Superelastic Scattering Of Electrons From Highly Charged Ions With Inner Shell Vacancies

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We report the measurement of electrons scattered superelastically from highly charged ions having an initial K-shell vacancy. In this process, the scattered electron gains ~725 eV of energy from the deexcitation of an excited He-like $F^{7+}(1s2s\,^3S)$ metastable ion to its ground state. Theoretical calculations based on an R-matrix approach agree well in position, shape, and magnitude with the experimental data.

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In collisions between electrons and excited atomic systems, it is well known that electrons can be scattered elastically or inelastically. A particularly interesting phenomenon occurs, however, when electrons are scattered from an initially excited atomic system in such a way so as to receive an energy "boost" while simultaneously deexciting the parent system. An electron that gains energy as a result of a collision is said to be *superelastically* scattered. Superelastic electron scattering is the time-reversed equivalent of inelastic electron scattering, i.e., electron impact excitation of ions, where the incident electron loses energy in the interaction. Then, from the principle of detailed balance, superelastic electron-deexcitation cross sections can be obtained from inelastic electron-excitation cross sections.

In order to observe electron superelastic scattering, an atomic system must be prepared in an excited metastable state. Futhermore, for scattering to take place, the excited atomic system must have a sufficiently long lifetime to permit the interaction.

With the advent of tunable dye lasers it has become possible to prepare atoms in selected fine and hyperfine excited metastable states, thereby making possible the study of the deexcitation of these states by means of electron scattering. Williams *et al.* [1] reported the first experimental observation of superelastic scattering of free electrons from positive ions. In this work, the collisional quenching of the $C^+(1s^2 2s 2p^2\,^4P)$ state at an excitation energy of 3.5 eV was observed.

There are a few investigations of electron superelastic scattering from excited states that cannot be readily produced by single-photon laser excitation. Jacka *et al.* [2] investigated the angular dependence of electrons superelastically scattered from the $He(1s2s\,^3S)$ metastable state at incident energies of 10 and 30 eV. The deexcitation of this excited state to the $He(1s^2\,^1S)$ ground state corresponds to the time-reversed process of electron-impact excitation with electron exchange. A similar time-reversed process was observed by Bannister *et al.* [3] in the near-threshold excitation of the $4s^2\,^1S \rightarrow 4s4p\,^3P$ intercombination transition in Kr^{6+}, where resonance structures were observed in the total electron-impact excitation cross section.

In this Letter we report the observation of superelastic scattering of quasifree, i.e., weakly bound, target electrons from $F^{7+}(1s2s\,^3S)$ metastable projectile ions. The approximation of quasifree electrons is valid when the projectile velocity is much larger than the orbital electron velocity in the light target atom or molecule (H_2 in this case). In the rest frame of the projectile ions, loosely bound target electrons, with an average incident velocity equal to the velocity of the ion beam in the laboratory frame, are scattered from the ion. If the effect of the target nucleus is neglected, the ion-atom collision interaction closely approximates an electron-ion scattering process, where the initial energy distribution of the impinging electrons is determined by the Compton profile of the target.

The reaction studied here can be written as

$$F^{7+}(1s2s\,^3S) + e^-(E_0) \rightarrow F^{7+}(1s^2\,^1S) + e^-(E_1), \quad (1)$$

where E_0 is the initial electron energy and E_1 is the final electron energy. The superelastically scattered electrons ($E_1 > E_0$) exit the collision region with an energy ~725 eV greater than the incident electron energy, as compared to previous laser excited atomic targets, where the energy gain resulting from superelastic scattering was only on the order of a few eV due to the intrashell transition.

