MECHANISM OF INELASTIC TRANSITIONS IN Li^+-He COLLISIONS

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The question of the relative role of different mechanisms of dynamic coupling between quasimolecular terms in atomic collisions was raised in connection with studies of adiabaticity violation in deep collisions. It was shown [1, 2] that in addition to inter-term transitions connected with the motion of the colliding particles (the Landau-Zener approximation), an important role can be played by transitions connected with the rotation of the internuclear axis of the colliding particles.

We have investigated inelastic transitions occurring in collisions between light particles, when very close approach of the nuclei can be easily attained at the specified collision velocities. Under these conditions, the speed of rotation of the internuclear axis is large, and one can therefore expect a high probability of excitation of inelastic transitions due to this rotation.

We used in our experiments a collimated monokinetic Li^+-ion beam that entered a collision chamber filled with helium. The ions scattered by the helium atoms were sorted by angle with a rotating collimator and energy-analyzed with an electrostatic analyzer. This yielded the differential cross sections for ion scattering at fixed angles as functions of the inelastic energy loss (the inelastic-loss spectra). The energy interval of the incident Li^+ ions was 0.6 - 4.0 keV, and the scattering interval was 1 - 10°.

It was found that the loss spectra consist of a series of peaks. The peaks were identified by data on the energy levels of the isolated particles (the ion and the atom). The peaks in the spectra correspond to elastic scattering, and also to inelastic scattering with excitation, ionization, and formation of auto-ionization states of the target atoms.

It was established that Li^+-He collisions excite with maximum probability the He level $1s2p\,^1P$ (the average energy position of the corresponding peak in the loss spectra is 21.2 eV) and the He autoionization levels $2s^2\ ^1S$, $2p^2\ ^1D$, and $2s2p\,^1P$ (average energy position of the corresponding peak 59.3 eV).

The differential cross sections for the excitation of these levels, and also the elastic-scattering cross section, are shown in Fig. 1. The cross sections are plotted in the coordinates $\rho = \theta \sin\theta\sigma(\tau)$ and $\tau = E\theta$, where θ, E, and σ are the scattering angle, the kinetic energy, and the differential cross section in c.m.s.

The differential cross section for the excitation of the He level $1s2p\,^1P$ has a number of characteristic features that distinguish the behavior of this cross section from the previously investigated

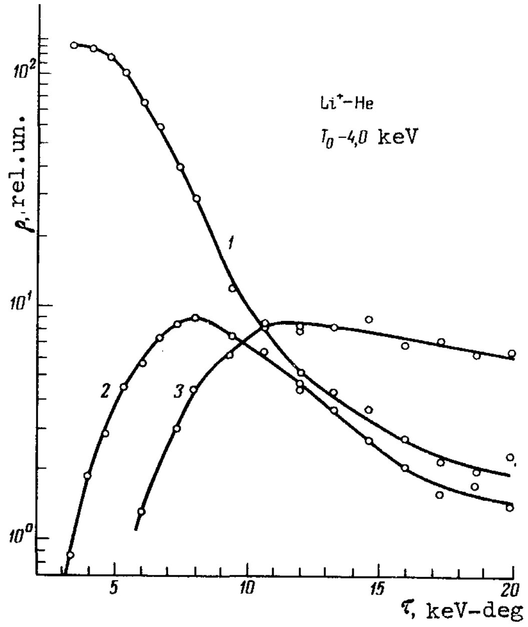

Fig. 1. Differential cross section vs. scattering angle: 1 - elastic scattering, 2 - excitation of He level $1s2p\,^1P$, 3 - excitation of He autoionization levels $2s^2\ ^1S$, $2p^1\ ^1D$, $2s2p\,^1P$.

cases of level excitation in atomic collisions (e.g., [3]). These features include a dependence of the position of the near-threshold region of the angular dependence of the cross section on the collision energy, a relatively slow growth of the differential cross section in the near-threshold region, and absence of oscillations of the cross section (Fig. 2). Another difference between the Li$^+$-He collisions and the previously investigated cases is that the ions causing excitation of the He level 1s2p^{1}P are scattered in the near-threshold region through smaller angles in comparison with the ions, the scattering of which is accompanied by auto-ionization of the target atom (Fig. 1, curves 2 and 3). These features of the Li$^+$-He collisions are confirmed by recent measurements of the ion scattering cross sections at energies 1.0, 1.5, and 2.0 keV [4] and at 1.5, 2.0, and 3.0 keV [5].

