Alignment of Ne^{7+} following electron capture by Ne^{8+} ions in a sodium target

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The alignment of excited Ne^{7+} ions produced in collisions of low-energy Ne^{8+} ions in a sodium beam target was studied. The linear polarization of both the 434-nm ($n=9\rightarrow 8$) and the 298-nm ($n=8\rightarrow 7$) emission lines was measured for beam energies from 4.8 to 32.8 keV/amu.

Excited atomic systems formed in ion-atom collisions are generally aligned,[1,2] with the result that decay radiation is emitted anisotropically and linearly polarized. Theories of ion-atom collisions can predict the amplitudes for capture into specific levels labeled by a complete set of quantum numbers n, l, and m.[1] However, cross-section measurements give only the n or (n,l) dependence[3,4] of the electron-capture process. Moreover, uncertainties due to anisotropic emission and polarization often contribute the largest errors to the determination of electron-capture cross sections to selective subshells.[4] Obviously, measuring the alignment or orientation of the states formed in the collisions provides additional information and constitutes a very stringent test of various theoretical calculations. Alignment is an important indicator of the relative importance of radial and rotational couplings[5] in the quasimolecule picture.[6,7] The energy dependence of the alignment of the hydrogen $2p$ level produced in H^+-He and He^+-H collisions has revealed a spin-dependent effect in the $(H\text{-}He)^+$ collision system.[8]

In this paper we report our measurements of the linear polarization of the 434- and 298-nm emission lines resulting from collisions of 4.8- to 32.8-keV/amu Ne^{8+} ions with unpolarized Na atoms. The linear polarization is defined as $[I(0°)-I(90°)]/[I(0°)+I(90°)]$, where $I(0°)$ and $I(90°)$ are the intensities of the observed photons with polarization vector along and perpendicular to the ion beam axis, respectively. This collision system has also been studied using a recoil ion source[9,10] in the energy region between 0.025 and 0.4 keV/amu. Lembo *et al.*[9] obtained a 100-pA Ne^{8+} beam by bombarding a Ne gas jet with highly-stripped Br ions (with an average charge state of 18.5) from the Stanford FN Van de Graaff accelerator. Their polarization measurements indicated the $m=0$ magnetic substates were preferentially populated[9] at low energy. The data reported here extend the previous work[9,10] from low energies (where, in the language of the close coupling treatment,[11] the molecular state expansion method prevails[12]) to higher energies where the atomic-state expansion method or the atomic-orbital–molecular-orbital matching method[11] has to be employed to calculate the magnetic substate distribution.

The experimental setup for our work is shown in Fig. 1. The $^{20}Ne^{8+}$ ions are produced by the Argonne PIIECR (positive-ion injector electron cyclotron resonance) ion source,[13] which operates at an rf frequency of 10 GHz. The source is on a high-voltage platform (350 kV maximum), which has a measured stability of ± 4 V. The ions are extracted, analyzed by a 90° magnet, accelerated, and delivered to the collision chamber. The beam currents obtained in the Faraday cup are typically between 1 and 2 μA, depending on the beam energy. The atomic sodium beam is formed using a two-stage oven[14] consisting of a reservior section and a nozzle section. The nozzle consists of a molybdenum plate with nine holes which form a 2×2 mm^2 array. Each hole is 200 μm in diameter and 3 mm long. The Na beam is directed onto a liquid-N_2-cooled surface in order to prevent deposition of a Na film on the observation window. The target thickness was determined to be 1.4×10^{11} atoms/cm^2 with the reservior at 387 °C and the nozzle at 449 °C by measuring the absorption profile of the sodium $D2$ line. To further minimize the possible deposition of a depolarizing film[10] on the observation window, we typically ran the oven at low temperatures, 306 °C at the reservoir and 360 °C at the nozzle. Under these conditions, the target thickness was estimated to be about 2×10^{10} atoms/cm^2.

