Recombination and Ionization Measurements at the Heidelberg Heavy Ion Storage Ring TSR

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Abstract

Reliable ionization balance calculations are needed to analyze spectra from a wide range of cosmic sources including photoionized objects such as AGNs and X-ray binaries and electron ionized objects such as stars, supernovae, galaxies, and clusters of galaxies. These theoretical charge state distributions (CSDs) depend in turn upon the underlying atomic data. Of particular importance are reliable rate coefficients for dielectronic recombination (DR), which is the dominant electron-ion recombination mechanism for most ions, and for electron impact ionization (EII). We are carrying out DR and EII measurements of astrophysically important ions using the heavy ion Test Storage Ring (TSR) at the Max-Plank-Institute for Nuclear Physics in Heidelberg, Germany. The storage ring measurements are largely free of the metastable contamination found in other experimental geometries. Storage ring measurements therefore result in more precise DR and EII reaction rate measurements. The measured rate coefficients can be used in plasma modeling as well as in the benchmarking of theoretical atomic calculations. Here we report some recent DR and EII measurements.

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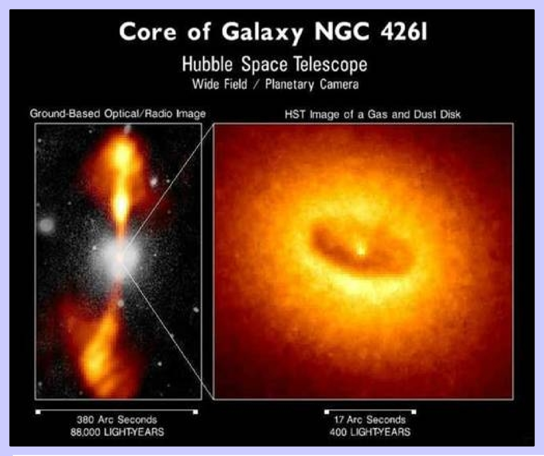
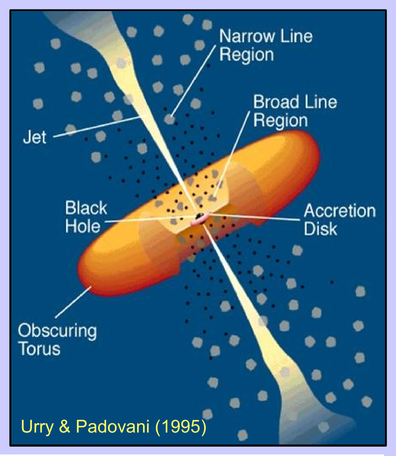
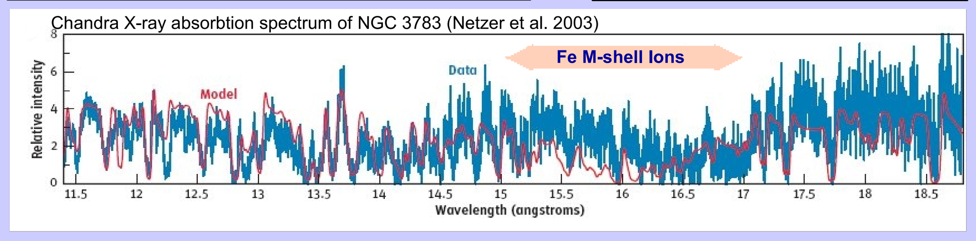
Astrophysical Motivation

