Search for a relative anisotropy in the velocity of light and the velocity of neutrons

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The time-of-flight difference between neutrons and γ rays over a flight path of 1000 m was measured as a function of time of day. It was found that the amplitude of the diurnal variation in this difference, which amounted to 130 μsec on average, did not exceed ~ 1 nsec. This means that if one assumes that the neutron velocity is isotropic, the upper limit of the anisotropy in the velocity of light due to the rotation of the Earth in space is less than about 3×10^{-4}, whereas, if the velocity of light is isotropic, the upper limit for the anisotropy in the velocity of neutrons is less than about 7×10^{-6}. The latter estimate can be used to obtain an upper limit for the anisotropy in the inertial mass of the free neutron and for the space anisotropy parameter in the Bogoslovskiĭ theory, as stated in Sov. Phys. Dokl. **18**, 810 (1974).

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1. Attempts are constantly reported in the literature at finding the best, or an alternative, description of known physical facts, or at explaining certain unexpected experimental results in terms of theories and models in which space is given anisotropic properties. There are, in fact, no *a priori* reasons for assuming that space is isotropic and it may well be that the currently assumed isotropy of space is only approximately valid.

On the other hand, accurate direct data on the kinematic isotropy of space are practically confined to the results of the Michelson experiment and its modern analogs, and to the researches reviewed by Hughes,[1] in which a search was made for the anisotropy in inertial mass resulting from Mach's principle in accordance with the Cocconi–Salpeter model.[2] The essential point here is that the two groups of experiments are sensitive only in the second order to the anisotropy $\Delta f/f_0$ in the velocity (in the first case) or the mass (in the second case) if one of these quantities has an angular dependence of the form

$$f(\vartheta)=f_0+\Delta f\cos\vartheta, \tag{1}$$

where θ is the angle between the direction of motion and some particular direction. It is difficult to obtain unambiguous data on the upper limit for the anisotropy of space from astronomical data, cosmic studies, or accelerator techniques, because all calculations performed in these fields involve many other physical principles as well. Moreover, the precision of such data is relatively low, and rough estimates show that they do not exclude anisotropies in the velocity of celestial bodies of the order of 10^{-6}–10^{-5} and in the velocity of accelerated particles of the order of 10^{-4}–10^{-3}. Special experiments are therefore essential to verify the isotropy of space in as pure a form as possible, and with high precision.

2. In this paper, we report an attempt to establish whether or not the time of flight[1)] over a given length, measured for γ rays and neutrons produced simultaneously at the same point, depends on the variation in the direction of the baseline in space, due to the diurnal rotation of the Earth. This experiment has a particular feature, namely, the baseline is traversed in one direction only and, therefore, the experiment is a first-order experiment in the above sense, which is possible only because it involves the participation of two signals of different nature. The point is that, since information cannot be transmitted instantaneously to a remote point, the measurement of velocity on an open path requires a special definition of simultaneity at the starting and finishing points along the route. In this definition, the velocity of some signal has to be taken as a standard, i.e., the angular dependence of any particular velocity can be measured in the first order only relative to another, whose angular velocity is assumed known. This means that it is pointless to attempt to measure only the anisotropy in the velocity of light when the baseline is traversed in only one direction.

A detailed analysis of this question and a critique of a number of incorrectly formulated experiments (see, for example, Refs. 19, 21–24, 30, and 33 in the review given in Ref. 3), in which attempts were made to verify the isotropy of the velocity of light, can be found in Refs. 4–6. In the references just quoted, and in Refs. 7–10, it is shown that it is possible to introduce anisotropy into the kinematics of all physical processes (subject to the appropriate convention with regard to the angular dependence of the standard velocity), but this anisotropy is, in principle, unobservable. On the other hand, the relative anisotropy of two physical processes does not depend on this convention and can be investigated experimentally.

A nonzero effect in an experiment of this kind would indicate that reference frames attached to the Earth but having different orientation relative to fixed stars are nonequivalent and, in this sense, would be a violation of the principle of relativity.

