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Observation of Radiative Double Electron Capture for Fluorine Ions on Nitrogen and Neon

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Abstract.
The capture of two electrons accompanied by the simultaneous emission of a single photon (RDEC) has been investigated for 2.11 MeV/u fluorine ions (F^{8+} and F^{9+}) colliding with gaseous N_2 and Ne and upper limits on the cross sections are determined. The measurements were performed at Western Michigan University using the tandem Van de Graaff accelerator. Preliminary analysis indicates that the RDEC cross sections for F^{9+} for both targets are very close in magnitude and comparable to previously recorded cross sections for fully-stripped ions colliding with thin-foil targets. The states of observable RDEC capture are discussed, as well as future work.

1. Introduction

A fundamental ion-atom interaction that has been studied for more than four decades is radiative electron capture (REC) [1]. REC occurs when a single electron is captured from the target to the projectile ion with the simultaneous emission of a photon and is considered the ion-atom inverse of the well-known process of photoionization. The energy of the emitted photon is described as follows:

$$\mathrm{E_{REC} = K_t + B_p - B_t} + \vec{\mathrm{v}} \cdot \vec{\mathrm{p}}$$

where $\mathrm{K_t}$ is the kinetic energy of the target electron as seen from the projectile rest frame, $\mathrm{B_p}$ is the positive binding energy in the projectile, $\mathrm{B_t}$ is the positive binding energy in the target, $\vec{\mathrm{v}}$ is the projectile velocity vector, and $\vec{\mathrm{p}}$ is the momentum vector of the bound target electron. The $\vec{\mathrm{v}} \cdot \vec{\mathrm{p}}$ term represents the Compton profile [2] resulting in the broadening of the transition peak at that energy.

It is also possible for a projectile to capture two electrons with the simultaneous emission of a single photon. This process is termed radiative double electron capture (RDEC) [3] and is the ion-atom inverse of double photoionization. In the weak field regime, a single photon can interact only with a single electron, which, in turn, interacts with another electron causing both to be liberated. In the same way, for two electrons to be captured with the emission of a single photon, the electrons must interact with each other. This interaction is termed electron correlation and provides the basis for the fundamental interest of this study. The energy of the released photon is given by:

$$\mathrm{E_{RDEC} = 2K_t + B_p^1 + B_p^2 - B_t^1 - B_t^2} + \vec{\mathrm{v}} \cdot \vec{\mathrm{p}}^1 + \vec{\mathrm{v}} \cdot \vec{\mathrm{p}}^2$$

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where the terms are defined as before and the superscripts 1 and 2 refer to the electrons captured.

Several experiments performed using mid- to high-Z, high energy projectiles on thin-foil and gaseous targets [4][5][6] were unsuccessful. Theory suggested [7] that mid-Z, low energy projectiles should yield higher RDEC cross sections. This was the basis for the previous and current work performed at Western Michigan University (WMU). The first successful observation of RDEC was performed for 2.38 MeV/u O^{8+} + C [8]. This work was continued for 2.21 MeV/u F^{9+} projectiles colliding with thin-foil carbon [9]. The first measurements for 2.11 MeV/u F^{9+} + N_2 have been reported [10] and are continued here. First measurements for 2.11 MeV/u F^{8+} + N_2, as well as for 2.11 MeV/u F^{8+}, F^{9+} + Ne are also reported.

2. Experimental Procedure

This work was performed using the tandem Van de Graaff accelerator facility at WMU. A fully-stripped beam of 2.11 MeV/u F^{9+} (or F^{8+}) ions was directed into a differentially-pumped cell holding the target gas at a constant pressure [Fig. 1]. The pressures were set to have values in the single collision regime. A Si(Li) x-ray detector was placed at 90^{o} to the beam line to view the interaction region. After this the ion beam was charge-state analyzed using a dipole magnet. The singly and doubly charge-changed components of the ion beam were then measured with silicon surface barrier particle detectors. The main beam was collected using a Faraday cup and a negative bias supressed electrons ejected from the cup by the beam striking it. The x-ray and particle detector data were collected using an event-mode acquisition system to assign the measured x rays coincident with their respective charge-changed particles.