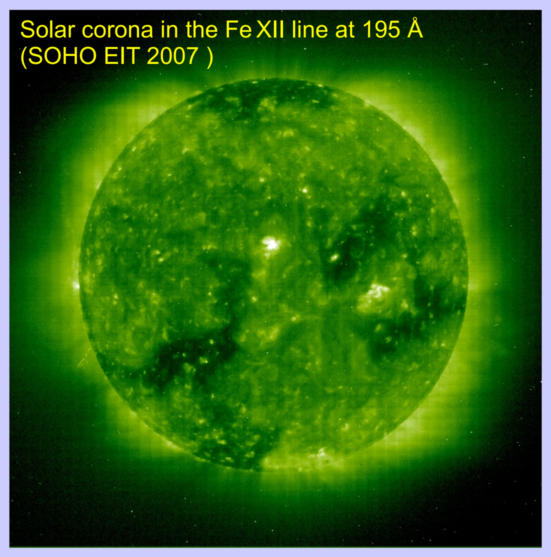


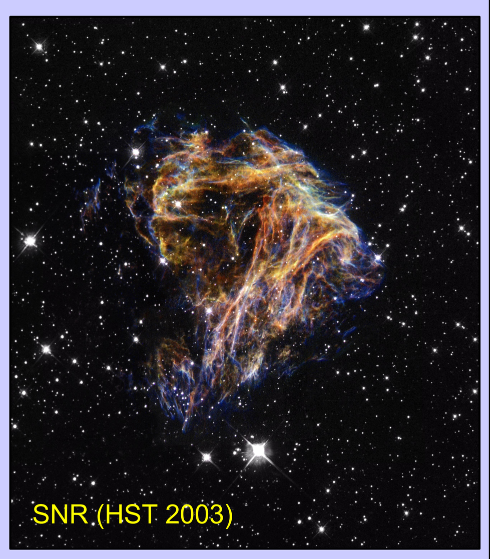


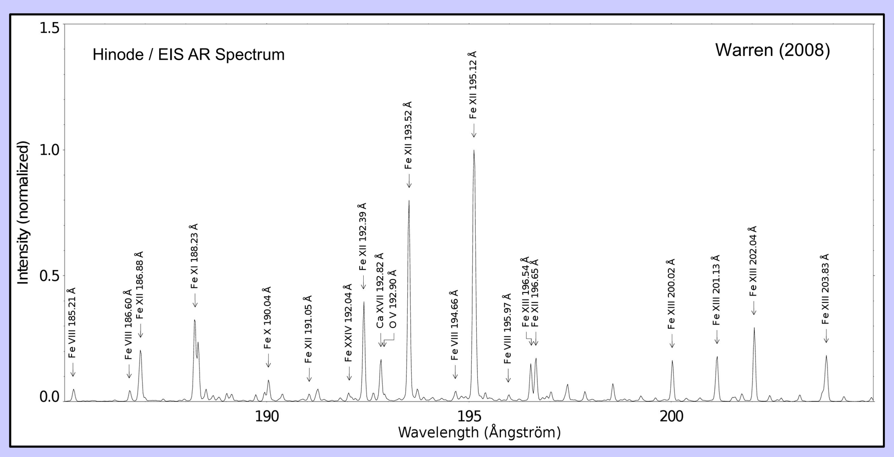


Recent observations of active galactic nuclei (AGN) with the X-ray satellite observatories XMM-Newton and Chandra have discovered an unresolved transition array (UTA) between 15 and 17 nm (Sako et al. 2001; Netzer et al. 2003). This has been identified as photoabsorption due to 2p-3d transitions in moderately charged iron ions. However, models were initially unable to correctly reproduce the shape of the UTAs (see above spectrum). This was attributed to an underestimation in the available low temperature M-shell iron DR rate coefficients which were used in the models (Netzer 2004; Kraemer et al. 2004). This has stimulated systematic experimental and theoretical studies of M-shell iron DR (Schmidt et al. 2006; Badnell 2006a,b; Lukić et al. 2007, Schmidt et al 2008, Lestinsky et al. 2009).

