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ABSOLUTE MEASUREMENTS OF THE EXCITATION FUNCTIONS FOR THE K II LINES GENERATED BY COLLISIONS BETWEEN K$^+$ IONS AND HELIUM ATOMS

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The absolute excitation functions for the K II lines at 3897.9, 4134.7, 4149.2, 4186.2, 4222.9 + 4225.7, 4263.4, 4305 + 4309.1, 4388.2, 4608.5 + 4595.6, and 4829.2 Å, and for the He I line at 5875.6 Å, have been measured in the ion energy range between 0.5 and 34 keV. The K II excitation functions have two peaks, and their behavior is generally similar for all the lines investigated. The maximum excitation cross sections for the K II lines investigated were found to lie between 0.25×10^{-18} and 2.9×10^{-18} cm^2, and the maximum total excitation cross section for all the lines investigated in the visible part of the spectrum was found to be 1.4×10^{-17} cm^2. Theoretical curves calculated from the Landau-Zener formula are in satisfactory agreement with experimental results.

INTRODUCTION

STUDIES of the excitation of heavy particles in slow collisions have recently attracted increasing attention. Such studies are of interest for the theory of atomic collisions in connection with the development of adequate models for the excitation processes during ion-atom collisions.

We have investigated experimentally excitation processes occurring during slow collisions between K$^+$ ions and helium atoms, and have determined the absolute excitation cross sections for the K II and He I lines. The experimental results were then analyzed in terms of the adiabatic Landau-Zener model.

The choice of the incident and target particles was dictated by the availability in our laboratory of a source producing a stable beam of potassium ions in a broad energy range including the near-threshold region, and by the fact that there are already some data on the shape of the excitation functions for the resonance lines of potassium ions[1] (in the ion energy range between 0.8 and 8 keV).

We note that the excitation of K$^+$ ions during collisions with helium atoms has been investigated by Maurer[2] as far back as 1936. Maurer used a photographic method at ion energies between 1.1 and 12 keV. However, the method employed by Maurer and the experimental conditions under which his measurements were carried out were very unsatisfactory and no reliable data were obtained on the excitation functions.

APPARATUS AND METHOD OF MEASUREMENT

The apparatus illustrated schematically in Fig. 1 was used to investigate the excitation of the spectral lines of K$^+$ ions.

The ion source 2 and the collision chamber 4 were placed in the cylindrical vacuum chamber 1400 mm in diameter, which was evacuated by the VA-05-4 pumping system with a liquid-nitrogen trap down to a pressure of 5×10^{-7} Torr. The potassium ions were produced by a special surface-ionization ion source generating a very stable ion current over long periods of time. The accelerating voltage applied to the source electrode (up to 40 kV) was derived from a rectifying set (55 kV, 30 mA) which was originally part of an x-ray machine. Voltage stabilization was produced by the circuit developed by Naftulin[3].

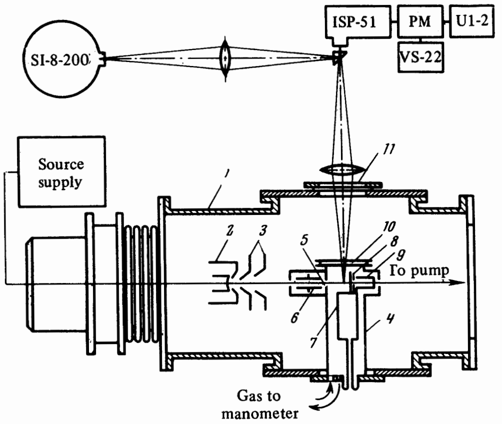

FIG. 1. Experimental arrangement: 1 – vacuum chamber; 2 – ion source; 3 – electrodes of the ion-optical system; 4 – collision chamber; 5 – entrance slit; 6 – deflecting plates of the modulator; 7 – liquid nitrogen trap; 8 – retarding electrode; 9 – ion receiver; 10, 11 – exit windows.

