Possible nature of the electric activity of He II observed in experiments with second sound

V. M. Loktev, M. D. Tomchenko

Bogoliubov Institute for Theoretical Physics, NAS of Ukraine,
14-b, Metrologichna str., Kiev, 03143, Ukraine
E-mail:vloktev@bitp.kiev.ua; mtomchenko@bitp.kiev.ua

An attempt is made to explain the nature of the electric signal observed in He II in a second-sound standing wave. Using the general quantum-mechanical principles, we show that, due to interatomic interaction, each atom of He-II acquires a small fluctuating induced dipole moment with the average value of its modulus $\bar{d}_{at} = 2e\delta$, $\delta \approx 2.6 \times 10^{-4}\text{Å}$. A directed flux of microscopic vortex rings — which, together with phonons, are thermal excitations of He II — forms in the second-sound standing halfwave. This flux partially orders the chaotically oriented dipole moments of the atoms, which results in volume polarization of He II. The observed electric induction $\Delta U \approx k_B\Delta T/2e$ can be explained theoretically under the assumption that each vortex ring possesses a dipole moment $d_{vr}$ of the order of ten atomic moments, $d_{vr} \sim 10\bar{d}_{at}$.

It is shown also that the theoretical value of the voltage $\Delta U$ induced in He II by the volume system of dipoles strongly depends on the dimensions of the resonator for dipoles of any origin. The experimental value of $\Delta U$ is the same for two resonators of different size; therefore, this voltage may be not connected with the volume polarization of He II.

PACS: 67.40.Pm
Keywords: Helium-II, electric activity, dipole moment, vortex rings.

1 Introduction

A series of experiments were recently carried out [1–3], in which electric properties of He II have been discovered. This is rather unexpected, given that He II is a dielectric and that a free He$^4$ atom does not possess either dipole or higher multipole moments. Several models have been proposed to explain the electric activity of He II [4–6], but each of them encounters with certain difficulties and does not explain the effects of [1–3] in a plausible way. In this work, we study a possible nature of the electric activity of He II observed by Rybalko [1] in experiments with second sound. More details of this analysis are presented in [7].

2 Induced dipole moment of He II atoms

It was found in the experiment [1] that the second-sound standing half-wave induces an alternating voltage $U$ in He II with the frequency $\omega_2$ of the second sound. It was established that, in the temperature range $T = 1.4–2\text{K}$, the amplitudes of the voltage ($\Delta U$) and the temperature ($\Delta T$) are related as $\Delta U/\Delta T \approx k_B/2e$. 
We assume that the effect observed in [1] is connected with volume polarization of helium-II, which is caused by the existence of microscopic dipole moments (DM). Its origin should be clarified. It is shown in [4] that atoms of He II possess an inertial DM caused by their acceleration in sound waves. However, such DM give polarization which is two to three orders of magnitude smaller than the observed value. Below we show that helium atoms possess not only inertial DM but also induced DM caused by interaction between neighboring atoms.

According to the standard perturbation theory [7], the ground-state wave function of two interacting helium-II atoms $A$ and $B$ has the form

$$
\Psi_{AB}^{0} = c_{0} \Psi_{A}^{0} \Psi_{B}^{0} + c_{1} \Psi_{A}^{1} \Psi_{B}^{0} + c_{2} \Psi_{A}^{0} \Psi_{B}^{1} + \ldots,
$$

(1)

where $\Psi_{0}$ is the $1s^{2}$ ground-state wave function of the He$^{4}$ atom, and $\Psi_{1}$ is the excited state $1s2p$ with $l = 1$ and $m = 0$. We neglect the next corrections in (1). In the quadrupole approximation for the perturbing potential, in the first order of perturbation theory, we obtain [7] $c_{1} = -8.15 a_{B} a^{3}/R^{4}$, $c_{2} = 1.43 a_{B} a^{2}/R^{3}$, where $R$ is the distance between atoms, $a = a_{B}/Z^{*} = 0.313 \text{Å}$, $Z^{*} = 2 - 5/16$, and $a_{B} = \hbar^{2}/m e^{2} = 0.529 \text{Å}$ is the Bohr radius. We calculate the DM of atom $A$ according to the general formula

$$
d_{A}^{0} = \int \Psi_{AB}^{0} e(r_{1}^{A} + r_{2}^{A}) \Psi_{AB}^{0} d\mathbf{r}_{1}^{A} d\mathbf{r}_{2}^{A} d\mathbf{r}_{1}^{B} d\mathbf{r}_{2}^{B},
$$

(2)

where $e$ is the electron charge. From (1) and (2), for $R$ equal to the average distance between the He II atoms (3.6 Å), we obtain:

$$
d_{0} \approx -2e\delta \frac{R}{R}, \quad \delta = 2.63 \times 10^{-4} \text{Å}.
$$

(3)

The DM arises as a result of stretching of the electronic cloud of an atom in the direction away from the neighboring atom.

