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EXPERIMENTAL VERIFICATION OF THE THEORY OF RELATIVITY

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EINSTEIN created the theory of relativity in 1905. In the 60 years that have passed since then, a number of experiments have been carried out (with ever increasing accuracy) to verify the basic postulates of the theory and its consequences, so that today the theory is generally accepted. However, in view of the great importance of the special theory of relativity, proposals for experiments providing further tests keep appearing in the literature (e.g.[34,38]). When artificial satellites came into use, proposals were also made to carry out such experiments on satellites.

For the derivation of the special theory of relativity one usually quotes relatively old experiments [36,37,6,29,43], although the most interesting experiments to verify its postulates were carried out in the last few years. We shall discuss some of these, but shall restrict ourselves to those which were done, or could have been done, in laboratory conditions. A complete bibliography of experimental tests of the special theory of relativity using astronomical observations can be found in [5].

The experiments which will be discussed below can be divided into three groups. The first group contains experiments whose results are not in doubt. This includes, for example, the Michelson-Morley experiment (not to be confused with the interpretation of its result, see below). Lately such experiments have been done with much greater accuracy (second-order Doppler shift [7], the two gas-laser experiment [28]). In addition, experiments have been done in conditions in which relativistic effects are of very considerable magnitude (variation of mass with velocity [8,9]).

In the second group we may include experiments to verify the independence of the velocity of light of the velocity of the source. Such experiments have not, until quite recently, given any useful results. Moreover, the experiments of Kantor [50] (which turned out to be erroneous [51]) appeared to show that the light velocity does depend on the motion of the source.

Recent direct experiments in laboratory conditions [2,3] have confirmed the independence of the light velocity of the motion of the source.

Finally, the third group of experiments [44,15,49,17] involves fundamentally new tests of the principle of relativity.

The special theory of relativity rests on two postulates [1]: (1) the principle of relativity, (2) the postulate of the constancy of the light velocity and its independence of the motion of the source.

I. TESTS OF THE INDEPENDENCE OF LIGHT VELOCITY OF THE VELOCITY OF THE SOURCE

Until recently the information on the independence of the light velocity of the velocity of the source depended on the analysis of astronomical data about the motion of double stars. [59,32] The interpretation of these data is not entirely unique.[12] A more promising experiment is that of A. N. Bonch-Bruevich and V. A. Molchanov (1956) [12] on the Doppler effect at the edge of the sun's disc.

Direct tests, in laboratory conditions, of the independence of the velocity of light of the velocity of the source were carried out in 1963.[2,3]

In the first of these [2] the time of flight of γ

quanta between a moving or stationary source and the detector was measured.

An excited carbon nucleus (C^{12*}) served as the moving source, and the stationary source was an excited oxygen nucleus (O^{16*}). The nuclei were excited by exposing a carbon or oxygen target to the α particle beam (of 14 MeV energy) from a cyclotron. Under α-particle impact the carbon or oxygen nuclei were excited by the reactions $C^{12}(\alpha, \alpha')C^{12*}$ or $O^{16}(\alpha, \alpha')O^{16*}$. The excited state of carbon (4.43 MeV) has a half-life of 6.5×10^{-14} sec. This means that it decays immediately, before the carbon nucleus has had time to come to rest (the carbon nucleus recoils under the impact of the α particle). By observing the Doppler effect it was found that at the instant of emission of the quantum the nucleus has a mean velocity of $(1.8 \pm 0.2) \times 10^{-2}c$ (c is the light velocity).

The excited state of oxygen (6.13 MeV) decays much more slowly (half-life 1.2×10^{-11} sec). As a result the oxygen nucleus comes to rest before emitting the γ quantum (this is confirmed by observation of the Doppler effect).