The ion beam entered the collision chamber 4 through collimating slits. A plane-parallel capacitor was placed between these slits and was used to deflect or to modulate the ion current. The ion current was detected by a Faraday cylinder with a shaped bottom. A small negative potential was applied to the electrode 8 to suppress secondary-electron emission from the surface of the ion receiver. The ion current density in the beam was varied between 0.3×10^{-5} and 5×10^{-5} A/cm^2 in the ion energy range between 0.5 and 34 keV.

Spectrally pure helium was leaked into the collision chamber through a needle valve. The helium pressure was measured with the VIT-2 gauge incorporating the LM-2 ionization converter. Corrections were made for its response to helium atoms. The residual pressure in the collision chamber with the ion source operating was

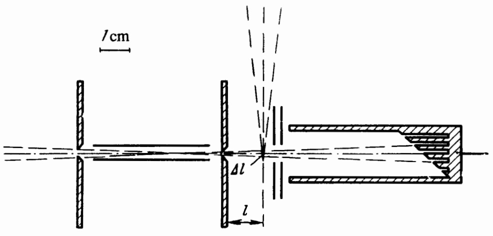

FIG. 2. Light collection geometry.

less than 5 × 10^{-6} Torr. A liquid-nitrogen trap was located inside the collision chamber. When the pressure in the collision chamber was about 10^{-3} Torr the pumping system ensured that the pressure gradient across the entrance slit (1.5 × 7 mm) was better than 150 : 1.

Figure 2 shows the collection geometry for light emitted during collisions between the particles from a volume $\Delta V = 0.2 \times 2 \times 8$ mm which was at a distance of $l = 16$ mm from the entrance slit. Radiation emitted by this volume was focused on the entrance slit of an ISP-51 spectrograph using a lens of f = 12.7 cm at a distance of 2f. The spectral-line intensities were measured with FÉU-64 or FÉU-18 photomultipliers and the U1-2 dc amplifier.

The detection system was calibrated against a standard source, i.e., the SI-8-200 tungsten strip lamp. Absolute measurements were carried out for the K II line at 4186.2 Å for K⁺ ion energies of 10 keV. The cross sections for the remaining lines were determined by relative measurements. The maximum error in the absolute measurements was not more than 40%, whereas the relative error did not exceed 10%.

No deviations were observed from the linear dependence of the line intensities on the ion current density and helium pressure up to 5 × 10^{-5} A/cm² and 6 × 10^{-3} torr respectively. Since our measurements were carried out at helium pressures in the collision chamber not exceeding 4 × 10^{-3} Torr, it may be assumed that all the measurements were carried out for single particle collisions.

RESULTS OF MEASUREMENTS

Our measurements have shown that most of the lines emitted during the above collisions are due to the K^+ ion. The table gives the data on the excitation cross sections for 13 strong K^+ lines and 2 helium lines at an ion energy of 10 keV. The spectral line classification is given in accordance with[10].

Figure 3 shows the absolute excitation functions for seven of the strongest K^+ lines measured in the energy range between 0.5 and 34 keV. The lower energy limit at which the measurements were performed was determined by the sensitivity of the measuring apparatus.

λ, Å	Transition	Q, 10^{-19} cm²	λ, Å	Transition	Q', 10^{-19} cm²
	Potassium ion		4305.0 4309.1	$3d\,[1^1/_2]^0 - 4p\,[1^1/_2]$ $4s'[^1/_2]^0 - 4p'\,[1^1/_2]$	14.9
3897.9	$4s\,[1^1/_2]^0 - 4p\,[1^1/_2]$	6,9	4388,2	$4s'[^1/_2]^0 - 4p'\,[1^1/_2]$	4.95
4039.7 4042.6	$3d\,[^1/_2]^0 - 4p'\,[1^1/_2]$ $3d\,[1^1/_2]^0 - 4p'\,[1^1/_2]$	2.40	4505.3	$3d\,[^1/_2]^0 - 4p\,[2^1/_2]$	2.74
4134.7	$4s\,[1^1/_2]^0 - 4p\,[2^1/_2]$	4.3	4595.6 4608.5	$3d\,[1^1/_2]^0 - 4p\,[2^1/_2]$ $4s'[^1/_2]^0 - 4p\,[1^1/_2]$	9.8
4149.2	$4s'\,[^1/_2]^0 - 4p'[1^1/_2]$	5.1	4829.2	$4s\,[1^1/_2]^0 - 4p\,[^1/_2]$	3.5
4186.2	$4s[\,1^1/_2]^0 - 4p\,[2^1/_2]$	7.2	5005.6	$4s\,[1^1/_2]^0 - 4p\,[^1/_2]$	2.5
4222.9 4225,7	$4s'\,[^1/_2]^0 - 4p'\,[^1/_2]$ $3d\,[^1/_2]^0 - 4p\,[1^1/_2]$	6.6		Helium ion	
4263.4	$4s\,[1^1/_2]^0 - 4p\,[2^1/_2]$	7.8	3888.6 5875.6	$2s^3S - 3p^3P^0$ $2p^3P^0 - 3d^3D$	0.9 3.9

