# Observation of Polarized Optical Radiation following Electron Capture into Slow, Highly Ionized Neon

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In charge-transfer collisions of 4-keV $Ne^{8+}$ recoil ions with Na, we have observed 434-nm photons emitted in the $n=9$ to 8 transition in $Ne^{7+}$. We find this radiation to be strongly polarized, with a degree of polarization $P=0.32\pm0.02$. This result is in accord with a recent calculation of Salin indicating that electron capture into slow, highly charged ions preferentially populates the $m=0, \pm1$ magnetic substates.

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Recent years have seen a proliferation of theoretical and experimental studies of electron capture by slow, multiply charged ions from atomic targets. These studies derive motivation from astrophysical problems, possibilities for fusion-plasma diagnostics,[1] and the development of vacuum ultraviolet (vuv) and x-ray lasers. Capture in such collision systems proceeds into selected excited states of the projectile ion. Spectroscopic studies of the post-capture radiation can yield information on the partial cross sections for capture into the various substates.

In this Letter, we report the observation of visible and uv photon emission following charge transfer from atomic sodium into multiply charged neon ions. We also report the observations of strong polarization of the visible light emitted from the Li-like $Ne^{7+}$ ions formed in the $n=9$ Rydberg state in $Ne^{8+}+Na$ collisions. This polarization indicates an alignment of the magnetic ($m$) substates in the $n=9$ shell of $Ne^{7+}$, in accordance with recent predictions by Salin.[2] Our experiment complements earlier studies reporting polarized-vuv[3] and soft–x-ray[4] emission from low-lying energy levels in multiply charged ions. Charge-exchange collisions utilizing $H_2$ targets and projectile velocities higher than ours were used to populate these states.

Theoretical descriptions of varying complexity exist for predicting the distribution of states populated in charge-transfer collisions. The classical barrier model[5] (CBM) describes electron transfer as a classical over-barrier transition from the Coulomb quantum well of the target core into that of the projectile ion. This picture allows a prediction of the principal quantum number ($n$) of the captured electron for collision systems involving slow, highly charged ions; experiment has shown the CBM to be very successful in this respect. Prediction of the angular momentum substate distribution requires more intricate theories. Salin[2] has performed coupled-state molecular calculations of electron capture from atomic hydrogen into slow ($v\leq1$ a.u.) fully stripped ions. Charge exchange occurs at well-defined distances (pseudocrossings); this primary charge-exchange process populates $m=0$ states almost exclusively. Subsequent rotational mixing is incomplete, with the result that the $m=0, \pm1$ magnetic substates dominate the final $m$ distribution. Strong post-collision Stark mixing in the electric field of the residual target ion results in a statistical population among possible $l$ values for a given $m$. The magnetic-substate alignment should manifest itself in the polarization of the subsequent spontaneous emission.

It should be emphasized that these calculations were performed for completely stripped projectiles. In the collision systems under investigation in our experiment, the incoming ion carries a core, thereby lifting the (near) $l$ degeneracy present in a hydrogenlike system; thus, the question of post-collision Stark mixing requires further consideration. One may expect, however, that the primary process still selectively populates $m=0$ states, and that the absence of the $l$ degeneracy only serves to partially inhibit subsequent Stark mixing.

The experimental arrangement is shown in Fig. 1. Unanalyzed Br ions in the high-energy beam line of the Stanford FN Van de Graaff accelerator impinged on a Ne gas jet emerging from a 100-$\mu$m-diam nozzle. The terminal of the accelerator was held at a voltage of $\sim7$ MV. The beam was stripped by a C foil in the terminal to an average charge state of +9.5. A second C foil 5 cm upstream from the Ne target poststripped the beam to an average charge state of +18.5. The Ne recoil ions were electrostatically extracted with a potential of $\sim500$ V and directed into a double-focusing magnet spectrometer.[6] Analyzed beams up to 2-pA $Ne^{10+}$, 7-pA $Ne^{9+}$, and 100-pA $Ne^{8+}$ could be obtained, as well as lower charge state beams (Fig. 2).

