds [9]. Extending these methods to quantum mixtures not only opens up new physics in the absence of buoyancy, but also faces challenges regarding their use for interferometry. Interferometers based on two chemical elements have been proposed for quantum tests of the equivalence principle on the ISS as well as on satellites. Currently we prepare a sounding rocket mission to investigate the simultaneous generation and manipulation of potassium and rubidium condensates [10]. Together with CAL [7], these experiments will prepare the DLR-NASA multi-user facility BECCAL for research on quantum gas mixtures and interferometry [11] as well as enhance the readiness level of methods required for STE-QUEST [12], a proposal for a satellite mission currently studied in an modified version within ESA's VOYAGE 2050 program [13].

Keywords: cold atoms, atom interferometry, gravity, quantum sensors, space geodesy

1. INTRODUCTION

1.1. Space-borne Atom Interferometry

Light-pulse atom interferometry became a central pillar of quantum technology and, in particular, of quantum sensing. Benefitting from the precise manipulation of atoms with laser light, these interferometers promise a large gain both in sensitivity and accuracy and are pursued for metrology as well as for inertial sensing e.g. measurement of accelerations. Among others, fields of application include gravimetry, observation of the Earth rotation, navigation and fundamental physics [2]. The latter covers experiments for performing stringent quantum tests of the equivalence principle, for explaining the nature of dark matter and energy as well as for observing gravitational waves in the infrasound frequency domain [1]. These applications place the highest demands on the performance of atom interferometers and are a strong motivation for the development of new methods.

Regarding inertial sensing, the sensitivity of atom interferometers ideally scales with the space-time area enclosed by the interferometer, which depends on the momentum transferred by the atom-light interactions creating the interferometer as well as on the square of the time the atoms freely fall in the interferometer. On ground, the free-fall time drives the height of the interferometer and, apart from special very-long-baseline-interferometers, usually stays below a second. In orbit, these times can be ideally extended over several seconds. Indeed, most ambitious proposals envision times of several ten to even hundreds of seconds [1].

1.2. Extending the interferometry time

In space, new limitations appear to increase the performance of atom interferometers such as the expansion rate of the atom ensemble as well as the relative atomic velocity transferred when coherently splitting the atomic ensemble. The expansion can lead to large and dilute ensembles, which can be hardly detected or are subject to undesired external influences such as gravity gradients or rotations leading to dephasing in the interferometer. For typical applications, the ensemble size at the interferometry ports should fall below hundred micrometers. Depending on the interferometry time, this requirement translates to atomic expansion rates less than few tens of micrometers per second.

With few remarkable exceptions, such as degenerate Raman side band cooling or narrow line cooling, standard laser cooling techniques allow to reach ensemble temperatures as low as fractions of microkelvins, combined with evaporative cooling even temperatures fractions of a nanoKelvin has been demonstrated. Considering Rubidium atoms, one of the workhorses in atom interferometry, those methods are not sufficient to achieve the desired low expansion rates. Indeed, one seeks for expansion energies corresponding to few ten picokelvins.

We explore as a promising route Rubidium Bose-Einstein condensates for reaching this regime of ultra-low expansion. Compared to thermal atomic ensembles, Bose-Einstein condensates occupying the ground state of an atomic trap feature a nice, compact spatial mode typically below ten micrometers in extension. However, when released in free fall, the atomic ensembles spread out due to their repulsive interaction leading to considerable kinetic expansion energies. The point-source-like mode of the Bose-Einstein condensate, however, allows to exploit delta-kick cooling or collimation of the expanding ensembles such that this energy is strongly reduced [14,15,16]. Compared to the expansion of a thermal atomic ensemble, which depends on its temperature, the expansion of the collimated Bose-Einstein condensates can reach few tens of picokelvins or less.

While the free evolution of a single quantum gas already is dominated by the atomic interactions, new phenomena arise in mixtures of quantum gases. In this case, buoyancy may lead in gravity to a layering or separation of the quantum gases [17] and breaks the symmetry, its absence in free fall makes the intra- or inter species interactions of the individual quantum gases prevail and, hence, have to be considered when employing quantum gas mixtures for interferometry, e.g. when performing a quantum test of the equivalence principle starting with mixtures of Bose-Einstein condensates as proposed for STE-QUEST.

