Ion Storage Ring Measurements of Dielectronic Recombination for Astrophysically Relevant Fe^{q+} Ions

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Iron ions provide many valuable plasma diagnostics for cosmic plasmas. The accuracy of these diagnostics, however, often depends on an accurate understanding of the ionization structure of the emitting gas. Dielectronic recombination (DR) is the dominant electron-ion recombination mechanism for most iron ions in cosmic plasmas. Using the heavy-ion storage ring at the Max-Planck-Institute for Nuclear Physics in Heidelberg, Germany, we have measured the low temperature DR rates for Fe^{q+} where $q = 15$, 17, 18, and 19. These rates are important for photoionized gases which form in the media surrounding active galactic nuclei, X-ray binaries, and cataclysmic variables. Our results demonstrate that commonly used theoretical approximations for calculating low temperature DR rates can easily under- or over-estimate the DR rate by a factor of ~ 2 or more. As essentially all DR rates used for modeling photoionized gases are calculated using these approximations, our results indicate that new DR rates are needed for almost all charge states of cosmically abundant elements. Measurements are underway for other charge states of iron.

INTRODUCTION

Heavy-ion storage rings, coupled with electron cooling techniques, are an important laboratory tool for studying electron collisions with highly charged ions (Müller & Wolf 1997). Of particular interest for astrophysics is the ability of storage rings to study low energy dielectronic recombination (DR), which at the low electron temperatures predicted for photoionized cosmic plasmas (Kallman *et al.* 1996) is the dominant electron-ion recombination process for most ions (Arnaud & Rothenflug 1985; Arnaud & Raymond 1992). Using storage rings, those DR resonances important in photoionized plasmas can be measured by merging the electron and ion beams. Using a co-linear geometry one can achieve near zero eV relative collision energies.

Storage rings are unique for their ability to study low energy DR of highly charged ions with a narrow energy resolution. Common laboratory techniques for measuring DR such as electron beam ion traps (Beiersdorfer *et al.* 1992) and tokamak plasmas (Bitter *et al.* 1993) can produce highly charged ions, but cannot simultaneously reach near zero relative velocities. Crossed electron-ion beams techniques also can achieve neither the required low relative velocities nor a narrow enough energy resolution for resolving DR resonance structure (Müller *et al.* 1987; Savin *et al.* 1996). A merged electron-ion beams technique is the only way to achieve the desired near zero eV collision energies. DR measurement can be carried out using a single-pass technique which merges an electron and ion beam for some distance, demerges them, and then separates the recombined ions from the primary beam and detects both beams separately (e.g., Andersen *et al.* 1992). One disadvantage of this method is the low signal rate. Also, for ions with partially-filled shells, data analysis is usually complicated by the presence of metastable ions in the beam.

Ion storage rings are the optimal method for measuring low energy DR. Storing the ions, one can accumulate ions and thus increase the signal rate. For our Fe^{17+} measurement (Savin *et al.* 1997), we stored currents of 30-50 μA as compared with typical ion currents of $\lesssim 1$ μA in single-pass experiments (Andersen, Bolko, & Kvistgaard 1990). Ions can typically be stored on the order of tens of seconds which is long enough for essentially all metastable ions to relax to their ground state before begining measurements. Electron cooling techniques can be used on the stored ions (Poth 1990). Cooling reduces the energy spread of the ions, and more ions can be stored. Using an adiabatically expanded electron beam (Pastuszka *et al.* 1996) in combination with the merged beams geometry results in typical electron energy spreads of $k_B T_\perp \sim 18$ meV transverse to

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the beam velocity and $k_B T_{\parallel} \sim 0.18$ meV longitudinally (Savin *et al.* 1997). With this narrow energy spread one can resolve a large number of individual DR resonances and determine their energies and strengths accurately.

ASTROPHYSICAL MOTIVATION

Photoionized plasmas form in planetary nebulae, H II regions, cold nova shells, stellar winds, and the intergalactic medium (IGM) and in the media surrounding active galactic nuclei (AGN), X-ray binaries, and cataclysmic variables. Spectroscopic observations of these objects can address fundamental questions in astrophysics. For example, observations of the IGM yields information on the chemical evolution of the universe (Giroux & Shull 1997) and AGN, which are thought to contain supermassive black holes, can be used to study General Relativity (Nandra *et al.* 1997).

Meeting the need of accurate atomic data is extremely timely. The upcoming launches of the *Advanced X-Ray Astrophysics Facility* (*AXAF*; Markert 1993) and the *X-Ray Multimirror Mission* (*XMM*; Brinkman 1993) will put in orbit satellites which will collect X-ray spectra from extrasolar objects of a higher quality and resolution than has been achieved in the past. These spectra are expected to revolutionize the field of X-ray astrophysics. Unambiguous interpretation of the collected spectra, though, will be impeded by errors and uncertainties in the atomic data base.

