

characteristic, with a sharp increase of the current, although there are no peaks whatever on the curve. At the same time, a pure ohmic dependence is retained for the current across the axis.

The anisotropy of the current-voltage characteristic is undoubtedly the result of the presence of a one-dimensional superlattice in the crystal. The most probable mechanism of the nonlinearity in this case is the resonant tunneling of the electrons [4].

Using the transverse relaxation time  $\tau = 10^{-14}$  sec estimated for SiC in [7], we obtain for the energy uncertainty a value of  $\delta E = 0.07$  eV, which is much larger than the widths of the microbands. Thus, the individual resonances cannot be resolved in this structure, and this explains the absence of peaks on the current-voltage characteristic. The increase of the current with increasing field is determined only by the increase of the density of states in the succeeding microbands with increasing energy.

At helium temperatures it is apparently possible to obtain in such a structure Bragg reflections from the boundaries of the microbands already at fields on the order of  $10^3$  V/cm.

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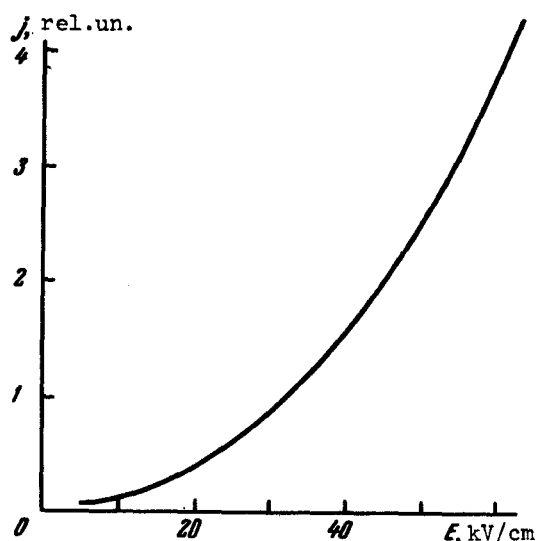
#### QUANTUM DIFFUSION OF He<sup>3</sup> IMPURITIES IN SOLID He<sup>4</sup>

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The purpose of this study was to observe and investigate He<sup>3</sup> impurity behavior features connected with the quantum nature of solid helium.



Current-voltage characteristic of SiC crystal 297R in a direction parallel to the crystal c axis. The current-voltage characteristic in the perpendicular direction is linear.

It is shown in a number of theoretical papers [1 - 3] that impurities in quantum crystals, owing to the possibility of tunneling, cease to be localized and turn into quasiparticles ("impuritons"), the motion of which in an ideal crystal is limited only by their collisions with one another or with phonons. These singularities become most pronounced in the behavior of the impurity diffusion coefficient ( $D$ ), the magnitude and temperature or concentration dependence of which are determined by the scattering of such quasiparticles by one another and by phonons.

The experimental investigations of the diffusion coefficient were performed by the spin-echo method using an NMR setup described earlier [4, 5]. We investigated solid solutions containing 0.75, 0.25, and 0.092%  $\text{He}^3$  at a molar volume  $21.0 \pm 0.05 \text{ cm}^3/\text{mole}$  down to the temperature  $0.4^\circ\text{K}$ .

The results are shown in Fig. 1 in the form of the temperature dependence of  $D$  for different concentrations ( $x$ ) of  $\text{He}^3$  in the HCP phase of solid helium. We note a number of features of the results.

First, in contrast to the high-temperature data [5], the diffusion coefficient ceases to depend on the temperature at  $T < 1.1^\circ\text{K}$  (a "plateau" region). This is typical of processes in which mutual collisions of the impuritons begin to play a decisive role. In addition, whereas  $D$  does not depend on the concentration in condensed solutions in the "plateau" region [6], a distinct increase of  $D$  with decreasing  $\text{He}^3$  content is observed in our case. This indicates, in accordance with [3], that the interactions between the impurities play an important role.

