Photoionization of Ions with Synchrotron Radiation

From Ions in Space to Atoms behind Bars

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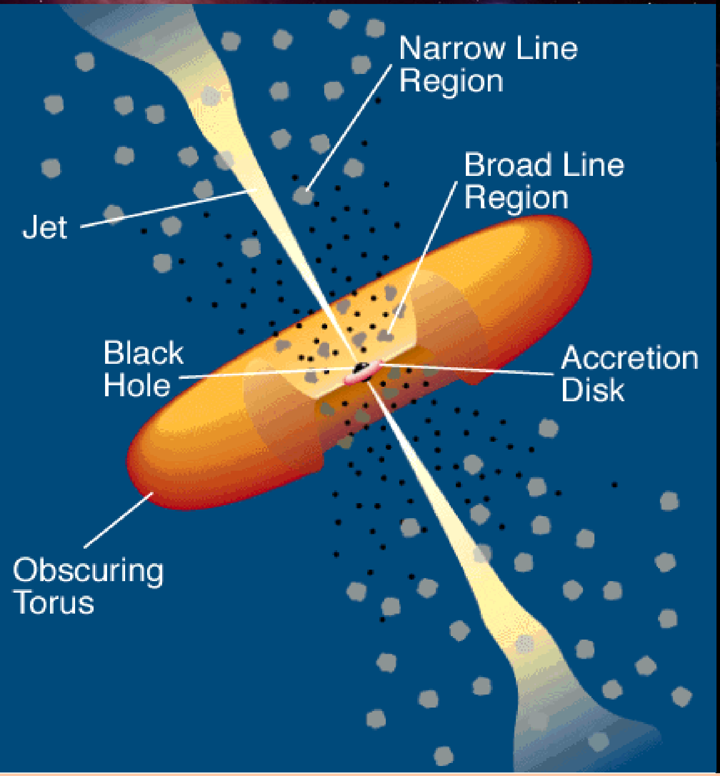
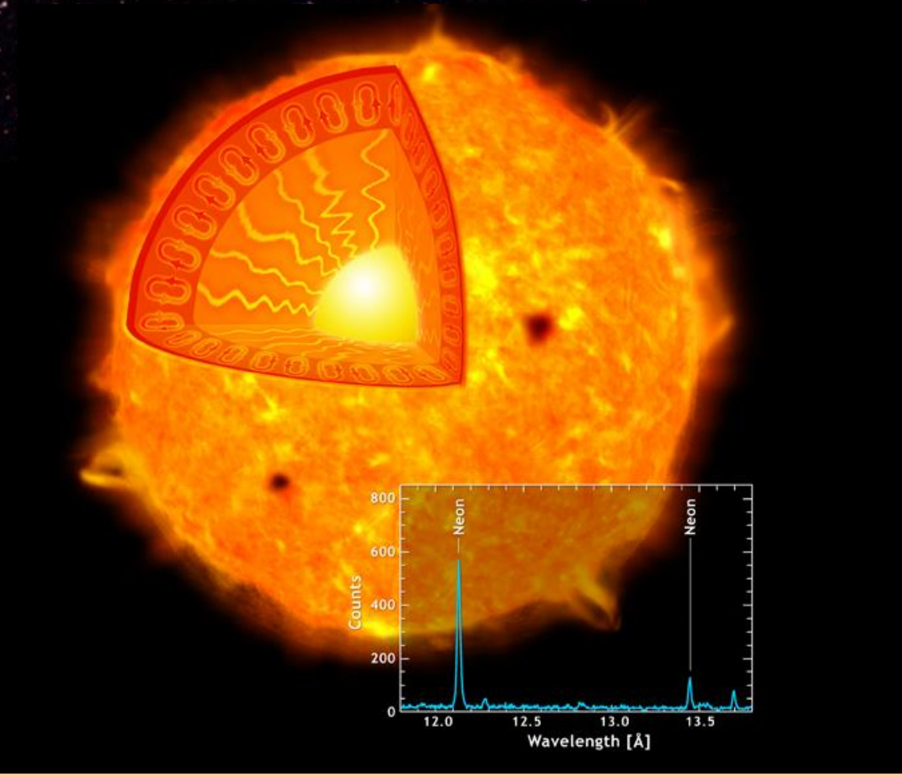
Outline

- (Astrophysical) Motivation
- Photon-ion merged-beams experiments
- Atomic ions
  - Valence shell ionization
  - Inner shell ionization
  - Multiple ionization
- Endohedral fullerenes
  - $Ce@C_{82}^{+}$
  - Confinement resonances in $Xe@C_{60}^{+}$