3. Possible violations of the special theory of relativity on very small space-time scales have been analyzed by Blokhintsev,[11] who showed, in particular, that the behavior of particles could be described with the aid of an approach in which a special direction was introduced in four-dimensional space and, consequently, relativistic invariance was violated. It is thus nature to expect that the anisotropy will have a different effect on different particles. Thus, Phillips[12] has introduced a

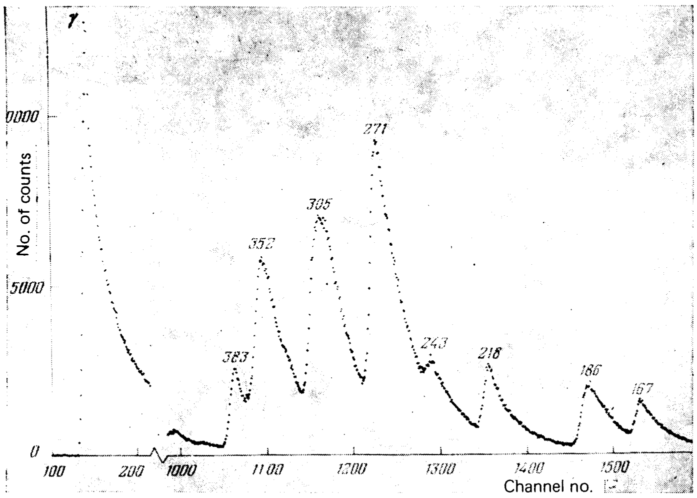

FIG. 1. One of the 33 time spectra of γ rays and neutrons measured at intervals of 4 h with analyzer channel width of 125 nsec. The neutron peak energies are indicated in keV.

"cosmic" field (which can be used, in particular, to explain CP violation in the decay of K_2^0 mesons) and Bogoslovskii[13] has introduced a certain special direction in space to explain the cutoff in the spectrum of primary cosmic particles at about 5×10^{19} eV, due to the interaction with the relict radiation. In both theories, photons are assumed to obey ordinary laws and the energy of a particle with nonzero rest mass is taken to depend on the orientation of the particle spin in the first theory and on its velocity in the second. The experiment reported here may serve as a direct verification of the "special theory of relativitity in a locally anisotropic space," developed by Bogoslovskii,[13] in which the kinetic energy of a particle of mass m and velocity $\mathbf{v}$ is approximately given by

$$W=(1-r)\frac{mv^2}{2}+r(1-r)\frac{m(\mathbf{v}\boldsymbol{\nu})^2}{2}, \tag{2}$$

where $\boldsymbol{\nu}$ is a unit vector in the special direction and r is a parameter representing the degree of anisotropy of space.

4. The experiment consisted of a periodic determination (at four-hour intervals) of the time-of-flight spectra of γ rays and neutrons traversing a 1000-m baseline. Lithium glass was used as the detector for both γ rays and neutrons. The measurements were performed on the pulsed reactor at the Joint Institute for Nuclear Research under booster conditions for which the half-width of the radiation burst was about 3 μsec. A thick iron filter was used as the neutron monochromator and provided sharp peaks in the spectrum corresponding to the interference minima in the total cross section. To achieve the optimum value of the γ-ray to neutron intensity ratio, two-thirds of the cross section of the beam was covered by iron and one-third by paraffin. The filters were placed at 70 m from the reactor and were about 25 cm thick. Figure 1 shows the relevant parts of one of the 33 spectra recorded by an analyzer with channel width of 125 nsec. The γ-ray peak and the neutron peaks can be clearly seen.

Figure 2 shows the experimental results. The upper curve shows the drift in the position of the γ-ray peak (full points) and the neutron peaks (open circles) on the time scale of the analyzer. This was due to instability in the time interval between the start of the analyzer and the reactor burst. The position of a peak was determined by approximating its front with a cubic parabola. For the neutron peaks, we calculated the weighted average of the fluctuation relative to the mean position of each peak, evaluated over 13 peaks. The differences between the peak shifts found in the upper graph are plotted in the lower graph. Since the points are scattered around the zero value, their departure from the abscissa axis can be used to examine whether or not the time-of-flight difference between neutrons and γ rays is constant.

We have also analyzed the possibility of another simple behavior of the time difference, namely, sinusoidal behavior with periods $T=24$ and 12 h, by fitting the experimental points to the formula