We used interference filters to isolate the 434 ($n=9$ to $n=8$) and the 298-nm ($n=8$ to $n=7$) transitions in Ne^{7+}. The light passed through a polarimeter, which consists of a rotatable wave plate and a linear polarization analyzer, before reaching the interference filter. The detector is a water-cooled photomultiplier tube. The filter used for the

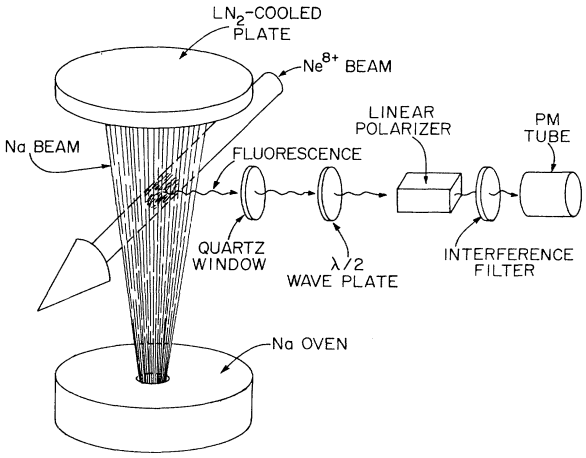

FIG. 1. Schematic of the experimental setup.

434-nm emission line is a ORIEL Model 5382 interference filter with the transmission peak at 440 nm and a bandwidth of 10 nm. For the 298-nm emission line we used an ORIEL Model 5337 filter with the peak wavelength at 300 nm and a bandwidth of 11 nm. Spectroscopy in the regions of 428–442 and 289–307 nm of the $Ne^{8+} \rightarrow Na$ system has been done by Lembo[10] using a 0.32-m normal incidence spectrometer with a resolution of 0.7 Å. It is found that $l=5,6,7,8$ of the $n=9$ to 8 transition and $l=5,6,7$ of the $n=8$ to 7 transition cannot be resolved. Transitions from the $l \leq 4$ states make a negligibly small contribution for both $n=9$ and $n=8$ states. The bandwidths of our filters allow all transitions[15] with $\Delta l = \pm 1$ and $l \geq 4$ to be seen by the detector. The $\Delta n \geq 2$ transitions are well outside the bandwidths of the filters.[10,15] The method for determining the state of polarization of a beam of light in terms of its Stokes parameters is described in detail in Ref. 16. We used a stepping motor to rotate the wave plate with respect to the polarizer which was fixed in orientation with respect to the detector. A multiple-order quartz wave plate was used for measuring the light polarization of the 434-nm emission line. The retardation was $\lambda/4$ at 539 nm and $\lambda/2$ at 434.2 nm. The wave plate for measuring the polarization of the 298-nm emission line was a zero-order quartz wave plate with a retardation of $\lambda/4$ at 638 nm and $\sim\lambda/2$ at 297.1 nm. The linear polarization analyzer was a Glan-Thompson prism polarizer, which is known to have an extinction ratio better than 5×10^{-5} at $\frac{2}{3}$ or less of its full aperture, between 320 and 2300 nm. The Stokes parameters can be measured by observing the variation of the transmitted light intensity through the polarimeter as the retardation plate is rotated.[16] The 2ω and 4ω signals are proportional to the circular and linear polarizations of the light source. A typical four-peak modulation pattern for the 434-nm line with one complete revolution of the $\lambda/2$ wave plate is shown in Fig. 2. Forty channels in the spectrum correspond to one complete revolution. The accumulated beam charge per channel in the spectrum is 1.2×10^{-4} C.

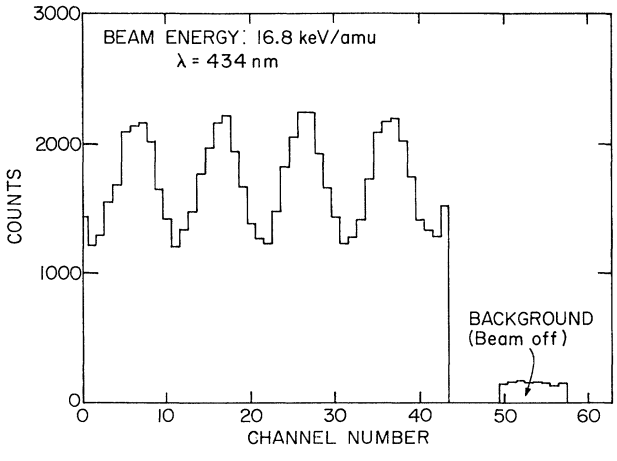

FIG. 2. Photomultiplier count rate as a function of the angle of the optical axis of the wave plate with respect to the linear polarizer. Forty channels correspond to one complete revolution of the wave plate. The four-peak modulation pattern observed with one revolution of the wave plate is characteristic of linear polarization.

