National Aeronautics and Space Administration

Scattering of a particle with internal structure from a single slit in microgravity

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Program: FY21 SURP **Strategic Focus Area: Gravitational astrophysics and fundamental physics**

Objectives

The objective of this project was to study novel scattering phenomena for a quantum system composed of a particle with internal structure and an optically engineered potential. Specifically, atomic tunneling processes were studied as a new and purely quantum avenue to the sensing of inertial forces: Here, the tunneling rate of a particle through an obstacle is enhanced at specific tunneling resonances. Resonances in turn are influenced by external perturbations like accelerations, rotations or gravity. Whereas large (gravitational) potentials change the behavior of the system drastically and may even inhibit quantum-tunneling processes, small perturbations only slightly modify the overall dynamics but can still drastically influence the tunneling behavior of the system. This fact makes these systems promising candidates for inertial sensors particularly suited for microgravity conditions. The development of technology based on such tunneling phenomena would be relevant for NASA's Fundamental Physics programs but also could provide enhanced performance for gravitational science and Position, Navigation, and Timing (PNT) capabilities.

Background

The efforts detailed in this report will establish enduring collaborations between researchers at Texas A&M, who have made fundamental contributions to the field of quantum optics and quantum science, and JPL, who have expertise in the fields of cold molecules, precision quantum sensors, and development of quantum gas facilities in space. The goal is to develop novel sensors and instruments based on quantum tunneling, scattering, and confinement (relevant to the "Instruments and Sensors – Coherent Detectors and Arrays, Remote Sensing Instruments" strategic focus area) and to integrate these sensors into upcoming missions to e.g., test the limits of the fundamental tenets of General Relativity and Quantum Mechanics and to simulate Unruh-Hawking radiation with these model systems (relevant to the "Astronomy and Fundamental Physics - Gravitational astrophysics and undamental physics" strategic focus area). To achieve these goals, extensive technical and theoretical investigations/preparations are required that would naturally align with a long-term collaborative effort between JPL and Texas A&M University.

Approach and Results

The central idea of studying scattering phenomena and even confinement of a complex quantum particle from a slit has been published by Professor Schleich in [1] and [2]. However, the analysis was based on an idealized model rotor of fixed length incident on a slit with hard walls. In order to enable future study and potential applications of this phenomena at ultra-low energy scales, e.g., with NASA's Cold Atom Lab (CAL) [3], it is necessary to analyze the underlying physics in detail and to build the theoretical models based on experimentally realizable systems in a highly integrated and iterative manner.

To this end, the project milestones for this project were:

Milestone 1: Formulation of the model system, including identification of the appropriate atoms, molecules, and barriers/slits.
Milestone 2: Derivation of bound states and transmission characteristics by numerical and semi-analytical methods.
Milestone 3: Develop acceleration sensitivity function for the model system.
Milestone 4: Experimental investigation of the model system at JPL for maturing the simulations and developing applications of the technology for furthering NASA's goals.

As a result of our efforts to formulate the model system (Milestone #1), we identified that a matter-wave Fabry-Perot cavity [4], as shown in Fig. 1, could be generated via painted potentials or light sheets [5] which would serve as a uniquely promising inertial sensor. Here, the variation of the transmission characteristics of ultracold neutral atoms depending on the applied acceleration will be exploited.

We have also explored the feasibility of such a matter-wave cavity system during this year (Milestone #2) and have applied it to inertial quantum sensing under microgravity conditions (Milestone #3). More specifically, we have developed the numerical toolbox necessary for the investigation of the dynamics of a particle/BEC with center-of-mass and internal degrees of freedom and its interaction with realistic trapping potentials. Furthermore, we have developed semi-analytical methods based on transfer matrices which allow us to determine the transmission characteristics of cavity systems.

The combination of the numerical toolbox and semi-analytical models has made it possible to characterize the behavior of a Fabry-Perot matter-wave cavity (see as an example Fig. 2), in particular its transmission and reflection coefficients. Based on these studies, we were able to identify experimentally realistic parameters for the realization of such a system to serve as an acceleration sensor. Improving even further on these results we have characterized the working regime of such a tunneling gravimeter as shown in Fig. 3, by obtaining the relative uncertainty of measured gravitational forces for different experimental parameters. These results underline that the device might serve as an alternative for quantum gravimetry or complement existing devices.

