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Can Heavy Ion Storage Rings Contribute to Our Understanding of the Charge State Distributions in Cosmic Atomic Plasmas?

Daniel Wolf Savin
Columbia Astrophysics Laboratory, MC 5247, 550 West 120th Street, New York, NY 10027, USA
E-mail: `savin@astro.columbia.edu`

Abstract.
Interpreting cosmic spectra from ionized atomic gas hinges on our understanding the underlying physical processes which produce the observed spectra. Of particular importance are electron-ion recombination and electron impact ionization. These processes control the charge state distribution (CSD) of the gas. The CSD is intimately tied in to the observed spectral features and can also affect the thermal structure of the plasma. Heavy ion storage rings play a crucial role in improving our knowledge of electron-ion recombination and electron impact ionization, thereby deepening our understanding of the cosmos. Here we will review some of the astrophysical motivation behind laboratory astrophysics research with atomic ions at heavy ion storage rings. We also present some recent results, discuss some of the astrophysical implications, and present future astrophysical needs.

1. Introduction

The initial title proposed by the conference organizers for this progress report was “Laboratory Astrophysics at Heavy Ion Storage Rings”. That is an extremely broad and very rich subject, more than can be covered in an 8 page progress report. So we will begin by defining laboratory astrophysics to demonstrate the breadth of the field and to help illustrate the range of contributions which storage rings can make. Then we will focus on one particular example.

Simply put, laboratory astrophysics consists of ground based theoretical and experimental work motivated by problems in astrophysics. Because astronomy is primarily an observational science detecting photons, a central focus of laboratory astrophysics is on the atomic, molecular, and solid state processes which produce the observed spectrum. Additionally, our knowledge of the universe depends on understanding the evolution of matter (nuclear and particle physics) and the dynamical processes which shaped it (plasma physics).

Heavy ion storage rings can be used for studies in a range of areas in laboratory astrophysics. The richness of this approach is demonstrated by the number of storage ring talks at this conference relevant to laboratory astrophysics and the resulting papers which are included in this *Journal of Physics: Conference Series* issue. In the area of molecular laboratory astrophysics, there are papers by Daniel Zajfman, Wolf Dietrich Geppert, and Holger Kreckel. In the area of nuclear laboratory astrophysics, there is the paper by Fritz Bosch. And in the area of atomic laboratory astrophysics, there are the papers by Reinhold Schuch and by us.

Here specifically we discuss experimental work using the heavy ion Test Storage Ring (TSR) at the Max-Planck-Institute for Nuclear Physics (MPI-K) in Heidelberg, Germany. This work aims to improve our understanding of the charge state distribution (CSD) in cosmic atomic plasmas. Since it is acceptable in *The Astrophysical Journal* to publish papers with questions for titles, we have decided to honor that tradition by posing our title as a question. The rest of this paper is organized as follows: Section 2 discusses the different types of cosmic plasmas one encounters in astrophysics and the relevant atomic physics determining the CSD. We focus on the electron-ion recombination process of dielectronic recombination (DR), which is described in Section 3. Section 4 discusses recent active galactic nuclei observations which indicate the need for new low temperature DR data for iron ions with a partially filled M-shell. Recent TSR DR work on M-shell iron is presented in Section 5, and Section 6 discusses how storage ring DR measurements have helped to improve the available DR data. In Section 7 we discuss the impact of these new DR data on ionization equilibrium calculations for cosmic atomic plasmas. Lastly, Section 8 discusses the atomic data needs remaining in order to further improve our ability to calculate fractional ionic abundance (i.e., CSDs) of elements in ionization equilibrium.

2. Cosmic Atomic Plasmas

Cosmic atomic plasmas can be divided into two broad classes: collisionally ionized and photoionized. Collisionally ionized gas is found in the sun, stars, supernova remnants, the interstellar medium, galaxies, and the intracluster medium in clusters of galaxies. Photoionized gas is found in planetary nebulae, H II regions, cold nova shells, cataclysmic variables, X-ray binaries, and active galactic nuclei (AGNs). Many cosmic plasmas are in ionization equilibrium or quasi-equilibrium, and are optically thin, of low density, and dust free. Hence time dependence, radiative transport, three-body recombination, and surface reactions can be ignored. These are the conditions we will focus on.

