Topical: Exploring tunneling physics with interacting quantum gases in microgravity

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Abstract. While in classical physics particles reflect from barriers, quantum theory allows them to tunnel through such classically forbidden regions. Tunneling is a purely quantum effect and at the heart of diverse phenomena in physics, chemistry, and biology. In addition to advances in atomic sources and the generation of optical potentials, microgravity facilitates experimental studies of tunneling of interacting quantum gases in unique regimes and timescales. We outline a program for spaceborne tunneling accelerometers as well as fundamental studies of synthetic gauge fields, Maxwell's demons, and black holes.

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Introduction. Tunneling is one of the most important quantum effects. It is the basis an extremely broad class of phenomena: alpha decay, ionization of atoms and molecules by strong laser fields [1], transport effects in condensed matter [2], single- and two-proton tunneling in large molecules [3], semiconductor technology [4], Josephson junctions [5], scanning tunneling microscopy [6], Hawking radiation from black holes [7], nuclear fusion and formation of low mass stars [8], and more. The role of tunneling in biochemical processes is one of the fundamental questions addressed in the burgeoning field of quantum biology [9]. Moreover, it is speculated in quantum cosmology that the universe may have tunneled into existence out of nothingness [10].

Physics of tunneling is incredibly rich [11] and goes far beyond the famous semi-classical formula predicting that tunneling probability in one-dimensional systems is exponentially small. When more than one degree of freedom is involved, this intuition no longer works. For example, interactions between different parts of a complex system may enhance or suppress tunneling rates compared to the case of no interactions [12]. There is an emergent dynamical asymmetry in tunneling of a composite system [13]. Tunneling through a barrier may be more likely than flying above it for a large class of potentials [14]. Tunneling of diatomic [15, 16] and polyatomic [17, 18] molecules has also been investigated. In recent years, experimental advances in the technology of Bose-Einstein condensation enabled direct observations of tunneling of complex systems [5, 19, 20].

Moreover, tunneling plays a dominant role in defining transport properties of solid state and nano systems. For example, electron transport in disordered systems is dominated by thermally assisted and resonant tunneling [21, 22]. Interband tunneling in graphen and other two-dimensional materials has also been observed [23, 24]. In nanoscale systems, electrons transport charge through junctions and contacts via tunneling [4, 5, 25–29]. Hence, tunneling puts fundamental bounds on ongoing miniaturization of transistors, fueling the celebrated Moore's law, because transistors' functionality is disrupted by tunneling of electrons through gates.

The above reviewed works mainly focus on closed quantum systems, whose evolution is unitary and described by the Schrödinger equation. Additionally, a tunneling particle may also interact with a larger external system, usually called environment, bath or thermostat. Such dynamics is described by the theory of open quantum systems [30, 31], where a master equation for the quantum particle gives rise to a non-unitary evolution and is derived by averaging out the bath. A common situation is that the coupling of a tunneling particle to an environment induces decoherence. This process leads to the emergence of the classical evolution, thereby halting tunneling. However, there are scenarios when a particle can extract additional kinetic energy from an environment giving rise to an enhancement of tunneling rates [32–35]. An aspect of environmentally-assisted tunneling has been experimentally demonstrated in lithium niobate [36]. It has been predicted [37–39] that the momentum kick acquired by an atom when spontaneously emitting a photon facilities tunneling through a trapping potential. In this process, tunneling enhancement is achieved by sacrificing quantum purity. However, there is an alternative mechanism [40] capable of not only achieving a near unity tunneling probability, but also leaving the quantum purity almost unchanged.

The aim of the current topical white paper is to propose an unprecedented experimental study of tunneling physics by utilizing microgravity environment enabling a fine control of all relevant physical parameters. In particular, we propose to investigate novel tunneling phenomena that may lead to a new generation of quantum metrology for navigation and tachyometry.

Asymmetric Tunneling for Synthetic Gauge Fields, Maxwell's Demons, and Black Holes. Gauge fields are the building blocks of the Standard Model. The unique physics of gauge interactions have opened new horizons in topological quantum matter and technology, attracting a significant effort to engineer gauge fields in the laboratory [41, 42]. Bose-Einstein condensates (BECs) are considered to be a leading platform in this pursuit. Experimentally realizing these fields is technically challenging, requiring multi-step processes, high strength magnetic fields, lasers, and even complex methods used to suppress natural quantum effects such as tunneling [41]. It is currently believed that gauge fields cannot be produced solely through tunneling since they require the introduction of phase differences through looping gates. However, this intuition is misleading because tunnelling dynamics can become asymmetric [13, 14, 43].

