Experiments and modeling of photoionized plasmas at Z

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This work involves a broad collaboration

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- J.E. Bailey, G. Rochau, SNL
- D. Cohen, M. Rosenberg, Swarthmore College
- M.E. Sherrill, J. Abdallah, LANL
- I.E. Golovkin, J.J. Macfarlane, Prism Computational Sciences
- M.E. Foord, R.F. Heeter, S. Glenzer, LLNL
- S. Rose, Imperial College, UK

Photoionized plasmas in the laboratory

• Most of the atomic and radiation physics research that has been done on laboratory plasmas is for collisional plasmas; relatively little work has been performed on laboratory photoionized plasmas.

• Unlike collisional plasmas, the atomic kinetics of photoionized plasmas is driven primarily by a flux of photons through photoionization and photoexcitation.

• The dearth of laboratory photoionized plasma data is due to inadequate x-ray radiation source energy.

• Z-produced x-rays: E ~ 1 - 2 MJ, fwhm ~ 6 ns, peak power ~ 200 TW.

• Initial experiments done at Z using gas cell and expanding foil type of targets have shown the feasibility of performing and diagnosing laboratory photoionized plasmas*.

• Science opportunity: combined experimental and theory/modeling effort to produce and study well characterized laboratory photoionized plasmas with emphasis on their atomic kinetics and radiative properties.

* J.E. Bailey et al, JQSRT **71**, 157 (2001); R.F. Heeter et al, RSI **72**, 1224 (2001); M.E. Foord et al PRL **93**, 055002 (2004)

Photoionized plasmas in astrophysics

- The availability of high-resolution x-ray spectra recorded by Chandra and XMM-Newton has motivated a renewed effort on the interpretation of x-ray emission from photoionized plasmas, which exist in a large class of astrophysical objects including x-ray binaries and active galactic nuclei.

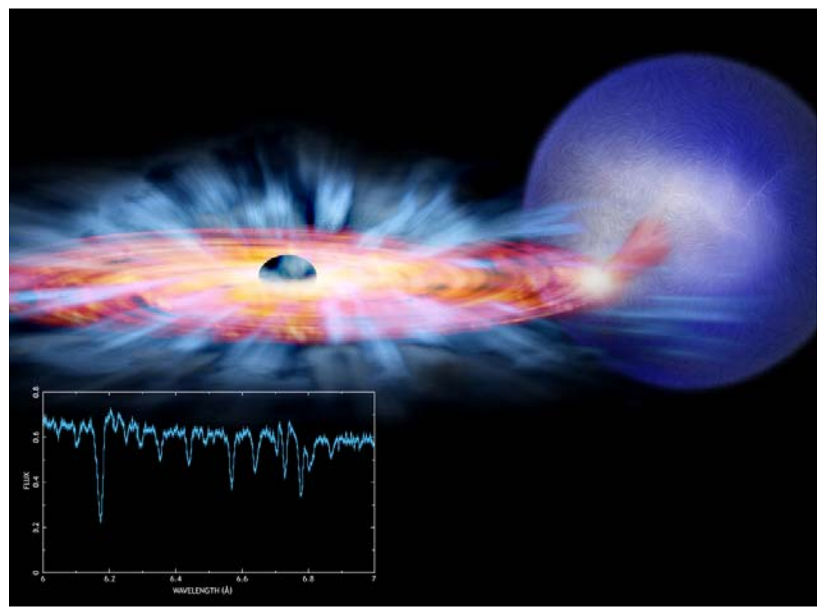
- Ionization distribution is determined by a balance between photoionization and radiative and dielectronic recombination (PIE).

- Ionization parameter $\xi = 4\pi I/N$, values up to a few thousands erg cm / s.

- Artist's illustration of binary system GRO J1655-40: 11,000 light-years away in constellation scorpius.

- Chandra x-ray spectrum data in the 6A to 7A wavelength range shows absorption features in highly-charged ions.

- Detailed analysis of spectrum yields information on accretion disk dynamics.



Laboratory experiments on photoionized plasmas benefit from:

• Previous (extensive) work on detailed theoretical and modeling work on atomic kinetics and radiation physics of collisional plasmas.

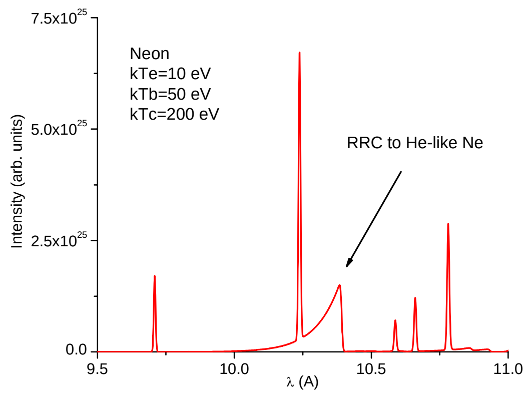
• Recent absolute photoionization cross section measurements at the Advanced Light Source (ALS) in Berkeley (R. Phaneuf and collaborators, UNR).