Due to interaction with neighbors and nonuniform distribution of atoms, each atom of He II acquires certain DM $d_{at}$. The direction and magnitude of $d_{at}$ are different for different atoms, but the average value is $\overline{d_{at}} \sim d_{0}$.

### 3 Focusing of the induced atomic dipole moments by vortex rings

In a second-sound standing half-wave, the temperature varies according to the law

$$
T = T_{0} - 0.5 \Delta T \cos(\omega_{2}t) \cos(z\pi/L),
$$

(4)

where $z$ is the coordinate along the resonator, and $L$ is the resonator length. By the reasoning of [7], microscopic vortex rings, being a type of He II thermal excitations [8], can possess their own DM $d_{vr}$, with values which are thus far unknown. An ordered flux of vortex rings (along the direction of decreasing $T$) is present in a second-sound standing half-wave due to the temperature difference. Because vortex rings possess DM, this flux creates the polarization of helium

$$
P_{z}(z) = \frac{\eta}{L} \cos(\omega_{2}t) \sin\left(\frac{z\pi}{L}\right), \quad \eta = \frac{\pi}{16 \varepsilon_{He}} \frac{\partial n_{vr}(T)}{\partial T} d_{vr} n_{vr}^{-1/3} \Delta T.
$$

(5)

Here, $n_{vr}(T)$ is the equilibrium distribution of rings [8]. Such polarization induces the following voltage $U$ between the end walls of the resonator:

$$
U = \eta \cos(\omega_{2}t) \gamma(R, L),
$$

(6)
where $\gamma(R, L)$ is the factor taking into account the boundary conditions. For a short resonator in [1], $\gamma \approx 1.38$; for a long one, $\gamma \approx 1/20$; for the infinite medium, we have $\gamma = 4$. It follows from [6] that, at $T = 1.4\text{K}$,

$$\frac{\Delta U}{\Delta T} \approx \frac{k_B \gamma(R, L)d_vr}{2e} \frac{3,9d_{at}}{3,9d_{at}}.$$ (7)

The experimental value $\Delta U/\Delta T \approx k_B/2e$ is obtained from [7] at $d_{vr} \sim 10d_{at}$. However, the value of $\Delta U/\Delta T$ strongly depends on the boundary conditions, which should be checked experimentally. The indicated dependence of $\gamma(R, L)$ on the boundary conditions takes place for DM of any origin, causing polarization of helium. The absence of this dependence in the experiment will indicate that the observed value of $\Delta U$ either is connected with certain boundary effect in He II or is not connect with He II at all, but results from one kind of thermo-e.m.f.

4 Summary

We proposed the idea that the electric signal $\Delta U$ observed in a standing wave of second sound is caused by a directed flux of vortex rings possessing proper dipole moment $\sim 10d_{at} \sim 5 \times 10^{-3}\text{Å}$. A ring may possess DM due to asymmetry in the location of atoms in front of and behind the ring. It is shown that, in the case of the volume nature of $\Delta U$, the theoretical value of $\Delta U$ should strongly depend on the dimensions of the resonator, which effect can be tested experimentally. Such a dependence was not observed in [1]; therefore, the effect of [1] may be connected not with volume but rather with the boundary properties of He II or with the electric properties of the materials used to measure $\Delta U$.

5 Acknowledgements

The authors are grateful to A.S.Rybalko and E.Ya.Rudavskiı for the explanation of the specific features of the experiment [1] and helpful remarks, and to Yu.V.Shtanov for valuable discussion.

REFERENCES

[1] A.S. Rybalko, Low Temp. Phys. 30, 994 (2004).
[2] A.S. Rybalko, S.P. Rubets, Low Temp. Phys. 31, 623 (2005).
[3] A. Rybalko, S. Rubets, E. Rudavskii, et al., Phys. Rev., B 76, 140503 (2007).
[4] L. A. Melnikovsky, arXiv:cond-mat/0505102 (2005).
[5] V.D. Natsik, Low Temp. Phys. 31, 915 (2005).
[6] E.A. Pashitskii, S.M. Ryabchenko, Low Temp. Phys. 33, 8 (2007).
[7] V.M. Loktev, M.D. Tomchenko, Low Temp. Phys. 34, 262 (2008).
[8] M. Tomchenko, Low Temp. Phys. 31, 365 (2005).