ON ELECTRIC POLARIZATION OF HELIUM ATOMS BY ACCELERATION

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Possibility of explanation of high electric activity in superfluid helium [1–3] by polarization of helium atoms caused by acceleration is researched. It is shown that this effect is insufficient to explain the phenomenon.

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1. INTRODUCTION

In a number of experimental works [1–3] an unexpected high electric activity of superfluid helium was observed, existing under different conditions. In work [1] it was discovered that propagation of second sound waves is followed by oscillations of electric field. In subsequent experiments [2, 3] it was shown that the polarization in helium can arise without temperature oscillations if continuous fluxes are present. In order to explain experiments [1–3], studying electric phenomena in superfluid helium, in [4, 5] a mechanism of polarization of helium atoms under the action of gravitation and acceleration was proposed. It was shown [4, 5], based on analogy with Stuart-Tolmen effect and some phenomenological arguments, that accelerated atom must gain dipole moment

$$\vec{d} = \gamma\dot{\vec{v}}, \tag{1}$$

where $\dot{\vec{v}}$ is the acceleration of atom, $\gamma = M\kappa_0/2Z|e|$ is the *"gravitoelectric"* susceptibility, κ_0 is the polarizability of single atom, M, Z are the atomic mass and nucleus charge, $|e|$ is the elementary charge.

Gravitational and inertia forces are sensitive neither to magnitude, nor to the sign of the charge, thus the nature of the predicted in [4, 5] effect needs more detailed analysis. In connection with this a quantum-mechanical problem of helium atom in the ground state under the action of external forces is considered in this work. It is shown, that if these forces are of gravitational and inertial nature, atom is not polarized. Accelerated atom in gravitational field can become polarized if there are also forces of other nature acting upon it. The obtained value of polarization is three orders of magnitude less than the estimated in works [4, 5] and is of different sign.

2. CONSIDERATIONS

Consider hamiltonian of helium atom in ground state with a constant force $\vec{F}$ acting upon its nucleus and $\vec{f}$ acting upon its electrons:

$$\begin{aligned} H = &-\frac{\hbar^2}{2M_0}\triangle_{\vec{R}} - \frac{\hbar^2}{2m}\triangle_{\vec{r}_1} - \frac{\hbar^2}{2m}\triangle_{\vec{r}_2} - \\ &-Ze^2/|\vec{R}-\vec{r}_1| - Ze^2/|\vec{R}-\vec{r}_2| + \\ &+e^2/|\vec{r}_1-\vec{r}_2| - \vec{F}\vec{R} - \vec{f}\vec{r}_1 - \vec{f}\vec{r}_2, \end{aligned} \tag{2}$$

where $\vec{R}$ denotes coordinate of nucleus, $\vec{r}_1, \vec{r}_2$ are coordinates of electrons, M_0, m are masses of nucleus and electron respectively. The next coordinate transformation:

$$\begin{aligned} \vec{x}_1 = \vec{r}_1 - \vec{R},\ \vec{x}_2 = \vec{r}_2 - \vec{R}, \\ \vec{X} = (M_0\vec{R} + m\vec{r}_1 + m\vec{r}_1)/(M_0+2m), \end{aligned} \tag{3}$$

reduces the problem to that of helium atom in effective electrical field with intensity of

$$\vec{E}_{eff} = (m\vec{F} - M_0\vec{f})/(|e|M). \tag{4}$$

Full wave function of helium atom can be presented in the next form

$$\Phi(\vec{X}, \vec{x}_1, \vec{x}_1) = \varphi(\vec{X})\Psi(\vec{x}_1, \vec{x}_1), \tag{5}$$

where $\varphi(\vec{X})$ is the wave function of whole atom motion and is not responsible for its polarization. Variational approach is used for calculations. For helium atom in ground state approximately $\Psi(\vec{x}_1, \vec{x}_1) = \psi(\vec{x}_1)\psi(\vec{x}_1)$, where probe function is

$$\psi(\vec{r}) = C(\psi_0(\vec{r}) + B\psi_1(\vec{r})), \tag{6}$$

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$C = (1 + B)^{1/2}$ is a normalization constant,

$$\psi_0(\vec{r}) = \sqrt{\frac{Z_*^3}{\pi a_0^3}} \exp(-Z_* \frac{r}{a_0}), \quad \psi_1(\vec{r}) = \sqrt{\frac{Z_*^5}{\pi a_0^5}} r \cos\vartheta \exp(-Z_* \frac{r}{a_0}), \tag{7}$$

$a_0 = \hbar^2/me^2$ denotes Bohr radius, ϑ is the angle between the electric field and radius-vector of electron. Wave function contains two variational parameters Z_* and B. Accuracy of calculation with this wave function is about 10%.