• Experience and developments on plasma spectroscopy diagnostics and instrumentation, e.g. space- and time-resolved crystal spectrometers.

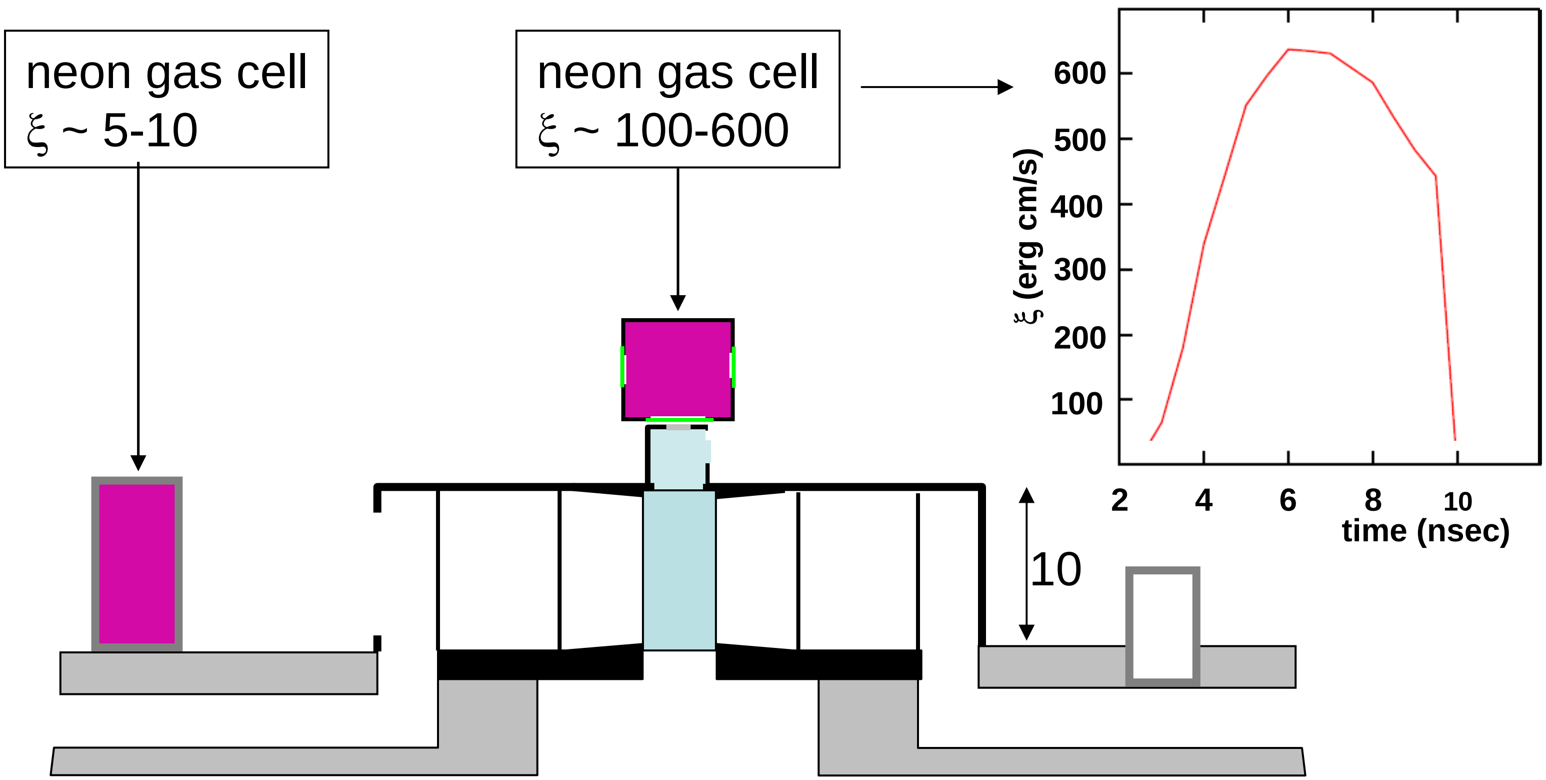
• And laser-driven diagnostics, e.g. interferometry and Thomson scattering.

