A Review of Cosmically Motivated Measurements for Atomic Ionization and Recombination Using Ion Storage Rings

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Supported by NASA

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Outline

I. Cosmic atomic plasmas
II. Ionization balance calculations
III. Ion storage rings
IV. Electron impact ionization (EII) work
V. Dielectronic recombination (DR) work
VI. The future

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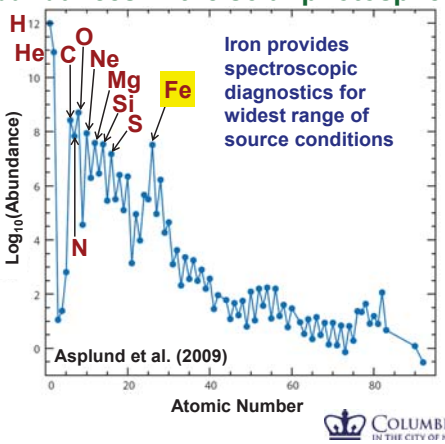
What atoms are up there?

Abundances in the solar photosphere.



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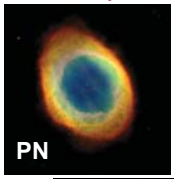
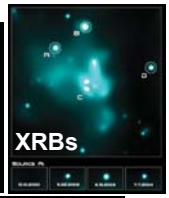
Cosmic atomic plasmas can be divided into two broad classes:

Electron ionized (stars, supernovae, galaxies,…)

Photoionized (PNe, XRBs, AGNs,…)





Cosmic atomic plasmas can be divided into two broad classes:

Collisionally ionized	Photoionized
• e⁻ impact ionization.	• Radiation field.
• In equilibrium an ion forms at $k_B T_e \sim I_p/2$.	• In equilibrium an ion forms at $k_B T_e \sim I_p/20$.
• High T_e dielectronic recombination (DR).	• Low T_e dielectronic recombination (DR).

- Charge transfer recombination and ionization.
- Radiative recombination (RR).

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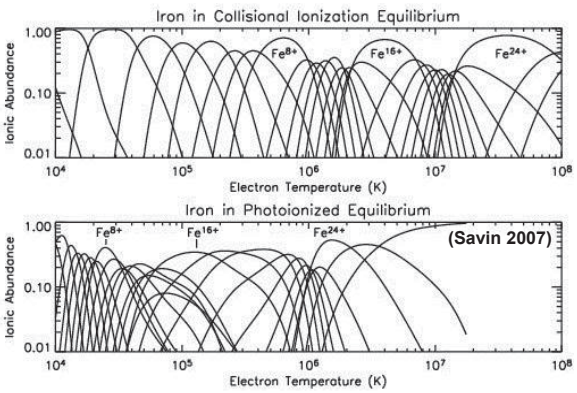
Differences in formation temperatures can readily be seen in the models.



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Electron impact ionization (EII)

Direct ionization (DI)

Excitation-autoionization (EA)

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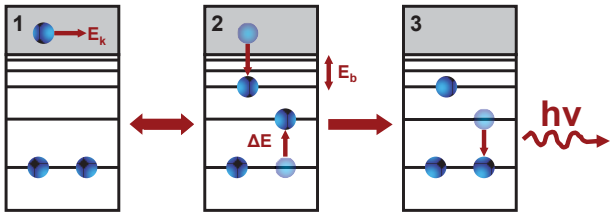
Dielectronic Recombination (DR)



Energy conservation requires $\Delta E = E_k + E_b$
Both ΔE and E_b quantized $\Rightarrow$ E_k quantized
High T_e DR occurs for $E_k \sim \Delta E$
Low T_e DR occurs for $E_k << \Delta E$

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Ionization balance calculations are used to determine relative abundances.