Models of photoionized plasmas require accurate DR rates for hundreds of ions. Laboratory measurements can provide only a fraction of the needed rates and modelers must rely on theoretical calculations. In the past, theorists calculated DR rates for a select number of ions along an isoelectronic sequence and then interpolated along the sequence for a needed DR rate. However, atomic structure does not scale smoothly along an isoelectronic sequence. Thus it is necessary explicitly to calculate all the needed DR rates. Laboratory measurements must be selected to test these calculations in the most efficient manner possible.

We have chosen to study DR of iron because iron is the highest-Z cosmically abundant element and an important constituent of almost all astronomical plasmas. Iron plays a pivotal role in determining the line emission and thermal and ionization structure of photoionized plasmas (Kallman *et al.* 1996; Hess, Kahn, & Paerels 1997). Also, due to its high Z, iron is the last cosmically abundant element to lose all its electrons. As such, iron can be used spectroscopically to probe extreme conditions where all other important elements have already been stripped to bare nuclei.

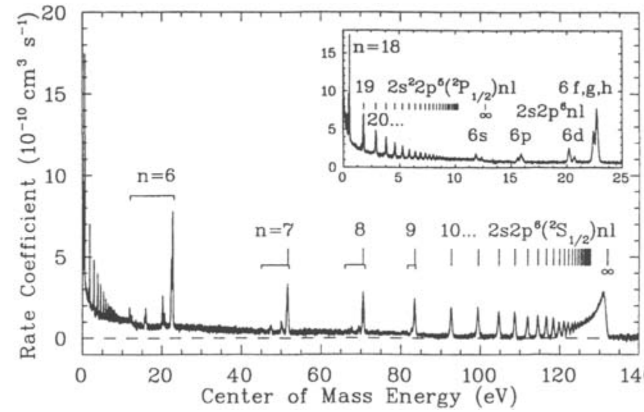

Figure 1: Measured Fe^{17+} to Fe^{16+} recombination rate coefficient versus collision energy. The nonresonant "background" is due to radiative recombination and charge transfer with residual gas in the storage ring.

EXPERIMENTAL PROGRAM

Using the heavy-ion test storage ring (TSR; Habs *et al.* 1989) at the Max Planck Institute for Nuclear Physics in Heidelberg, Germany, we have undertaken to measure the low temperature DR rates for a wide range of iron ions. These measurements will provide a comprehensive set of benchmark measurements for a number of important isoelectronic sequences. To date we have measured DR for Fe^{15+} (Linkemann *et al.* 1995), Fe^{17+} (Savin *et al.* 1997), Fe^{18+}, and Fe^{19+} (Savin *et al.*, in preparation).

DR is a two-step electron-ion recombination process that begins when a free electron collisionally excites an ion, via an $nl_j \to n'l'_{j'}$ excitation of a bound core electron, and is simultaneously captured. DR is complete when this state emits a photon which reduces the energy of the recombined system to below its ionization limit. Low energy DR usually involves a $\Delta n = 0$ excitation of a core electron.

DR measurements using a storage ring are carried out by merging, in one of the straight sections of the ring, an ion beam with an electron beam. After demerging, any recombined ions formed are magnetically separated from the stored ions and directed onto a detector. The relative electron-ion collision energy can be precisely controlled and the recombination signal is measured as a function of this energy. Detailed descriptions of DR measurement techniques using storage rings have been given elsewhere (e.g., Kilgus *et al.* 1992; Lampert *et al.* 1996).

Our recent measurement of Fe^{17+} DR (Savin *et al.* 1997) is shown in Figure 1. Fe^{17+} can undergo $\Delta n = 0$ DR via two different channels,

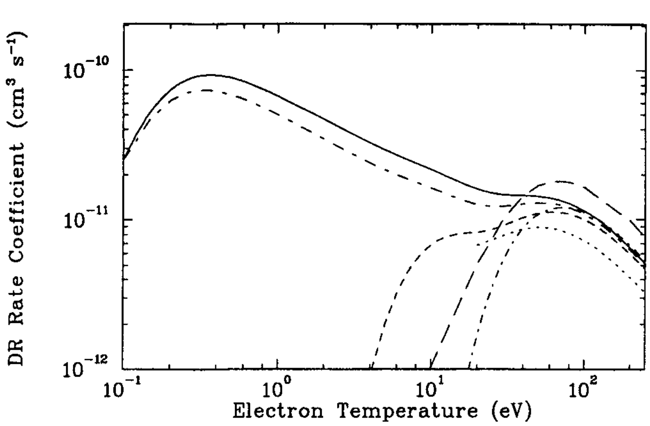

Figure 2: Fe^{17+} to Fe^{16+} Maxwellian-averaged $\Delta n = 0$ DR rate coefficients. See text for explanation.

$$Fe^{17+}(2s^2 2p^5[^2P_{3/2}]) + e^- \rightarrow \begin{cases} Fe^{16+}(2s^2 2p^5[^2P_{1/2}]nl) & (n \geq 18) \\ Fe^{16+}(2s 2p^6[^2S_{1/2}]nl) & (n \geq 6). \end{cases} \quad (1)$$

The radiative stabilization of either of the above Fe^{16+} autoionizing states to bound configurations of Fe^{16+} leads to DR resonances for electron-ion collision energies between 0 and 132 eV.