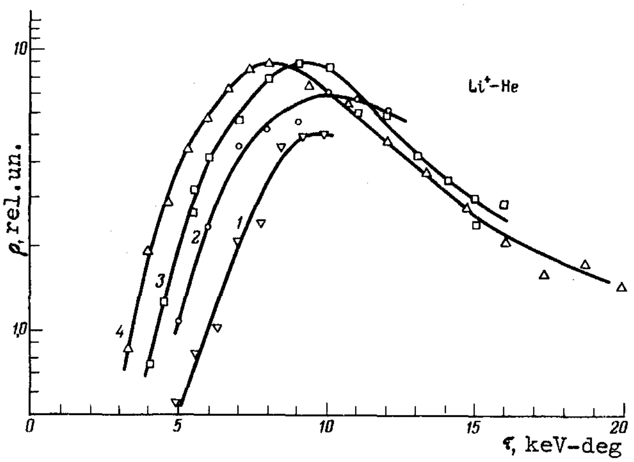

Fig. 2. Differential cross sections for the excitation of the He level 1s2p^{1}P vs. the scattering angle at different ion energies: 1) T_0 - 1.4 keV, 2) T_0 - 2.0 keV, 3) T_0 - 3.0 keV, 4) T_0 - 4.0 keV.

The mechanism of excitation of the inelastic transition was analyzed on the basis of the correlation diagram of the diabatic terms of the Li$^+$-He system (Fig. 3). The diagram was obtained from the corresponding correlation diagram of the molecular orbitals. In the construction of the orbital diagram it was assumed that the number of zeroes of the radial parts of the electron wave functions does not change on going from the limiting case of isolated atoms to the combined atom. When choosing the most probable amount the possible electron states in the limiting case of the joined atom, we took into account the change of the effective charges, in the field of which the electrons move, on going from one limiting case to the other.

A comparison of the correlation diagram of the terms with the experimental results makes it possible to draw the following conclusions concerning the mechanism of excitation of inelastic transitions in Li$^+$-He collisions.

1. The excitation of the levels of the He atom is connected with transitions both between terms of like symmetry ($^1\Sigma$ - $^1\Sigma$ and $^1\pi$ - $^1\pi$ transitions), and with transitions between terms of different symmetry ($^1\Sigma$ - $^1\pi$ and $^1\pi$ - $^1\Delta$ transitions).

The He atom turns out to be in the excited state 1s2p^{1}P as a result of successive transitions occurring when the term $(2p\sigma^2)^1\Sigma$ interacts with the terms $(2s\sigma^2)$ $^1\Sigma$, $(2s\sigma 2p\sigma)$ $^1\Sigma$, $(2s\sigma 2p\pi)$ $^1\pi$, and $(2p\sigma 2p\pi)$ $^1\pi$, and also as a result of an interaction of the indicated π-terms with each other. An important role is played here by transitions due to rotation of the internuclear axis between the terms $(2p\sigma^2)$ $^1\Sigma$ and $(2p\sigma 2p\pi)$ $^1\pi$, which come closer with decreasing internuclear distance and degenerate in the limit of the combined atom into the term $(2p^2)$ ^{1}D.

In the near-threshold region of the scattering angles, the experimental cross section for the excitation of the He level 1s2p^{1}P exceeds considerably (by up to several times) the theoretical value [6] calculated with allowance for only the interaction between the terms $(2p\sigma^2)$ $^1\Sigma$, $(2p\sigma 2p\pi)$ $^1\pi$, and

$(2p\pi^2)\,{}^1\Delta$. The cause of this discrepancy, in our opinion, may be the appreciable role of the transition as a result of the rotation of the internuclear axis between the terms $(2p\sigma^2)\,{}^1\Sigma$ and $(2s\sigma 2p\pi)\,{}^1\pi$, which were not taken into account in [6].

2. The most important of the inelastic processes in Li^+-He collisions is charge exchange. The differential charge-exchange cross sections obtained by us by subtracting the total inelastic-loss cross section from the calculated total scattering cross section have the same distinguishing features as listed above for the cross section of the excitation of the $1s2p\,{}^1P$ level of He. These features are typical for transitions whose excitation mechanism is connected with rotation of the internuclear axis. It is therefore quite probable that the charge exchange is effected via decay at large internuclear distances of the molecular state $(2p\sigma 2p\pi)\,{}^1\pi$ into the atomic states $Li^+(1s^2)$-$He(1s2p)\,{}^1P$ and $Li(1s^2 2p)\,{}^2P$-$He^+(1s)$.

However, the smallness of the oscillations of the total charge-exchange cross section as a function of the energy, observed in [7], gives grounds for assuming that a certain contribution to the experimental cross section is made by the process $Li^+\text{-}He \rightarrow Li(1s^2 2s)\text{-}He^+(1s)$ and the process $Li^+\text{-}He \rightarrow Li(1s^2 2s)\text{-}He^+(2p)$ (capture with excitation). The latter process is connected with the interaction (resulting from the rotation of the internuclear axis) of the terms $(2p\sigma^2)\,{}^1\Sigma$ and $(2s\sigma 2p\pi)\,{}^1\pi$ and with the large probability of the transition at the point of crossing of the terms $(2s\sigma 2p\pi)\,{}^1\pi$ and $(2p\sigma 2p\pi)\,{}^1\pi$. A confirmation of this hypothesis would be of great interest, in view of the relatively high energy of the emission photons (40.8 eV).

