Electron-Impact Ionization of Fe^{15+} Ions: An Ion Storage Ring Cross Section Measurement

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We report the first electron-impact ionization experiment employing an ion storage ring. Absolute cross sections for Na-like Fe^{15+} ions were measured at energies between 450 and 1030 eV with a precision and energy resolution unprecedented for highly charged ions. Breit-Pauli distorted-wave calculations accompanying the measurements and previous Dirac-Fock distorted-wave data are in substantial agreement with the magnitude and the general appearance of the measured cross sections but do not reproduce all details of the rich structure seen in the experiment.

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Ionization in electron-ion encounters is one of the most fundamental atomic collision processes. Its importance for all kinds of plasmas has stimulated theoretical and experimental studies since the first systematic investigations of gas discharge phenomena 100 years ago [1,2]. Regarding collisions with electrons the ion that has received particular attention over the last 15 years is $Fe^{15+}(1s^2 2s^2 2p^6 3s)$ [3]. Iron is an abundant element in the solar corona and in fusion plasmas. This fact together with the relatively simple structure of sodiumlike iron with only one active electron has made Fe^{15+} a testing ground for theoretical calculations of electron-impact ionization [4–10].

The net production of Fe^{16+} in $e + Fe^{15+}$ collisions can proceed via several different mechanisms. Besides the direct ionization (DI) of the outer electron, important contributions to the ionization cross section are due to inner-shell excitation with subsequent autoionization (EA) [4,5]. A perplexing additional indirect ionization process was postulated for Fe^{15+} by LaGattuta and Hahn [7]. It involves dielectronic (i.e., resonant radiationless) capture of the incident free electron with simultaneous excitation of an inner-shell electron of the ion and subsequent sequential emission of two electrons. This three-step mechanism was termed resonant-excitation double autoionization (REDA). Naively, such a high-order process would be expected to be negligible compared to DI and EA. However, by using the semiempirical Lotz formula [11] for DI, and crude estimates for EA and REDA, LaGattuta and Hahn predicted the REDA contribution to even dominate the total ionization cross section of Fe^{15+} ions at certain energies. This provoking prediction stimulated extensive efforts in both theory and experiment to establish the REDA process and to assess the importance of indirect mechanisms in electron-impact ionization including resonance formation [3].

It was not until 1987, however, that a first experiment with ions as highly charged as Fe^{15+} became possible. By using an electron-cyclotron-resonance ion source Gregory *et al.* [12] were able to measure ionization cross sections of Fe^{15+} employing well established crossed-beams techniques. Intensity problems, however, did not allow them to see unambiguous evidence for the REDA mechanism. Other attempts to see resonant contributions in the ionization of multiply charged Na-like ions, particularly of Ar^{7+} [13], Ti^{11+}, and Cr^{13+} [14], also failed.

Following the first measurements on Fe^{15+} by Gregory *et al.* [12], the theoretical predictions of LaGattuta and Hahn [7] were reexamined using more sophisticated multiconfiguration distorted-wave [8] and close-coupling [9] methods. The distorted-wave calculations did not include REDA, but the agreement of theory within the large error bars of experiment indicated that the REDA contribution was not as large as first predicted. The close-coupling treatment by Tayal and Henry [9] included the REDA process, but did not find large resonance enhancements of the ionization cross section. A year later, a multiconfiguration distorted-wave calculation was carried out by Chen, Reed, and Moores [10], including a comprehensive treatment of the REDA cross sections. They found that the REDA process contributed about 30% to the average total ionization cross section and provided a detailed map of resonance structures as a challenge to further experimental efforts.

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Although the REDA mechanism could be demonstrated in experiments with ions in low charge states q between 1 and 6 [15–17], and although the crossed-beams approach was successfully used also in precision experiments with Na-like Mg^+ [18,19], the presence of increasingly huge backgrounds in the ionization signal channel made it impossible to study more highly charged members of the sodium isoelectronic sequence by the same experimental techniques. The origin of these backgrounds was traced back [20] to ion-beam contaminations by metastable autoionizing Na-like ions with $2p^5 3s3p$ configurations which can survive the μs flight to the collision region. Little hope was therefore left to ever resolve the Fe^{15+} issue by the conventional crossed-beams techniques.

With the advent of heavy ion storage rings, however, an entirely new approach to the problem has become feasible. The two main drawbacks of previous measurements with multiply charged sodiumlike ions—the low signal rate and the high background due to decaying metastable ions—can be circumvented by using a storage ring equipped with an electron cooler. Thus, even within short storage times of the order of only 1 s before the measurement, practically all metastable ions in the injected beam decay, which avoids the background problems inherent in the previous small-scale colliding-beams experiments. Furthermore, signal rates are substantially enhanced as compared to conventional experiments; by the accumulation of ions in the ring currents of the order of hundreds of μA are easily reached, and the electron cooling device provides a dense cold electron target for the circulating ions with a merging path of typically 2 m, exceeding the interaction lengths available in conventional experiments by 2 orders of magnitude. In addition, electron cooling in a storage ring produces ion beams of excellent quality. Together with the low energy spread in the electron beam this results in unprecedented energy resolution in electron-ion collision experiments with observed energy spreads as low as 25 meV at low center-of-mass energies.