In the experiment one compares the time of flight of the γ quanta from the moving source (carbon target) and from the stationary source (oxygen target) to the detector. The targets were placed at a distance of 30 cm from each other and could easily be interchanged. We denote by τ_1 and τ_2 the time intervals between the pulses caused by the targets in the detector (say, τ_1 for the case in which the carbon target is in front, τ_2 when the targets have been interchanged, i.e., the oxygen target is first). If $\tau_1 = \tau_2$, the velocity of the γ quanta does not depend on the motion of the source. If, on the other hand, the velocity of the γ quantum depends on the source velocity v_S, and equals $V = c + v_S$,

$$\Delta\tau = \tau_1 - \tau_2 = \frac{2Lv_s}{c^2} ;$$

L is the distance to the detector, which in the experiment was 4 metres. Inserting the values for L, v_S and c, we find

$$\Delta\tau = 0.5 \cdot 10^{-9} \text{ sec}$$

The value observed in the experiment was

$$\Delta\tau = (-0{,}2 \pm 0{,}2) \cdot 10^{-9} \text{ sec}$$

We now discuss the second experiment [3].

Here the electron-positron annihilation is used to test the independence of the light velocity of the velocity of the source. In the center-of-mass system the electron and the positron move towards each other with equal speeds of approximately ½c. In the annihilation two γ quanta are produced. If the radiation source (the center of mass of electron and positron) is at rest, the quanta are emitted at an angle of 180° with equal velocity. If the center of mass of electron and positron (the *radiation* source) is moving the quanta are emitted at an angle of less than 180°, whose magnitude depends on the positron energy.

If the γ quanta pass through counters, two alternative results may be found: (1) if the second postulate of the special theory of relativity is correct the γ quanta will reach the counters simultaneously (one must of course, ensure that the distances from the point of annihilation to the two counters are equal); (2) if this postulate is wrong and the source velocity is superimposed on the velocity of light, then the γ quantum emitted in the direction of the incident positron velocity should have a velocity greater than c, and the one moving in the opposite direction should have a velocity less than c. The *first* γ quantum then travels to the counter more quickly than the second.

The positron source was a disc of Cu^{64} of 2 cm diameter and 0.1 mm thickness, which was placed in a reactor. The positron-electron annihilation took place in a 1 mm thick perspex disc. The counters were at a distance of 60 cm. from this. A coincidence circuit was used to measure the time of flight of the γ quanta from the disc to the counters. The measurement showed that to within 10% the velocity of γ quanta from a moving source is the same as that from a stationary source.

The results of the two experiments which have been described are rather crude, but they do confirm the second postulate of the special theory of relativity.[12] They are also of interest in connection with the foundations of the general theory of relativity[45].

Note that, whereas the astronomical tests of the second postulate[5] use cosmic sources moving with relatively low velocities, the source velocity in the experiments just described is much higher (comparable with light velocity).

It is well known that the "ballistic" theory rests on a denial of the second postulate. This theory is mainly associated with the name of Ritz[4]. This theory assumes that the velocity of light is the resultant of the source velocity and the velocity of light from a stationary source. Clearly the experiments described above provide yet another strong argument against the "ballistic" theory. (In addition, the experiments were done in a frequency region of electromagnetic radiation in which there were no previous tests of the second postulate)*.

II. TESTS OF THE CONSEQUENCES OF THE SPECIAL THEORY OF RELATIVITY

Many experiments do not test the postulates, but rather the consequences of the special theory of relativity.

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*The only experiment dealing with the question of the dependence of the velocity of γ rays on the velocity of the source is reported in[41]. However, according to[42], the results of[41] are not very clear.

One of these is the observation of the second-order Doppler shift, of the order of $(1 - \beta^2)^{-1/2}$, predicted by the special theory of relativity.