• **But photoionized plasmas have their own characteristics**:

- different line intensity distributions compared to those of coronal ionization equilibrium,
- plasma is "over-ionized",
- radiative recombination (RRC) edges with steep drops above threshold.



Current/future experiments at Z combine previous and new neon gas cell designs, and better diagnostics



<u>Diagnostics:</u>

Emission spectroscopy – test line ratio and width signatures used by astronomers

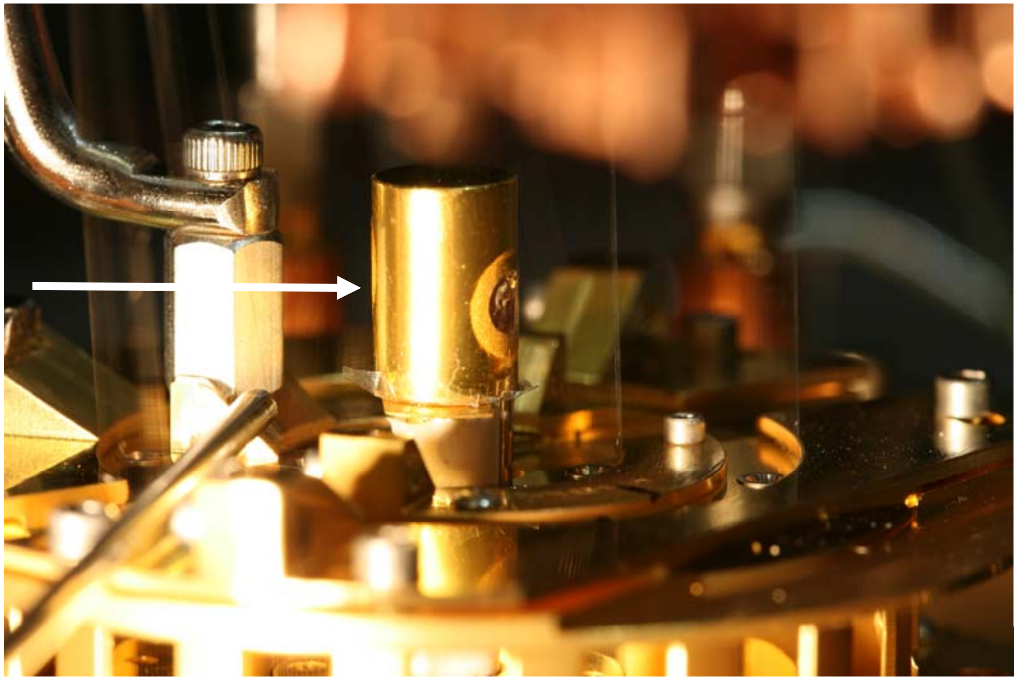
Absorption spectroscopy – measure charge state distribution and compare models

Thomson scattering – independent temperature diagnostic

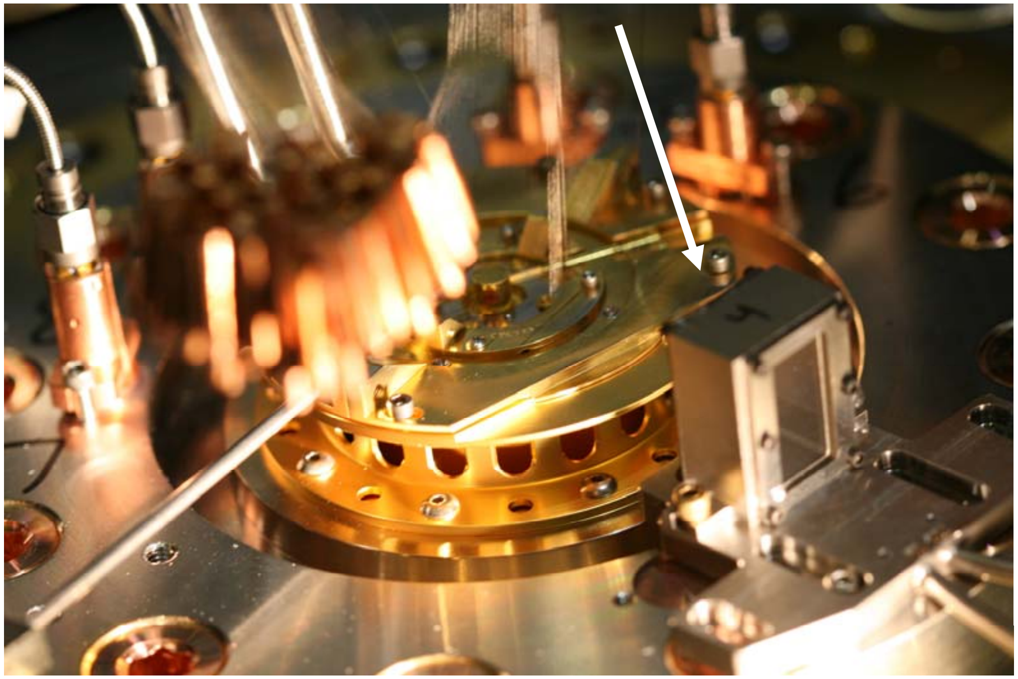
Laser interferometry – plasma density uniformity