Let us give the concept behind asymmetric tunneling using an example of a two particle system[1]. Recall that the dynamics generated by a time-independent Hamiltonian conserves the total energy. To understand the underlying physics of the two particle system, it is convenient to describe it using the center of mass and interparticle *degree of freedom* (d.o.f.) A tunneling barrier couples these two d.o.f. Consider a triangular potential barrier as depicted in Fig. 1. Assume that the interparticle d.o.f. is initially in the lowest energy (i.e., ground) state when the wave packet approaches the slanted side of the potential barrier, shown in Fig. 1(a). As the system moves from the left to right, the potential barrier gradually increases. According to the adiabatic theorem, the interparticle d.o.f. will not be excited. Hence, the tunneling dynamics of the two-particle system effectively resembles the one-dimensional case since the interparticle d.o.f. is frozen. A very different dynamical process takes place when the wave packet approaches the vertical side of the triangular barrier, as shown in Fig. 1(b). Upon colliding with the edge of the barrier, the interparticle d.o.f. experiences a sudden shakeup, which induces a change of state. Since the interparticle d.o.f. is originally in the ground state, the only allowed transition is to the excited state. The total energy, which is the sum of the center-of-mass and interparticle energies, is conserved, hence the excitation takes place by decreasing the center-of-mass kinetic energy. As a result, the center-of-mass d.o.f. effectively plunges deeper under the potential barrier, depicted in Fig. 1(b). The gray shaded regions in Figs. 1(a, b) denote the areas which are related to the tunneling probability according to the semi-classical formula [44]. Thus, we achieve asymmetric tunneling since the probability of tunneling from left to right [Fig. 1(a)] is larger in the opposite direction [Fig. 1(b)]. This phenomenon has also been recently computationally established for BECs [43].

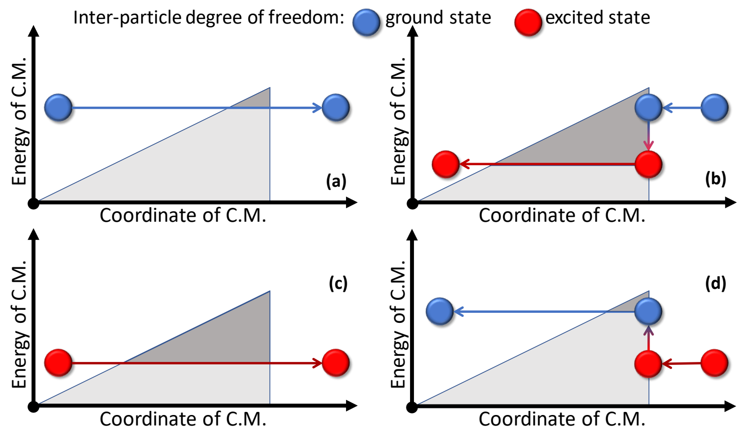

Figure 1: Principle of asymmetric tunneling

The complexity of the current experimental setups realizing synthetic gauge fields results from the assumption that tunneling is symmetric [41, 42]. The presented asymmetric tunneling dynamics [43] suggests a much simpler implementation: *At the bottom of a deep ring-shaped trap,*

[1]Note that within the Schrödinger equation, tunnelling dynamics is symmetric for a single one-dimensional particle interacting with an arbitrary potential [43, 44].

arrange several triangular barriers while preserving their orientation, such that the vertical side of one triangular barrier abuts the slanted side of the next triangle. Such a trap should exhibit a strong left-right asymmetry in the tunneling probability, inducing a chiral motion into the BEC. This is a signature of synthetic gauge fields, with the chiral current appearing as if it were induced by a magnetic field.

The triangular potential barrier also acts as a Maxwell's demon since the induced tunneling dynamics is sensitive to the state of the interparticle d.o.f. As discussed above, the left-to-right tunneling probability [see Fig. 1(a)] is smaller than the opposite direction [see Fig. 1(b)] when the interparticle d.o.f. is initially in the ground state. This asymmetry is reversed when the system is initially in the exited state. If the excited interparticle d.o.f. hits the vertical side of the barrier [see Fig. 1(d)], the resulting shakeup forces a state transition to the ground state. The energy difference will be transferred to the kinetic energy of the center of mass in order to preserve the total energy, hence the system will be able to fly above the barrier as shown in Fig. 1(d). Comparing Figs. 1(a) and 1(c), we conclude that if the wavepacket is initially placed on the left side of the barrier, transport rates across the barrier are insensitive to the initial state of the interparticle d.o.f. Conversely, the transport rates shown in Figs. 1(b) and 1(d), are very sensitive to the state of the interparticle d.o.f. In this case *it is much more likely for a system initially in the excited state to cross the barrier than for the system is the ground state. Hence, the triangular barrier with the vertical side facing the wavepacket acts as Maxwell's demon.*

