Auger ionization in a He^+–He quasimolecule

V. R. Asatryan and A. P. Shergin
A. F. Ioffe Physicotechnical Institute, Academy of Sciences of the USSR

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The Auger transitions in a very simple quasimolecule produced in the collisions of He^+–He at keV energies are studied. The Auger spectra are described well by the quantum-mechanical model for the emission of electrons from a quasimolecule, which is based on the Airy approximation.

The applicability of a quantum-mechanical model[1] for the emission of Auger electrons from a quasimolecule—a system which forms upon collision of two atoms and which exists $\sim 10^{-15}$–10^{-16} s— has recently been discussed frequently. Experimental studies[2–5] have not, however, been able to give an unambiguous result, principally because the quasimolecules being studied have many electrons and because the quasimolecular levels have a complex structure, which accounts for the population of various initial states that decay by means of Auger transitions.

We have studied the Auger ionization in a He^+–He quasimolecule in which there are just enough electrons to effect an Auger transition. Simple quasimolecules are most suitable for studying the properties of Auger ionization, but the measurement of quasimolecular spectra in this case is hampered considerably by the fact that the predicted cross sections of the Auger transitions are much smaller than those for many-electron systems such as[4] Kr^+–Kr. Estimates have shown, nevertheless, that an experiment can be carried out under certain conditions, but whether such an experiment is useful is contingent upon an unambiguous answer to the question as to whether this model can be used. There is a strong probability for the formation of an inner $1s\sigma$ vacancy in a He^+–He quasimolecule chosen for experimental study. The energies, $E(R)$, and Auger widths, $\Gamma_A(R)$, of the level with $1s\sigma$ vacancy have also been calculated in this case for various internuclear distances.[6,7]

We have measured the quasimolecular Auger spectra, $d^3\sigma(E_e)/dE_e d\Omega_e db$, at fixed impact parameters b (and, correspondingly, at distances of closest approach R_0), which are much more sensitive to the results of the model than the spectra integrated over all possible values of b. The measurement of these spectra requires the use of a coincidence method by which the coincidence between the Auger electron and an ion scattered through a fixed angle is detected and which, accordingly, is time-consuming. This circumstance makes it necessary to choose optimum experimental conditions. The identification of Auger transitions is complicated by the crossover transitions of electrons to the continuum,[8] which also lead to a continuous energy distribution of the emitted electrons. In the experimental measurement of the spectra $d^3\sigma/dE_e d\Omega_e db$, the collision energies (E_0) and the distances of closest approach (R_0) were chosen by making use of the results of Ref. 9. In Ref. 9 the Auger ionization was distinguished from the direct ionization on the basis of the difference in the behavior of the cross sections of the processes as a function of the collision rate.

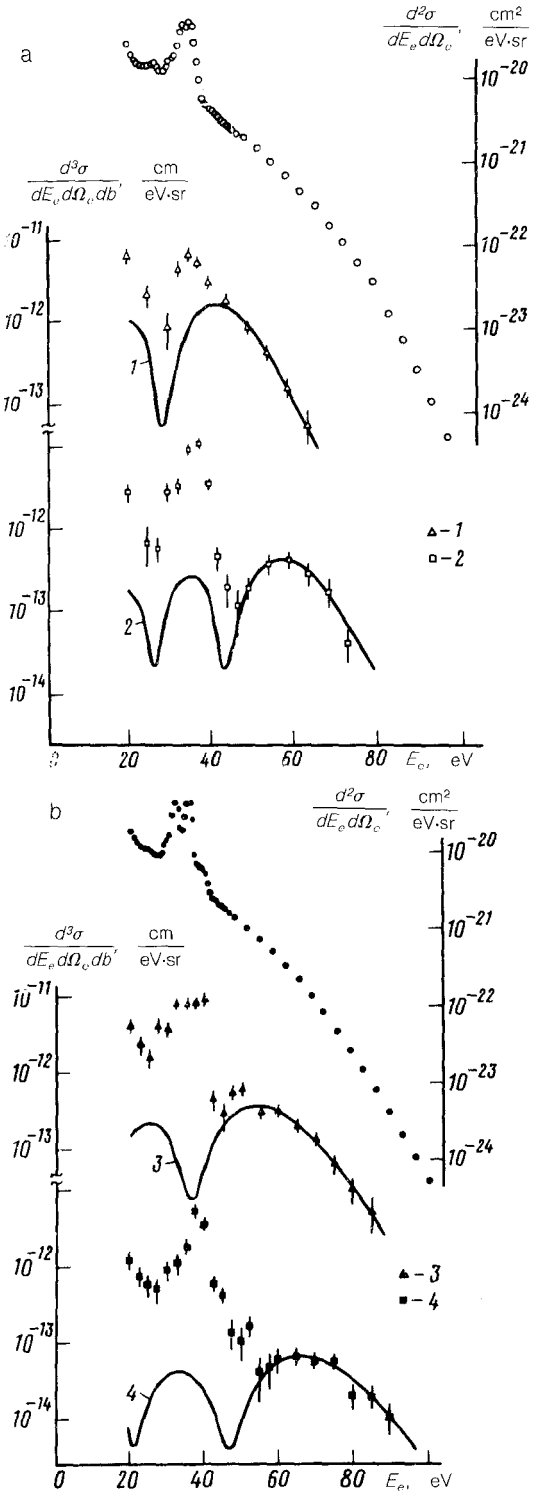

FIG. 1. Energy spectra of electrons produced in the collisions of He^+–He at the following collision energies: a—$E_0 = 1.25$ keV and b—$E_0 = 2.5$ keV. 1—$\theta_i = 5°$, $R_0 = 0.55$ a.u.; 2—$\theta_i = 9°$, $R_0 = 0.38$ a.u.; 3—$\theta_i = 4°20'$, $R_0 = 0.38$ a.u.; 4—$\theta_i = 9°$, $R_0 = 0.23$ a.u. The distances R_0 are calculated for the interatomic potential.[10] The solid curves—calculation based on Eq. (1).