The experiment was first carried out in 1938 [6], then again in 1939 [43], and repeated in 1961 with greatly increased accuracy [7]. In this experiment hydrogen molecule ions (H_2^+ and H_3^+) were accelerated in an external field (maximum voltage 76 kV) to a speed of 2.8×10^8 cm/sec. In the collisions between the hydrogen molecules some fast excited hydrogen atoms were produced. These atoms emitted radiation. The theory of relativity predicts that an observation of the radiation emitted at an angle θ to the direction of the beam of hydrogen atoms should give the wavelength

$$\lambda_B = \lambda_0 \frac{1-\beta\cos\theta}{(1-\beta^2)^{1/2}} \approx \lambda_0\left(1-\beta\cos\theta+\frac{1}{2}\beta^2\right), \tag{1}$$

$$\lambda_R = \lambda_0 \frac{1+\beta\cos\theta}{(1-\beta^2)^{1/2}} \approx \lambda_0\left(1+\beta\cos\theta+\frac{1}{2}\beta^2\right). \tag{2}$$

Here, (and below) $\beta = v/c$, where v is the speed of the atomic beam (light source) and λ_0 the wavelength in a reference frame attached to the moving atoms. (The expansion used in (1) and (2) is legitimate since $\beta < 0.01$.)

Equation (1) applies when the beam is travelling towards the observer, and (2) when it travels away from the observer.

Subtracting (1) from (2) gives

$$2\lambda_D = \lambda_R - \lambda_B = 2\lambda_0\beta\cos\theta. \tag{3}$$

This shows that from the knowledge of λ_R, λ_B, λ_0, and θ one can determine β (this was done in the experiment).

On the other hand we find by adding (1) and (2), for the mean wavelength

$$\lambda_Q = \frac{1}{2}(\lambda_R + \lambda_B) = \lambda_0\left(1+\frac{\beta^2}{2}\right). \tag{4}$$

One finds therefore for the relativistic change in wavelength

$$\delta\lambda_{\text{rel}} = K\lambda_0\beta^2, \tag{5}$$

with $K = \frac{1}{2}$. The experiment showed that $K = 0.498 \pm 0.025$. This is much more accurate than the result of ref.[6] where the error was 10-15%.

The second experiment of this type [8,9] is the determination of the variation of mass with velocity.

The special theory of relativity predicts that for a particle of rest mass m_0 moving with velocity v, the mass increases to

$$m = m_0(1-\beta^2)^{-1/2}. \tag{6}$$

But the momentum, p, of the particle is related to its mass and velocity by

$$m = \frac{p}{v}. \tag{7}$$

A comparison between the masses given by (6) and (7) was carried out in [8,9]. In [8], a proton beam of 660 MeV energy was used. It is evident from (6) and (7) that the comparison requires a measurement of the velocity v of the proton and of its momentum p.

The proton velocity was determined from the angle at which it emitted Cerenkov radiation (the experiment zone gave a substantial correction to the Bragg curve).

The momentum was measured as follows. It is well known that a current-carrying wire under tension will, in a magnetic field, take the shape of the orbit of a charged particle in the same field. The tension in the filament is usually produced by a small weight. From the knowledge of the weight, and the magnitude of the current one easily find the momentum of the particles whose orbit coincides with the shape of the wire.

The final conclusion of [8] is: The expressions (6) and (7) agree, apart from an observed deviation

$$\frac{\Delta m}{m} = 0.004(1 \pm 0.6).$$

There are many other papers in which the consequences of the theory of relativity are discussed. For example, Farago and Janossy [14] deduce from the agreement between experiment and theory on the fine structure of the spectrum of atomic hydrogen that Eq. (6) must be correct to within 0.05%.

It is of interest to note that the variation of mass with velocity may be very substantial. In modern cyclic electron accelerators* the electrons move with velocities so close to c that their mass exceeds the rest mass of the proton.

III. EXPERIMENTS OF THE MICHELSON-MORLEY TYPE

The Michelson-Morley experiment [36,37] was done in 1887, long before the appearance of the special theory of relativity, in order to test the hypothesis of a "mechanical" light ether. This experiment is now described in every textbook (for example [35], which also gives the arguments originally used by Michelson and Morley). There are also many good popular accounts of this experiment,[10,11] and there is no need to describe it here.

