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Double electron capture probability at He^{2+} ion Xe atom collisions with different impact parameters

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Received June 16, 2021
revised July 6, 2021
accepted July 6, 2021

Differential cross sections for scattering of helium atoms formed at collisions of He^{2+} ions with kinetic energies of 1.97, 3.00, and 7.17 keV/a.m.u with Xe atoms in processes with the formation of slow xenon ions with charges 2−4 have been measured. The projectiles deflection function is calculated. The probability of all these processes occurring at various values of the impact parameter of colliding particles is determined. The role of the electron shells of the Xe atom $5(s, p)$ and $4(s, p, d)$ for the capture of two electrons is determined depending on the speed of approach of the colliding particles, the impact parameter and the charge of the formed xenon ions.

Keywords: Double electron capture, capture with ionization, scattering differential cross section, impact parameter.

DOI: 10.21883/TPL.2022.13.53368.18921

Studies of the neutralization of He^{2+} ions at interaction with many-electron atoms are important for creation of models of their interaction with the atoms of structural materials (for example, tungsten), contained in the installations with high-temperature plasma, but difficult to obtain targets in laboratory conditions. Electronic shells of these atoms feature the proximity of electron binding energies at the outer and lower shells. This type of electron shells structure is possessed by the xenon atom.

At the moment of their formation alpha particles in controlled thermonuclear fusion plants have high kinetic energies and, therefore, high velocities of collisions with plasma components. However, after thermalization, their velocities correspond to the adiabatic interaction between particles, when collision can be considered as restructuring of electronic levels of a diatomic quasi-molecular ion. As a result of this restructuring when particles fly apart, they change their charge states. Thus, in this region of velocities the electron structure of particles is important for understanding their interaction. Within the framework of this approach, one can be based on the scattering angles of the formed He atoms to calculate the probabilities of processes for different minimum distances of approach of particles (impact parameters) and compare the distances with the sizes of electron shells.

For relatively light targets, for example, Ar atoms, the binding energy of internal electrons $2s^2 2p^6$ is about 240 eV [1]. As a result, the process electron transition from the shell of an Ar atom with $n = 2$ to the helium ion is practically impossible in the considered range of collision velocities. The processes of charge state changes in this case only affect the electrons of the outer shell. At the same time $4d$-electrons in the Xe shell are at a depth of about 70 eV [1]. Thus, for the alpha particle the probability can be high for the process of capturing two electrons, one of which belonging to the $4d$- shell, that is the process

$$He^{2+} + Xe(4d^{10}5s^2 5p^6) \rightarrow He(1s^2) + Xe^{2+}(4d^9 5s^2 5p^5),$$

with a resonance defect of ~ 3 eV [2].

The purpose of this work is to study the mechanism of processes of changing the charge state of the collision partners accompanying the capture of two electrons, as well as to identify the role of internal shell electrons of heavy atoms in such processes. For this purpose the scattering differential cross-sections of the formed atoms of helium were measured. Three alpha projectile energies were selected: 1.97, 3.00 and 7.17 keV/a.m.u. For each energy, the scattering cross-sections were measured for the helium atoms formed in the following three elementary processes:

$$He^{2+} + Xe^0 \rightarrow He^0 + Xe^{(2+n)+} + ne^-, \ \ n = 0{-}2.$$

To denote an elementary process, charges of the collision partners before and after the interaction $\{200(2+n)\}$ are used.

Measurements were carried out on the facility described in detail in [3]. Here we just give details of the facility characteristics important for measuring the differential cross-sections. In the experiment we used a collimated beam of He^{2+} fast ions with a cross-section of 1×1 mm and an angular spread of $4'$, which was directly determined at the beginning of measurements in the absence of scattering on the gas target. The target of Xe atoms was created by a gas jet from a capillary with a diameter of 1 mm. This provided a target of neutral atoms with a length of ~ 1 mm in the region of intersection with the ion beam. The inlet slit of the neutral atom detector had a diameter of 1 mm as well, and was at a distance of 60 cm from the interaction

