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T-INVARIANCE VIOLATION IN SUPERFLUID ^{3}He

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Abstract

The electric dipole moments (edm) of the neutron and the electron, as well as T-odd weak electron-neutron interaction, induce the edm of the ^{3}He atom. Due to it the macroscopic edm in the polarized A_1 phase of superfluid ^{3}He and T-odd effects in the NMR in the A and B phases arise.

The origin of the T-invariance violation observed up to now only in the decays of the neutral K-mesons is undoubtedly one of the central problems in the modern elementary particle physics. This is the cause of the great interest roused by the searches for another manifestation of T-odd interaction - the edm of the elementary particles. In particular, the experimental bounds obtained for the neutron edm allowed to reduce considerably the scope of competing models of the T-invariance violation.

In the present note I wish to attract attention to the principal possibility to increase considerably the sensitivity of the searches for the neutron and electron edm using in them superfluid ^{3}He. The pairing of ^{3}He atoms takes place in the triplet p-state. There are some superfluid phases of ^{3}He differing in orientation of the spin $\mathbf{S}$ and the orbital angular momentum $\mathbf{L}$ of the Cooper pairs.

For the first time the possibility to use ^{3}He in the searches for the T-invariance violation was considered, as it is mentioned in Ref[1], by Fairbank who had proposed to use a dilute solution of ^{3}He in ^{4}He. In Ref[2] it was predicted that in the so-called B phase of superfluid ^{3}He where all Cooper pairs have the same vector $\mathbf{L}\times\mathbf{S}$, due to parity violating weak interaction an edm arises directed along $\mathbf{L}\times\mathbf{S}$. Since an axial vector $\mathbf{L}\times\mathbf{S}$ does not change sign under time reversal, this edm violating spatial parity conserves time parity. It is of crucial importance here that the orientation energy of the edm in an external field is proportional to the total number of particles in condensate. From the comparison of this energy with the thermal one kT, and the temperature here is $T \sim 10^{-3}$K, the conclusion is made in Ref[2] that the measurement of such an edm constitutes more or less realistic problem.

The same advantage due to the number of particles in the condensate is had in mind also in the present work. In the polarized A_1 phase of superfluid ^{3}He if both P- and T-invariance are violated, the edm of a sample arises directed along its spin. If following Ref[2] one assumes that in superfluid ^{3}He the edm density about 10^{-12}e·cm^{-2} can be measured, then at the particle density $N \sim 10^{-22}$cm^{-3} it means that the edm of a single atom can be measured in this way at the fantastic level

$$d_a \sim 10^{-34} \text{e·cm} \qquad (1)$$

However the degree of polarization in the A_1 phase attained now is far from unity. But since a high degree of polarization is obtained already in normal ^{3}He [3,4], one can hope that in superfluid ^{3}He a polarization close to unity will be attained as well.

In other superfluid phases the atom edm should lead to a NMR frequency shift in an external electric field. Curious in this respect looks the longitudinal resonance in the A phase which can be interpreted as the Josephson transition between the condensate subsystems with $S_z=+1$ and $S_z=-1$ [5]. The edm interaction with an electric field leads to the change of the difference of chemical potentials between these subsystems.

Unfortunately, for the ^{3}He atom edm to arise at the level $\sim 10^{-34}$e·cm, the nucleus or the electron should possess an incomparably larger edm. The point is that in a system of point-like particles with electrostatic interaction the edm of each of them is totally screened [1]. However, due mainly to non-electrostatic hyperfine interaction the nucleus edm d_N leads to the atom edm, the contribution being [1]:

$$d_a^{(1)} = -\frac{5}{6} Z^2 \alpha^2 \frac{m}{m_p} \mu d_N \simeq 1.5 \cdot 10^{-7} \text{e·cm} \qquad (2)$$

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

Although the ground state of the helium atom is a singlet one, the electron edm d_e contributes also to d_a. Since $\boldsymbol{d}_a$ in ^{3}He is directed along the nucleus spin $\boldsymbol{i}$, it is clear that the effect arises only due to hyperfine interaction H_{hf}. Using the considerations close to those described in Ref[1], the effective Hamiltonian leading to the atom edm can be written as $\frac{id_e}{e}[\boldsymbol{\sigma}\boldsymbol{p}, H_{hf}]$ where (-e), $\frac{1}{2}\boldsymbol{\sigma}$ and $\boldsymbol{p}$ are the charge, spin and momentum of the electron. The part of this expression that does not depend on $\boldsymbol{\sigma}$ is transformed to

$$H = -\frac{2\pi e \mu d_e}{m m_p} (\boldsymbol{i}\cdot\boldsymbol{\nabla}) \delta(\boldsymbol{r}) \qquad (3)$$

Using the approximate expression

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

for the wave function of the atomic ground state in a field $\boldsymbol{\mathcal{E}}$ [1] we find the contribution to d_a induced by the interaction (3):

$$d_a^{(2)} = 2Z^2 \alpha^2 \frac{m}{m_p} \mu d_e \simeq -3.5 \cdot 10^{-7} d_e \qquad (5)$$

And at last d_a can be induced by a contact T-odd electron-neutron interaction. In the non-relativistic approximation the part of this interaction independent of $\boldsymbol{\sigma}$ looks like (3):

$$H = \frac{G k}{\sqrt{2}\, m} (\boldsymbol{i}\cdot\boldsymbol{\nabla}) \delta(\boldsymbol{r}) \qquad (6)$$

Here $G = 10^{-5} m_p^{-2}$ is the Fermi constant, k is a dimensionless number characteristic of this interaction that should be measured. The spin of the nucleus $\boldsymbol{i}$ is assumed to coincide with the spin of the non-paired neutron. The atom edm induced by the interaction (6) is

$$d_a = -\frac{G m^2 \alpha^2 Z^2}{\sqrt{2}\, \pi} eak \simeq -0.5 \cdot 10^{-24} k \text{ e·cm} \qquad (7)$$

Comparing (2), (5) and (7) with (1), we see that the experiment with superfluid ^{3}He could have the sensitivity ($10^{-27} \div 10^{-28}$) e·cm in the measurement of the neutron edm d_n (to simplify the matter we assume d_N to be equal to the edm d_n of the non-paired neutron although a contribution to d_N can be given also by a T-odd nucleon-nucleon interaction) and the electron edm d_e, as well as the sensitivity $\sim 10^{-10}$ in the measurement of the constant k. The best bounds on d_n and d_e are now: $|d_n/e| < 4.2 \cdot 10^{-25}$ cm [6], $|d_e/e| < 2.8 \cdot 10^{-24}$ cm [7]. For the constant k of the electron-neutron interaction (6) no bounds are known at all; for the corresponding characteristic of the electron-proton interaction the best bound is: $|k_p| < 2 \cdot 10^{-4}$ [8].

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