Test of Spatial Isotropy Using a Cryogenic Torsion Pendulum

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Motion of the earth through the cosmic neutrino background, or through certain kinds of vacuum states, produces a term of the form $g\boldsymbol{\sigma}\cdot\mathbf{v}$ in the energy of an electron. To search for such a term a cryogenic torsion pendulum carrying a transversely polarized magnet was used. Superconducting shields reduced magnetic torques. A $\boldsymbol{\sigma}\cdot\mathbf{v}$ term would produce a sinusoidal oscillation of the pendulum with a period of one sidereal day. Such an oscillation was not detected, and a new limit of 8.5×10^{-18} eV has been set for the splitting of the spin states of an electron at rest on the Earth.

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Two recent experiments[1,2] have greatly increased our confidence in the isotropy of space. The experiment reported here is also a search for spatial anisotropy, but uses electron spins as the sensing element rather than nuclear spins. We look for a term in the energy of the electron spin of the form $\boldsymbol{\sigma}\cdot\mathbf{v}$, where $\boldsymbol{\sigma}$ is the spin vector and $\mathbf{v}$ is the velocity of the Earth with respect to a preferred frame of rest. Such a frame can arise in two distinct ways, from a sea of particles (for example, the 3-K photon background, as in the experiment of Smoot, Gorenstein, and Muller[3], or as a result of an anisotropy in the vacuum state itself. In an earlier investigation[4] we conjectured that such an anisotropy could arise in the context of broken-symmetry theory. Since that time, Stodolsky has pointed out[5] that the interaction of electrons with a sea of neutrinos would produce an average energy of the form sought here, though it is too small to be detected at present.

We can express the magnitude of such an anomalous torque in terms of the magnetic field that would produce the same torque. The previous best result[4] set a limit of 4×10^{-12} T; I have now extended that limit to below 10^{-13} T (1 nG). The most recent experiment with nuclear spins[2] attains a similar sensitivity, but it attains, of course, a much higher sensitivity in terms of energy, because of the small size of the nuclear magnetic moment. The present experiment is complementary to that one; not only does it use a different particle (important in exploring unknown interactions) but it is also sensitive (as the other experiment is not) to torques which are proportional to the magnetic moment of the particles involved. This is because the experiment of Ref. 2 compares the precession of two isotopes in the same field, whereas I try to eliminate the magnetic field altogether.

As in Ref. 4, I used a torsion pendulum carrying a shielded, transversely polarized magnet. The basic design change consisted of performing the experiment at liquid helium temperature, and using superconducting shields to reduce the effect of magnetic fields. A $\boldsymbol{\sigma}\cdot\mathbf{v}$ term will result in a sinusoidal variation in the orientation of the pendulum with a period of one (sidereal) day. The experimental problems were (1) shielding the pendulum from external magnetic fields, (2) achieving maximum sensitivity to changes in orientation, and (3) achieving long-term stability for a run lasting several days (in practice, five). Of these, (3) was much the hardest to solve.

The experiment was conducted in the same laboratory as our previous one, at a rural site about 40 km from St. Louis. Local vibrations due to cars and other machinery were negligible, though the experiment was, of course, sensitive to major seismic events.

The general layout of the pendulum in its vacuum chamber is shown by Phillips,[6] where details of magnetic shielding are also given. The vacuum chamber is 1.8 m high, and is surrounded by a liquid-helium container and two Molypermalloy shields to attenuate the Earth's magnetic field. The pendulum is a thin-walled aluminum cylinder, 1.2 cm in diam and 60 cm long. At its upper end, it carries the mirror for the optical lever and plates for electrostatic feedback. At the lower end, it carries the magnet, which is a cylinder 5 cm high and 0.6 cm diam, polarized in the horizontal direction. The magnet material is an alloy of copper, cobalt, and cerium. The magnetic moment (which is dominated by the spin contribution for this material) is 150×10^{-3} N m/T. The magnet is aligned North-South for greatest sensitivity.

The pendulum is suspended by a Kevlar fiber with torsion constant 3.45×10^{-9} N m/rad. This leads to an easily detectable angle of 4.35×10^{-6} rad if the magnet is subject to a torque equivalent to 10^{-13} T. To prevent the buildup of electrostatic charge on the pendulum, I included in the vacuum chamber a weak radioactive source, which created an ionizing path in the surrounding gas.

The orientation of the pendulum is measured by an optical level, with a technique similar to those of Phillips and Woolum[4] and Roll, Krotkov, and Dicke.[7] In the present experiment, the light source and light detector are located outside the top of the vacuum chamber at room temperature. Light is first focused onto a vertical slit 2.5×10^{-3} cm wide. The light then enters the vacuum chamber horizontally and is reflected downwards to an achromat. After passing through the lens, it is reflected again to the horizontal direction. Part of the light is then reflected from the mirror on the pendulum, and part from a fixed mirror just above it. After the light retraces its path, it forms two images, separated vertically by about 4 mm. I refer to these as the "moving" and "fixed" images, respectively. A rotating chopper wheel admits light alternately from these two images to the detection system. The light is refocused onto a 2.5×10^{-3}-cm-diam tungsten wire vibrating at 3072 Hz. Light passing the wire is detected by a photomultiplier tube whose output goes to a phase-sensitive detector. The chopper wheel is driven at a submultiple of the wire frequency.