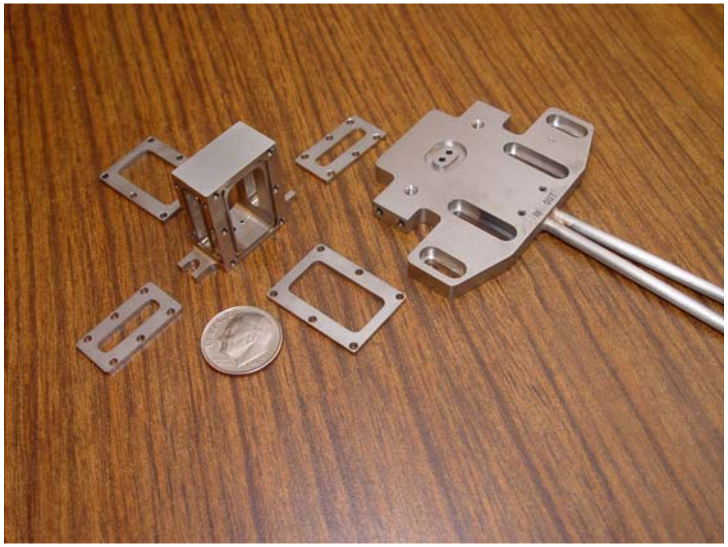
cm-scale gas cells

Top gas cell

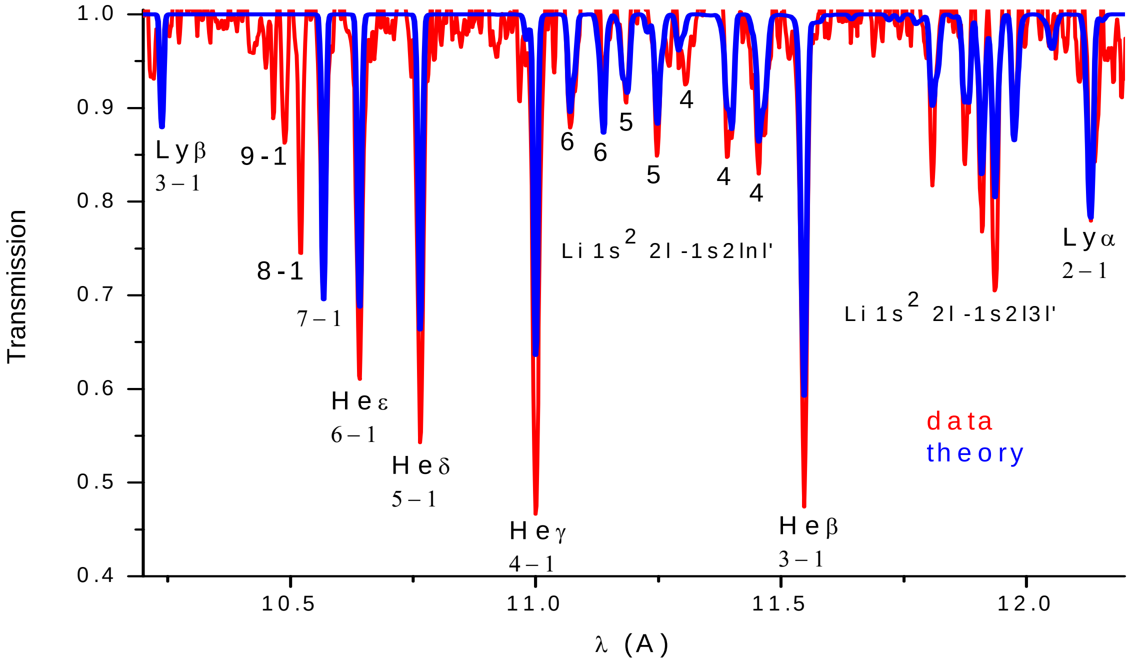


Side gas cell





Side neon gas cell absorption measurements show many line transitions in highly-charged neon ions