In collisionally ionized gas, ionization is due to electrons. As a result, in ionization equilibrium an ion forms at a temperature roughly half of its ionization potential and high temperature DR is the dominant electron-ion recombination mechanism for most ions [1]. In photoionized gas, the ionization is driven by the radiation field and not by electrons. As a result, the electrons can thermalize at a much lower temperature than in collisionally ionized gas and in photoionization equilibrium a given ion forms at a temperature roughly one twentieth of its ionization potential [2, 3]. Under these conditions, low temperature DR is the dominant electron-ion recombination mechanism for most ions. Atomic processes which are important for determining the ionization balance in both collisionally ionized and photoionized gas include radiative recombination (RR), charge transfer recombination and ionization (primarily for ions of charge 4 or less colliding with atomic H and He), and innershell ionization followed by subsequent Auger ionization to higher charge states.

The temperature differences between collisional ionization equilibrium (CIE) and photoionization equilibrium (PIE) are shown in Figures 1 and 2. Figure 1 shows the calculated fractional ionic abundance for Fe in CIE. Figure 2 shows the same, but for PIE of gas with cosmic abundances illuminated by a 10 keV bremstrahlung ionizing spectrum [2]. The solid curves in the top panel of each figure show the results using state-of-the-art DR and RR data [4, 5], respectively, for bare through Na-like ions. The DR and RR data for the remaining charge states and the electron impact ionization (EII) data are from [6]. Additional discussion of these figures is given in Section 7.

In ionization equilibrium, the ionization and recombination rates are equal. The accuracy of these rates determines the reliability of any CSD calculations. Accurate CSDs are needed for relative abundance determinations inferred from observed spectral line intensities. For a given line I_{line}, we can write $I_{line} \propto n_q n_e \alpha_{line} = (n_q/n_A)(n_A/n_H)(n_H/n_e)n_e^2\alpha_{line}$ where n_q is the density of charge state q for element A; n_A, n_H, and n_e are the density of element A,

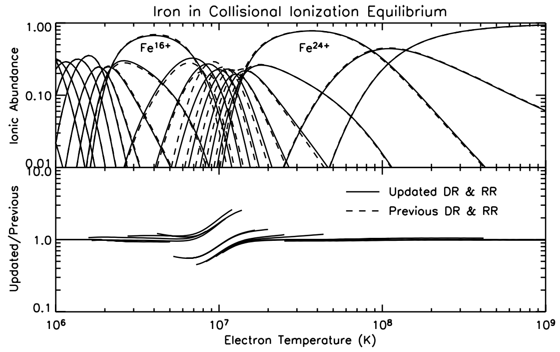

Figure 1. Calculated fractional ionic abundances for Fe in collisional ionization equilibrium. See Sections 2 and 7 for details.

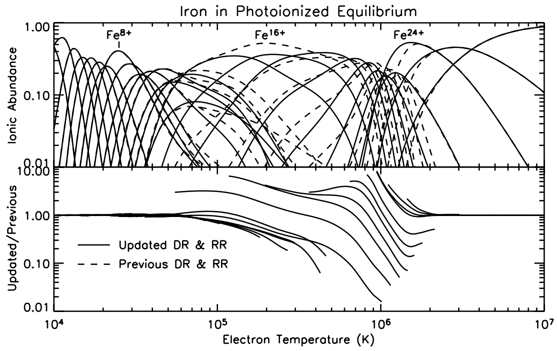

Figure 2. Calculated fractional ionic abundances for Fe in photoionization equilibrium. See Sections 2 and 7 for details.

hydrogen, and electrons, respectively; and α_{line} is the rate coefficient for producing the observed line. Rewriting this, we find $n_A/n_H \propto 1/(n_q/n_A)$. Thus, meaningful relative abundance determinations require reliable CSDs. Errors in recombination and ionization data can also cause uncertainties in predicted line ratios for collisionally ionized gas. In CIE, the ionization and recombination rates are equal, giving $n_e n_q C_q = n_e n_{q+1} \alpha_{q+1}$, where C_q is the ionization rate coefficient for charge state q and α_{q+1} is the electron-ion recombination rate coefficient for charge state $q+1$. Rewriting gives $n_{q+1}/n_q = C_q/\alpha_{q+1}$, thus making clear the importance of accurate recombination and ionization data.

