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EXPERIMENTAL INVESTIGATION OF INELASTIC HEAVY PARTICLE COLLISIONS IN THE ENERGY RANGE 5 — 30 keV

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Abstract: One-electron capture and one-electron loss processes were investigated for metal ions Mg^+, Fe^+ and Cu^+. The investigation of two-electron capture processes was done for Fe^+, C^+, O^+ and O_2^+ ions. The measurements were done in the energy range of 5–30 keV and for gas targets of Ne, Kr and N_2. The experimental set-up allowed measurements of the cross section values as low as 10^{-22} cm^2. It was found, for metal ions with the low second ionization potential, that one-electron loss cross sections could be of the same order of magnitude as those for one-electron capture process. The role of two-step processes in the formation of negative ions, influencing the measurements of two-electron capture crossections, was analysed for the gas target thickness range of 10^{-3} — 10^{-2} torr · cm.

1. Introduction

For many years, the inelastic heavy particle collisions have been the subject of a great deal of attention. Apart from their fundamental importance, such processes have an important role in many natural phenomena and practical applications, as accelerators, ion and plasma sources, MHD and thermoionic convertors and controlled thermonuclear devices. An enormous number of experimental and theoretical investigations of these processes have been done mainly for atomic systems with simple electron configuration[1, 2, 3]. In order to broaden this field, the reactions which are of the particular interest, are those involving the inelastic processes of metal ions of different electron configuration. From the theoretical point of view, the experimentally determined cross sections are of special interest, in order to find out to which the metal ions processes approximate to the adiabatic conditions.

The study of the formation of negative ions in heavy particle collisions, provides a new insight into the understanding of the role of negative ions in different ionization phenomena. The experiments on the formation of negative ions in heavy particle collisions, will give more data about the existence of negative ions of different elements and about their electron affinities.

2. Experimental method and set-up

Method. Inelastic collisions of heavy particles involve great number of processes, such as charge transfer, ionization, dissociation, excitation, etc. In the present work, attention was paid to the one- and two-electron transfer and one-electron loss processes appearing in the collision of fast singly charged ions with gas targets, in the single collision conditions.

The experimental method is as follows: the beam of the incident particles, monochromated in mass number, charge state and energy, enters the interaction chamber of length L, filled with the target gas at a pressure p. Passing through the interaction chamber the particles can change their charge state in inelastic collisions with gas target particles, but retain approximately the same initial velocity, as the momentum transfer is very low at such high energies (5 — 30 keV). By measuring the yield of differently charged components of the beam passed through the interaction chamber, it is possible to determine the cross section values of the particular process taking place in the interaction. For the process, in which the incident particle changes its charge state from (ie) to (fe), the cross section is denoted as σ_{if}. If one process only takes part in the formation of the component with charge f, the yield of that component is determined by the relation

$$dI_f = \sigma_{if} I_i n \cdot dx ,$$

where I is the particle beam intensity, n gas target density and x the interaction length.

Special attention had to be paid to the measurements of the low values of cross sections, as for the two-electron capture process (10—12), where the other processes, with high probabilities[4, 5)], can influence the formation of negative ions, even in the so called single collision conditions. Taking into account all processes influencing the formation of negative ions, including the reactions of fast positive, negative and neutral particles, one obtains the system of the following equations:

$$\begin{aligned}
\frac{dI^+}{d(nx)} &= -(\sigma_{10} + \sigma_{1-1}) I^+ + \sigma_{01} I^\circ + \sigma_{-11} I^- , \\
\frac{dI^\circ}{d(nx)} &= \sigma_{10} I^+ + (\sigma_{01} + \sigma_{0-1}) I^\circ + \sigma_{-10} I^- , \qquad (1) \\
\frac{dI^-}{d(nx)} &= \sigma_{1-1} I^+ + \sigma_{0-1} I^\circ - (\sigma_{-11} + \sigma_{-10}) I^- .
\end{aligned}$$