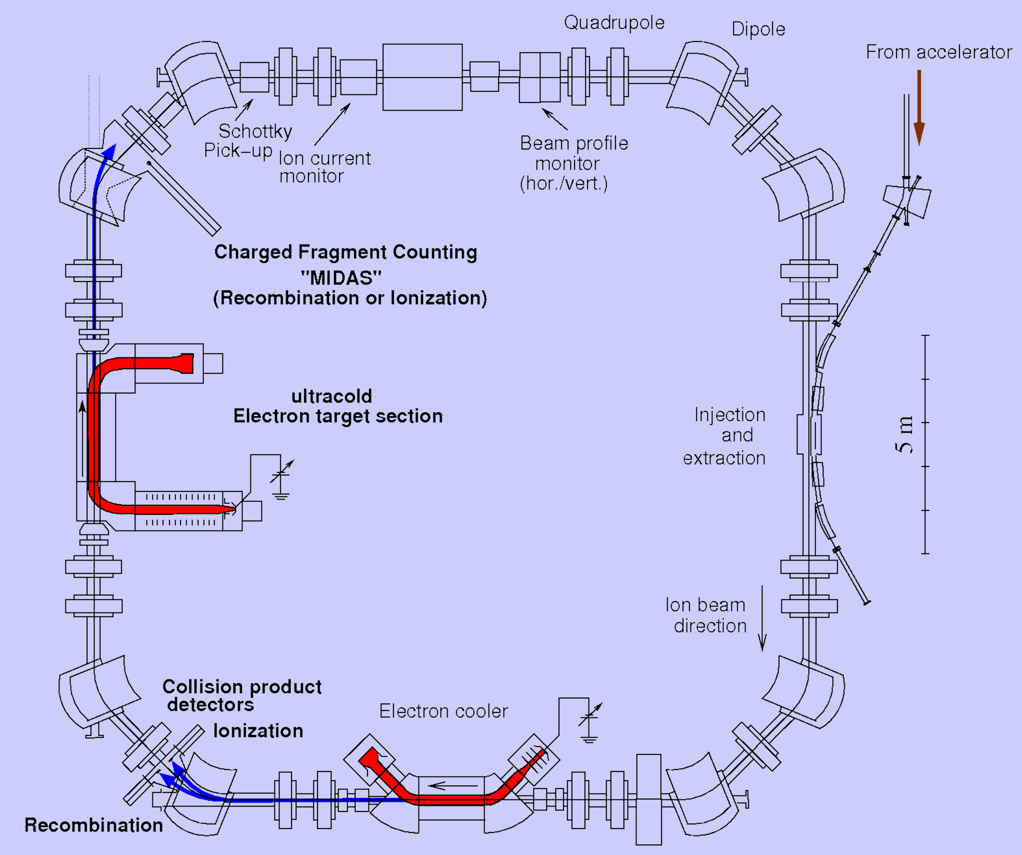
EII is the dominant ionization mechanism in collisional ionization equilibrium (CIE) which occurs in gas ranging from stellar atmospheres to clusters of galaxies and in ionizing plasmas such as supernova remnants (SNRs). Accurate EII data are necessary for deriving reliable elemental abundances and temperatures for gas in CIE and for gas in non-equilibrium ionization (NEI) such as SNRs in order to derive the ionization age $n_e t$ (where n_e is electron density and t is time). In the past few years there have been several attempts to improve the state of the EII database (Suno & Kato 2006; Dere 2007; Mattioli et al. 2007). However difference of up to a factor of 5 between these latest recommended data indicate significant additional experimental and theoretical work remains.