3. Dielectronic Recombination (DR)

DR is a two-step recombination process that begins when a free electron approaches an ion, collisionally excites a bound electron of the ion and is simultaneously captured into a Rydberg level n. The electron excitation can be labeled $Nl_j \rightarrow N'l'_{j'}$ where N is the principal quantum number of the core electron, l its orbital angular momentum, and j its total angular momentum. The intermediate state, formed by simultaneous excitation and capture, may autoionize. The DR process is complete when the intermediate state emits one or more photons which reduces the total energy of the recombined ion to below its ionization limit. Conservation of energy requires that for DR to go forward $E_k = \Delta E - E_b$ where E_k is the kinetic energy of the initial electron, ΔE the excitation energy of the initially bound electron in the presence of the captured electron, and E_b the binding energy released when the incident electron is captured. Because ΔE and E_b are quantized, DR is a resonant process. Low temperature DR is typically defined as occurring for $E_k \ll \Delta E$ and high temperature DR for $E_k \sim \Delta E$.

The DR rate coefficient α for a plasma with a Maxwell-Boltzmann (MB) electron energy distribution (EED) at a temperature T_e is given by $\alpha(T_e) = \int \sigma_{DR}(E) v(E) P(T_e, E) dE$. Here $\sigma_{DR}(E)$ is the DR cross section at energy E, $v(E)$ the relative electron-ion collision velocity, and $P(T_e, E)$ the MB EED. DR resonances are generally extremely narrow in width and the cross section can be approximated as a series of delta functions given by $\sigma_{DR}(E) = \sum_r \hat{\sigma}_r \delta(E - E_r)$ where the sum is over all resonances r, $\hat{\sigma}_r$ is the resonance r cross section integrated over energy (commonly called the resonance strength), and E_r is the resonance energy. Inserting this expression and the well known MB EED function into the integral for $\alpha(T_e)$ yields $\alpha(T_e) \propto \sum_r \exp(-E_r/k_B T_e)$ where k_B is the Boltzmann factor and we have also made use of the $1/E_r$ dependence in $\hat{\sigma}_r$. Thus one can readily see the exponential dependence of $\alpha(T_e)$ on uncertainties in E_r.

4. Active Galactic Nuclei (AGNs)

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. In the center lies a supermassive black hole which is surrounded by a disc of material being accreted onto the black hole. This material is drawn into the black hole, converting the gravitational potential energy into kinetic energy and ultimately into X-rays. These X-rays then leave the vicinity of the nucleus and photoionize the surrounding material. It is thought that most galaxies possess a supermassive black hole in their center. Furthermore it is believed that all galaxies have all gone through an AGN phase in the course of their evolution.

Spectroscopic studies of AGNs have undergone a revolution in the past decade. This can readily be seen in observations of the AGN NGC 3783. Observations with the X-ray satellite observatory *ASCA* (launched in 1993) show broad absorption features but no individual line features (see figure 3 of [7]). In 1999 the X-ray observatories *Chandra* and *XMM-Newton* were both launched. These satellites have telescopes with larger collecting area and spectrometers with higher resolving power than those onboard *ASCA*. As a result AGN spectra can now be collected which are rich in line absorption (see figure 7 of [8]).

A particularly exciting discovery in AGN studies, first published in 2001, has been a broad absorption feature between $\lambda \approx 15 - 17$ Å which is due mainly to $2p - 3d$ inner shell photoabsorption in Fe ions with a partially filled M-shell [9]. The shape, central wavelength, and equivalent width of this feature can be used to diagnose the properties of these AGN warm absorbers [10]. However, models which match AGN spectral features of abundant second and third row elements over-predict the Fe ionization stage [8]. This has been attributed to an underestimate of the low temperature DR rate coefficients in Fe M-shell ions [8]. Subsequent modeling studies support this hypothesis [11, 12].