For these reasons, we have used the Heidelberg storage ring TSR to measure electron-impact ionization of $^{56}Fe^{15+}$ ions stored at a beam energy of 300 MeV. As in previous recombination measurements [21] at the TSR the cooling device served as an electron target in a merged-beams geometry. By variation of the cathode voltage the electron-ion impact energy was set between 450 and 1030 eV (electron-ion center-of-mass frame). This range covers the ground-state ionization threshold and the energies corresponding to the most important EA and REDA cross section contributions.

With an ion detector mounted on the inner side of the ring behind the first dipole magnet downbeam from the electron cooler we recorded the number N of ionized Fe^{16+} ions in time intervals Δt while the energy of the cooler electron beam was scanned in small steps with intermittent phases of injection of new ions and subsequent cooling. At the same time the electrical ion current I_i in the ring was recorded as well as the electron current I_e and the relevant gate time Δt of the scalers. Absolute cross sections σ were determined from the relation

$$\sigma = \frac{qe^2 NA v_i v_e}{\Delta t L I_i I_e |v_i - v_e|} . \tag{1}$$

Here, $q = 15$ is the incident ion charge, e is the electron charge, A the cross section area of the electron beam, v_i the ion velocity, v_e the electron velocity, and L the interaction length of electron and ion beams. Homogeneous electron density in the cooler beam is assumed, as justified by previous storage ring experiments [21].

For the cross section measurements the electron cooler was switched back and forth between a fixed energy, where a reference count rate was determined, and continuously increasing energies covering the complete scan range in up to 1250 steps, each step taking only ≈20 ms. By this technique slow fluctuations of experimental conditions are averaged out, and relative uncertainties from one cross section to the next can be made very small. Thus, the technique is particularly well suited to measure fine details and structures in the ionization cross section. The ionization detector registered a high background of about 300 kHz arising from Fe^{16+} ions produced by electron stripping in the residual gas, while the true ionization signal (the count rate difference with respect to the reference energy below the ionization threshold) was less than 40 kHz. About 13 h of data recording yielded ±0.5% statistical uncertainties of the ionization cross section in the interesting energy range. The residual-gas-induced background showed a remaining fast variation correlated with the switching of the electron beam energy. The effect on the signal count rate of this background modulation, increasing smoothly with the electron beam energy, was corrected for by using the two-electron-stripping signal (of Fe^{17+} ions) as a monitor of the residual-gas pressure modulation. No additional structure in the cross section energy dependence was introduced by this effect. The subtracted correction amounted to ≈10% of the true ionization signal and introduced an uncertainty of ≈ ±2%. An additional correction had to be made to account for contributions to the signal channel from the regions of the interaction path where the electron beam is bent onto and away from the ion-beam axis, respectively. With an increasing angle between the electron and ion-beam trajectories the center-of-mass energies increase, and, correspondingly, a small fraction of the high-energy ionization cross section is smeared into the region of lower energy. This correction was deduced from the measured energy dependence of the ionization signal and the distribution of electron-ion center-of-mass energies resulting from the known spatial distribution of the magnetic field which guides the electron beam. It amounted to 35% at energies just below the EA threshold but was less than 20% in the range of the REDA resonances. The uncertainty of the final experimental cross section due to this correction is estimated to be about ±15%. This was added to the other systematic uncertainties related predominantly to the detector efficiency and the measurement of particle currents. The total (quadrature-sum) systematic uncertainty of the ionization cross sections σ is estimated to be ±20%. In the present center-of-mass energy range the experimental energy spread can be represented by $\Delta E = 0.17\sqrt{E}$ where both ΔE and E are in eV. The uncertainty of the absolute energy calibration is less than 5 eV in this energy range.

In support of the ion storage ring experiment the previous multiconfiguration distorted-wave calculations of Griffin, Pindzola, and Bottcher [8] were extended, in a manner described by Badnell and Pindzola [22], to include REDA contributions. Radiation damping is fully included but interference between the three main ionization processes (DI, EA, and REDA) is ignored. The main difference between the previous distorted-wave calculations of Chen, Reed, and Moores [10] and the present distorted-wave calculations is that the former are based on a fully relativistic Dirac-Fock Hamiltonian while the latter are based on a semirelativistic Breit-Pauli Hamiltonian. The choice of Hamiltonian, however, should make little difference for a moderately charged ion like Fe^{15+}. The differences in the two calculations are more probably attributable to choices of configuration-interaction and reaction pathways for the thousands of resonances present.