The intensity of an observed spectral line is

$$I_{line} \propto n_q n_e \alpha_{line}$$

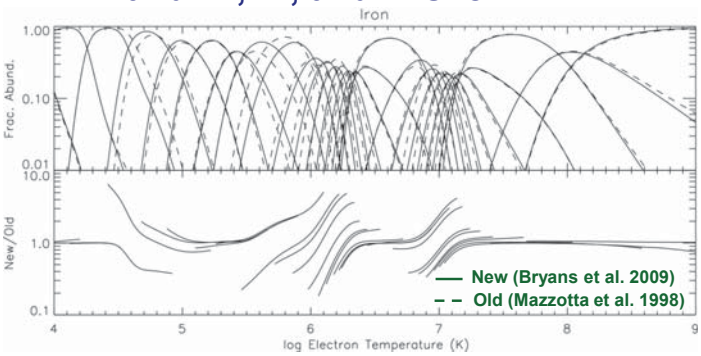
Rewriting this gives

$$\frac{n_A}{n_H} \propto \frac{I_{line}}{\alpha_{line}\left(\frac{n_q}{n_A}\right)}.$$

Reliable abundance determinations need good ionization balance calculations.

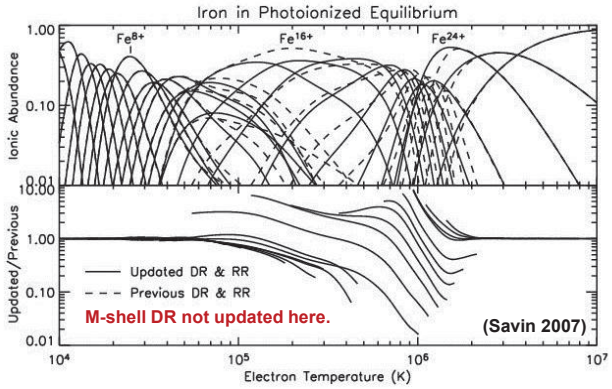
These depend on accurate ionization and recombination data.

Effects on CIE from updated data for EII and K-, L-, and M-shell DR.



Changes in ionization and recombination data can have a large effect.

Effects of new K- and L-shell DR data on photoionization equilibrium.



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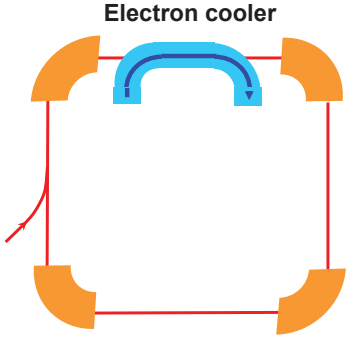
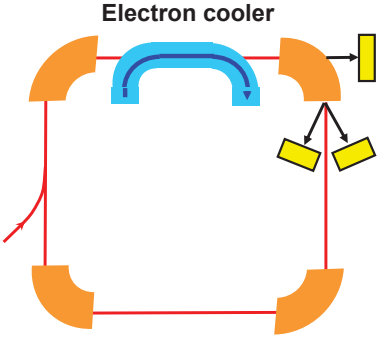
(Atomic) Ion Storage Rings



- **Stored ions**
  - Magnetic or electrostatic
  - Mass selected
  - Charge selected
  - Velocity selected
  - Radiatively relax to ground state (usually)
- **Electron cooling reduces**
  - Ion velocity spread
  - Ion beam diameter

Can study electron-ion charge changing collisions

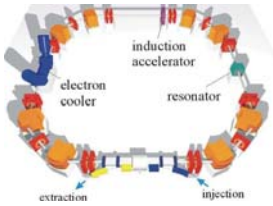


- **Reactions**
  - Recombination
  - Ionization
  - 20 μeV to 3 keV
- **Reaction products**
  - Highly directed
  - High lab frame energy
  - ~100% detected

Most astrophysical EII and DR studies have been done on CRYRING and TSR.

CRYRING (Schuch et al.)

TSR (Wolf, Müller, Schippers, Savin et al.)