The shortcomings of the DR data used in the models is a symptom of the sometimes poor communication between the atomic physics and astrophysics communities. In 1999, it was already clear from TSR measurements on Fe^{15+} that there were problems with the recommended low temperature DR rate coefficients [13]. This is not surprising considering that the Fe M-shell DR data used for the models were calculated for high temperature plasmas [14, 15]. However, this information never made it into the astrophysics community.

Partly as a result of the recognized need for reliable Fe M-shell DR rate coefficients, in the last couple of years there has been a concerted experimental and theoretical effort to generate reliable DR data for Fe M-shell ions [16, 17, 18, 19]. Here we report on some of the recent TSR experimental progress in this area.

5. Test Storage Ring (TSR) DR Measurements

DR measurements are carried out by merging, in one of the straight sections of TSR, a circulating ion beam with an electron beam for a distance of ≈ 1.5 m. The electrons are demerged from the primary and recombined ion beams using toroidal magnets. After demerging, recombined ions are separated from the stored ions using a dipole magnet and directed onto a detector. The relative electron-ion collision energy can be precisely controlled and the recombination signal measured as a function of this energy. Further details of the merged-beams technique to measure DR using TSR can be found in [16, 19, 20, 21] and the references therein.

The TSR collaboration has now carried out measurements for DR of the Fe M-shell ions Fe^{15+} [13, 22], Fe^{14+} [19], Fe^{13+} [16, 21], Fe^{10+} [23], Fe^{9+} [23], Fe^{8+} [21], and Fe^{7+} [21]. We use the labeling convention here of giving the charge state of the ion before recombination. Figures 3 and 4 present our recently published results for Fe^{14+} [19], and Fe^{13+} [16, 21], respectively. The solid curves show our TSR results for each ion. The resonances in the strongest $\Delta N = 0$ DR

Rydberg series are noted in each figure along with the series limit. The shaded curves represent the recent multiconfiguration Breit-Pauli (MCBP) results of [5, 17]. As can be readily seen from the figures, we find poor agreement between experiment and theory for energies up to $\sim 25-30$ eV. Theory does not correctly predict the strength of many DR resonances which are seen in the measurements. The differences between theory and experiment at the series limit is due to field ionization in the experiment limiting the maximum n level of the recombined ion which can be detected.

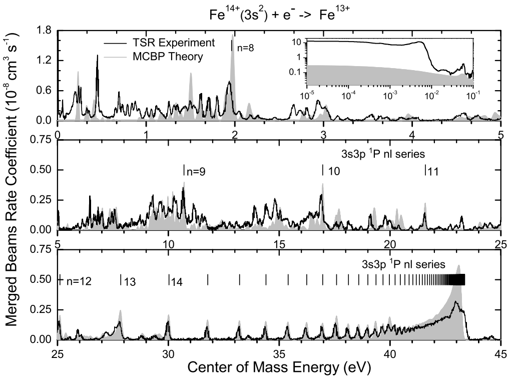

Figure 3. TSR measurements and MCBP calculations for DR of Fe^{14+} forming Fe^{13+} [19]. See section 5 for details.

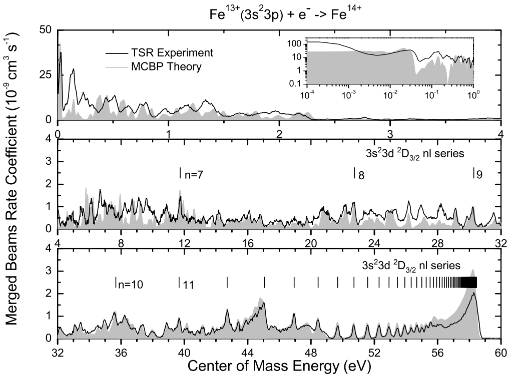

Figure 4. TSR measurements [16] and MCBP calculations [17] for DR of Fe^{13+} forming Fe^{12+}. See section 5 for details.

