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Laboratory X-Ray Spectroscopy Experiments in Support of NASA's X-Ray Satellite Missions

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With support from NASA, we are performing a series of laboratory astrophysics investigations designed to address fundamental uncertainties in basic atomic physics processes relevant to the interpretation of discrete X-ray spectra of cosmic plasmas. Moderate resolution spectra acquired by the *ASCA* Observatory already demonstrate the inadequacy of currently available spectral modelling codes for this wavelength band. With the upcoming launches of *AXAF*, *XMM*, *ASTRO E*, and *Spektrum Roentgen-Gamma*, the demand for significant advances in this field will increase dramatically. Our program is based on the exploitation of the Electron Beam Ion Trap facility at the Lawrence Livermore National Laboratory, and a unique set of spectrometers and experimental techiques specifically developed for this purpose. Recent experiments have been devoted to definitive measurements of line emissivities for iron L-shell ions in optically thin, collisional plasmas.

1. Introduction

As the field of X-ray astronomy has matured over the years, there has been a paradigm shift in the field, from an initial focus on simple source detection, to a more recent emphasis on detailed spectroscopic investigation. Early satellite experiments incorporated extensive arrays of proportional counters, which provided large area with high quantum efficiency, but relatively poor spectral and spatial resolution. The advent of true X-ray focussing, using grazing incidence telescopes, led to dramatic increases in sensitivity for source detection, but still relatively few detailed constraints on source spectra. The culmination of this work came with *ROSAT*, which provided a catalogue of over 60,000 detected sources, covering nearly all categories of known astronomical systems. Given such a large sample, it no longer makes sense to continue the search for fainter and fainter sources. Rather, the main thrust of current research in this field, is to achieve a better understanding of physical conditions in the cosmic plasmas responsible for the X-ray emission. As in all other wavelength bands, the primary tool for this is spectroscopy with sufficient resolution and sensitivity to enable the detection of individual discrete features.

The conventional X-ray band, 0.1 - 10 keV, is especially rich in discrete spectral detail since it contains the K-shell transitions of carbon through iron, and the L-shell transitions of silicon through iron. A very wide range of gas temperatures, $10^5 - 10^8 K$, yields prominent line emission at X-ray energies. Indeed, the "power" of discrete line X-ray spectroscopy has now been demonstrated dramatically by observations conducted with *ASCA*, which have provided a wealth of information about physical processes occurring in some of the most exotic astrophysical environments. Further, in the next few years, a new suite of major X-ray observatories (*AXAF*, *XMM*, *ASTRO E*, and *Spek-*

trum Roentgen-Gamma) will significantly extend our capabilities for high resolution spectroscopy in this important spectral band.

The successful interpretation of these current and upcoming X-ray spectra, however, requires an adequate understanding of the underlying atomic physics responsible for the observed line features. Unfortunately, at X-ray energies, this is complicated by a number of issues. First, cosmic X-ray plasmas are never in local thermodynamic equilibrium. That implies that the details of the spectra involve a delicate balance between all microphysical processes which feed and deplete the relevant quantum levels. In equilibrium situations, it is a manageable task to decide which processes dominate, but out of equilibrium, new processes become important, few of which have been investigated in detail. Second, the rates for many processes are difficult to calculate accurately. The atoms are partially ionized, so that many levels contribute. The atomic structure for intermediate-Z ions is mildly relativistic, and thus intermediate coupling must be included. In addition, higher order multipole terms are important. Finally, very few experimental data are available to constrain most of these calculations.

There is clearly a need for a vigorous laboratory astrophysics program in this field! However, the principal challenge for such an effort is the shear number of relevant microphysical processes which must be investigated. The conventional approach in experimental atomic physics is to design the experiment to isolate a particular process. This is hopeless for X-ray laboratory astrophysics. An alternative is to conduct parasitic experiments on laboratory plasmas, such as tokamaks or laser implosions. Such experiments can provide the whole spectrum at one go, but its interpretation usually requires simultaneous modelling of physical conditions in the device, which can be fraught with its own uncertainties.

Our group has been engaged in an X-ray spectroscopic laboratory astrophysics program for the past seven years, which takes an intermediate approach, centered on the use of the Electron Beam Ion Trap (EBIT) facility at the Lawrence Livermore National Laboratory, a unique experimental "tool" that allows us to create and trap specific charge states of particular elements, and to probe them with a nearly monoenergetic electron beam, either at fixed energy or at a rapid succession of different energies. This permits the unique experimental capability that coupled excitation and radiative processes can be measured at almost any level of detail desirable, from studying a single process to measuring the all-coupled processes associated with a Maxwellian electron temperature distribution simultaneously. In comparison to other types of laboratory plasmas, EBIT offers tremendous versatility and flexibility, allowing us to simulate all relevant processes that can possibly contribute to the astrophysical spectra.

The Livermore EBIT (see Levine *et al.* 1988) is a modified electron beam source explicitly built to study X-rays emitted from the interaction of highly charged ions with an electron beam. Magnetic fields confine and focus the electrons, which can be accelerated at any energy between a few hundred and thirty thousand electron volts. Neutral atoms or ions with low charge are injected into the beam where they are collisionally ionized and excited. As the electrons pass through a short "trap" region, the beam is compressed down to a diameter of approximately 70 μm by a 3 Tesla magnetic field, generated by a pair of superconducting Helmholtz coils. There, the ions are longitudinally confined within the trap, where they may be observed for an extended period, before the next ion injection occurs. The electrostatic trap itself is created by applying the appropriate voltages to a set of three copper drift tubes through which the beam passes. The drift tubes both accelerate the beam to the desired energy and provide axial confinement of the ions. Radial confinement is provided by electrostatic attraction to the electron beam, as well as flux freezing of the ions within the magnetic field. Six axial slots cut in the drift tubes permit X-rays from the trapped ions to be observed by a suite of spectroscopic instrumentation, custom designed for the laboratory astrophysics program. The electron beam density at a given beam energy can be selected by varying the beam current and the magnetic confinement fields. A typical density in the trap is $\sim 2 \times 10^{12}$ cm^{-3}, but achievable densities range from 5×10^{11} to 1×10^{13} cm^{-3}.