The electronics is shown schematically in Fig. 1. Two separate feedback loops are used, involving the "fixed" and "moving" images, respectively. Consider first the signal from the fixed image. This is used to control the orientation of a glass plate located in the light path for both images, just ahead of the chopper wheel. A change in the orientation of this plate shifts both images together transversely. The feedback signal adjusts this plate to keep the fixed image centered on the vibrating wire. With this technique, any disturbances which affect the position of the fixed image are automatically subtracted from the record for the moving image.

The signal from the moving mirror, on the other hand, is used to generate a feedback voltage which is applied to plates surrounding the pendulum. Both a "differentiated" and an "integrated" signal are applied, so that the equation of motion of the pendulum is converted from $I\ddot{\theta}+k\theta=f$ to $I\ddot{\theta}+b\dot{\theta}+k\theta+c\int\theta\,dt=f$, where I denotes the moment of inertia of the pendulum and k the torsion constant of the suspension fiber. f represent any external torque acting on the pendulum.

The coefficients b and c are at our disposal; they are chosen in such a way that all the roots of the (cubic) characteristic equation are equal. In the absence of external torques the differential equation can then be written $\dddot{\theta}+3p\ddot{\theta}+3p^2\dot{\theta}+p^3\theta=0$, where p is a constant related to the undamped period of swing of the pendulum, T, by $p=2\pi\sqrt{3}T$. (For our pendulum, $T=180$ sec.) The integrator signal acts to keep the moving image centered on the wire. This automatic nulling cannot, of course, follow external disturbances on a time scale faster than about $1/p$, but it is quite adequate for the diurnal torque which is of chief interest in this experiment. The data of the experiment consist of readings of the integrator taken every minute. These data are formed into 15-min averages for data analysis.

We need to know how much torque is exerted on the pendulum by the feedback plates when unit voltage is applied to them. For this purpose the magnet was removed from the pendulum and the intermediate image was observed through a telescope while the voltage on

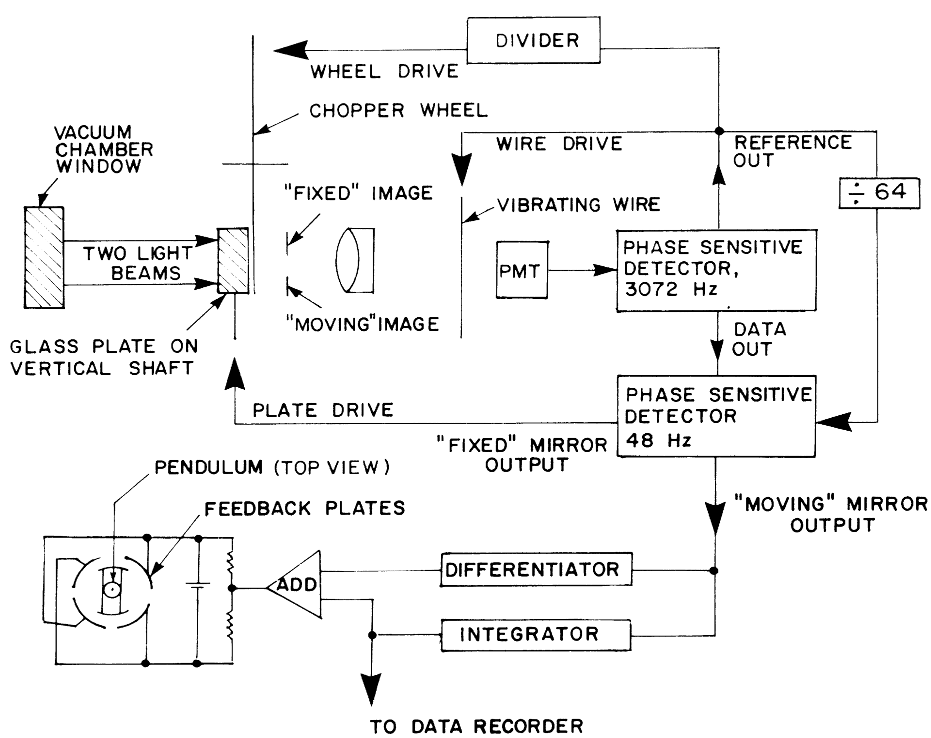

FIG. 1. Schematic diagram of the final stage of the optical detection system and the following electronics.

the plates was varied. The image is moved through about 1 cm during these measurements, corresponding to an angle of about 4×10^{-3} rad. The measured number (4.20×10^{-12} N m/V) is about 25% lower than the theoretical estimate, because of edge corrections. There is a 100:1 attenuator between the integrator output and the plates, so the relation between torque and integrator output voltage is 4.20×10^{-14} N m/V.

