Search for an exotic long-range interaction which breaks *T* and *P* parity

P. V. Vorob'ev

G. I. Budker Institute of Nuclear Physics, Siberian Branch of the Russian Academy of Sciences, 630090 Novosibirsk, Russia

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The results of an experimental search for an exotic long-range interaction which breaks T and P parity are presented. These results can be interpreted as a test of the equivalence principle for spin-polarized matter.

1. Introduction

Such (pseudo-) Goldstone bosons as the arion, the axion, the familon, and the majoron (among many others) have recently been discussed extensively in the literature.[1–3] If any of these bosons are massless or very light, their exchange should result in the appearance of some new long-range forces. Moreover, one cannot rule out the possibility of a long-range force associated with the existence of arbitrarily long strings connecting particles.[4]

The exchange of a massless or very light boson with $J^P=0^-$ or $J^P=1^+$ does not result in the appearance of resultant forces between unpolarized matter. If the fermions in the interacting bodies are polarized, however, there will be a resultant force, and there will be a torque. In generalizations of the general theory of relativity which include twisting, the twisting field should give rise to an induced magnetization.[5,6]

An exotic scalar–pseudoscalar long-range force of fermions has been discussed in many places.[7–20] In this case a scalar boson at one vertex behaves as a scalar, while a scalar boson at another vertex behaves as a pseudoscalar. A monopole–dipole interaction of this sort breaks both T and P parity; it also violates the equivalence principle. Macroscopic manifestations of this interaction would be a polarization of the spins of a ferromagnet in the exotic field of a large mass and a moment of force acting on a permanent magnet.

Although the exotic long-range forces are exceedingly weak, they can be sought experimentally because the interaction with matter is coherent, and the small value of the coupling constant is offset by the huge number of fermions involved in the interaction of macroscopic objects.

In the nonrelativistic approximation, the scalar–pseudoscalar interaction can be written[10]

$$V(r)=\hbar^2 G_{pp}\frac{\bar{\sigma}\bar{n}}{r}\left(\frac{1}{\lambda_a}+\frac{1}{r}\right)e^{-\frac{r}{\lambda_e}} \qquad (1)$$

or, in the case $m_a=0$, which is the case discussed below,

$$V(r)=\hbar^2 G_{pp}(\bar{\sigma}\bar{n})/r^2. \tag{2}$$

Here $G_{pp}=g_p g_p/8\pi m_F$, m_F is the mass of the fermion, $\lambda_a=h/m_a c$ is the Compton wavelength of the boson, and σ are the spin matrices. An interaction of this sort breaks P and T parity because of the $\bar{\sigma}\bar{n}$ term.

Gibbons[11] and Peres[12] write the interaction of the fermion with the field of the massive object in the form

$$V_a=\alpha g\hbar/c. \tag{3}$$

Here $g=G_N M/r^2$ is the acceleration due to gravity, G_N is the gravitational constant, M is the mass of the scalar source of the exotic field (the earth or the sun), and r is the distance from the center of mass of the source to the observer. The quantity V_a is evidently the interaction energy of the gravitational dipole, which has a dipole moment $mr_c=\hbar/c$. Comparing (2) and (3), we find

$$\alpha=k(G_{pp}/G_N)\hbar c/m, \tag{4}$$

where m is the mass of the fermion at the scalar vertex, and k is the mass of the fermions which are the sources of the scalar field, divided by the total mass of the unpolarized source object. Such an interaction leads to a precession of the fermion spin in the field of a massive unpolarized object. The precession axis would be oriented vertically. The behavior of a spinor in the earth's field was analyzed in detail in Refs. 11–14. The spin precession frequency is

$$\omega=2V_a\hbar=2\alpha g/c. \tag{5}$$

Leitner and Okubo[14] suggest characterizing P- and T-breaking interactions of the type in (2) by means of a parameter A:

$$E(r)=E_0(r)(1+A\bar{\sigma}\bar{n}), \tag{6}$$

where $E_0(r)=G_N Mm/r$ is the energy of the Newtonian gravitational interaction, and m is the mass of the fermion. As was pointed out in Ref. 11, the parametrization in (6) is not a natural one for this problem. However, the parameter A corresponds to the relative change in the effective mass (or weight) of the spin-polarized object, which is measured in experimental tests of the equivalence principle using twisting weights:

$$\delta m/m=A. \tag{7}$$

The relationship between the Leitner–Okubo parameter A and the constant α is

$$A=\alpha(r_c/R), \tag{8}$$

where $r_c=\hbar/mc$ is the Compton radius of the fermion.