The result of the experiment (not to be confused with its interpretation, see below) is now beyond doubt, although some attempts were made to disprove it. The best known of these is the work of Miller (1925-26)[53-55] in which a rotation of the interferome-

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*The example of an accelerator demonstrates very lucidly that it is impossible to accelerate particles to velocities greater than c. Indeed, it is easy to show that

$$\beta^2 = \left(\frac{v}{c}\right)^2 = 1 - \frac{1}{2}\left(\frac{m_0c^2}{mc^2}\right)^2 = 1 - \frac{1}{2}\left(\frac{W_0}{W}\right)^2.$$

In other words, for an energy $W = 10^9$ eV, $v = 0.999999987c$ (for electrons $W_0 = m_0c^2 \approx 0.5 \times 10^6$ eV).

ter produced a noticeable shift of the interference fringes. Other experimenters [16,28,55-58] failed to reproduce anything like Miller's results.

It is known that Michelson and Morley did not find any shift of the fringes and interpreted this as the absence of the motion of the earth relative to the "ether." Michelson wrote to Rayleigh about this:

"My dear Lord Rayleigh, the experiments on the relative motion of the Earth and the ether are completed, and the result is definitely negative. The expected shift of the interference fringes from the null position should have been 0.4 fringes; the greatest shift was 0.02 and the average less than 0.01. . ."

The Michelson experiment was repeated several times with increasing accuracy. It was shown already in [16] that the motion of the earth relative to the ether, if it exists, must have a speed less than 1.5 km/sec. The latest, and most accurate, experiment of this type was carried out in 1963 by a group of American physicists using a gas (He-Ne) laser [28].

The experiment is based on the following considerations. The frequency (ν) of a laser with a parallel-plane resonator is given by the expression

$$\nu = \frac{\nu_m Q_m + \nu_c Q_c}{Q_m + Q_c}, \qquad (8)$$

where ν_m is the transition frequency, $\nu_c = nc/2L$ the frequency of the oscillation mode; $Q_m = \nu_m/\Delta\nu_m$, where $\Delta\nu_m$ is the half-width of the resonance line of the medium; $Q_c = \nu_c/\Delta\nu_c$ is the half-width of the oscillator spectrum.

Since usually $Q_c \gg Q_m$,

$$\nu \approx \nu_c = \frac{nc}{2L} = \frac{nc}{2L_0}.$$

If the axis of the resonator is parallel to the velocity (v) of the "ether" the laser frequency will be

$$\nu_c(1) = \frac{nc}{2L_0}(1 - \beta^2); \qquad (9)$$

if it is at right angles,

$$\nu_c(2) = \frac{nc}{2L_0}(1 - \beta^2)^{1/2}. \qquad (10)$$

In the apparatus two lasers are placed at right angles to each other, and a rotation by 90° should give a change in frequency

$$\frac{2[\nu_c(2) - \nu_c(1)]}{\nu_c} = \beta^2$$

(if there exists an ether relative to which the apparatus is in motion).

For $\nu_c = 3 \times 10^{14}$ cps and v = 30 km/sec (the velocity of the orbital motion of the earth), so that $\beta^2 = 10^{-8}$, the observable frequency change should be about 10^6 cps, which is easily detectable.

The precision of the measurement is limited (1) by the frequency shift due to spontaneous emission (2) by the variations in L (and hence of the frequency) due to thermal fluctuations.

The spontaneous emission changes the frequency by

$$2\delta = \frac{8\pi h\nu}{P(\Delta\nu_c)^2},$$

where P is the power generated, and $h\nu$ the energy of each quantum of radiation. Typical values for a gas laser with a He-Ne mixture, $P = 10^{-3}$ W, and $\Delta\nu_c/\nu_c = 10^{-8}$, make the quantity 2δ about 0.1 cps.

The variations in L due to thermal fluctuations can cause a greater error in the measurement of the frequency. If the resonator mirrors are mounted on cylindrical supports, the possible frequency shift is

$$2\delta' = 2\nu\left(\frac{2kT}{YV}\right)^{1/2},$$

where Y is Young's modulus, V the volume, and T the temperature of the supports. For typical values of the parameters, δ' is about 3 cps. The apparatus is shown schematically in Fig. 1.

