Violation of T invariance in superfluid ^{3}He

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The electric dipole moments of the neutron and the electron and the T-odd weak electron-neutron interaction give the ^{3}He atom an electric dipole moment. As a consequence, a macroscopic electric dipole moment arises in the polarized A_1 phase of superfluid ^{3}He, and T-odd effects occur in the NMR in the A and B phases.

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The violation of T invariance, which has previously been observed only in the decays of neutral K mesons, is one of the central questions in the physics of elementary particles. There is accordingly much interest in finding a different manifestation of a T-odd interaction: electric dipole moments of elementary particles. In particular, the experimental limitations which have been determined for the electric dipole moment of the neutron have greatly shortened the list of candidate models for the violation of T invariance.

In this letter I wish to point out that it is possible, in principle, to significantly improve the sensitivity of the search for the electric dipole moments of the neutron and the electron, by making use of superfluid ^{3}He. The pairing of ^{3}He atoms occurs in a triplet p state. There are different superfluid phases of ^{3}He, with different orientations of the spin **S** and of the orbital angular momentum of the Cooper pairs, **L**.

As Schiff[1] has pointed out, Fairbank was the first to discuss the possible use of ^{3}He to search for violations of T invariance. Fairbank suggested using a dilute solution of ^{3}He in ^{4}He for this purpose. Leggett[2] predicted that in the so-called B phase of superfluid ^{3}He, in which all the Cooper pairs have the same vector $\langle \mathbf{L} \times \mathbf{S} \rangle$, an electric dipole moment directed along $\langle \mathbf{L} \times \mathbf{S} \rangle$ would arise because of the weak interaction which violates spatial parity. Since the axial vector $\langle \mathbf{L} \times \mathbf{S} \rangle$ does not change sign upon time inversion, the appearance of such an electric dipole moment, while violating spatial parity, would not violate temporal parity. An important point here is that the orientation energy of the electric dipole moment in an external field is proportional to the total number of particles in the condensate, which is huge. Leggett's comparison[2] of this energy with the thermal energy, kT (we are dealing with temperatures $T \sim 10^{-3}$ K here), led to the conclusion that to measure such an electric dipole moment seemed to be more or less feasible.

Again in the present paper we are interested in this advantage presented by the number of particles in the condensate. In the polarized A_1 phase of superfluid ^{3}He, a sample acquires an electric dipole moment, directed along the spin, upon a violation of P and T invariance. If, following Leggett,[2] we assume that it is possible to measure an electric-dipole-moment density on the order of 10^{-12} electron/cm^2 in superfluid ^{3}He, then with a particle density $N \sim 10^{22}$ cm^{-3} we conclude that the electric dipole moment of a single atom could be measured in this manner even if it had the fantastically low value

$$d_a \sim 10^{-34} \text{ electron} \cdot \text{cm}. \qquad (1)$$

So far, however, the degree of polarization which has been attained in the A_1 phase is far less than unity. Since ^{3}He in the normal phase has already been produced with a high degree of polarization,[3,4] there is the hope that a polarization approaching unity can be achieved in superfluid ^{3}He.

In the other superfluid phases, the electric dipole moment of the atom should give rise to an NMR frequency shift in an external electric field. A curious point in this connection is the longitudinal resonance in the A phase, which may be regarded as a Josephson junction between subsystems of the condensate with $S_z = 1$ and $S_z = -1$ (Ref. 5). The interaction of the electric dipole moment with the electric field changes the difference between the chemical potentials of these subsystems.

Unfortunately, for a ^{3}He atom to have an electric dipole moment $\sim 10^{-34}$ electron · cm, the nucleus or electron would have to have an incomparably larger electric dipole moment. The reason is that in a system of point particles having an electrostatic interaction the electric dipole moment of any of the particles would be completely screened.[1] However, thanks to the hyperfine interaction, primarily, rather than the electrostatic interaction, the electric dipole moment of the nucleus, d_{nuc}, makes the following contribution to the electric dipole moment of the atom[1]:

$$d_a^{(1)} = -\frac{5}{6} Z^2 \alpha^2 \frac{m}{m_p} \mu d_{\text{nuc}} \simeq 1{,}5 \times 10^{-7} d_{\text{nuc}}. \qquad (2)$$

Here $Z = 27/16$ is the effective charge of the exponential variational function of the ground state of the atom, $\alpha = 1/137$, m and m_p are the masses of the electron and the proton, and $\mu = -2.13$ is the magnetic moment of the nucleus.

