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Extreme Dispersion and Clocks in Space: Advancing Tests of the Aharonov-Bohm Effect due to Scalar Potentials

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Abstract

The Aharonov-Bohm (AB) effect highlights the significance of electromagnetic and gravitational potentials in quantum mechanics, even in regions devoid of classical fields. We examine the gravitational AB effect as a generalization of the gravitational redshift. By considering a quantum system, in orbit around a massive body, we predict the emergence of side-bands in the energy spectrum due to time-dependent gravitational potentials, which could be observed using precision atomic clocks aboard satellites. In parallel, we extend recent experimental and theoretical studies of the electric-scalar AB effect. Utilizing a balanced interferometric excitation scheme in a microwave cavity, achieving 25 dB suppression of the resonant electric field while maintaining a time-varying electric-scalar potential. This setup provides a promising platform for directly probing the electric-scalar AB effect in a cancelled electric field regime while maintaining a time varying scalar potential, as well as producing a resonant system with extreme dispersion. These complementary approaches provide new experimental pathways to test fundamental quantum effects in electromagnetic and gravitational potentials.

1 Introduction

The AB effect is a cornerstone of quantum mechanics, demonstrating that potentials can directly influence quantum systems despite the lack of classical fields [1]. Initially proposed in the context of electromagnetism, the AB effect shows that a charged particle can acquire a phase shift (or Berry phase) when passing through a region of non-zero magnetic-vector, or electric-scalar potential, even when the associated electric and magnetic fields are absent. This phase shift theoretically leads to observable interference effects [1, 2], highlighting the fundamental role of potentials in quantum theory. Whilst there is experimental evidence of interactions with the magnetic-vector potential [3, 4, 5], and combined magnetic-vector and electric-scalar potential measurements [6], there are no experiments isolating the effect of the electric-scalar potential.

Beyond its electromagnetic origins, recent theory has extended the AB effect to the splitting of energy levels of a quantum system, i.e, the appearance of energy side-bands [7, 8], rather than only interference effects. The gravitational AB effect arises due to the interaction between quantum systems and time-dependent gravitational potentials, predicting frequency modulations in atomic clocks in eccentric orbits. We show that this effect generalizes the gravitational redshift, showing that, in addition to a constant frequency shift, atomic clocks should exhibit sidebands due to the time-varying nature of the gravitational potential. The study of these sidebands provides a novel avenue for testing general relativity and the interaction between gravity and quantum mechanics.

Similarly, the electric-scalar AB effect predicts that a quantum system enclosed within a region with a time-varying electric potential, but no electric field, should acquire a measurable phase shift. This effect has been challenging to observe experimentally due to the difficulty of creating a purely time-dependent scalar potential without residual electric fields. However, our experimental advancements using microwave cavity resonators have provided a platform for testing this phenomenon, achieving extreme dispersion effects through a balanced interferometric excitation scheme, providing the necessary conditions required to scan for predicted energy level side-bands. The extreme dispersion feature results from a suppressed electric field, analogous to electromagnetically induced absorption [9, 10, 11, 12, 13].

This paper summarizes our contributions to recent theoretical and experimental advancements in the study of the gravitational and electric-scalar AB effects. The gravitational AB effect is analyzed within the context of atomic clocks in space, while the electric-scalar AB effect is examined through controlled laboratory experiments in microwave resonators. By exploring these phenomena, we gain deeper insight into the fundamental role of potentials in quantum mechanics and their implications for precision metrology and fundamental physics.

2 Gravitational Energy Level Splitting

The gravitational AB effect can be understood as a generalization of the gravitational redshift [14]. When a quantum system experiences a time-dependent gravitational potential, its energy levels shift, leading to the emergence of modulation sidebands in atomic transition frequencies.

This effect is particularly relevant for precision atomic clocks in space, where satellites in eccentric orbits experience a varying gravitational potential, but no gravitational field due to Einstein's equivalence principle. To begin the

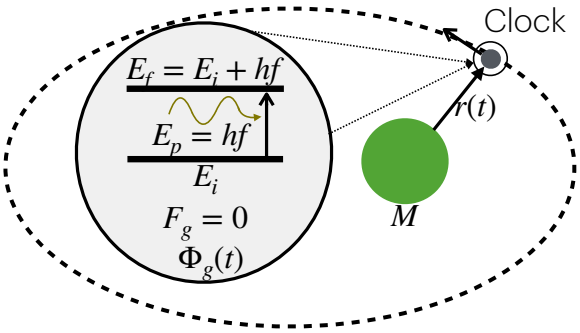

Figure 1. A clock in an elliptical orbit around a massive object with mass M. The satellite in free-fall passes through a time-varying scalar potential, $\Phi_g(t)$, and experiences no gravitational force. The clock has a ground state E_i and excited state E_f, seperated by energy equivalent to that of absorbing a photon, $E = hf$.