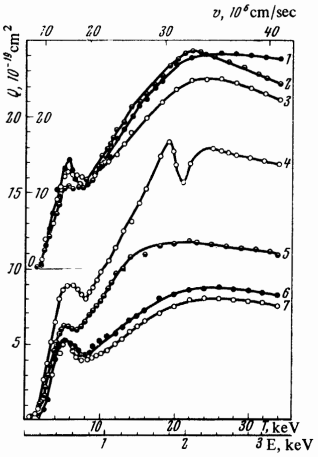

FIG. 3

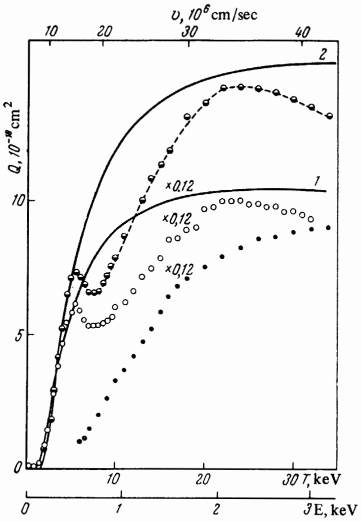

FIG. 4

FIG. 3. Excitation cross sections for the K II lines as functions of ion energy: 1 – λ = 3898 Å; 2 – λ = 4305/9 Å; 3 – λ = 4323/26 Å; 4 – λ = 4596 + 4608 Å; 5 – λ = 4263 Å; 6 – λ = 4149 Å; 7 – λ = 4135 Å; v – K^+ ion velocity in laboratory system, T – kinetic energy of K^+ ions, E – energy of relative motion.

FIG. 4. Absolute excitation functions: ○ – 4186.2 Å line of K II; ● – 5875.6 Å line of He I; ◒ – total cross section for all the measured lines in the visible part of the spectrum; 1 – Landau-Zener curve based on Eq. (3) with $U_0 = 0.11$ keV, a = 0.35 keV, $r_0 = 0.096$ Å; 2 – ditto with $U_0 = 0.125$ keV, a = 0.45 keV, $r_0 = 0.334$ Å; T – kinetic energy of K^+ ions; E – energy of relative motion.

Figure 4 shows the excitation function for the 4186.2 Å line of K II for which particularly careful measurements were carried out. The same figure gives the experimental data for the 5875.6 Å line of He I, the resultant curve for all the measured K II lines whose upper levels were 4p and 4p′, and the calculated curves.

It is clear from these graphs that the excitation functions for the K^+ ions have a number of features. The most characteristic feature of all the curves is the presence of a relatively well-defined peak at the lower ion energies (≈ 5.5 keV) and a second less-well defined peak at energies in excess of 22 keV. The behavior of the curves near the threshold (for ion energies $T \gtrsim 1$ keV in the case of K II lines and $T \gtrsim 5$ keV for He I lines), where they rise very rapidly, is particularly interesting. We also note that the maximum excitation cross sections for all the K II lines shown in Fig. 3 are not very different [$Q_{\max} \sim (0.8-2.9) \times 10^{-18}$ cm²], and all the excitation functions have essentially similar shapes.