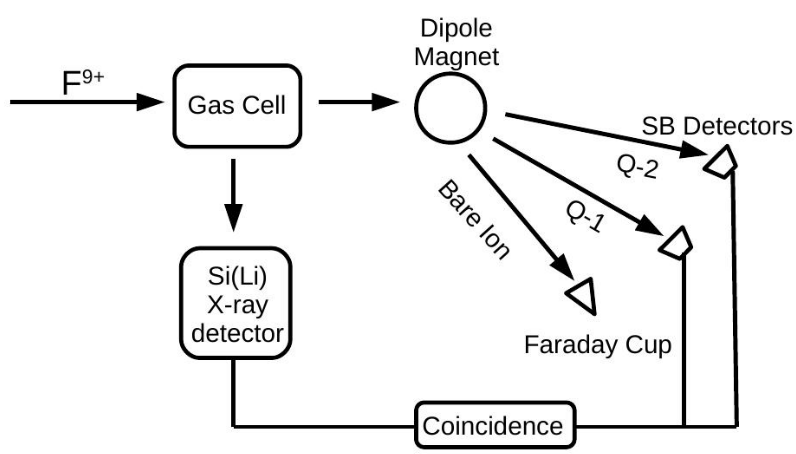

Figure 1. Schematic for the experimental setup at WMU. Following the collision chamber a dipole magnet separated the charge-changed ion beams. Detected x rays and particles were recorded in coincidence.

3. Results/Discussion

The doubly charge-changed spectra (Q-2) for 2.11 MeV/u F^{8+}, F^{9+} + N_2 and Ne are shown in Figures 2 and 3, respectively. The characteristic K x rays for F are prominent and can be seen in the large, low energy peak for both spectra. In Fig. 3, the Ne K x rays are also included in this peak. The gas cell was constructed of aluminum; therefore, Al K x rays due to the halo of the incident beam striking the cell can also be seen in the spectra. The REC and RDEC regions lie beyond this peak. The relevant parameters and data for the observation of RDEC are shown in Tables 1 and 2 for N_2 and Ne, respectively.

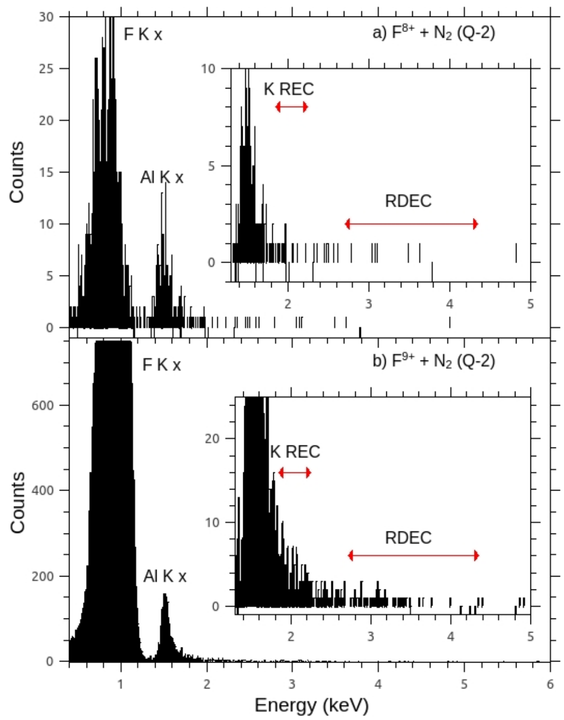

Figure 2. Doubly charge-changed coincidence spectra (Q-2) for 2.11 MeV/u (a) F^{8+} and (b) F^{9+} projectiles + N_2