An atomic Na beam from an oven at $\sim400\,°C$ intersected the analyzed Ne ion beam at right angles. The percentage of $Na_2$ dimers at this temperature is approximately 3%.[7] Photons emerging from the interaction region were collimated by a lens (solid angle $\approx0.31$ sr) onto the photocathode of an RCA 8850 photon-counting photomultiplier. The latter has a

 

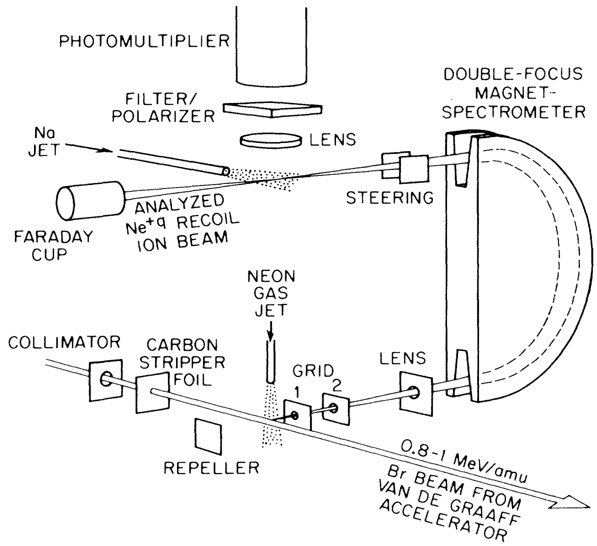


FIG. 1. Experimental arrangement. Neon recoils created in collisions of the Br beam provided by the Van de Graaff accelerator with the neon gas jet are repelled into the magnet spectrometer. The analyzed neon charge state passes through an atomic Na beam. Photons emitted from the interaction region are filtered and then counted by a photomultiplier. The analyzed recoil current is measured with a Faraday cup.

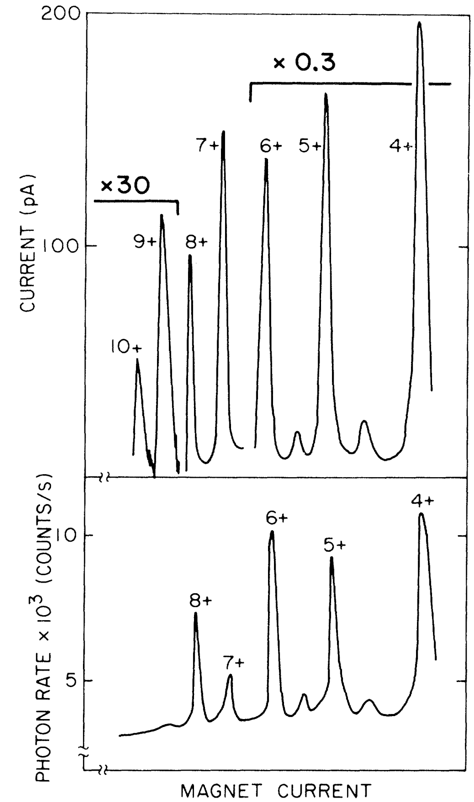


FIG. 2. Simultaneous scans of neon recoil current (upper trace) and corresponding unfiltered photon emission rate into 0.31 sr (lower trace) vs analyzing magnet current. Recoil current peaks and photon peaks are labeled according to recoil charge state $^{20}Ne^{+q}$ prior to capture. Smaller, unlabeled peaks correspond to $^{22}Ne^{+q}$ recoil ions.

quantum efficiency greater than 5% in the spectral range 290–550 nm. A series of narrow-band interference filters were used to determine the wavelengths of the photons emitted from the interaction region. A Polaroid sheet filter was then added to this arrangement for the polarization measurements.

Figure 2 shows simultaneous scans of projectile (recoil) ion current and photon count rate versus analyzing magnet current. Photons are detected for $Ne^{q+}$ projectiles from $q=9$ to 4; we were able to identify the wavelengths of these photons for $q=8$ and 6, i.e., $q'=7$ and 5 after capture.

The CBM predicts that in $Ne^{8+}+Na$ collisions, electron transfer should take place predominantly into the $n=9$ shell of $Ne^{7+}$. The Rydberg-type $n=9$ to 8 transition has a wavelength of 434 nm and the $n=8$ to 7 transition 298 nm. By using a variety of monopass interference filters, we determined that $(63\pm3)\%$ of the photons detected in $Ne^{8+}+Na$ collisions had wavelengths of $434\pm2$ nm and $(37\pm3)\%$ had wavelengths of $300\pm15$ nm. With a correction for the efficiency of the photomultiplier tube, we find the ratio of the number of photons emitted in the $n=9$ to 8 transition to those emitted in the $n=8$ to 7 transition is equal to $0.89\pm0.12$. This result cannot by itself determine the ratio of the capture cross section into the $n=9$ state to that into the $n=8$ state; knowledge of the $l$ distribution of capture, together with the known radiative branching ratios, is also required to make such a determination. Similarly, the CBM applied to the $Ne^{6+}+Ne$ collision system predicts that capture proceeds principally into $n=7$; the $n=7$ to 6 transition in $Ne^{5+}$ has a Rydberg-type wavelength of 343 nm. We found that $(95\pm5)\%$ of the detected photons had wavelengths of $344\pm2$ nm. These results, as well as CBM predictions for the other charge states of neon, are summarized in Table I.