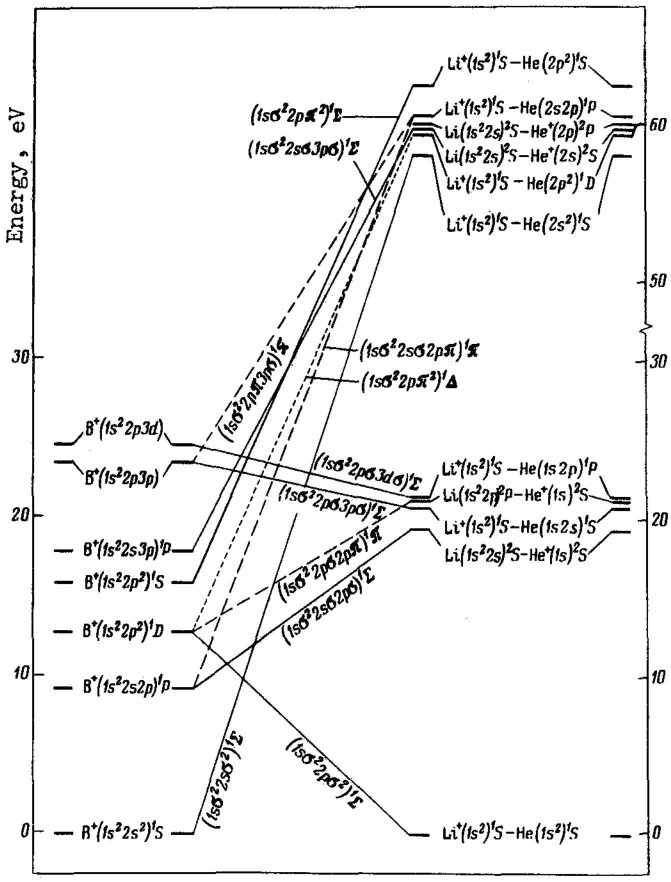

Fig. 3. Correlation diagram of diabatic terms of the Li^+-He system.

3. Internuclear distances ∿0.2 - 0.4 at. un. are easily attained in the entire collision-energy range investigated by us. The perturbation caused by the rotation of the internuclear axis (∿5 - 20 eV) turns out to suffice for an intense mixing of system terms that differ in their symmetry properties: the term $(2p\sigma^2)\,{}^1\Sigma$ interacts with the terms $(2p\sigma 2p\pi)\,{}^1\pi$ and $(2s\sigma 2p\pi)\,{}^1\pi$, and these in turn interact with the terms $(2p\pi^2)\,{}^1\Delta$ and $(2s\sigma 2p\sigma)\,{}^1\Sigma$, respectively. As a result, in a quantitative study of the excitation processes one is faced with the problem of taking simultaneous account of the entire aggregate of interacting terms.

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THE SHUBNIKOV - DE HAAS EFFECT IN THIN CONDUCTORS

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In the quasiclassical region of magnetic fields, when the distance $\hbar\Omega$ between the quantized energy levels of the conduction electrons is much less than the Fermi energy ε_0 but is larger than their width $\hbar/\tau$, the resistivity ρ of bulky conductors oscillates as a function of the reciprocal magnetic field, and the extremal areas of the sections of the Fermi surface can be determined from the periods of the oscillations [1, 2]. In sufficiently thin plates and wires, the electron orbit corresponding to the maximum area S_{max} of the section of the Fermi surface cannot be contained in the cross section of the conductor, and at magnetic field values H at which the diameter of such an orbit is equal to the thickness d of the conductor, i.e.,

$$\frac{cD_p}{eH} = d, \qquad (1)$$

the Shubnikov - de Haas oscillations with period $\Delta(1/H) = 2\pi\hbar e/cS_{max}$ should vanish, in analogy with the cutoff of cyclotron resonance frequencies [3]. Here e is the electron charge, Ω is the frequency of its revolution in the magnetic field, τ is the free-path time, $\hbar$ is Planck's constant, c is the speed of light, and D_p is the parameter of the cross section of the Fermi surface.

Just as in the case of cyclotron resonance, when a new resonant frequency that depends on the sample thickness appears in place of the cut-off frequency [4], one should expect at $H < (cD_p/ed)$ the appearance of a new oscillatory dependence of the resistance on the magnetic field and on the conductor thickness. The period of these oscillations is connected with the characteristics of the electrons that do not collide with the sample boundary and for which the cross section of the Fermi surface is maximal. Since the diameter of the orbit of such electrons satisfies relation (1), it is possible to determine from the periods of the $\rho(H)$ oscillations, at different values of d, the connection between the area $S(\varepsilon_0, p_z)$ and the diameter $D(p_z)$ of the section of the Fermi surface for all values of the electron monentum projection p_z on the magnetic-field direction.

The character of the reflection of the carriers from the sample boundary is immaterial for this oscillatory effect. We shall assume that the electrons are diffusely scattered upon collision with the surface of the conductor, and that it suffices to take into account their contribution to the electron-current