$$\tau=\Delta\tau\sin\frac{2\pi}{T}(t-t_0), \tag{3}$$

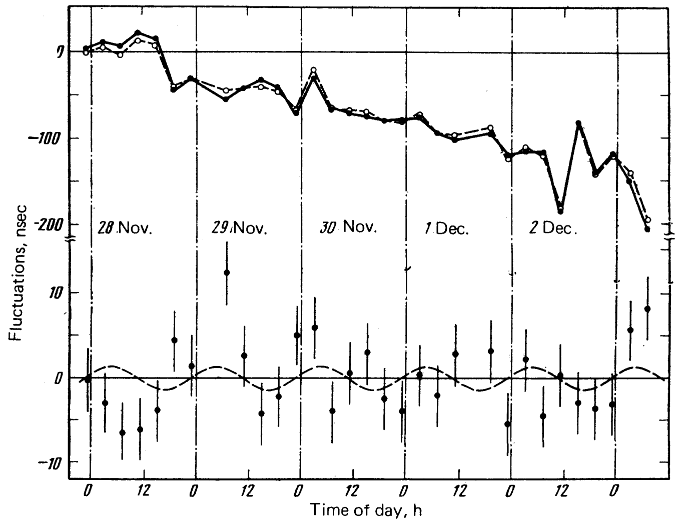

FIG. 2. Upper curves—drift in the position of the γ-ray peak (full points) and neutron peaks (open circles) along the time scale of the analyzer relative to their positions on the first measured spectrum; lower part—difference between the fluctuations shown at the top, shown as variations around zero value.

TABLE I.

Fit	Sinusoid, $T=24$ h			Sinusoid, $T=12$ h			Direct
	$\Delta\tau$, nsec	t_0, h	χ^2/n	$\Delta\tau$, nsec	t_0, h	χ^2/n	χ^2/n
All points	1,4±1.0	23±3	1.4	0.6±0.9	2±3	1.4	1.4
Without the point corresponding to 7 h on Nov. 29	0.9±1.0	21±4	1.1	0.8±1.0	−1±2	1.1	1.1
Without points at 7 h on Nov. 29 and Dec. 3	0.8±1.0	18±5	0,9	1.3±1.0	−1±2	0.9	1.0
Without points corresponding to Nov. 29 and Dec. 3	0.8±1.1	14±5	0.8	1.3±1.1	0±2	0,8	0.9

where t is the time of day. The broken line in the figure shows the results of fitting all the points to a sinusoidal curve with $T=24$ h. The Table lists the results obtained from different trial fits (χ^2/n is the value of χ^2 per point). These data lead us to the conclusion that the diurnal variation in the time-of-flight difference which, on average, amounts to 130 μsec, has an amplitude of ~1 nsec.

5. Thus, the null effect of the above experiment may be looked upon as a confirmation of the principle of relativity in the sense defined above (see Sec. 2). The important point here is that this verification was obtained in a direct experiment in which two different signals traveled in the same direction.[2)]

If we suppose that the running of the quartz clocks in the analyzer was independent of its orientation in space (see Ref. 16 and its interpretation in Ref. 1), and if we determine the time at different points, we can say something about the velocity as well. In the traditional definition of simultaneity adopted in the theory of relativity (in which it is assumed that the velocity of light is isotropic), the above result means that the neutron velocity is isotropic to an accuracy ~7×10^{-6}. If we then assume that the energy corresponding to the neutron peaks should be independent of the variation in the orientation of the iron filter (which contains unoriented nuclei), we can obtain an experimental upper limit for the anisotropy $\Delta m/m_0$ in the inertial mass of the free neutron and the space anisotropy parameter r in the Bogoslovskii theory.[13]

If one of these quantities is nonzero, and the kinetic energy of the neutron is fixed by the filter, its time of flight can be represented to within second-order terms by one of the following functions of the time of day:

$$\tau=\tau_0\left(1+\frac{1}{2}\frac{\Delta m}{m_0}\delta\sin\beta\cos\omega t\right), \qquad (4)$$

$$\tau=\tau_0\left[1+\frac{1}{2}r\delta\left(\cos\alpha\cos\varphi\sin 2\beta\cos\omega t+\frac{\delta}{2}\sin^2\beta\cos 2\omega t\right)\right], \qquad (5)$$

the first of which is obtained on the assumption that the neutron mass is of the form given by (1) and is related to velocity and kinetic energy in the usual way, and the second assumes that the neutron mass is constant and its kinetic energy is given by (2). In the formulas given by (4) and (5), τ_0 is the usual time of flight, $\alpha\approx31^\circ$ E is the azimuth of the beam direction, $\varphi\approx56^\circ$ is the latitude of Dubna, $\delta=(1-\cos^2\alpha\cos^2\varphi)^{1/2}\approx0.88$, β is the angle between the Earth's axis and the special direction, ω is the Earth's angular velocity, and ωt is the angle between the projections of the beam and of the special direction onto the equatorial plane. The absence of the 24-h periodic effect enables us to estimate from (4) that

