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Measurements of X-Ray Polarization from EBIT

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Abstract

The Electron Beam Ion Trap (EBIT) has been used to generate and excite several helium-like and neon-like ions. Polarization measurements have been made using three different techniques. Two detectors at 0° and 90° to the collision direction have been used for low resolution measurements on neon-like barium and for radiative recombination measurements. The polarization of the 2 to 1 emission lines for helium-like scandium have been measured with a rotatable focusing Johann spectrometer at an electron-ion collision energy of 4.36 keV. The results are in agreement with calculations that include the hyperfine interaction with the Sc nucleus. Calculations of the line polarization ignoring the hyperfine interaction are significantly different and not in agreement with the experimental results. The same spectrometer has been used to measure the polarization of neon-like barium (Ba46+). A multiple crystal technique has been used with a flat crystal spectrometer to measure the polarization of neon-like barium and several helium like ions (Sc19+, Ti20+, V21+).
1. Introduction

The Electron Beam Ion Trap (EBIT) uses an electron beam to ionize and excite ions. The ions are essentially stationary and the beam is highly directional, so x ray emission following collisional excitation can be polarized [1], and have an anisotropic angular distribution. Polarization measurements were started to allow comparison to measurements from thermal sources and to theoretical calculations. Additionally, some measurements using a Bragg crystal for energy dispersion require a correction for the polarization of the observed x rays in order to calculate total line intensities and total cross sections. Most recently, we have found [1] that polarization measurements can be used to investigate the hyperfine interaction in the highly ionized atoms studied in EBIT.

Three methods have been used to measure the polarization of x rays from EBIT. Consider classical dipole emission with the dipole axis along the z (vertical) axis. There will be no emission along the z axis (at 0° to the collision direction) and full emission with parallel (to the electron beam) polarization in the x-y plane (at 90°). Isotropic emission will have equal intensity at 0° and 90°, the emission at 90° being equally distributed between the parallel and perpendicular components. We can observe the following:

- Total intensity at 0° \( I_0 \)
- Total intensity at 90° \( I_{90} = I_\parallel + I_\perp \)
- Intensity at 90° with polarization parallel to the beam \( I_\parallel \)
- Intensity at 90° with polarization perpendicular to the beam \( I_\perp \)

The polarization \( P \) at 90° is defined [2] by

\[
P = ( I_\parallel - I_\perp ) / ( I_\parallel + I_\perp ).
\]  

(1)

This can be reformulated in terms of the other observable quantities as

\[
P = 1 - ( I_0 / I_{90} )
\]  

(2)

and

\[
P = 2 ( I_\parallel / I_{90} ) - 1.
\]  

(3)

The three methods of polarization measurement used are based on these formulae. Before
discussing the measurements in detail we will describe some of the relevant physics of EBIT and its electron beam.

2. EBIT

EBIT is described in detail elsewhere [3,4]. Briefly, ions are injected into a cylindrical electrostatic well approximately 2 cm long and 70 microns in diameter. Ions are injected by either a MEVVA [5] ion source at the 0° port, a gas injector at a 90° port, or evaporated from the electron gun. 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 (FWHM). 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 [6] (at one-half the cyclotron frequency in the limit of Brillouin flow) which must be added to the thermal motion. Here, the actual line polarization (as would be due to mono-directional electrons) is approximately 10% greater than the polarization of the emitted line radiation. The details of this correction are discussed elsewhere [7].

3. Results

Each of the three measurement methods will be described and data shown. The relative advantages and limitations of each technique will be discussed. Data from the rotatable spectrometer has been most extensively analyzed and results are presented in section 3.2.
3.1 Angular measurements

Solid state Ge detectors have been used to observe total emission intensities at 0° and 90° for neon-like Ba and for bare, H-like, and He-like Ti. The polarization is calculated from equation 2. The solid angle for observation at 0° is much less than at 90°, so a correction term (calculated from the geometry or measured using an isotropic line) is necessary. Measurements at 0° are presently only possible for barium, which is evaporated from the electron gun, or for ions that can be injected as a gas or evaporated in through a 90° port. Data for Ne-like Ba are shown in Figure 1. Because these detectors have a resolution of ~180 eV, the three strongest lines, \( (2p_{3/2}^{-1} 3s_{1/2})_1, (2p_{3/2}^{-1} 3d_{5/2})_1, \) and \( (2p_{1/2}^{-1} 3d_{3/2})_1, \) are not resolved from weaker lines and the accuracy of measuring their polarization is limited. Assuming the unresolved \( 3s_{1/2} \) line has a polarization of zero, both unresolved 3d lines have a polarization of \( P = -0.3. \) This is close to the difference in polarization of the 3s and 3d lines measured accurately below. The small solid angle at 0° makes the use of a crystal spectrometer for greater resolution a prohibitively time consuming (~800 hours of data collection) procedure. The advantage of this technique is that the solid state detectors have a quantum efficiency near unity and measurements can be completed quickly.