In the first order of magnitude by small ratio of external field to field, created by elementary charge at distance of Bohr radius, the equation for dipole moment is

$$\vec{d} = \kappa \vec{E}_{eff}, \tag{8}$$

where in used estimation $\kappa = 8a_0^3/AZ_1^3$, $A = 31/16$, $Z_1 = 27/16$.

Consider helium atom in gravity field $\vec{g}$ and uniform electric field $\vec{E}$. In addition, consider a force of another nature $\vec{F}_e$ acting upon atomic nucleus and a force $\vec{f}_e$ acting upon electrons. We do not specify the nature of these forces yet. Then the resultant force acting upon nucleus is $\vec{F} = M_0\vec{g} + Z|e|\vec{E} + \vec{F}_e$, and resultant force acting upon electrons is $\vec{f} = M_0\vec{g} - |e|\vec{E} + \vec{f}_e$. Taking (4) into account, effective intensity becomes

$$\vec{E}_{eff} = \vec{E} + (m\vec{F}_e - M_0\vec{f}_e)/(|e|M). \tag{9}$$

There is no term containing gravity in this equation. Thus, in absence of electric field and forces of another nature, $\vec{E}_{eff} = 0$, the atom can not be polarized. For forces resulting in polarization the next condition must be satisfied

$$m\vec{F}_e - M_0\vec{f}_e \neq 0. \tag{10}$$

For gravitational forces this condition is not satisfied, so gravity itself can not lead to polarization. It is natural, because under the action of gravity nucleus and electrons move with the same acceleration and no charge separation occurs. Inertial force $-M\dot{\vec{v}}$ is also proportional to the mass, and therefore, as in the case of gravity, can not itself result in polarization of atom. Resultant force acting upon atom

$$\vec{F}_a = M\vec{g} + \vec{F}_e + Z\vec{f}_e, \tag{11}$$

is the sum of gravitational force and forces of other nature. Under act of this force atom in non-relativistic approximation moves with acceleration $\dot{\vec{v}} = \vec{F}_a/M$. Consider separately two cases. The first, when the force of another nature acting upon electron is zero: $\vec{f}_e = 0$. Also assume the absence of electric field $\vec{E} = 0$. Taking into account (8) and (9) the dipole moment of a single atom is

$$\vec{d} = \frac{\kappa m}{|e|}(\dot{\vec{v}} - \vec{g}). \tag{12}$$

If the force $\vec{F}_e$ is so that atom is not accelerated $\dot{\vec{v}} = 0$, then from (12) can be concluded that direction of dipole moment of atom is opposite to the direction of gravitational field. It is simple, because the position of nucleus is fixed by the force of another nature, $\vec{F}_e$, and electrons, that are assumed not to experience another nature force, shift in the direction of gravity. If there is no gravity, atom moves with acceleration $\dot{\vec{v}}$ under the action of force $\vec{F}_e$, and dipole moment has the same direction as acceleration. Electron, that experiences coulomb force of the nucleus, *lags* from accelerated nucleus. Then the force $\vec{F}_e$ must be understood as force acting upon nucleus from accelerated lattice.

Now consider $\vec{F}_e = 0$ and force $\vec{f}_e$ acting upon electrons. It is not clear how the case, when there is a force that fixes the position of electron cloud and does not affect the nucleus, can be implemented. Most likely, this is just a hypothetical possibility. In this case the mass of nucleus, instead of electron mass, enters the numerator of the equation for dipole moment, and its sign changes to the opposite:

$$\vec{d} = -\frac{\kappa M_0}{Z|e|}(\dot{\vec{v}} - \vec{g}). \tag{13}$$

Note that in this form (1) the dipole moment, induced by polarization and acceleration, is presented in works [4, 5].