In the case when primary particles are singly-charged positive ions, the cross section for the formation of negative ions is given from the above relations by

$$\sigma_- = \frac{I^-}{nLI^+_0} = \sigma_{1-1} + \frac{a}{2}(nL) + \frac{b}{6}(nL)^2 + \dots, \tag{2}$$

where, I^+_0 is primary positive ion beam intensity and

$$a = \sigma_{10}\sigma_{0-1} - \sigma_{1-1}(\sigma_{10} + \sigma_{1-1} + \sigma_{-10} + \sigma_{-11}); \tag{3}$$

$$\begin{aligned} b = & -\sigma_{10}\sigma_{0-1}(\sigma_{10} + \sigma_{01} + \sigma_{1-1} + \sigma_{-11} + \sigma_{-10} + \sigma_{0-1}) + \\ & + \sigma_{1-1}[\sigma^2_{10} + \sigma_{-10}\sigma_{10} + \sigma_{-11}\sigma_{10} + \sigma_{10}\sigma_{01} + \sigma_{0-1}\sigma_{-10} + \\ & + (\sigma_{-10} + \sigma_{-11})^2] + \sigma^2_{1-1}(2\sigma_{10} + \sigma_{1-1} + \sigma_{-10} + 2\sigma_{-11}). \end{aligned} \tag{4}$$

By measuring the I^+ and I^- intensities, one-step two-electron capture cross section σ_{1-1} can be determined if the gas target thickness (nL) is so low that second and higher terms in the relation (2) may be neglected. In this case, the single collision conditions are defined as a gas target thickness, when the inequality $\sigma_{1-1} \gg a/2\,(nL)$ is fulfilled, what is qualitatively different from the single collision conditions, defined by $\lambda \gg L$ (λ means free path of the incident particles). For the gas target thickness, when the second term of the relation (2) is of the same order of magnitude as σ_{1-1} cross section and the third term is negligible, two-electron capture cross sections can be obtained by the extrapolation of the curve $\sigma_- = f(nL)$ to $\sigma_- = f(0)$.

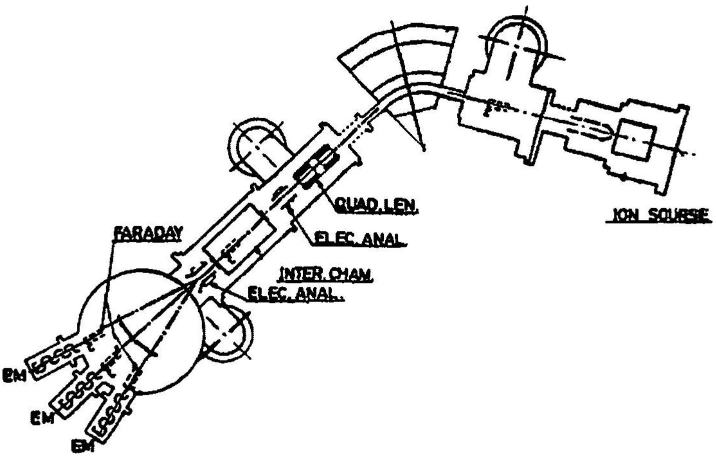

Fig. 1. Schematic diagram of the experimental arrangement.

Experimental set-up. The experimental arrangement is shown in Fig. 1. The ion beam was produced by using a magnetron ion source[6] especially developed for intense ion beams of metals. One of the cathodes in the source was used as an emission filament, and the other, as a metal probe. Ion beam intensities, obtained at the entrance slit of the interaction chamber, reached up to 10^{-6} A for metal ions, and up to 10^{-5} A for gaseous ions. The ion beam focussing system consisted of einzel lens, a magnetic monochromator and quadrupol lenses. The gas target pressure, in the interaction chamber of length 17.8 cm varied in the range of 1 to $5 \cdot 10^{-4}$ torr, while the pressure in the rest of the apparatus was kept below $1 \cdot 10^{-5}$ torr. The outside controlled slits on the interaction chamber and on the detectors allowed the control of the ion beam transmission. The beam passed through the interaction chamber and was analysed by an electrostatic plate analyser. The geometry of the analyser and the detection chamber allowed simultaneous measurements of positive, negative and neutral components of the beam. The current intensities down to 10^{-15} A were measured by a vibrating reed electrometer. The secondary electron emission yield from the collector plate was taken as a measure of the neutral component yield. This method is based on the assumption on equality of secondary electron emission coefficients for ions and corresponding neutrals at high energies.