The polarization of radiative recombination (RR) to bare and H-like Ti has been measured with this method. Since the RR x rays to the two charge states are separated by 377 eV, the detector resolution does not limit the measurement. The measurements agree with the theoretical prediction that RR to bare and H-like ions has \( P = 1 \) [8].

3.2 Rotatable spectrometer

The components of the emission at 90° can be measured separately by using a spectrometer that is sensitive to only one component, making a measurement, rotating the spectrometer through 90° about the line of sight to EBIT, and making a measurement of the
Figure 1. Low resolution spectra of Ne-like Ba at an electron beam energy of 8.02 keV viewed at (a) 0° and (b) 90° to the electron beam. Note that the 3d peaks are reduced in amplitude at 0° relative to the 3s peak.
other component. We take advantage of the fact that a diffraction crystal at a Bragg angle of 45° preferentially reflects the polarization component that is perpendicular to the plane of dispersion. The polarization is calculated using equation 1 with corrections for the electron beam transverse energy and the slightly non-zero reflectivity of the weakly reflected polarization component.

The measurements were made in collaboration with the Naval Research Laboratory with a Johann spectrometer [9]. He-like Sc was chosen for study because the \( n=2 \) to \( n=1 \) lines have energies that correspond to Bragg angles of about 45° for the Ge (220) \( (2d=4.00\text{Å}) \) curved crystal used in the spectrometer. 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 [10]. The polarization component parallel to the beam is measured when the dispersion plane of the spectrometer is horizontally oriented. A low resolution solid state detector was used to monitor the unblended intensities of the He-like Sc lines; this was used to normalize the observed intensities of each polarization component for differing run times and number of trapped ions. Because EBIT is a line source, the geometric efficiency of the spectrometer is different in the two orientations [1]. This was measured using the unpolarized Ly-\( \alpha_2 \) \( (1s^2 S_{1/2} - 2p^2 P_{1/2}) \) line of H-like Sc. Due to low count rates, the determination of the relative geometric efficiency is difficult to measure with great accuracy. The present value took several days of run time and has an uncertainty of 11%. Because the relative geometric efficiency is linked to the distribution of ions in EBIT, it is not possible to calculate it accurately or measure it using a separate, more intense x-ray source.

Polarization was measured [1] 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 \( 1s2s \, ^3S_1 \) (labeled as \( w \), \( x \), \( y \), and \( z \) [11]). We chose an electron beam energy of 4.36 keV. Since this is just above the threshold for excitation of the \( n=2 \) levels, the only mechanism to populate the levels is direct impact excitation. Spectra for both components are shown in Figure 2, and the measured polarizations
Figure 2. Spectra of lines w, x, y, and z for He-like Sc obtained at 4.36 keV with the rotatable spectrometer. Vignetting in the horizontal (parallel) orientation prevents simultaneously viewing 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.
are given in Table 1. The polarizations for x, y, and z are all near zero, while the polarization of line w is quite large. Theoretical predictions of the polarization excluding the hyperfine interaction agree with observation for lines w and z, but disagree for lines x and y. The disagreement is removed when the hyperfine interaction is included [1].

The polarization of the three strong lines for Ne-like Ba have also been measured. Unlike for He-like Sc, the lines are widely separated in energy and it is necessary to readjust the spectrometer Bragg angle to measure each line separately. Consequently, large amounts of time are required to measure the polarization of a series of lines. Also, as the Bragg angle differs from 45°, there is more mixing of the polarization components in the spectrometer, hence loss of sensitivity and a need to have better statistics to maintain a reasonably small uncertainty in the measurement. For Ne-like Ba, the Bragg angle varied from 43° to 36° with a reflectivity ratio for the weakly reflected to strongly reflected components of 0.019 to 0.227 [10]. At 8.05 keV, the polarizations for the \( (2p_3/2^\text{-1} 3s_{1/2})_1 \), \( (2p_3/2^\text{-1} 3d_{5/2})_1 \), and \( (2p_1/2^\text{-1} 3d_{3/2})_1 \) lines are, respectively: 0.15±0.09, 0.54±0.10, and 0.49±0.16. Note that the

