Importance of M-Shell Iron Dielectronic Recombination in Active Galactic Nuclei

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Abstract.
The recent launches of the X-ray satellite observatories, *Chandra* and *XMM-Newton*, have opened up a new era in studies of active galactic nuclei (AGNs). The high resolution spectroscopy made possible by these observatories has revealed the presence of previously unknown gas phases in AGNs. Here we discuss the importance for understanding these gas phases of M-shell iron dielectronic recombination (DR) via 3-3 core electron excitations. We also present recent laboratory M-shell iron DR measurements which we have carried out to improve our understanding of these recenlty discovered gas phases. The measurements have been carried out using the heavy-ion storage ring TSR at the Max-Planck-Institute for Nuclear Physics in Heidelberg, Germany.

ACTIVE GALACTIC NUCLEI

Active galaxies have a small core of emission embedded in an otherwise typical galaxy. The nuclei of these galaxies often emit more radiation than the entire rest of the galaxy. This emission is believed to be powered by accretion onto a supermassive black hole in the center of such galaxies [1].

The intense emission from these active galactic nuclei (AGNs) can photoionize the gas surrounding the central black hole. The resulting photoionized plasma has conditions dramatically different from an electron-ionized plasma. For example, in photoionization equilibrium a given ion forms at an electron temperature over an order of magnitude lower than the electron temperature at which the ion would form in collisional ionization equilibrium [2]. As a result, low temperature dielectronic recombination (DR) is typically the dominant recombination mechanism for determining the ionization structure of photoionized gas. This is to be contrasted with an electron-ionized plasma where high temperature DR typically dominates (e.g., Ref. [3]).

The importance of reliable low temperature DR data, particularly for M-shell iron ions, has been demonstrated recently by data from the X-ray satellite observatories *Chandra* and *XMM-Newton*. These two satellites, which were launched in 1999, have produced a revolution in X-ray astronomy. The large collecting area of their telescopes combined with their high resolution spectrometers have opened up a new era in X-ray spectroscopy of cosmic sources.

One particularly exciting result has been the detection of phases of gas surrounding AGN which were previously unknown. These phases manifest themselves in the collected spectra as a broad absorption feature around $\lambda \approx 16-17$ Å. The feature has been identified as an unresolved transition array (UTA) due mainly to $2p-3d$ inner-shell absorption in M-shell iron [4].

However, AGN photoionization models which are able to reproduce spectral lines due to second and third row elements fail to reproduce correctly the shape of the iron M-shell UTA feature. These models overpredict the average ionization stage of iron. This discrepancy is attributed to an underestimate in the relevant low temperature DR rate coefficients for M-shell iron [5, 6].

STATUS OF LOW TEMPERATURE DR DATA FOR M-SHELL IRON

DR is a two-step electron-ion recombination process which begins when a free electron collisionally excites an ion and is simultaneously captured. The excitation involves either a $\Delta N = 0$ or $\Delta N \geq 1$ transition of a core electron of the ion. The total energy of this recombined state lies in the continuum and the system may autoionize. DR is complete when the state radiatively relaxes, emitting a photon which reduces the total energy of the

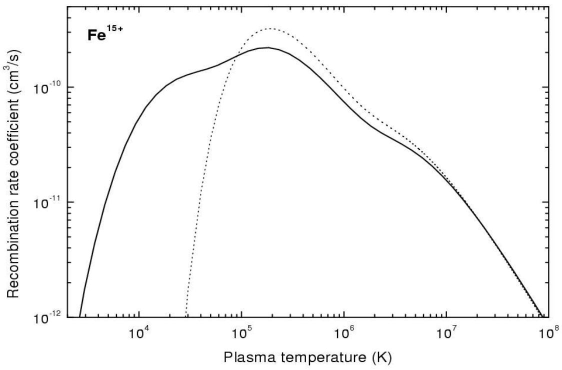

FIGURE 1. DR rate coefficient for Fe^{15+} forming Fe^{14+}. The solid line is dervied from the data of Linkemann et al. [9] and the dotted line is the recommended data of Arnaud and Raymond [7]. Adapted from Müller [10].

system to below its ionization threshold.

The most recent reviews of DR calculations for M-shell iron have been carried out by Arnaud and Raymond [7] and Mazzotta et al. [8]. Based on their surveys, these authors present lists of recommended DR rate coefficients. However, there are a number of shortcomings in the DR data which they use. First, most of published DR calculations were carried out for fusion related plasmas such as tokamaks and theta pinches or for stellar coronae. These are electron-ionized, high temperature plasmas and the DR data were computed with this in mind. Second, most of the calculations were carried out using either semi-empircal formulae or LS-coupling. Each of these methods is known to become unreliable for low temperature plasmas (e.g., Refs. [13, 14]). Third, most of these calculations were carried out before recent advances in computer technology. Hence approximations needed to be made to make the calculations computationally tractable. Some of the approximates made included improper handling (or even leaving out) the low energy resonances responsible for low temperature DR. To summarize the state of DR data for M-shell iron ions, we note that we are unaware of any published state-of-the-art theoretical rate coefficients for these ions.