Z experiment column densities are similar to astrophysical objects (10^{18} cm^{-2})

Two series of absorption lines are observed in highly-charged Ne ions:

He-like Ne: *$1s^2 – 1snp$, up to n=10*

Li-like Ne: *$1s^2\ 2l – 1s2lnl'$, up to n=6*

Emission measurements are work in progress

Progression of ξ in Z photoionized plasma experiments is impressive:

- Side gas cell[1]: ξ = 5 – 7 erg cm /s
- Expanding foil[2]: ξ = 20 – 25 erg cm / s
- Top gas cell[3]: ξ = 100 – 600 erg cm / s

Large values of ξ make the laboratory photoionized plasma relevant for astrophysics applications

[1]J.E. Bailey et al, JQSRT **71**, 157 (2001), and current experiments
[2]M.E. Foord et al PRL **93**, 055002 (2004)
[3]Future experiments

A photoionization sample outside a NIF- class hohlraum could reach conditions relevant to black hole physics

NIF Promises Higher Radiation Temperature:

- **Present Facilities: ~350 eV**
- **NIF (semi-empirical est.): >700 eV (!)**
  - Dewald et al., ***PRL* 95,** 215004 (2005)

Photoionization Scaling $\xi = 4\pi$ Flux / density

ξ ~ 1000 is typical of X-ray binaries

(accretion disks around black holes consuming stars)

Z early exps: ξ = 5 - 25. Z new exps: ξ up to 600.

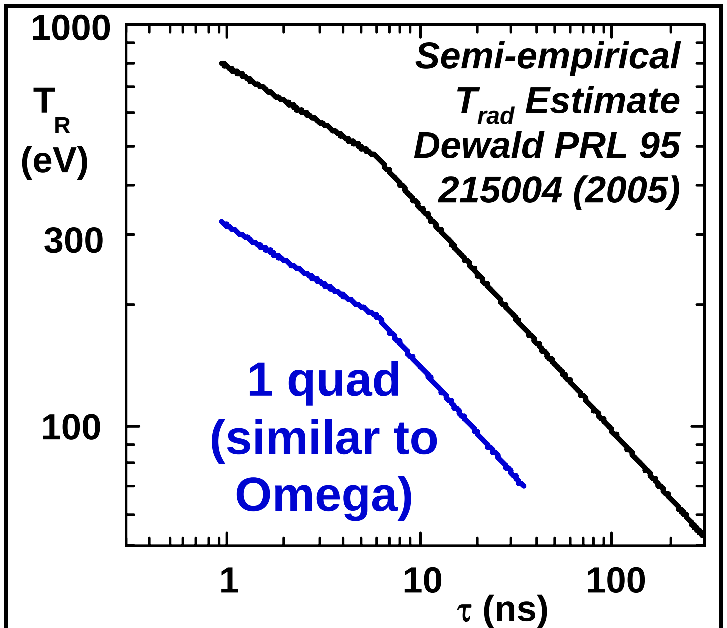
NIF could achieve $\xi \geq 1200$ as follows:

$n_e = 10^{18}/cm^3$ (CH-tamped exploding foil)

Flux = $\sigma T_r^4 * R^2_{hohlraum} / D^2_{sample}$.

with T_r = 300 eV, R = 0.2 cm, D = 1.8 cm:

$\xi = 4\pi$ Flux / $n_e \approx 12.6 \times 10^{20} / 10^{18} \approx 1200$



Slide courtesy of
R. Heeter (LLNL)

Our team (via Heeter) is working out a detailed experimental design

Summary

- Science opportunity: combined experimental and theory/modeling effort to produce and study well characterized laboratory photoionized plasmas with emphasis on their atomic kinetics and radiative properties.

- We can do high-energy density laboratory astrophysics while cutting into a relatively unexplored laboratory plasma.

- Data from large-ξ photoionized plasmas is important to benchmark models and codes used in both laboratory and astrophysical plasmas.

- There is a lot of learning to do and many challenges:

  - produce well diagnosed laboratory photoionized plasmas,
  - understand emissivity and opacity, and x-ray line formation,
  - determine whether or not plasma is in steady-state,
  - perform simultaneous absorption and emission spectroscopy,
  - establish laser-driven diagnostics for photoionized plasmas,
  - continue working on new experiment designs and diagnostics.