The COVID-19 work-from-home requirements from FY'20 and FY'21 impeded progress for Milestone #4. Instead, the effort for this year concentrated on developing the concept as a whitepaper for the Decadal Survey on Biological and Physical SciencesResearch in Space 2023-2032 (BPS2023).The Fabry-Perot matter-wave cavity concept is being integrated into a Topical Whitepaper titled "Fundamental physics and enabling technologies based on quantum tunneling studies in microgravity".

Significance/Benefits to JPL and NASA

This study is expected to spawn a new class of inertial force sensors based on scattering, tunneling, and confinement of ultracold atoms and molecules from optically engineered barriers and/or slits. Considering even the first results discussed in Section D and shown in Figure 2, acceleration sensitivities on the order of 100 microGal/rt(Hz) or below are reasonable with a continuous BEC source assuming a flux of a million atoms per second. Future venues of investigation include efforts to further optimize the sensitivity of the matter-wave Fabry-Perot cavity to inertial and fundamental forces and to miniaturize the system as a uniquely compact and simple quantum sensor. We therefore expect that our research can produce both technological and fundamental advances that can have a deep impact for the scientific community as well as open ways in which precise metrology using ultracold quantum gases can be used to advance NASA's research programs. Based on the recent success of CAL and ongoing efforts to bring precision quantum sensors into space [6], results of this study could reveal new capabilities at the critical time when missions are under development to capitalize on the capabilities given by state-of-the-art quantum sensors.

