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THRESHOLD IONISATION BY ELECTRON IMPACT

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Abstract

Multiple ionisation of rare gas atoms by electron impact has been studied experimentally close to the ionisation thresholds. In this energy range the cross sections are described by threshold laws, yielding reasonable agreement with theory for He and Ne. In the heavier targets the exponent value is found to be smaller than predicted and the results can be interpreted in terms of a pure statistical theory.

1) Introduction

The electron impact ionisation process close to the ionisation threshold represents an interesting phenomenon which has attracted much interest during recent years. It is characterized by a long range Coulomb interaction between several particles, which can be hardly treated quantum mechanically over large internuclear distances.

Thus, the first description dating to 1953 by Wannier and deriving a threshold law mainly follows arguments of classical mechanics /1/ yielding the famous relation

$$\sigma \sim E^{1.127}. \quad (1)$$

Here E represents the amount of energy by which the total energy of the system exceeds the ionisation energy of the atom. This relation holds only for small values of E and describes the escape of two electrons, i.e. the process of photo-double detachment of negative ions and single ionisation of atoms by electron impact.

An extension to the case of multiple ionisation was made by Wannier in 1955 /2/ using simple phase space arguments. The q -fold ionisation cross section for electron-atom collisions is described close to the ionisation threshold by

$$\sigma \sim (E_{e1} - E_{thr})^{\kappa} \quad \text{with } \kappa \approx q \quad (2)$$

whereby E_{e1} represents the electron energy and E_{thr} the threshold energy for direct ionisation.

Meanwhile further classical, semiclassical or quantum-mechanical calculations have been performed to study the multiple-electron escape process including electron correlation effects /3-9/. In general equation (2) is confirmed, however, the exponent κ should be slightly larger than the charge q of the produced ion. For double, triple and fourfold ionisation of neutral atoms by electron impact the ratio κ/q is expected to be 1.135, 1.175 and >1.175 .

Up to now experiments have been mainly concerned with the single ionisation process confirming the Wannier exponent of 1.127. However, in the case of multiple ionisation the number of experiments is very small. Therefore, we analysed the threshold behavior of the multiple ionisation cross section in different rare gases and studied the importance of electron correlation effects for different numbers of electrons involved.

II) Experiment

The apparatus being used in this experiment is shown in figure 1. Within an electron impact ion source multiply charged ions are produced under single collision conditions. The pulsed electron beam is emitted

Figure 1 Experimental setup: 1-ion source, 2-electrostatic lenses, 3 and 7a-deflection plates, 4-magnetic sector field, 5-collision chamber, 6-energy analyser, 7b-zoom lenses, 8-channeltron

from an equipotential cathode with an energetic halfwidth of about 500 meV. The ions are softly extracted and focused onto the entrance aperture of a magnetic sector field. After mass and charge state analysis the ions pass a collision chamber, some ion optics, an energy filter and finally are detected with the aid of a channeltron.

The collision chamber and the energy analyser may be used in order to perform translational energy spectroscopy; by this means the internal states of the produced ions can be determined and state-selective cross sections can be measured /10/. The results presented below have been obtained without an internal state analysis.

During the experiment all voltages are kept constant with the exception of the electron acceleration voltage and the voltage of the electron lens in the ion source. For further details see e.g. ref. /11/.

III) Results and discussion

Cross sections for multiple ionisation of He, Ne, Kr and Xe by electron impact have been measured and analysed in the energy range close to the ionisation threshold. The charge states of the produced ions vary from one to four. As far as the evaluated range of electron energies lies below the threshold for the first excited state (neglecting the spin-orbit splitting of the ground state) the results represent state-selective cross sections.

Figure 2 shows the threshold region of the double ionisation cross section in He. In the energy range up to 5 eV above threshold the experimental data can be described quite well by a threshold law with

an exponent of $K = 2.14$, which is in very good agreement with theory considering the total error of K which amounts to 10%. Previous measurements of Brion and Thomas /12/ yielded as a best fit a quadratic dependence of σ on E . This gives a less good agreement with our measurements.

