Differential Cross Sections for the $3s$-$3p$ Excitation of Sodiumlike Ar^{7+} Ions by Electron Impact

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Differential cross sections have been measured for the electron-impact excitation of a multiply charged ion. In a crossed-beam experiment the resonant $3s$-$3p$ transition of sodiumlike Ar^{7+} is studied at an electron energy of 100 eV in an angular range between 13° and 29°. The experimental cross sections are found to be in good agreement with theoretical predictions obtained in Coulomb-Born distorted-wave approximation.

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Electron-impact excitation of ions plays an important role in all kinds of plasmas. For example, it drives the population of excited levels of multiply charged impurities in high-temperature plasmas and hence contributes significantly to the energy loss of the confined system. Accurate electron-excitation rates are needed in the modeling of dense plasmas such as stellar plasmas or short-wavelength (vacuum-ultraviolet or x-ray) lasers, although plasma screening effects, which may influence the excitation rates, may no longer be negligible in dense plasmas.

Electron-ion excitation rates are difficult to measure and, despite newly available powerful ion sources, ion storage rings, and ion traps, the number of experimental studies has remained rather small. The necessary information comes, therefore, mainly from theoretical calculations, which ought to be carefully checked.

A few total excitation cross sections have been measured. Several resonance transitions in Li-like (C^{3+}, N^{4+}) [1,2] and Na-like (Al^{2+}) [3] systems from nonautoionizing low-lying states have been studied by counting the photons emitted after the excitation process. More recently, the same method was used for the $2p$-$3l$ excitation of Ba^{46+} within an electron-beam ion-trap (EBIT) arrangement [4]. Alternatively the $3s$-$3p$ excitation of Si^{3+} has been analyzed by applying the electron-energy-loss technique [5] near the excitation threshold. Experimental information on differential excitation cross sections has been limited so far to forward angle scattering for three singly charged systems: Mg^+, Zn^+, and Cd^+ [6–8].

In this paper we report on the first measurement of differential excitation cross sections of multicharged ions. These data have been obtained in a crossed-beam experiment. A beam of multiply charged ions is intersected by an electron beam at an angle of 90°. Electrons which are scattered at an angle between 13° and 29° are analyzed with respect to their kinetic energy. At a fixed scattering angle the ratio of inelastic to elastic scattering signals is measured and used to derive absolute differential excitation cross sections.

In a first experiment we have focused our effort on the resonant $3s$-$3p$ transition in Ar^{7+},

$$e^- + Ar^{7+}(3s\,^2S) \rightarrow e^- + Ar^{7+}(3p\,^2P) - 17.4\ \text{eV},$$

mainly for two reasons. First, the cross section is expected to be relatively high, and second, a high-quality intense ion beam has been available.

The ion beam which is delivered by the LAGRIPPA accelerator has a kinetic energy of 20 keV per charge. Before entering the interaction region it is focused with the aid of a double Einzel lens to a beam diameter of 2 to 3 mm. The ion current is measured with a Faraday cup in a separate vacuum chamber. This turned out to be necessary in order to allow for a differential pumping system and to reduce the noise caused by the ion beam. During the actual measurements the electrical ion current has been of the order of 10 μA.

At an electron energy of $E_0 = 100$ eV the electron-beam diameter in the interaction zone is about 1.5 to 2 mm and the half-width of its energy distribution is below 500 meV. Because of an important background arising mainly from scattering on metallic surfaces the electron current had to be kept at a value of about 4 μA.

For optimizing the overlap of both beams and the zone seen by the spectrometer, the positions of the electron and ion beams have been adjusted with the aid of two pairs of deflection plates. The optimum setting is controlled by a removable aperture, which can be positioned directly at the desired interaction region. Furthermore, the elastic electron-ion signal is used for a final adjustment.