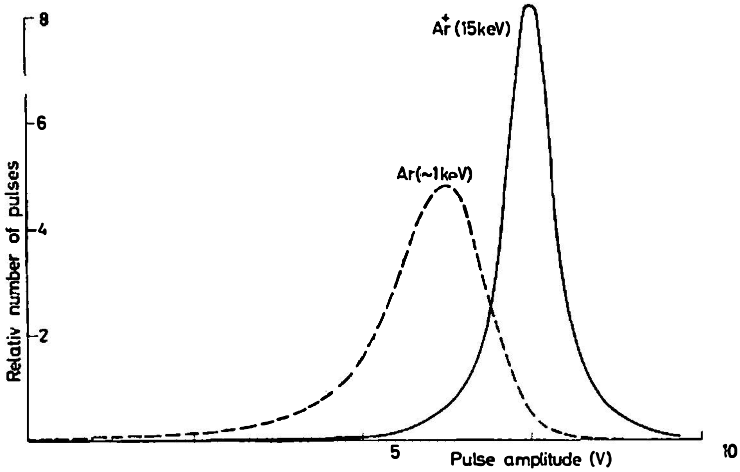

Fig. 2. Multipler output pulse height distribution for Ar^+ and Ar incident particles.

The small intensities of the interaction product particles were detected by pulse counting method, using an electron multiplier specially developed for this purpose[7]. It is a 26-stage Ag-Mg multiplier with a maximum gain of about $2 \cdot 10^9$ electrons per incident particle. At the maximum gain, the mul-

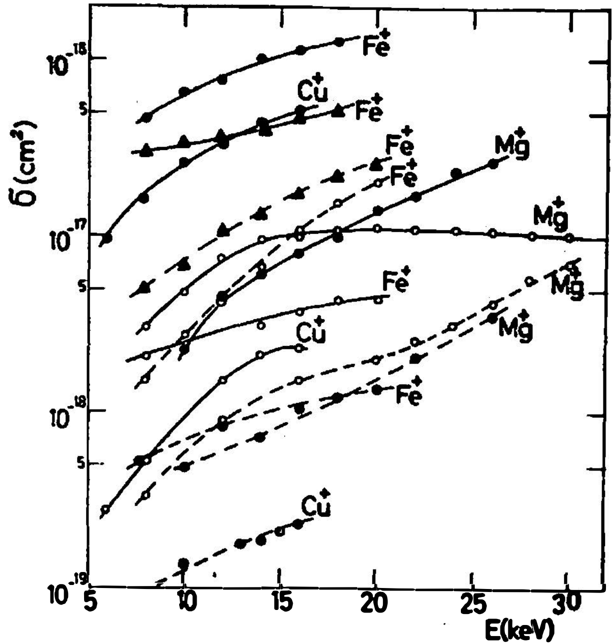

Fig. 3. One-electron capture σ_{10} (full lines) and one-electron loss σ_{12} (dashed lines) cross section: ○ — Ne target; ● — Kr Target; △ — N_2 target.

tiplier was in a pulse saturated mode of operation, with main pulse amplitude of about 7 V. So the whole spectrum (shown in Fig. 2.), could be easily registred without additional amplification. Counting efficiency was determined by pulse losses over a few entrance dynodes of the multiplier. For high energy ions, $E > 5$ keV, counting efficiency was close to 100 %. Low noise of about 3 puls/min., enabled high sensitivity of the detector.

3. Results and discussion

One-electron capture σ_{10} and one-electron loss σ_{12} cross sections for metal ions. One-electron capture σ_{10} and one-electron loss σ_{12} cross section were measured for metal ions Mg^+, Fe^+ and Cu^+ and gas targets Ne, Kr and N_2.