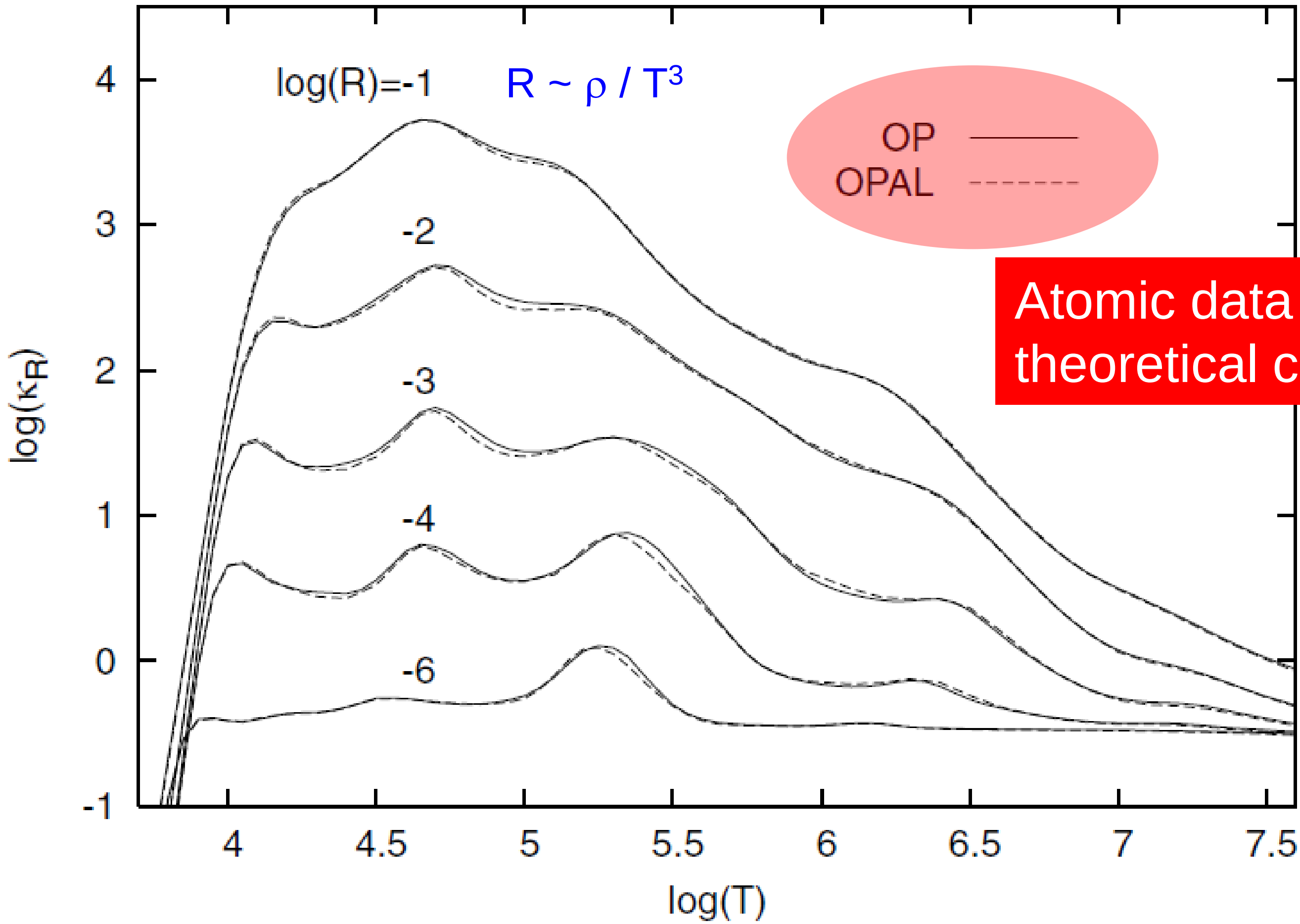
X-Rays in Astrophysics





Opacities for Stellar Envelopes

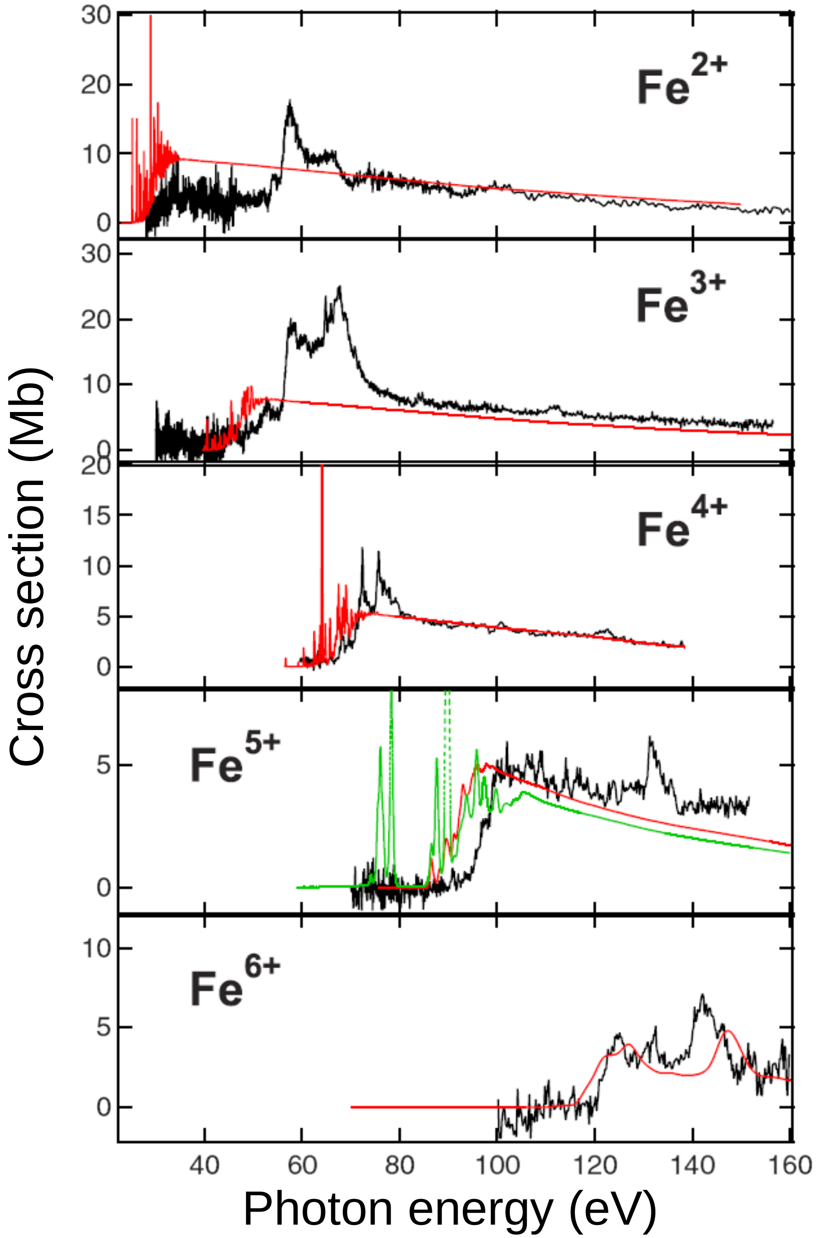
Discrepancies between **standard solar model** and **helioseismology** opacities may be too low by up to 15%   Serenelli et al., ApJ **705** (2009) L123



