Metastability exchange in a mixture of helium isotopes at liquid nitrogen temperature

R. A. Zhitnikov, V. A. Kartoshkin, G. V. Klement'ev, and L. V. Usacheva

A. P. Ioffe Physico-technical Institute, USSR Academy of Sciences
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We investigated the optical orientation and the magnetic resonance of He^3 and He^4 atoms in $2\ ^3S_1$ states in He^3-He^4 isotope mixtures. We measured the metastability exchange cross sections σ (He^3-He^3) and σ(He^3-He^4) at liquid-nitrogen temperature. An appreciable difference between these cross sections was observed.

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It was suggested in[1] that the metastability exchange cross sections $\sigma(He^3-He^3)$ and $\sigma(He^4-He^4)$ of the isotopes He^3 and He^4 are equal to each other and to the cross section $\sigma(He^3-He^4)$ of metastability exchange between the atoms He^3 and He^4, since these cross sections should not depend on the nuclear moments. This statement does not seem to be obvious, owing to the difference between the excitation energies of the metastable $2\ ^3S_1$ state of the isotopes He^3 and He^4. This can cause, under certain experimental conditions, the cross sections for metastability exchange between atoms of one and the same isotopes and between atoms of different isotopes of heliums to be noticeably different.

The present paper is devoted to the measurement of the metastability exchange cross sections $\sigma(He^3-He^3)$ and $\sigma(He^3-He^4)$ and to a determination of the difference between these cross sections at liquid nitrogen temperature, where this difference should be significantly larger than at room temperature.

To find these cross sections, we determined the dependence of the magnetic-resonance line width of optically oriented He^3 and He^4 atoms in the $2\ ^3S_1$ state on the percentage content of the He^3 in the He^3-He^4 mixture at a constant total gas pressure. The contribution of the metastability exchange to the magnetic-resonance line width is determined by collisions of the following three types:

1) $He^{3*} + He^3 \to He^3 + He^{3*}$,

2) $He^{3*} + He^4 \to He^3 + He^{4*}$,

3) $He^{4*} + He^3 \to He^4 + He^{3*}$

(the asterisks mark atoms in the metastable $2\ ^3S_1$ state).

An examination of these processes shows that their contribution to the magnetic-resonance line width is given by the expressions

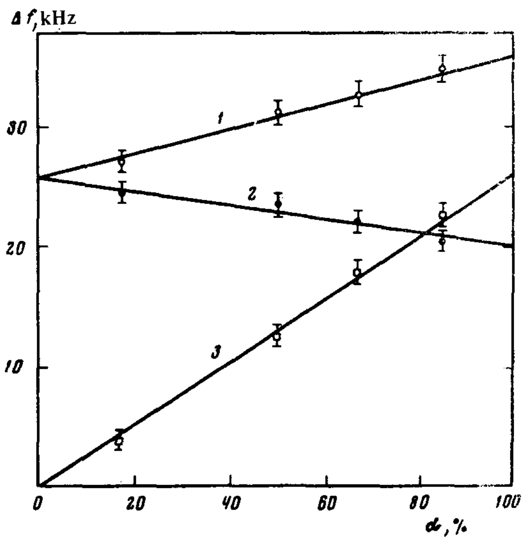
$$(\Delta\omega)_{3/2} = \frac{4}{9}\alpha N\bar{v}_1\sigma_1 + (1-\alpha)N\bar{v}_2\sigma_2, \quad (1)$$

$$(\Delta\omega)_{1/2} = \frac{7}{9}\alpha N\bar{v}_1\sigma_1 + (1-\alpha)N\bar{v}_2\sigma_2, \quad (2)$$

