EXCITATION OF K II RESONANCE LINES IN SLOW COLLISIONS BETWEEN K^+ IONS AND HELIUM ATOMS

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The relative intensities of the K II λ 600.7, 607.9 and 612.6 resonance lines, excited in collisions between positive potassium ions and helium atoms, were measured for K^+ ion energies between 0.8 and 9.0 keV. The experimental excitation curve for the K II λ 600.7 Å line at energies above 1.3 keV coincided with the theoretical curve calculated using the Landau–Zener formula. The relative intensities of the K II λ 600.7, 607.9 and 612.6 Å lines (4 : 1 : 1) indicated that the probability of the excitation of the singlet resonance level $^1P_1$ was greater than that of the triplet level $^3P_1$.

1. INTRODUCTION

THE excitation of two atomic particles in a slow collision is one of the processes which can be analyzed theoretically in a simple manner on the basis of representations taken from the theory of diatomic molecules. The transitions of a system of two approaching atoms to excited states have been considered in the well-known papers of Landau[1] and Zener,[2] as well as in later papers,[3,4] and the formulas have been given for the determination of the probabilities of such transitions.

The purpose of the present investigation was to obtain experimental data on the excitation in atomic collisions and to compare these data with the Landau–Zener theory. We investigated the excitation of the K II λ 600.7, 607.9, and 612.6 Å resonance lines excited in slow collisions of K^+ ions with He atoms. These collision partners were selected because of the possibility of determining the excitation curve near the excitation threshold.

2. EXPERIMENTAL METHOD

The apparatus used is shown schematically in Fig. 1. K^+ ions, emitted by a thermionic source, were accelerated and focused by a system of electrodes. The focused ion beam passed through a parallel-plate capacitor, used to modulate the intensity, and then reached a collision chamber, in which the pressure of helium was maintained at 3×10^{-3} mm Hg. The energy of the ions was varied within the limits 0.8–9.0 keV, while the density of the current in the beam ranged from 5×10^{-7} to 1.5×10^{-5} A/cm^2. The radiation generated by the collisions of K^+ ions with He atoms was analyzed using a vacuum spectrometer with a bent diffraction grating. The light was detected by a photoelectric converter (a gold-coated plate) which was placed behind the exit slit of the spectrometer. Photoelectrons, emitted after the absorption of light quanta, were accelerated to an energy of 25 keV and recorded with a scintillation counter. The amplitude discrimination method was used to distinguish pulses representing flashes in the scintillator from the background pulses of the photomultiplier. Modulation of the ion beam at a frequency of 2.5 $\times 10^4$ cps made it possible to count simultaneously

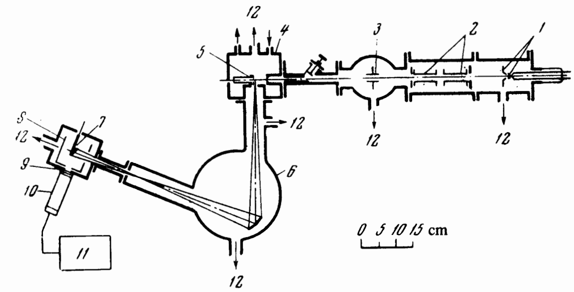

FIG. 1. Schematic diagram of the apparatus. 1) Ion source; 2) focusing electrodes; 3) capacitor used to modulate ion beam; 4) collision chamber; 5) ion detector; 6) vacuum spectrometer; 7) photoelectric converter; 8) focusing electrode; 9) scintillation counter; 10) photomultiplier; 11) electronic unit; 12) connections to vacuum pumps.

(using two separate counting devices): 1) the number of background pulses and 2) the number of the photoelectron pulses mixed with the background. At the same time, we measured the total charge of ions which had traversed the collision chamber. This method made it possible reliably to record very weak light fluxes.

The intensity of the K^+ ion lines was found to depend linearly on the helium pressure in the range from 1×10^{-4} to 5×10^{-3} mm Hg. This showed that multiple collisions and the absorption of the K^+ lines in the collision chamber could be neglected.

3. RESULTS

The radiation generated in the collisions of K^+ ions with helium atoms included three resonance lines of the K^+ ion and one resonance line of the He atom at λ 584.3 Å. Figure 2 shows the spectrum obtained for K^+ ions of 6.0 keV energy. The K II λ 600.7 Å line, representing a transition from the $^1P_1(3s^23p^5[^2P_{1/2}]^04s)$ level to the ground state $^1S_0(3s^23p^6)$, was much stronger than the λ 607.9 and λ 612.6 Å lines, corresponding to transitions from the states $^1P_1$, $^3P_1(3s^23p^5[^2P_{3/2}]^03d)$ and $^3P_1(3s^23p^5[^2P_{3/2}]^04s)$, to the ground state.

The measured intensity of the He λ 584.3 Å line was distorted by the absorption in helium between the point where this line was generated in the collision chamber and the radiation detector.