The energetics of the electron superelastic scattering is shown in the fluorine 3-electron energy diagram depicted in Fig. 1 and labeled as NRS (nonresonant superelastic). The time reversal of this process is the electron inelastic scattering and can be visualized by reversing the arrows in the nonresonant process. Also shown in Fig. 1 is the nonresonant elastic scattering from the metastable state. Direct and resonant elastic scattering and inelastic scattering from ground state ions have been observed. Studies of resonances in elastic electron scattering cross sections have been reported under the name of resonant-transfer excitation with Auger emission [4], while Hvelplund *et al.* [5], Toth *et al.* [6], and Zavodszky *et al.* [7] studied the resonant inelastic scattering of quasifree electrons from H-like projectile ions.

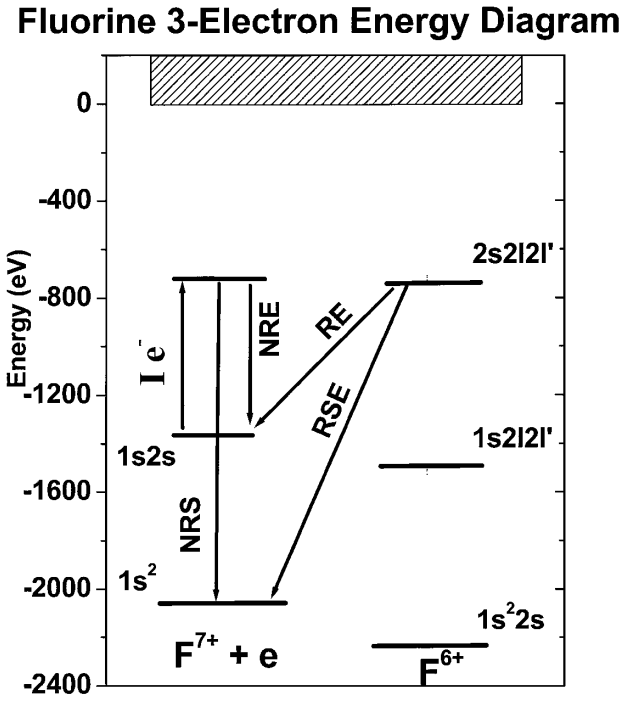

FIG. 1. A fluorine 3-electron energy diagram is given. Ie^- is the incident electron. The deexcitation process of interest for this experiment is labeled NRS, nonresonant superelastic. NRE is nonresonant elastic, RE is resonant elastic, and RSE is resonant superelastic.

The dominant superelastic electron scattering process is expected to be a "hard" binary encounter involving electron exchange in which the excited metastable ion gives its $2s - 1s$ excitation energy to the outgoing electron and the residual ion is left in its ground state. Also, resonant excitation and subsequent deexcitation can give rise to superelastic electron scattering via the formation of triply excited states, e.g., $F^{6+}(2s2l2l')$, as shown in Fig. 1. The resonance can decay back to the metastable $(1s2s\,^3S)$ state [labeled RE (resonant elastic)] or to the ground $(1s^2)\,^1S$ state [labeled RSE (resonant superelastic)]. In the latter case, the triply excited states must decay by the simultaneous deexcitation of *two* electrons accompanied by the emission of an Auger electron with higher energy than the incoming electron in the excitation part of the process. This latter type deexcitation process was observed by Afrosimov *et al.* [8]. Superelastic scattering resulting from the cooperative deexcitation of two electrons from triply excited states is expected to be much less probable than from binary collisions since the former requires a correlated 3-electron transition.

The experiment was carried out using the Kansas State University EN tandem Van de Graaff accelerator. Fluorine ions were accelerated to 20.7 MeV (1.1 MeV/u) and analyzed with a 90° magnet. Analyzed F^{4+} ions were stripped to higher charge states by a 5-μg/cm^2 carbon poststripping foil. After stripping, the desired charge state beam component was magnetically separated and focused into the target chamber located approximately 13 m from the carbon stripper foil.