Using the gas approximation to describe the impuritons, we can write  $D \sim v^2\tau$ , where  $v$  is the average velocity of the quasiparticles and  $\tau$  is the relaxation time. If we assume the contributions due to the collisions of the impurities with one another and with the phonons to be independent and use the Matthiessen rule  $\tau^{-1} = \tau_{\text{imp}}^{-1} + \tau_{\text{phon}}^{-1}$ , where  $\tau_{\text{imp}}^{-1} \sim J_{34}x/\hbar$  is the time of relaxation due to the mutual scattering of the impurities [3] and  $\tau_{\text{phon}}^{-1} \sim (\theta/\hbar)(T/\theta)^3$  is

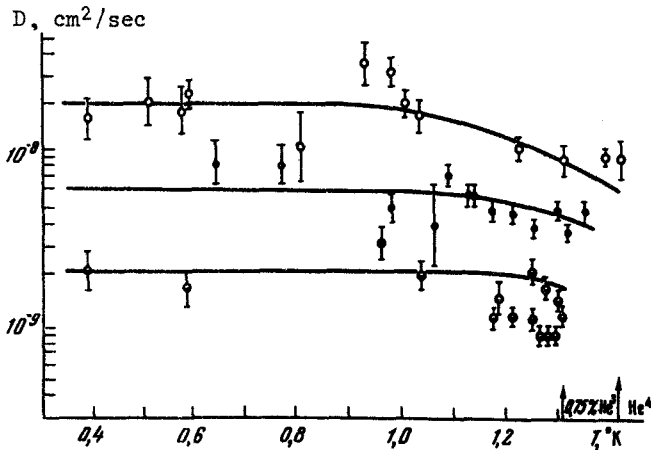


Fig. 1

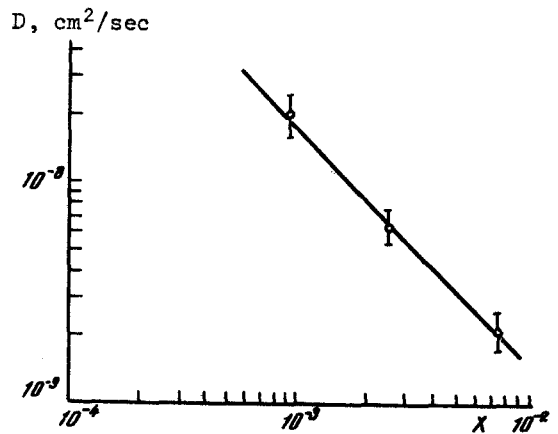


Fig. 2

Fig. 1. Diffusion coefficient of  $\text{He}^3$  vs. temperature for different  $\text{He}^3$  concentrations:  $\circ$  - 0.092%,  $\bullet$  - 0.25%,  $\bullet$  - 0.75%. The solid curves correspond to the equation  $D^{-1} = 6.25 \times 10^{10}x + 4.6 \times 10^6 T^3$ . The arrows on the  $T$  axis indicate the limits of the BCC-HCP transition.

Fig. 2. Diffusion coefficient of  $\text{He}^3$  vs. the  $\text{He}^3$  concentration in solid  $\text{He}^4$ .  $V = 21.0 \pm 0.05 \text{ cm}^3/\text{mole}$ .

the phonon relaxation time [1], then we obtain a convenient interpolation formula

$$D^{-1} \sim \frac{\hbar^2}{J_{34}^2 a^2} \left[ \frac{J_{34} x}{\hbar} + \frac{\Theta}{\hbar} \left( \frac{T}{\Theta} \right)^n \right]. \quad (1)$$

Here  $x$  is the  $\text{He}^3$  concentration,  $\Theta$  is the Debye temperature, and  $a$  is a quantity of the order of the distance between the nearest neighbors. In the "plateau" region, the first of the aforementioned processes predominates, and we can rewrite (1) in the form

$$D \sim \frac{J_{34} a^2}{\hbar x}. \quad (2)$$

Figure 2 shows the concentration dependence of the values of  $D$  obtained by averaging the experimental data for  $T < 1.2^\circ\text{K}$ . The straight line in the diagram corresponds to the equation  $D = 1.6 \times 10^{-11} x^{-1} \text{ cm}^2 \text{ sec}^{-1}$ ,<sup>1)</sup> which is in good agreement with (2). The resultant value of  $J_{34}$  is of the order of  $10^{-7}^\circ\text{K}$ . We call attention also to the noticeable decrease of  $D$  when the temperature rises above  $1.1^\circ\text{K}$  in all the investigated solutions. This is apparently connected with the increased role played in this region by scattering of the impurities by phonons (see formula (1)). To confirm this assumption, we have reduced all the experimental data in accordance with formula (1), and the exponent ( $n$ ) of the temperature term was assumed not to be known beforehand. Using two sections of each curve ( $T < 1.1^\circ\text{K}$  and  $T > 1.1^\circ\text{K}$ ), we can obtain two independent values for the exchange integral  $J_{34}$  (width of the quasiparticle energy band). The reduction yields  $n = 9 \pm 2$ , and the band widths calculated by two independent methods had the same order of magnitude,  $10^{-7}^\circ\text{K}$ . We note that the obtained values of the exchange integral  $J_{34}$  is smaller by approximately three orders of magnitude than the corresponding values of  $J_{33}$  for pure  $\text{He}^3$  (at the same molar volume).

