

# Discrete states of an electron bubble in solid helium

A. I. Golov

*Institute of Solid State Physics, Academy of Sciences of the USSR*

(Submitted 8 February 1989)

Pis'ma Zh. Eksp. Teor. Fiz. **49**, No. 6, 346–348 (25 March 1989)

The pressure dependence of the radius of an electron bubble in solid helium should be stepped because of the discrete nature of the crystal lattice.

1. An excess electron in liquid or solid helium is known<sup>1-5</sup> to localize in a cavity (or bubble) of radius  $R \sim 10 \text{ \AA}$ . In liquid helium this cavity is spherical.

If a cavity is to form in a crystal, a certain number ( $N$ ) of atoms must be displaced from the interior to the surface, in precisely the same way as in the formation of Schottky vacancies ( $N$  varies from about 100 to 50 over the pressure range 30–130 atm). At a zero temperature  $T$  the equilibrium shape of the bubble surface for each value of  $N$  corresponds to a minimum of the total energy ( $W_N$ ) of the system consisting of the electron and the solid helium. A family of alternative states of the bubble with various values of  $N$ , arises. The energies  $W_N$  of these states depend on the pressure  $p$ . At each pressure  $p$  the state  $N(p)$  corresponding to the lowest energy  $W_N(p)$  is realized.

The pressure scale thus breaks up into intervals  $[p_N]$ , within each of which the particular value of  $N$  remains constant. Corresponding to approximately equal pressures within an interval are states which are approximately the same, differing only in the degree of elastic deformation of the crystal (for simplicity we are ignoring the situation in which the bubble surface has different shapes for one value of  $N$  and different values of  $p$ ; there will then be a corresponding partitioning with  $[p_N]$ ). Because of the small shear moduli of solid helium, the only cavities which will actually arise will be approximately spherical, and each can be assigned a characteristic radius  $R_N(p)$ . Within one interval  $[p_{N_1}]$  the decrease in the radius  $R_{N_1}(p)$  with increasing pressure is restrained by elastic forces. A transition from  $N_1$  to  $N_2$  occurs at a pressure  $p_{N_1N_2}$  such that the relation  $W_{N_1}(p_{N_1N_2}) = W_{N_2}(p_{N_1N_2})$  holds. The radius changes abruptly from  $R_{N_1}$  to  $R_{N_2}$  (Fig. 1).

For different values of  $[p_N]$  the sizes of the energy gap to the nearest excited state  $N^*$ ,

$$\Delta W_N(p) = W_{N^*}(p) - W_N(p), \quad (1)$$

may differ noticeably. At certain "magic numbers"  $N$  (as in clustering) we should observe stable configurations with a large gap  $\Delta W$ , in cases in which the bubble can be inscribed neatly in the crystal lattice.

At a nonzero  $T$  the distribution with respect to state  $N$  will be a Boltzmann distribution, and the steps for which the relation  $\Delta W_N \lesssim k_B T$  holds will be rounded.

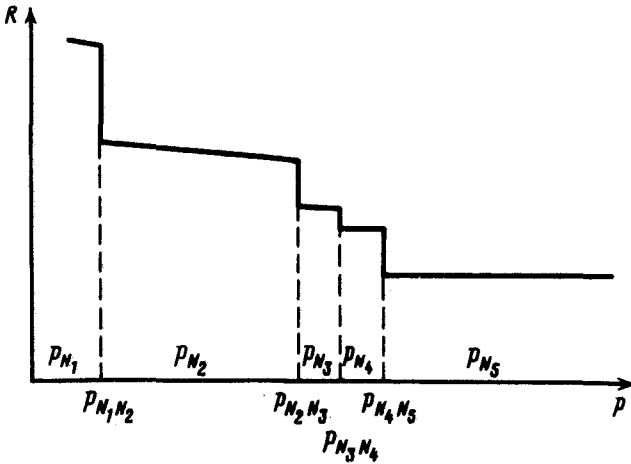


FIG. 1. Sketch of the pressure dependence of the bubble radius in a crystal. The wide steps  $p_{N2}$  and  $p_{N5}$  correspond to stable states (see the text proper for an explanation).

