第 19 卷 第 2 期
2002 年 6 月

原子核物理评论
Nuclear Physics Review

Vol. 19, No. 2
June, 2002

Article ID: 1007-4627(2002)02-0144-03

Electron-impact Ionization of Multiply-charged Ions

K. Aichele, W. Arnold, D. Hathiramani, F. Scheuermann, E. Salzborn[1)]
(*Institut fuer Kernphysik, Universitaet Giessen*, 35392 *Giessen, Germany*)

Abstract: Electron-impact ionization of ions is one of the most fundamental processes in every kind of plasma. Especially in high-temperature plasmas-whether in laboratory (nuclear fusion) or in astrophysics (atmosphere of stars)-atoms become ionized into multiply-charged ions by electron impact. The main purpose of our investigations is to unravel the contributions from different ionization mechanisms-like direct ionization (one-step process), excitation-autoionization (two-step process) and inner-shell Auger processes to the cross sections of single and multiple ionization of highly-charged ions. As the experimental database is still rather small, theoretical cross sections are often used for the calculation of different plasma parameters. Cross sections for ions with an outer $4f$ shell are usually small and experimental data is needed in order to test theories in that region. In the present study, we investigate the ionization of praseodymium ions, where cross section data has not been available up to now.

Key word: excitation; ionization; electron impact; multiply-charged ions
CLC number: O562.4 **Document code**: A

Experimental Technique The measurements were performed employing our electron-ion crossed-beams set-up[1] which is shown in Fig. 1. Using an oven, praseodymium was evaporated into the plasma of a 10 GHz electron-cyclotron-resonance (ECR) ion source. The Pr^{q+}-ions were extracted with energies of $q \times 10$ keV. After magnetic separation of the desired mass-to-charge ratio, the ion beam was collimated to typically 2 mm × 2 mm and crossed with an intense electron beam at an angle of 90°. The electron gun supplies electrons with energies between 1 0 eV and 1 keV with

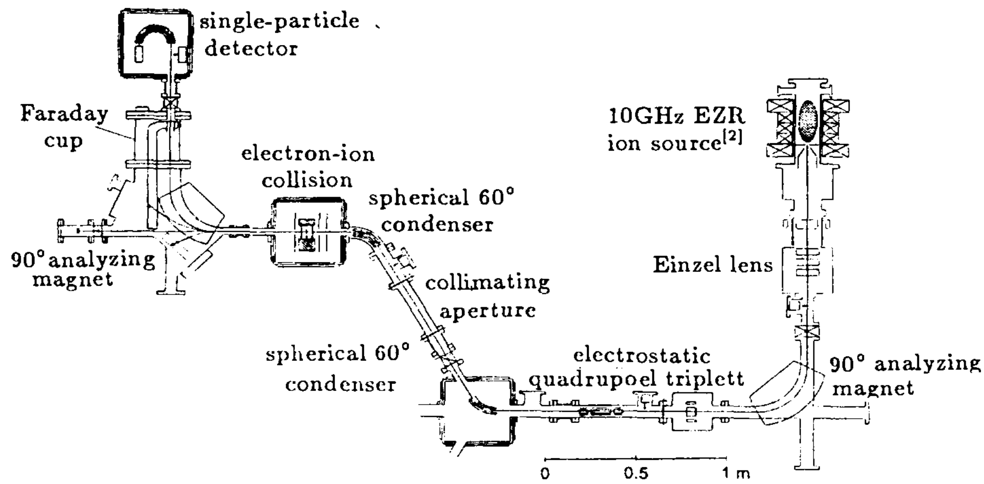

Fig. 1 Schematic diagram of the electron-ion crossed-beams set-up for the measurement of absolute cross sections for electron-impact ionization of multiply-charged ions.

Received date: 8 April 2002; **Corrected date**: 00 - 00 - 2002

1) **Corresponding allthor**: E. Salzborn, Institut fuer Kernphysik Leihaesterner Weg 217, D-35392 Giessen; Salzborn@ strz. uni-qiessen. cle.

currents up to 430 mA[2]. After magnetic separation of the product ions from the parent ion beam, they were detected by a single-particle detector while the parent ions were collected in a Faraday cup. Absolute cross sections were obtained by employing the dynamic crossed-beams technique[3], where the electron beam is moved vertically through the ion beam.

