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Transition conduction types of electrons in cryogenic media

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Discussed in the paper are possibilities for description of electron conduction in transitional density range separating electron free and localized states in cryogenic media.

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1. One of the most interesting and important problems in condensed matter physics remains the study of electron-related clusters and techniques of their detection. Experimentally, the main source of information on these clusters is the effective conductivity σ_{eff} of the medium containing artificially injected charged particles.

When considering the conduction phenomena, it is convenient to identify two different domains of external parameters. In the first one, where rather complex quasiparticles (bubbles or charged clusters) have already been formed, their ohmic mobility (and, hence, conductivity) can be calculated with standard methods. However, there exist (and seem to be most interesting) some transition domains where the bare charge energy is substantially changed due to autolocalization or reverse process. In particular, the involved phenomena include:

A. Sharp change in electron conductivity of the media with positive scattering length as the gas density n_g is varied in the vicinity of the point where electron bubbles start to appear.

B. Sharp nonmonotonous variations of this conductivity in media with negative scattering length as the density is changed near the point of electron localization-delocalization transition.

C. 2D electron transition from free to 2D bubble state as the vapor density n_g above the cryogenic liquid surface is changed.

D. 2D electron transition from free to 2D dimple state as the magnetic field normal to the surface is monotonously raised.

Almost in all the above cases a number of concepts have been developed which provide to some extent description of the observed details in the $\sigma_{\text{eff}}(n_g)$ behavior. For the problems of type A, this means a variety of the general formalism of description of electron conduction in systems with spatial disorder (e.g., see Refs. 1–4). Special attention was paid to problem B where the existing analysis, mainly for electrons in argon, was focused on finding out whether the electron mobility is governed by their single-particle collisions with gas atoms [5–8] or by collective electron interaction with gas density fluctuations [9–13]. The latter viewpoint proved to be dominating in later studies. Sections C and D consider kinetics of formation of 2D electron bubbles [14,15] and formally very similar problem of 2D electron transition from free to dimple state [16].

The characteristic feature of all indicated studies are manipulations with electron mobility. Their autolocalization (in our opinion, the most important factor affecting transition domain kinetics) proves to be almost hidden and lacking the status it deserves in transition kinetics. That is one of the reason (the other one is the availability of new results [17] on the mechanism of electron localization in media with negative scattering length) why we have decided to address once again the transition phenomena in electron conduction in cryogenic media (judging by available references, the problem first considered in 1970s). The present paper provides a uniform description of transition kinetics where the idea of dominating role played by electron localization in the transition conductivity $\sigma_{\text{eff}}(n)$ is employed from the outset. Within this approach,

$$\sigma_{\text{eff}}(n_g) = n_{\text{loc}}\mu_{\text{loc}} + n_{\text{free}}\mu_{\text{free}}, \quad (1)$$

$$n_{\text{loc}} + n_{\text{free}} = n_e, \quad (2)$$

where n_e is the total electron density, μ_{loc}, μ_{free} are mobilities corresponding to localized and free electrons, and

the relative fractions of localized $n_{\rm loc}$ and free $n_{\rm free}$ electrons are found from the law of mass action [18] which explicitly takes into account the energy difference of free and bound electron states. It should be noted that almost evident equations (1) and (2) have already been mentioned in the literature [19,20]. The only problem is how to relate the fractions $n_{\rm loc}$ and $n_{\rm free}$ to energy parameters of the system. The appropriate analysis has not yet been performed.

2. The problem with positive scattering length. The formalism on which the scheme (1), (2) should be implemented looks rather impressive. For example, following Ref. 1, the theory starts with the general expression for mobility μ in terms of Kubo formula with the Hamiltonian including a δ-shaped repulsion with scattering length $a_0 > 0$ for the interaction between the gas atom and electron. In this formulation, the problem of electron mobility in dense cryogenic medium is finally reduced to the problem of metal–dielectric transition occurring in all studies of mobility in inhomogeneous media. Within the general analysis, it is only possible to prove the existence of this transition. It is this transition that can be associated with the observed rapid variations in $\mu(n_g)$. As to the details, one can only resort to numerical calculations or employ expansion in powers of the gas parameter $n_g a_0^3 < 1$. In the latter case it is possible to show that mobility threshold n_g^c is shifted with temperature as [2,3]

$$n_g^c \propto T^{3/4} . \tag{3}$$

Authors of Refs. 1–3 also note that the formalism they employ does not involve electron localization.