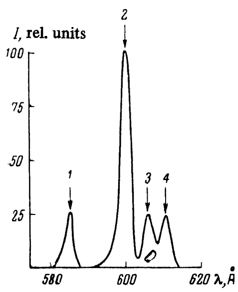

FIG. 2. Radiation spectrum: 1) He I λ 584.3 Å lines; 2) K II λ 600.7 Å line; 3) K II λ 607.9 Å line; 4) K II λ 612.6 Å line.

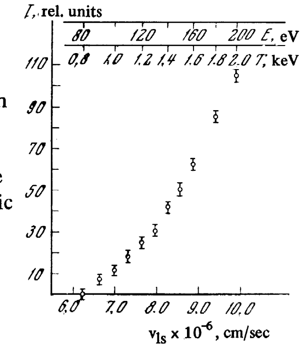

FIG. 4. Initial part of the excitation function of the K II λ 600.7 Å line; v_{ls} is the velocity of K^+ ions in the laboratory system of coordinates; T is the kinetic energy of K^+ ions; E is the kinetic energy of the relative motion.

Figures 3 and 4 show the experimentally determined excitation curves of the K II resonance lines recorded in the K^+ ion energy range from 0.8 to 9.0 keV. It is evident from these two figures that the excitation of the λ 600.7 Å line had a threshold at a K^+ ion energy of 0.8 keV, which was governed by the sensitivity of the measuring apparatus (the threshold for the excitation of this line, calculated from the laws of conservation of energy and momentum, was 0.2 keV). The excitation curve rose rapidly from the threshold, reached a maximum at 5.5 keV, and then decreased slowly. In the ascending part of the curve, the rate of rise of the line intensity increased strongly at an energy of 1.3 keV (Fig. 4). The excitation functions of the K II lines at λ 607.9 and 612.6 Å were similar. The curve for the λ 600.7 Å line did not differ in shape from the other two curves and could be obtained from these curves by multiplying the ordinate by a constant factor of ~4.

4. DISCUSSION OF RESULTS

To compare the theory with the experimental data, we shall use a hypothetical dependence of the potential energy U(r) of the K^+He system on the internuclear distance r, shown in Fig. 5. Curve 1 represents the normal state corresponding to the approach of K^+ to He, both in the ground states; curve 2 represents the dependence U(r) for a K^+ ion excited to one of the resonance levels and an He atom in the ground state.

When the kinetic energy of the relative motion of the system, E, is much larger than U_0, which is the ordinate of the pseudointersection point of the $U_1(r)$ and $U_2(r)$ potential curves corresponding to the initial and final states, i.e., when the turning point is sufficiently far from the pseudointersection, the probability W_{12} of a transition between these initial and final states is given by the Landau–Zener formula:[5]

$$W_{12}(v) = 2\exp\left(-\frac{2\pi V^2}{\hbar v|F_2-F_1|}\right)\left[1-\exp\left(-\frac{2\pi V^2}{\hbar v|F_2-F|}\right)\right], \quad (1)$$

where v is the relative (radial) velocity at the pseudointersection point $r = r_0$ of the $U_1(r)$ and $U_2(r)$ potential curves; $F_{1,2} = -\partial U_{1,2}(r)/\partial r|_{r=r_0}$ and V is the matrix element relating the two states being considered.

The velocity v can be represented in the form

$$v = \left\{\frac{2}{\mu}\left[E - U_0 - \left(\frac{\rho}{r_0}\right)^2 E\right]\right\}^{1/2}, \quad (2)$$

where μ is the reduced mass and ρ is the impact parameter.

The cross section for this transition is given by the formula

$$\sigma(E) = 2\pi \int_0^{\rho_{max}} W_{12}(v)\rho d\rho, \quad (3)$$

where $\rho_{max} = r_0\sqrt{1-(U_0/E)}$ is calculated using Eq. (2) and v = 0. If the matrix element V in Eq. (1) is independent of the relative velocity, integration over the impact parameter gives the following dependence:

$$\sigma(E) = \frac{\pi a^2 r_0^2}{E}\left\{\left[\frac{e^{-z}}{z^2} - \frac{e^{-z}}{z} - \mathrm{Ei}(-z)\right] - 4\left[\frac{e^{-\xi}}{\xi^2} - \frac{e^{-\xi}}{\xi} - \mathrm{Ei}(-\xi)\right]\right\}, \quad (4)$$

where

$$\mathrm{Ei}(-z) = -\int_z^\infty \frac{e^{-t}}{t}dt, \quad z>0$$

is the integral exponential function, and

$$z = \frac{1}{2}\xi = \frac{a}{\sqrt{E-U_0}} \qquad a = \frac{\sqrt{2\mu}\,\pi V^2}{\hbar|F_2-F_1|}. \quad (5)$$

In order to determine the energy dependence of the

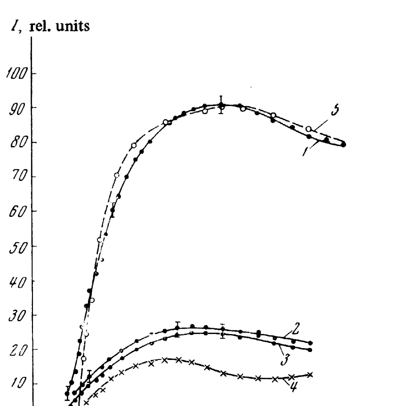

FIG. 3. Excitation functions: 1) K II λ 600.7 Å line; 2) K II λ 607.9 Å line; 3) K II λ 612.6 Å line; 4) He I λ 584.3 Å line; 5) curve plotted using Eq. (4). T is the kinetic energy of K^+ ions and I is the line intensity in relative units.