The electron energy is determined with a double-stage cylindrical energy spectrometer the position of which can be varied between 13° and 29°. With an entrance aperture of 1 mm×2 mm, a solid angle of 4×10^{-4} sr is covered. The acceptance angle of the spectrometer is $\pm 0.4°$, leading, together with the finite interaction volume, to an angular resolution of about 1°. The energetic resolving power of this system is of the order of 50 depending on the exact size of the interaction volume and the scattering angle. In order to guarantee good vacuum

conditions and to obtain an effective shielding of the spectrometer, a negatively biased double mesh shielding is used.

The main difficulty in such an experiment is caused by the low target thickness. The target ion-beam density is as low as 10^6 particles per cm^2 which corresponds to a gas pressure of 5×10^{-11} Torr. Thus, the measurement requires the residual gas pressure to be at least of the same order of magnitude. Under the present conditions the expected ion excitation counting rate is estimated to range between 0.1 and 1 count per s whereas the total background which is due to the interaction of the primary electron beam (10^{13} electrons per s) with the residual gas has been estimated to be of the order of 10^6 events per s. In addition, contributions from the ion-gas interaction and the electron-surface scattering make the situation even worse. To achieve a successful measurement under such conditions it has been crucial to satisfy the following points.

(1) A differential pumping system provides a base pressure of 3×10^{-11} Torr, which increases to 1×10^{-10} Torr with both beams in operation.

(2) A chopping technique has been applied to both beams. The energy distribution of the scattered electrons has been measured for four different conditions, namely, with both beams in operation, with both beams off, and alternatively with only one of the two beams working. During the analysis of these spectra the slight increase (15%) of the background pressure in the case of the ion beam being on had to be taken into account.

(3) Because of the finite velocity of the ion beam the peak which is due to the elastic electron-ion scattering appears in the laboratory frame at an energy higher than that for the elastic scattering from the residual gas, i.e., in a part of the energy spectrum free of any electronic noise. Correspondingly, by a proper adjustment of the accelerating ion voltage it is possible to position the desired inelastic electron-ion peak in a region of the energy spectrum where the background is low. This is demonstrated in Fig. 1, which shows the energy distribution of electrons scattered at an angle of 24,°. For an electron energy of 100 eV, an Ar-ion-beam energy of 140 keV, and a scattering angle of 24°, one obtains an energy shift for the elastically scattered electrons of about 12 eV. Therefore, this well separated peak can be measured with high accuracy and can be used to normalize the inelastic signal.

Under these conditions typical counting rates, which depend strongly on the scattering angle and the range of the energy spectrum, are as follows: excitation signal rate, 0.02–0.3 count/s; elastic electron-ion signal, 1–250 counts/s; background by the ions, 0.1–5 counts/s; and background by the electrons, 0.1–20 counts/s. The collection time for one data point was of the order of several hours up to one day. Further details on the experimental setup as well as on the procedure being applied in evaluating the measured data will be given in a forthcoming paper [9].

The quantity actually being measured in the experiment is the ratio of the two signals which are due to the inelastic and elastic electron-ion scattering, respectively. Figure 2 shows this ratio for the excitation of the first excited state $3p\,^2P$ (the substates $3p\,^2P_{1/2}$ and $3p\,^2P_{3/2}$ separated by 0.3 eV are not resolved) at an electron energy of 100 eV and at scattering angles between 14° and 29°. The ratios are found to be of the order of 10^{-2} to 10^{-3}, thus allowing for a calculation using perturbation theory to which the experimental values are compared.

