HIGH-ENERGY ELECTRON-IMPACT EXCITATION CROSS SECTIONS OF HYDROGENLIKE IRON AND NICKEL IONS

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Abstract. We present a measurement of the cross section for electron-impact excitation of Lyman-α in hydrogen-like iron (Z=26) and nickel (Z=28) over a broad range of energies using the Lawrence Livermore National Laboratory SuperEBIT electron beam ion trap facility. The measurement was performed with electron beam energies between 35 keV and 85 keV. The hydrogen-like spectrum of iron and nickel was observed, and fully resolved, with the XRS/EBIT x-ray microcalorimeter spectrometer, which allowed for an absolute cross section to be measured by normalizing to the RR x-ray emission. These results are compared to theory.

1. Introduction
Electron-impact excitation (EIE) cross sections of K-shell ions are used in interpreting the spectra from astrophysical and laboratory-produced high-temperature plasmas. Of special importance are K-shell cross sections of iron and nickel as they have relatively high elemental abundances in celestial sources as well as being present in many laboratory plasmas. In K-shell systems the cross section for EIE rises till roughly 3 times the threshold energy. To construct a good model for high-Z K-shell emission from a high-temperature plasma, cross sections for electron energies up to 10 times threshold need to be included. Furthermore, for electron energies in excess of 100 keV relativistic effects are expected to play a role in the excitation process and modify the cross section [1]. Yet, for energies well above excitation threshold, no experimental data exist to benchmark and guide theory [2].

The emitted intensity of an EIE produced spectral line can be written as
\[ I = n_e n_i < v_e \sigma_{EIE} > , \]
where \( n_e \) is the density of electrons, \( n_i \) is the density of the ions, \( v_e \) is the velocity of the electrons, and \( \sigma_{EIE} \) is the EIE cross section. The difficulty in making EIE measurements comes from the uncertainty in the knowledge of the density of the ions and electrons. However with a source that is mono-energetic there exists a way by which to remove the influence of the uncertain terms. That is by normalizing the direct excitation cross section to the cross section for radiative recombination (RR) since RR can be calculated to a much greater accuracy.

Radiative recombination is produced by the capture of an electron into a vacant atomic level. The photon that is produced has the energy of the binding energy of the atomic level.
plus the energy of the free electron. The mathematical expression for the intensity of a RR spectral feature has the same form as for EIE. Dividing the intensity of a given line from the EIE spectrum by that of a feature produced by RR forms a ratio of the two cross sections, and the terms with large uncertainties cancel out, leaving the EIE cross-section related to the RR cross section (which in turn has been shown to be calculated to an accuracy of 3%-5% [3]).

In this paper we present a measurement of the EIE cross sections for the Lyman-α line in hydrogenlike nickel and iron. The result of the measurement is compared to theory.

2. Experiment

Hydrogenlike iron ions were produced by a 35, 65, and 75 keV energy electron beam and the nickel ions were produced by a 65 and 85 keV energy electron beam in the SuperEBIT electron beam ion trap. The iron and nickel atoms were injected as metallo-organic gases (nickelocene and iron pentacarbonyl) by way of a ballistic gas injector. The hydrogenlike spectrum from the two elements was observed at 90° with a 6 mm thick coaxial EG&G IGLET-X high purity germanium detector and by the XRS/EBIT x-ray microcalorimeter spectrometer [4].

For iron and nickel, the K-shell RR spectrum sits roughly 10 keV higher in energy than the electron beam energy. The XRS/EBIT, which has a 6 eV full width half maximum resolution at 6 keV, has a low quantum efficiency (QE) at these high energies, and thus, cannot observe the RR spectrum (which is already 100 times less intense than the EIE emission). For that reason, the IGLET was used, as the QE of the Ge detector is above 85 % for photons under 100 keV. On the other hand, the Ge detector cannot resolve the DE hydrogenlike emission because of its poor resolution (roughly 200 eV at 6 keV). Thus a hybrid measurement system was used, whereby the K-shell emission was recorded with both the Ge detector and the XRS/EBIT, but only the Ge detector recorded the RR spectrum, as shown in Figs. 1 and 2.