The same problem considered with the autolocalization phenomena taken into account looks much more physically transparent. Starting with the experimentally confirmed [21] statement on the existence of electron injection energy

$$V_0 = \frac{2\pi\hbar^2 a_0}{m} n_g , \quad a_0 > 0 \tag{4}$$

where n_g is the gas density, m is the free electron mass, a_0 is the electron scattering length on the gas atom possessing polarizability α, the autolocalization scenario reveals that starting from certain critical density n_g^c, it s more favorable for the electron to break the medium continuity and reside in created cavity of radius $R \gg a_0$ which is practically free from gas atoms (this cavity is maintained by electron pressure from inside). The critical point position estimated (without any adjustable parameters, if the scale of a_0 is found from independent experiments, e.g., see Ref. 21) coincides with observed critical drop in the telectron conductivity [22]. This point predictably moves with the temperature [23],

$$n_g^c \propto T^{2/3}. \tag{5}$$

The expression for V_0 (4) which is linear in gas density is consistent with more refined theory [24,25].

Turning back to Eqs. (1) and (2), we now specify expressions for $n_{\rm loc}$ and n_{free}. According to the law of mass action [18],

$$T \ln\left(\frac{n_{\rm loc}}{n_{\rm free}}\right) = \Delta, \quad \Delta = (V_0 - W) > 0, \quad n_{\rm loc} + n_{\rm free} = n_e , \tag{6}$$

where W is the autolocalized electron energy. The difference $(V_0 - W) > 0$ is calculated according to [22] or [26,27]. Results of such calculations preformed with spherical potential well model are given in Fig. 1. For $\Delta \gg T$ one naturally has $n_{\rm loc} \gg n_{\rm free}$.

For electron mobility $\mu_{\rm free}$ the classical Langevin result on electron mobility in gases reads

$$\mu_{\rm free} = \frac{4e}{3n_g \sigma (2\pi m T)^{1/2}} . \tag{7}$$

Here σ is the electron scattering cross-section at a single atom.

When dealing with electron scattering at the fluctuations δV of the potential (4)

$$\delta V = \frac{2\pi\hbar^2 a_0}{m} \delta n_g , \tag{8}$$

one can note that its structure is similar to that of electron-phonon interaction in semiconductors. This analogy yields

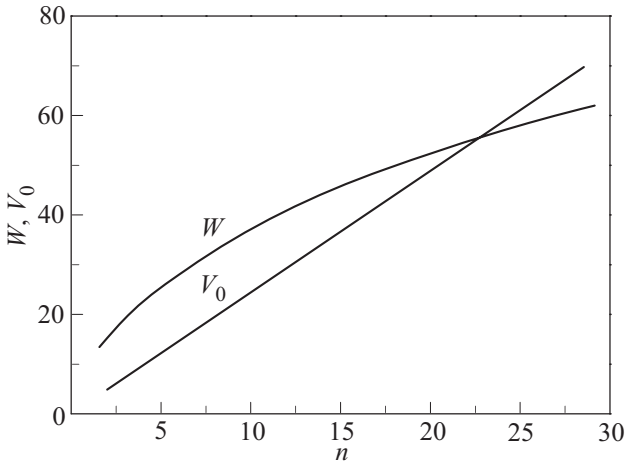

Fig. 1. Energies: V_0 is the energy of free electron in a cryogenic media obtained within the optical approximation [4] with negative scattering length $a_0 > 0$ for helium; W is the energy of autolocalized electron calculated for a spherically symmetric potential well with the following dimensionless parameters: $n = n_g / \tilde{n}$, $\tilde{R} = R / R_{\max}$, $\tilde{n} = \pi / (16 a_0 R_{\max}^2)$, $R_{\max}^3 = 6 a_0 \hbar / m_e T$. Intersection of the curves $V_0(n)$ and $W(n)$ at the point $n_c = 23$ corresponds to usual dimensional density of $n_g^c = 2.7 \cdot 10^{21}$ cm^{-3}.

$$\tilde{\mu}_{\text{free}} = \left(\frac{c_p}{c_v}\right)\frac{e}{8\pi n_g a_0^2 (mT)^{1/2}}, \qquad (9)$$

where c_p / c_v is the heat capacities ratio. Equations (7) and (9) possess similar structures, and that is why in the problem with positive scattering length transition from one density limit to the other at the critical level is not very prominent.

As to the mobility μ_{loc}, it can be approximated by the simplest Stokes-type formula

$$\mu_{\text{loc}} \simeq C\frac{e}{R\eta}, \qquad (10)$$

where R is the effective cluster radius, η is the cryogenic media density, and C is the a numerical factor which equals $1/6\pi$ for a solid sphere or $1/4\pi$ for a bubble of different liquid.

