



Soviet-era science, translated into English

Reports of the Academy of Sciences of the USSR

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1964

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Abstract

Full Text

Reports of the Academy of Sciences of the USSR

1964. Volume 159, No. 1

PHYSICS

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PAIR COLLISIONS OF METASTABLE HELIUM ATOMS IN A PLASMA

(Presented by Academician I. V. Obreimov on 9 V 1964)

1. It is known that for several milliseconds after the discharge is terminated in a helium plasma, afterglow is observed, associated with the presence of long-lived atoms in the metastable state 2^3S ($1-3$). In the absence of impurities, destruction of this state is, generally speaking, determined by the following processes: (a) diffusion of metastable atoms to the walls; (b) collisions of an excited atom with two atoms in the normal state with formation of a metastable helium molecule ($2^3\Sigma_n^+$); (c) pair collisions of metastable atoms with one another.

The continuity equation for the concentration of metastable atoms M , taking these processes into account, has the form

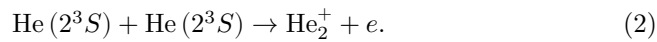
$$\frac{\partial M}{\partial t} = D_M \nabla^2 M - Ap^2 M - kM^2. \quad (1)$$

The diffusion coefficient $D_M = \alpha/P$ is inversely proportional to the pressure p . The second term, describing deactivation of metastables in triple collisions—process (b)—is proportional to p^2 . The quantity k characterizes the rate of process (c).

In the works of Phelps^(4,5) it was shown that at small concentrations of metastables ($M \simeq 10^{11} \text{ cm}^{-3}$) in the pressure range not exceeding several millimeters of mercury, the principal process of deactivation of the 2^3S He states is diffusion (a). At pressures $p > 15$ mm, destruction of metastables is determined by process (b). The efficiency of triple collisions decreases sharply with decreasing temperature. At a temperature of 77°K the coefficient A is approximately 100 times smaller than at room temperature⁽⁴⁾. This may be explained by the presence of an activation energy required for formation of a metastable helium molecule in this process.

In the intermediate pressure region ($5 \div 15$ mm) at $T = 300^\circ\text{K}$, the rates of processes (a) and (b) are minimal, the concentration of metastable atoms increases, and their collisions with one another—process (c)—begin to play a substantial role. Until now the features of this process have practically not been studied. The only known experiment is that of Phelps at 300°K and $p = 10$ mm, when the kinetics of destruction of metastable atoms was governed by their pair inelastic collisions (⁴).

As a result of reaction (c), either an atomic or a molecular helium ion and a free electron may arise. Such collisions of two metastable atoms lead to additional ionization of the helium plasma in the afterglow (²). This same process is responsible for the effect of intense afterglow discovered in the work of the authors and G. P. Reznikov (³) at 77°K . Analysis of the experimental facts currently available (^{2,6,7,3}) convincingly proves that, when a pair of metastables collides, molecular helium ions are formed with the greatest probability. Therefore, in the literature process (c) is interpreted according to the following scheme:



The aim of the present work is to study the mechanism and rate of the process of inelastic pair collisions of metastable 2^3S helium atoms. The study was carried out at the temperature of liquid nitrogen.

2. The sharp decrease in the probability of process (b) with decreasing temperature gives grounds to suppose that at $T = 77^\circ\text{K}$ the destruction of metastables over a wide range of pressures will be determined by process (c). We experimentally studied the dependences of the concentration of metastables on time after termination of the high-frequency discharge pulse at 77°K . The experiments were carried out in the pressure range from 6 to 74 mm (the pressures are expressed in reduced units, $p_{\text{red}} = 300/77p$). The concentration of metastables was measured from the absorption of the 3889 \AA line (3^3P-2^3S) in a discharge tube of diameter 20 mm and length 150 mm. Details of the experiment are described in Ref. (³). The concentration of metastable atoms was calculated from the formula

$$M = \frac{mc\Delta\nu}{\pi e^2 l f} \ln \frac{I_0}{I}, \quad (3)$$

where I_0 and I are the intensities of the incident and transmitted light; $\Delta\nu$ is the width of the emission line*; l is the tube length; f is the oscillator strength of the given transition; c is the speed of light; e, m are the charge and mass of the electron.