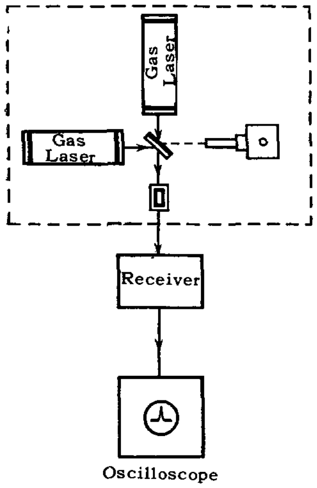

FIG. 1. Schematic diagram of the apparatus using two He-Ne gas lasers placed at right angles to each other on a turntable. The diagram shows the lasers. The broken line indicates the turntable on which the apparatus is mounted.

The experiment was set up as follows. Two lasers were mounted on a turntable at right angles to each other. The effect of vibrations was reduced by a complicated suspension in which the turntable and other equipment (weight 200 lb) were suspended on rubber cords. The turntable was operated by means of a soft rubber belt. By this arrangement it was possible to reduce the effect of acoustic vibrations considerably. (The effect of sound waves in the air seems to have been negligible.)

The results of the experiment led to the conclusion that no motion of the earth relative to the "ether" was detected, and in any case the velocity of the Earth relative to the "ether" cannot exceed 30 m/sec. (This is 45 times more accurate than the result of Joos [16].)

The conclusions of Michelson, as well as those of the authors of the gas laser experiment, relate to the absence of motion of the earth relative to the "ether" (i.e., to a preferred frame of reference).

In general the result of experiments of the Michelson-Morley type is often regarded as a proof of the principle of relativity, i.e., of the non-existence of a preferred frame of reference. This is evidently not correct. The result of experiments of the Michelson-Morley type proves, in fact, the existence of the relativistic contraction of lengths in the moving frame of reference. In order to show this, we shall give a more consistent treatment of the experiment [27] (the treatment by Michelson himself, which has passed since into the textbooks, does not allow for the relativistic contraction).

We shall start from the assumption that there exists a reference frame Σ (Einstein's "rest frame") in which light travels isotropically and rectilinearly with a constant velocity c.

For the quantitative formulation of this statement one must assume that an observer in the frame Σ has a "ruler" and a "clock" at his disposal with which he can measure space and time intervals.

In the frame Σ (a four-dimensional Euclidean space) the metric is defined to be

$$d\sigma^2 = d\tau^2 - \frac{1}{c^2}(d\xi^2 + d\eta^2 + d\zeta^2). \tag{11}$$

Consider now a second reference frame S, which moves relative to the first with uniform velocity v. The observer moving with the system S should naturally also be equipped with a "ruler" and a "clock" so that he can measure space and time intervals in the system S (t, x, y, z).

Without making any assumption about the behavior of the light velocity or any other physical law in the system S, we may consider the problem of finding the transformation T between the systems (t, x, y, z) and (τ, ξ, η, ζ). In a sufficiently small neighborhood T can be treated as linear. If we take into account the fact that the only relevant parameter in this transformation T can be the velocity vector v, and that the reference frames coincide for v = 0, it can be shown that the most general metric in the frame S is of the form

$$d\sigma^2 = g_0^2 dt^2 - \frac{1}{c^2}[g_1^2 dx^2 + g_2^2 (dy^2 + dz^2)], \tag{12}$$

where

$$\left.\begin{aligned} g_0 &= (1-\beta^2)^{1/2} a_0^0, \\ g_1 &= (1-\beta^2)^{1/2} a_1^1, \\ g_2 &= a_2^2. \end{aligned}\right\} \tag{13}$$

From the postulates of the theory of relativity

$$g_0 = g_1 = g_2 = 1.$$

In the relations (13) a_0^0 is the transformation coefficient between $d\tau$ and dt, a_1^1 that between ζ and x, and a_2^2 that between η and y (and between ζ and z).