Our experimental results are shown in Fig. 1 by the solid dots. Within total error bars they agree with the data of Gregory *et al.* [12] (open circles). Relative uncertainties of the present measurements are about a factor of 40 lower than those of the previous work and the density of the data points clearly reveals the rich structure caused by EA steps and REDA peaks in the cross section function.

Between the threshold of direct outer-shell ionization at 489 eV and the onset of EA processes at about 710 eV the ionization cross section rises to $\approx 5 \times 10^{-20}$ cm^2. The Lotz formula [11], which can describe only the direct process, is in excellent agreement with the measured cross section in this energy range. Above 710 eV the cross section rises by about a factor of 5 within a narrow energy span of little more than 100 eV. Obviously, the indirect ionization mechanisms dominate the ionization cross section of Fe^{15+} ions at energies above 800 eV.

The present data allow for the first time a detailed comparison of theory with experiment for a highly charged Na-like ion. Figure 2 shows the experimental data in the energy range 680 to 1030 eV together with the present theoretical calculations (dotted line) and the previous calculations of Chen, Reed, and Moores [10] (dashed line). Although the theoretical results are in good agreement with the overall magnitude of the experimental cross section, they disagree with each other and with the experiment with respect to the fine details of the ionization spectrum.

The major differences between theory and experiment, and indeed between different theoretical results, arise in two ways. First, the REDA cross section sits on a rapidly varying EA contribution. Second, there are contributions from many different resonance series. Small uncertainties in the energy position of the different autoionizing levels, and hence the resonances attached to them, can give rise to large differences in the superposed results. The main omission from the present calculations, and those of Chen, Reed, and Moores [10], is due to the use of the independent processes and isolated resonance approximations. The interference between EA and REDA is expected to be small [23]. However, the effect of interacting resonances can be significant, changing the resonance peak heights by a factor of up to 2 [24].

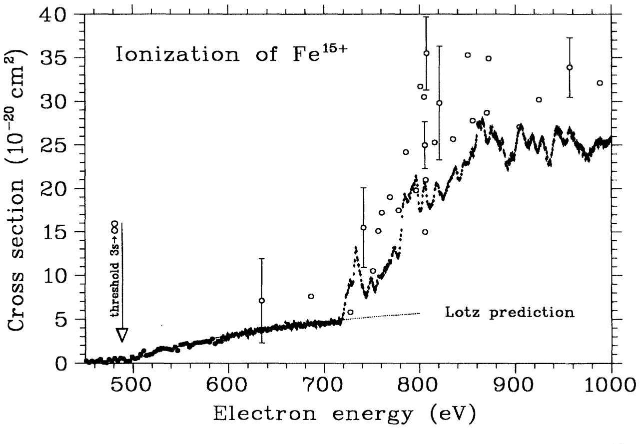

FIG. 1. Cross sections for electron-impact ionization of Fe^{15+} ions. Present data are indicated by solid dots, measurements of Gregory *et al.* [12] by open circles. In both cases statistical error bars are given. The threshold of ground-state ionization is marked by an arrow. The dotted line represents the Lotz formula [11] for direct single ionization.

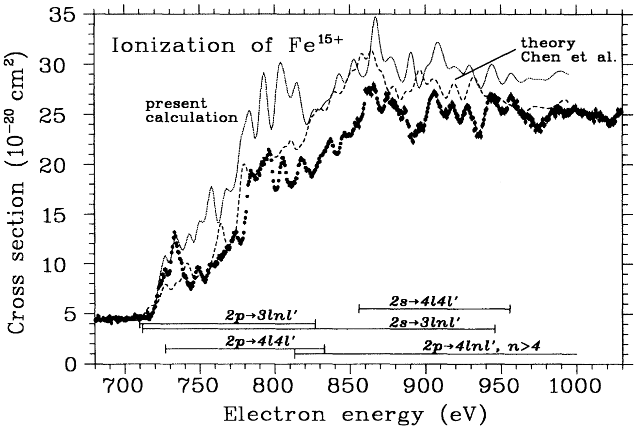

FIG. 2. Expanded view of present experimental cross section data from Fig. 1 and theoretical results. The present calculation using the Breit-Pauli distorted-wave method [22] is the dotted line, the Dirac-Fock distorted-wave theory of Chen, Reed, and Moores [10] is shown by the dashed line. Energy ranges of the most important REDA contributions are marked by horizontal bars.

In summary, we report on the first ionization experiment carried out at a heavy ion storage ring. The debate about the influence of resonant processes on the electron-impact ionization cross section of Fe^{15+} has been resolved by a precision measurement which reveals the rich structure in the cross section due to resonant and nonresonant inner-shell excitation processes. The comparison of the experimental data with theoretical calculations shows remarkable agreement in the overall size and the gross features of the cross sections, but it also reveals the difficulty to predict the fine details arising from the presence of indirect ionization mechanisms.

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