theoretical framework we consider an atomic clock as a two-level system undergoing continuous Rabi oscillations between its ground and excited states seen in Fig. 1. The gravitational potential modifies the energy levels of the system, leading to a phase accumulation described by the gravitational AB phase

$$\varphi_g(t) = \frac{m_e}{\hbar}\int_0^t \Phi_g(t)dt, \tag{1}$$

with $\hbar$ the reduced Planck's constant, m_e the mass of the ground state electron, and $\Phi_g(t)$ the time-varying gravitational potential at a time t. In the presence of a time-varying gravitational potential, we obtain the energy levels

$$E_i(t) = E_{i0} + m_e\Phi_g(t) \tag{2}$$

and

$$E_f(t) = E_{f0} + m_e^*\Phi_g(t) \tag{3}$$

where E_{i0}, E_{f0} and f_{p0} are the ground and excited energy levels, and photon/clock frequency in a zero gravitational potential. Notably, $m_e^* = m_e + \frac{hf_p}{c^2}$, the effective mass of of the electron has increased according to the mass-energy relation $E = mc^2$ where we have added the kinetic mass of the photon hf_p/c^2 with f_p the photon frequency. By formulating the Hamiltonian and following the derivation procedure in [14], we acquire the final wave function

$$\Psi_f(\mathbf{r},t) = \Psi_f(\mathbf{r})\sum_{n=-\infty}^{\infty}(-1)^n J_n(\alpha) \times \exp\left(-\frac{i(\Delta E_0(1+\frac{2GM}{(r_a+r_p)c^2}) - n\hbar\Omega)t}{\hbar}\right), \tag{4}$$

for orbital angular frequency Ω. Here, G is Newton's gravitational constant, c is the speed of light, $\Delta E_0 = E_{f0} - E_{i0} = hf_{p0}$, and Bessel functions of the n-th kind $J_n(\alpha)$ at α, the modulation parameter

$$\alpha = (\frac{r_a - r_p}{(r_a+r_p)^2})(\frac{2GM}{c^2})(\frac{2\pi f_{p0}}{\Omega}), \tag{5}$$

with apogee and perigee radii r_a and r_p, respectively. Finally, we can extract the energy levels of this wave function

$$\Delta E(n) = \Delta E_0(1+\frac{2GM}{(r_a+r_p)c^2}) \pm n\hbar\Omega = \Delta E \pm n\hbar\Omega, \tag{6}$$

retrieving the gravitational red shift here $\Delta E \equiv \Delta E_0(1+\frac{2GM}{(r_a+r_p)c^2})$. Appearing from these energy levels is a splitting of order n appearing from the modulation of gravitational potential. This result opens up a new avenue to test for the gravitational AB effect, unlocking the capabilities of high precision clocks to measure these energy side-bands.

3 Extreme Dispersion Resonator

Our recent experimental work has focused on probing the electric-scalar Aharonov-Bohm effect using a highly controlled microwave cavity resonator [15]. This set-up, shown in Fig. 2, utilizes a balanced interferometric excitation scheme and a unique microwave cavity resonator to suppress the resonant electric field while maintaining a time-varying scalar-electric potential, a crucial condition for testing the electric-scalar AB effect.

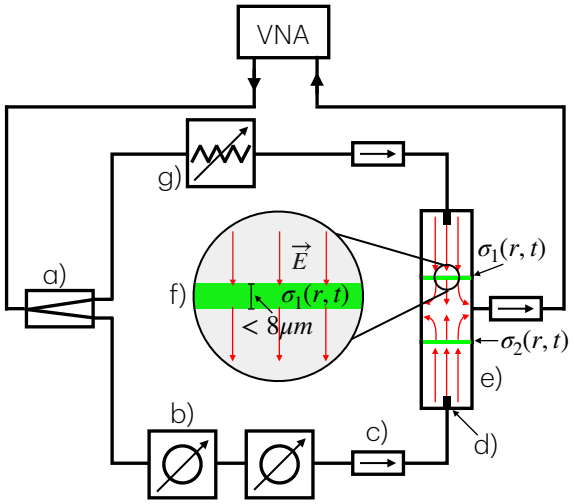

Figure 2. The experimental configuration used to achieve a suppressed electric field, while maintaining a time-varying scalar electric potential. a) Power splitter, b) variable attenuator, c) isolator, d) resonator tuning rod, e) triple microwave cavity resonator separated by copper foil, f) copper foil with thickness $< 8\mu m$, g) variable attenuator.

