DIFFUSION OF METASTABLE HELIUM ATOMS IN A CRYOGENIC PLASMA

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We have investigated the rate of diffusion disintegration of metastable helium atoms in a decaying helium plasma at a temperature lower than 6°K. A plsama whose atoms have so low a temperature will henceforth be called a cryogenic plasma. The helium plasma was excited in a quartz cylindrical cuvette which was immersed directly in liquid helium at 4.2 and 1.8°K (pumped-on helium). The excitation was by an electrodeless method with pulses from a high-frequency discharge of 0.08 msec duration, repeated every 40 msec. The concentration of the metastable helium atoms in the state 2^3S_1 was determined from the resonance absorption of the 3889 Å line from an external source. The details of a similar experiment at 77 and 20°K can be found in the authors' earlier papers [1,2].

The kinetics of the variation of the density of the metastable helium atoms was measured 150 msec after the cessation of the high-frequency pulse. This time is several times longer than the electron thermalization time or the time necessary to establish thermal equilibrium inside the plasma. To monitor the gas temperature inside the discharge vessel, we measured the gas pressure in the excitation mode and the pressure of the unexcited gas. These measurements have shown that the high-frequency heating of the cuvette raises the average temperature of the plasma atoms not more than 1.5°K compared with the temperature of the cryogenic liquid. Similar observations were reported also for a cryogenic plasma by Golden and Goldstein [3].

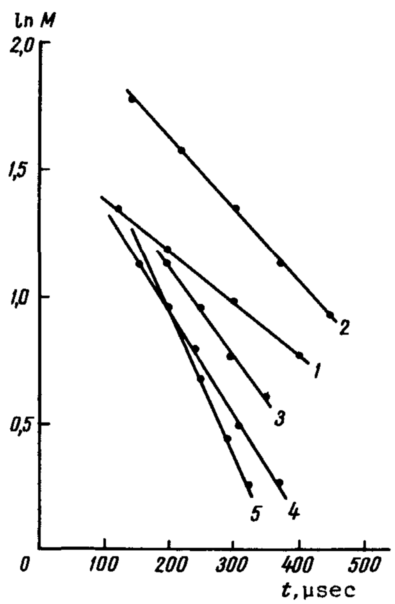

Fig. 1. Change in the concentration of the metastable helium atoms in a decaying cryogenic plasma at 5.5°K and p [mm Hg] = 1.1 (curve 1), 0.85 (2), 0.6 (3), 0.55 (4), and 0.4 (5). (The pressure is in units of p = p(300/T).)

The characteristic curves showing the variation of the concentration of the metastable 2^3S helium atoms in the cryogenic plasma are shown in Fig. 1. In accordance with the previously obtained results at 300, 77, and 20°K [1,2,4], the disintegration of the metastable states M at low gas densities ($n \simeq 1$--6×10^{16} cm^{-3}) is exponential

$$M(t) = M_0 \exp(-\nu(p)t). \qquad (1)$$

The exponent $\nu(p)$ is inversely proportional to the pressure p. The dependence of the exponent on the pressure is illustrated in Fig. 2 for liquid-helium temperatures 4.2 and 1.8°K (these measurements corresponded to approximate atom temperatures 5.5 and 2.5°K, accurate to 1.5°K). The scatter of the points on Fig. 2 does not go beyond the limits of experimental error, which amounts to 20%. (In all the figures the pressures

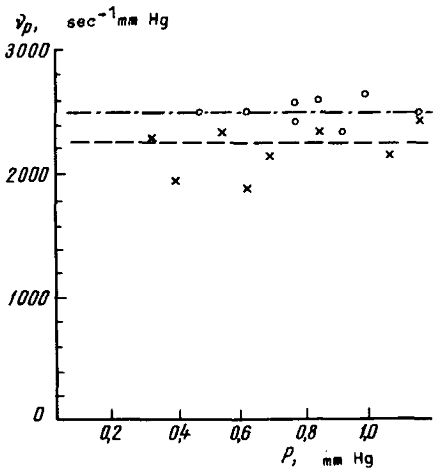

Fig. 2. Dependence of the quantity $\nu(p)p$ on the pressure p. o-·- T = 5.5°K, x--- T = 2.5°K.