It is well known that He-like ion beams produced in a tandem Van de Graaff accelerator contain a long-lived $1s2s\,^3S$ metastable component due to the stripping process that is used to produce the desired charge state [9]. The production of a significant fraction of metastable $1s2s\,^3S$ ions can be exploited to investigate the superelastic scattering of quasifree electrons by colliding the ions with a light target such as H_2 or He, for which each of the electrons is weakly bound. In the experimental arrangement used, more than 99% of the metastable $F^{7+}(1s2s\,^3S)$ ions (lifetime = 275 μsec as reported in Ref. [10]), produced in the stripper foil at 20.7 MeV, reached the target. From the measurements of Terasawa *et al.* [9], it is estimated that the $F^{7+}(1s2s\,^3S)$ metastable beam fraction for this paper was about 30%.

The target consisted of H_2 gas under sufficiently low pressures to fulfill single collision conditions (less than 50 mTorr in the 10-cm-long differentially pumped gas cell). Electrons emitted from the collision at 0° in the laboratory frame were energy analyzed by using a tandem 45° parallel-plate electron spectrometer, which had an energy resolution of 2.8% [11]. The ion beam was collimated by two sets of slits and apertures, and scattered electrons were removed before reaching the target cell with a weak transverse electric field. The transmitted ions were collected in a Faraday cup and used for normalization. The absolute efficiency of the electron spectrometer was determined by normalizing to the binary encounter electron scattering peak for a F^{9+} beam, and using a Rutherford scattering model [12].

Figure 2 shows the measured and calculated double differential cross section (DDCS) for F^{6+} and F^{7+} projectiles. The F^{6+} spectrum is used as a control, since it contains no electron superelastic scattering. The calculations include only the nonresonant elastic scattering of the quasifree electrons. In the experimental spectrum, at the top of the binary encounter peak, the resonant elastic scattering to doubly excited states from ground state F^{6+} and F^{7+} ions is seen. The Compton profile for the H_2 target used in the calculations was experimentally determined by Lee [13]. The experimental DDCS is larger than the theoretical calculation on the low-energy side of the binary encounter peak due to the tail of the cusp electrons produced by electron capture to the continuum or electron loss to the continuum processes. On the high-energy side of the binary encounter peak there is fairly good agreement between theory and experiment. To see more clearly any difference between the theoretical calculations and the experimental data, the DDCS's were plotted on logarithmic scales in Figs. 2(b) and 2(d). There are two differences to note. First, the theory is higher than the experiment starting from ~2800 eV, with a crossover at ~3600 eV. The most likely explanation for this difference is that the parametric form used for the Compton profile [13] does not describe correctly the momentum distribution of the electrons in the H_2 target for such distant values from the maximum. Second, for the F^{7+} data in Fig. 2(d), there

