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LLNL-PROC-482252

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May 2, 2011

NASA Laboratory Astrophysics Workshop
Gatlinburg, TN, United States
October 25, 2010 through October 28, 2010

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NASA LAW, October 25-28, 2010, Gatlinburg

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ABSTRACT

Here we give a brief review of the recent atomic physics measurements of interest to X-ray astronomy as well as of current and future needs.

1. Introduction

The high-resolution spectral instrumentation of current and future X-ray astronomy missions (e.g.,*Chandra*, *XMM-Newton*, *Astro-H*, *IXO*) has driven a strong need for laboratory astrophysics data. An important issue has been to understand the Fe L-shell emission, and the Fe XVII spectrum in particular (Beiersdorfer 2003). A lot of progress has been made. In addition, new laboratory techniques have provided calibrations of spectral electron-density density diagnostics (Lepson et al. 2010, 2011) as well as wavelengths and cross sections for lines important for understanding absorption features (Simon et al. 2009). Measurements of dielectronic recombination and ionization rates have improved the quality of charge balance calculations (Bryans et al. 2006, 2009), and measurements of X-ray production by charge exchange have emboldened the search for such processes in the heliosphere, the ISM, and other stellar systems. In the following we will discuss some of the recent laboratory X-ray astrophysics measurements and point out areas in need of further measurements.

2. Emission Spectroscopy

Despite many years – one may argue centuries – of effort, there is still a large need for for emission spectroscopy experiments to identify lines and measure their wavelength. A recent measurement of the Fe XVI L-shell emission lines on the Livermore electron beam ion trap device (Graf et al. 2009) between 15 and 18 Å illustrates this need.

The position of the collisional Fe XVI L-shell lines were known from several calculations, as shown in Fig. 1(a,b). The measurement by Graf et al. (2009) identified lines and assigned wavelengths that were quite different from those calculated earlier, as shown in Fig. 1(c). New calculations, which managed to more closely reproduce the measured wavelengths, then confirmed the identifications (cf. Fig. 1(d)).

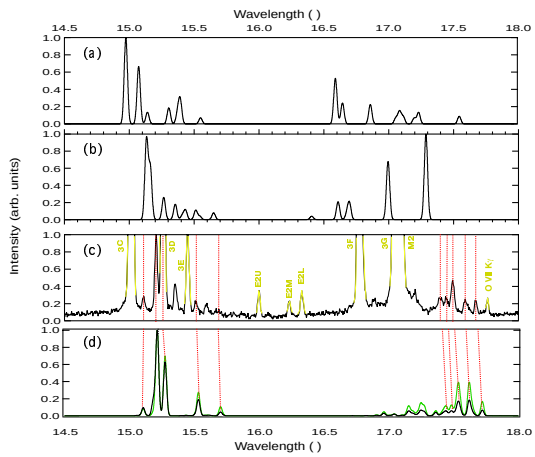

Fig. 1.— Measured and calculated L-shell emission from Fe XVI. Calculations are from (a) Cornille et al. (1994), (b) Phillips et al. (1997), and (d) Graf et al. (2009). The measured spectrum in (c) is from Graf et al. (2009). Known lines from Fe XVII and O VII are marked.

Similarly, the spectra from many astrophysically important ions in the 30–180 Å region are still not well known. Recent measurements of the L-shell emission lines of aluminum were presented by Gu et al. (2011), and almost none of the lines had been tabulated before.

3. Absoprtion Spectroscopy

Spectra from AGNs, which show a plethora of absorption features, have demonstrated the need for accurate atomic energy levels of complex ions with an innershell hole and a partially filled outer shell. For example, photoabsorption by an L-shell electron in an M-shell iron ion produces distinct absoprtion lines in the 15 – 17 Å region, which cannot be readily be calculated with spectroscopic accuracy. The resultant excited level typically does not de-excite by X-ray emission, and thus emission spectroscopy cannot be used to measure the energy level. The level decays instead by emisison of an Auger electron.

To make progress in measuring photoionization processes, efforts have been started to study photoexcitation and photoionization by probing complex ions from an EBIT with a

monoenergetic sychrotron or free-electron laser beam (Simon et al. 2009). The method has produced the first photoionization measurements of complex ions, including those of L-shell ionization of the M-shell Fe^{14+} ion Simon et al. (2010a,b). Highly accurate measurements of Fe XVI spectra are being carried out at the Berlin BESSY-II synchrotron and the Stanford LCLS X-ray laser (cf. Fig. 2).

Fig. 2.— Installation of the Heidelberg EBIT at the BESSY-II sychrotron. The EBIT is rolled to the beam line and connected within a few hours.

4. Ionization Equilibrium Measurements

The collisional ionization equilibrium is a key astrophysical parameter, which still needs much experimental data to check the theoretical data used by equilibrium codes. Atomic data are needed both for ionization and recombination. Such measurements are currently performed on the Test Storage Ring in Heidelberg (Lestinsky et al. 2009; Schmidt et al. 2008). Measurements include rates of recombination of neonlike Fe^{16+} ions forming Fe^{15+} (Schmidt et al. 2009) and electron-impact ionization cross sections of Mg^{7+} forming Mg^{8+} (Hahn et al. 2010). The measured rates are fed back into ionization equilibrium calculations, which are adjusted to provide updated ionization fractions for a given electron temperature. The most recent updates for iron have yielded considerable changes in the ionization fractions (Bryans et al. 2006, 2009).