$$(\Delta\omega)_{He^4} = \alpha N\bar{v}_2\sigma_2. \quad (3)$$

Here $(\Delta\omega)_{3/2}$ and $(\Delta\omega)_{1/2}$ are the half-widths of the magnetic resonance lines of He^3 in the $2\ ^3S_1$ state with $F = \frac{3}{2}$ and $F = \frac{1}{2}$, while $(\Delta\omega)_{He^4}$ is the half-width of the magnetic-resonance line of He^4 in the $2\ ^3S_1$ state, N is the density of the helium atoms in the working cell, $\alpha = N_{He^3}/N$ is the fraction of the He^3 atoms in helium-isotope mixture, $\bar{v}_1$ and $\bar{v}_2$ are the average relative velocities for the atoms He^3-He^3 and He^3-He^4, respectively, $\sigma_1 = \sigma(He^3-He^3)$, and $\sigma_2 = \sigma(He^3-He^4)$. The coefficients $\frac{4}{9}$ and $\frac{7}{9}$ take into account the incomplete loss of orientation in the states with $F = \frac{3}{2}$ and $F = \frac{1}{2}$ when the He^3 atoms collide with one another.[1,2] Expressions (1)–(3) were used by us to calculate the metastability exchange cross sections.

We used in the experiment the well-known technique of optical orientation of the $2\ ^3S_1$ metastable helium atoms.[3] For experiments with the isotope mixture He^3-He^4 we used a set of absorption chambers with total pressures 0.3 and 0.4 Torr. The absorption chamber was immersed in liquid nitrogen and a weak high-frequency gas discharge was excited in it. The optical orientation of the helium atoms was produced by circularly-polarized lamp with the isotope He^4. The resonance signals were registered by means of absorption of 1.08-micron pumping light. The figure shows plots of the magnetic-resonance line widths on the He^3 concentration at a total pressure 0.3 Torr. The data in



Dependence of the magnetic-resonance line widths of optically oriented helium atoms in the isotope mixtures He^3-He^4 on the percentage content α of the He^3 at a total pressure 0.3 Torr: 1—resonance-line widths of He^3 in the $2\ ^3S_1$ state with $F = \frac{1}{2}$, 2—the same with $F = \frac{3}{2}$, 3—widths of resonance lines of He^4 in the $2\ ^3S_1$ state.

the figure have been corrected for the radio-frequency broadening, for modulation effects, for the inhomogeneity of the constant magnetic field, for the influence of the discharge, and for the diffusion of the metastable atoms towards the walls of the cell. It is seen from the figure that when the He^3-atom concentration is increased the magnetic-resonance line of He^4 is significantly broadened. The magnetic-resonance line of the He^3 atoms in the state with $F=\frac{1}{2}$ is only insignificantly broadened in this case, while the magnetic resonance line in the state with $F=\frac{3}{2}$ becomes somewhat narrower. These experimental plots were used to calculate the metastability exchange cross sections. They were found to be

$$\sigma_1 = (1.41 \pm 0.11) \cdot 10^{-16}\ \text{cm}^2,$$

$$\sigma_2 = (0.78 \pm 0.06) \cdot 10^{-16}\ \text{cm}^2.$$

Thus, at nitrogen temperature the ratio of the metastability exchange cross section is $\sigma_2/\sigma_1 = 0.58 \pm 0.09$.

The result points to an appreciable difference between the metastability exchange cross sections $\sigma(He^3-He^3)$ and $\sigma(He^3-He^4)$ at low temperatures. This is apparently due to the nonresonant character of the metastability exchange when different helium isotope atoms collide. Similar effects were considered in[4] for the case of mercury isotopes.

Indeed, in collisions of He^3 and He^4 atoms, of which one is in the ground $1\ ^1S_0$ state and the other is in the $2\ ^3S_1$ metastable state, the resonance defect following metastability exchange is $\Delta E \cong 6\ \text{cm}^{-1}$.[5] Here ΔE is the difference between the energies needed to excite the $2\ ^3S_1$ states of the atoms He^3 and He^4. Such a resonance defect is significant in metastability exchange at low temperatures, for in this case $\tau_{exch}\Delta E \sim h/2\pi$, where τ_{exch} is the metastability exchange time and is determined by the effective region of interaction and by the velocity of the helium atoms, while h is Planck's constant. In addition, the difference between the potential energies of the symmetrical and antisymmetrical excited states of the He_2^* molecule,[6,7] which determines the metastability exchange cross section, may become small enough and comparable with the resonance defect.

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