We can use the experimental and theoretical data in Figures 3 and 4 to produce rate coefficients for plasma modeling as is explained in [16, 19]. Figures 5 and 6 show the resulting rate coefficients. The solid curves show our experimental results and the error bars the total experimental uncertainty (systematic and statistical) at a 90% confidence limit. The dashed lines are the recommended DR data of [15] which until recently were the data used for analyzing AGN spectra. As expected, based on the earlier experimental work of [13, 22] and the hypothesis of [8], at temperatures relevant for photoionized gas the previously recommended DR rate coefficients lie factors of a few to orders of magnitude below the experimentally derived rate coefficients. The dot-dashed curves show the modern DR calculations of [17] and [19] using MCPB theory. The dotted curves show for comparison the recommended RR rate coefficients of [15]. Plotted in both figures is the temperature range where each ion is predicted to form in PIE [3]. For Fe^{13+} DR resonance data were collected at energies high enough for us to produce an experimentally-derived rate coefficient relevant for CIE [1] and the corresponding temperature range is plotted in Figure 6.

Figures 5 and 6 show that modern DR theory can be up to $\sim 30-40\%$ smaller than our experimental results at temperatures relevant for PIE [17, 19]. This is larger than the typically $\lesssim 30\%$ total experimental uncertainties at a 90% confidence level. Another way to view this is that the Fe^{13+} and Fe^{14+} MCBP theoretical data need to be multiplied by factors of $\sim 1.4-1.7$ in order to match the experimentally-derived DR rate coefficients at temperatures relevant for PIE. Without future theoretical advances, it is likely that similar scalings will be necessary for other M-shell ions in photoionized gas. This is an important point to keep in mind because the resources do not exist to measure DR for every M-shell ion needed for astrophysics. Modelers are going to have to rely on theory to produce the vast majority of the needed DR data.

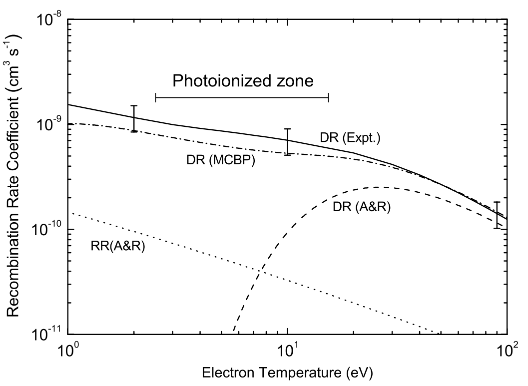

Figure 5. Experimentally-derived and theoretical DR rate coefficients for Fe^{14+} forming Fe^{13+} [19]. See section 5 for details.

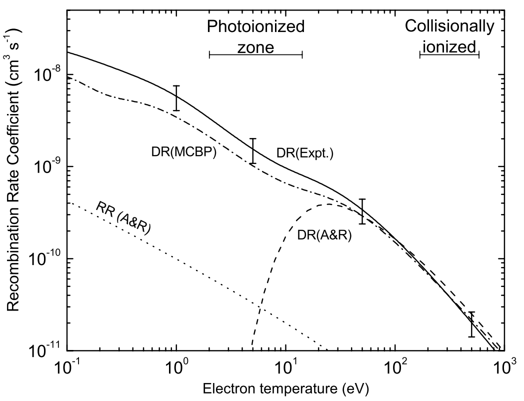

Figure 6. Experimentally-derived and theoretical DR rate coefficients for Fe^{13+} forming Fe^{12+} [16, 17]. See section 5 for details.

