Excitation of the resonance level of He^+ in electron-atom, electron-ion, and ion-atom collisions

A. I. Dashchenko, I. P. Zapesochnyĭ, A. I. Imre, V. S. Bukstich, F. F. Danch, and V. A. Kel'man

Uzhgorod State University

(Submitted February 20, 1974)
Zh. Eksp. Teor. Fiz. **67**, 503–509 (August 1974)

We have used a mass spectrometer with intersecting modulated electron and ion beams to study spectroscopically the excitation of the resonance level of the He^+ ion in the three collision processes e–$He^+(1s)$, e–$He(1s^2)$, and $He^+(1s)$–$He(1s^2)$. The energy dependence of the cross sections for excitation of $He^+(2p)$ in electron-ion collisions is compared with theoretical calculations in various approximations and with the results on excitation in electron-atom and ion-atom collisions.

INTRODUCTION

Information on the excitation of energy levels of the helium ion is of considerable interest both for the physics of electronic and atomic collisions and for various applied problems. Since the wave functions of the helium ions are known analytic functions (similar to all hydrogen-like ions), the excitation of energy levels in the process e-He^+ can be discussed as the problem of collisions of electrons with atoms of hydrogen. Of course, some complication is introduced by the Coulomb forces.

When we take into account that problems with pure Coulomb scattering of colliding particles are solved rather accurately both in the Coulomb-Born approximation and by the strong-coupling method, we can expect that the reliability of using these methods to calculate excitation cross sections in the case e-He^+ will be greater than in calculations for neutral hydrogen atoms. Therefore special theoretical interest is presented by the experimental study of the efficiency of excitation of the He^+ resonance level in electron-ion collisions.

For these reasons we have set up in our laboratory experiments to study the processes of excitation of the He^+ resonance level in electron-ion collisions, and also in electron-atom and ion-atom collisions, occurring according to the following main reactions:

$$He^+(1s)+e\to He^+(2p)+e\to h\nu+He^+(1s)+e, \tag{1}$$

$$He(1s^2)+e\to He^+(2p)+2e\to h\nu+He^+(1s)+2e, \tag{2}$$

$$\overline{He}^+(1s)+He(1s^2)\to\begin{cases}\overline{He}^+(2p)+He(nl)\to h\nu+\overline{He}^+(1s)+He(nl)\\ \overline{He}^+(nl)+He^+(2p)+e\to\overline{He}^+(nl)+h\nu+He^+(1s)+e,\\ \overline{He}(nl)+He^+(2p)\to\overline{He}(nl)+h\nu+He^+(1s).\end{cases} \tag{3}$$

The experimental study of these processes, in particular of the excitation in electron-ion collisions, is an extraordinarily complex problem, primarily because of the need of detecting extremely weak radiation in the far vacuum ultraviolet region of the spectrum (λ = 30.4 nm). It is evidently for this reason that there are in the literature only two known experimental studies[1,2] of excitation of the metastable 2s level of He^+.

REMARKS ON APPARATUS AND TECHNIQUE

The study was carried out in the mass-spectrometric apparatus "Karpaty" with intersecting electron and ion beams, in which we previously performed experiments on excitation of laser lines of Ar^+ and Kr^+ ions[3] and the bands of the first negative system of the N_2^+ ion.[4] Of course, in investigation of the present problem it was necessary to modernize the apparatus substantially. Since the main parts of the apparatus have been described in sufficient detail previously,[3] we will dwell below for the most part only on those changes which were carried out in the course of the present experiment.

A sufficiently intense and pure beam of He^+ ions was obtained by using a gas-discharge source with constriction of the plasma by a longitudinal magnetic field, and a 180° mass spectrometer with double focusing. Constancy of the helium-ion current during the experiment was achieved by stabilization of the ion-source discharge current and the accelerating voltage and magnetic field of the mass spectrometer. In addition, we developed a special system that followed the position of the ion beam and automatically kept it in the entrance slit of the collision chamber. This permitted the variations in the ion current to be maintained within ±1.5% of the average value.

The collision chamber was differentially pumped with a TRION-150 magnetic discharge pump which made possible an ultimate vacuum of $\sim 10^{-8}$ Torr in the region of the intersection of the beams.

In investigation of the excitation in the e-He^+ process the electron and ion beams intersected at right angles in the collision chamber, the electron beam passing completely inside the ion beam, and the radiation was detected in a direction perpendicular to the plane of their intersection. In the experiments on excitation of the He^+ resonance level in electron-atom and ion-atom collisions, the collision chamber was filled with spectroscopically pure helium through a needle valve.