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TSR

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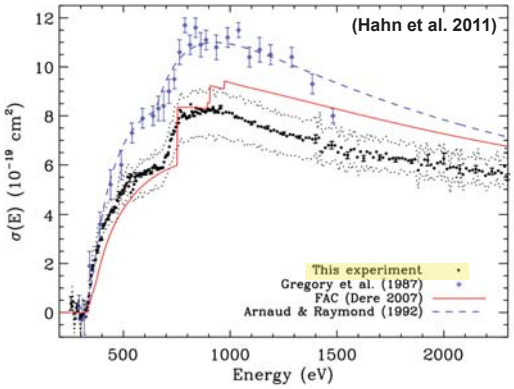
$e^- + Fe^{11+} \rightarrow Fe^{12+} + e^- + e^-$

TSR ground state results accurate to ~ 15%.



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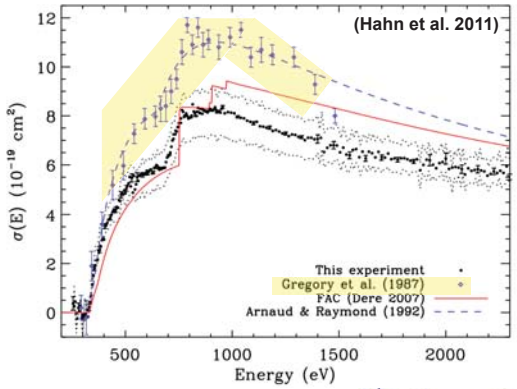
$e^- + Fe^{11+} \rightarrow Fe^{12+} + e^- + e^-$

Past single pass work contaminated by metastables.



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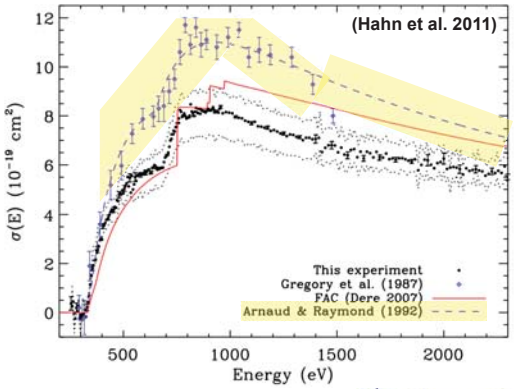
$e^- + Fe^{11+} \rightarrow Fe^{12+} + e^- + e^-$

Astro-folks used these results for plasma modeling.



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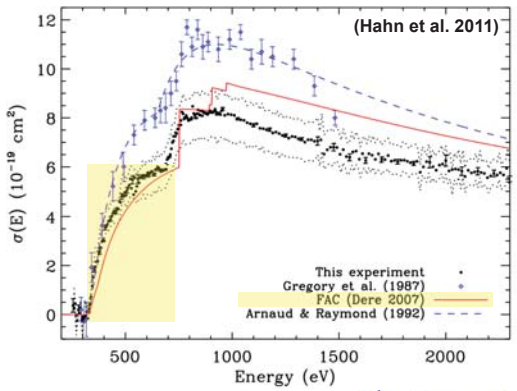
$e^- + Fe^{11+} \rightarrow Fe^{12+} + e^- + e^-$

Theory does not include $3l \rightarrow nl'$ EA channels.



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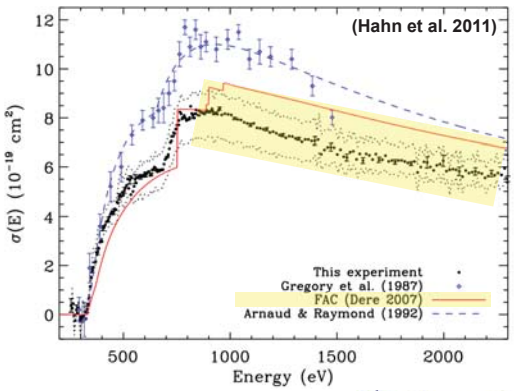
$e^- + Fe^{11+} \rightarrow Fe^{12+} + e^- + e^-$

Theory overestimates $2l \rightarrow \geq 4l'$ EA channels.