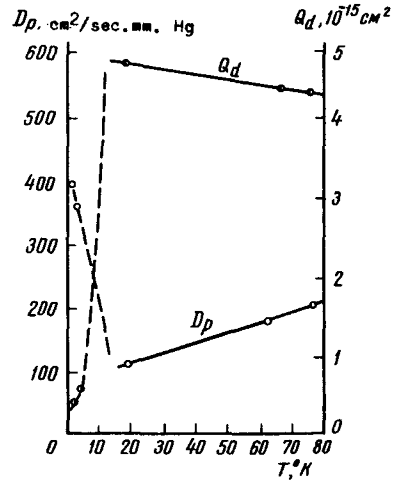

Fig. 3. Temperature dependence of the diffusion coefficient D and of the diffusion cross section Q_d.

are given in reduced units p = p(300/T).)

The results obtained for a cryogenic plasma, like those for a plasma at higher temperatures, can be explained with the aid of the diffusion mechanism of disintegration of metastable atoms. Indeed, the diffusion leads to the exponential time variation of the concentration (1). In this case $\nu(p)$ has the meaning of the diffusion collision frequency

$$\nu(p) = D/\Lambda^2, \quad (2)$$

where D is the diffusion coefficient, which is inversely proportional to the pressure, and Λ is the diffusion length of the vessel.

Using (1) and (2), we have determined the diffusion coefficients from the plots of Fig. 1. Their values are shown in Fig. 3, which shows also the temperature dependence of the diffusion coefficient from 2.5 to 77°K. The solid curve is drawn for the region where the experiment agrees well with the theoretical calculations. The points at 20, 64, and 77°K are taken from our earlier papers [1,5]. An analysis of the temperature dependence of the diffusion coefficient of metastable helium atoms shows that it increases sharply in a cryogenic plasma.

The unusual behavior of the diffusion coefficient at low temperatures may be connected with the change in the diffusion scattering cross section for slow collisions. According to kinetic theory [6] the diffusion coefficient is given by

$$D = \frac{3\pi}{32}\frac{\bar{v}}{n\bar{Q}_d}, \quad (3)$$

where $\bar{v} = (16kT/\pi\mu)^{1/2}$ is the average relative velocity of two gas molecules, n the gas density, and $\bar{Q}_d$ the effective diffusion cross section [1]. The values of the diffusion scattering cross section $\bar{Q}_d$ calculated from relation (3) are shown in Fig. 3. In this figure the $\bar{Q}_d(T)$ curve has been continued into the region of higher temperatures, where theory and experiment are in good agreement [5]. At temperatures below 20°K we see an anomalous temperature variation of the scattering cross section.

Calculation of the scattering of metastable helium atoms in the quasiclassical approximation was made by Buckingham and Dalgarno [7] down to 30°K, corresponding to an atomic wave number $q = 2 \times 10^8$ cm^{-1} and deBroglie wavelength $\lambda = 3.1 \times 10^{-8}$ cm. At lower temperatures, when the wavelength exceeds the effective diameter of the atom, the quasiclassical approximation is not valid. There are no theoretical calculation of the scattering cross section for these conditions.

A peculiarity of the scattering of a metastable helium atom by a normal one is the presence of a "hump" ($V \simeq 0.1$ eV) on the potential curve of their interaction at an internuclear distance $d = 4a_0$ [8], where a_0 is the Bohr radius. For metastable atoms in a cryogenic helium plasma the inequality $q \ll q_0 = (2\mu V\hbar^{-2})^{1/2}$ is satisfied. At such scattering parameters, no minimum can be expected on the plot of the cross section against q (or against the temperature) as $q \to 0$. The effective cross section should in this case increase monotonically. Thus, by following the usual scheme of solving the scattering problem, we cannot explain the observed decrease of the diffusion cross section at low energies. We note that recent theoretical and experimental papers on the scattering of slow electrons, with allowance for the repulsive pseudopotential of the thelium atoms, discuss also the decrease in the scattering cross sections at energies from 0.05 eV to zero (the corresponding electron temperature is lower than 500°K) [3,9]. We can propose the existence of an analogy between these results and our data on the value of the cross section for the diffusion of metastable atoms in a cryogenic helium plasma.

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1) The density of the metastable states in an excited plasma is four orders of magnitude lower than the density of the normal helium atoms.