$$(\Delta m/m_0)\sin\beta<2\cdot10^{-5}, \qquad (6)$$

where $\sin\beta\approx0.87$ if the special direction passes through the center of our Galaxy.[2] If we suppose that the vector $\boldsymbol{\nu}$ is perpedicular[13] to the plane of the ecliptic, then $\beta\approx23.5^\circ$ and, according to (5), the amplitude of the 12-h component of τ is smaller by a factor of about five than the amplitude of the 24-h component. The data listed in the table then enable us to conclude that:

$$r<5\cdot10^{-5}, \qquad (7)$$

Both (6) and (7) correspond to one root-mean square standard error in the parameter $\Delta\tau$ of (3).

It is important to note, in connection with (6), that all other methods used to search for the mass anisotropy[1,17] are based only on studies of the periods of oscillatory motions or quantum-mechanical transitions in atoms and nuclei, and that the effect was not previously investigated for free particles. The only published estimate of the value of r is $(1.3\pm2.4)\times10^{-8}$ and was obtained by Bogoslovskiĭ[13] from measurements of the Doppler shift of a Mössbauer line in a centrifuge.[18] This, of course, is a purely electromagnetic phenomenon. In our experiments, we have verified a different and independent consequence of this theory, so that the estimate given by (7) is of independent interest.

In principle, the clocks can be synchronized by sending out a neutron signal. If we assume that the velocity of the signal is the same in all directions, then our experimental result indicates that the velocity of light is isotropic to an accuracy of about 3×10^{-4}. In the language of the pre-Lorentzian ether, this indicates that the first-order experiment which we have carried out sets an upper limit of about 90 km/sec for the ether drift velocity.

The estimates given above are only the first results and do not exhaust the possibilities of experiments similar to those described above. Their precision can be increased by two or three orders.

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1) We are, in fact, interested in the difference in the time of "arrival", i.e., the time difference at a given point.

2) Brown *et al.*[14] and Guiragossian[15] appear to have been in a position to obtain this information in the case of light and

11-GeV electrons. However, the aim of their work was different, and it is difficult to establish anything about the diurnal variation in the time-of-flight difference between the electrons and photons from their papers as published.

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Orientation of nucleus excited in annihilation of positron on heavy-atom shell

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A calculation is made of the cross sections and orientation spin tensors of a nucleus excited in nonradiative annihilation of a positron by an electron from an (nlj) shell of an atom. Use is made of relativistic wave functions of the electron and positron, obtained by numerical integration of the Dirac equation with a single average Hartree–Fock–Slater atomic potential. The results of calculations of the factors governing the cross sections and orientation of the excited nucleus as a function of the positron energy $E_+ = 0.5$–6.55 MeV are presented graphically for the series of multipole transitions $E0$, $E1$, and $M1$ in annihilation on the K shell of an atom. The results are given for the atoms with $Z = 41,49,60,70,82$, and 92. Estimates are also obtained for the annihilation of a positron on the L shell of lead ($Z = 82$). The results are used to estimate the cross sections of nuclear excitation in positron annihilation and the angular distributions of the decay products (quanta, fission fragments, etc.) of a nucleus excited in this way. A brief discussion is made of possible applications of low-energy positron beams in nuclear spectroscopy.

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§1. INTRODUCTION

When a positron collides with an atom, we can expect not only two- and one-photon annihilation of the positron by an atomic-shell electron but also excitation of the nucleus of the atom as a result of nonradiative EL or ML transition from the ground nuclear state E_1 to a level E_2 is the sum of the positron (E_+) and (nlj)-shell electron (E_{nlj}) energies, agrees—within the width Γ—with the nuclear transition energy $E_2 - E_1$. This nuclear excitation process is of the resonance type and the width Γ is governed by the lifetime of the excited state of the system; in the case of annihilation on the K shell the value of Γ is usually equal to the width of a hole $\Gamma(K)$, but there are some exceptions to this rule.[1)] The resonance nature of the nonradiative excitation of a nucleus as a result of positron annihilation provides a new potential method for investigating the nuclear structure, whose practical implementation required a fairly strong "monochromatic" positron beam of controlled energy E_+; we shall be concerned with the range of low nuclear excitation energies $E^* < 10$ MeV.

Our earlier[1,2] results of calculations of the cross sections of some nuclei in the $40 < Z \leqslant 92$ range show that it is desirable to have positron beams with a cur-