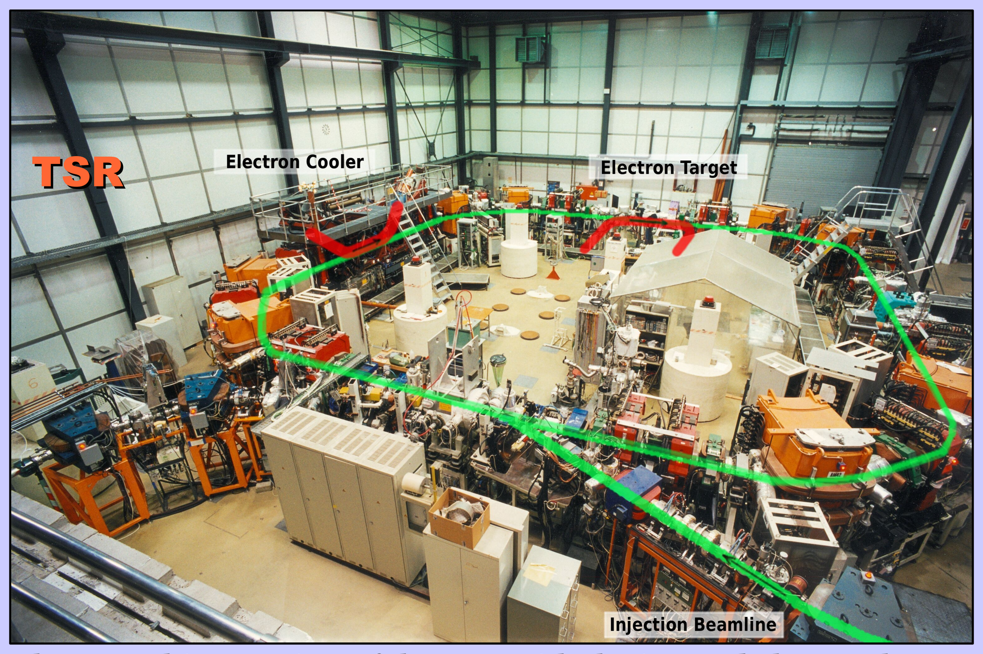




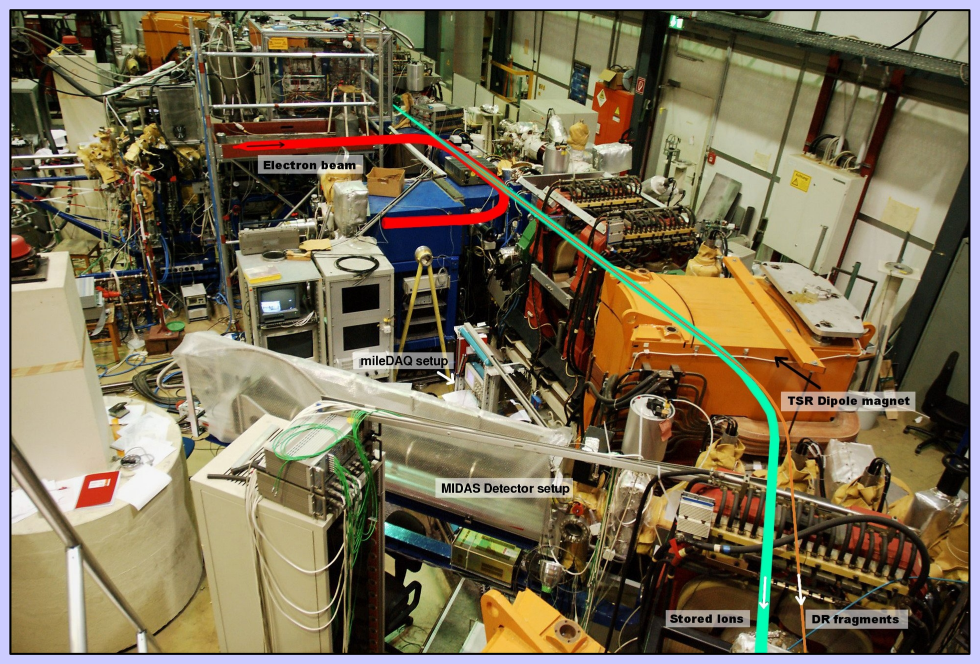
Measurements at TSR



- Ions are prepared in a tandem accelerator and injected into TSR at about 3 MeV/u energy (8% speed of light).
- Ion storage times of tens of seconds are much longer than lifetimes for most metastable states.
- Metastable levels are allowed to decay before data are collected so that nearly all ions are in the ground state during measurement.
- Two beams of cold electrons are co-linear with the stored ion beam.
- This "double-beam" configuration permits simultaneous phase-space cooling of stored ions with one electron beam, while the other operates as a target with tunable collision energy relative to the ion beam (Sprenger et al. 2004).
- Electron beam temperatures set the energy resolution.
- Electron Target beam typically $k_B T_\perp \approx 3$ meV, $k_B T_{||} \approx 30$ μeV.
- Electron Cooler beam typically $k_B T_\perp \approx 13.5$ meV, $k_B T_{||} \approx 180$ μeV.
- A dipole magnet downstream of the electron beam deflects reaction products according to charge state away from the parent ion beam and into particle detectors.
- Cross sections and rate coefficients can be calculated from the count rates and characteristics of the ion and electron beams.
- The ion current measurement is the dominant source of systematic uncertainty, and leads to a 1σ error of 15%.



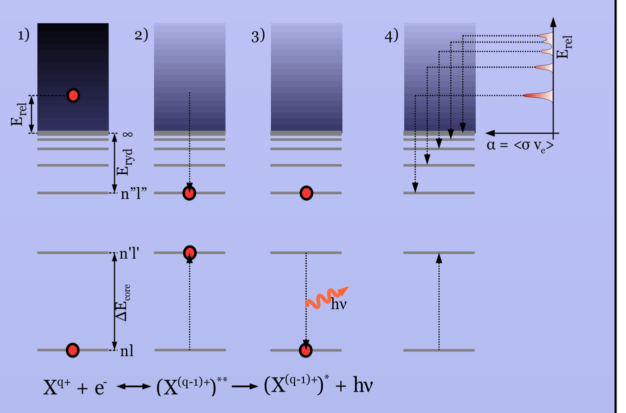
Photographic overview of the TSR with the ion and electron beam paths highlighted (green and red, respectively).