The radiation from the collision chamber was passed through a grazing-incidence vacuum monochromator built in our laboratory. The monochromator covered the spectral region 20–150 nm with an average inverse linear dispersion ~0.9 nm/mm. The entrance slit of the monochromator was mounted directly on the electron gun, and the radiation passed through a long channel which provided differential pumping. The radiation was detected by an open secondary electron multiplier, type VÉU-OT-8M, which counted individual photoelectrons.

In study of excitation of ions by reaction (1), in order to separate the useful signal from the background produced by processes (2) and (3), we used the technique of double modulation of the beams by rectangular pulses shifted by a quarter period and detection of the pulses with a secondary electron multiplier in two counting channels.[5] In study of the excitation in electron-atom collisions (2) and ion-atom collisions (3), only the electron or ion beam, respectively, was modulated, and the radiation was detected in two channels synchronously with the modulation pulses.

All experiments were carried out under conditions assuring single collisions, which was checked by measuring the linearity of the useful signal amplitude as a function of the beam currents and the concentration of target particles. The helium-ion current density in the energy region 1–28 keV was $10^{-5}-10^{-3}$ A/cm^2, and the corresponding ion concentration in the collision region was 5×10^{6}–10^{8} cm^{-3}. The electron current density in the energy region 30–500 eV was $\sim 10^{-2}$ A/cm^2, and the energy inhomogeneity at the half-height of the distribution curve was ~ 2 eV. Measurements of the excitation in electron-atom and ion-atom collisions were carried out at a helium pressure of $\sim 10^{-4}$ Torr (concentration $\sim 3 \times 10^{12}$ cm^{-3}).

RESULTS AND DISCUSSION

Figures 1–3 show the energy dependence of the cross sections for excitation of the resonance line of the He$^+$ ion, measured respectively in processes (1), (2), and (3).[1)] Calibration of the electron energy in a study of processes (1) and (2) was carried out on the basis of the distinctly locatable threshold for excitation of the

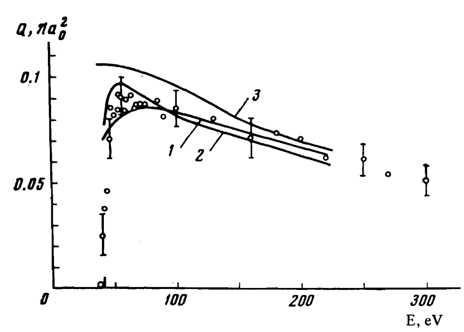

FIG. 1. Energy dependence of cross section for excitation of He$^+$ resonance level in electron-ion collisions: Points–experiment: 1–theory and second Coulomb-Born approximation, [8] 2–theory in strong-coupling approximation, [9] 3–theory in first Coulomb-Born approximation. [8]

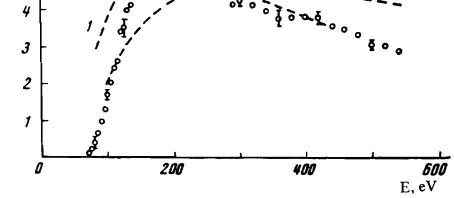

FIG. 2. Experimental dependence of cross section for excitation of He$^+$-ion resonance level in electron-atom collisions: points–experiments: 1–theory, [11] 2–theory. [12]

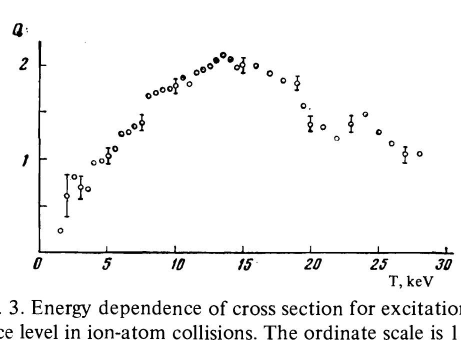

FIG. 3. Energy dependence of cross section for excitation of He$^+$ resonance level in ion-atom collisions. The ordinate scale is $10^3 \pi a_0^2$.

resonance line of the neutral He atom (λ = 58.4 nm). In all three figures the vertical lines on the curves show the 90% confidence level of the relative measurements.

We will dwell in more detail on the analysis of the results obtained.