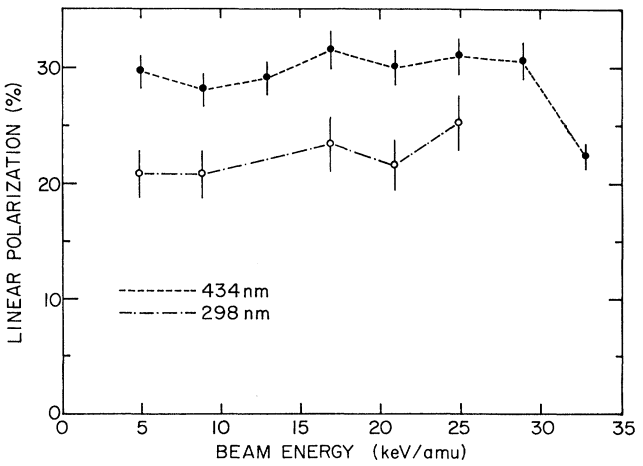

FIG. 3. Measured linear polarization of the 434- and 298-nm emission lines vs ion beam energy. The data for the 298-nm emission line are connected by a dotted line, while a short-dashed line is for the 434-nm emission line data. The connecting lines are only to guide the eye.

The overall counting rate decreases as the beam energy is increased. With the polarimeter in place, the signal with the background subtracted at 434 nm was about 12 counts/sec at a beam energy of 12.8 keV/amu, and about 3 counts/sec at 32.8 keV/amu. The background, ~2 counts/sec, was fairly constant throughout the measured energy range.

The observed linear polarization of the 434-nm emission line (see Fig. 3) is $\sim+30\%$ and almost constant in the energy range between 5 and 30 keV/amu. As shown in Fig. 3, there is a hint that the alignment of the excited

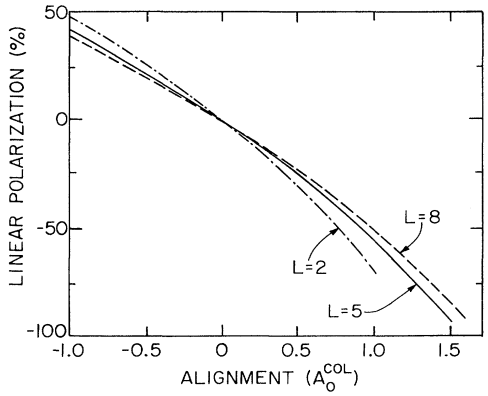

FIG. 4. This figure shows a typical dependence of expected linear polarization on the alignment produced in the capture process, for captured states with orbital angular momentum $L=2$, 5, and 8.

state decreases substantially at energies above 30 keV/amu in this system. The observed linear polarization of the 298-nm emission line is also shown in Fig. 3. It is noted that the observed linear polarization of the two emission lines at energies between 4.8 and 30 keV/amu is about the same as that measured by Lembo *et al.*[9] for energies between 0.025 and 0.4 keV/amu. Figure 4 shows a typical dependence of expected linear polarization on the collision-produced alignment[2] for various transitions. The definition of the parameter $A_0^{\rm col}$ (Ref. 2) is given by

$$A_0^{\rm col}=\frac{\sum_{m_z}[3m_z^2-L(L+1)]\sigma(m_z)}{L(L+1)\sum_{m_z}\sigma(m_z)}\ , \tag{1}$$