Figure 2 Partial double ionisation cross section for He. $E_{thr} = 79$ eV; the full curve represents a fit with $K = 2.14$.

The variation of the exponent with the charge state q of the produced ions becomes very obvious in figure 3, where cross sections for single, double and triple ionisation of Ne are presented. Whereas for the single ionisation the cross section rises nearly linear with E , in the case of multiple ionisation the curvature close to the ionisation threshold strongly increases with increasing q as predicted by theory. A detailed analysis yields exponent values of $K_1 = 1.06$, $K_2 = 2.04$ and $K_3 = 3.16$; all values being larger than q and agreeing with the theoretical predictions within the obtained error bounds.

Similar experiments have been performed with Kr and Xe as target gases, whereby Kr ions in charge states 2 and 3 and Xe ions in charge states 2 to 4 have been measured. Surprisingly, in both cases the K values are smaller than the produced charge state q , the deviations being larger than the experimental error in several cases.

An overview on the exponent values determined in various systems is given in table 1, together with predictions of the above mentioned theories and with results of a pure statistical calculation according to the statistical energy deposition model (SED) of Russek /13/.

The results for Kr and Xe with $q = 2$ and 3 can be reproduced quite well by the statistical energy deposition model as can be seen from table 1. The theoretical values are smaller than q as we consider a finite range of E above threshold (a few eV); only in the case $E \rightarrow 0$ one might expect K to be equal to q . Within this model the surplus energy E is distributed statistically among the escaping electrons and thus no restrictions with respect to favourable geometries in the escaping process are considered in the SED model.

Figure 3 Partial cross sections for single, double and triple ionisation of Ne atoms by electron impact (one arbitrary unit corresponds $5 \cdot 10^{-19} \text{ cm}^2$, $4.5 \cdot 10^{-22} \text{ cm}^2$ and $4.8 \cdot 10^{-24} \text{ cm}^2$ for Ne^+ , Ne^{2+} and Ne^{3+} , respectively).

Table 1 Threshold law exponents for various single and multiple ionisation processes.

produced ion	experiment κ	$\Delta \kappa$	E_{max}/eV	theory	SED
He^+	1.15	0.06	6.0	1.127	
He^{2+}	2.14	0.21	5.5	2.270	
Ne^+	1.06	0.05	5.3	1.127	
Ne^{2+}	2.04	0.14	4.5	2.270	
Ne^{3+}	3.16	0.32	4.8	3.525	
Ne^{4+}	4.15	0.63	4.5	>4.7	
Kr^{2+}	1.97	0.1	4.6	2.270	1.88
Kr^{3+}	2.63	0.3	6.5	3.525	2.85
Xe^{2+}	1.85	0.1	5.7	2.270	1.83
Xe^{3+}	2.80	0.1	6.6	3.525	2.82
Xe^{4+}	2.6			>4.7	3.7 (2.8)

The four-fold ionisation of Xe atoms seems to be a special case, as the experimental κ value is found to be well below the SED result. However, if we assume that in a first step an autoionising state of Xe^{3+} is formed decaying by an Auger process into Xe^{4+} , we find good agreement with the SED predictions. A comparison is made in figure 4, where κ has been determined by fitting procedures overlapping a wider range of E_{max} . The dotted curves represent the result for a primary process where three electrons are emitted in addition to the incoming electron.

Figure 4: exponent value k versus the length of the fitting interval above threshold in the case of Xe^{4+} .
 + experimental values; - SED result for a direct process; ... SED result assuming an intermediate autoionising Xe^{3+} state.

Summarizing we may say, that in the case of few electron systems like He good agreement is found with theories which include the electron correlation effects. If we increase the number of electrons in the system k becomes smaller and the process can be described more or less as a statistical one. Furthermore, the influence of autoionising states, which are located close to the ionisation threshold, becomes more important for heavier rare gas atoms.

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