Atomic data from theoretical calculations

N. R. Badnell et al., MNRAS **360** (2005) 458

Present Status of Astrophysical Data Base



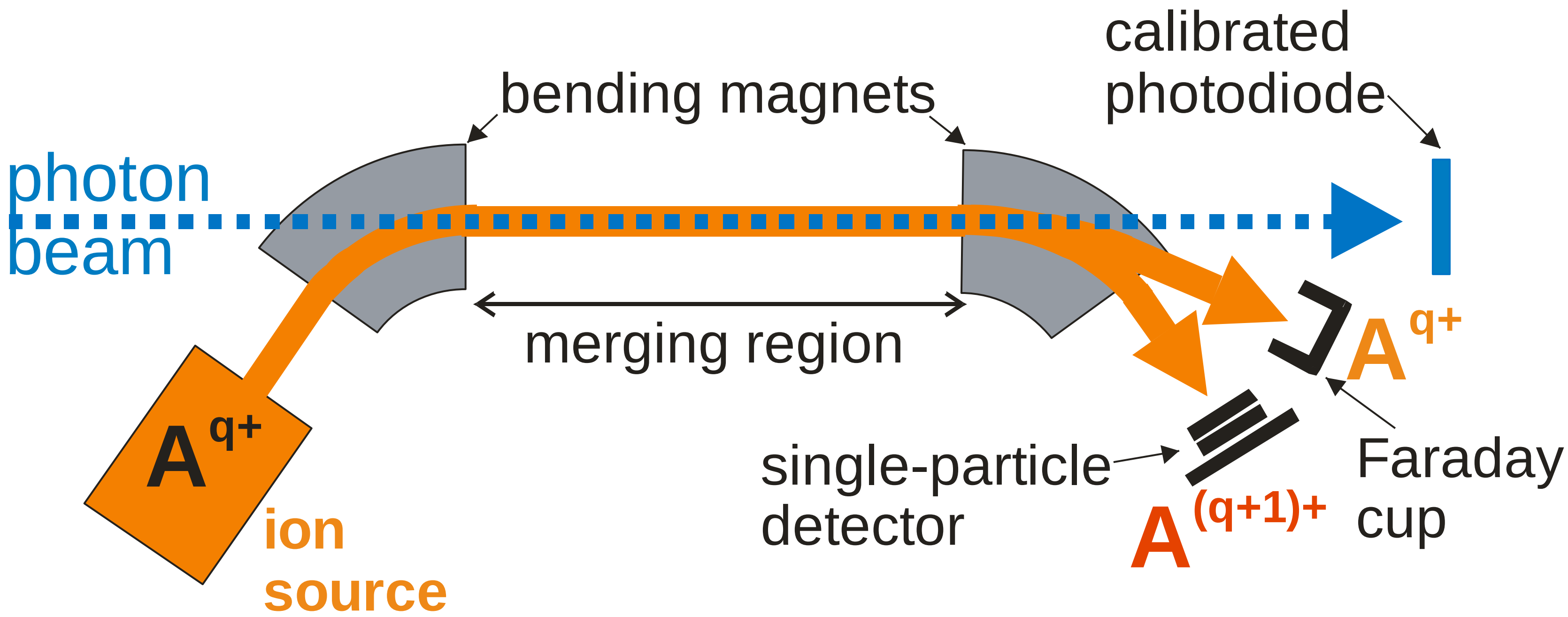
Comparison between **experiment** and **TOP base**

Large discrepancies between experimental and tabulated data are abundant!