5. The Fe XVII Problem

Historically, the line intensities of the Fe XVII L-shell spectrum produced by theoretical predictions do not match laboratory measurement at the level needed for analyzing *Chandra* or *XMM-Newton* observations (e.g., confer Beiersdorfer et al. (2004)). In particular, theory overestimated the ratio of line $3C$ to line $3D$ and underestimated the intensity of the $2p-3s$ transitions, i.e. lines $3F$, $3G$, and $M2$. For over a decade there was the additional controversy that the laboratory measurements performed on the NIST EBIT (Laming et al. 2000) did

not agree with those performed on the two Livermore EBITs (Beiersdorfer et al. 2002).

Much progress has been made. Very recently, the NIST EBIT line ratio measurements were repeated and now agree with those performed at Livermore (Gillaspy et al. 2011). This result is not surprising, as a similar measurement of the corresponding ratios in Ni XIX by the NIST EBIT group (Chen et al. 2006, 2007) also reproduced the ratios observed earlier by the Livermore EBIT group (Gu et al. 2004).

The ratio of lines $3C$ and $3D$ is now experimentally well established, and differences between this value and astrophysical observations are now known in most cases to be due to blending of line $3D$ with a line from Fe XVI, as first demonstrated by Brown et al. (2001) in laboratory measurements. The search for other Fe XVI lines in the iron L-shell spectra that confirms such blending is helped by the line list published recently by Graf et al. (2009).

Many theoretical approaches have been published to reproduce the laboratory data (e.g. Chen & Pradhan (2002); Fournier & Hansen (2005)). The R-matrix value by Chen & Pradhan (2002) gives a $3C/3D$ ratio of 3.27, which compares to an earlier calculation of 3.78 (Zhang & Sampson 1989) using the distorted-wave (DW) method and favorably to the measured ratio of 3.0 ± 0.1 (Brown et al. 1998). However, ratios can be deceiving, as errors in the numerator and denominator often cancel out. Indeed, when comparing the calculated absolute cross sections for $3D$ and $3C$ to those measured four years later Brown et al. (2006), the old DW calculations (Zhang & Sampson 1989) do a better job in reproducing the measurement than the R-matrix result of Chen & Pradhan (2002).

R-matrix calculations published subsequently by Chen (2007) revised the value for $3C$ and attained much better agreement with the cross section measurements. A disagreement of 25%, however, remained between the measured and calculated values. A year later, Chen (2008) reaffirmed his most recent results and suggested the difference with experiment was caused by an experimental error. In a seperate paper Chen (2008) argued that the theoretical values used for normalization of the experimental data were incorrect by 24%, i.e., by the amount needed to produce agreement between theory and measurement.

More recently, Chen et al. (2009) has argued that the theoretical X-ray line polarization adjustment used in the experiment is incorrect. He argued that the polarization may differ as much as 30% from the values given by the theory of Zhang et al. (1990). This assertion has now been refuted by Zhang et al. (2010).

While a 24% error in the theoretical values used for normalization of the experimental data would bring excellent agreement with the absolute cross sections, as mentioned by Chen (2008) and more recently by Gillaspy et al. (2011), there is doubt that this is the full or correct answer. First, the ratio of $3C/3D$ predicted by the most recent R-matrix calculations

is 2.74, which is 10% too small (while the earlier ratio was 10% too big). Second, the issue of calculating the correct cross section is less a matter of including all the many resonances, as is attempted by the R-matrix method, than a matter of correctly mixing the two upper levels of lines $3C$ and $3D$. An attempt to do this correctly was outlined by Gu (2009). Publication of this paper was unfortunately stopped by a referee who favored the R-matrix approach.

Progress has also been made concerning the $2p - 3s$ transitions. A recent measurement at Livermore concentrated on the radiative rate of the $M2$ transition. Predictions varied between 4.0 and 7.2 μs. The measurement narrowed this to 4.9 μs (Crepo López-Urrutia & Beiersdorfer 2010).

A recent effort has noted that Fe XVII dielectronic recombination satellites can be observed in *Chandra* spectra (Beiersdorfer et al. 2011). These can be used to determine the electron temperature experienced by the Fe^{16+} ions. Investigations will be needed to fully explore this diagnostic.

6. Charge Exchange

Historically, charge exchange has been considered relevant mostly as a recombination mechanism that reduces the average ionization fraction of a given plasma. In the past decade, charge exchange has been recognized as an X-ray line formation mechanism, which can add significant flux to the soft X-ray background (e.g., Wargelin et al. (2009)).

A variety of measurements of charge exchange cross sections of astrophysical ions colliding with neutral molecules have been carried out in recent years (Mawhorter et al. 2007; Djurić et al. 2008; Simcic et al. 2010a,b). These measurements employed the electron cyclotron resonance ion source at the Jet Propolusion Laboratory.

X-ray spectra produced by charge exchange have also been reported (Beiersdorfer et al. 2008; Frankel et al. 2009; Ali et al. 2010). In most cases, the theoretical description does not match the experimental data. The observed discrepancies are much worse than those afflicting the "Fe XVII problem" discussed above. An X-ray measurement of the Lyman transitions of argon and phosphor produced by charge exchange and reported by Leutenegger et al. (2010) demonstrated that even for such simple systems, there is no theoretical description that can match measurements: Theory predicts that the Lyman series emission for the two hydrogenlike ions should look similar, but the measurements showed unexpectedly that the two spectra look strikingly different. This means that X-ray production by charge exchange needs a lot more laboratory investigations before a satisfactory X-ray production model can be put together.

7. Conclusion

The need for accurate laboratory X-ray data persists unabatedly. However, specific needs have changed, as astronomers have shifted their sights to different objects. Photoionization spectra and line formation by charge exchange are two important new areas with many needs.

Work at LLNL was performed under the auspices of DOE under contract DE-AC52-07NA27344 and supported by NASA's APRA program under contracts NNH07AF81I and NNG06WF08I.

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