In the present case the energy of the incoming electron is about 6 times the transferred energy and the transition

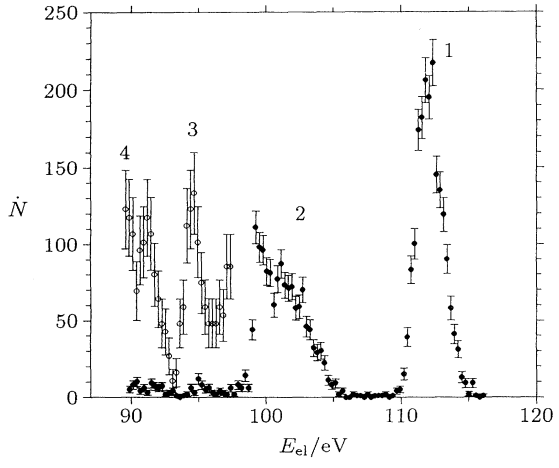

FIG. 1. Energy distribution of electrons being scattered at an angle of 24° by Ar^{7+} ions and by the background gas. Primary electron energy: 100 eV. 1, Elastic electron-ion signal; 2, elastic scattering by the residual gas; 3, signal due to the $3s$-$3p$ excitation; 4, inelastic electron–residual-gas scattering.

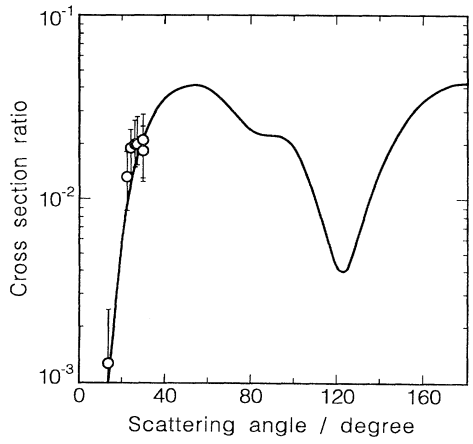

FIG. 2. Ratio r of differential cross sections for the inelastic and elastic scattering of electrons by Ar^{7+} ions. $r=(3s\rightarrow 3p$ excitation signal)/(elastic signal). Experiment: open circles; theory: solid curve. Electron energy: 100 eV.

involves the $3s$-$3p$ valence-particle dipole excitation. This makes it legitimate to carry out the calculations of the transition matrix element in first-order perturbation theory. The distorted-wave approximation provides such a framework. The single-particle wave functions of the target are calculated in the frozen-core Hartree-Fock potential. Two different distorting potentials for the incoming and outgoing electron waves have been considered: first a pure Coulomb potential due to the ion charge (7+), resulting in the so-called Coulomb-Born approximation, and second, a screened potential. This screened potential is taken to be the Hartree-Fock potential built by the total charge distribution of the core plus one valence electron ($3s$ and $3p$ in the entrance and exit channels, respectively). The same potential has been used to calculate the elastic cross section.

The first important observation is that the restriction to pure continuum Coulomb waves represents an excellent approximation in the angular range of the present experimental interest. Moreover, exchange contributions may safely be neglected. These are not surprising results because of the strong ionic charge. Note that an agreement within about 20% is observed between measured and calculated ratios.

The excitation cross section has been calculated over the entire angular range. As illustrated in Fig. 3 the electron screening of the nuclear charge need not be considered for scattering at angles below 70°. For backward angles, electon mean-field effects on the continuum wave functions do lead to dramatic changes of the inelastic cross section. Note, however, that exchange corrections at this high energy are still negligible. These features are also true for elastic scattering; forward elastic scattering is simply given by the classical Rutherford formula. These theoretical calculations support our experimental strategy. For forward scattering it is well justified to extract the differential excitation cross section by multiplying the measured ratio of Fig. 2 with the e^--Ar^{7+} Rutherford cross section calculated at the same angle.

The experimental excitation cross sections are shown in Fig. 4 together with our theoretical predictions. The given error bars correspond to the statistical errors calculated from the counting rates and the subtraction procedure. A further error is introduced by normalizing to the elastic scattering signal, which requires the exact knowledge of the scattering angle. This is determined from the kinematic shift of the elastic electron-ion signal with an accuracy of 0.5°. This uncertainty leads to an additional error of the determined cross section between 6% and 15%.