danish-french collaboration
El Hassan et al., Phys. Rev. A **79** (2009) 033415

The Photon-Ion Merged-Beams Technique

pioneered by Lyon, West, Peart & Dolder, JPB **19** (1986) 4137



low ion densities: ~ 10^6 cm^{-3}

long interaction region (~ 1 m) makes up for diluteness of ionic targets

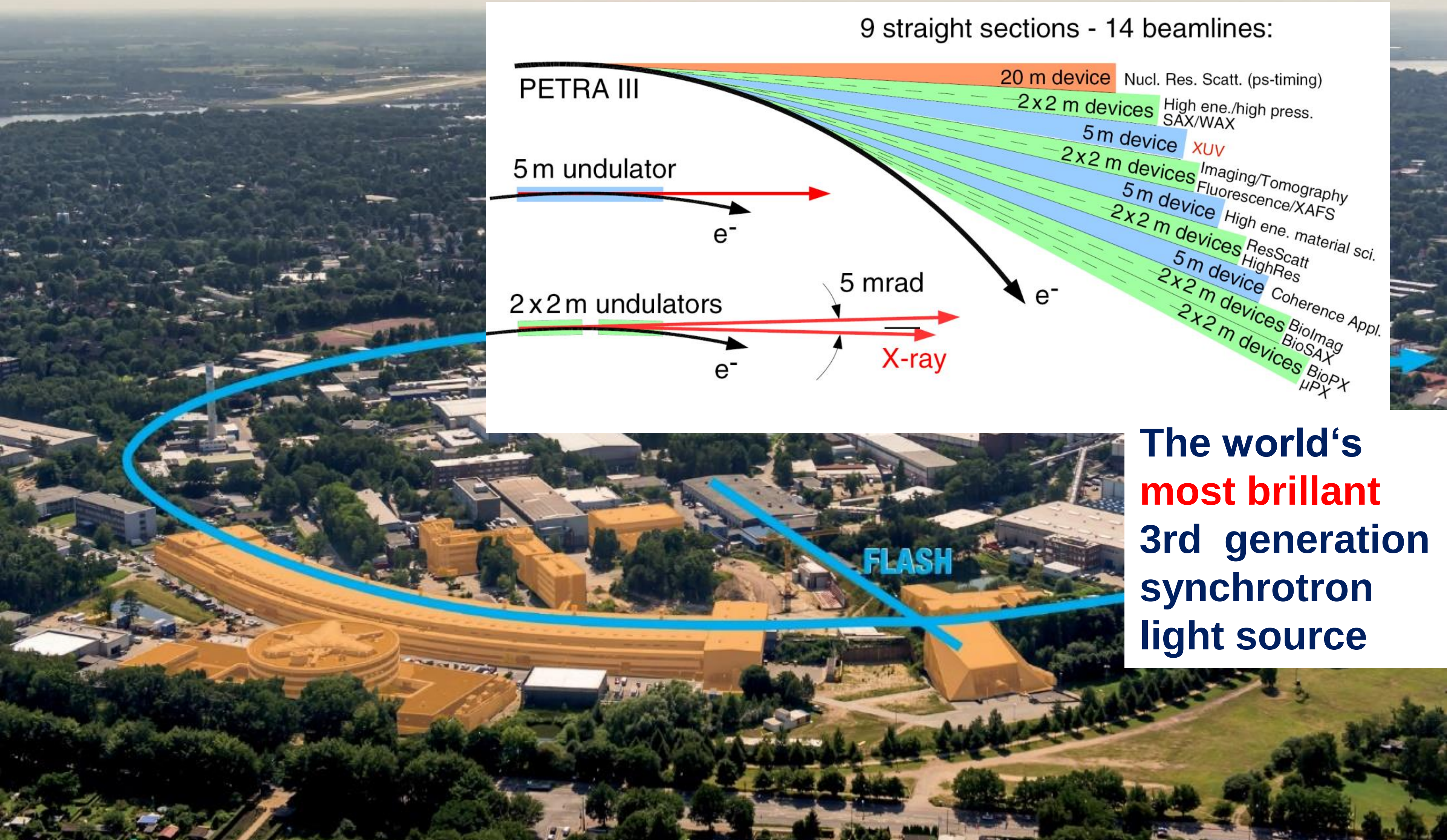