1.3. Microgravity platforms

The development and demonstration of the feasibility of the required methods manipulating single-component or mixtures of quantum gases requires operation in extended free-fall, i.e. under microgravity conditions. While parabolic flights provide extended free-fall times of about 20s in rather dynamic environment, drop towers or sounding rockets allow to operate in microgravity. The presented experiments exploit two strategies to extend interferometry with Bose-Einstein condensates to space.

i) Methods necessary for lowering the expansion of a Bose-Einstein condensate to an equivalent temperature of few tens of pikokelvins have been explored in the Bremen drop tower, which offers two modes of operations, simple release from the top of the tower or a catapult launch from the bottom. The latter allows ideally to double the free fall time from 4.7s to 9.2s. For our current experiments on reaching an ultra-low expansion, we exploited the drop mode.

ii) For the experiments on quantum mixtures, we are preparing a sounding rocket mission exploiting a VSB30 rocket with a two-stage booster [10]. Depending on the mass of the payload, the latter allows up to six minutes of space operation. The short time in space requires fast succession rate of the experiments and a predetermined experimental sequence.

Moreover, on ground, new opportunities for extended free-fall experiments in microgravity, with high repetition rates arise due to the development of elevators such as the Einstein Elevator in Hannover or the Bremen gravitower. In future, they will allow experiments with a large succession rate.

Last but not least, NASA's cold atom laboratory (CAL) [7] and the NASA-DLR Bose-Einstein-condensate/cold-atom laboratory (BECCAL) [11], currently in implementation, open up exciting opportunities to continue the presents experiments in future making the exploration of an even wider parameter range possible.

2. GENERATING BOSE-EINSTEIN CONDENSATES WITH ULTRA-LOW EXPANSION RATES

2.1. Collective mode-enhanced matter-wave optics

In free-fall, the unique mode-features of a Bose-Einstein condensate are compromised by the interactions, which accelerate the expansion of the ensemble and limits its advantages for interferometry. So far, delta-kicks exerted by conservative potentials based on electro-magnetic interactions of the atoms have been exploited to reduce the expansion velocity after the interaction energy has been converted to kinetic energy. In order to achieve this, the potential is briefly applied to the expanded ensemble. In this way, equivalent temperatures as low as 50pK have been so far achieved in two dimensions.

Even lower expansions in all three dimensions corresponding to 38pK have been demonstrated in our experiments on an atom chip.i Atom chips allow the reliable and fast production of Bose-Einstein condensates in compact and robust set-ups. They offer planar wire structures for generating the inhomogeneous magnetic fields for trapping atoms close by such that evaporative cooling is very effective and fast. However, due to the wire arrangement, the magnetic traps have generally a cylindrical geometry. Collimation with a magnetic delta-kick generated by an atom chip is therefore intrinsic asymmetric.

Therefore, we employ the excitation of collective modes together with a magnetic lens [9]. The combination of both methods allows to compensate for the asymmetry inherent to the potential generated by the atom chip. With our method we have a tool at hand forming a time-domain matter-wave lens system to control the expansion in all three dimensions. Moreover, by releasing the Bose-Einstein condensate at a specific phase of the oscillation, we are able to adjust the focus of the lens.

2.2. Experimental facility

Our time-domain matter-wave lens-system has been developed and tested in the 146m-tall Bremen drop tower. The experiments have been performed with a high-flux source generating Bose-Einstein condensates containing about hundred-thousand atoms in a cylindric shaped Ioffe-Pritchard trap [18]. Out of a cold atomic beam, atoms are trapped by magneto-optical cooling on the chip and transferred to the magnetic trap for evaporation to achieve quantum degeneracy.

Collective oscillations are excited by quickly changing trap parameters. The quadrupole mode is induced by changing the magnetic field in away that mainly the two axes of the trap with higher frequencies are affected. After an appropriate holding time, i.e. at the desired phase of the oscillation, the Bose-Einstein condensate is released and expands for 80ms. During this time the interaction energy is converted into kinetic energy resulting in an asymmetric expansion. Hereafter, the kinetic energy is reduced by a magnetic delta-kick acting as cylindrical lens. Thanks to the quadrupole oscillation, we are able to minimize the expansion along the axis where the cylindrical lens is weakest. The expansion is analyzed after variable flight-time of up to two seconds by absorption imaging with two CCD cameras providing information about all three spatial dimensions.

2.3. Evolution of a simple release, a delta-kick collimated and a collective-mode enhanced collimated Bose-Einstein condensate

In order to demonstrate the benefits of our time-domain matter-wave lens system, we compare the evolution of the atomic ensemble for the case of an immediate release after production of the Bose-Einstein condensate i) without and ii) with collimation of a magnetic lens and iii) when employing our lens system based on exciting the collective oscillation in the trap. Minimal expansion rates have been achieved by optimizing the hold time before release of the Bose-Einstein condensate and, hereafter, applying a magnetic lens. The expansion of the atomic ensemble is recorded for all three cases in experiments with varying time-of-flights with the two CCD cameras. The drop tower allows to follow the evolution of up two seconds. While the simple release of the Bose-Einstein condensates results in an ensemble with an expansion corresponding to a temperature of 2 nK, the collimation of the condensate with a magnetic lens already reduces the temperature to 167 pK. However, exploiting both the collective oscillation and the magnetic lens together, allows to further lower the expansion rate in three dimensions equivalent to a thermal temperature of 38 pK.