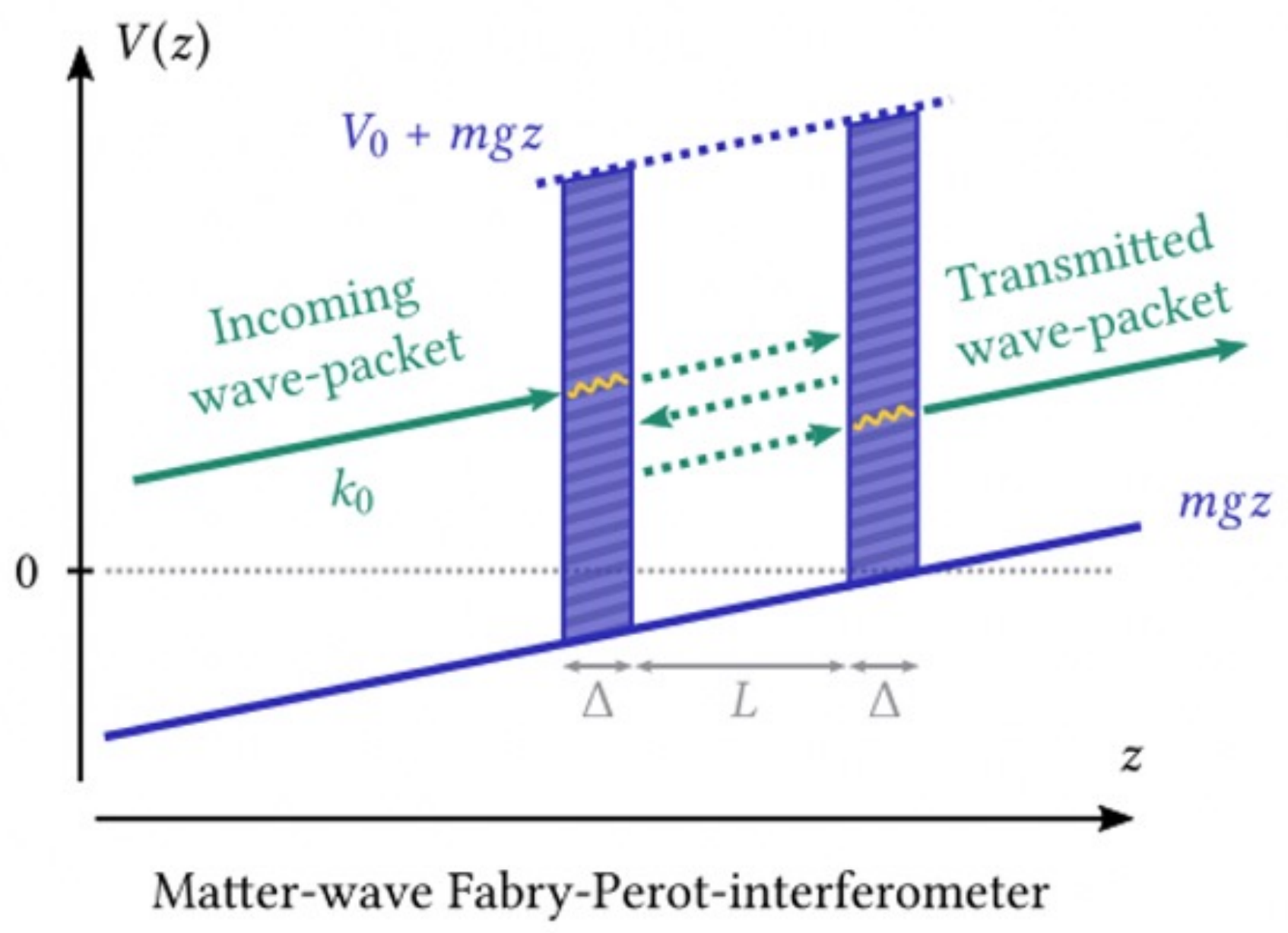

Figure 1: Schematic of a matter-wave Fabry-Perot cavity: A wave-packet with center-of-mass momentum $\hbar k_0$ impacting below the barrier height on the Fabry-Perot cavity formed by two light-generated potential barriers. The transmission resonances of the barrier act as a filter. The fraction of transmitted atoms after the barrier serves as an observable. Once a gravitational acceleration is present the transmission resonances of the cavity system are shifted and hence the number of transmitted atoms changes. The placement and form of the tunneling resonances and thus the sensitivity of the device can be engineered by tuning the barrier form, barrier separation L and thickness Δ.