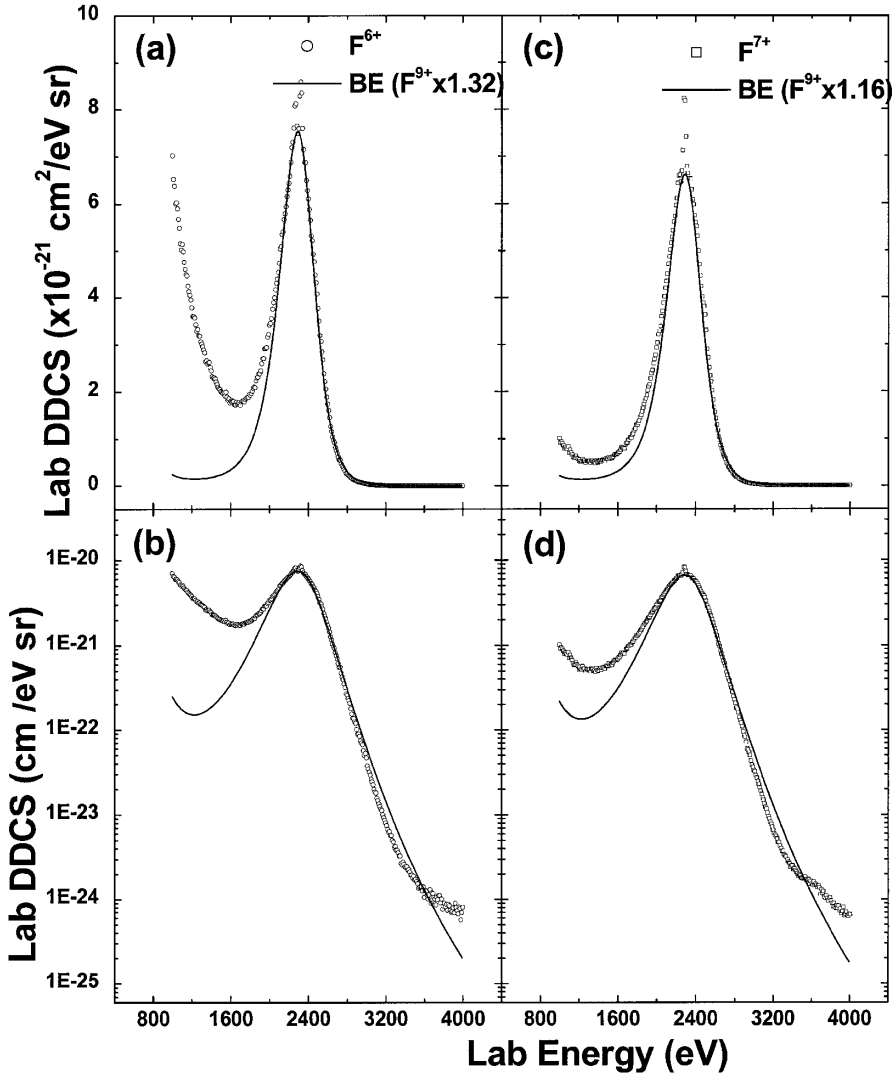

FIG. 2. The measured DDCS for F^{6+} + H_2 [(a) linear and (b) log plot] and F^{7+} + H_2 [(c) linear and (d) log plot] collisions are given. The binary encounter peak corresponding to electron-projectile elastic scattering occurs at ~2300 eV in the lab and the superelastic scattering occurs at ~3600 eV in the lab. The solid lines are a calculation of the electron elastic scattering.

is a small broad peak in the data, with a maximum at ~3600 eV, while the data for F^{6+} shown in Fig. 2(b), obtained under identical conditions, do not show this feature. This latter Li-like system is in the ground state at the interaction region, without any excited metastable component, and the data show only the well-known nonresonant and resonant elastic scattering peaks in the region of interest as expected.

In order to separate the elastic and superelastic scattering contributions to the DDCS, the data obtained for F^{6+} were normalized to the data obtained for F^{7+} projectiles. Figure 3 shows the high-energy part of the binary encounter peaks for F^{7+} and F^{6+} projectiles, after the two spectra were normalized. To normalize these data, the factor 0.87 was applied to the F^{6+} data. The need for the normalization factor arises from the fact that, as found by Richard *et al.* [14] for 1.0 and 1.5 MeV/u F^{q+} + He or H_2 collisions, binary encounter electron production

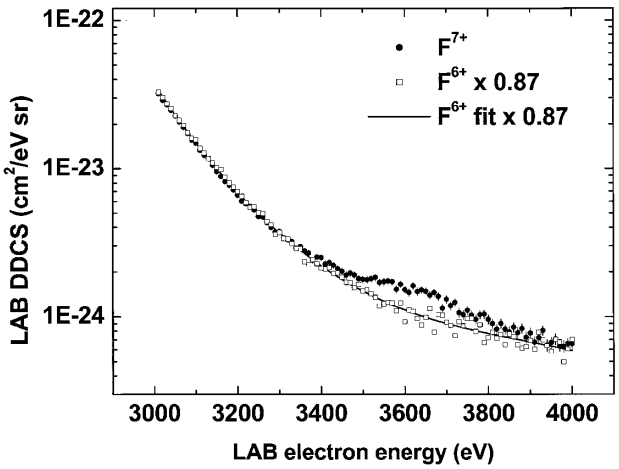

FIG. 3. The DDCS for F^{6+} normalized to the F^{7+} data at energies near 3000 eV are shown for comparison. The solid line is a polynomial fit to the F^{6+} data.