The result of the Michelson-Morley experiment can be formulated as follows: The total time required by light to travel in vacuo a certain distance l and back does not depend on the direction in which the light travels.

The time which light requires to cover a distance l in vacuo (travelling at an angle h to the x axis), can be obtained immediately by setting $d\sigma = 0$. We then find from (12)

$$t = \frac{l}{c g_0}(g_1^2 \cos^2 h + g_2^2 \sin^2 h)^{1/2}. \tag{14}$$

This time should be independent of h, i.e., it is necessary that $g^1 = g^2$ or

$$a_2^2 = a_1^1 (1-\beta^2)^{1/2}. \tag{15}$$

This relation indicates that any object in the moving system is shortened* in the ratio $(1-\beta^2)^{1/2}: 1$, in comparison with the rest system.

From the results of experiments of the Michelson-Morley type one can also conclude that the average velocity of the light on the outward and return journey is constant, but we cannot say anything about the independence of the light velocity (without averaging) of the velocity of the observer, i.e., whether the principle of relativity is valid, or whether there exists a preferred frame of reference.

It is evident that quite generally the principle of relativity cannot be checked by second-order experiments [33,52] (experiments in which the expected effect is proportional to β^2; experiments of the Michelson-Morley type are also second-order experiments). This is stressed by many authors, including Eddington [47]: "Strictly speaking, the Michelson-Morley experiment does not prove that the velocity of light is the same in all directions, it only tells us that the average velocity there and back is the same in all direction."

The question whether or not the principle of relativity is valid could be settled by first-order experiments (expected effect proportional to β). First-order experiments are also interesting because the magnitude of the expected effects is of the order of 10^{-4}, i.e., much larger than for second-order experiments [13].

When we speak of first-order experiments we have in mind experiments capable of establishing the independence of the velocity of light of the velocity of the observer (not only its independence of the velocity of the source).

It is obvious that the numerous experiments of the interference type, or any experiments using closed

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*We note that, in spite of the considerable magnitude of the contraction of fast-moving bodies in the direction of motion, this contraction cannot be observed[46, 49]. The light quanta from objects *at different distances from the eye or from the photographic* plate do not arrive simultaneously on the retina or the photographic plate. As a result, the image of a moving body is distorted. For a moving body this distortion is precisely such as to compensate the contraction. The visible form of the body does not change, but it appears to have turned a little.

light paths, are unsuitable for this purpose. For such experiments already Lorentz[48] showed generally that they must always give a null result.

IV. FIRST-ORDER TESTS OF THE SPECIAL THEORY OF RELATIVITY

Proposals for first-order tests of the special theory of relativity keep appearing in the journals[13,19–25,26,33] although many of them turn out, under careful examination, to be actually second-order experiments[20].

At present two first-order experiments have been carried out, and both are based on a suggestion by Møller[44].

He considered the following problem. Assume that the velocity of a radiating source is u in the laboratory frame, and that the direction of observation is given by the unit vector e. Then, if the laboratory system in turn is moving relative to the absolute reference frame of the aether with a velocity v, the observer sees a frequency

$$\nu = \nu_0 \left(1 + \frac{eu}{c} + \frac{(eu)^2}{c^2} + \frac{vu}{c^2} \right). \qquad (16)$$

How can this relation be verified experimentally? The first experiment[15,39] was carried out in the following way. Two molecular light generators were mounted on a turntable. The molecular beams of ammonia which excited the generators were in the opposite directions to each other. The beat frequency of the two generators was determined with an accuracy of 10^{-12}.

If there were an "ether," then a rotation of the turntable by 180° should result in a change of the beat frequency ($\Delta\nu/\nu$) by $4vu/c^2$, where u is the mean thermal velocity of the ammonia molecules, and v the velocity of the Earth relative to the "ether."