Low temperature DR of M-shell iron is dominated by $\Delta N = 0$ core excitations (i.e., 3-3 transitions). We are aware of only one published laboratory measurement for low temperature DR of an M-shell iron ion. DR measurements were carried out for Fe^{15+} forming Fe^{14+} by Linkemann et al. [9]. Based on these results, Müller [10] has derived a DR rate coefficient which we show in Fig. 1. Also shown in this figure is the recommended DR rate coefficient of Arnaud and Raymond [7]. Fe^{15+} is predicted to form in a photoionized plasma over a temperature range of $T_e \sim 30,000 - 250,000$ K [11] (though the true temperature depends on a range of factors including the shape of the ionization spectrum and the metallicity of the gas [12]). What is clear from Fig. 1 is that at temperatures where Fe^{15+} is predicted to form, the recommended DR rate coefficient can be up to orders of magnitude smaller than the true value. As discussed in Sec. 1, a similar conclusion was proposed to explain why AGN spectral models do not correctly reproduce the iron M-shell UTA feature.

RECENT LABORATORY MEASUREMENTS

As demonstrated by Fig. 1, based on our laboratory work we have known since 1999 of the shortcomings in the current M-shell iron DR rate coefficients being used by astrophysicists to model photoionized plasmas. It is humourous to note that just as we were finally getting around to resuming DR measurements for M-shell iron ions, two papers were posted on xxx.lanl.gov/archive/astro-ph [5, 6] which through observations and modeling demonstrated just how important are reliable M-shell iron DR data for AGN.

Our laboratory measurements are carried out using the heavy-ion test storage ring (TSR) located at the Max Planck Institute for Nuclear Physics in Heidelberg, Germany [15]. TSR is the premier facility in the world for carrying out low temperature (i.e., low energy) DR measurements of M-shell iron. This is particularly true with the impending closing of CRYRING, the only other comparable storage ring currently operating.

With TSR one can store large ion currents and measurements can be carried out at low collision energies. This is to be contrasted with electron beam ion traps (EBITs) which are the other major modern laboratory method for studying DR. However, due to technical limitations on the electron beam confinement, EBITs have been unable to measure DR for collision energies below ~ 600 eV [16, 17]. This precludes using EBITs to study low energy DR of astrophysically important ions.

In the past, DR measurements were carried out on TSR using a single electron cooler to both cool the ions and to study DR. First the electron beam energy was selected to reduce the energy spread of the ions (i.e., cooling). Then the electron beam energy was increased or decreased (detuned from cooling) to measure the DR signal as a function of relative electron-ion collision energy. During detuning the ion beam energy spread increases, thereby reducing the resolution with which one can measure the DR resonance structure.

Recently, TSR has been upgraded with the addition of a second electron cooler (called the target). This allows one to use the first cooler to maintain a stored ion beam with a low energy spread and then to probe the stored

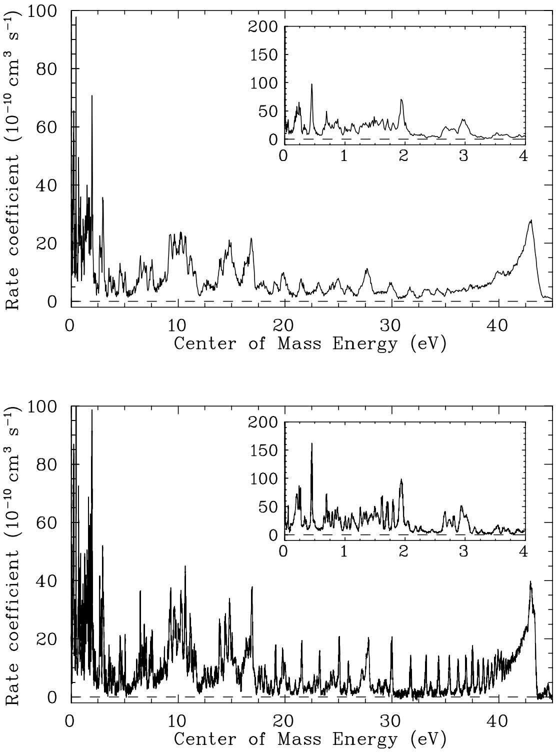

FIGURE 2. Preliminary resonance structure for 3-3 DR of Fe^{14+} forming Fe^{13+} measured using the TSR electron cooler (*top plot*) and using the TSR electron target with continual cooling (*bottom plot*).

ions using the target electron beam. In this way the ions maintain a low energy spread throughout the course of a DR measurement. This is discussed in more detail in the contribution by Schnell et al. to this conference proceedings.

In the top plot of Fig. 2 we show our recent electron cooler measurements for 3-3 DR of Fe^{14+} forming Fe^{13+}. In the bottom plot of Fig. 2 we show these same DR resonances measured using the new electron target in combination with continuous cooling by the electron cooler. One can immediately see the improved energy resolution which can be achieved using this new configuration.

Using data such as those shown in Fig. 2, we can produce low temperature DR rate coefficients for modeling AGN spectra (e.g., Fig. 1). However, the amount of M-shell ion DR data needed is prohibitively large and we will not be able to measure all the needed data. Theory must be relied upon to fill in the missing blanks.

To this end, our measurements provide valuable benchmarks for theorists to test the theoretical methods and computational approximations they use for their calculation of low energy DR of M-shell ions. Our research plan is to carry out such measurements for a number of M-shell iron ions. In this way the theorists will be able to test the validity of their methods for a range of M-shell ions. They will then be able to produce more reliable low temperature DR data for the vast number of astrophysically important M-shell ions which are needed.

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