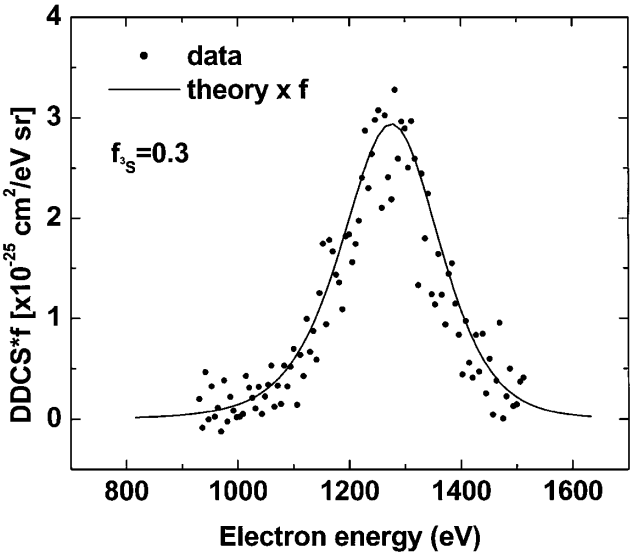

FIG. 4. The F^{7+} DDCS minus the fitted curve representing the F^{6+} DDCS [see Fig. 3] exhibits the superelastic scattering peak. The solid line is a theoretical calculation of the superelastic scattering assuming a metastable fraction of 0.3.

increases steadily with each electron added to the projectile, giving rise to a net antiscreening effect. Reinhold *et al.* [15] showed that this behavior can be explained in terms of the short-range, static screening produced by a non-Coulomb potential used to represent the target electron–projectile core interaction. The result is an enhancement of the elastic scattering of an electron from the statically screened projectile. Richard *et al.* [14] found that the ratio of the binary encounter peak obtained with F^{6+} and F^{7+} projectiles is 0.93 ± 0.09, in agreement with the normalization factor of 0.87, mentioned above.

The final result of this paper is presented in Fig. 4. After subtraction of the elastic scattering contribution for F^{6+} projectiles, and transforming the spectrum to the projectile reference frame, we obtained the DDCS for superelastic scattering of quasifree electrons from $(1s2s)\,^3S$ F^{7+} metastable ions. This figure also shows an R-matrix, 5-state-based theoretical [7] calculation for the same collision process. The calculation was done for the time-reversed nonresonant electron inelastic scattering process, and the principle of detailed balance was used to adapt the result to the electron superelastic scattering.

There is very good agreement in the position and shape of the experimental data and the theory. The superelastic peak is located at a position $\sim$725 eV higher than the average incident electron energy of $\sim$570 eV in the projectile frame. This energy value corresponds to the energy difference between the $1s2s\,^3S$ and $1s^2\,^1S$ states of F^{7+}. The shape of the nonresonant elastic scattering peak reflects the Compton profile of the target electrons. The theoretical calculation was performed for a 100% ^3S metastable F^{7+} beam. In order to compare with the experimental spectrum, the theory was multiplied by a factor of 0.3, corresponding to the expected metastable fraction of the F^{7+} beam used in the experiment [9].

In conclusion, we observed the superelastic scattering of quasifree electrons from $F^{7+}(1s2s)\,^3S$ metastable ions. The process is nonresonant and reflects the original momentum distribution (Compton profile) of the target electrons. Theoretical calculations for the time-reversed nonresonant inelastic scattering were used to obtain the superelastic scattering cross section using the principle of detailed balance. The agreement between the experiment and theory is excellent in both the position and the magnitude of the superelastic peak.

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