Polarization of X-Ray Emission Lines from Heliumlike Scandium as a Probe of the Hyperfine Interaction

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We report the first measurements of the polarization of x rays emitted from bound-bound transitions in a highly ionized He-like ion. Polarization was measured for the decay to the ground state, $1s^2\,{}^1S_0$, of the He-like Sc^{19+} levels $1s2p\,{}^1P_1$, $1s2p\,{}^3P_2$, $1s2p\,{}^3P_1$, and $1s2s\,{}^3S_1$. The measurements were made with the Electron Beam Ion Trap at two electron-beam energies: 4.36 and 5.62 keV. Polarization of two of the lines is strongly influenced by the hyperfine interaction with the Sc nucleus, demonstrating that polarization measurements can be used to investigate hyperfine interactions in highly ionized atoms.

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Evidence for the hyperfine interaction in He-like ions has been seen in beam-foil spectroscopy, where hyperfine effects were found[1] to explain the measured lifetime of the $1s2p\,{}^3P_2$ level in V^{21+}. The hyperfine interaction can mix "pure" atomic levels, changing the level lifetimes and even allowing decay by an otherwise forbidden transition. The hyperfine interaction also effects the populations of magnetic sublevels, thus affecting the polarization of the radiation emitted when a state decays. Measurements of the polarization of line emission can be used to test the theory of the hyperfine interaction, as well as provide information relevant to the understanding of solar flares and tokamaks,[2] where nonthermal electron distributions can produce polarized radiation.

We have measured, for the first time, the polarization of electric dipole ($E1$), magnetic dipole ($M1$), and magnetic quadrupole ($M2$) emission lines emitted from a highly ionized He-like ion. The particular emission lines that were observed are the $E1$ resonance line $1s^2\,{}^1S_0$-$1s2p\,{}^1P_1$, the $M2$ quadrupole line $1s^2\,{}^1S_0$-$1s2p\,{}^3P_2$, the $E1$ intercombination line $1s^2\,{}^1S_0$-$1s2p\,{}^3P_1$, and the $M1$ line $1s^2\,{}^1S_0$-$1s2s\,{}^3S_1$ in Sc^{19+}. These transitions are known as w, x, y, and z, respectively,[3] and are important for solar and tokamak plasma diagnostics.[4,5] The emission lines of Sc^{19+} appear in the x-ray region near 2.9 Å and were observed with a Bragg crystal spectrometer attached to the Lawrence Livermore National Laboratory Electron Beam Ion Trap (EBIT). Their energies[6] are shown on an energy-level diagram in Fig. 1.

Sc^{19+} was chosen because it was the He-like ion most suitable for polarization studies with our apparatus. The He-like Sc ($Z=21$) $n=2$ to $n=1$ lines fall at wavelengths[7] that correspond to Bragg angles of about 45° for the Ge(220) ($2d=4.00$ Å) curved crystal installed in our Johann spectrometer.[8] Sc is monoisotopic with an $I=\frac{7}{2}$ nuclear spin. The hyperfine interaction with the nuclear magnetic moment of Sc can influence the polarization of the atomic transitions.

EBIT is described in detail elsewhere.[9,10] Briefly, ions are injected into a cylindrical electrostatic well approximately 2 cm long and 70 μm in diameter. The ions are ionized to high charge states and collisionally excited by a tunable (in energy) electron beam. The electron beam is nearly monoenergetic with a width of 50 eV

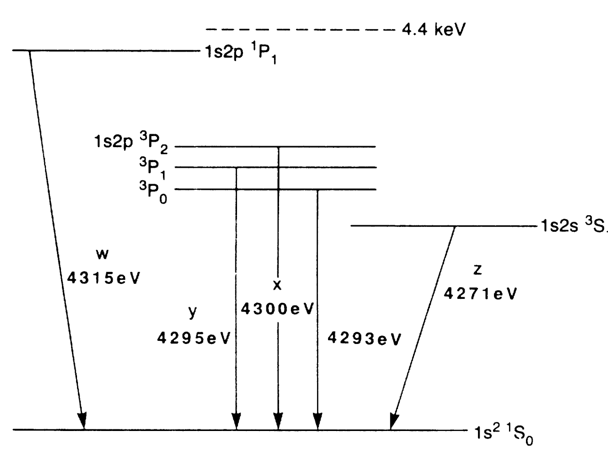

FIG. 1. Energy-level diagram for the Sc^{19+} ion. The lines discussed in the text are shown.