2. Let us find the distance along the pressure scale between two stable states. We will use a crude model. We use the sites of an undistorted lattice to form a surface which is approximately a sphere of radius  $R$ . For an arbitrary radius the greatest deviations from a spherical shape occur in the direction in which the perpendicular atomic planes are spaced farthest apart. We write the condition for a stable configuration as follows: The bubble diameter calculated without consideration of the discrete nature of the lattice<sup>3-5</sup> fits into an integer number of interplanar distances, i.e.,

$$2R_0(p) = mb(p), \quad (2)$$

where  $m$  is an integer, and  $b(p)$  is the distance between the planes with the closest packing. For bcc  $^3\text{He}$  and for hcp  $^4\text{He}$  at  $p = 30$  atm we would have  $b_{(110)} = 3.1 \text{ \AA}$  and  $b_{(0001)} = 3.0 \text{ \AA}$ , respectively. To calculate specific solutions  $p_m$  from condition (2) would be to go beyond the accuracy level here, if only because the calculated values of  $R_0(p)$  are known only within  $\pm 1 \text{ \AA}$  (Ref. 3). It is better to determine a rate of change of  $R_0(p)$ : Over the  $p$  range from 30 to 130 atm  $R_0$  decreases by 2-3  $\text{\AA}$  (and  $b$  decreases by 0.2  $\text{\AA}$ ). The difference between two neighboring solutions (2),  $p_m$ , is thus a few tens of atmospheres in this pressure range.

The activation energies for the diffusion of negative charges in bcc  $^3\text{He}$  and hcp  $^4\text{He}$ , measured from the temperature dependence of the mobility, vary in a nonmonotonic way with the pressure<sup>3,6-8</sup> (Fig. 2). This behavior can be linked with the presence of different states of an electron bubble at different pressures if we assume that the diffusion of a stable bubble with a large gap  $\Delta W_N$  is hindered in comparison with that of other configurations for which there are states of similar energy. At pressures  $p$  at which stable bubbles are realized the activation energy for the diffusion would then have a local maximum.

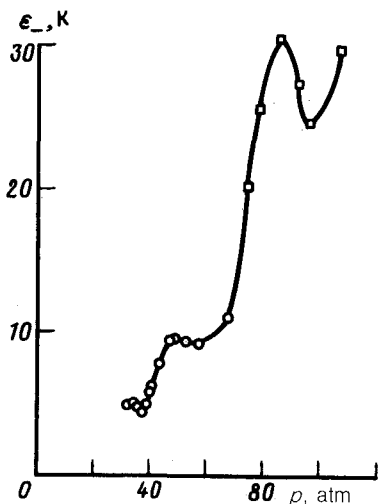


FIG. 2. Pressure dependence of the activation energy for the diffusion of negative charges in bcc  $^3\text{He}$ .  $\circ$ —From Ref. 7;  $\square$ —from Ref. 6 (the curve simply connects the experimental points).

It would be interesting to see direct measurements of the  $R(p)$  dependence and a calculation of the bubble structure at various pressures based on elementary considerations. A comparison of theory with experiment would make it possible to decipher the specific structure of a cavity. Methods for determining  $R$  in liquid and solid helium are described in Refs. 2 and 4; here we would simply like to point out that solid helium is more convenient than liquid helium for spectroscopic studies, since it is possible to arrange large concentrations of charges ( $n \gtrsim 10^{12} \text{ cm}^{-3}$ ).

I wish to thank V. I. Marchenko for assistance in refining the contents of this paper and also L. P. Mezhov-Deglin, D. E. Khmiel'nitskiĭ, and V. B. Shikin for interest in this study and for useful comments.

<sup>1</sup>R. A. Ferrell, Phys. Rev. **108**, 167 (1957).

<sup>2</sup>K. M. Schwarz, in: Advances in Chemical Physics (ed. I. Prigogine and S. A. Rice), Vol. XXXIII, Wiley, New York, p. 1.

<sup>3</sup>A. J. Dahm, in: Progress in Low Temperature Physics (ed. D. F. Brewer), Vol. IX, North-Holland Publishing Company, Amsterdam, 1985.

<sup>4</sup>M. H. J. Cohen and J. Jortner, Phys. Rev. **180**, 238 (1969).

<sup>5</sup>V. B. Shikin, Zh. Eksp. Teor. Fiz. **61**, 2053 (1971) [Sov. Phys. JETP **34**, 1095 (1971)].

<sup>6</sup>D. Marty and F. I. B. Williams, J. Phys. (Paris) **34**, 989 (1973).

<sup>7</sup>K. O. Keshishev, in: Proceedings of the Fourteenth School on the Physics of Quantum Liquids and Crystals, Bakuriani, 1978.

<sup>8</sup>K. O. Keshishev, Zh. Eksp. Teor. Fiz. **72**, 521 (1977) [Sov. Phys. JETP **45**, 273 (1977)].

Translated by Dave Parsons