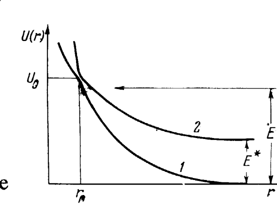

FIG. 5. Hypothetical dependence of the potential energy U of the K^+He system on the internuclear distance r. 1) Electron term of the ground state; 2) electron term of the excited state. E* is the excitation energy of the K^+ ion; E is the kinetic energy of the relative motion; r_0 and U_0 are the coordinates of the point of pseudointersection of the terms 1 and 2.

Process	λ, Å	Transition	Type of perturbation
$K^+ (^1S) + He (^1S) \rightarrow K^+ (^1P) + He (^1S)$	600.7	$^1\Sigma^+ \rightarrow {}^1\Pi$	rotation–orbit
$K^+ (^1S) + He (^1S) \rightarrow K^+ (^3P) + He (^1S)$	612.6	$^1\Sigma^+ \rightarrow {}^3\Pi$	spin–orbit
		$^1\Sigma^+ \rightarrow {}^3\Sigma^-$	spin–orbit

cross section by means of Eq. (4), it is necessary to know two parameters, $-U_0$ and a, which depend on the behavior of $U_1(r)$ and $U_2(r)$. Curve 5 in Fig. 3 is plotted using Eq. (4) and the values a = 0.35 $(keV)^{1/2}$ and U_0 = 130 eV. The normalization is carried out in such a way that the calculated and experimentally determined distributions have the same value at the maximum.

Comparison shows that when the parameters a and U_0 are selected in this way, the Landau–Zener theory describes satisfactorily the experimentally obtained dependence for E > 130 eV.

The quantum theory of nonadiabatic transitions in those cases when the turning point is close to the pseudointersection point has been given in[4]. It follows from this theory that the probability of a transition, W_{12}, has a finite value when $E = U_0$. When $E > U_0$, the probability W_{12} can be described sufficiently accurately by the Landau–Zener formula (1); when $E < U_0$ (i.e., when the transition is of the tunnel type), the probability of a transition decreases exponentially with increasing $|E - U_0|$. It is possible that this applies to our experiments.

We note that the two-term approximation should be satisfied best in the excitation of resonance levels when the electron term of the initial state intersects, during the variation of the internuclear distance, first all the terms which represent these resonance levels and then possibly other higher terms. This, in fact, applies to our experiments.

Let us now consider the problem of the relative probabilities of the excitation of various states of the K^+ ion in collisions with He atoms and the scheme of quasimolecular terms of the K^+He system on the basis of some assumptions about the nature of the coupling between the moments of the interacting particles. Since, in the case of small values of the principal quantum number, the positions of the terms of atoms and ions with closed electron shells are still similar to the positions in the case of singlets and triplets, we shall consider the processes of the excitation of K^+ ions to the first "resonance" states by classifying the terms in accordance with the L-S coupling scheme.

We shall consider the case when only one particle (a positive K^+ ion) is excited in a collision; we shall assume that the He atom remains in the ground state. The table shows the processes, transitions, and types of perturbation which yield the transitions considered here even when the first-order perturbation theory is used.[5]

The experimental results (Fig. 3) show that the intensity of the K II λ 600.7 Å line is approximately four times as high as the intensity of the K II λ 612.6 Å line, while the ratio of the oscillator strengths for these lines[6] is only 2. Consequently, if we neglect the contribution of cascade transitions, the observed ratio of the intensities of the lines, representing the excitation of the K^+ ion to the singlet and triplet states, is due to the different cross sections of the processes listed in the table or, in the final analysis, the higher probability of a transition of the K^+He system in that case when the total spin of the system of the interacting particles is conserved.

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[1] L. D. Landau, Phys. Z. d. Sowjetunion **2**, 46 (1932).

[2] C. Zener, Proc. Roy. Soc. (London) **A137**, 696 (1932).

[3] E. E. Nikitin, Opt. Spektrosk. **11**, 452 (1961) [Opt. Spectrosc. **11**, 246 (1961)].

[4] V. K. Bykhovskii, E. E. Nikitin, and M. Ya. Ovchinnikova, Zh. Eksp. Teor. Fiz. **47**, 750 (1964) [Sov. Phys.-JETP **20**, 500 (1965)].

[5] L. D. Landau and E. M. Lifshitz, Quantum Mechanics: Non-Relativistic Theory, 2nd ed., Pergamon Press, Oxford, 1965.

[6] P. F. Gruzdev, Opt. Spektrosk. **22**, 313 (1967) [Opt. Spectrosc. **22**, 170 (1967)].

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