In atomic or ionic systems with one active electron making transitions in the presence of a spectator core, one expects the transition wavelengths to approach their Rydberg-type values for large values of $n$ and $l$. Thus, for example, the value of $\lambda=434\pm2$ nm measured in the $Ne^{8+}+Na$ system indicates that the majority of the $n=9$ to 8 transitions originate from $l(\text{initial})\geq3$.[8] Unfortunately, this allows one to draw only very weak conclusions regarding the $l$ distribution resulting from electron capture, since the branching ratios of radiative $n=9$, $l<2$ to $n=8$ transitions are small.

TABLE I. Rydberg-type $\Delta n = -1$ transitions after electron capture in slow $Ne^{q+} + Na$ collisions.

| $q$ | $n$(initial)[a] | $\lambda$(expected) (nm) | $\lambda$(measured) (nm) | Percentage of total intensity |
|---|---|---|---|---|
| 10 | 11 | 525 | . . . | . . . |
| 9 | 10 | 480 | $480 \pm 10$ | . . . |
| 8[b] | 9 | 434 | $434 \pm 2$ | $63 \pm 3$ |
| 7 | 8 | 389 | . . . | . . . |
| 6 | 7 | 343 | $344 \pm 2$ | $95 \pm 5$ |

[a]Dominant $n$ value according to classical barrier model.
[b]For $n = 8$ to $n = 7$, $\lambda$(expected) = 298 nm, and $\lambda$(measured) = $300 \pm 15$ nm.

The 434-nm radiation emitted in the $Ne^{8+} + Na$ collision system was found to be strongly linearly polarized along the ion path, with a degree of polarization

$$P = (R_{\parallel} - R_{\perp})/(R_{\parallel} + R_{\perp}) = 0.32 \pm 0.02, \qquad (1)$$

where $R_{\parallel}$ and $R_{\perp}$ are the counting rates for radiation polarized parallel and perpendicular to the velocity of the Ne ions (the quantization axis used in Ref. 2). This clearly indicates that the $m$-substate distribution is not a statistical one, for which symmetry demands that no polarization effect be seen ($P = 0$).

Examination of the branching ratios for $n = 9$ to 8 transitions in lithiumlike neon indicates that transitions for which $\Delta l = -1$ and $l(\text{initial}) \geq 4$ are dominant. For $\Delta l = -1$ transitions originating from the $m = 0$ sublevel of the upper state, the polarization ratio for radiation emitted in a direction perpendicular to the quantization axis can be shown to be

$$P = (l+1)/(3l-1), \qquad (2)$$

where $l$ is the initial $l$ value. For example, this expression yields $P = 0.45$ for $l = 4$ and $P = 0.39$ for $l = 8$.

In reality, the photons emitted in the $n = 9$ to 8 transition in $Ne^{7+}$ result from the decay of a distribution of sublevels populated by the capture process. This distribution is presently unknown for this collision system, but Salin has calculated the $l$ and $m$ distributions for the collision system $Ne^{10+} + H(1s)$, for which capture proceeds predominantly into $n = 6$. With the assumption that the same $m$ distribution describes the $n = 9$ shell of $Ne^{7+}$, and that the emissions from the allowed transitions add incoherently, one derives an expected polarization of $P = 0.33$ for the $n = 9$ to 8 manifold. This compares favorably with the measured value $P = 0.32 \pm 0.02$.

We have also made a preliminary determination of the wavelength and polarization of photons emitted in $Ne^{9+} + Na$ collisions. The CBM predicts capture to take place predominantly into $n = 10$; the Rydberg-type $n = 10$ to 9 transition has a wavelength of 480 nm, and the measured wavelength is $480 \pm 10$ nm. The degree of polarization was measured to be $0.32 \pm 0.11$. The fact that the polarization of the $n = 10$ to 9 transition in $Ne^{8+}$ has a value close to that of the $n = 9$ to 8 transition in $Ne^{7+}$ shows that the $1s$ core electrons do not affect the alignment in an important way.

We have succeeded in obtaining recoil-ion currents sufficient for performing optical studies of highly charged ion collision with atoms. In those cases were suitable optical filters were available, the observed photons could be attributed to Rydberg-type transitions in neon ions following electron transfer from sodium. The CBM was successful in helping to predict the observed transitions.

The polarization of radiation detected in the $n = 9$ to 8 transition in lithiumlike neon demonstrates that the magnetic substates are not populated statistically by the capture process. The results of Salin's calculations for the $Ne^{10+} + H$ system, when applied to the $Ne^{8+} + Na$ system, predict a degree of polarization in close agreement with that which is observed. Further theoretical studies are necessary for a valid comparison.

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