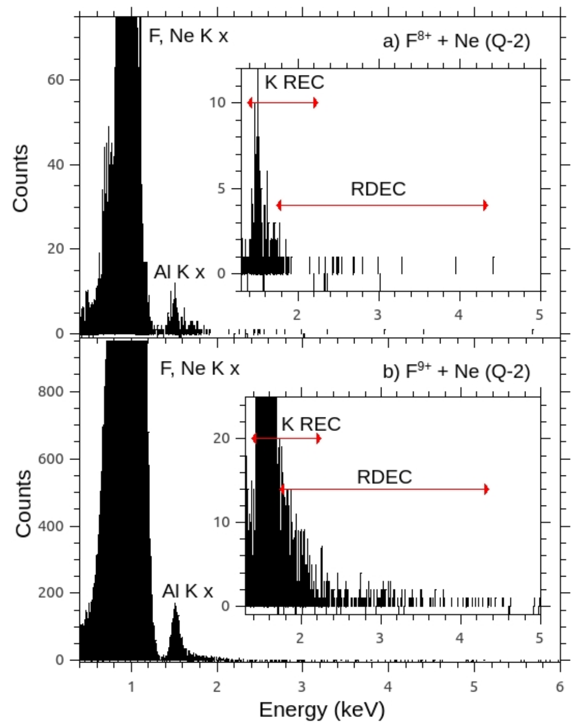

Figure 3. Doubly charge-changed coincidence spectra (Q-2) for 2.11 MeV/u (a) F^{8+} and (b) F^{9+} projectiles + Ne

Table 1. Parameters and data for 2.11 MeV/u F^{8+} and F^{9+} + N_2

N_2	F^{8+}	F^{9+}
Pressure	6 mTorr	6 mTorr
No. Incident Particles	1.51x10^{13}	2.30x10^{13}
No. RDEC Counts	∼10	∼79
$\frac{d\sigma_{\mathrm{RDEC}}}{d\Omega}(90^{o})$	∼0.120 barn	∼0.430 barn

Table 2. Parameters and data for 2.11 MeV/u F^{8+} and F^{9+} + Ne

Ne	F^{8+}	F^{9+}
Pressure	25 mTorr	15 mTorr
No. Incident Particles	5.24x10^{12}	1.41x10^{13}
No. RDEC Counts	∼18	∼100
$\frac{d\sigma_{\mathrm{RDEC}}}{d\Omega}(90^{o})$	∼0.130 barn	∼0.460 barn

The F^{9+} RDEC cross sections reported in this work are the same order of magnitude as those reported for O^{8+} and F^{9+} ions of similar energies in Refs. 8 and 9, with those in the present work being about a factor of two smaller. This is an indication that the measured cross sections are correct. However, the cross sections for F^{9+} are still about 50 times larger than those predicted by the recent theory of Mistonova and Andreev [11]. The reason for this discrepancy is not known at present.

The RDEC cross sections for F^{8+} + N_2 and Ne are a factor of about four smaller than those for F^{9+}. This result is due to the fact that for F^{8+} there is initially an electron in the projectile K shell, thereby disallowing the capture of both electrons to the projectile K shell. More data must be collected so that Compton profiles can be fit to the REC and RDEC transition peaks, thereby giving better accuracy in determining the cross sections.

Capture of the two electrons from the target K and L shells is possible but is not generally observed. This is most likely due to electrons in different shells having a low level of correlation compared to electrons in the same shell. Therefore, only capture of both electrons from the target K or the target L shell to the projectile K shell or the K and L shells is observed, a result that is consistent with those reported in Ref. 8. These energies are shown in Tables 3 and 4 for 2.11 MeV/u F^{9+} + N_2 and Ne, respectively. The REC and RDEC energy regions for Ne overlap, therefore creating difficulty in separating x rays from these processes.

Table 3. RDEC transition energies for 2.11 MeV/u F^{9+} + N_2

Transition	Energy (keV)
KK → KL	2.71
KK → KK	3.45
LL → KL	3.61
LL → KK	4.35

Table 4. RDEC transition energies for 2.11 MeV/u F^{9+} + Ne

Transition	Energy (keV)
KK → KL	1.73
KK → KK	2.47
LL → KL	3.61
LL → KK	4.35

4. Conclusion

RDEC has been investigated for F^{9+} (and F^{8+}) projectiles colliding with gaseous N_2 and Ne targets. Preliminary data provide results from which cross section estimates are calculated. Upper limits on the RDEC cross sections for N_2 and Ne targets have been determined. The cross sections for F^{9+} are comparable to previous experimental data for O^{8+} and F^{9+} projectiles incident on thin-foil carbon targets [8] [9], and are significantly larger than recent theoretical calculations [11]. The F^{8+} ions give cross sections that are about four times smaller than for F^{9+}. The F^{9+} data represents about three weeks of continuous beam time for each target (N_2 and Ne). It is estimated that a total of two months of continuous beam time will be needed to obtain reliable RDEC cross sections for each target and these measurements are now ongoing. In the future, work will also be undertaken for F^{9+} + He and thin-foil C.

Acknowledgments

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