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Electric field ionization of foil-excited Rydberg states of fast heavy ions

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The absolute yield of beam-foil-excited Rydberg states is measured, with the use of field-ionization techniques, for 125-MeV sulfur ions. The result, which agrees with a simple estimate, is compared with yields inferred from recent measurements of delayed K x rays.

In a recent Letter, Betz, Röschenthaler, and Rothermel[1] have presented measurements of the target-thickness dependence of delayed Lyman-α and Lyman-β yields for foil-excited sulfur ions. These authors point out that these results demonstrate that the long-lived Rydberg states which feed these transitions are not formed entirely by "last-layer" capture. It is the purpose of this Rapid Communication to report a direct measurement of the absolute yield of highly excited states of foil-excited sulfur ions. We further demonstrate that the measured absolute yields disagree with those assumed in Ref. 1.

The basic technique used here has been described in a previous publication.[2] 125-MeV S^{14+} ions were obtained from the Argonne tandem-Linac accelerator. The beam was collimated to 2 mm diam before striking a thin carbon target. The target thicknesses were 5 and 10- $\mu g/cm^2$. A small positive bias voltage (typically $\sim +200$ V) was applied to the target. Beginning 15 mm after the target a 10-cm-long pair of parallel electrostatic deflector plates were mounted to produce an electric field transverse to the beam direction. 126 mm after the exit of this deflector field, the beam entered a 45° parallel-plate electrostatic electron spectrometer (as described in Ref. 2). Upon exiting the spectrometer, the beam was stopped in a Faraday cup which was used to monitor beam intensity. The entire apparatus consisting of target, deflectors, and spectrometer was surrounded by magnetic shielding.

A typical electron energy spectrum, at 0° observation angle, is shown in Fig. 1. This spectrum resulted from bombardment of a 5-$\mu g/cm^2$ carbon target biased at +200 V.

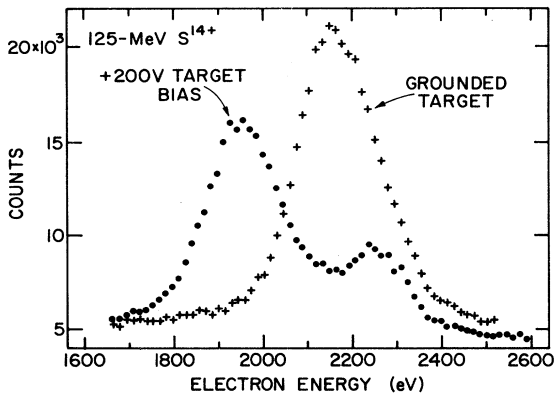

FIG. 1. Electron energy spectra at 0° observation angle for 125-MeV S^{14+} ions incident upon a 5-$\mu g/cm^2$ carbon foil. The spectrum with +200 V bias on target reveals the presence of high Rydberg atoms which are field ionized in the spectrometer. The resulting electrons form the peak which does not shift with target bias.

The post deflectors were removed to ensure that the electric field between the target and spectrometer was weak. Electrons originating at the target are lowered in energy by 200 eV. In particular, one sees the peak due to convoy electrons[3] is shifted to ~ 1930 eV. At an apparent energy of ~ 2250 eV, slightly higher than that corresponding to beam-velocity electrons (2132 eV), one observes a peak which has been identified previously.[2] This peak results from field ionization of high Rydberg atoms in the field of the electron spectrometer. Assuming the classical ionization threshold,[4]

$$F_c \simeq \frac{10^9 Z^3}{n^4} \text{ V/cm} , \tag{1}$$

then for a core charge of 15^+ we expect atoms with principal quantum numbers in the range $250 \lesssim n \lesssim 650$ to contribute to this peak. The upper limit arises from the weak field behind the target (~ 20 V/cm). The lower limit corresponds to the spectrometer field required to analyze beam-velocity electrons (~ 860 V/cm).