The measurements were carried out with use of the "electron-scattered ion" coincidence method[4] at energies $E_0 = 1.25$ and 2.5 keV and at ion scattering angles $\theta_i = 4°20'$, 5°, and 9°, which corresponds to distances of closest approach $R_0 = 0.23$, 0.38, and 0.55 a.u., and at emitted electron energies $E_e \approx 20$–100 eV. The electrons emitted at an angle $\theta_e = 125°$ to the direction of the primary beam of He^+ ions were detected when the spectra $d^2\sigma(E_e)/dE_e d\Omega_e$ were measured. When the spectra were studied by the coincidence method, the luminosity was increased by completely opening the annulus of the cylindrical electron analyzer and detecting the electrons with $\theta_e = 55$–125°.

According to Ref. 1, the quasimolecular Auger spectrum is described by an expression which contains an Airy function $Ai(x)$,

$$\frac{d^3\sigma}{dE_e d\Omega_e db} = \pi \Gamma_A n b \alpha^{-2/3} Ai^2\{\alpha^{-1/3}[E_e - E_e(R_0)]\}, \quad (1)$$

where n is the probability for the formation of the $1s\sigma$ vacancy, and $\alpha = \frac{1}{2}(dE_e/dR)(d^2R/dt^2)|_{R=R_0}$. The principal maximum, which propagates into the region $E_e \gtrsim E_e(R_0)$, is situated near $E_e(R_0)$. The appearance of electrons in this region, which is linked with the uncertainty principle, is called collisional broadening. Oscillations arise to the left of the principal maximum. These oscillations are caused by the interference of waves corresponding to the electrons with the same energy, which are emitted upon convergence and dispersal of particles. Approximation (1) is called a simple Airy approximation, since $\Gamma_A n$ is assumed to be independent of R in its derivation.

The experimental spectra are shown in Fig. 1. The Auger transitions in the quasimolecule determine the electron spectra at $E_e \gtrsim 50$ eV. At lower energies E_e the dominant transitions are the crosssover transitions to the continuum and the autoionization transitions to single He atoms after the collision (the structure in the vicinity of $E_e \simeq 35$ eV). In the spectra $d^2\sigma/dE_e d\Omega_e$ the quasimolecular Auger transitions are manifested as a broad band. In the spectra $d^3\sigma/dE_e d\Omega_e db$ the principal quasimolecular maximum, which is predicted by the emission model and which is displaced as the internuclear distance is changed, is clearly identifiable.

In the calculation of the spectra on the basis of relation (1), the probability for the transition of the $1s$ vacancy in the He^+ ion to the quasimolecular $1s\sigma$ vacancy was assumed equal to 0.5 from statistical considerations. The energies $E_e(R)$ calculated in Refs. 6 and 7 are plotted in Fig. 2. The energies E_e for the three values of the internuclear distance also were determined experimentally. The procedure for determining $E_e R$ from the spectra is based on the fact that the function $Ai^2(x)$ takes on a value equal to 0.44 of its maximum value. Figure 2 shows that the values of E_e obtained experimentally are in good agreement with the calculated[5] $E_e(R)$ level which was used to describe the experimental spectra. In the model proposed in Ref. 1, $\Gamma_A \simeq$ const. This condition is satisfied for the spectra measured at constant impact parameters, since the Auger transitions are concentrated in a narrow region near the reversal point R_0. The widths $\Gamma_A(R)$ were determined from the absolute values of the experimental cross sections by using relation (1). In all cases cited here the $\Gamma_A(R)$ values which we

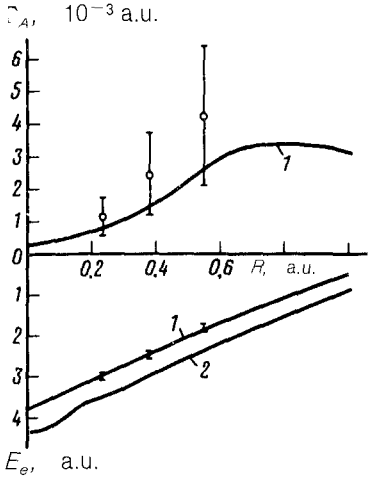

FIG 2. The energy level $E_e(R)$ and the level width $\Gamma_A(R)$ for a He^+–He quasimolecule. 1—Calculation from Ref. 6; 2—calculation from Ref. 7.

obtained are in agreement, within error limits of the absolute calibration of the spectra, with $\Gamma_A(R)$ values calculated in Ref. 6 (Fig. 2).

The calculated spectra, in which the correction for the Doppler effect is taken into account, are shown in Fig. 1. A good fit between the calculated and experimental spectra can be seen from the analysis of the shape of the principal maximum. The first oscillatory maximum situated in the region of lower electron energies could not be singled out against the background of direct and autoionization transitions in single atoms. Figure 1 shows that the principal quasimolecular maximum is described accurately by expression (1). The width of the principal maximum and the exponentially decreasing high-energy part of the spectrum induced by collisional broadening change with increasing collision rate, in complete agreement with the model.

A good agreement between the experimental and calculated spectra in terms of shape and behavior of the principal maximum suggests that a simple Airy approximation describes accurately the Auger transitions in a quasimolecule.

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