The results obtained for σ_{10} and σ_{12} cross sections for the investigated elements are shown in Figs. 3 and 4. All measured cross section values increase with energy, as it is expected for this velocity region $v < 10^8$ cm/s. The values are in accordance with the magnitudes of the energy defect for the particular pairs of the interacting particles. The only deviation is noticeable in the case

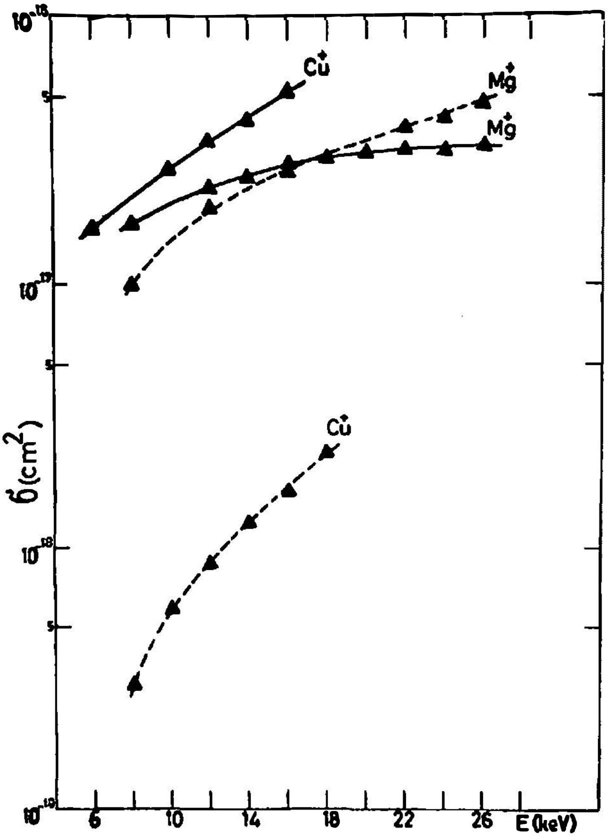

Fig. 4. Comparison of one-electron capture σ_{10} (full lines) and one-electron loss σ_{12} (dashed lines) cross sections for Mg^+/N_2 and Cu^+/N_2.

of N_2 gas target, where σ_{10} and σ_{12} cross section values are higher than those obtained for inert gas targets, and corresponding energy defects. Similar effects for molecular gas targets were noticed in some earlier works[8, 9]. The leveling of the $\sigma_{10} = f(E)$ curve for Mg^+/Ne, N_2, in this energy range, could not be explained simply by the adiabatic theory. The comparison of the experimentally obtained results for σ_{10} and σ_{12} cross sections showed that the probability of one-electron loss process increased with decreasing of the second ionization potential of the primary ion. In some cases, as for Mg^+, with the lowest second ionization potential in the group of the investigated metal ions, σ_{12} cross sections are of the same order of magnitude as σ_{10}, what is evident in Fig. 4. For comparison, σ_{12} and σ_{10} cross section for Cu^+, with the highest second ionization potential, are included in Fig. 4.

Two-electron capture cross sections σ_{1-1}. The formation of negative ions in two-electron capture process (10/—12) was investigated for ions C^+, O^+, O_2^+ and metal ion Fe^+. The results are shown in Fig. 5, and for comparison Fogel's results are included[10]. As it can be seen, the cross section values increase with energy, showing a few maxima. These maxima appear below the maximum corresponding to the ground state ions, and could be attributed to the reactions of excited ions present in the primary ion beams[11]. The cross section values for different elements increase with the magnitudes of their electron affinities. It is interesting to notice, that for the investigated gaseous ions, two-electron capture process is of rather high probability in comparison with that for one-electron capture and one-electron loss process.

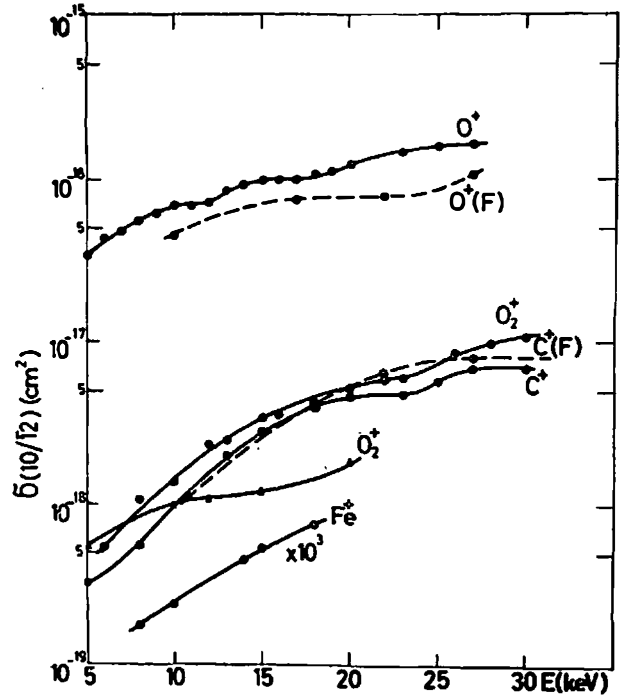

Fig. 5. Two-electron capture cross sections σ_{1-1} (full lines): ● — Kr target; △ — N_2 target. Fogel's results [9] are included as dashed lines.

