

QUANTUM PHASE SHIFT AND GRAVITATIONAL TIME DILATION

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CONTENTS

1. Introduction	1
2. Gravitational Time Dilation	1
3. Quantum Phase Shift	2
4. Interpretation and Experimental Verification	2
5. Limitations	3
6. Summary	3
References	3

1. INTRODUCTION

In general relativity, clocks at different heights in a gravitational field run at different rates. In quantum mechanics, particles at different energy levels rotate their quantum phase at different rates. We investigate whether these two phenomena can be viewed as essentially identical.

2. GRAVITATIONAL TIME DILATION

In general relativity, for the case of a uniform (non-curved) gravitational field g , the time dilation between two observers at different heights is

$$T_d = 1 + \frac{gh}{c^2}$$

where h is the height difference and c is the speed of light. For a particle of mass m , the energy difference between the two observers is $\Delta E = mgh$, so we can rewrite the previous equation as

$$T_d = 1 + \frac{\Delta E}{mc^2} = 1 + \frac{\Delta E}{E}$$

where $E = mc^2$ is the energy equivalent of the mass m . Taking the lower observer to be the reference clock, the time difference between t , and $t_h = T_d t$, will be $\Delta t = t_h - t = t \cdot (T_d - 1)$ so that

$$\frac{\Delta t}{t} = \frac{\Delta E}{E}$$

3. QUANTUM PHASE SHIFT

From the Schrödinger equation, we have that the phase of an eigenstate with energy E oscillates as $e^{iEt/\hbar}$. Absolute phase appears impossible to measure and may in fact have no physical meaning whatsoever; however, relative phase can be easily observed through various interference experiments. For identical particles, or different trajectories of the same particle, higher energy will cause the wave function to oscillate more rapidly, leading to a relative phase shift

$$\Delta\phi(t) = e^{i\Delta Et/\hbar}$$

For any wave at a constant energy level, and thus constant phase velocity, a shift in phase is equivalent to a shift in time. If we set the shift due an energy difference to be equal to the shift due to a time delay,

$$(E + \Delta E)t = E(t + \Delta t)$$

we get that

$$\Delta E \cdot t = E \cdot \Delta t$$

or

$$\frac{\Delta t}{t} = \frac{\Delta E}{E}$$

which is the same equation arrived at in the previous section. Thus it appears reasonable to view the phase shift as being due to time dilation, with the local clocks on different particle paths running at different rates. In terms of pure interference effects, this is experimentally indistinguishable from the standard interpretation. However, the standard interpretation assumes a single universal time at all points in space and is clearly not compatible with general relativity. Interpreting the phase shift as being due to time dilation, on the other hand, appears to be compatible with relativity, and indeed, if one chooses to view a particle's phase oscillation as its own local clock, may be inescapable.

A third possibility, that the actual speed and hence arrival time of the particle are affected, would be measurable by time-of-flight experiments. This effect is not predicted to occur in standard QM, and would very surprising given the field-free (and hence force-free) phase shifts predicted and observed in various Aharonov-Bohm effects. It should, however, be relatively straightforward to test.

4. INTERPRETATION AND EXPERIMENTAL VERIFICATION

For the remainder of this paper we assume the time-dilation interpretation is correct. Changes in the rate of time flow and changes in level of potential energy are therefore the same thing. The electrons in different orbitals in the same atom must be viewed as having different time dilations, even though they span the same space and have the same (non-moving) center of reference. Relativity shows that time is not a universal absolute, but rather depends on the position and velocity of the observer. To this, we must now also add the energy of the observer.

This is experimentally testable. For example, it predicts that a charged clock, placed inside a conductive cage, will run faster when the cage is given the same polarity charge, thereby raising the energy level of the clock, and slower when the cage is given the opposite charge. It predicts that radioactive ions will decay faster (or slower) under similar circumstances, and that their decay rate will be different on different sides of the solenoid in a magnetic Aharonov-Bohm setup even though they never encounter any field. There are many other possibilities, but these few should suffice to demonstrate that the time dilation view makes different predictions than the phase shift view and that the differences are accessible to experimental test.

Of course, there remain vexing questions about which object or particle should be considered when calculating the time dilation. Is it, for example, an entire atom (or ion) with its nucleus and electrons taken as a whole? Or should we, in the case of nuclear decay, only consider the nucleus? This is an empirical question, but there is evidence that the entire atom is the proper entity. The detection of interference fringes for large molecules such as C_{70} [1, 2] implies that such bound collections have their own quantum phase which is independent of the phases of the components.

5. LIMITATIONS

In special relativity, we have that the time dilation for a particle or observer moving at velocity v is $\sqrt{1 - v^2/c^2}$. The higher the velocity, the higher the kinetic energy, but the *slower* the clock is perceived to run. Thus kinetic energy does not appear to have the same relationship to time that potential energy does; even the sign is reversed.

6. SUMMARY

We propose an alternate interpretation of the well known quantum phase shift as instead a time-dilation effect. The mathematics of this is essentially identical to that of gravitational time dilation in general relativity, indicating perhaps a deep connection between QM and GR. This interpretation is shown to have measurable consequences, and experiments are proposed that could test its validity.

REFERENCES

- [1] M. Arndt, O. Nairz, J. Petschinka, A. Zeilinger, "High Contrast Interference with C_{60} and C_{70} ", *C. R. Acad. Sci. Paris*, t.2 Srie IV, 581-585 (2001)
- [2] O. Nairz, M. Arndt, A. Zeilinger, "Quantum Interference Experiments with Large Molecules", *American Journal of Physics* 71, 319 (2003)