Close-up of the target section and detector. The Movable Ion Detector for Atomic Spectroscopy (MIDAS) can be positioned on the recombination or ionization side of the ion beam to detect products created by electron collisions in the target section.

Dielectronic Recombination

In dielectronic recombination a free electron collides with an ion exciting a bound electron in the target ion (Fig. 1 below) and is simultaneously captured into a Rydberg level (Fig. 2 below). The resulting doubly-excited state lies in the continuum of the recombined system. DR is completed when the excited state decays by emitting a photon, leaving the system below the ionization threshold. Alternatively, autoionization can occur leaving the ion in its original charge state.

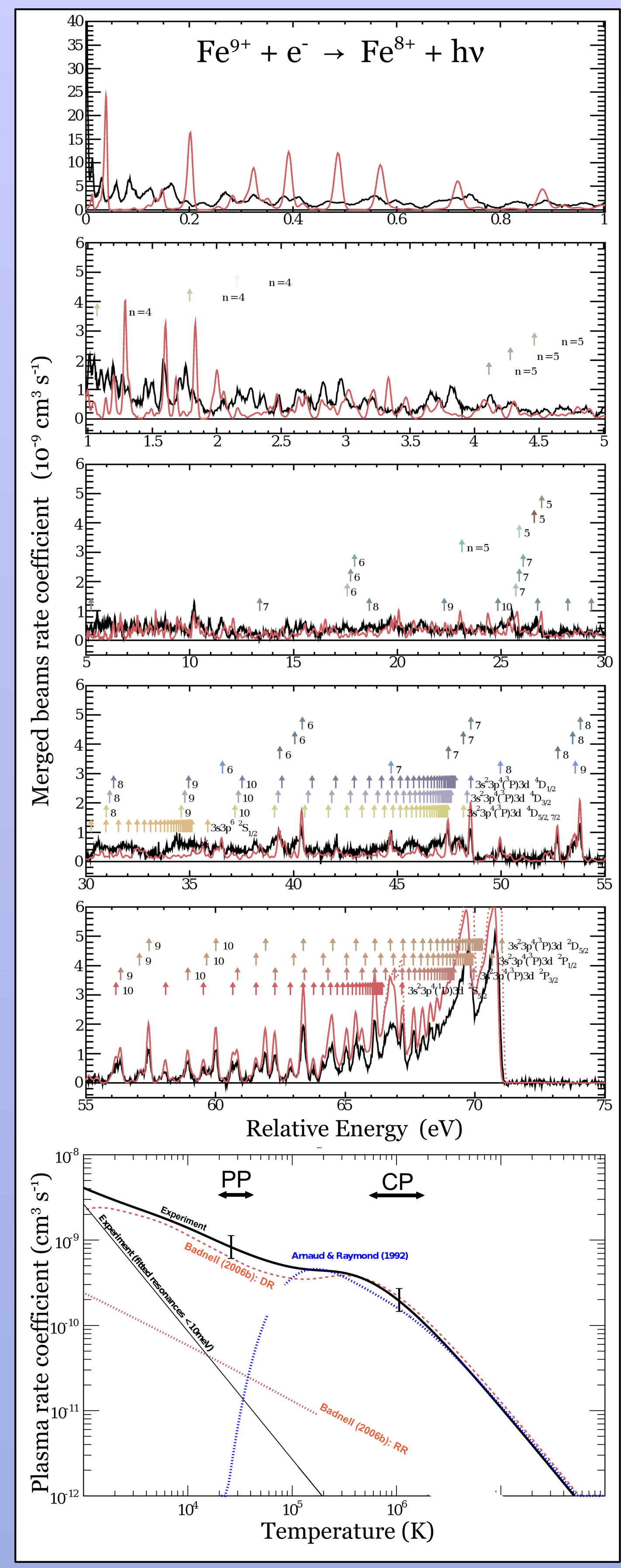


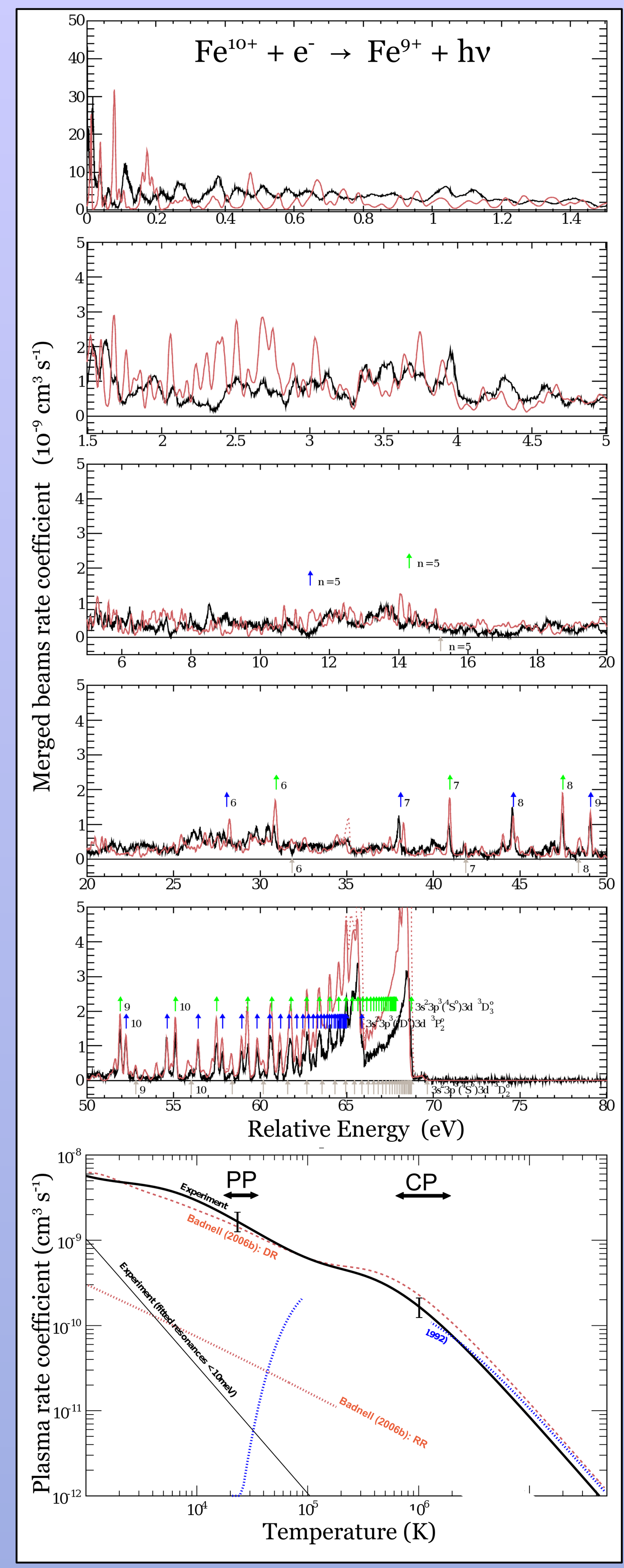
Energy conservation requires that the relative kinetic energy of the colliding electron and ion (E_{rel}) and the binding energy released (E_{ryd}) sum up to the excitation energy of the core electron (ΔE_{core}) giving

$$\Delta E_{core} = E_{rel} + E_{ryd}.$$

Because E_{ryd} and ΔE_{core} are quantized, the kinetic energies at which DR can go forward is also quantized. Therefore DR is a resonant process.

Our experimental results (Lestinsky, et al. 2009) for Fe X and Fe XI are shown on the right (black curves) and compared to recent theoretical cross section calculations (Badnell 2006b) convolved with the electron beam temperatures of the experiment (red curves). Arrows denote the Rydberg series for core excitations. The upper five panes in each figure show the measured merged beams rate coefficient $\alpha(E_{rel})$. In the lowest panes the plasma rate coefficients $\alpha(T)$ is shown.