Two-electron capture process, for Fe^+ has a very low probability in this energy range. The obtained results for Fe^+/Kr case, are in a good agreement with the empirical curve given by Kozlov and Bondar[12] for the process (10/—12), as shown in Fig. 6.

Special attention was paid to the analysis of $\sigma_- = f(nL)$ curves, in order to detect the influence of two-step processes on the formation of negative ions. Linear dependence of the measured σ_- on (nL), was found in the case of C^+/Kr only, indicating the influence of two-step processes on the formation of negative C^- ions. The analysis of these curves, for the gas target thickness range of 10^{-3} — 10^{-2} torr · cm, revealed that dependence of $\sigma_- = f(nL)$ could be represented by the relation (2) reduced to the following expression:

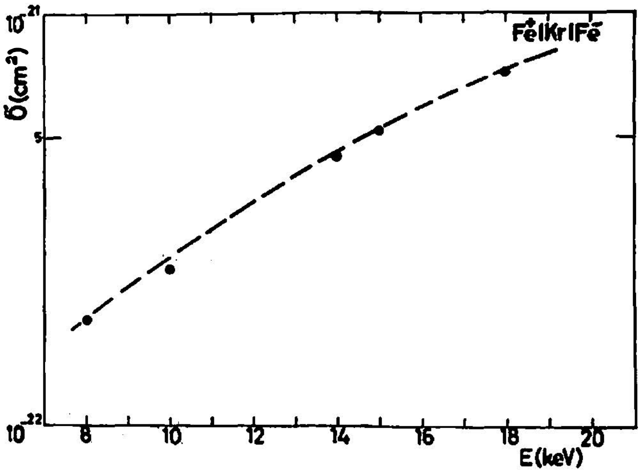

Fig. 6. Comparison of the experimental results for two-electron capture cross section σ_{1-1} for Fe^+/Kr (points) with the empirical curve (dashed line), given by Kozlov and Bondar[12].

$$\sigma_- = \sigma_{1-1} + {}^1/_2\, \sigma_{10}\, \sigma_{0-1}\, (nL).$$

Two-electron capture cross sections σ_{1-1} for different energies were determined by the extrapolation of the curves $\sigma_- = f(nL)$ to $\sigma_- = f(0)$.

In the other investigated cases, the influence of two-step processes on the measurements of σ_{1-1} was in the range of the experimental error.

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EKSPERIMENTALNO ISPITIVANJE NEELASTIČNIH SUDARA TEŠKIH ČESTICA U OPSEGU ENERGIJA 5 — 30 keV

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Sadržaj

Eksperimentalno su ispitani sudarni procesi zahvata i otkidanja jednog elektrona za jone metala Mg^+, Fe^+ i Cu^+, kao i procesi zahvata dva elektrona sa formiranjem negativnog jona za jone Fe^+, C^+, O^+ i O_2^+. Efikasni preseci za ove procese izmereni su u uslovima jednostrukog sudara, primenom metoda interakcije snopa brzih jona sa gasnom metom (neon, kripton, azot), u opsegu energija 5 — 30 keV. Primenjena eksperimentalna tehnika omogućila je merenje efikasnih preseka u opsegu 10^{-15} — 10^{-22} cm^2.

Rezultati su pokazali da efikasni preseci za gubitak jednog elektrona mogu biti istog reda veličine kao i efikasni preseci za zahvat jednog elektrona, u slučaju jona metala sa niskim drugim jonizacionim potencijalom. Analizirani su uslovi uticaja dvostepenih procesa na formiranje negativnih jona, pri merenju efikasnih preseka za zahvat dva elektrona u opsegu gustina gasne mete od 10^{-3} — 10^{-2} torr · cm.