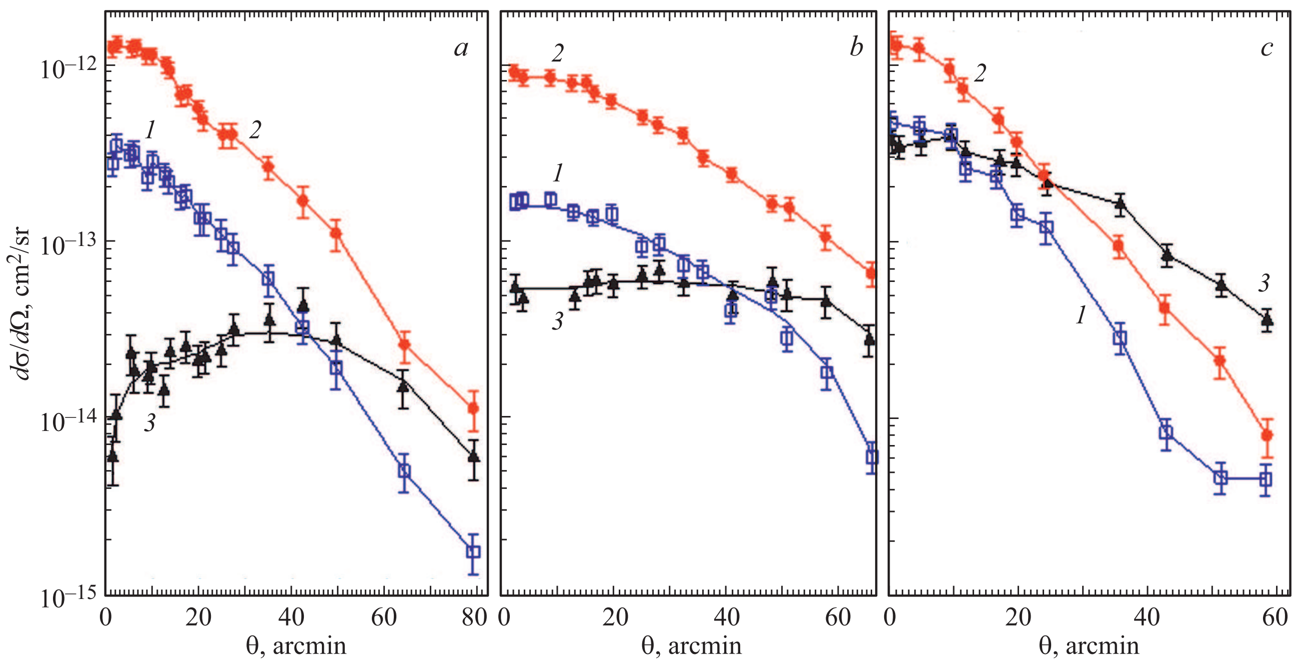

Figure 1. Cross-sections of the processes differential with respect to the scattering angle of the projectile ion, that take place during the capture of two electrons by He^{2+} ions from Xe atoms: *1* — {2002}, *2* — {2003}, *3* — {2004}. Collision energy, keV/a.m.u.: *a* — 1.97, *b* — 3.00, *c* — 7.17.

region. All these dimensions determined the total angular resolution of the device, that was $7'$. The formed slow xenon ions were extracted from the region of interaction by means of electric field with a strength of 50 V/cm and separated by charge by their time of flight to the recoil ion detector. Deviation of the primary beam of He^{2+} ions on a path of 1 mm was negligible and did not distort the measured scattering differential cross-sections.

Scattering differential cross-sections were measured in relative values for each energy He^{2+} reduced to the same density of the gas target and the intensity of the beam of He^{2+} ions. Absolute values were determined from the ratio of absolute values of the total cross-sections of slow ions formation with a certain charge in the process of capturing two electrons from our work [4] and the differential cross-section in accordance with the following expression

$$\sigma = 2\pi \int_0^{\pi} \frac{d\sigma}{d\Omega}(\theta) \sin(\theta) d\theta. \quad (1)$$

The results of these measurements are shown in Fig. 1.

Values of the differential cross-sections of the processes of two electrons capture {2002} and two electrons capture with ionization {2003} have their maximum at the minimum scattering angle, i.e. at high parameters of the impact. Both of these processes are exothermic and can be realized due to the potential energy of He^{2+} ion. With an increase in the scattering angle up to $\sim 1^\circ$ cross-sections of these processes decrease by more than two orders of magnitude. This dependence of the cross-sections on the scattering angle persists with increase in the kinetic energy of projectile ions. At all investigated energies and scattering angles, the cross-section of the process {2003} exceeds the size of the {2002} cross-section. In the process {2002} a decrease in potential energy in the $(XeHe)^{2+}$ quasi-molecular system is converted into the excitation energy of the xenon ion and an increase in the kinetic energy of collision partners. In the case of the capture process with ionization (process {2003}) reaction channels appear, which are associated with the formation of a free electron.

