Isotope effect in charge exchange of He^+ ions with helium atoms

V. A. Kartoshkin

A. F. Ioffe Physicotechnical Institute, Academy of Sciences of the USSR, Leningrad

(Submitted 26, December 1986)
Pis'ma Zh. Eksp. Teor. Fiz. **45**, No. 3, 126–127 (10 February 1987)

An isotope effect has been established for the first time in the rate constant for charge exchange of an ion with the corresponding atom (helium).

Resonant charge exchange in helium has been studied in many places, both experimentally and theoretically.[1] The rate constant for this process is[1] $C_1 = \langle \sigma v \rangle_1 = 6 \times 10^{-10}$ cm^{-3}, and the results reported by different authors have been found to be in good agreement. At the same time, it is unclear whether the rate constant for the resonant process (C_1)

$$^3\mathrm{He}(1\,^1S_0) + {}^3\mathrm{He}^+(1\,^2S_{1/2}) \rightarrow {}^3\mathrm{He}^+(1\,^2S_{1/2}) + {}^3\mathrm{He}(1\,^1S_0) \qquad (1)$$

will differ from that of the nonresonant process ($C_2 = \langle \sigma v \rangle_2$)

 0021-3640/87/030154-03$01.00

$$^3\mathrm{He}(1\,^1S_0) + {}^4\mathrm{He}^+(1\,^2S_{1/2}) \rightarrow {}^3\mathrm{He}^+(1\,^2S_{1/2}) + {}^4\mathrm{He}(1\,^1S_0), \qquad (2)$$

since the deviation from resonance in reaction (2) is very slight. Specifically, the resonance defect,[2] $\Delta E = 4\times 10^{-5}$ a.u., stems from an isotopic shift of the levels in the ^{3}He atom and ion with respect to the levels in ^{4}He.

In the present study we have established that there is a difference in the rate constants for reactions (1) and (2), by studying transients in a system of optically oriented helium atoms. It was shown in Ref. 3 that the longitudinal relaxation of atoms of the isotope ^{3}He in the $1\,^1S_0$ ground state stems from a resonant charge exchange of atoms which are oriented in terms of nuclear spin in the $1\,^1S_0$ state and $^3\mathrm{He}^+$ ions in the $1\,^2S_{1/2}$ state. In this letter we consider the relaxation of the nuclear moments of ^{3}He in the isotopic mixture ^{3}He–^{4}He at $T = 77$ K. It is easy to show, working from the results of Refs. 3 and 4, that the nuclear relaxation time T_r for a relaxation in a mixture of isotopes, which is not due to an exchange of metastability between atoms in the ground state and the 2^3S_1 metastable state, is given by the expression

$$\frac{1}{T_r} = \frac{1}{T_0} + \left(\frac{1}{T_1} + \frac{1}{T_2}\right) \frac{\dfrac{1}{\tau_{r_1}} + \dfrac{1}{2\tau_3}\,\dfrac{\epsilon}{\epsilon+1}}{\dfrac{1}{\tau_{r_1}} + \dfrac{1}{2\tau_1} + \dfrac{1}{2\tau_3}\,\dfrac{1+2\epsilon}{1+\epsilon}} \qquad (3)$$

where $1/T_1 = \alpha n_i C_1$, $1/T_2 = (1-\alpha) n_i C_2$, $\epsilon = \tau_2/\tau_{r_2}$, $1/\tau_1 = \alpha N C_1$, $1/\tau_2 = \alpha N C_2$, $1/\tau_3 = (1-\alpha) N C_2$, α is the relative number of ^{3}He atoms in the mixture of helium isotopes, n_i is the density of He^+ ions in the absorption chamber, N is the density of atoms in the ground state, and τ_{r_1} and τ_{r_2} are the electron relaxation times of the $^3\mathrm{He}^+$ and $^4\mathrm{He}^+$ ions, respectively. The difference between these times stems from the different rates of diffusion to the walls of the absorption chamber due to the difference in the mass of the ions. Here T_0 is the relaxation time of the nuclear moments of ^{3}He, which is unrelated to the presence of a discharge in the absorption chamber, which can be determined with the help of Ref. 5.

The nuclear relaxation time T_r is found in accordance with the technique of Ref. 3 for absorption chambers with various fractions of the isotope ^{3}He at a fixed discharge intensity. The value of $1/\tau_{ri}$, which is determined primarily by the diffusion of He^+ ions to the walls of the absorption chamber, changes only very slightly (because of a change in the reduced mass of the system of two colliding particles). This change can be taken into account quite easily. From (3) we then find a system of equations from which we find the ratio of rate constants C_2/C_1. Measurements have been carried out for various fixed discharge intensities (as α was varied). In other words, measurements were carried out at various densities of the He^+ ions, so that a statistical analysis of the results was possible.

It was finally found that at $T = 77$ K the ratio of the rate constants for reactions (2) and (1), respectively the nonresonant and resonant charge exchange of He^+ ions with the corresponding atom, is $C_2/C_1 = 0.87 \pm 0.09$.

This figure agrees with the theoretical value C_2/C_1 (theo) $= 0.8$, found from the

equations of Ref. 6 and the interaction potentials in the $He–He^+$ system from Ref. 7. It should be noted that the isotope effect which we have observed is not due to a difference in the reduced masses of the colliding particles in reactions (1) and (2), since a simple calculation shows that there is no "capture" of one particle by the other in the collision: The average probability for charge exchange during one pass of an ion by an atom is about 0.2. Consequently, the rate constant is nearly independent of the reduced mass of the particles; i.e., $C_2/C_1 \approx 1$. The isotope effect due to the nonresonant nature of process (2) is therefore about 10%.

We should point out in conclusion that until now the only process in which a small resonance defect, close to the energy defect of process (2), has caused a significant difference in the rate constants for resonant and nonresonant processes has been the exchange of metastability in helium.[6]

[1]B. M. Smirnov, Iony i vozbuzhdennye atomy v plazme (Ions and Excited Atoms in Plasmas), Atomizdat, Moscow (1974).
[2]N. P. Van Asselt, J. G. Maas, and J. Los, Chem. Phys. **16**, 81 (1986).
[3]V. A. Kartoshkin and G. V. Klement'ev, Zh. Tekh. Fiz. **56**, 178 (1986) [Sov. Phys. Tech. Phys. **31**, 103 (1986)].
[4]M. Pinard and M. Leduc, J. Phys. (Paris) **35**, 741 (1974).
[5]V. A. Kartoshkin, Zh. Tekh. Fiz. **56**, 968 (1986) [Sov. Phys. Tech. Phys. **31**, 591 (1986)].
[6]Yu. N. Demkov, Zh. Eksp. Teor. Fiz. **45**, 195 (1963) [Sov. Phys. JETP **18**, 138 (1963)].
[7]B. L. Moiseiwitsch, Proc. Phys. Soc. **69**, 653 (1956).
[8]V. A. Khitnikov, V. A. Kartoshkin, G. V. Klement'ev, and L. V. Usacheva, Pis'ma Zh. Eksp. Teor. Fiz. **22**, 293 (1975) [JETP Lett. **22**, 136 (1975)].

Translated by Dave Parsons