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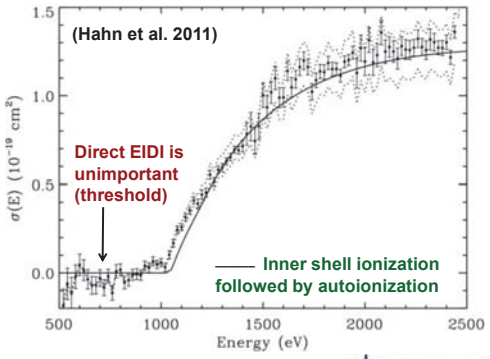
Ground state single ionization data now exist for the isoelectronic sequences

Li-like Si^{11+} Cl^{14+}	Be-like S^{12+}	B-like Mg^{7+}				F-like Fe^{17+}	Ne-like Fe^{16+}
Na-like Fe^{15+}	Mg-like Fe^{14+}	Al-like Fe^{13+}	Si-like Fe^{12+}	P-like Fe^{11+}	S-like Fe^{10+}	Cl-like Fe^{9+}	
K-like Fe^{7+}							

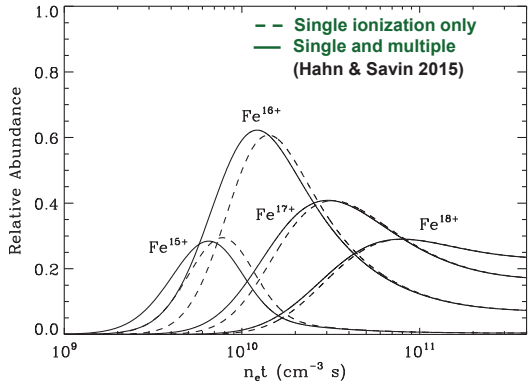
Hahn (2014)

Storage ring data can also measure electron impact double ionization (EIDI).

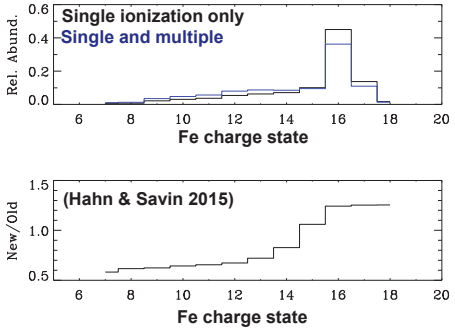
$e^- + Fe^{11+} \rightarrow Fe^{13+} + e^- + e^- + e^-$



Multiple ionization reduces response time to impulsive events.



Multiple ionization alters charge balance due to nanoflare heating in the Sun.



Theory cannot generate needed multiple ionization data. More experiments needed.

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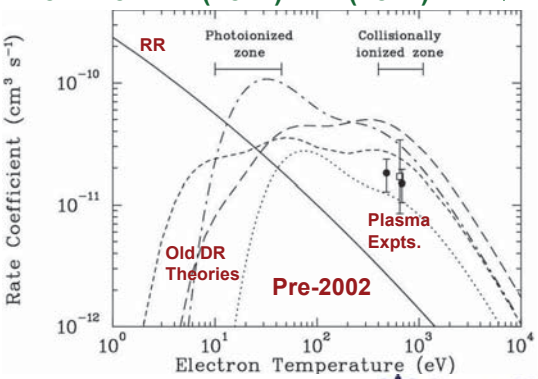
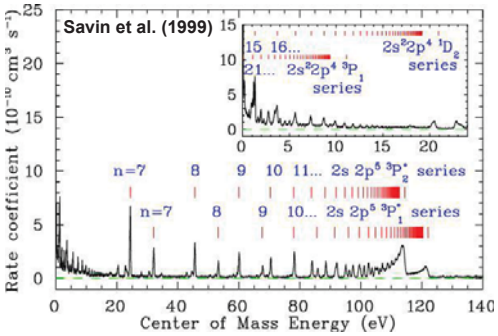
Reliable theoretical DR rate coefficients have been a challenge for many years.

