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Viatcheslav Shevelko
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Atomic Multielectron Processes

With 110 Figures and 17 Tables

Springer

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Preface

Multielectron processes occurring in collisions of atoms, ions and molecules with photons and charged particles belong to one of the most interesting and challenging areas of the modern physics of atomic and electronic collisions. While single-electron processes associated with transitions of one electron in the target or projectile are well understood conceptually and mathematically, a basic understanding and study of many-electron processes require the use of highly advanced experimental techniques and sophisticated theoretical methods which should come out of the framework of the traditional one-electron approximations.

In the present monograph, we will consider such processes as multielectron excitation, multiple ionization, multiple-electron transfer, excitation with simultaneous ionization, multielectron photoionization arising in a single collision of an atomic particle with a photon, electron or another charged particle. These collisions take place via various multielectron channels such as multiple excitation or ionization of the outermost electrons or a single inner-shell excitation or ionization accompanied by relaxation of many-electron Auger or radiative processes.

Multielectron processes are very interesting in understanding the nature of the many-electron and many-particle transitions. On the other hand, under certain conditions, the effective cross sections of these processes can be quite large and reach up to 30–50% of the total cross sections. They play a quite significant role in different physical applications: modeling of plasma processes, charge-state evolution of atoms exposed to an electron beam, projectile charge-changing reactions responsible for the beam lifetimes of stored ions in acceleration devices such as a storage ring or a synchrotron.

Multiple-electron transitions are basically many-body phenomena depending significantly on the correlation effects between electrons involved. This fact is in a sharp contrast to the single-electron transitions where electron-electron correlations play, as a rule, a minor role. The term 'correlation' usually refers to the correlation effects between electrons caused by the Coulomb interaction, however, other kinds of correlation, e.g., time or spin correlations, are also possible.

Effective cross sections (or probabilities) of the multielectron atomic processes may be very large. Here are a few examples. The experimental double- and single-ionization cross sections of Mg atoms by electrons with the energies $E \approx 1\,\mathrm{keV}$ are of comparable size: $\sigma_2(E) \approx \sigma_1(E) \approx 10^{-17}\,\mathrm{cm}^2$. This can be understood due to a significant contribution of the inner-shell electron ionization followed by autoionization processes. Experimental cross section for an ionization of $m = 30$ electrons from a Xe atom in collisions with a 15.5 MeV/u U^{75+} ion is about $\sigma_{30} \approx 10^{-18}\,\mathrm{cm}^2$, compared with the single-electron ionization cross section of $10^{-14}\,\mathrm{cm}^2$. Here, the involvement of the inner-shell ionization processes followed by a series of cascades is evident. The maximum four-electron photoionization cross section of Xe at the photon energy $\hbar\omega \approx 160\,\mathrm{eV}$ is $\sigma_4(\omega) \approx 3.2 \times 10^{-19}\,\mathrm{cm}^2$. Therefore, multielectron processes play an important role in elementary atomic reactions and should be properly accounted for in analysis of the collision processes, e.g., in calculations of the beam attenuation kinetics.

At present, multielectron processes are more or less understood at incident ion energies higher than those corresponding to the electron-orbital velocities. They can be reasonably well described in terms of the independent one-electron processes (so-called Independent Particle Model, IPM). The role of multielectron processes significantly increases with the projectile and target charges and the relative velocity as well. More precisely, the ratio of the projectile charge to the relative velocity is known to be the important parameter. For example, the cross sections of multiple-electron capture at low-collision energies have been found to be large. In 4 keV/u Xe^{27+}+Xe collisions, the process $Xe^{27+} + Xe \rightarrow (Xe^{11+})^* + Xe^{16+} \rightarrow Xe^{22+} + Xe^{16+} + 11e^-$ has been observed, indicating that 16 electrons are captured into the projectile which, in turn, is stabilized through 11 cascades of the autoionization. Such multiple-electron processes are presently out of accurate theoretical treatments.

The present book is aiming at the first comprehensive collection of the cross sections for many-electron processes together with the physical background including dependences on the relative velocity, the projectile and target charges, transition energies, the number of the ejected electrons and other atomic parameters. The book comprises a series of tables, figures and empirical formulas which can be used conveniently for students and specialists working in the fields of atomic and plasma physics, chemical and laser physics and in a number of the applied sciences.

We would like to express our sincere gratitude to all colleagues who helped us in preparing this manuscript, especially, C.L. Cocke, B. DePaola, A. Müller, N.V. Novikov, L.P. Presnyakov, P. Richard, R.D. Rivarola, E. Salzborn, V.A. Sidorovich, N. Stolterfoht, Th. Stöhlker, J. Ullrich, D.B. Uskov and T.J.M. Zouros.

Moscow-Toki, Summer 1998 *H. Tawara, V. Shevelko*

Glossary of Terms

Fundamental Atomic Constants

The system of the atomic units (a.u.) is used: $e^2 = m_\mathrm{e} = \hbar = 1$.

$a_0 = \hbar^2/m_\mathrm{e}e^2$ $= 0.529\ 177\ 249(24) \times 10^{-8}$ cm	Bohr radius
$E_0 = e^2/a_0 = 27.211\ 3961(81)$ eV $= 2\ Ry$	Energy
$1\ Ry = m_\mathrm{e}e^4/2\hbar^2$ $= 13.605\ 6981(40)$ eV	Rydberg energy
$\tau_0 = \hbar^3/m_\mathrm{e}e^4 = a_0/v_0$ $= 2.418\ 884\ 33(11) \times 10^{-17}$ s	Time
$v_0 = e^2/\hbar = 2.187\ 691\ 417(98) \times 10^8$ cm/s	Velocity
$\pi a_0^2 = 0.879\ 735\ 6696(80) \times 10^{-16}$ cm^2	Cross section
$\alpha = e^2/\hbar c$ $= 1/137.035\ 9895(61)$	Fine-structure constant
$c = 1/\alpha = 2.997\ 924\ 58 \times 10^{10}$ cm/s	Velocity of light in vacuum

The values given above are extracted from the set of constants recommended for international use by the Committee on Data for Science and Technology (CODATA), [E.R. Cohen and B.N. Taylor: *The Fundamental Physical Constants*, Phys. Today **48**, Part 2 (August 1995)].

List of Symbols

A^a	Autoionization transition probability
A^r	Radiative transition probability
B	Branching-ratio coefficient
E	Projectile energy
E_{cm}	Center-of-mass energy
f	Distribution function
I	Binding energy; ionization potential
I_m	Ionization energy to remove m electrons
K	Momentum transfer
ℓ	Orbital quantum number
m	Number of ejected electrons
n	Principal quantum number
N	Total number of the target electrons
P_s	Probability for single-electron process
R_m	Ratio of $m-$fold to single-ionization cross sections
TI	Transfer ionization
TS	Two-step process
v	Relative velocity
v_p	Projectile velocity
X^{q+}	Ion with charge q
Z	Nuclear charge
Z_p	Projectile charge
Z_T	Target nuclear charge
β	Electric polarizability
λ	Wavelength
ρ	Impact parameter
σ_m	m-fold ionization cross section
σ_+	Net ionization cross section
θ	Scattering angle
ω	Photon frequency

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