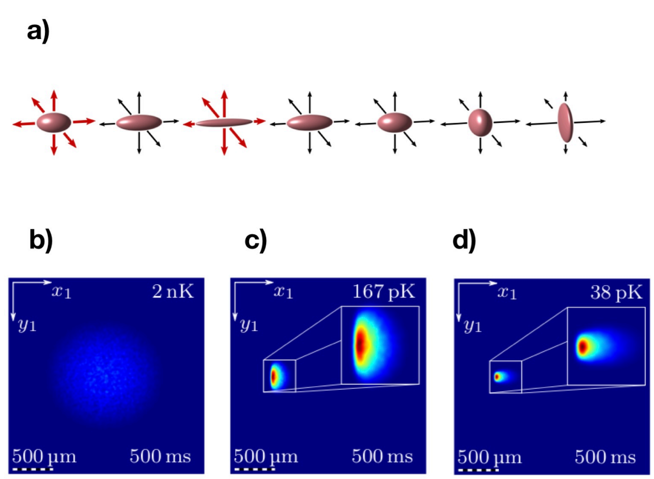

Figure 1: a) Visualisation of the shape of a Bose-Einstein condensate in dependence of the hold time before its release out of the trap. The arrows represents the direction and rate of expansion of the condensate along the three axes. The red arrows indicate the cases studied in the experiment and correspond to a vanishing hold time as well as for the situation where the expansion along the weak axis of the magnetic trap is minimised. b), c) and d) show the extension of the Bose-Einstein condensate after an expansion of 500 ms for a release without and with a delta-kick collimation and for our time-domain lens system combining the quadrupole mode oscillation with a delta-kick, respectively.

The residual interaction energy amounts to approximately 26 pK. Hence, further reduction of the expansion rate could be achieved by extending the expansion previous the magnetic lens. However, this is compromised by deviations of the magnetic potential from a pure parabolic shape acting as lens errors appearing already in Fig.1 . Noting the minimal atomic densities observable with our detection noise ($3 \cdot 10^7$ atoms/shot), the evolution of an atomic ensemble can be followed in our system up to about 17 s, which is largely beyond the duration of a drop or parabolic free fall after a catapult launch. Exploiting such an ensemble for a double Bragg Mach-Zehnder interferometer, our current detection sensitivity sets an upper bound of six seconds for the time atoms can spend in the interferometer.

3. TOWARDS SPACE-BORNE TWO-SPECIES INTERFEROMETRY

Mixtures of quantum gases are studied for a wide range of phenomena emerging due to the inter-species interaction as well as for research on quantum gas chemistry and long-range interactions of molecules. In our experiments, we employ bosonic rubidium ^{87}Rb as well as potassium ^{41}K, which are a promising combination for a future quantum test of the Einstein equivalence principle as proposed for STE-QUEST. Indeed, the latter is based on atom interferometry using Bose-Einstein condensates of these two chemical elements.

On ground, layering of the two trapped components has been observed as well as the influence of the interspecies interactions during the free evolution. In space, buoyancy is absent and, hence, the atomic interactions prevail and can lead to shell-like structures, where ideally the ensemble of Rubidium atoms is nested inside the one of Potassium atoms. In space, these phenomena can be studied in a clean environment, moreover, the dynamics induced by the interactions have to be taken into account and tailored for the state preparation before interferometry. Actually, this is of particular importance for quantum tests of the equivalence principle, where a precise superposition of the mixture is important in order to suppress the influence of spurious differential forces e.g. due to gravity gradients.

3.1. Instrument description

The sounding rocket mission MAIUS-2 builds on the heritage of the first MAIUS sounding rocket campaign [], which was based on a high-flux source for Rubidium Bose-Einstein condensates employing a three-layered atom chip loaded from a cold atomic beam and diode lasers for all light-based manipulations. The payload concept was already successfully tested both in release and catapult experiments in the Bremen tower [18]. The source can generate Bose-Einstein condensates of hundred thousand atoms within one second. Even faster production cycles of 800ms are possible, albeit with considerable lower atom number, the maximum atom number of $5 \cdot 10^5$ was achieved by stretching the sequence of evaporation to 1.5s. Adding the generation of potassium Bose-Einstein condensates not only extends largely the functionalities of the set-up, but also requires the integration of additional laser systems and control electronics. Moreover, the new payload allows to perform synchronous operation of Double Raman diffraction with both species. Last but not least, an optical dipole trap is foreseen to tune the two-species interactions [10]. Despite the addition of the functionalities for the second species, the payload can be still carried by a VSB30 rocket. In order to maximise the time for experiments between five to six minutes, the payload mass has not to exceed 330 kg and fit into a cylindrical volume of 0.5m times 3m in diameter and length.