Photons from Synchrotrons

The Advanced Light Source in Berkeley, California

Photons from PETRA III, Hamburg

Aerial view of the DESY site in Hamburg

petra3.desy.de

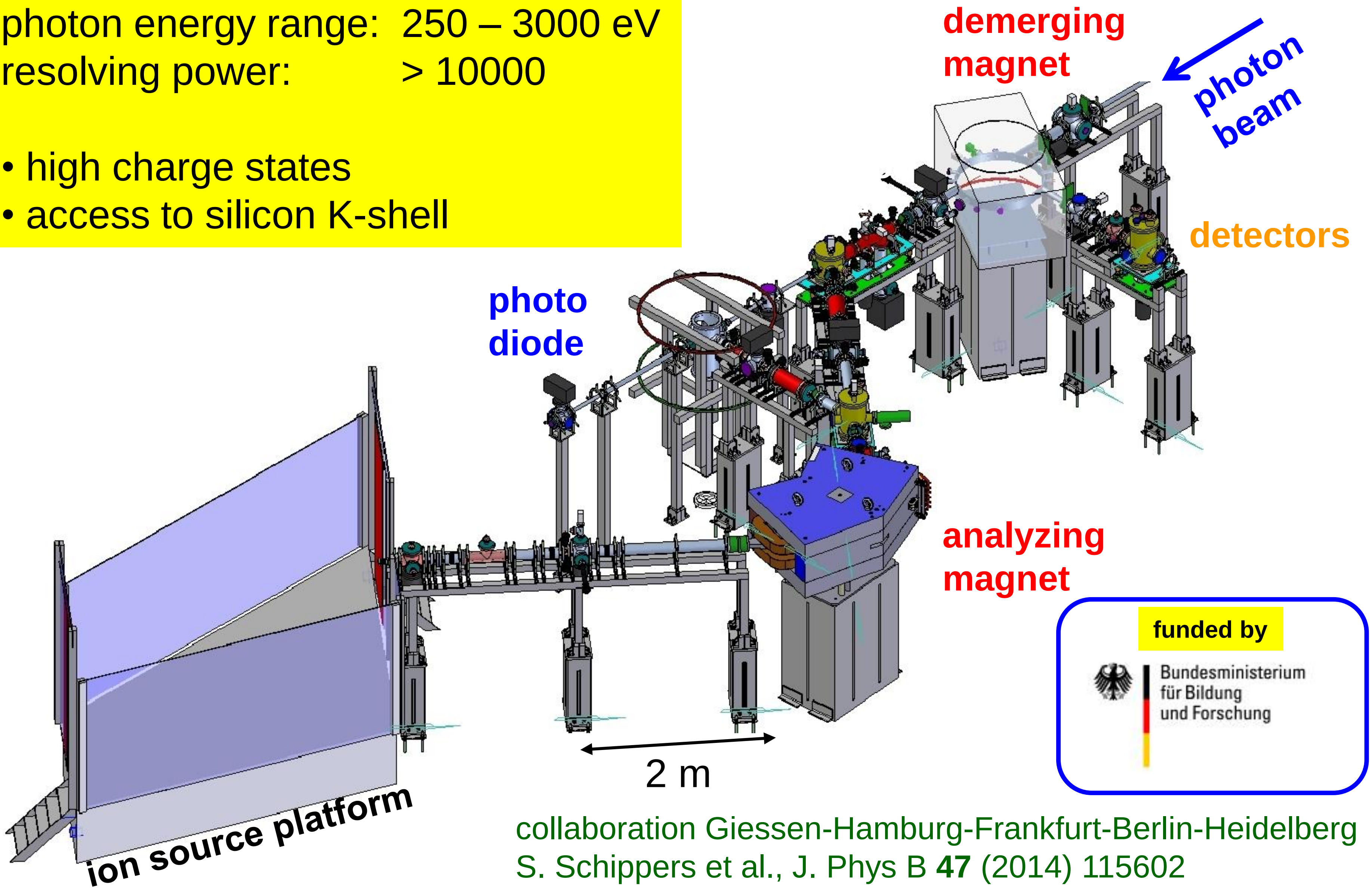


The world‘s
most brillant
3rd generation
synchrotron
light source

PIPE: Photon-Ion Spectrometer at PETRA III

photon energy range: 250 – 3000 eV