We have integrated the measured DR resonance strengths and energies with a Maxwellian electron velocity distribution to yield a total Fe^{17+} $\Delta n = 0$ DR rate coefficient as a function of $k_B T_e$ (Figure 2, upper solid line). The estimated total experimental uncertainty in our inferred DR rate is better than 20%. Various theoretical DR rates are also shown in Figure 2. At $k_B T_e \sim$ 15 eV, near where Fe^{17+} is predicted to peak in fractional abundance in photoionized gas with cosmic abundances (Kallman *et al.* 1996), our measured DR rate is a factor of $\sim$ 2 larger than the calculations of Roszman (1987; long dashed curve), Chen (1988; dotted curve), and Dasgupta & Whitney (1990; short dashed curve). These theoretical rates all tend rapidly to zero at $k_B T_e < 20$ eV because they have not included DR via $2p_{1/2} \rightarrow 2p_{3/2}$ fine-structure core excitations.

At higher plasma temperatures, where the $2p_{1/2} \rightarrow 2p_{3/2}$ channel is unimportant, significant discrepancies exist between our inferred rate and the calculations of Chen and Roszman. Chen underestimates the DR rate by a factor of $\sim$ 1.5. This may be partly due to approximations which ignore DR via core excitations to levels with $l > 8$. Including these additional DR channels would increase the calculated DR rate. Roszman overestimates the DR rate by a factor of $\sim$ 1.6. This may be partly due to the extrapolation technique to high n levels used to calculate the DR rate. If the extrapolation was initiated for $n < 18$, as is likely, this leaves out an important autoionization channel which reduces the DR rate. However, it is likely that Roszman also made many of the same approximations as Chen and so the true source of the discrepancy is unclear. The low temperature rate of Roszman goes to zero faster than that of Dasgupta & Whitney because Roszman calculated that DR via $2s2p^5nl$ configurations becomes energetically possible at $n = 7$ whereas Dasgupta & Whitney find DR starts at $n = 6$. Our measurements show that DR via this channel is allowed for $n \geq 6$.

The agreement between our inferred rate and that of Dasgupta & Whitney is probably serendipitous. They made many of the same approximations as Chen and also began their extrapolations at $n = 16$. It is unclear, but it may be that the agreement is a result of approximations roughly canceling one another out. What is clear is that comparisons only of rate coefficients cannot be used to distinguish definitively between the various theoretical techniques. Measurements of DR resonance strengths and energies are needed to provide benchmarks for the detailed atomic physics which goes into calculating DR rates.

Using the data shown in Figure 1, we have extracted DR resonance strengths and energies for comparison with theory (Savin *et al.*, in preparation). A direct comparison of these results with the work of Chen, Roszman, and Dasgupta & Whitney is not possible because they do not present resonance strengths resolved as a function of n. We have carried out a new calculation which includes the $2p_{1/2} \rightarrow 2p_{3/2}$ channel and accounts for DR for $l \leq 12$. The calculated resonance strengths for DR via the $2p_{1/2} \rightarrow 2p_{3/2}$ agree with experiment to within $\lesssim$30% which is larger than the estimated 20% total experimental uncertainty limits. Our measurements agree with the new calculations to within $\lesssim$20% for DR via the $2s \rightarrow 2p$ channel. Using the new calculations we have generated a DR rate coefficient which agrees well for $k_B T_e \gtrsim 60$ eV, but differ by $\sim$ 30% below 60 eV (Figure 2, lower solid curve; Savin *et al.* 1997).

ASTROPHYSICAL IMPLICATIONS

Photoionized plasmas are most commonly modeled using the DR rates of Aldrovandi & Péquignot (1973), Shull & van Steenberg (1982), Nussbaumer & Storey (1983), Arnaud & Rothenflug (1985), and Arnaud & Raymond (1992). But for a few exceptions, all of these DR rates have been calculated using either pure LS-coupling or the Burgess formula approximation (Burgess 1965). Neither approximation accounts for DR via fine-structure core excitations ($nl_j \rightarrow nl_{j'}$). If an ion forms at a temperature $k_B T_e \lesssim \Delta E_{fs}$, where ΔE_{fs} is the energy of the fine-structure core excitation, existing DR rate coefficients can under-estimate the DR rate by rather large factors. For ions which form at $k_B T_e \gtrsim \Delta E_{fs}$, the approximations used for most of the existing DR rates could easily result in under- or over-estimating the DR rate by a significant factor.

In conclusion, there are major uncertainties in the low temperature DR rates for most ions with partially filled shells. Determining the magnitude of the effect these uncertainties will have on modeling and interpreting spectra of photoionized plasmas requires reliable DR rates for all the relevant charge states. Our laboratory studies of iron ions will help to provide many of the needed DR rates; and for those charge states not measured, our work will provide valuable benchmarks to test the various techniques for calculating DR along isoelectronic sequences.

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