Owing to the high power of the high-frequency discharge, comparatively high concentrations of metastable atoms M were attained during the pulse. In the first moments of afterglow, $M_0 \simeq 10^{13} \text{ cm}^{-3}$. Then the density of metastables decreased according to a hyperbolic law. In Fig. 1 are shown the dependences

Figure 1

Figure 1: Figure 1

of $1/M$ as a function of time at various pressures. It follows from Fig. 1 that $1/M$ is a linear function of time.

Fig. 1. Dependence on afterglow time of the reciprocal concentration $1/M$ of metastable helium atoms 2^3S in a decaying plasma at different pressures: 1–8 mm Hg, 2–12 mm, 3–14 mm, 4–16 mm, 5–20 mm, 6–28 mm, 7–76 mm

The linear dependence of $1/M$ on t confirms the assumption that the principal role in the destruction of metastables in our experiments is played by their pair collisions—process (c). Indeed, in this case equation (1) reduces to

$$-\frac{\partial M}{\partial t} = kM^2. \quad (4)$$

Its solution has the form

$$\frac{1}{M} = \frac{1}{M_0} + kt. \quad (5)$$

Dependence (5) does not give a definite lifetime of the metastable state, as would be the case for an exponential dependence. The role of the characteristic “lifetime” is played by the quantity $(kM_0)^{-1}$.

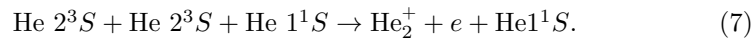
From the slopes of the curves shown in Fig. 1 one can determine the value of the coefficient k . The coefficient k turns out to depend on pressure. In Fig. 2 the function k versus p is plotted; it represents a straight line with slope $k' \equiv dk/dp = 8.5 \cdot 10^{-11} \text{ cm}^3/\text{sec} \cdot \text{mm Hg}$.

$$k = k'p + k_0, \quad (6)$$

* In our experiments the width of the absorption line was 2-3 times smaller than the width of the emission line. The measurements were performed with a spectral slit width of the DFS-8 instrument equal to 0.2 Å for the 3889 Å line.

where k_0 is a term independent of pressure. In our experiments the value of k_0 is negligibly small in comparison with $k'p$.

Thus, the rate of destruction of metastable 2^3S He atoms is proportional to the gas pressure. It follows directly from this that, in the collision process of a pair of metastables, a helium atom in the normal state takes part. The scheme of process (2) must therefore be modified as follows:



Since the concentration of unexcited helium atoms is directly proportional to the pressure, the coefficient k in formulas (4) and (5) proves to be proportional to p . The quantity k_0 in formula (6) characterizes the rate of the process according to scheme (2).

The characteristic destruction time of metastable atoms ("lifetime") in process (7), at a pressure of 8 mm and an initial concentration $M_0 = 1 \cdot 10^{13} \text{ cm}^{-3}$, is equal to $(kM_0)^{-1} = 200 \text{ } \mu\text{s}$.

It is of interest to compare the results of the present work with measurements of the rate of the process studied according to the data of Phelps⁴. Our treatment of the dependence of M on t , obtained in work⁴ for $p = 10 \text{ mm}$ and $T = 300^\circ\text{K}$, gives the value $k \simeq 1.8 \cdot 10^{-9} \text{ cm}^3/\text{s}$. From our data for $p = 10 \text{ mm}$ and $T = 77^\circ\text{K}$ we obtain the value $k = 8 \cdot 10^{-10} \text{ cm}^3/\text{s}$.

Fig. 2. Dependence of the rate of the process of paired collisions of two metastable He (2^3S) atoms on pressure. Slope of the straight line: $8.5 \cdot 10^{-3} \text{ cm}^3/\text{s} \cdot \text{mm Hg}$. 77°K .

Consequently, when the temperature is lowered from 300 to 77°K , the rate of the process decreases by a factor of 2. This is apparently connected with a decrease in the particle velocity \bar{v} . An estimate of the cross section of the process gives $Q \simeq 10^{14} \text{ cm}^2$, in agreement with the estimate of Phelps and Molnar⁴ at 300°K .

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Received
6 V 1964

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Note: Figure translations are in progress. See original paper for figures.

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