resolving power: > 10000

- high charge states
- access to silicon K-shell



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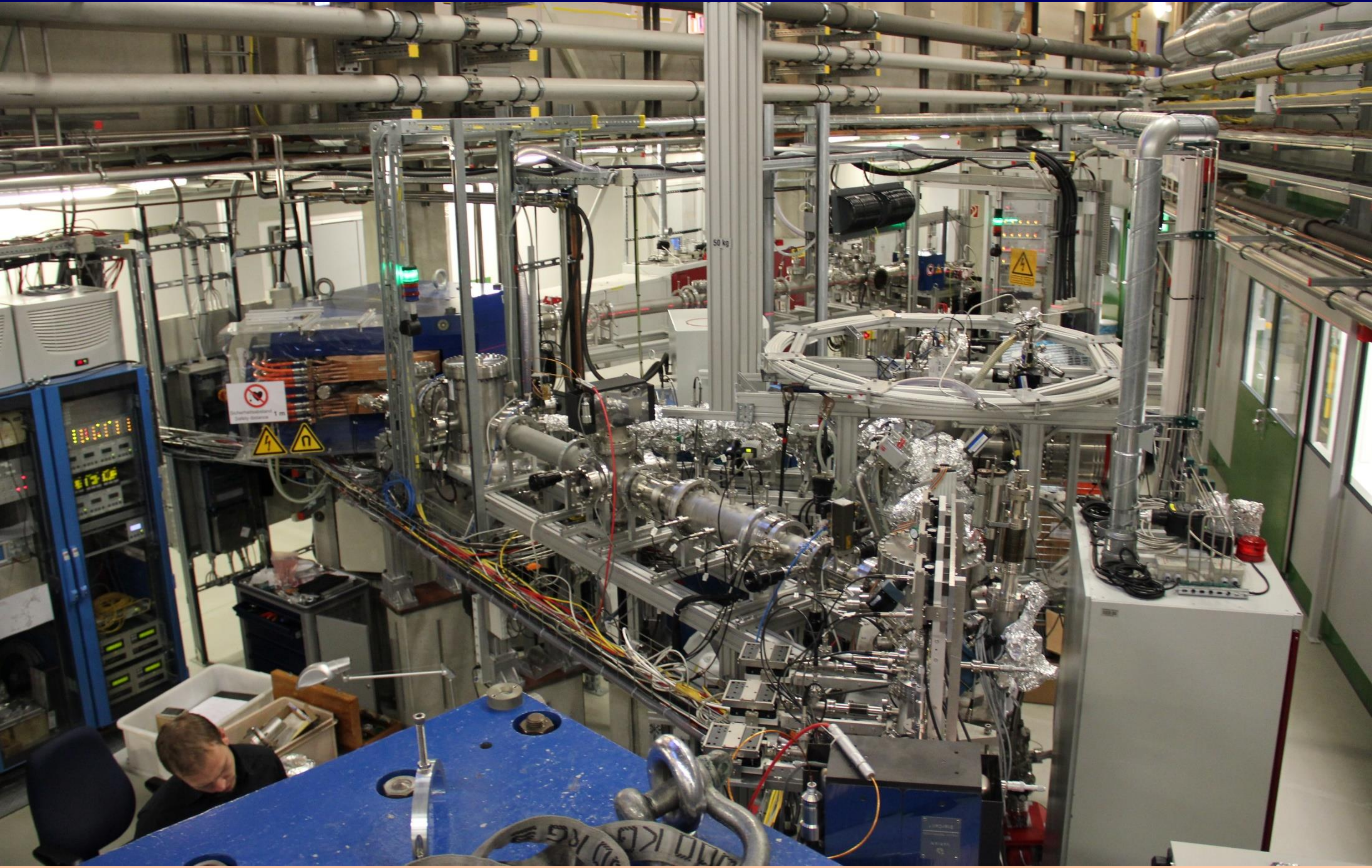
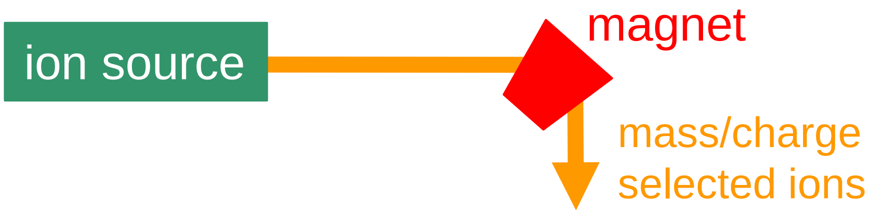
collaboration Giessen-Hamburg-Frankfurt-Berlin-Heidelberg
S. Schippers et al., J. Phys B **47** (2014) 115602