Consider polarization of solid dielectric, that contains n atoms in unit volume and is accelerated under the action of external force $\vec{F}_e = M\dot{\vec{v}}$. The coulomb force, that acts on electron from its nucleus, was taken into account in the derivation of formula for effective intensity (9). Atoms in the accelerated dielectric are polarized under the action of effective field. It means, that electric field $\vec{E}$ appears acting upon electrons of every atom. For displacement vector $\vec{D} = \vec{E} + 4\pi\vec{P}$ in absence of external charges and currents the equations $\mathrm{div}\vec{D} = 0$ and $\partial\vec{D}/\partial t = 0$ are true. Thus, in assumption of no spontaneous symmetry breakdown, $\vec{E} = -4\pi\vec{P}$, where polarization density $\vec{P} = n\vec{d}$. Consider forces of another nature acting upon electron $\vec{f}_e = 0$. Taking into account the last equations and (8), one finds

$$\vec{P} = \frac{\kappa n m}{\varepsilon|e|}\dot{\vec{v}} = \gamma\dot{\vec{v}}, \tag{14}$$

where $\varepsilon = 1 + 4\pi\kappa n$ is the dielectric permittivity and $\gamma = \kappa nm/\varepsilon|e|$ is the *gravitoelectric* susceptibility. In our case this coefficient significantly differs from (1) presented in [4, 5] because there is the electron mass in the numerator instead of the atom mass. It means, that the effect is three orders of magnitude less than that given in works [4, 5]. Besides, equation (14) differs in sign from the corresponding equation in works [4, 5].

Estimated value of acceleration necessary for gaining dipole moment of polar molecule, that is about one debye, is $\dot{v} = 0.5 \cdot 10^{24}$ cm/s^2. Due to some estimations (private communication from A.S.

Rybalko) atom in superfluid helium can have static dipole moment about $d \approx 10^{-4}$D. Such value is reached at acceleration $\dot{\vec{v}} = 10^{20}$ cm/s^2. Amplitude of acceleration in first sound wave is $a = \omega u(\Delta\rho/\rho_0)$, where u denotes sound velocity, ω is the frequency, $\Delta\rho/\rho_0$ is the ratio of density oscillation amplitude to equilibrium density. At sound velocity $u \approx 2.8{\cdot}10^4$ cm/s and wavelength $\lambda \approx 10^{-1}$ cm the frequency is $\omega \approx 1.8{\cdot}10^6$ s^{-1}. For typical value $\Delta\rho/\rho_0 = 10^{-5}$ the amplitude of acceleration in sound wave is $a = 5{\cdot}10^5$ cm/s^2. This value is three orders of magnitude less than necessary for obtaining needed dipole moment. At such acceleration and atomic density $n \approx 10^{-22}$ cm^{-3} an electric field $E = 4\pi nd \approx 10^{-13}$ CGSE units arises in dielectric. At wavelength $\lambda \approx 10^{-1}$ cm the appropriate potential difference is $U \approx 10^{-12}$ V, that is three orders of magnitude less, than observed in work [1].

3. CONCLUSIONS

The research made in the present work allows to conclude the following:

- Neither gravitational nor inertial forces can lead to the polarization of atom, since they are not sensitive to the sign and magnitude of charge, and the acceleration under the action of these forces do not depend on the particle mass. Action of forces of another nature is necessary to respond for the polarization of atom.
- Estimation of polarization of an accelerated solid dielectric, obtained in this work, is three orders of magnitude less than given in works [4,5].
- Considered effect in normal fluids must be even less than in solid dielectrics because of absence of long-range correlations.
- There is a specific long-range order in superfluids, connected with the phase symmetry breakdown, but apparently it cannot significantly increase the considered effect. Thus, estimations and considerations given in this paper allow us to conclude that observed electric activity of superfluid cannot be explained by the effect of polarization of helium due to acceleration.

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ОБ ЭЛЕКТРИЧЕСКОЙ ПОЛЯРИЗАЦИИ АТОМОВ ГЕЛИЯ ПРИ УСКОРЕНИИ

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Исследована возможность объяснения наблюдаемой повышенной электрической активности сверхтекучего гелия [1–3] эффектом поляризации атома гелия при его ускорении. Показано, что этой причины не достаточно для объяснения величины эффекта.

ОБ ЕЛЕКТРИЧНІЙ ПОЛЯРИЗАЦІЇ АТОМІВ ГЕЛІЮ ПРИ ПРИСКОРЕННІ

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Досліджена можливість пояснення спостереженої підвищеної електричної активності надплинного гелію [1–3] ефектом поляризації атома гелію при його прискоренні. Показано, що цієї причини недостатньо для пояснення величини ефекту.