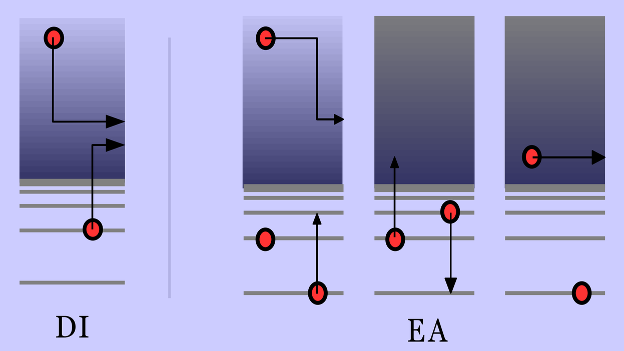




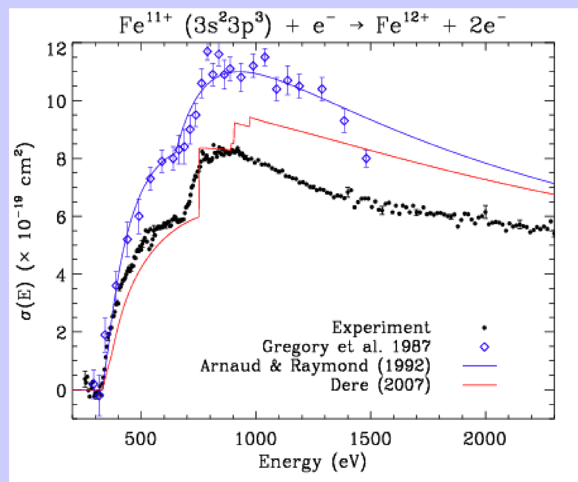
Temperature ranges important for photoionized plasma (PP; Kallman et al. 2004) and collisionally ionized plasma (CP; Bryans et al. 2006) are indicated by the horizontal arrows. The error bars on the experimentally derived plasma rate coefficients are estimated to be 15% at 1σ.

Electron Impact Ionization

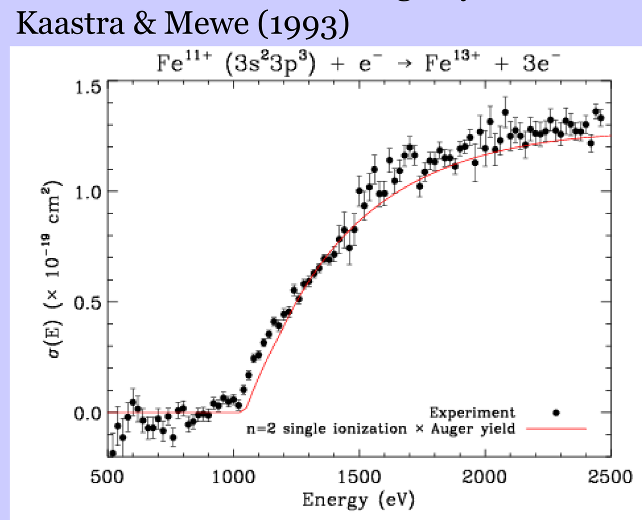
EII can occur through different channels. In direct ionization a bound electron is knocked off an ion in a non-resonant Coluomb collision. Excitation-Autoionization (EA) is a higher order process in which collision with a free electron excites the core into a doubly excited state that then autoionizes. EII can also occur by resonant processes where the doubly excited state following dielectronic capture does not radiatively stabilize, but instead autoionizes two electrons leading to net single ionization.



Recently we measured EII of Fe^{11+}. This measurement (black circles) is compared to an earlier measurement affected by metastable levels (blue diamonds). Those results were fit (blue curve) and used in ionization equilibrium models. The current results are in better agreement with theory (red curve), though significant differences remain in the calculation of the EA contribution to the total cross section.



We also measured the double ionization cross section of Fe^{11+}. It is dominated by direct single ionization of an L-shell electron followed by auto-ionization when the system decays to fill the hole. The theoretical cross section shown is an estimate of this ionization-autoionization process using the LANL atomic code and the Auger yields from Kaastra & Mewe (1993)



Conclusions

Storage ring measurements have confirmed the hypotheses of Netzer (2004) and Kraemer et al. (2004) that the low-temperature DR rate coefficients for iron M-shell ions were severely underestimated. This has been supported by recent experimental and theoretical work (Schmidt et al. 2006; Badnell 2006a,b; Lukić et al. 2007) as well as by the results shown here. Differences remain, however, between experiment and state-of-the-art theory which require further study. We recommend the experimental results be incorporated into AGN models and the spectral analysis revisited.

EII measurements with the storage ring technique can be a significant improvement over crossed beams experiments, which can have large metastable populations in the ion beam. Comparisons with theoretical calculations show rough agreement, and the experimental results can be used as a guide for improved calculations.

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