We can introduce an effective magnetic field B_{eff}. If the fermion at the vertex with the pseudoscalar interaction is an electron, then we have

$$B_{\text{eff}}=2\alpha\hbar/c\mu_B, \tag{9}$$

where μ_B is the Bohr magneton. With $\alpha=1$ in the earth's field, $B \simeq 2.3\times 10^{-14}$ G, we would have $\omega=7\times 10^{-8}$ Hz. Note that since we are dealing here with an interaction with the spin of the fermion, not with the magnetic moment, this interaction therefore is not screened by superconducting shields.

2. Brief review of experimental constraints imposed on the constant of *T*-violating interactions

Apparently the first study in this direction was that carried out by Cokkoni and Salpeter.[15] Some later papers[16,17] showed that the NMR frequency for various nuclei is independent of the orientation of the spins with respect to the sun and the earth. The best limitations currently available for the interaction of nucleons with the earth's field come from experiments involving ions confined in a trap:

$$\omega<8.5\times 10^{-5}, \quad \alpha<1.3\times 10^{3}, \tag{10}$$

according to a study carried out by Wineland *et al.*[18] by a $^{9}\mathrm{Be}^{+}$ NMR method; and

$$\omega<1.3\times 10^{-6}, \quad \alpha<30, \tag{11}$$

according to a study by Venema *et al.*[19] using a $^{199}\mathrm{Hg}$ NMR method. The best limitations for the interaction with the field of the sun are

$$\omega<1.5\times 10^{-5}, \quad \alpha<3.7\times 10^{5}, \tag{12}$$

according to a study by Lamoreaux *et al.*[20] who used a $^{199}\mathrm{Hg}$ NMR method.

Limitations on the interaction of electrons with earth's field can be found from g-2 experiments,

$$\omega<10^{-1}, \quad \alpha<1.5\times 10^{6}, \tag{13}$$

according to a study by Vasserman *et al.*[21] using the g-2 $e^{+}e^{-}$ method; from experiments involving ions confined in a trap,

$$\omega<8.5\times 10^{-5}, \quad \alpha<2.6\times 10^{7}, \tag{14}$$

according to a study by Wineland *et al.*[18] using a $^{9}\mathrm{Be}^{+}$ NMR method; and from experiments using the method of an induced magnetization of a ferromagnet,

$$\omega<10^{-3}, \quad \alpha<2.5\times 10^{7}, \tag{15}$$

according to a study by Vorob'ev[9] and

$$\omega<2\times 10^{-4}, \quad \alpha<5\times 10^{6}, \tag{16}$$

according to the present study.

3. The *T*-1 experiment of the Institute of Nuclear Physics

We have carried out an experimental search for a T-violating long-range interaction. We used an induced-magnetization method which we had developed for an experimental search for a quasimagnetic arion field.[6-9] We found a limitation on the constant of the T-violating interaction of an electron with the sun's field.

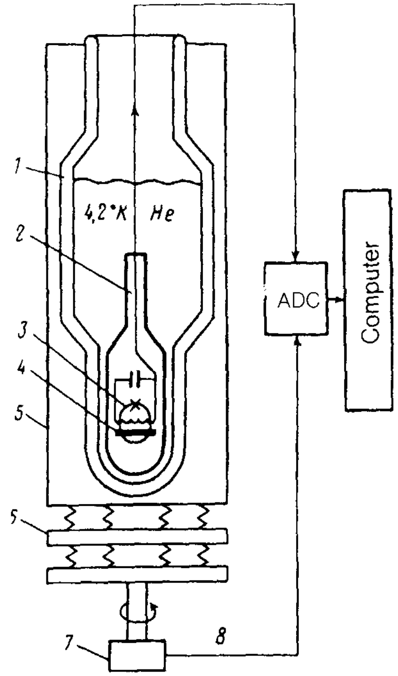

FIG. 1. Schematic diagram of the detector. *1*—Cryostat; *2*—superconducting magnetic shield; *3*—SQUID magnetometer; *4*—probe of the cryogenic Permalloy-like alloy 78ND2M; *5*—housing; *6*—acoustic filter; *7*—drive and photographic coordination system; *8*—strobe.