$e^- + Fe^{18+} \leftrightarrow (Fe^{17+})^{**} \rightarrow (Fe^{17+})^* + h\nu$



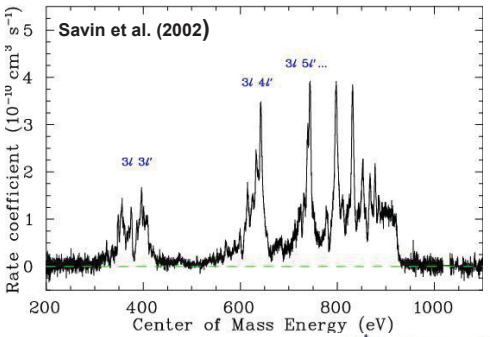
Storage ring work has provided important low energy benchmarks…

$e^- + Fe^{18+} \leftrightarrow (Fe^{17+})^{**} \rightarrow (Fe^{17+})^* + h\nu$



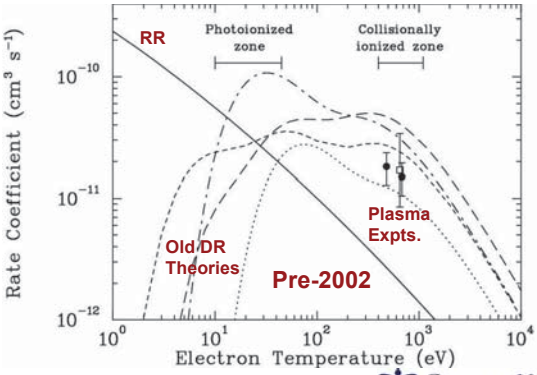
…as well as important high energy benchmarks…

$e^- + Fe^{18+} \leftrightarrow (Fe^{17+})^{**} \rightarrow (Fe^{17+})^* + h\nu$



…resulting in significant improvements in DR theory for K- and L-shell ions...

$e^- + Fe^{18+} \leftrightarrow (Fe^{17+})^{**} \rightarrow (Fe^{17+})^{*} + h\nu$



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…resulting in significant improvements in DR theory for K- and L-shell ions...

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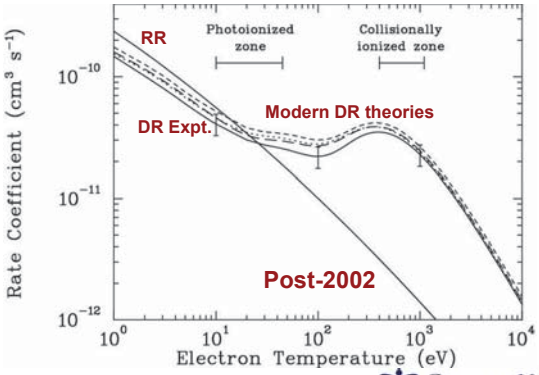

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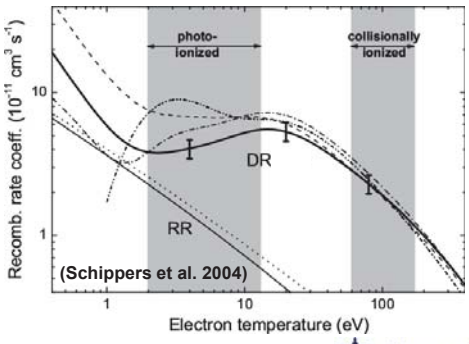
…but modern L-shell theory can still be wrong for low T_e DR.

$e^- + Mg^{8+} \leftrightarrow (Mg^{7+})^{**} \rightarrow (Mg^{7+})^{*} + h\nu$



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Theoretical errors due to uncertainties in predicted DR resonance energies.