(FWHM). Sc ion measurements were made at two electron beam energies: 4.36 and 5.62 keV, ± 0.02 keV. The lower energy is just above the excitation threshold of the most energetic transition observed (w), and the higher energy is just below the ionization potential of He-like Sc. The Sc^{19+} radiation was observed in a direction perpendicular to the vertical electron-beam axis. The emitted radiation can therefore be strongly linearly polarized, the degree of polarization depending on the type of transition and the incident electron energy.

Measurements were made at two crystal orientations, which we call horizontal and vertical. In the horizontal orientation, the plane of dispersion of the crystal is normal to the electron beam. In this orientation, radiation with its electric-field vector parallel to the electron beam is reflected preferentially. In contrast, radiation emitted with its electric vector perpendicular to the electron beam is almost entirely absorbed. In the vertical orientation, the crystal spectrometer is rotated by 90° about the line of sight to EBIT, and the reflection conditions for the two electric vector orientations are reversed. Thus, the spectrometer is a near-perfect polarization analyzer for Bragg angles near 45°. The ratio of the reflectivity for the (mostly) absorbed component to the reflectivity for the preferentially reflected component varies from 0.001 to 0.003. Calculations of the Ge crystal reflectivities as a function of Bragg angle were provided by Gullikson.[11]

The polarization of an x-ray emission line is defined as $P=(I_{\parallel}-I_{\perp})/(I_{\parallel}+I_{\perp})$, where $I_{\parallel}$ and $I_{\perp}$ are the intensities of the emission components with electric vectors parallel and perpendicular to the electron beam, respectively. Since the crystal reflects either $I_{\parallel}$ or $I_{\perp}$, depending on its orientation, a direct comparison of spectra obtained in the two different orientations yields the polarization P.

There were two experimental considerations that had to be taken into account in order to compare intensities from spectra in the horizontal and vertical orientations. First, variations in the x-ray flux out of the trap must be measured since the horizontal and vertical spectra were not obtained simultaneously. A low-resolution, solid-state Ge detector was used to monitor the blended intensities of the Sc^{19+} lines. The solid-state detector is not polarization sensitive and was kept in a fixed position for all measurements. Time variations in the Sc^{19+} x-ray flux were removed by normalizing the high-resolution intensities with the low-resolution blended intensities.

The second consideration is that the optical geometry in the two orientations is different because the x-ray source is a vertical line. In the horizontal orientation, the same part of the source contributes radiation for all four lines. In the vertical orientation, diffracted radiation of different wavelengths comes from different ~7-mm segments along the source. (The EBIT is inside the Rowland circle of the spectrometer.) Therefore, the overall efficiency of the spectrometer (or effective source size) is different for the two orientations.

Two supporting measurements were needed to determine the efficiency of the spectrometer. First, variations of intensity along the beam axis for the vertical orientation could be determined by varying the central Bragg angle so that the radiation detected from a selected strong line came from different regions of the trap. This measures vignetting and the x-ray intensity along the source. Second, radiation from an unpolarized line was used to determine the efficiency of the spectrometer in the vertical orientation relative to the efficiency in the horizontal orientation. The line used for this purpose was the Ly-α_2 ($1s\,^2S_{1/2}$-$2p\,^2P_{1/2}$) line of H-like Sc. In the absence of the hyperfine interaction, a $J=\frac{1}{2}$ to $J=\frac{1}{2}$ line is unpolarized.[2] Since the individual hyperfine-split lines are not resolved here, the corrections to the polarization due to the hyperfine interaction[12] will be less than 10^{-5}, which is negligible compared to other uncertainties involved in the measurements. This is also true for the single-photon ($M1$) ground-state decay of the $2s\,^2S_{1/2}$ level which is unresolved from the Ly-α_2 line. H-like Sc was produced by increasing the beam energy to above 6.13 keV. By comparing count rates for the Ly-α_2 line, normalized to the Ge-solid-state-detector count rate, the spectrometer efficiency was found to be a factor of 1.42 ± 0.16 larger in the horizontal orientation.