To see this we may apply equation (16) to this situation, treating the ammonia molecules as the moving source of radiation, and the resonator as the receiver (observer). Since $e \cdot u = 0$ (the molecules travel along the axis of the resonator, and radiate in the transverse direction), Eq. (16) gives for the frequency of the radiation from the generator

$$\nu = \nu_0 \left(1 + \frac{vu}{c^2} \right). \qquad (17)$$

The sign of the term $\mathbf{v} \cdot \mathbf{u}/c^2$ is obviously positive for one of the generators and negative for the other (since their molecular beams move in opposite directions).

We then see from (17) that, on rotating the turntable by 180°, i.e., by interchanging the generators, we should obtain a change of $4vu/c^2$ in the beat frequency. Although this effect is of second order in the velocity of light, it is of first order in terms of the velocity (v) of the laboratory relative to the "ether." Taking v as the velocity of the Earth (30 km/sec) and u as 0.6 km/sec, the change in the beat frequency should be

$$\Delta\nu = 4 \frac{uv}{c^2} \nu_0 \approx 20 \text{ cps}.$$

According to the special theory of relativity the beat frequency should not be affected by the rotation of the turntable.

The measurements showed a systematic variation of the beat frequency of ± 1/20 cps in a day. In a series of measurements carried out on weekends the variations in the beat frequency were found to be only ± 1/50 cps. These variations were much less than expected, and evidently connected with disturbances from other equipment.

Thus the experiment with two molecular generators contradicts the "ether" theory and confirms the principle of relativity.*

These deductions met, however, with strong objections[23]. Essentially, these were that the system of "molecule and resonator" was not equivalent to a molecule radiating in free space, and a radiation receiver. Carnahan[23] came to the conclusion that the experiment with two molecular generators should give a negative answer regardless of whether or not the aether exists. To this discussion Møller also made a contribution[13] in which he provided a more careful analysis of the experiment, with the conclusion that the experiment establishes the principle of relativity.

The other first-order test of the principle of relativity[17] is based on the Mössbauer effect. A γ-ray source (a foil of Fe^{56} containing Co^{57}) and an absorber (a foil of ordinary iron, containing 2% Fe^{57}) were placed on opposite ends of a fast rotor (the rotor speed was either 100 rps or 600 rps).

The rotor was inside an evacuated glass vessel. A window was provided in the vessel, outside of which there was a counter.

We shall discuss the possible results of this experiment, following Møller[13]. For this purpose one must generalize Eq. (16) somewhat, since in this case both the source and the receiver (absorber) are moving. Møller has shown that, if the ether exists, and source and absorber are at the same distance from the axis of rotation, the frequency of the radiation "seen" by the absorber is given by (17). During the rotation of the rotor the scalar product $\mathbf{v} \cdot \mathbf{u}$

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*In the beginning of this article we already mentioned the Michelson-Morley type experiment with two He-Ne gas lasers on a turntable, and stated that this experiment only confirms the relativistic contraction, and cannot settle the question whether the ether exists. The point is that the frequency of the He-Ne gas laser is defined by the frequency of the resonator (i.e., its length), whereas the frequency of the molecular generator is defined by the transition. For this reason the gas laser experiment belongs to the experiments of second order and differs essentially from the molecular generator experiment.

varies between zero and $|v||u|$, and accordingly the frequency ν_a must vary, this change of frequency must cause a substantial change in the absorption, and this can be verified by means of the counter.

The theory of relativity, on the other hand, gives $\nu_a = \nu_0$, and there should be no variation except for the dependence of frequency on the velocity of rotation.

The experiment did not show any change in the radiation frequency, and consequently any ether, or, more accurately, did not show any motion of the earth relative to the ether with a speed exceeding 17 m/sec, at any rate.

Although the two experiments referred to are first-order experiments [cf. Eq. (17)], it is easy to see that the expected effect is proportional to $1/c^2$. It would be useful to carry out an experiment in which the expected effect is proportional to $1/c$.