6. How Storage Ring Work improves DR Data

Producing reliable DR rate coefficients experimentally and theoretically has been a challenge for many years. Plasma measurements using tokamaks and theta-pinches have been unreliable and until recently theoretical calculations from different groups had failed to converge [24]. Experiment has improved due in part both to the advent of storage ring technology coupled with electron coolers and to electron beam ion traps (EBITs). Theory has improved due in part to the recent dramatic increase in computational power. A stark example of the before and after situation is shown in Figure 3 of [24] which shows for DR of L-shell oxygenlike Fe^{18+} both the poor agreement of plasma measurements and pre-existing theory with storage ring results, as well as the poor agreement of the various pre-existing theories with one another. The figure also presents the convergence between storage ring results and modern DR theory.

Recently there have been major advances in DR experiment and theory. Modern calculations now exist for K-, L-, and some M-shell ions [4, 25, 26]. Additionally K-shell ions have been well studied using EBITs and storage rings and agreement between experimental and theoretical DR rate coefficients is on the order of $\sim 20\%$ [27, 28]. However, modern L- and M-shell theory can still be off for low E DR resonance positions. For L-shell ions theory can be less reliable for DR resonances at $E_k \lesssim 3$ eV and for M-shell ions for $E_k \lesssim 25 - 30$ eV (e.g, Section 5). These uncertainties in the theoretical resonance energies can lead to factors of 2 or larger errors in the calculated rate coefficients [29]. Experiments are often the only reliable way to generate low temperature DR rate coefficients. At high temperatures, theoretical and experimental DR rate coefficients agree to within $\sim 35\%$ for the few systems studied. But in general for both low and high temperature DR little experimental work exists for the L-shell B-, C-, N-, O-, F-, and Ne-like ions as well as for all of the M-shell isoelectronic sequences (except Na-like).

7. Ionization Equilibrium Calculations

Ionization equilibrium has been defined in Section 2. Updating models to reflect the current state of atomic data is a continual process and there have been a number of models published over the years for both collisionally ionized gas [1, 6, 15, 30, 31, 32] and photoionized gas [2, 3].

Recently state-of-the-art DR and RR rate coefficients have become available for all ions from bare to Na-like of all elements from H through Zn [4, 5, 25, 26, 33]. These data have been incorporated into models for both collisionally-ionized [1] and photoionized [2] gas. Using these updated DR and RR data, the solid curves in the top panel in Figures 1 and 2 present the calculated CSD for Fe for each class of plasma. Also shown by the dashed curves in these two figures are the CSD results using the previously recommended set of DR and RR data [6]. The bottom panel in each figure gives the ratio of the fractional ionic abundances using the updated recombination data over the fractional ionic abundances using the previously recommended recombination data. A large difference is readily apparent for the L-shell ions. Little difference is seen for any of the M-shell ions because the recombination data have yet to be updated (though this is now possible for some of the Fe M-shell ions using the recent work of [18]).

8. Future Needs

Reliable CSD calculations for cosmic plasmas continue to need vast quantities of updated atomic data. For L- and M-shell ions laboratory measurements are needed to benchmark the calculations for the many isoelectronic sequences with few to no experimental results. Heavy ion storage rings are well suited for this work. Also, for many ions, storage ring measurements remain the only way to produce reliable low temperature DR rate coefficients. This is a direct result of uncertainties in current atomic structure calculations. A major increase in the reliability of low temperature DR theory is going to require a breakthrough in atomic structure theory.

Though we have not had time or space to discuss other atomic data needs in any depth, CSD work is also going to require an updating of the EII data available. Most of the experimental work that exists uses beams with a significant (often unknown) metastable contamination. That limits the ability to use the experimental results to benchmark theory and calls into question the reliability of the currently recommended EII data [1, 31, 34]. Heavy ion storage rings can help to address this issue and have been used to carry out EII measurements of a number of systems [22, 39, 40, 41].

Continuing the list of needs, state-of-the-art RR data do not exist for most M-shell ions. Photoionization data are important in many situations. State-of-the-art results are needed for innershell ionization and the subsequent fluorescence and Auger yields [35, 36, 37]. Lastly, charge transfer data for ions up to quadruply ionized colliding with H and He are needed [1, 31, 38] In producing all the required data, researchers should aim for accuracies of better than 35% to at least match the quality of the best state-of-the-art experimental and theoretical results.

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