1. In the case of electron-ion collisions the possible contribution to population of the 2p upper level of the resonance line as the result of spontaneous transitions from higher levels should not be significant. If we make an estimate of this contribution by a means similar to that described by Morrison and Rudge[7] for the hydrogen atom, then, at least for electron energies of 100 eV or higher, it turns out to be less than 10%. We can therefore assume that the experimental curve obtained by us faithfully reproduces the excitation function of the resonance 2p level of He$^+$.

It is then easy to represent the result obtained on an absolute scale, for example, by normalization of the experimental curve to a calculation in the second Coulomb-Born approximation[8] for high energies. This has been done in Fig. 1 (for an electron energy of 217 eV), where we have compared theoretically curves in the first Coulomb-Born approximation[8] and in the strong-coupling approximation.[9] It is evident from the figure that the experimental results over a wide energy range (starting with 80 eV) are in very satisfactory agreement with these calculations and in particularly good agreement with the second Coulomb-Born approximation. At lower energies and down to the excitation threshold of the 2p level, the experimental data lie in the region between the theoretical values calculated in the strong-coupling approximation and in the second Coulomb-Born approximation.

2. The behavior of the excitation function for the He$^+$ resonance level in electron-ion collisions is shown in more detail in Fig. 4. The appearance of radiation somewhat below the threshold for process (1), which is 40.8 eV, is explained by the energy spread of the electrons in the beam. We therefore corrected the experimental curve right at threshold by the method of successive approximations, proceeding by taking into account the distribution of electrons in energy and the finite cross section for excitation of ions at threshold. The behavior of the experimental curve at threshod is in good agreement with the strong-coupling calculation, normalized to unity at the maximum.

The comparison carried out in this figure of our data with the experimental result on electron excitation of helium ions in the He$^+$(2s) metastable state[1] is readily seen to confirm the substantial difference in the

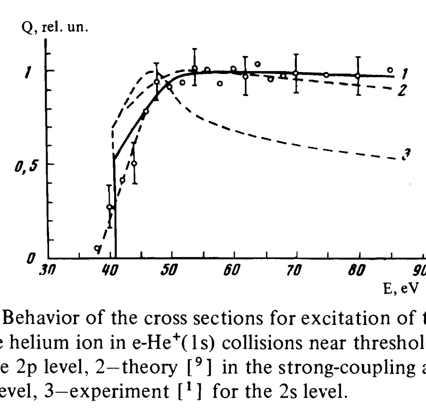

FIG. 4. Behavior of the cross sections for excitation of the lower levels of the helium ion in e-He$^+$(1s) collisions near threshold: 1–experiment for the 2p level, 2–theory [9] in the strong-coupling approximation for the 2p level, 3–experiment [1] for the 2s level.

excitation mechanisms of the 2p and 2s states, similar to that which appears in excitation of hydrogen atoms in similar states.[10]

3. The experimental curve in Fig. 2, it can be suggested, also reflects rather completely the energy dependence of the cross section for excitation of the He^+ resonance level in electron-atom collisions.[2)] Therefore it has also been normalized (at an electron energy 436 eV) to the theoretical calculation[11] in the Born approximation with inclusion of the effect of configuration interaction for ionization with simultaneous excitation to the 2p state of the helium ion. It is evident that for electron energies above 150 eV the experimental and theoretical results are in very good agreement, but at lower energies the theory gives somewhat exaggerated values. Poorer agreement with experiment is given by the calculations[12] carried out in the Born approximation with use of the simple Hylleras function describing the ground state of the helium atom.

Also not without interest is the comparison of the experimental results on process (2) with data on excitation of the He^+(4f) level in electron-atom collisions, obtained previously in refs. 13 and 14. The comparison shows that the behavior of the experimental dependence of the cross sections is for the most part quite similar, but the values at the maximum of the excitation functions of the 2p and 4f levels differ by about a factor of five.

4. Let us discuss the excitation of the He^+(2p) level in ion-atom collisions. We note first that it is not possible to separate experimentally the contribution to excitation of the He^+(2p) state resulting from each of the reactions (3). Therefore in our experiments we can discuss only the efficiency for excitation of the state being studied as the sum of the three differing processes (3).

Normalization of the experimental curves for excitation of the resonance level in processes (1) and (2) to the theoretical calculations has permitted determination of the sensitivity of the detection system and plotting of the energy dependence of the combined cross section for processes (3) on an absolute scale (see Fig. 3). Here the energy of the ions is given in the laboratory system.