Although the ground state of the helium atom is a singlet, a contribution to d_a is also made by the electric dipole moment of the electron, $\mathbf{d}_e$. Since $\mathbf{d}_a$ in ^{3}He is directed along the nuclear spin $\mathbf{i}$, it is clear that the effect will arise only because of the hyperfine interaction, H_{hf}. Working from arguments similar to those used by Schiff,[1] we can write the effective Hamiltonian which leads to the electric dipole moment of an atom as $i d_e/e\,[\vec{\sigma}\mathbf{p}, H_{\text{hf}}]$, where $(-e)$, $(1/2)\vec{\sigma}$, and $\vec{\mathbf{p}}$ are the charge, spin, and momentum of the electron. The part of this expression which does not depend on $\vec{\sigma}$ can be written in the form

$$H = -\frac{2\pi e \mu d_e}{m m_p} (\mathrm{i}\vec{\nabla})\,\delta(\mathbf{r}). \qquad (3)$$

Using the approximate expression[1]

$$\psi(\mathbf{r}_1, \mathbf{r}_2) = \frac{Z^3}{\pi a^3} \exp\left[-\frac{Z}{a}(r_1 + r_2)\right]\left\{1 - \frac{\vec{\mathscr{E}}}{4e} \sum_{i=1,2} \mathbf{r}_i\left(r_i + \frac{2a}{Z}\right)\right\} \qquad (4)$$

for the wave function of the ground state of the atom in a field $\vec{\mathscr{E}}$, we can find the contribution to d_a induced by interation (3):

$$d_a^{(2)} = 2Z^2 a^2 \frac{m}{m_p} \mu d_e \simeq -3.5\times 10^{-7} d_e. \tag{5}$$

Finally, a moment d_e may be produced by a T-odd contact interaction of an electron with a neutron. In the nonrelativistic approximation, the $\vec{\sigma}$-independent part of this interaction can be written in a form similar to (3):

$$H = \frac{Gk}{\sqrt{2}m} (\mathbf{i}\vec{\nabla})\delta(\mathbf{r}). \tag{6}$$

Here $G = 10^{-5} m_p^{-2}$ is the Fermi constant, and k is a dimensionless number which is to be measured. We assume that the nuclear spin $\mathbf{i}$ is the same as the spin of the unpaired neutron. The electric dipole moment of the atom which is induced by interaction (6) is

$$d_a^{(3)} = -\frac{Gm^2 a^2 Z^2}{\sqrt{2}\pi} eak \simeq -0.5\times 10^{-24} k \text{ electron}\cdot\text{cm}. \tag{7}$$

Comparing (2), (5), and (7) with (1), we see that an experiment with superfluid ^{3}He could have a sensitivity $\sim 10^{-27}$-10^{-28} electron $\cdot$ cm in a measurement of the electric dipole moment of a neutron, d_n (for simplicity, we are assuming that d_{nuc} is equal to the moment d_n of the unpaired neutron, although a T-odd nucleon-nucleon interaction could also make a contribution to d_{nuc}), and that of the electron, d_e, and it might have a sensitivity $\sim 10^{-10}$ in the measurement of the coefficient k. At present, the best constraints on d_n and d_e are $|d_n/e| < 4.2 \cdot 10^{-25}$ cm (Ref. 6) and $|d_e/e| < 2.8 \cdot 10^{-24}$ cm (Ref. 7). For the constant k of the electron-neutron interaction in (6), no bounds at all have been reported. For the corresponding characteristic of the electron-proton interaction, the best bound is[8] $|k_p| < 2\times 10^{-4}$.

In conclusion, we wish to point out that the sensitivity of experiments in superfluid ^{3}He suggested by Leggett and in the present letter would also be sufficient to observe a precession of **S** and **L** due to an interaction with a "quasimagnetic" component g_{0n} of the gravitational field caused by the rotation of the earth.

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