The electron beam in EBIT has a transverse temperature of approximately 250 eV. Consequently, the direction of individual electron-ion collisions can be tipped from the vertical electron-beam axis. The distribution of collision directions will be centered on the electron-beam axis and have a width that is proportional to the square root of the transverse electron temperature. The effect of the transverse temperature is to make the collisions tend toward isotropy, reducing the degree of polarization of radiation emitted from the trap. Additionally, there is a rigid-rotor motion of the electron beam[13] at one-half the cyclotron frequency which must be added to the thermal motion. Here, the actual line polarization (as would be due to monodirectional electrons) is approximately 10% greater than the polarization of the emitted line radiation. The details of this correction are discussed elsewhere.[14]

The spectrum that is most straightforward to interpret is the one for which the beam energy was just above the threshold for production of line w. In this case, only electron-impact excitation from the $1s^2\,^1S_0$ state populates the excited states at the electron densities in EBIT. Figure 2 shows the spectra from both crystal orientations for the 4.36-keV case. It can be seen that the effect of polarization is quite dramatic. There is a slight complication for line z in that the $1s2p\,^3P_2$ level decays partly to the $1s2s\,^3S_1$ level with a branching ratio of about 0.3.

The $1s2p\,^3P_0$ level and its possible decays are interesting because single-photon decay from $1s2p\,^3P_0$ to $1s^2\,^1S_0$ is strictly forbidden for spin-zero nuclei. Howev-

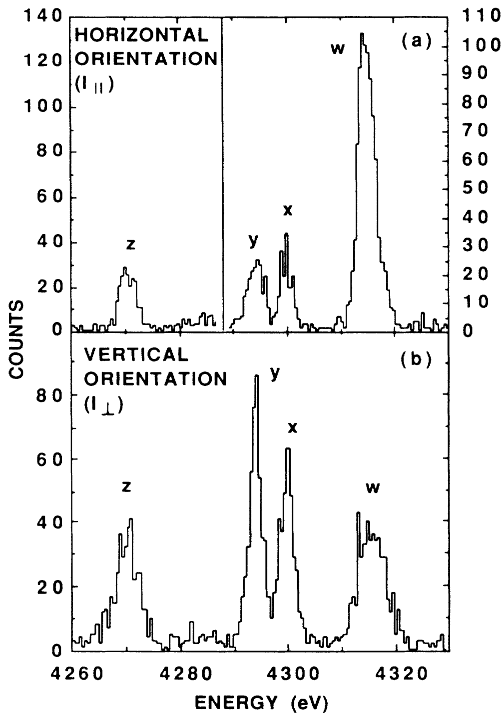

FIG. 2. Spectra of w, x, y, and z obtained at 4.36 keV. Vignetting in the horizontal (parallel) orientation prevents simultaneous viewing of lines w, x, y, and z. The horizontal spectrum is a composite of two spectra with the vertical expansions adjusted to compensate for differing accumulation times and trapped ion densities. When comparing line intensities, note that the spectrometer resolution changes across the spectrum. Line w has a positive polarization and a strong parallel component. Lines x, y, and z are essentially unpolarized.

er, for Sc, Mohr[15] predicts that, due to the hyperfine interaction, the primary decay will be to $1s^2\,{}^1S_0$ rather than to $1s2s\,{}^3S_1$. This produces a line at 4293.35 eV[6] which should appear on the low-energy side of line y. The cross section for excitation of the $1s2p\,{}^3P_0$ level is roughly $\frac{1}{3}$ that of the $1s2p\,{}^3P_1$ level. Because the line is weak and is blended with line y, it is not separately resolved.

