A NEW EXPERIMENTAL TEST OF SPECIAL RELATIVITY

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EXPERIMENTS which have tested special relativity have usually been forced to rely on great delicacy and precision in order to detect or examine the small differences between predictions of special relativity and those of alternate theories. This is because these differences appear multiplied by a very small quantity $(v/c)^2$, where c is the velocity of light and v is some relative velocity which is generally much smaller than c. While giving a clear-cut support to special relativity over some other theories such as a simple ether, experiments have not generally measured the small terms in $(v/c)^2$ with impressive fractional accuracy. Michelson and Morley's first experiment[1], for example, was of remarkable precision. But it was searching for a change in light-path of only about one part in 10^8 due to the motion of the Earth about the Sun on the basis of the then current ether theory, and was able to set an upper limit no less than 1/40 of this, or an ether drift of about one-sixth the orbital velocity of the Earth. Subsequent very refined experiments[2] of a similar type succeeded, a half-century later, in setting an upper limit on any ether drift of 1/20 the velocity of the Earth around the Sun. Others[3] even suggested the existence of an ether drift as large as about one-fifth of the orbital velocity of the Earth. The advent of very high precision atomic clocks suggests that still more exacting experimental tests may now be made; one such, which is now more or less completed, is reported here.

The experiment compares the frequencies of two maser oscillators[4] with their beams of ammonia molecules pointed in opposite directions, but both parallel to a supposed direction of motion through the ether. If both masers are rotated 180°, and their frequencies again compared, a change in relative frequency should be found due to motion of the masers through the ether, assuming the molecular vibrations are unchanged by such motion. A precision of one part in 10^{12} has been achieved in this frequency comparison, and failure to find a frequency change of the predicted type allows setting the upper limit on an ether drift as low as 1/1,000 of the orbital velocity of the Earth. This precision also provides a test for some other effects which will be discussed below.

The effect on the frequency of a beam-type maser oscillator of motion through the ether was first worked out by Møller[5]. A brief, somewhat intuitive explanation of this shift follows. In this device, ammonia molecules in an excited state travel at thermal velocities along the axis of a circular cylindrical cavity, giving it energy. If the cavity is stationary in the ether, the standing waves may be considered to be made of travelling waves with wave-fronts nearly parallel to the axis. As the molecule moves along the axis, there is then no Doppler shift. If the apparatus is moving axially through the ether at velocity v, the wave-fronts must tilt at an angle $\alpha = v/c$ in order to follow this axial velocity. Hence, molecules travelling at velocity u through the cavity produce a frequency shifted by the Doppler effect of an amount $\nu u\alpha/c = \nu uv/c^2$. Here ν is the molecular frequency. Since $uv\nu/c^2$ depends on the relative direction of u and v, two masers with oppositely directed beams should have frequencies which differ by $2uv\nu/c^2$ due to this effect. If each is rotated 180°, the total change in their frequency difference is $4uv\nu/c^2$.

A more precise derivation of this effect is obtained from the fact that special relativity predicts the same result as does an ether theory, provided that the FitzGerald contraction $\sqrt{\left(1 - \frac{V^2}{c^2}\right)}$ is introduced for any length parallel to the motion v through the ether, and also that the proper time of any clock or oscillator is modified by the same factor $\sqrt{\left(1 - \frac{V^2}{c^2}\right)}$ due to this motion. In other words, any effect due to motion through a simple ether is just compensated by appropriate changes in scale for length and time which correspond to the Lorentz transformation. If, then, an ether theory is used without FitzGerald contraction and time dilation, the expected shift in frequency may be computed from an examination of the effects of these changes of scale for length and time.

Consider first the FitzGerald contraction. Its effect on the frequency of maser oscillation is very small and may be neglected because this frequency is rather insensitive to the dimensions and resonant frequency of the cavity[4].

The time dilation, however, produces the effect we seek. If the cavity moves through the ether at a velocity v and the molecule through the cavity at velocity u, then the molecular velocity through the ether is $V = u + v$, and the molecular time will be slow, for an observer in the framework of the ether, for the factor:

$$\sqrt{\left\{1 - \frac{(u+v)^2}{c^2}\right\}} \approx 1 - \frac{u^2}{2c^2} - \frac{uv}{c^2} - \frac{v^2}{c^2}$$

But time in the actual laboratory framework, which is fixed with respect to the cavity, is slow by the factor:

$$\sqrt{\left(1 - \frac{v^2}{c^2}\right)} \approx 1 - \frac{v^2}{2c^2}$$

Hence the molecule would appear slow to an observer in the laboratory by the difference between these two, or by the factor:

$$1 - \frac{u^2}{2c^2} - \frac{uv}{c^2}$$

The first small correction is the well-known transverse Doppler effect, and is independent of ether drift. The second small correction is the discrepancy uv/c^2 which would occur if we were to accept a simple ether and no time dilation in the proper oscillation of the molecule, as postulated in Møller's original discussion[5].

The above derivation makes it clear that failure to see any change in time equivalent to the small fractional amount uv/c^2 may be explained away by the assumption of a time dilation for those who wish to adhere to an ether with such peculiarities. Hence the experiment is more closely related to the Kennedy–Thorndike experiment[6] than to that of Michelson and Morley. A null result in the latter needs, of course, only a FitzGerald contraction for an explanation in terms of an ether theory.