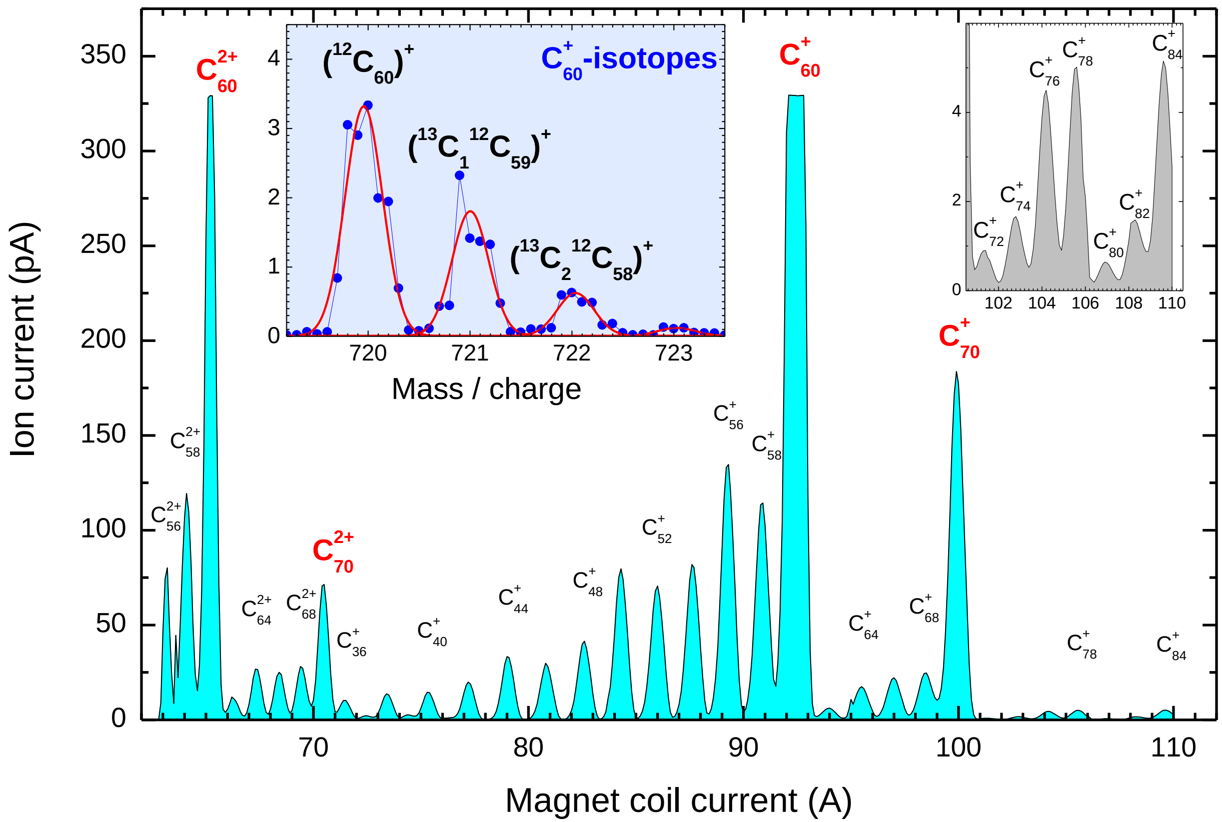
View towards the Ion Source



Mass/Charge Selection of Ions

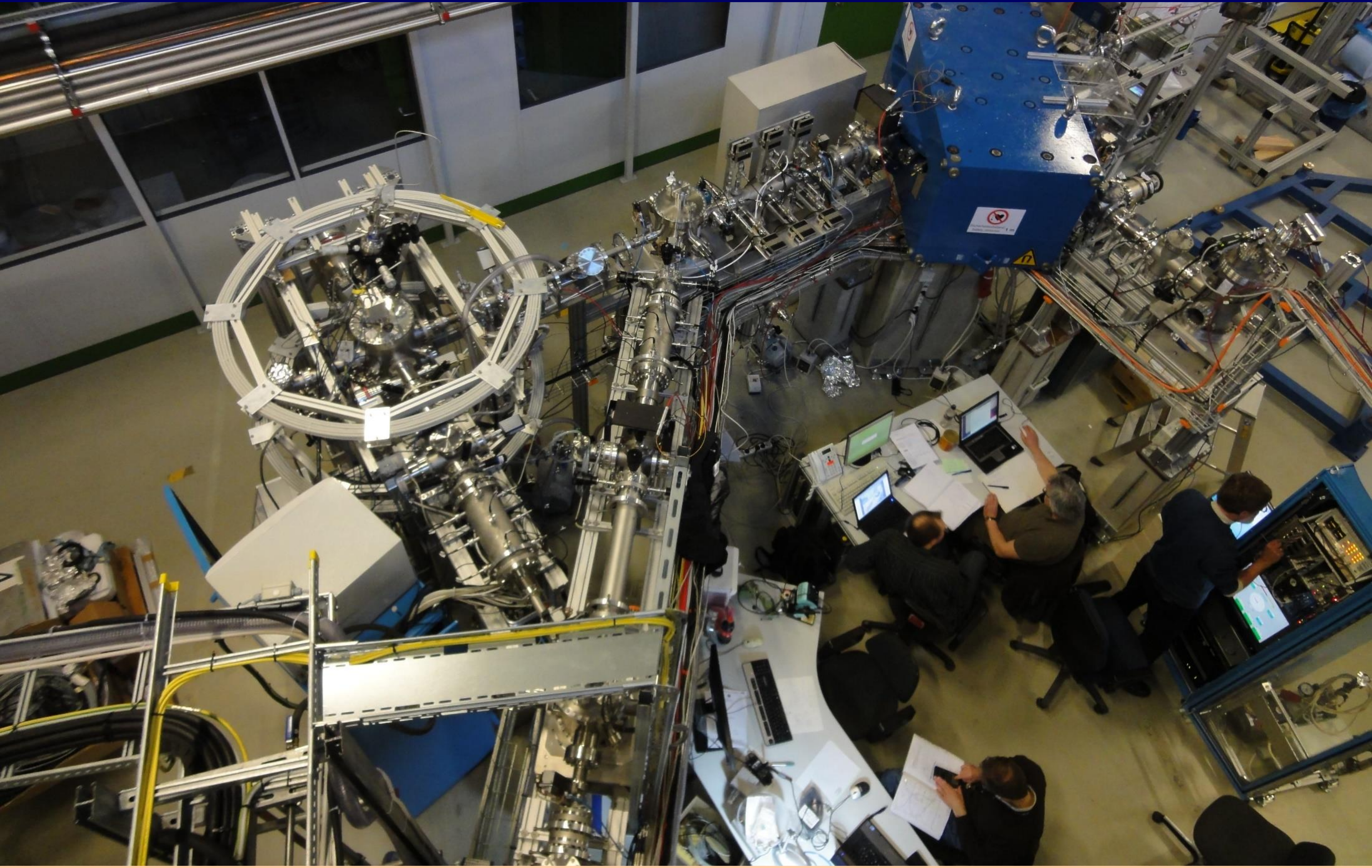
powder of **mixed fullerenes** in the ion source