<table>
<thead>
<tr>
<th>Table 1. Polarization of ( \text{n}=2 ) to ( \text{n}=1 ) x-ray emission lines of He-like Sc at 4.4 keV electron beam energy. The theory for line y assumes an unresolved blend of the (unpolarized) ( ^3\text{P}_0 ) decay having one third the intensity of line y.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line</td>
</tr>
<tr>
<td>w (4315 eV)</td>
</tr>
<tr>
<td>x (4300 eV)</td>
</tr>
<tr>
<td>y (4295 eV)</td>
</tr>
<tr>
<td>z (4271 eV)</td>
</tr>
</tbody>
</table>
uncertainty in the last polarization is significantly larger despite comparable line intensities and data accumulation times.

3.3 Multiple crystal technique

A variation of the above procedure is to use two (or more) Bragg diffraction crystals to observe the lines of interest. In the ideal experiment, one would use two crystals with Bragg angles of 45° and ~0° for the lines of interest. The 45° crystal would give the $I_\parallel$ intensity, and the 0° crystal would give the $(I_\parallel + I_\perp)$ intensity. Alternatively, a solid state detector (appropriately normalized) could be used for the $(I_\parallel + I_\perp)$ intensity if it has adequate resolution for the measurement. Equation 3 with corrections for non-ideal Bragg angles and the electron beam transverse energy would be used to analyze the data. The line intensities observed in each crystal need to be normalized by the relative crystal reflectivity at that energy. This was not a consideration for the rotatable spectrometer because the same crystal is used for measurement of both polarization components.

Measurements have been made of Ne-like Ba, and several H-like and He-like ions (Sc, Ti, V) with this technique using four crystals: PET (002), Ge (111), LiF (200), and Si (220), with central Bragg angles ranging from 17° to 44°. Data for Ne-like Ba is shown in Figure 3. The top spectrum showing both polarization components is noticeably different from the bottom spectrum which contains predominately only the $I_\parallel$ component. Note that the $3s_{1/2}$ line is significantly less intense than the 3d lines in the lower spectrum. This indicates that the 3s line has relatively less strength in the parallel component and is less positively polarized, in agreement with the polarizations measured with the rotatable spectrometer. A quantitative comparison needs to include the crystal reflectivities. For Si (220) the reflectivity increases by almost a factor of two from the $3s_{1/2}$ line to the $3d_{5/2}$ line.

The multiple crystal technique has the advantage of greater energy coverage than the
Figure 3. Spectra of Ne-like Ba obtained at 8.02 keV using the multi-crystal technique. The top spectrum was taken with a PET (002) crystal at an angle that diffracts both polarization components almost equally. The lower spectrum was taken with a Si (220) crystal at an angle that diffracts almost none of the perpendicular component of the x rays from EBIT.
rotatable spectrometer. (Compare figures 2 and 3.) It is also possible to accurately calculate and separately measure the relative crystal reflectivities. The factor of two multiplying the measured quantities in equation 3 effectively means that statistical uncertainties are magnified by this amount. Consequently, a given level of statistical accuracy requires that four times as many counts must be accumulated, compared to the other techniques. This disadvantage is partially compensated because all of the run time can be spent looking at the lines of interest rather than having to spend time calibrating the spectrometer, and more lines may be viewed simultaneously.

3.4 Comparison of techniques

Measuring the angular dependence is restricted to a limited range of ion sources and is not capable of good energy resolution. For certain situations, it would be the fastest technique. The rotatable spectrometer is conceptually the most direct technique. It is best suited for looking at lines in a narrow energy range corresponding to a Bragg angle of 45°. Run time needs to be allocated between calibration data and data on the lines of interest. The multiple crystal technique is probably the most versatile, but the data analysis is considerably more complicated and the technique requires better statistics to achieve a particular final uncertainty. Calibration of the crystal reflectivities is best done using an intense x ray source. This technique is probably best for measurements involving lines in a broad (±10%) energy range. Given the range in integrated crystal reflectivities, these conclusions could be significantly different for different requirements of resolution and energy range.

4. Summary

Three techniques to measure the polarization of emitted x rays from EBIT have been used. Each technique is most suitable for certain situations. The rotatable spectrometer
technique has been used to make extensive comparison of experiment and theory, pointing out the importance of including the hyperfine interaction when calculating line polarizations. The multiple crystal technique is being used to find polarization corrections [12] for relative line intensities, and to measure the polarization of several isoelectronic sequences. This work is being extended to measure the polarization of lines excited by dielectronic recombination and other processes.

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