We measured the magnetization of a ferromagnetic sample inside a superconducting magnetic shield as a function of the orientation with respect to the sun. The orientation was varied by mounting the detector on a platform and rotating the platform at a velocity of about 1 rpm. The platform had an acoustic filter, on which the cryostat and the rf electronic unit of the SQUID were mounted. The angular position of the probe was monitored by a photographic coordination scheme. Figure 1 is a schematic diagram of the detector. The sensitive element of the detector is a probe of the cryogenic Permalloy-like alloy 78ND2M with dimensions of $10 \times 1 \times 2$ mm. This probe is enclosed by a three-layer lead superconducting magnetic shield 20 mm in diameter and 150 mm long. The magnetization of the probe is measured by a SQUID magnetometer with a sensitivity based on magnetic flux of $\delta\Phi \leqslant 10^{-4}\ \Phi_0\sqrt{\mathrm{Hz}}$. The effective magnetic susceptibility of the probe, μ_F, was measured in fields corresponding to $(1\text{–}10^{-2})\Phi_0$ (Φ_0 is the flux quantum) in the volume of the detector. The result was $\mu_F \simeq 10$. A small solenoid which created a weak magnetic field at the position of the probe was used to calibrate the system. The superconducting shield with the probe and the SQUID were enclosed in a nitrogen-free glass cryostat with a volume of about 2.5 liters.

The SQUID output signal was digitized by a Ts0609 analog-to-digital converter (ADC), which was strobed by the photographic system which made the coordination with the angular position of the detector. We thus did not need to worry about stabilizing the detector rotation velocity. The entire system was monitored and controlled by a microcomputer. The SQUID output signal was subjected to Fourier analysis. The Fourier component of the magnetization of the probe at the detector

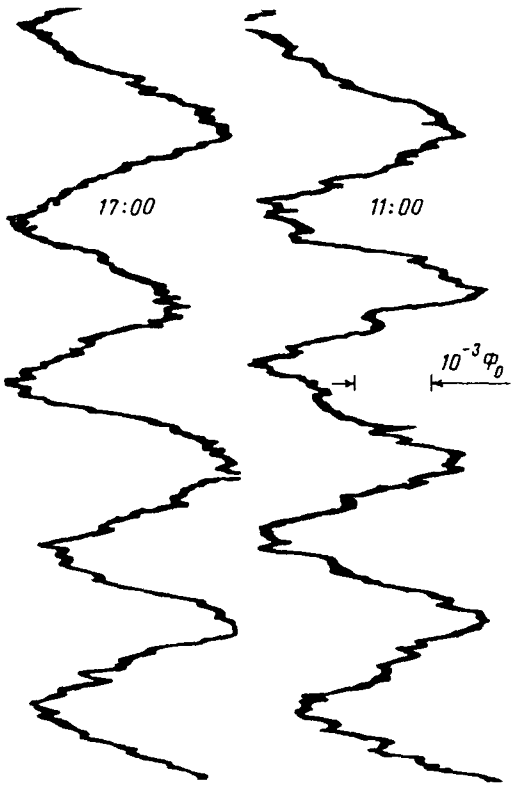

FIG. 2. Recordings of the SQUID signal from two experimental runs carried 6 h apart.

rotation frequency was singled out. The other harmonics of the Fourier expansion were used to evaluate the noise.

It was found that the detector output signal at the rotation frequency was highly sensitive to the tilt of the rotation axis with respect to the vertical. The appreciable amplitude of the first harmonic of the magnetization is attributable to a magnetostriction effect of the probe material in the earth's gravitational field. A 5° tilt of the rotation axis with respect to the vertical increases the SQUID signal by a factor of 10. This effect may have been the effect we were seeking, i.e., an exotic T-violating field of the earth. However, an effect of that magnitude contradicts the results found in the g-2 experiments.[21] In a detector of this sort, a systematic noise at the observation frequency is evidently unavoidable. An interaction of the detector with the field of the sun and the local galaxy should be manifested primarily as a change in the phase of the signal with the period of the solar or sidereal day.

Figure 2 shows an illustrative recording of the SQUID signal for two experimental runs, carried out 6 h apart. From the absence of a significant phase shift in the series of recordings of the signal separated by intervals of 1/4 of a day we find the following limitation:

$$B<7\times10^{-11}\ \text{G},\quad \omega<2\times10^{-4}\ \text{Hz},\quad \alpha<5\times10^{6}. \qquad (17)$$

We plan to significantly improve the accuracy in the very near future, by installing a universal joint for the detector and by increasing the statistical base.

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