Additionally, a black hole analogue in BECs may also be created by asymmetric tunneling overlying self-trapping: Recall that when a wave packet is placed on one side of a symmetric double well potential, the Schrödinger equation predicts recurrent oscillatory tunneling between the two wells. However, for sufficiently strong interparticle interactions, a BEC placed on one side of the symmetric double well potential will remain trapped. This phenomenon is known as self-trapping [5]. It should be possible to find an asymmetric double well barrier such that a condensate placed in one well is able to tunnel to the other, but not be able to tunnel back.

Self-trapping and asymmetric tunneling can be seen as two complementary phenomena. Self-trapping reveals asymmetric dynamics of BECs even in a symmetric potential; hence, it is natural to expect asymmetric tunneling through a non-symmetric barrier.

A microgravity environment offers the unique possibility to experimentally test and capitalize on the physics of asymmetric tunneling. Not only does microgravity provide unprecedented low-energy atom sources to minimize the energy distribution of the atoms impinging on a barrier but, in ground based experiments, the gravitational force induces an additional asymmetry that is expected to overwhelm the desired effect.

Tunneling accelerometry. Interferometric experiments [45–47] with macroscopic matter waves such as BECs [48] pave the way to a new generation of quantum sensors for inertial forces [49]. Besides their application to navigation [49–51] and Earth observation [52], they provide a new and promising avenue to probe yet unknown physics [53, 54] and shed light on fundamental aspects of current physical theories [55–61]. This development has triggered major efforts to study sensors in unique environments and in microgravity conditions [62–67], or to construct large-scale facilities [68–71]. Today's state-of-the-art sensors are mostly based on the diffraction of atoms from periodic optical potentials [45, 46]. In contrast, quantum tunneling provides an additional, yet unused, leverage point to exploit the quantum nature of matter waves in sensing applications. Tunneling is an effect inherent to the external motion of matter waves [72]. Because accelerations and forces are also acting on the very same d.o.f., there is a natural and intrinsic link between tunneling and sensors of inertial forces. Moreover, the combination of tunneling with the superposition properties of coherent matter waves brings tunneling-based Fabry-Pérot interferometers into reach [73, 74].

The transmission spectrum of an optical cavity formed by two mirrors of finite transmittance depends on the cavity geometry and the wavelength of the incident light due to the repeated interference of the light bouncing back and forth inside the cavity. The resulting structure of such Fabry-Pérot interferometers is routinely used as a filter and monochromator. While matter-wave interferometers reverse the role of matter and light by using optical potentials as mirrors and the wave nature of quantum gases for interference effects, the working principle of a Fabry-Pérot interferometer remains unchanged. In matter-wave cavities quantum tunneling [75] and self-interference inside the cavity causes the emergence of sharp resonances for specific momenta of the quantum gas [74], whereas optical Fabry-Pérot cavities filter the wavelengths of light. However, in contrast to light, the external motion of atoms also couples to forces like gravity, but also to rotations and other accelerations. As such, matter-wave Fabry-Pérot interferometers are susceptible to these effects and can be used as accelerometers, in addition to existing approaches towards quantum sensing with light-pulse atom interferometry [45].

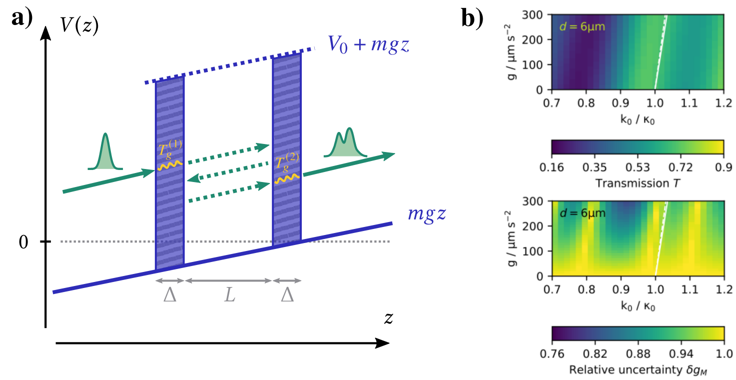

Figure 2: (a) Transmission through a matter-wave Fabry-Pérot cavity. (b) Sensitivity study of a gravity sensor [2].