Equations (1), (2), (6), (9), and (10) together with the data of Fig. 1 allows to calculate the curve $\sigma_{\text{eff}}(n_g)$ in the transition domain within the framework of the autolocalization scenario. This approach to the critical domain is at least not inferior to the metal–dielectric scenario [1–3] in its qualitative content. Actually, it seems to be preferable in the sense of comparing predictions (3), (5) with the experiment and it certainly contains the correct (Stokes-type) asymptotic behavior of the conductivity $\sigma_{\text{eff}}(n_g)$ for large helium (neon) densities (the metal–dielectric scenario does not possess these properties).

3. The problem of electron mobility in media with negative scattering length (cryogenic gases starting with argon, and heavier atoms with rising polarizability) was addressed in a large number of papers (e.g., see Refs. 5–13) initially within the approach different from that outlined in the preceding section. Possible role of electron localization (autolocalization) processes in the transition conductivity in these studies was not considered. The analysis was focused on finding out whether the electron mobility is governed by their single-particle collisions with gas atoms [5–8] or by collective electron interaction with gas density fluctuations [9–13]. That was partly due to the data of Refs. 5 and 9–13 revealing that electron mobility in such media is sufficiently high, at least in typical systematically observed peaks, and only later [28–30] it has became clear that electron autolocalization involving formation of density enhancement clusters is unavoidable in media with V_0 from (4) and $a_0 < 0$. The corresponding density singularity develops just in the range of enhanced electron mobility (in the rest of the paper we shall denote the energy defined by Eq. (4) as V_-). This point makes the concept of free electrons in heavy cryogenic media with linear interaction (4) completely unjustifiable. Nevertheless, the approach of Refs. 5–13 is still sometimes used in the literature (see Ref. 29).

The paradox with mobility is resolved simultaneously with the problem of divergency in the self-energy of electron cluster in the case of negative a_0. The situation was found to be mainly controlled by the density range in the vicinity of the point

$$\partial V_-(n_g)/\partial n_{|n=n_{\min}} = 0, \qquad (11)$$

and this non-linearity was indeed observed in the behavior of $W(n_g)$ (photoinjection of electrons from metal into cryogenic medium [31–33]). Actually, to develop a nonlinear theory of electron clusters we used the simplest approximation of the type

$$V_-(n_g) = \frac{2\pi\hbar^2 a_0}{m} n(1 + An_g + Bn_g^2). \qquad (12)$$

Here the parameters A and B are chosen to correctly reproduce for each gas the minimum $V_-^{\min}$ position on the density scale n_g (i.e., at $n_g = n_{\min}$) and its depth $V_-^{\min}$.

For electron energy described by Eq. (12) the minimal cluster free energy $\delta F_{\min}$ is no longer a monotonous function of n_g (in contrast to the problem for V_0 and W in the case of positive scattering length $a_0 > 0$, see Fig. 1). Results of calculations of $\delta F_{\min}$ performed, e.g., for Xe [17] are shown in Fig. 2. In addition to finite values of $\delta F_{\min}$ in a wide density range (which means that the singularities have been successfully eliminated), one can clearly see a gap where electrons prove to be free. This result dots the i's and crosses the t's in the interpretation of extremely high electron mobility.

Thus, the acceptable scenario for calculations of electron conductivity $\sigma_{\text{eff}}(n_g)$ in the media with negative scattering length within the critical density range should necessarily have the structure (1), (2) with the components n_{loc} and n_{free} following from Eq. (6) and data of Fig. 2 for $\delta F_{\min}$ and mobilities μ_{loc} (10), μ_{free} (7). The result (7) should of course be corrected by using Lekner ideas [6–8]. However, in the present case there is no analogy between (7) and (9) since the mobility (9) based on Eq. (8) could hardly be correctly defined in the density range (11).

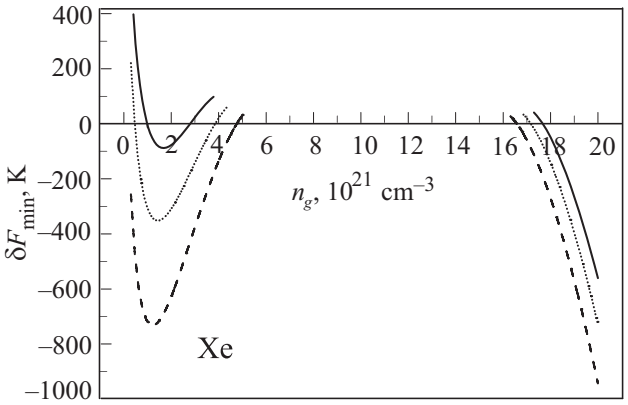

Fig. 2. Gain in free energy due to electron localization in Xe as a function of gas atom density for three different temperatures T, K: 150 (---), 200 (···), 250 (—).