A different dependence is observed for the {2004} — an endothermic process of neutralization of the projectile ion of helium accompanied by the formation of two free electrons. At a low velocity of particle approach, a corresponding kinetic energy of the He^{2+} ion of 1.97 keV/a.m.u., the differential cross-section even increases with an increase in the scattering angle from 0 to 40 arcmin, reaching its maximum of $4.4 \cdot 10^{-14}$ cm^2/sr. At an energy of 3.0 keV/a.m.u. in the same range of scattering angles, a weak growth of the differential cross-section is observed with an increase in θ and a much slower decrease in this cross-section as compared with the cross-sections of other processes in the range of θ from 40 to 70 arcmin — just by 1.7 times. At a collision energy of 7.17 keV/a.m.u., at scattering angles greater than 30 arcmin, the cross-section of process {2004} becomes greater than not only the cross-section of process {2002}, but also the cross-section of process {2003} (Fig. 1, *c*).

Based on the measured values of scattering differential cross-sections, one can determine the probabilities of process realization depending on the maximum approach

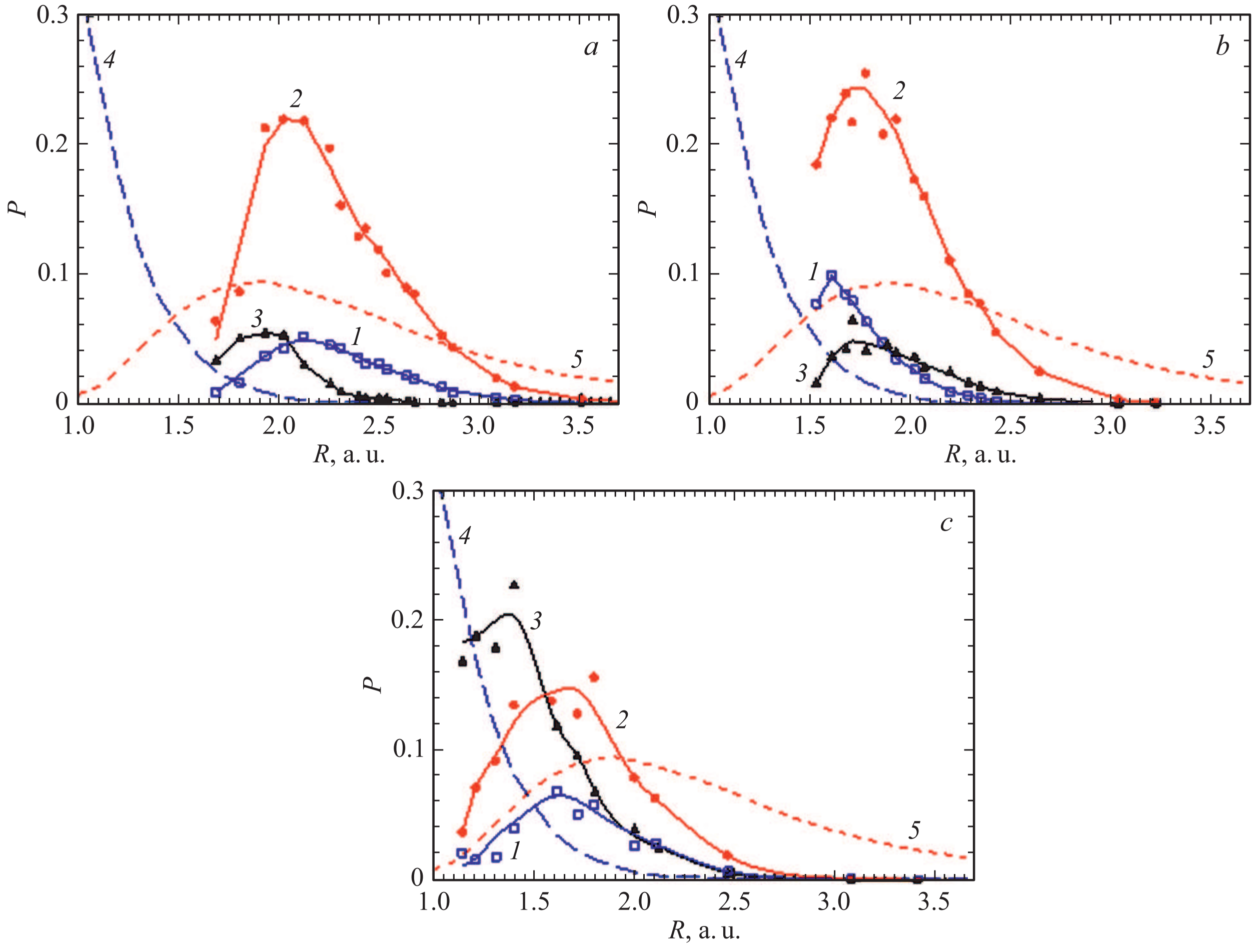

Figure 2. Probabilities of elementary processes as a function of internuclear distance (*1* — $P_{\{2002\}}$, *2* — $P_{\{2003\}}$, *3* — $P_{\{2004\}}$) and distribution of outer shell electron density in the Xe atom as a function of distance to the atomic nucleus (*4* — $n = 4\Sigma s, p, d$; *5* — $n = 5\Sigma s, p$). Collision energy, keV/a.m.u.: *a* — 1.97, *b* — 3.00, *c* — 7.17.

distance of colliding particles by converting the dependence of the process on the angle θ to its dependence on the impact parameter R

$$P(R) = \frac{\pi}{2(180 \cdot 60)^2 R} \frac{d\sigma}{d\Omega}(\theta)\theta(R)\frac{d\theta}{dR} \tag{2}$$

(at scattering angles less than 1° the impact parameter and the maximum approach distance are almost the same [5]). The first factor in expression (2) arises as a result of the conversion of the cross-section values expressed in cm^2/sr into the sections expressed in cm^2/sq.arcmin. The rest factors reflect the recalculation of the cross-section as a function of θ into the cross-section as a function of R. As can be seen from expression (2), the calculations require to determine the deviation function $\theta(R)$ and its derivative $d\theta/dR$. In the calculation of the deflection function we have used the Coulomb model for the interaction of the projectile helium ion