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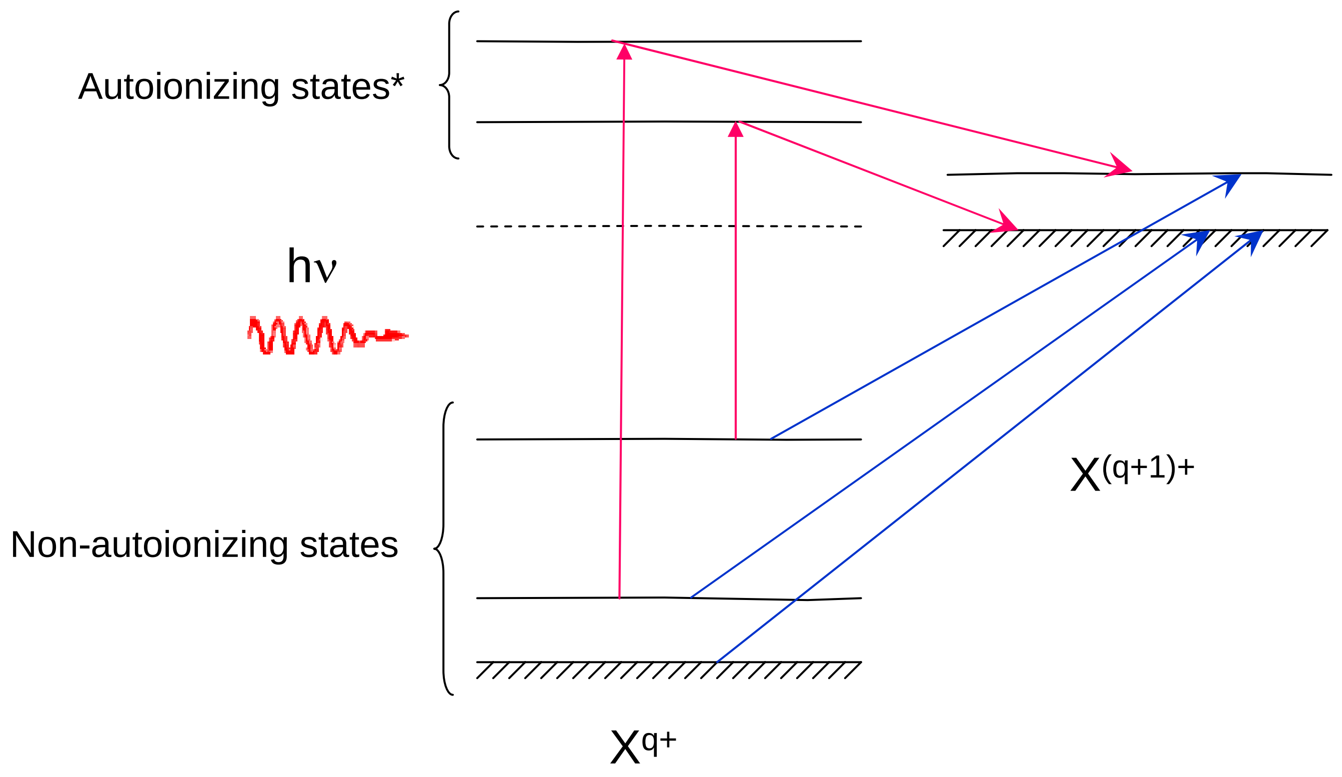
Photoionization

Direct photoionization: $X^{q+} + h\nu \rightarrow X^{(q+1)+} + e$

Resonant photoionization: $X^{q+} + h\nu \rightarrow X^{q+*} \rightarrow X^{(q+1)+} + e$



Both processes
are observed
in photoionization
experiments

Absolute photoionization cross sections

- Absolute measurements of photoionization cross sections provide critical data to test and benchmark theory approximations and calculations

- During the last few years, R. Phaneuf (UNR) and students and collaborators have been performing absolute photoionization cross sections with the ion-photon-beam end-station at the Advanced Light Source (ALS) at Berkeley using a merged-beam technique (*)

- As a result, data is available for absolute photoionization cross sections for a wide variety of elements (Li, B, C, O, F, Ne, Ar, Fe, Kr, Sn, Ti, Kr, Xe) including several ionization stages and processes