3.2. Performance analysis of atom-chip experiments

Parallel to the development of the flight components including lasers, electronics and software, the high-flux atom-chip set-up of the flight module has been subject of intensive testing with ground equipment. The measurements show that atom-chips allow for a fast production of mixtures of condensates by sympathetic cooling of potassium with rubidium, which is evaporatively cooling employing microwave radiation. With the apparatus we could generate within 3.4s single condensates of rubidium or potassium with a maximum number of three hundred thousand or sixty thousand atoms respectively, which sets the limits for the maximum atom numbers in mixtures of both species. On ground, we observe the free evolution where both species are separated which indicates layering due to gravity.

Apart from optimization of the atom number, the source is currently used to implement the necessary techniques required for state preparation such as transport of the mixtures away from the chip, transfer to the non-magnetic states as well as release for performing Raman double diffraction.

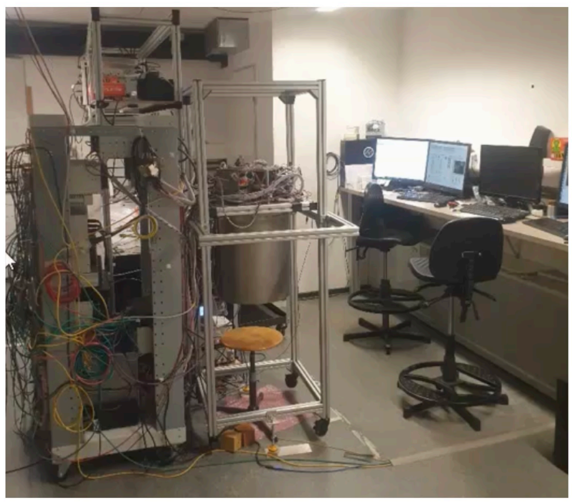

Figure 2: Picture of the physics package of the flight payload of the MAIUS-2 sounding rocket mission serving for functional tests performed with test hardware of lasers and electronics. The physics package is covered by a three-layered cylindrical magnetic shield.

3.3. Planned flight experiments

Currently, the MAIUS sounding-rocket program comprises three space flights. While the first space flight early 2017 served to demonstrate and study the generation and manipulation of rubidium Bose-Einstein condensates as well as of their spatial coherence via Bragg interferometry [5,6], the second and third campaign will serve the generation and manipulation of mixtures of rubidium and potassium condensates and the first space-borne demonstration of Raman double diffraction [19] with both species respectively. For the second and third MAIUS mission a new flight hardware was designed building on the experiences of the MAIUS-1 campaign. As, in the latter case, the apparatus was still operational after parachute-assisted landing of the rocket, it was decided perform the next two space flights with the same payload.

Thanks to miniaturization efforts and reduction of the payload mass the duration of the space flight will last about six minutes. Taking advantage of the relatively short production time for mixtures [10], one can envision of up to hundred experimental cycles during each mission. Nevertheless, the limited number of experiments requires a careful planning of the experimental sequence and extensive theoretical simulations. During the MAIUS-2 mission, targeting a launch in 2023, i) sympathetic cooling of potassium with rubidium will be compared with ground performance of the apparatus. Moreover, ii) transport of mixtures on the atom chip as an important step of the state preparation for interferometry will be investigated in the absence of gravitational sag. The focus is here in particular optimal transport in the presence of the interspecies interactions. This is combined with iii) an analysis of the dynamics due to the release out of the trap and the free evolution which will give insight in the ground state and the dynamics of the trapped mixtures as well as in the impact of the atomic interactions. iiii) The generation of the non-magnetic states of both potassium and rubidium will prepare v) first experiments on Raman double diffraction [19]. However, synchronous interferometry will be the main focus of the third MAIUS-mission.

CONCLUSION

The paper reports on two experimental activities developing methods for space-borne high-precision interferometry. In the Bremen drop tower we demonstrated atomic ensembles with so far the lowest expansion energies corresponding to 38pK [9]. The latter is about five orders of magnitude less than what can be achieved with standard molasses cooling and below the requirements stated in various proposals proposing quantum accelerometers for satellite gravimetry. Combined with a reduction of the current detection noise, the parameters should also allow to reach the necessary interferometry times of up to ten seconds. Future experiments in the Bremen tower will aim to extend the interferometry times approaching the ones for envisioned for space and to investigate the spatial coherence of the atomic ensemble in dependence of the interferometry time. These results will be important for space mission based on Bose-Einstein condensates such as the planned CARIOQA mission [1].

Moreover, within the MAIUS sounding rocket program, we prepare a mission to generate, manipulate and study quantum mixtures as well as to exploit them for dual interferometry based on Raman double diffraction. These experiments will pave the way for implementing ambitious space missions as STE-QUEST proposed within the VOYAGE 2050 program [13].

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