In our setup the XRS/EBIT is used to resolve the K-shell spectrum, and to relate the number of counts in the Lyman-α and Lyman-α2 lines to the intensity of the single spectral feature observed with the Ge detector, see Fig. 2. The Ge detector spectrum (as shown in Fig. 1), then, with the proper weightings of the lines, is used as the basis of the RR normalization. This allows for elimination of systematic errors due to uncertainty in the geometry of the experimental setup. The spectral peaks recorded with both detectors are fit with gaussian fitting functions. This procedure is similar to that employed in [5] except that we employ the XRS/EBIT instead of a crystal spectrometer. It should be noted, that a new x-ray microcalorimeter spectrometer has been installed at EBIT after the completion of the measurements that negates the need for a Ge detector as it has good QE for photons under 100 keV [6].

In EBIT there are several processes that modify the intensity of the observed Lyman-α lines. These processes are polarization, cascades from higher levels, and charge exchange. Polarization, affects the geometric emission of photons for Lyman-α, which is important for relating the differential cross section (at 90°) to the total cross section for comparison to theory. Cascades can produce extra Lyman-α photons by the decay of higher lying atomic levels (like the n=3 level) down to the n=2 level, which, if not taken into account would cause the experiment to measure a larger cross section. Charge exchange occurs when a neutral atom is stripped of one of its valence electrons. The electron is captured into a high lying level, which may cascade down, and possibly make a Lyman-α photon. To take into account polarization and cascades, calculations were made with the Flexible Atomic Code [8] (FAC) to adjust the data. Since the contribution to the Lyman-α line for cascades and polarization is less than 10 % (using an estimated uncertainty of 20 %) the effect of including calculations only minimally affects the

1 The absorption percentage was calculated using the mass attenuation coefficient taken from the NIST webpage http://physics.nist.gov/PhysRefData/XrayMassCoef/cover.html.

2 RR capture into the n=2 shell can also affect the emission but the cross section is weaker as compared to the EIE cross sections by over a factor of 100, and thus, is not considered.
end result. We estimate that charge exchange effects the intensity of Lyman-α₁ on the order of a few %\(^3\). Even with a possible order of magnitude uncertainty in the neutral density and the collision energy, the effect is still small and as such is not included in the analysis.

When taking into account the absorption percentage for RR photons, cascade, and polarization modifications to the DE, the formula for obtaining the EIE cross section takes the form,

\[
\sigma_{EIE} = \frac{I_{DE}}{I_{RR}} \sigma_{RR} A_{RR} G(E),
\]

where \(\sigma_{EIE}\) is the cross-section for EIE, \(\sigma_{RR}\) is the calculated cross section for RR, \(I_{DE}\) is the number of counts in the DE line, \(I_{RR}\) is the number of counts observed in the RR peak, \(A_{RR}\) is the QE for RR photons in the Ge detector, and \(G(E)\) is a factor that relates to the polarization and cascade contributions.

The RR cross sections used here are provided by Jim Scofield [11] and are not from FAC. Figure 3 shows the cross sections for the various energies for both nickel and iron ions and compared to FAC calculations. Each point is the average of several measurements (except for

\(^3\) The cross-section for charge exchange is estimated from Müller and Salzborn and Salzborn and Müller [9, 10] to be the ion charge times 10\(^{-15}\) cm\(^2\), the ion collision energy is estimated as 10 eV/amu, and the neutral density is around 3\(\cdot\)10\(^6\) cm\(^{-3}\). Compared with the EIE cross section for Lyman-α₁ of 10\(^{-22}\) cm\(^2\), the electron collision energy of 35 keV to 85 keV, and the electron density around 5\(\cdot\)10\(^11\) cm\(^{-3}\).
Figure 3. Experimental EIE cross sections for the Lyman-α line in hydrogenlike iron and nickel. Graph (a) represents the EIE cross sections for iron at energies of 35 keV, 65 keV and 75 keV. Graph (b) represents EIE cross sections for nickel at energies of 65 keV and 85 keV. The solid line is calculated by FAC.

the 35 keV and 75 keV measurements done with iron). The 15 % error bars are dominated by the approximately 10% statistical error associated with the determination of the number of counts in the H-like RR peak and, take into account the uncertainty in the calculation of the cascades, polarization and QE.

3. Conclusion
The cross sections measured here are the highest-energy cross sections that have been measured for a high-Z hydrogenlike ion. The results show that for the hydrogenlike ion, theory at high electron energies agrees well with experiment to roughly the 15 % level. Future studies may include a focus on heliumlike ions and go to higher-Z elements where QED effects become significant in the calculations of EIE cross sections [12].

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