An atmosphere of helium gas was maintained in the vacuum chamber, at a pressure of 0.1 T. This produced adequate damping of the transverse modes of the pendulum (which involve comparatively rapid motions) while hardly affecting the torsional mode. The damping of the torsional mode was dominated by the feedback circuit, and gas damping was less effective by at least an order of magnitude. I therefore anticipated that the thermal noise due to bombardment by the molecules of the damping gas would be unimportant, and was concerned instead with the noise generated in the feedback loop itself. Direct measurement of this, however, showed that it could not account for the observed noise in the pendulum. I believe that the dominant contribution to the noise actually came from vibration due to the boiling of the liquid helium and from turbulence in the damping gas.

To provide a sufficiently stable environment for the pendulum, I had to devise a way to keep the liquid-helium level constant in the tank surrounding the vacuum chamber (the "working tank"). The technique for doing this[8] involved the controlled supply of liquid helium from a second tank (the "supply tank"). The liquid level could be maintained constant to within $\frac{1}{2}$ cm over the whole period of the run. The data-taking portion of each run was limited to 4.5 days by the capacity of the supply tank. The temperature in the laboratory was regulated to within $\frac{1}{2}$ °C. An insulated box around the optical equipment at the top of the vacuum chamber made it possible to keep the temperature in this region constant to within 0.1 °C.

Data were taken for three such periods, in April, September, and December of 1986, with results shown in Fig. 2. Had I seen a noticeable sinusoidal signal, spreading the data over a year in this way would have helped us to see any modulation of the effect due to the earth's motion around the sun. (This modulation may be of order 10% for a velocity of order 400 km/sec[3].) In practice, since I obtained a null result, data from all three runs were conflated as a function of sidereal time.

The most obvious long-term pattern in each run was a steady counterclockwise drift which always stayed within range of the integrator. This linear drift was subtracted from the data before more detailed analysis was done. I recorded the laboratory temperature along with the integrator readings, but the two were not appreciably correlated. Control runs with magnet removed give similar data, so we do not have to correct for diurnal variations due to nonmagnetic causes.

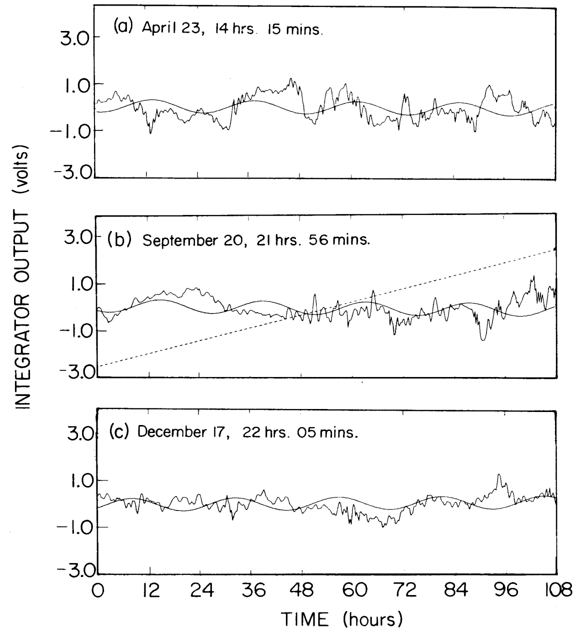

FIG. 2. Graphs of integrator voltage vs time for the three runs referred to in the text. Also shown on each graph is the sinusoidal variation expected from a $\boldsymbol{\sigma}\cdot\mathbf{v}$ coupling at the limiting magnitude cited (equivalent to a magnetic field of 7.3×10^{-14} T). The dashed line on the second graph shows the mean slope of the data before the drift was subtracted by a linear transformation. The times shown on each graph are the GMT times (for the year 1986) at which the runs began.

The data were analyzed by adapting the Bayesian method of Jaynes[9] to the present situation in which we want a limit on the amplitude A of a sinusoidal variation of known frequency ω in the presence of noise. I assume the pendulum is subject to white Gaussian noise torques whose variance η^2 can be estimated from the data. I also make the same approximations as in Sec. 6 of Ref. 9. Integrating over the irrelevant phase angle I find that the probability density that describes the state of our knowledge of the amplitude is proportional to $A\times\exp(-NA^2/4\eta^2)I_0(A[NC(\omega)]^{1/2}/\eta^2)$, where N is the number of data points and $C(\omega)$ the Schuster periodogram. The 99% limit for this density occurs at $A=0.259$ V. The equivalent magnetic field is then $0.259\times4.2\times10^{-14}/150\times10^{-3}=7.3\times10^{-14}$ T. In this field the two electron spin states are split by 8.5×10^{-18} eV.

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