where $\sigma(m_z)$ is the capture cross section of the magnetic substate (L,m_z). Since $[I(0°)-I(90°)]/[I(0°)+I(90°)] \gg 0$, the data indicate that the collision strongly favors the $m=0$ magnetic substate in this system[10,12] over a very wide energy region. Also the alignment in the $n=9$ states seems to be larger than that in the $n=8$ states. Salin[12] has performed coupled-state molecular calculations of electron capture from atomic hydrogen into slow ($v \leq 1$ a.u.) fully stripped ions. The results of Salin's calculation for the $Ne^{10+}+H$ system, when applied to the quasi-one-electron system $Ne^{8+}+Na$, predicts a degree of polarization in close agreement with observed data.[9,10] Salin's calculation also predicts a statistical population among possible l values for a given m (Refs. 9 and 12) by taking into account strong post-collision Stark mixing in the electric field of the residual target ion. As pointed out by Lembo *et al.*[9] the absence of the l degeneracy in lithiumlike neon will serve to partially inhibit subsequent Stark mixing. It will be interesting to study the state-selective capture cross section[4,17] with a high-resolution spectrometer,[18] instead of a simple interference filter, to probe the extent of post-collision Stark mixing.

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[1]C. D. Lin and J. H. Macek, Phys. Rev. A **35**, 5005 (1987).
[2]U. Fano and J. H. Macek, Rev. Mod. Phys. **45**, 553 (1973).
[3]Yu. S. Gordeev, D. Dijkkamp, A. G. Drentje, and F. J. de Heer, Phys. Rev. Lett. **50**, 1842 (1983).
[4]C. J. Liu, R. W. Dunford, H. G. Berry, R. C. Pardo, K. -O. Groeneveld, M. Hass, and M. L. A. Raphaelian, J. Phys. B **22**, 1217 (1989).
[5]Rainer Hippler, in *Proceedings of the NATO Advanced Study Institute on Fundamental Processes in Atomic Collision Physics Santa Flavia, 1984,* edited by H. Kleinpoppen, J. S. Briggs, and H. O. Lutz (Plenum, New York, 1985).
[6]U. Fano and W. Lichten, Phys. Rev. Lett. **14**, 627 (1965).
[7]William Lichten, Phys. Rev. **164**, 31 (1976).
[8]R. Hippler, H. Madeheim, H. O. Lutz, M. Kimura, and N. F. Lane, Phys. Rev. A **40**, 3446 (1989).
[9]L. J. Lembo, K. Danzmann, Ch. Stoller, W. E. Meyerhof, and T. W. Hänsch, Phys. Rev. Lett. **55**, 1874 (1985).
[10]L. J. Lembo, Ph.D. theseis, Stanford University, Stanford, California (1987).
[11]Mineo Kimura and Neal F. Lane, Adv. At. Mol. Opt. Phys. **26**, 79 (1990).
[12]A. Salin, J. Phys. **45**, 671 (1984).
[13]R. Pardo, Nucl. Instrum. Methods B **40/41**, 1014 (1989).
[14]R. W. Dunford, C. J. Liu, N. B. Mansour, Y. Azuma, H. G. Berry, D. A. Church, T. P. Dinneen, L. Young, and B. J. Zabransky, Nucl. Instrum. Methods B **43**, 459 (1989).
[15]Anders Lindgard and Svend Erik Nielsen, At. Data Nucl. Data Tables **19**, 533 (1977).
[16]H. G. Berry, G. Gabrielse, and A. E. Livingston, Appl. Opt. **16**, 3200 (1977).
[17]J. Sorensen, L. H. Anderson, P. Hvelplund, H. Knudsen, L. Liljeby, and E. H. Nielsen, J. Phys. B **17**, 4743 (1984); P. Hvelplund, E. Samsoe, L. H. Andersen, H. K. Haugen, and H. Knudsen, Phys. Scr. **T3**, 176 (1983).
[18]R. W. Dunford, H. G. Berry, C. J. Liu, M. Hass, R. C. Pardo, M. L. A. Raphaelian, and B. J. Zabransky, Nucl. Instrum. Methods B **40/41**, 9 (1989).