The microwave cavity is a triple resonator system separated by thin copper foils, allowing TM_{010} modes from the upper and lower resonator to deposit an effective charge onto the foil, allowing it to excite the central microwave resonator. The charge density phasors on the top and bottom foil, respectively, within the central resonator take the form

$$\tilde{\sigma}_{1,2}(r,t) = \sigma_{01,02}J_0(\chi_{0,1}r/R)e^{i\omega t+\phi_{1,2}}, \tag{7}$$

with $\chi_{0,1}$ the first root of the first kind Bessel function with a value of 2.405 and r is the radial coordinate. A complete derivation can be seen in [15]. The phase term $e^{i\omega t+\phi_{1,2}}$ at frequency and time, ω and t, highlights how we obtain phase control, $\phi_{1,2}$, of each charge density phasor due to the phase shifters shown in Fig. 2. Additionally, the charge density magnitudes, $\sigma_{01,02}$, are matched with the capabilities of the introduced variable attenutator. Matching the phase and amplitude of the charge density distribution on the central resonator foils is precisely the conditions required to cancel the electric field at the centre of the resonator. The effect of changing the relative phase, $\Delta\phi = \phi_2 - \phi_1$ between the two resonators is shown in Fig. 3.

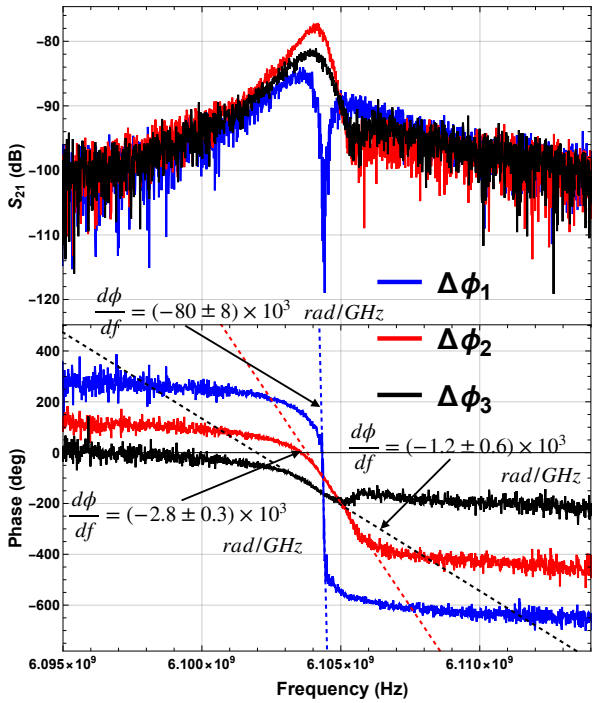

Figure 3. The frequency response spectra (S_{21}, top) and phase response (deg, bottom) of the circuit at three different relative phase differences, $\Delta\phi_{1,2,3}$. The blue spectra correspond to the case of electric field cancellation at the resonant frequency, suggesting $\Delta\phi_1 \approx 0$, with a phase response an order of magnitude larger than for other phases.

The asymmetry in Fig. 3 is due to non-ideal balance conditions such as ensuring all three resonators have precisely the same resonant frequency, matching the amplitude of power entering the resonators which power the TM_{010} modes and hence charge buildup on both foils, and the phases of each interferometric arm. By optimising these parameters into anti-resonance, a phase response an order of magnitude larger than the relative resonance condition, as well as around 25 dB of field suppression can be achieved. We have achieved an extreme dispersion regime analogous to electromagnetically induced absorption, where sharp absorption features emerge due to destructive interference between excitation pathways. The result is a system in which the energy shifts of quantum states can be studied in the presence of a pure potential, without classical field contributions when excited at this suppressed frequency. This experimental framework provides a novel pathway for investigating fundamental quantum mechanical effects and could pave the way for future precision measurements that distinguish potential-induced phase shifts from conventional field interactions.

4 Conclusion

The exploration of both the gravitational and electric-scalar AB effects has broad implications for quantum field theory, precision metrology, and fundamental physics. The new theoretical understandings of the gravitational AB effect offers a new avenue for testing general relativity in the quantum regime, potentially informing the development of quantum gravity theories. The electric-scalar AB effect, if experimentally confirmed, would provide further evidence of the physical significance of potentials beyond their traditional classical interpretations.

Future work may focus on refining the experimental setups to achieve even greater suppression of unwanted fields while maintaining strong potentials, as well as placing a quantum system in this region to actually scan for the predicted energy level shifts as a test of the scalar-electric AB effect. Additionally, precise space-based experiments using optical atomic clocks could scan with high sensitivity the gravitational AB effect. With advancements in both theoretical modelling and experimental techniques, we may be on the brink of understanding and detecting of these elusive quantum phenomena.

For now, the Aharonov-Bohm effect remains one of the most intriguing demonstrations of the fundamental role of potentials in quantum mechanics. Our recent theoretical work has extended the AB effect to gravitational systems, predicting measurable sidebands in orbiting atomic clocks due to time-dependent gravitational potentials. Our experimental efforts have also made significant strides in probing the electric-scalar AB effect using microwave cavity resonators. The electric field suppression resonator with increased phase response, not only are they useful in the field of precision metrology, provide the conditions required to test the illusive electric-scalar AB effect. Together, these advances contribute to our understanding of quantum potentials and their impact on physical systems, opening new directions for both fundamental research and practical applications in precision measurement technologies.

5 Acknowledgements

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