For the energy-scan technique[4], both beams are fixed for an optimum beam overlap position. The same parameters as above are measured with a simultaneous fast variation of the electron energy in small steps of typically 0.04 eV and dwell times of 5 ms. By repeating scans many times, we average out possible fluctuations in the beam overlap, the measurement of the beam currents and count rates. With this method only relative cross sections can be obtained, but by applying both techniques we get a very high resolution in the absolute cross sections by matching the energy-scan measurements to the absolute cross section data achieved with the dynamic technique.

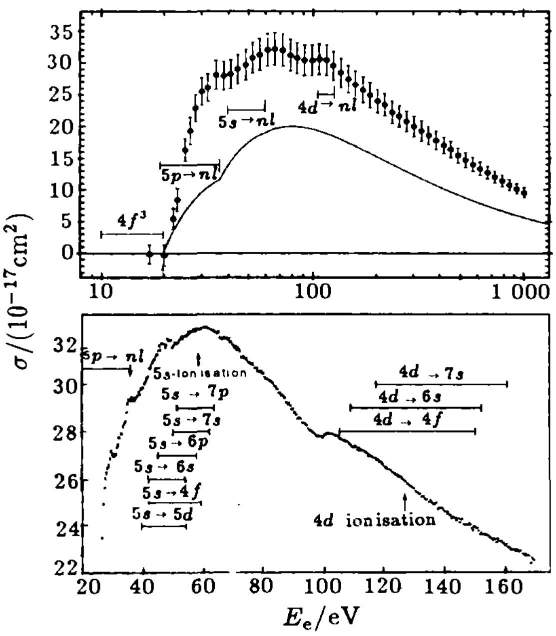

Fig. 2 Upper part: Cross sections for the single ionization of Pr^{2+}-ions. The error bars represent the total experimental uncertainties and the arrow indicates the calculated threshold energy for ionization from the ground state. Solid line: Lotz formula[6]. Lower part: Energy-scan measurement in the range 20—170 eV. Error bars show the statistical error only.

Results and Discussion Examples of the measured electron-impact ionization cross sections for Pr^{q+}-ions are shown in Fig. 2 and Fig. 3. The error bars indicate the total experimental uncertainties for the absolute measurements. The threshold energies for ground state ionization, marked by arrows below the energy axis, were calculated by the MCDF code of Grant et al[5].

The following table lists our measured cross sections ($\sigma_{q,\,q+n}$) for n-fold ionization:

$n=1$: $\sigma_{2,3}$ $\sigma_{3,4}$ $\sigma_{4,5}$ $\sigma_{6,7}$ $\sigma_{7,8}$ $\sigma_{8,9}$ $\sigma_{11,12}$ $\sigma_{12,13}$

$n=2$: $\sigma_{1,3}$ $\sigma_{2,4}$ $\sigma_{3,5}$ $\sigma_{4,6}$

$n=3$: $\sigma_{1,4}$ $\sigma_{2,5}$ $\sigma_{3,6}$

For $\sigma_{12,13}$ only relative measurements in a small energy range were made. A few single ionization cross sections could not be measured due to experimental problems, e.g. the same mass to charge ratio as for nitrogen ions.

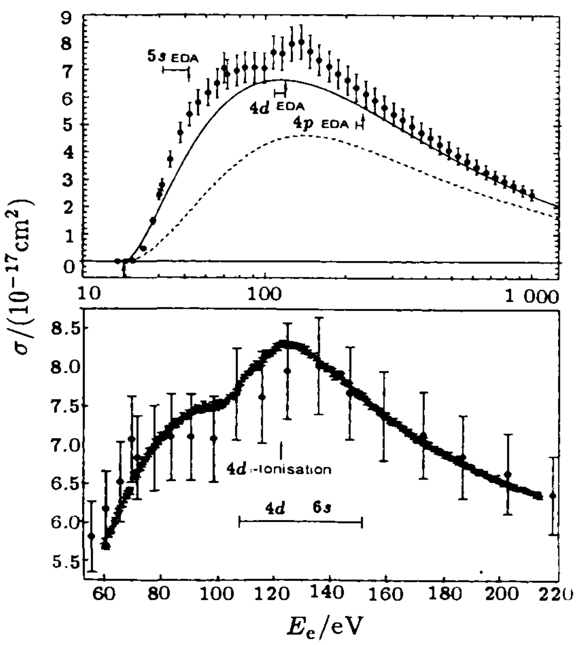

Fig. 3 (a) Cross sections for the double ionization of Pr^{+} ions. The error bars represent the total experimental uncertainties, and the arrow indicates the calculated threshold energy for ionization from the ground state. Solid line: Shevelko et al[7], dashed line: Fisher et al[9]. (b) Energy-scan measurement in the range 60—215 eV. Error bars show the statistical error only.