Thus, the data obtained on the concentration dependence of  $D$  and the fact that  $J_{34}$  calculated for two different quasiparticle-scattering processes are of the same order of magnitude, serve as an experimental confirmation of the quantum character of the diffusion of  $\text{He}^3$  impurities in the HCP phase of solid helium.

The preliminary measurements of  $D$  in the BCC phase confirm the earlier [5] result that  $D$  differs strongly in the BCC and HCP phases. The large value of the classical diffusion in the BCC phase masks the quantum effects strongly. Nevertheless, the observed small increase of  $D$  with decreasing  $\text{He}^3$  concentration can apparently also be connected with the existence of quantum diffusion. We are continuing the experimental study of these phenomena.

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<sup>1)</sup> After the present research was completed, a paper was published [7] reporting observation of a  $D = \text{const}/x$  dependence at  $T = 0.53^\circ\text{K}$ , with  $\text{const} = (1.2 \pm 0.4) \times 10^{-11} \text{ cm}^2/\text{sec}$ .

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#### FEASIBILITY OF HIGH-PRESSURE NOBLE-GAS LASERS

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We propose here a new type of noble-gas-discharge laser operating at high pressure (on the order of atmospheric) generating ultraviolet radiation, and having a wavelength tunable over a wide range, on the order of  $5000 \text{ cm}^{-1}$ . To be specific, we use xenon as an example. The proposed working transition is from the  ${}^3\Sigma_u^+$  state of the  $\text{Xe}_2$  molecule (corresponding to an internuclear potential with a minimum [3, 4]) into the  ${}^1\Sigma_g^+$  state. The question of the use of these transitions to produce an optically pumped laser was discussed earlier in [1]. Superradiance of condensed xenon was observed in [2] following excitation of excitons, which are analogous in their nature to the  $\text{Xe}_2$  molecule in the  ${}^3\Sigma_u^+$  state by an electron beam.

At moderate temperatures, the lower energy states corresponding to transitions from the  ${}^3\Sigma_u^+$  bound state are practically free; population inversion can be therefore attained relatively easily. The problem is to obtain an acceptable gain and consequently a sufficiently high population of the upper states. The excitation mechanism proposed here is based on the following assumptions: 1) At high pressures, the radiation corresponding to the  ${}^3P - {}^1S_0$  transitions is dragged, and this contributes to the attainment of a high  $\text{Xe}^3P$  density in the discharge. 2) If the number of excited atoms per unit volume is  $N^*$ , then there exist also  $N_{\text{un}}$  unstabilized  $\text{Xe}_2$   ${}^3\Sigma_u^+$  molecules, with  $N_{\text{un}} = N^* Z_{\text{bi}} \tau_{\text{st}}$ , where  $Z_{\text{bi}}$  is the frequency of the collisions of the excited and unexcited atoms, and  $\tau_{\text{st}}$  is the duration of the collision process. 3) Stabilized  $\text{Xe}_2$   ${}^3\Sigma_u^+$  molecules are produced, with high probability, in the triple  $\text{Xe}^3P + \text{Xe}^1S_0 + \text{Xe}^1S_0$  collisions. The inverse process of molecule dissociation in collisions with atoms calls for additional energy and has very low probability at low temperatures. Allowance for such a dissociation does not change qualitatively the arguments that follow. The lifetime of the stabilized molecules is the time of the radiative transition  $\tau_{\text{rad}}$ ; the rate of their production is  $N^* a Z_{\text{tr}}$ , where  $Z_{\text{tr}} = Z_{\text{bi}}^2 \tau_{\text{st}}$  is the frequency of the triple collisions of the excited atoms with the unexcited ones, and  $a$  is a probability-theory factor close to unity.

Thus, the production of  $\text{Xe}_2$   ${}^3\Sigma_u^+$  molecules proceeds in two stages: the first is excitation of the atom by electron impact, and the second is the formation of a molecule by collision of the atoms. The kinetics of the system is described roughly by the equations

$$\frac{\partial N^*}{\partial t} = - \frac{1}{\tau} N^* + W,$$