DR rate coefficients exponentially sensitive to uncertainties in resonance energies E_r

$$\alpha(T_e) \propto \sum_r \hat{\sigma}_r \exp\left(-\frac{E_r}{k_B T_e}\right)$$

Problems at low energies where $\delta E_r \sim k_B T_e$ at which an ion forms.

Accurate structure calculations are one of the largest unresolved issue for DR theory.

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Storage ring DR data now exist for the following cosmically abundant ions

H-like He, C, O, Mg, S							He-like Li, C
Li-like C, N, O, Ne, Na, Si, Ar, Fe, Ni	Be-like C, N, O, Ne, Mg, Si, S, Fe	B-like C, Mg, Ar, Fe	C-like Mg, Fe	N-like Fe	O-like Fe	F-like Fe	Ne-like Si, Fe
Na-like Si,S, Ar, Fe, Ni	Mg-like Fe	Al-like Fe	Si-like Fe	P-like Fe	S-like Fe	Cl-like Fe	Ar-like Fe
K-like Fe							

Schippers (2009)

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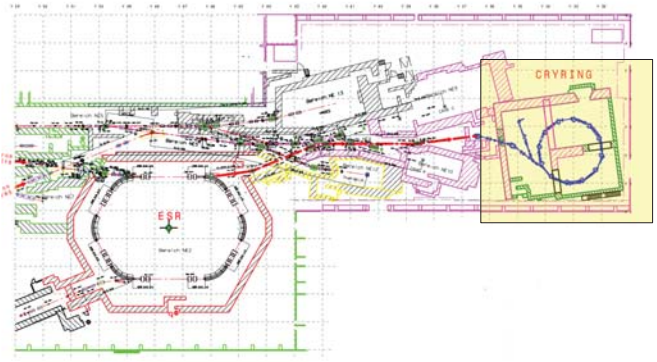
CRYRING has moved to GSI.



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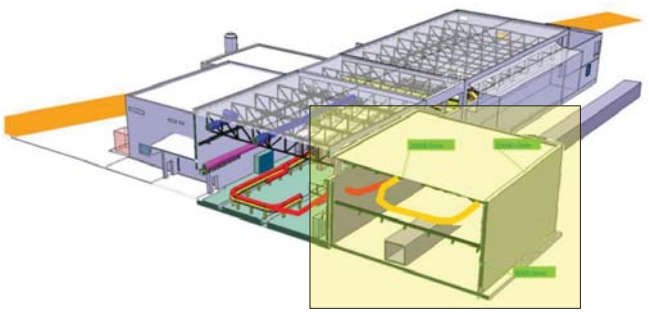
TSR will be moved to CERN.



(Greiser et al. 2012)

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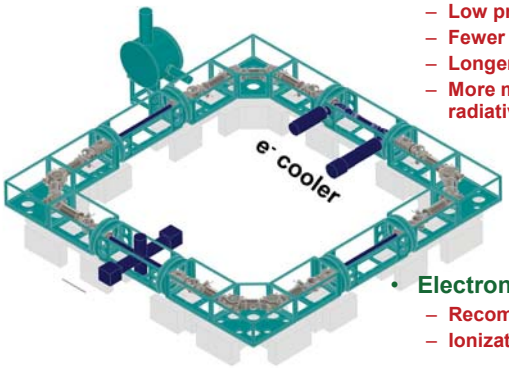
Cryogenic Storage Ring (CSR): commissioning has begun

- Ambient T < 10 K
  - Low pressure
  - Fewer collisional losses
  - Longer storage times
  - More metastables can radiatively relax



- Electron driven reactions
  - Recombination
  - Ionization

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Lots of atomic data needs for astrophysics remain.

- Single ionization for more isoelectronic sequences.
- More multiple ionization measurements.
- Experiments only way to get reliable low T_e DR where $\delta E_r \sim k_B T_e$ of ion formation.

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Collaborators (past and present)

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Max-Planck-Institut für Kernphysik

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N. R. Badnell

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