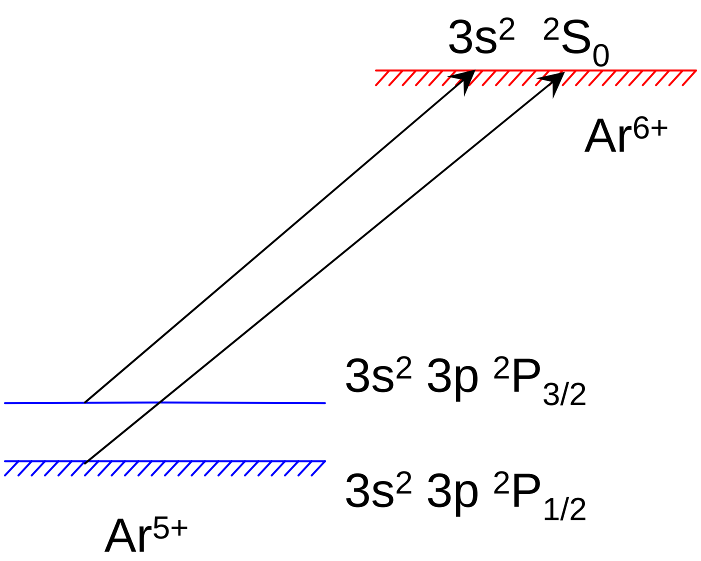
- There is also recent data on Li, Na and K from another group using a different experimental method based on laser-driven photoionization (**)

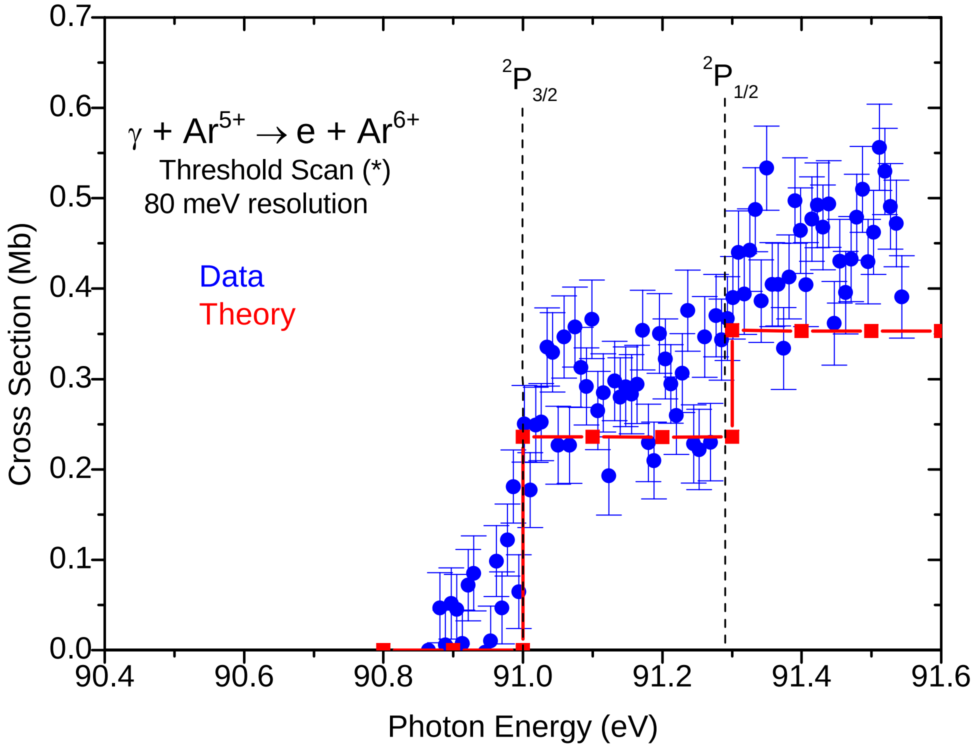
(*) A.M. Covington et al, Phys. Rev. Letters **87**, 243002 (2001); A.M. Covington et al, Phys. Rev. A **66**, 062710 (2002); A. Müller et al J. Phys. B **35**, L137 (2002); A.M. Convington et al, J. Phys B **34**, L735 (2001); A. Aguilar et al, Phys. Rev A **67**, 012701 (2003); A. Aguilar et al, Astrophys. J. Suppl. Ser. **146**, 467 (2003); …

(**) N. Amin et al, Eur. Phys. J. D **40**, 331 (2006)