Single Ionization Fig. 2 shows the cross sections for single ionization of doubly-charged praseodymium ions. In the upper part the results of the absolute measurements are displayed. The steep rise right above the threshold indicates strong contributions from indirect processes. Here, 5*p*-excitation-autoionization (EA) and 5*s*-EA processes significantly enhance the cross section. The semiempirical formula of Lotz[6] underestimates the measured cross section as it describes direct processes only. For a more detailed examination we employed the energy-scan technique in the range from threshold to 170 eV(see the lower part of Fig. 2). The step at about 100 eV nearly coincides with the threshold for 4*d*-EA processes. 4*d* → 5*d*-EA processes could not be calculated since more than 1 900 levels are involved.

Multiple Ionization In Fig. 3 the cross sections for double ionization of Pr^{+}-ions are shown. Obviously, 5*s*-excitation followed by double autoionization (5*s*-EDA) as well as 4*p*-EDA-processes show no significant contributions to the cross sections. However, 4*d*-EDA processes result in a steep rise in the cross section at about 100 eV. The prediction by the semiempirical formula of Shevelko et al[7, 8] is in good agreement with the measured data, whereas the semiempirical formula of Fisher et al[9] considerably underestimates the cross section. In the lower part of Fig. 3 the energy-scan measurement in the range 60—215 eV is shown.

References:

[1] Tinschert K, *et al*. Experimental Cross Sections for Electron Impact Ionisation of Hydrogen-like Li^{2+} Ions[J]. J Phys B: At Mol Opt Phys, 1989, **22**: 531.

[2] Becker R, Müller A, Achenbach C, *et al*. A Dense Electron Target for Electron-ion Collisions[J]. Nucl Instr and Meth, 1985, **B9**: 385.

[3] Müller A, Tinschert K, Achenbach C, *et al*. A New Technique for the Measurement of Ionization Cross Sections with Crossed Electron and Ion Beams[J]. Nucl Instr and Meth, 1985, **B10/11**: 204.

[4] Müller A, Tinschert K, Hofmann G, *et al*. Resonances in Electron-impact Single, Double and Triple Ionization of Heavy Metal Ions[J]. Phys Rev Lett, 1988, **61**: 70.

[5] Grant I P, McKenzie B J, Norrington P, *et al*. An Atomic Multiconfigurational Dirac-Fock Package [J]. Comp Phys Comm, 1980, **21**: 207.

[6] Lotz W. Electron-impact Ionization Cross-sections for Atoms up to $Z=108$[J]. Zeitschrift für Physik, 1970, **232**: 101.

[7] Belenger C, *et al*. Double Ionization of Neutral Atoms, Positive and Negative Ions by Electron Impact[J]. J Phys B: At Mol Opt Phys, 1997, **30**: 2 667.

[8] Shevelko V P, Tawara H J. Semiempirical Formulae for Multiple Ionization of Neutral Atoms and Positive Ions by Electron Impact[J]. Phys B: At Mol Opt Phys, 1995, **28**: L589.

[9] Fisher V, Ralchenk Y, Goldgirsh A, *et al*. A Scaling of Multiple Ionization Cross Sections[J]. J Phys B: At Mol Opt Phys, 1995, **28**: 3 027.

电子与多电荷离子的碰撞电离

K. Aichele, W. Arnold, D. Hathiramani, F. Scheuermann, E. Salzborn

(德国吉森大学核物理研究所)

摘　要：主要揭示了不同电离机制对高电荷态离子单电离和多重电离的贡献，包括直接电离(一步过程)、激发-自电离(两步过程)以及内壳 Auger 过程，研究了高电荷态错离子的电子碰撞电离.

关 键 词：激发；电离；电子碰撞；多电荷离子