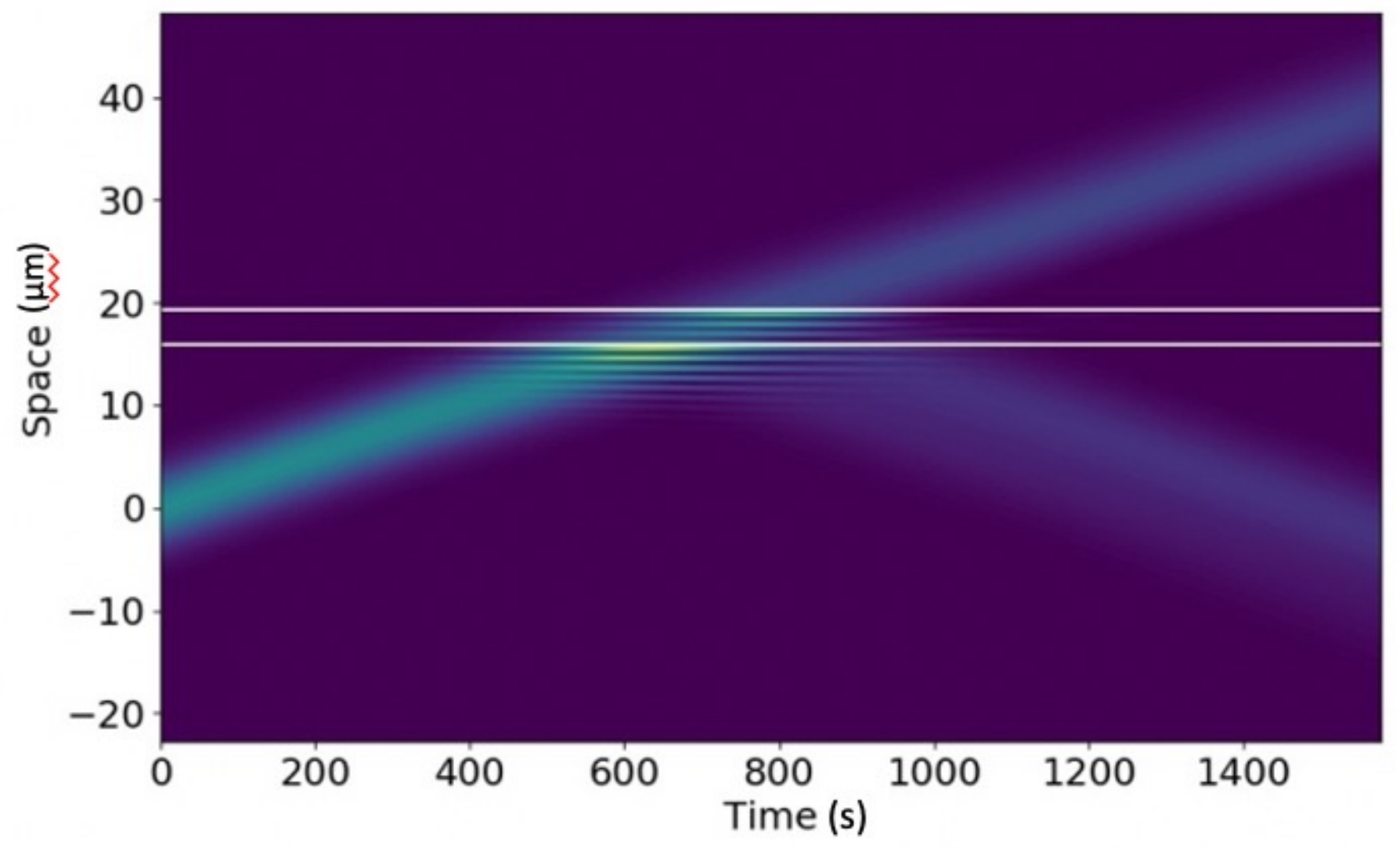

Figure 2: Numerical simulation of the spatial time-evolution of a BEC wave-packet (with width 12 μm and initial center-of-mass velocity of 5 mm/s) transmitted through a Fabry-Perot cavity, indicated by white horizontal lines, and generated by two Gaussian barriers separated by 4 μm.

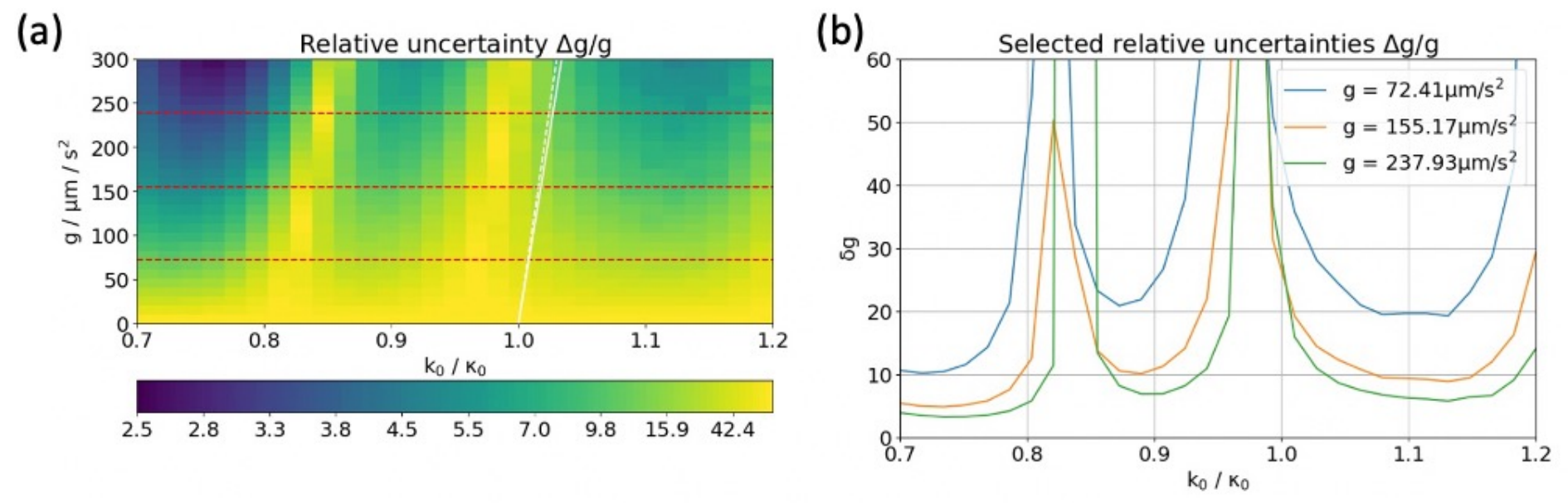

Figure 3: (a) Scaled relative uncertainty Δg/g (per atom) of the proposed Fabry-Perot matter-wave cavity as a function of initial center-of-mass energy $(\hbar k_0)^2$ in units of the effective barrier height $(\hbar \kappa_0)^2$ and gravitational acceleration. The cavity parameters are a width of 4 μm and an experimental duration on the order of ~100 ms. Optimal sensitivity for operation is obtained in the low-value (blue) regions of the density plot.
(b) Relative uncertainty Δg/g (per atom) at selected gravitational accelerations (slices along the red dashed-lines in part a of the figure). Optimal sensitivity is obtained in the minima of the respective curves.

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