Direct photoionization of Ar^{5+}

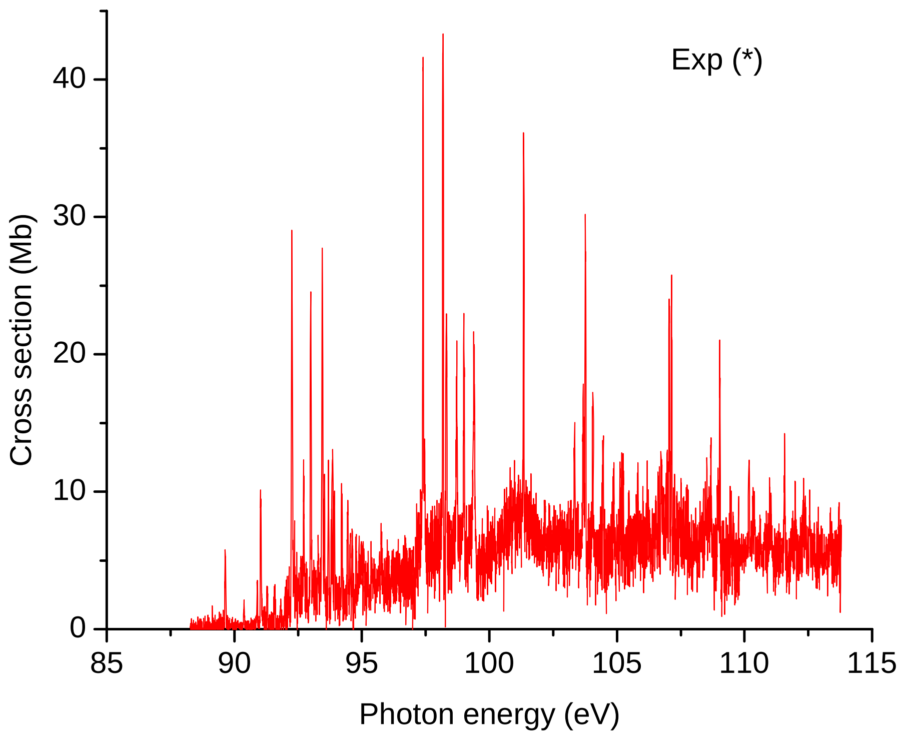
- Direct photoionization from Al-like Ar to Mg-like Ar
- Only ground state $^2P_{1/2}$ and metastable $^2P_{3/2}$ are significantly populated
- Fine structure splitting is ~ 0.3 eV
- Good test for direct photoionization (i.e. without resonant contributions)

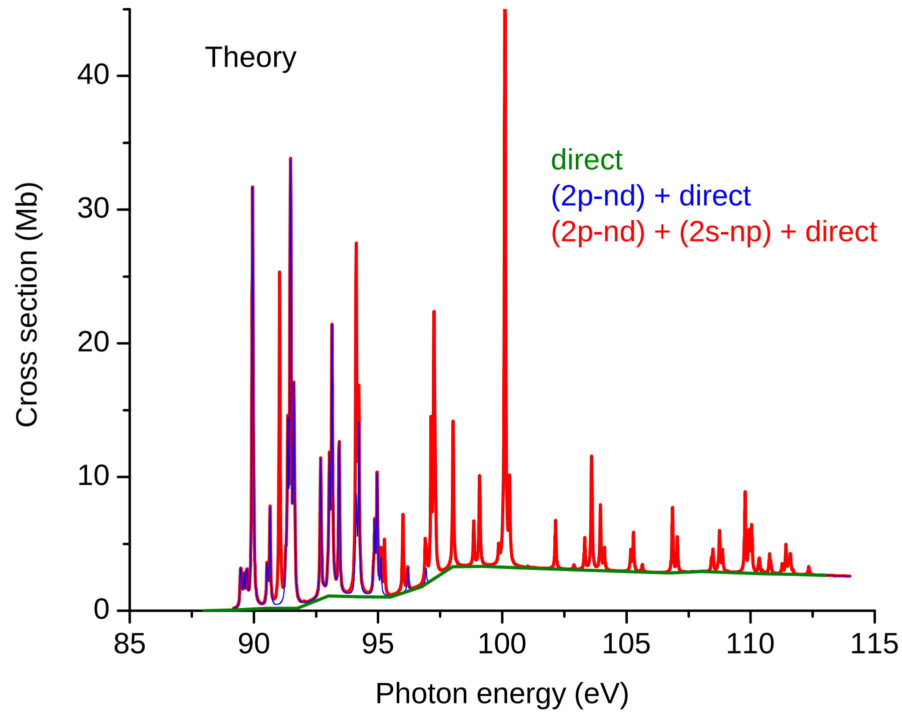




(*) Wang M.S., M.S. Thesis (UNR 2006), in preparation for publication

Complete calculation is challenging





- Ne^{3+} absolute photoionization cross section data and theory calculation
- Theory includes 25 direct photoionization processes (i.e. thresholds) and 1069 photoexcitation resonant contributions, including:
  $1s^2\,2s^2\,2p^3 – 1s^2\,2s^2\,2p^2\,nd$ and $1s^2\,2s^2\,2p^3 – 1s^2\,2s^1\,2p^3\,np$ with n=3, 4, …, 9
- First approximation: theory calculation does not include interference effect

(*) A. Aguilar et al J. Phys. B **38**, 343 (2005)