For performance of the present experiment, two ammonia beam masers were mounted with oppositely directed beams on a rack which rotated about a vertical axis. The frequencies of these oscillators are near 23,870 Mc./s. The thermal velocity u = 0·6 km./s. for NH_3 at room temperature. If the orbital velocity of the Earth is assumed to be the rate of motion through the ether, then v = 30 km./s. and the frequency change $4uv\nu/c^2$ = 20 c./s. when the masers are rotated 180° from an initial east–west position at noon or midnight.

During a small fraction of a second the relative frequency of the two masers fluctuates randomly about $\frac{1}{10}$ c./s. Over somewhat longer periods, such as those required for measurement before and after rotation, the average frequency difference does not vary more than about $\frac{1}{50}$ c./s. or one part in 10^{12}. Hence the 20 c./s. variation expected on an ether theory would be very easily detected. Variation of about 1 c./s. on rotation of the two masers was in fact observed. However, this variation could be eliminated by magnetically shielding the masers, and without shielding it remained constant to within about $\frac{1}{50}$ c./s. as the Earth rotated throughout a 24-hr. run. This shows that no more than about $\frac{1}{50}$ c./s. shift could be attributed to an ether drift.

The experiment involving rotation of the two masers was carefully done for the first time on September 20, 1958[7]. No proper effect as large as $\frac{1}{50}$ c./s. was found. Hence, since the orbital velocity of the Earth of 30 km./s. would have given an effect of 20 c./s., the ether drift could not have been larger than 1/1,000 of this value, or 30 m./s. It is, of course, possible for the motion of the Earth to be just cancelled by the motion of the solar system through the ether at some particular time of the year. The experiment has now been repeated at the Watson Laboratory during 24-hr. runs at approximately three-month intervals throughout the year. In none of these runs was any effect as large as $\frac{1}{50}$ c./s. found.

The present experiment sets an upper limit on an ether-drift velocity about one-fiftieth that allowed by previous experiments. This is in part because the effect measured is linear in the ether drift velocity v. An experiment of the Michelson–Morley type is designed to detect a fractional change of the form $\frac{1}{2}v^2/c^2$, which is an order of magnitude larger than the term uv/c^2 discussed here. An upper limit of 1/400 of $\frac{1}{2}v^2c^2$ has been set by the very careful experiments of Joos[2] with a Michelson interferometer. However, since this term is second order in v, the upper limit given for the ether-drift velocity is one-twentieth of the orbital velocity of the Earth, or 1·5 km./s. The present experiments have the advantage that the expected effect is linear in v, and also that two clocks can now be compared with much greater precision than can two distances. This experiment, involving a comparison of two maser oscillators to an accuracy of one part in 10^{12}, may perhaps represent the most precise experiment so far reported.

For most physicists, a confirmation of the fundamental postulate of special relativity that no absolute motion can be detected comes as no surprise, and a more precise experimental test may not even seem important because this postulate is so intuitively satisfactory and firmly accepted. It should be noted, however, that the positive detection of an effect in the present experiment could give some new information without necessarily contradicting the general principles of relativity. The motion of the Earth involves velocity relative to other parts of the solar system, as well as to the fixed stars and external galaxies. Hence this relative motion might, in principle, produce some anisotropy in space and some shift in relative frequency of the two masers when they are rotated by 180°.

Dicke[8] has suggested that an effect due to motion with respect to fixed masses in the universe should be present which is of the order of the fine structure constant, α, times the effect due to ether drift. This would correspond to a frequency shift in the present experiment of the order of $\frac{1}{7}$ c./s. Reasons given by Dicke why such a shift might occur are speculative, but very interesting. The present results allow no shift larger than $\frac{1}{50}$ c./s., which gives some indication against a term of the order $4\alpha uv\nu/c^2$.

Optical maser oscillators[9] should also lend themselves to interesting experiments on relativity, since they will probably be capable of examining changes in length as small as one part in 10^{12}. An optical maser oscillator could be constructed with a resonance between two étalon plates which is narrower in frequency than the atomic resonance supplying energy. In this case the frequency would depend primarily on the spacing between the plates, rather than on the atomic frequency. It is estimated that the oscillation would be monochromatic to about one part in 10^{11}. This suggests an experiment in which the oscillations of two optical masers are beat together in a photocell. One of the masers may be rotated about a vertical axis. On the basis of an ether theory, the beat frequency should then vary by an amount $\pm\ v^2\nu/2c^2$, for the same reasons that the Michelson–Morley experiment was expected to show a variation of path length. The fraction v^2/c^2 is 10^{-8}, so that its presence could probably be tested with excellent precision.

[1] Michelson, A. A., and Morley, E. W., *Amer. J. Sci.*, **34**, 333 (1887).

[2] Joos, G., *Ann. Phys.*, **7**, 385 (1930).

[3] Miller, D. C., *Revs. Mod. Phys.*, **5**, 203 (1933). See, however, Shankland, R. S., McCuskey, S. W., Leone, F. C., and Kuerti, G., *ibid.*, **27**, 167 (1955).

[4] Gordon, J. P., Zeiger, H. J., and Townes, C. H., *Phys. Rev.*, **99**, 1264 (1955).

[5] Møller, C., *Nuovo Cimento*, **6**, Supp., 381 (1957).

[6] Kennedy, R. J., and Thorndike, E. M., *Phys. Rev.*, **42**, 400 (1932).

[7] Cedarholm, J. P., Bland, G. F., Havens, B. L., and Townes, C. H., *Phys. Rev. Letters*, **1**, 342 (1958).

[8] Dicke, R. H., Proc. Symp. Quantum Electronics, Columbia Univ. Press (to be published).

[9] Schawlow, A. L., and Townes, C. H., *Phys. Rev.*, **112**, 1940 (1958).