The indistinct structure observed in the experimental curve is explained apparently by the addition of the contributions from the various processes (3), and the more rapid drop in the cross section after the maximum, compared to calculations based on the Landau-Zener formula, indicates that the contribution of helium-atom excitation with charge exchange may be rather large.

5. It is now useful to compare the nature and efficiency of excitation of the helium-ion resonance level in all three of the elementary processes studied, by representing the corresponding cross sections as a function of the relative velocity of the interacting particles. This has been done in Fig. 5, from which it is evident that a very small relative velocity of the interacting particles—of the order of only a fraction of 10^8 cm/sec—is sufficient for excitation of the He^+(2p) level only in ion-atom collisions and then in a very narrow range of velocities. Here the cross section at the peak amounts to $\sim 2 \times 10^{-19}$ cm^2.

Excitation in e-He^+ collisions is distinguished by a much greater efficiency for excitation of this same He^+

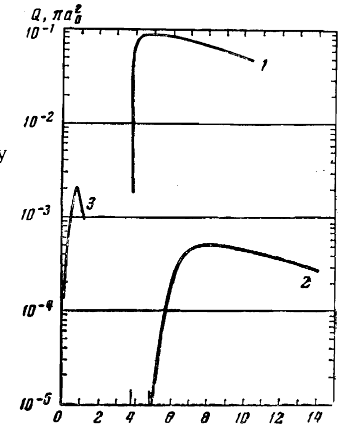

FIG. 5. Cross sections for excitation of resonance 2p level of He^+ as a function of the relative velocity of the interacting particles: 1—for e-He^+(1s) collisions, 2—for e-He ($1s^2$) collisions, 3—for He^+(1s)-He($1s^2$) collisions. The vertical lines on the velocity axis denote the corresponding excitation thresholds.

level in comparison with process (3), beginning at a relative velocity of the interacting particles V = 3.8 $\times 10^8$ cm/sec. It is characterized by a cross section $\sim 80 \times 10^{-19}$ cm^2 near threshold, which slowly falls off over a wide range of velocities.

Finally, for electron-atom collisions the excitation of the He^+ resonance level sets in only at $V = 4.8 \times 10^8$ cm/sec and is the least efficient (the maximum cross section amounts to only $\sim 0.5 \times 10^{-19}$ cm^2).

1)A brief report on excitation of the He^+ resonance line in process (1) has been published previously. [6]

2)The excitation threshold in this process is 65.4 eV.

1D. F. Dance, M. F. A. Harrison, and A. C. H. Smith, Proc. Roy. Soc. A290, 74 (1966).

2K. T. Dolder and B. Peart, Abstracts of papers, VIII ICPEAC, Belgrade, 1973, p. 281.

3I. P. Zapesochnyĭ, A. I. Imre, A. I. Dashchenko, V. S. Bustich, F. F. Danch, and V. A. Kel'man, Zh. Éksp. Teor. Fiz. 63, 2000 (1972) [Sov. Phys. JETP 36, 1056 (1973)].

4A. I. Dashchenko, I. P. Zapesochnyĭ, and A. I. Imre, Optika i spektroskopiya 35, 970 (1973) [Optics and Spectroscopy 35, 562 (1973)].

5A. I. Dashchenko, É. P. Stakhno, and A. I. Imre, Prib. Tekh. Éksp., No. 4, 196 (1972) [Instrum. Exp. Tech.].

6A. I. Dashchenko, I. P. Zapesochnyĭ, and A. I. Imre, ZhÉTF Pis. Red. 19, 223 (1974) [JETP Lett. 19, 137 (1974)].

7D. J. T. Morrison and M. R. H. Rudge, Proc. Phys. Soc. 89, 45 (1966).

8A. Burgess, D. G. Hummer, and J. A. Tully, Phil. Trans. Roy. Soc., London, A266, 225 (1970).

9P. G. Burke, D. D. McVicar, and K. Smith, Proc. Phys. Soc. 83, 397 (1964).

10B. L. Moiseiwitsch and S. J. Smith, Rev. Mod. Phys. 40, 238 (1968).

11E. Stingl., J. of Phys. B, 5, 1688 (1972).

12A. Dalgarno and M. R. C. McDowell, The Airglow and the Aurorae, N. Y., Pergamon Press, 1965, p. 240.

13I. P. Zapesochnyĭ and P. V. Fel'tsan, Ukr. Fiz. Zhur. 10, 1197 (1965).

14R. J. Anderson, E. T. P. Lee, and C. C. Lin, Phys. Rev. 160, 20 (1967).

Translated by C. S. Robinson
57