DISCUSSION

The emission of the above K II and He I lines during single K^+-He collisions is the result of the direct excitation processes

$$K^+ + He \begin{cases} \nearrow K^{+*} + He + \Delta E_1, & (1) \\ \searrow K^+ + He^* + \Delta E_2, & (2) \end{cases}$$

where the energy defects $\Delta E_1 = 22.71-23.75$ eV for the K II lines and $\Delta E_2 = 23.07$ eV for the 5875.6 Å He I line were determined from known energy levels of isolated K^+ and He particles.

The results could not be interpreted in terms of the well-known and frequently used adiabatic criterion given by Massey[4] because, according to this criterion, the cross sections for the two processes given by Eqs. (1) and (2) should reach maxima at energies of a few hundred keV, whereas at lower energies they should fall exponentially. On the other hand, our data show that the cross sections for these processes are substantially different from zero at much lower energies. For example, the experimental threshold for the 4186.2 Å line of K II was observed at 0.5 keV, i.e., practically at an energy only just greater than the true threshold value of 0.25 keV determined from conservation of energy and momentum.

The discrepancy between the experimental results and the predictions based on the adiabatic criterion is probably due to the fact that, when the energy defects $\Delta E_{1,2}$ were estimated, no allowance was made for their possible variation during the interaction between the colliding particles. Owing to the low velocity of approach, the two particles may form the quasimolecule K^+He during the collision time, and the levels of this configuration may be substantially different from the levels of the isolated particles. We note that a similar interpretation was given in[5] in connection with the excitation of He^+ in He. It is therefore natural to try and employ the methods of molecular physics, which were developed for the investigation of transitions between different states of quasimolecules.

Let us use the adiabatic Landau-Zener model (see, for example,[6]) for the process defined by Eq. (1), by analogy with the procedure adopted in[1,7] for the interpretation of experimental results on the excitation of resonance lines of K^+ and Cs^+ ions in helium. According to this model, the excitation cross section can be written in the following form which is convenient for calculations:

$$Q(E) = 2\pi r_0^2 (1 - U_0/E)\,[f(z) - f(2z)], \tag{3}$$

where

$$f(z) = (1 - z)e^{-z} - z^2\,\mathrm{Ei}(-z), \qquad \mathrm{Ei}(-z) = -\int_0^\infty \frac{e^{-t}}{t}\,dt, \tag{4}$$

$$z = \sqrt{\frac{a}{E - U_0}}, \quad a = \frac{2\mu\pi^2 V^4}{\hbar^2 |F_0 - F_n|^2}, \quad F_{0,n} = -\frac{\partial U_{0,n}}{\partial r}\bigg|_{r=r_0}, \tag{5}$$

E is the relative energy of the K^+ + He system, μ is its reduced mass, U_0 and r_0 are the coordinates of the point of pseudocrossing of the terms $U_0(r)$ and $U_n(r)$ of the ground and excited states of the quasimolecule K^+He, and V is the matrix element between these two states. It is clear from Eqs. (3) and (5) that the cross section for the process defined by Eq. (1) in the Landau-Zener model is determined by three independent parameters which can be taken to be a, U_0, and r_0.

Curves 1 and 2 in Fig. 4 were calculated from Eq. (3). The parameters a, U_0, and r_0 were chosen so that the best possible fit between the theoretical cross sections and the corresponding experimental data was achieved in the ion energy range T = 1–5 keV. Curve 1 refers to the data for the 4186.2 Å line of K II and curve 2 refers to data obtained by adding up all the cross sections for all the measured lines of the K^+ ion (taking into account the ~6% contribution due to the weakest lines recorded by the measuring apparatus in the visible part of the spectrum). We note that the overall behavior of the theoretical curves in this energy region has an essential dependence only on the parameters a and U_0, and is not very sensitive to r_0. The last parameter was, in fact, determined by normalization in the region of the peak.