Microgravity environments are of particular use to study the behavior of tunneling accelerometers, as they allow for ultra-long evolution times of matter waves in regimes inaccessible to on-ground experiments. One key aspect is the wave packet's decreased density impinging on the cavity, where nonlinear interactions are suppressed. However, interatomic scattering [72] inside the cavity might still play a crucial role for the dynamics. Moreover, the long timescales available in microgravity allow for the study of time-resolved wave-packet tunneling; and since atoms possess an internal structure that can be utilized as an atomic clock, these systems might shine more light onto the role of time for tunneling processes [20, 76] and the possible asymmetries in tunneling [13, 14]. Therefore, tunneling accelerometers can complement existing or planned matter-wave quantum sensors for Earth observation, navigation, and fundamental physics. As such, they are of relevance for the Fundamental Physics programs but also could provide enhanced performance for gravitational science as well as Position, Navigation, and Timing capabilities.

Realization of potentials. The experiments described above require highly flexible and tunable potentials with high spatial resolution. To this end, with their intrinsic versatility time-averaged optical potentials realized using acousto-optical elements are a suitable candidate for experimental implementation [77–79].

[2] Figure 2(b) and data therein courtesy of P. Schach and JPL's Strategic University Research Partnership Task # 01STSP/SP.20.0014.032.

Spatially modulating a focused Gaussian beam – at frequencies much larger than the atom dynamics resulting from trapping frequencies – allows one to realize arbitrary time-averaged potentials with resolutions down to the spot size given by the beam's waist (Fig. 3). Whether the resulting potential is of attractive or repulsive nature is given by the sign of the detuning of the laser from the dominant optical transition. Experimental trade offs need to be considered when designing the optical system for painting. For instance, the spatial dimensions of the focusing lens outside the chamber govern the minimum focal length, yielding a waist at the center of the system. The initial beam waist and the wavelength in use are intimately linked to the final spot size but larger beams may bring upon technical challenges, e.g., regarding the size of available high-quality optics. Likewise, the telescope focusing the laser beam through the acousto-optical element governs the initial beam's waist and the translation of radio frequency modulation into spatial translation of the beam. As such, for any implementation, e.g., when tailoring the tunneling barriers as described above, one needs to weigh spot size against the maximum painting stroke, the largest acceptable waist for the initial beam, as well as overall lengths of the optical system. Finally, special care has to be taken with respect to imaging errors when considering very short focal lengths for tiniest spot sizes at the order of 1 µm and below.

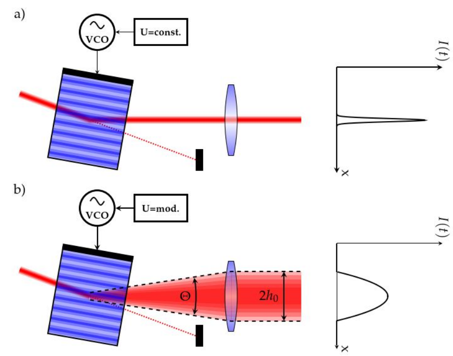

Figure 3: Using a "Gaussian brush" (a) to paint an exemplary harmonic potential (b) by frequency modulating the radio frequency input on an acousto-optical element. Figure adapted from Ref. [80].

Alternative approaches for creation of dynamic optical potentials may utilize spatial light modulators or digital mirror devices although for any specific solution similar considerations as above, but in addition regarding accessible bandwidths, need to be made.

Platforms. Various microgravity platforms enable the Assymetric Tunneling and Tunneling Accelerometry technologies, but a persistent space environment is necessary to utilize or realize the full potential of either system. Proof-of-principle demonstrations using the droptower in Bremen or the Einstein Elevator in Hannover, DE, can mature the technologies for flight. Initial opportunities with NASA's Cold Atom Lab (CAL) are currently available onboard the ISS to produce the appropriate atom sources. Further, a joint NASA/DLR mission called Bose Einstein Condensate Cold Atom Lab (BECCAL) is under development for launch to the ISS in 2026 to bring advanced capabilities for studying cold atoms and maturing quantum sensors for space applications. We anticipate that the repulsive tunable (painted) potentials baselined in BECCAL will be capable of directly demonstrating our proposed systems. Follow-on missions to BECCAL will then utilize the technologies enabled by quantum tunneling in microgravity for transformative science.

Microgravity-enabled studies of scattering, tunneling, and confinement of ultracold atoms and molecules from optically engineered barriers will provide unique insights into the nature of matter at the most fundamental level. *In this topical white paper, we described two novel research strategies that are important to be done in space because their promise for quantum sensing, atomtronics, and quantum simulation answers important fundamental research questions spanning the physics of fundamental particles to that of the cosmos.*

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