Reprinted from AMERICAN JOURNAL OF PHYSICS, Vol. 26, No. 3, 197–198, March, 1958
Printed in U. S. A.

# Relativistic Clock Experiments

IN response to a recent letter[1] concerning the effect of a gravitational field on the frequency of light, it may be worth while to note that whether there is or is not a Doppler shift depends on the coordinate system from which we view the experiment. In fact, Einstein's original demonstration of the effect[2] was based on the Doppler shift as seen in an inertial (i.e., freely falling) coordinate system.

Einstein's argument is a direct application of the equivalence principle, so simple that it can be given in any elementary physics course. Let $A$ be at a height $z$ above $B$, in a gravitational field $g$. All phenomena observed by $A$ and $B$ are the same as if there were no gravitational field, but as if they were accelerated upward, at rate $g$. Light travels from $A$ to $B$ in time $t=z/c$. During this time, $B$ is accelerated by $\delta v=gt=gz/c$; therefore he sees the light raised in frequency by the Dopper shift, $\delta f/f=\delta v/c=\varphi/c^2$, where $\varphi=gz$ is the gravitational potential difference.

There is also a better known, but less convincing, argument. A photon of frequency $f$ has energy $E=hf$, therefore mass $m=hf/c^2$. In falling through a gravitational potential difference $\varphi$, it gains energy $\delta E=h\delta f=m\varphi$. Once again, $\delta f/f=\varphi/c^2$. This is, of course, not a new effect in addition to Einstein's, but the same effect viewed in a different way. It is best to regard the argument just given as a handy mnemonic rather than a derivation; it is a typical application of quantum theory as it existed in, say, 1918.

In order to discuss the effect in terms of current theory, one must look at the formalism of quantum electrodynamics. Although a union of quantum theory and general relativity has not yet been accomplished,[3] it seems safe to expect that one feature, in essence just Bohr's correspondence principle, will be preserved in future theories. This feature is that both quantum theory and classical theory use the same (Maxwell's) equations to describe all light propagation effects.[4] In any situation where such things as phase, frequency, field strength are observable, quantum theory will make the same predictions as classical theory. This requirement was one of the guiding principles in the development of present quantum theory.

The fact that quantum theory, when adapted to gravitation, must still agree with Einstein's theory as regards frequencies and time scales, is shown strikingly by the fact that Bohr[5] was once forced to use this effect in order to answer one of Einstein's objections to quantum theory. This famous discussion showed that, without the gravitational effect, in just the amount predicted by Einstein, we would lose the perfect correspondence between commutation rules and possibilities of measurement, on which the logical consistency of quantum theory depends.[5,6] Thus any new gravitational effect on frequencies in addition to Einstein's, far from being a "quantum effect," would be as harmful to quantum theory as to Einstein's theory.

The question has been raised whether the effect is due to a change in frequency of a photon while traveling from $A$ to $B$, or only to a difference in time scales at $A$ and $B$. Physicists have learned a very convenient trick for disposing of such questions. Unless it can be stated in terms of an experiment which would give different results on the two hypotheses, it is not a question of physics, but only one of the meaning of words.

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[1] M. J. E. Golay, Am. J. Phys. 25, 494 (1957).
[2] A. Einstein, Ann. Phys. 35, 898 (1911).
[3] For a survey of the current situation, see the July, 1957 issue of Revs. Modern Phys.
[4] L. I. Schiff, *Quantum Mechanics* (McGraw-Hill Book Company, Inc., New York, 1949), Chap. XIV.
[5] N. Bohr in *Albert Einstein—Philosopher Scientist*, edited by P. A. Schilpp, (Library of Living Philosophers, Inc., Evanston, Illinois, 1949), p. 227.
[6] L. Rosenfeld in *Niels Bohr and the Development of Physics*, edited by W. Pauli, (Pergamon Press, London, 1955).