Those atoms which are ionized in the spectrometer field are detected with essentially 100% efficiency by use of an open electron multiplier tube. The efficiency of the detection system was confirmed with the use of a biased filament as a collimated monoenergetic source of electrons. The absolute yield per incident ion of Rydberg atoms is

$$Y_R = \sum_i N(E_i) \frac{\Delta E_i}{\epsilon E_i} \frac{\bar{q}e}{Q} , \tag{2}$$

where $N(E_i)$ is the number of counts obtained, after background subtraction, when the spectrometer is set to analyze electrons of energy E_i and the change in analyzed energy is ΔE_i for each step. The relative energy resolution of the spectrometer was $\epsilon = \delta E_i / E_i = 0.06$ (full width at half maximum). The total charge collected in the Faraday cup is Q and $\bar{q}e$ is the mean charge of the emerging ions. Based on the experimental data of Scharfer *et. al.*[5] we assumed $\bar{q} = 14.1$ for both 5- and 10-$\mu g/cm^2$ carbon foils. Using Eq. (2), we find $Y_R = (1.04 \pm 0.02) \times 10^{-5}$ and $Y_R = (1.17 \pm 0.02) \times 10^{-5}$ atoms/ion for 5- and 10-$\mu g/cm^2$ carbon foils, respectively. The errors quoted are statistical.

If these atoms are formed by a last-layer capture process, one would expect to observe a quantum state population per ion after the foil, $P(n)$, varying as n^{-3}.[6] With such an assumption, it is easy to show that the measured yield should be given by

$$Y_R = \frac{\sum_{n=250}^{650} n^{-3}}{\int_{n=250}^{\infty} n^{-3}\, dn} \frac{P(n=1)\sqrt{F}}{2(F_0 Z^3)^{1/2}}$$
$$= 1.35 \times 10^{-5} P(n=1) \left[\frac{F(\text{V/cm})}{Z^3} \right]^{1/2} , \tag{3}$$

where F_0 is the multiplicative constant (10^9 V/cm) given in Eq. (1) and F is the ionizing field. For the 5-μg/cm^2 target data, this formula gives $P(n) = (1.5 \pm 0.4) n^{-3}$. The principal contribution to the error is due to an assumed 50% uncertainty in the constant F_0.[7]

One can make a crude estimate of $P(n)$ using the cross section for capture of carbon $1s$ electrons by 125-MeV sulfur projectiles that is given in Ref. 1,

$$\sigma_c(1s \rightarrow n >> 1) \simeq 1.3 \times 10^{-16}\, n^{-3}\text{cm}^2 \ .$$

For high-velocity Rydberg atoms (ion velocity $>>$ Rydberg electron orbital velocity) the Rydberg electron is essentially free. The mean free path for collisional destruction for $n >> 1$ is therefore n independent and essentially given by the mean free path for free-electron scattering (λ_e).[8] For this case, $\lambda_e = (16 \pm 3)$ Å.[9] Combining these with the atomic density of thin carbon foils (0.1/Å^3) gives an estimated population $P(n) = (2.1 \pm 0.4) n^{-3}$ in excellent agreement with our experimental finding.

To compare this population to the delayed Lyman-α yield requires an estimate of the angular momenta l of the Rydberg states formed. Cascade calculations give values of $P(n) = (30 \pm 15) n^{-3}$ for a similar beam energy and target thickness.[10] This is a factor of 10–20 greater than the direct ionization results we find. This discrepancy is an indication of the inadequacy of such cascade calculations, particularly the n,l dependence of the assumed initial population. It is this large calculated yield which is in large part the basis of the argument which has been used against last-layer capture.[1] Our results demonstrate that the data of Betz, Röschenthaler, and Rothermel are apparently insufficient to prove what role is played by last-layer capture in the formation of these high Rydberg ions. Further data are needed to clarify the situation, particularly the n,l distributions of the ions emerging from the target.

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