2. Recent Results

In recent years, the primary thrust of our program has been devoted to providing definitive measurements of iron L-shell emission spectra relevant to optically thin thermal plasmas in collisional equilibrium. The iron L complex extends from $\sim 0.7 - 1.5$ keV, and contains a number of very useful plasma diagnostics for a wide range of plasma conditions (Kahn and Liedahl 1990). Emissivities of these lines for collisional plasmas have been well-studied theoretically. However, *ASCA* spectra have shown the largest and clearest discrepancies with the models in this region. The first and most glaring example was provided by the cooling flow in the Centaurus cluster of galaxies (Fabian *et al.* 1994). The data exhibit a rather significant complex of lines near 1 keV associated with the $n = 3-2$ transitions of C-like through Li-like iron, but signficantly less emission than expected for the $n = 4 - 2$ transitions near 1.4 keV from the same charge states. Motivated by this discrepancy, Liedahl, Osterheld, and Goldstein (1995) recalculated the expected emission from these charge states using the *HULLAC* atomic physics package, and were able to achieve an apparently better, but still formally unacceptable, fit to the data.

In our first attempt to address this problem experimentally (Savin *et al.* 1996), we chose an especially simple case. We measured the $n = 4-2$ to $n = 3-2$ line ratios for Li-like iron, *Fe XXIV*, which has only a single valence electron. Our measurements were performed using a monoenergetic electron beam with the beam energy selected well above the ionization potential of this charge state to ensure that the measured line ratios were due solely to electron impact excitation. After careful accounting for potential systematic uncertainties, our measured line ratios agree to within $\sim 1\sigma$ with the *HULLAC* predictions.

More recently (Gu *et al.* 1998), we have attempted to constrain the role of *resonant* processes, which can be important in the vicinity of the ionization threshold. These include dielectronic recombination, which produces high n satellites blended with the primary line, and resonant excitation, which involves dielectronic capture to a higher lying level, followed by Auger decay to the upper level of the transition. Proper accounting of the contribution from these processes is generally not included in the standard codes, and is only partially included in the *HULLAC* calculations. However, when averaged over a Maxwellian distribution of electron energies, they can make a significant contribution to selected line intensities, especially given that the abundance of a given charge state tends to peak when the Maxwellian temperature is comparable to the ionization potential.

We again studied *Fe XXIV*, but this time measured relative cross-sections for line emission in the energy range $0.7 - 1.5$ keV, bracketing the ionization threshold. An example of the resultant data is shown in Figure 1, where we have plotted the measured cross-section for excitation of the $3d_{5/2} \rightarrow 2p_{3/2}$ transition at $\lambda = 11.18$ Å, as a function of electron energy. The solid line represents the predicted cross-section due to electron impact excitation alone. Note the prominent dielectronic recombination resonances below threshold. The $3d5l$ and $3d6l$ resonances are well-resolved, but those due to higher n levels produce an an unresolved "lump" in the cross-section between $\sim$ 1.0 keV and the threshold at 1.2 keV. The features labeled $4l5l'$ and $4l6l'$ are due to resonant excitation. We find that the high n dielectronic recombination satellites contribute

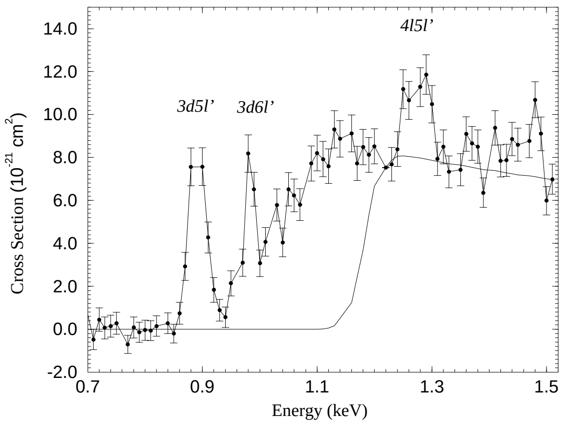

Figure 1: The measured cross-section for excitation of the $3d_{5/2} \rightarrow 2p_{3/2}$ transition of *Fe XXIV* as a function of electron energy. The solid line is the prediction of the contribution from electron impact excitation alone.

$15 - 20\%$, and resonant excitation contributes $5 - 12\%$ of the line emissivity for *Fe XXIV* $3 - 2$ transitions in a collisional plasma at temperatures near where this charge state peaks in abundance. These results illustrate the importance of benchmarking the atomic calculations with experimental data under the controlled plasma conditions that the *EBIT* facility provides.

3. Conclusion

The successful interpretation of upcoming high resolution X-ray spectra of astrophysical sources will require significant improvements in our understanding of the basic atomic processes underlying the observed emission. While new atomic calculations will certainly help to meet this need, it is already clear that new laboratory astrophysics experimental data are also essential. The Livermore *EBIT* facility offers the rare combination of significant flexibility for isolating particular conditions, and broadband spectroscopic capability for inclusive measurements of all coupled collisional/radiative processes. As such it is ideally suited to this research program.

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