It is interesting to note that the cross section shows a maximum at a quite large angle of about $\Theta_{max}=23°$ and that it falls off very rapidly towards 0°. Indeed, this behavior is also predicted by a semiclassical approach. Describing the motion of the free electron by a classical Coulomb trajectory and treating the excitation process in first-order perturbation theory, one finds the excitation cross section to peak approximately at the same scattering angle with a similar absolute value [10].

The physics involved in this result becomes comprehensible when assuming that a highly polarized excited state is formed at the scattering angle Θ_{max} after a $\Delta m=+1$ transition. This implies that the exciting electron has to transfer in a sudden process at the distance of closest approach, r_0, one unit of angular momentum to the atom. Therefore, the classical trajectory has to fulfill the condi-

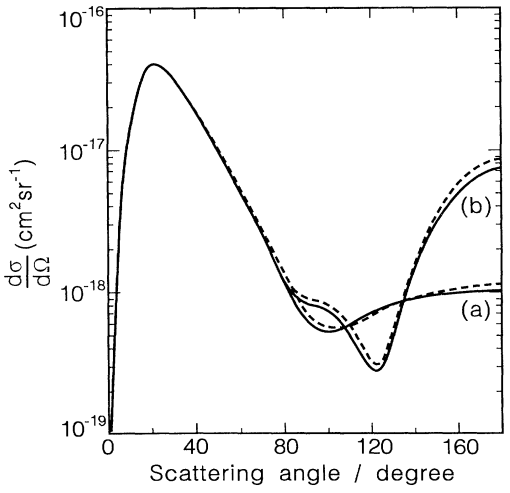

FIG. 3. Differential cross section for the $3s$-$3p$ excitation of Ar^{7+} by electron impact. Electron energy: 100 eV. Curves *a*, Coulomb-Born calculation; curves *b*, Hartree-Fock wave calculation: with electron exchange, dashed curves; without electron exchange, solid curves.

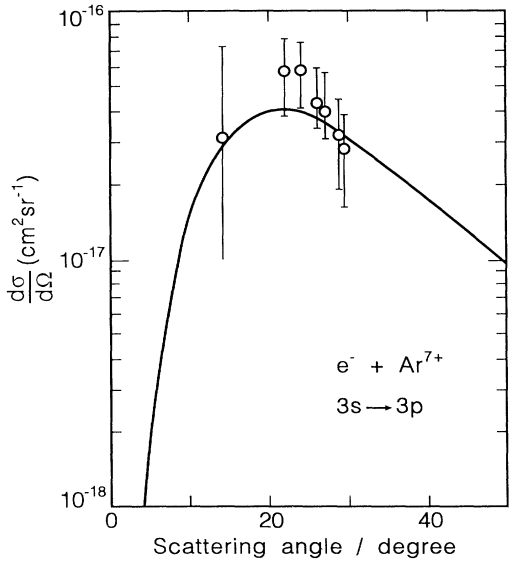

FIG. 4. Angular differential excitation cross section for the resonant $3s$-$3p$ transition in Ar^{7+}. Electron energy: 100 eV. Experiment: open circles; theory: solid curve.

tion $h/2\pi = r_0 \Delta p$. The momentum transfer Δp and the excitation energy ΔE are related by $\Delta p = \Delta E / v$, where v is the average electron velocity before and after the excitation. This condition yields indeed a scattering angle of 23° when dividing the classical trajectory into an incoming part at the energy E_0 and an outgoing part at $E_0 - \Delta E$.

This study has demonstrated the importance of large scattering angles contributing to the electon-impact excitation of multiply charged ions. Thus, in the near future our experimental setup will be modified in order to cover a larger angular region. At large angles the Coulombic force is no longer dominant and effects due to the ionic core can be studied in comparison with our calculation. Recently, close-coupling and distorted-wave calculations have been performed by Pindzola *et al.* [11] which show a very good agreement with our own theoretical results over the entire angular region.

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