Resume. Qualitative analysis of the critical conductivity of electron gas in cryogenic media allows to conclude that substantial part of the observed kinetics is governed by formation of autolocalized charged clusters in these domains (in the liquid phase these clusters are called cryogenic ions). This circumstance allows to describe the transition kinetics with Eqs. (1), (2), (6)–(9) using the equilibrium densities of autolocalized and free electrons with their effective mobilities. This approach proves to be useful not only in the cases A and B considered above but also in scenarios C and D which were only briefly mentioned earlier.

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1. H. Neustadter and M. Coopersmith, *Phys. Rev. Lett*. **23**, 585 (1969).
2. T. Eggarter and M. Cohen, *Phys. Rev. Lett*. **25**, 807 (1970); T. Eggarter and M. Cohen, *ibid*. **27**, 129 (1971).
3. T. Eggarter, *Phys. Rev*. **A5**, 2496 (1972).
4. M. Cohen, *Can. J. Chem*. **55**, 1906 (1977).
5. H. Schnyders, S. Rice, and L. Meyer, *Phys. Rev. Lett.* **15**, 187 (1965); H. Schnyders, S. Rice, and L. Meyer, *Phys. Rev*. **150**, 127 (1966).
6. J. Lekner, *Phys. Rev*. **158**, 130 (1967).
7. M. Cohen and J. Lekner, *Phys. Rev*. **158**, 305 (1967).
8. J. Lekner, *Phys. Lett*. **A27**, 341 (1968); J. Lekner, *Philos. Mag*. **18**, 1281 (1968).
9. J. Jahnke, L. Meyer, and S. Rice, *Phys. Rev*. **A3**, 734 (1971).
10. J. Jahnke, N. Holzwarth, and S. Rice, *Phys. Rev*. **A5**, 463 (1972).
11. L. Christophorou, R. Blaunstein, and D. Pitman, *Chem. Phys. Lett.* **18**, 509 (1973).
12. S. Basak and M. Cohen, *Phys. Rev*. **B20**, 3404 (1979).
13. A. Borghesani, M. Santini, and P. Lamp, *Phys. Rev*. **A46**, 7902 (1992).
14. P. Adams and M. Paalanen, *Phys. Rev. Lett.* **58**, 2106 (1987); P. Adams and M. Paalanen, *ibid*. **61**, 451 (1988).
15. P. Adams, *Surf. Sci*. **263**, 663 (1991).
16. S. Nazin and V. Shikin, *Physica* **E40**, 1476 (2008).
17. S. Nazin and V. Shikin, *Phys. Rev. Lett.* **101**, 166406 (2008).
18. L. Landau and E. Lifshitz, *Statistical Physics*, Nauka, Moscow (1976), Pt. 1 (in Russian).
19. R. Young, *Phys. Rev*. **A2**, 1983 (1970).
20. A. Khrapak and I. Yakubov, *Usp. Fiz. Nauk* **129**, 45 (1979) (in Russian).
21. W. Sommer, *Phys. Rev. Lett*. **12**, 271 (1964).
22. J. Levin and T. Sanders, *Phys. Rev*. **154**, 138 (1967).
23. H. Harisson and B. Springett, *Phys. Lett*. **A35**, 73 (1971).
24. I.M. Lifshitz, S.A. Gredeskul, and L.A. Pastur, *Introduction to the Theory of Disordered Systems*, Nauka, Moscow (1982) (in Russian).
25. S. Doniach and E.H. Sondheimer, *Green's Functions for Solid State Physicists*, Imperial College Press (1998).
26. B. Springett, J. Jortner, and M. Cohen, *J. Chem. Phys*. **48**, 2720 (1968).
27. V. Shikin, *Usp. Fiz. Nauk* **121**, 457 (1977) (in Russian).
28. A. Khrapak and I. Yakubov, *Sov. Phys. JETP* **42**, 1036 (1976).
29. I. Yakubov and A. Khrapak, *Chem. Phys. Lett.* **39**, 160 (1976).
30. A.G. Khrapak and I.T. Yakubov, *Electrons in Dense Gases and Plasma*, Nauka, Moscow (1981) (in Russian).
31. M. Nishikawa and K. Itoh, in: *Electronic Excitations in Liquefied Rare Gases*, W.F. Schmidt and E. Illenberger (eds.), American Scientific Publishers, Stevenson Ranch, USA (2005).
32. C. Evance and G. Findley, *Phys. Rev.* **A72**, 022717 (2005).
33. I. Stainberger, in: *Electronic Excitations in Liquefied Rare Gases*, W.F. Schimidt and E. Illenberger (eds.), American Scientific Publishers, Stevenson Ranch, USA (2005).