Let us now discuss the validity of the Landau-Zener model for the interpretation of these experiments. We note that, as $r \to \infty$, all the terms $U_n(r)$ of the K^+He quasimolecule in different excited states corresponding to both the 3d, 4s, and 4s′ resonance levels, and the 4p and 4p′ levels of K^+ ions investigated here, do not differ substantially from each other (the difference is 0.0022–0.0033 keV) in comparison with the difference as $r \to \infty$ between any of the $U_n(r)$ terms and the term $U_0(r)$ for the ground state of this quasimolecule ($U_n - U_0 \sim 0.02$ keV, $r \to \infty$).

Next, it is clear from the data reported in[1] and our own data that the so-called practical thresholds U_0 (i.e. the values of the energy E at which the rapid rise in the excitation cross sections begins) are roughly the same for all these lines of the K^+ ions ($U_0 \sim 0.1$ keV). This means that the terms $U_n(r)$ for all the above excited states are not very different even near the point r_0 of the pseudocrossing with $U_0(r)$.

Moreover, the overall shape of the experimental excitation curves for all the K^+ lines, i.e., both resonance lines and those investigated here, is roughly the same. As noted above, the overall shape of the theoretical curves corresponding to these experiments was determined by the parameter a (in addition to U_0) which characterizes the behavior of $U_n(r)$ in the region of the pseudocrossing with $U_0(r)$.

All this leads us to the conclusion that for the satisfactory application of the Landau-Zener model to the description of processes such as that given by Eq. (1) it is reasonable to assume that all the $U_n(r)$ are practically indistinguishable and replace them by a single effective term $U_{\mathrm{eff}}(r)$. This term will describe the excited states of the quasimolecule K^+He corresponding to all the excited states of the K^+ ion, and the formula given by Eq. (3) will represent the total excitation cross section for all these levels. The experimental values of this total cross section should enable us to determine the "true" (from the standpoint of a satisfactory validity of the Landau-Zener model) parameter R_0 which will, of course, be greater than the figure $r_0 = 0.334$ Å which we have determined from the total excitation cross section for practically all the lines in the visible part of the spectrum.

The extent to which the Landau-Zener model is valid for the interpretation of the excitation cross sections of individual levels, and even the K^+ lines, is also clear from the above considerations. Thus, the values of a and U_0 determined from a comparison of the corresponding experimental and theoretical cross sections for these cases are not very different from the "true" values characterizing the term $U_{\mathrm{eff}}(r)$, whereas the values of r_0 merely play the role of normalization coefficients and do not correspond to the pseudocrossing of the ground and the corresponding excited states.

When the differences between the experimental and theoretical curves are discussed it is important to bear in mind the shape of the experimental excitation curve for the target atoms, i.e. the 5875.6 Å line of He I which is connected with the process defined by Eq. (2). It is clear from Fig. 4 that the practical threshold U_0' of this process for this particular line lies near T = 4 keV (i.e. E ~ 0.4 keV) and, consequently, from the standpoint of the adiabatic model the value of $U_m(r)$ for the K^+He molecule corresponding to the process defined by Eq. (2) in the region of quasicrossing with $U_0(r)$ is U_0' ~ 0.4 keV. It seems probable that it is precisely this process that is responsible for the structure of the experimental excitation functions for the K^+ lines in the energy range T = 5—12 keV.

If we adopt this interpretation we can readily understand the differences between the theoretical and experimental curves. Thus, the formula given by Eq. (3) is derived by assuming the presence of two isolated terms and, therefore, when $E > U_0'$ it predicts cross sections for the process defined by Eq. (1) that are too high. It is natural to expect that the structure of the excitation functions for the process defined by Eq. (1) can be obtained theoretically by taking into account the effect of the process given by Eq. (2) on the process given by Eq. (1), using the multiterm approximation (see, for example,[8]). We note that questions concerned with the application of the multiterm model to the interpretation of experiments of this kind have been discussed in[9]. The corresponding numerical calculations are being carried out at the present time.

We note in conclusion that a more detailed theoretical interpretation of the above processes will require experimental data on other pairs of colliding particles and information on the probabilities of other processes occurring during the collisions of these particles (ionization, charge transfer, etc.). We intend to investigate experimentally the excitation functions for K^+ in neon, argon, etc.

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