One proposal for such a first-order experiment is, for example, contained in [30,31]. The suggestion is to carry out a measurement of the phase difference of the oscillations of two non-synchronized molecular generators placed a few metres from each other on a turntable. If the distance is L, the phase difference is

$$\varphi = \omega t = 2\pi \frac{L}{\lambda}, \quad \lambda = \frac{c_{\text{phase}}}{\nu}.$$

If the relative signal velocity (light velocity) depends on the velocity of the receiver (observer) the phase difference should change with the direction of motion. According to the special theory of relativity there should be no change in the phase difference. The change in the direction of motion can be obtained by turning the turntable through 180°. The magnitude of this effect depends on the first power of β. Indeed, the difference between the times of flight for the outward and return journey is

$$\frac{\Delta t}{t} = \frac{t_1 - t_2}{t} = \frac{\frac{L}{c-v} - \frac{L}{c+v}}{t} = 2\frac{\beta}{1-\beta^2} \approx 2\beta.$$

The phase change corresponding to this difference is $\Delta\varphi/\varphi = 2\beta$, or $\Delta\varphi = 2\beta\varphi = 2\beta \cdot 2\pi L/\lambda$. For $\lambda = 1.25$ cm, L = 12.5 m and $\beta = 10^{-4}$ (taking for v the orbital velocity of the earth of 30 km/sec) we find $\Delta\varphi = 0.4\pi$.

The phase difference can be measured by using the arrangement shown in Fig. 2. This uses three molecular generators (the third being auxiliary). The phase difference between the two main generators is observed from a Lissajous figure on the oscilloscope. On rotating the apparatus the Lissajous figure should alter its shape if the light velocity depends on the velocity of the laboratory relative to the ether.

For this experiment one requires a very high relative stability of the two molecular generators. During the time taken for rotating the turntable the relative phase of the generators should not change appreciably.

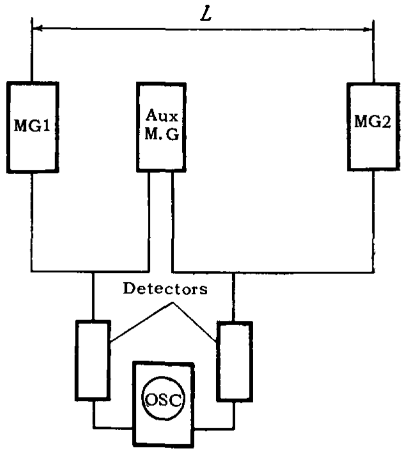

FIG. 2. Schematic diagram showing the layout of the first-order experiment to test the special theory of relativity. The diagram shows the two molecular generators (M.G.1 and M.G.2) and the auxiliary molecular generator (Aux. M.G.)

This leads to a required phase stability of

$$\frac{\Delta\nu}{\nu} = \frac{\Delta\varphi}{\omega\tau} < \frac{0.4\pi}{2\pi \cdot 10^{10} \cdot 10} = 10^{-12}$$

(the time for rotating the turntable has been taken as 10 sec). The sensitivity of the experiment can be increased by using as the link between the generators a wave guide in which the radiation travels with a reduced phase velocity.

A similar experiment was proposed in [19] but, since this would make use of lasers, its dimensions can be made much smaller (L = 30 cm) and therefore the apparatus can be screened.

Amongst other proposals we should mention [33], which suggests using the Mössbauer effect. In summing up the present state of the experimental verification of the special theory of relativity it may be said that the existence of relativistic effects (the contraction of length, the time dilation, the increase of the mass, etc.) is sufficiently securely established. To doubt this would really amount to doubting the existence of atomic energy or of particle accelerators. (The design principle of high-energy accelerators depends essentially on the special theory of relativity.) From the quantitative point of view it would naturally be useful to increase the accuracy of direct experiments testing the postulate of the independence of the light velocity of the velocity of the source. In view of the great importance of the principle of relativity it would also be desirable to carry out further experiments to verify this principle, in particularly those in which the light velocity enters linearly rather than quadratically.

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