The spectrum observed at the 5.62-keV beam energy is more complicated to interpret theoretically due to cascade feeding of w, x, y, and z. In fact, calculations for He-like Ca show that cascades make a very large contribution to line z.[16]

Line intensities normalized to the Ge detector and corrected for geometric efficiency are given in Table I for both orientations and both energies. The last three rows in Table I are the line ratios for emission at 90° to the electron beam, and are obtained by summing the horizontal and vertical intensities and include a small correction for the varying crystal reflectivity.

The measured polarizations of all four lines at both energies are given in Table II. The polarizations derived from the observations for lines x, y, and z are all near

TABLE I. Normalized line intensities (in arbitrary units) and line ratios at 90° for Sc^{19+}. H denotes horizontal orientation ($I_\parallel$); V denotes vertical orientation ($I_\perp$) corrected for geometric efficiency. The last three ratios are obtained by summing the horizontal and vertical intensities (including a small correction for the change in crystal reflectivity with angle) for each line and then taking the ratio of the line intensities.

Line	4.36 keV	5.62 keV
w_H	37.38 ± 1.84	40.31 ± 1.70
w_V	8.25 ± 1.09	10.07 ± 1.31
x_H	5.78 ± 0.48	3.89 ± 0.42
x_V	6.30 ± 0.87	4.47 ± 0.66
y_H	8.28 ± 0.57	4.74 ± 0.46
y_V	8.28 ± 1.10	5.13 ± 0.74
z_H	6.09 ± 0.66	7.68 ± 0.94
z_V	6.30 ± 0.87	8.12 ± 1.08
x/w	0.26 ± 0.03	0.17 ± 0.02
y/w	0.36 ± 0.03	0.20 ± 0.02
z/w	0.27 ± 0.03	0.31 ± 0.03

zero. In contrast, the polarization of the electric dipole resonance line w is quite large. Theoretical values for the polarization of the scandium lines for the 4.36-keV case, excluding the hyperfine interaction, have been calculated by one of us (J.D., following Ref. 17) and are compared with the data in Table II. The theoretical polarizations for lines w and z agree well with observation, but the polarizations predicted for lines x and y (particularly line x) disagree strongly with the data.

We have found that this disagreement can be completely removed by considering the hyperfine interaction with the nucleus. The primary effect of the hyperfine interaction is to change the population of the magnetic sublevels, although the line polarization can also be affected by altering the branching ratios for the decay channels. The predicted polarizations[18] with hyperfine interactions are shown in Table II. The polarizations for lines w and z do not change, but the polarizations of lines x and y are greatly reduced. The predicted polarization for the blend of line y, $P=-0.072$, with the unpolarized ${}^3P_0$ to ${}^1S_0$ transition, which has about $\frac{1}{3}$ the intensity of line y, is $P=-0.054$.

This work shows that high-resolution polarization measurements are a novel means to study hyperfine interactions, at least in highly ionized He-like ions. Our measurements support existing theoretical calculations and should complement the methods used in beam-foil spectroscopy[1] to investigate the hyperfine interaction.

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TABLE II. Polarization of x-ray emission lines of He-like Sc^{19+}.

Line	Theory at 4.4 keV		Experiment	
	No hyperfine	With hyperfine	4.36 keV	5.62 keV
w (4315.24 eV)	0.60	0.60	0.70 ± 0.06	0.65 ± 0.05
x (4300.04 eV)	−0.52	−0.068	-0.05 ± 0.09	-0.08 ± 0.10
y (4294.51 eV)	−0.37	−0.054 [a]	0.00 ± 0.09 [b]	-0.04 ± 0.10 [b]
z (4270.96 eV)	0.00	0.00	-0.02 ± 0.10	-0.03 ± 0.10

[a]To facilitate comparison with the experiment, this value is for the blend of line y ($P = -0.072$) and the $^3P_0$ decay ($P = 0.0$), assuming the $^3P_0$ decay has one-third the intensity of line y.

[b]This includes the unresolved blend of the $^3P_0$-to-$^1S_0$ transition with line y.

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