with a charge of $2e$ and a charge of the xenon atom nucleus screened by electrons at distances less than the distance between the colliding particles. The model was implemented using the distribution of electrons along the radius in a xenon atom, calculated by the Hartree–Fock method. The deflection function of helium ions with a kinetic energy of 1.97 keV/a.m.u. is calculated in the range of impact parameters of 1.3–3.5 a.u. with a step of 0.1 a.u. It is described well by the following expression

$$\theta = 1763.44\frac{1.97}{E}\exp(-1.87095R), \tag{3}$$

where E is the energy of the He^{2+} ion (in keV/a.m.u.).

The realization probabilities of the elementary processes of two electrons capture with the formation of Xe^{2+}, Xe^{3+} and Xe^{4+} ions depending on the impact parameter are shown in Fig. 2. Dashed lines in this figure represent the distribution density of electrons as a function of the distance to the nucleus of the Xe atom in $5s^2 5p^6$ and $4s^2 4p^6 4d^{10}$ shells.

For all investigated collision energies the most likely is the process of two electrons capture with ionization {2003}. Probabilities of processes {2002} and {2003} have maxima at the impact parameters corresponding to the maximum electron density of the $5s^2 5p^6$ shell. With a collision energy of 1.97 keV/a.m.u., the maximum probability of process {2004} also corresponds to the maximum electron density of the outer shell. However, with an increase in collision energy for this process, the position of the probability maximum is shifted to the region of smaller impact parameters, while a significant increase in the probability of process {2004} takes place. As it follows from Fig. 2, *c*, at impact parameters of ~ 1.5 a.u. the He^{2+} ion reaches the electrons of the 4*d*-shell. Obviously, it is the involvement of inner shell electrons in the process that results in an increase in the probability of formation of multicharged Xe^{4+} ions.

The results obtained indicate that the analysis of interaction between the He^{2+} ions and the scattered material of the first wall of the controlled thermonuclear fusion plant must take into account that not only outer shell electrons of the atoms are involved in this interaction, which leads to an efficient formation of multicharged ions of impurities.

Funding

The work has been performed under the state assignment (topic № 0040-2019-0023).

Conflict of interest

The authors declare that they have no conflict of interest.

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