experiments with extremely dilute beams

View of Interaction Regions

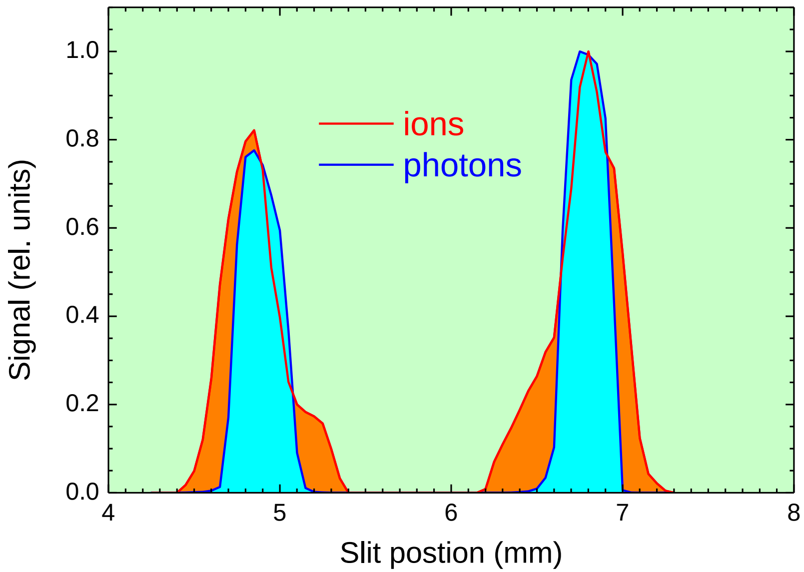


Measurement of Absolute Cross Sections

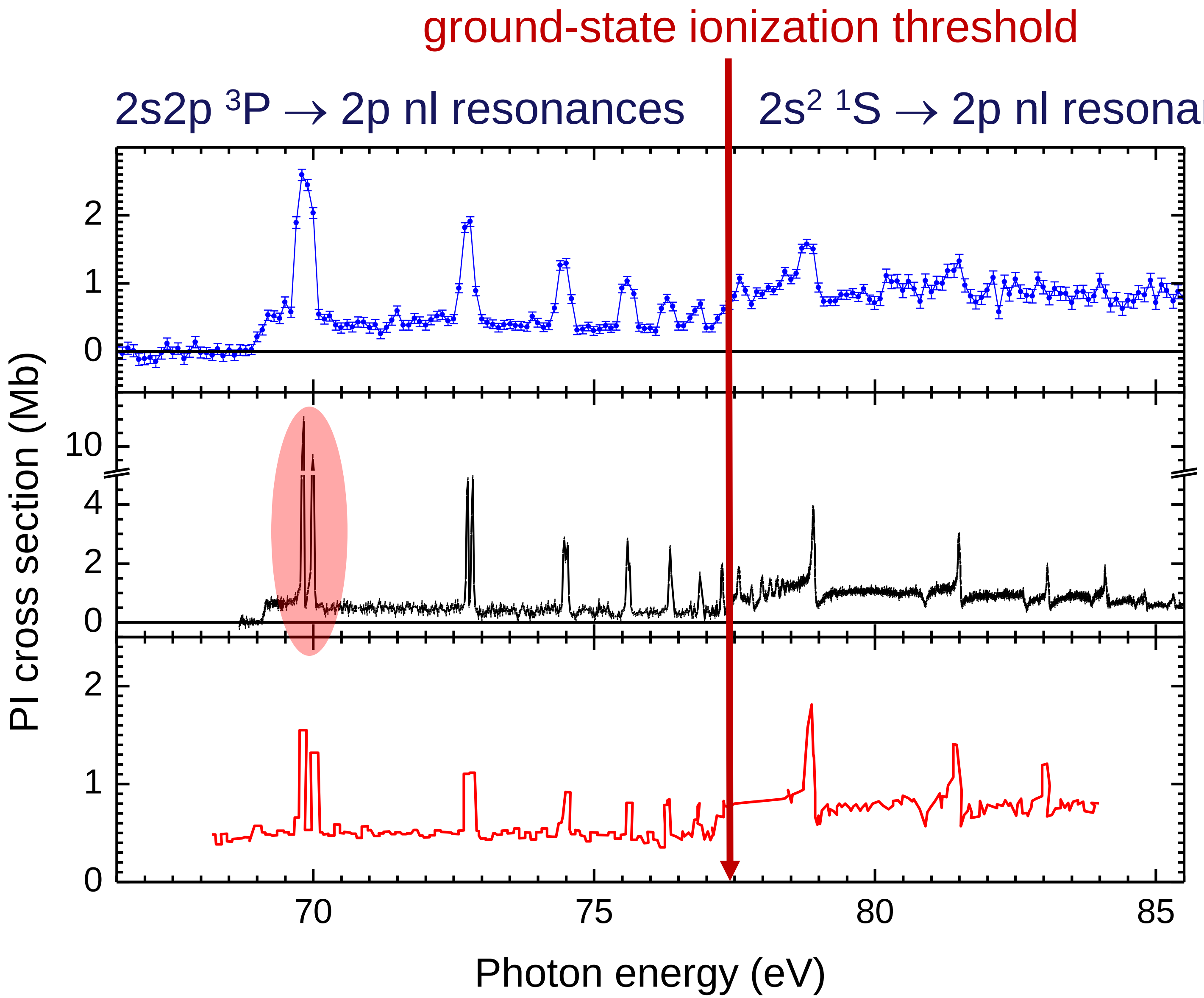
measured count rate: $R = \boxed{\sigma} \boxed{\frac{I_{ion} L}{qev_{ion}}} \boxed{\phi_{ph}} \boxed{\frac{1}{F}}$

cross section | number of ions | photon flux | beam overlap

typical **uncertainty** of absolute cross section: **10-20%**



Photoionization of Be-like N^{3+}



ASTRID, Bizau et al.
A&A **439** (2005) 387

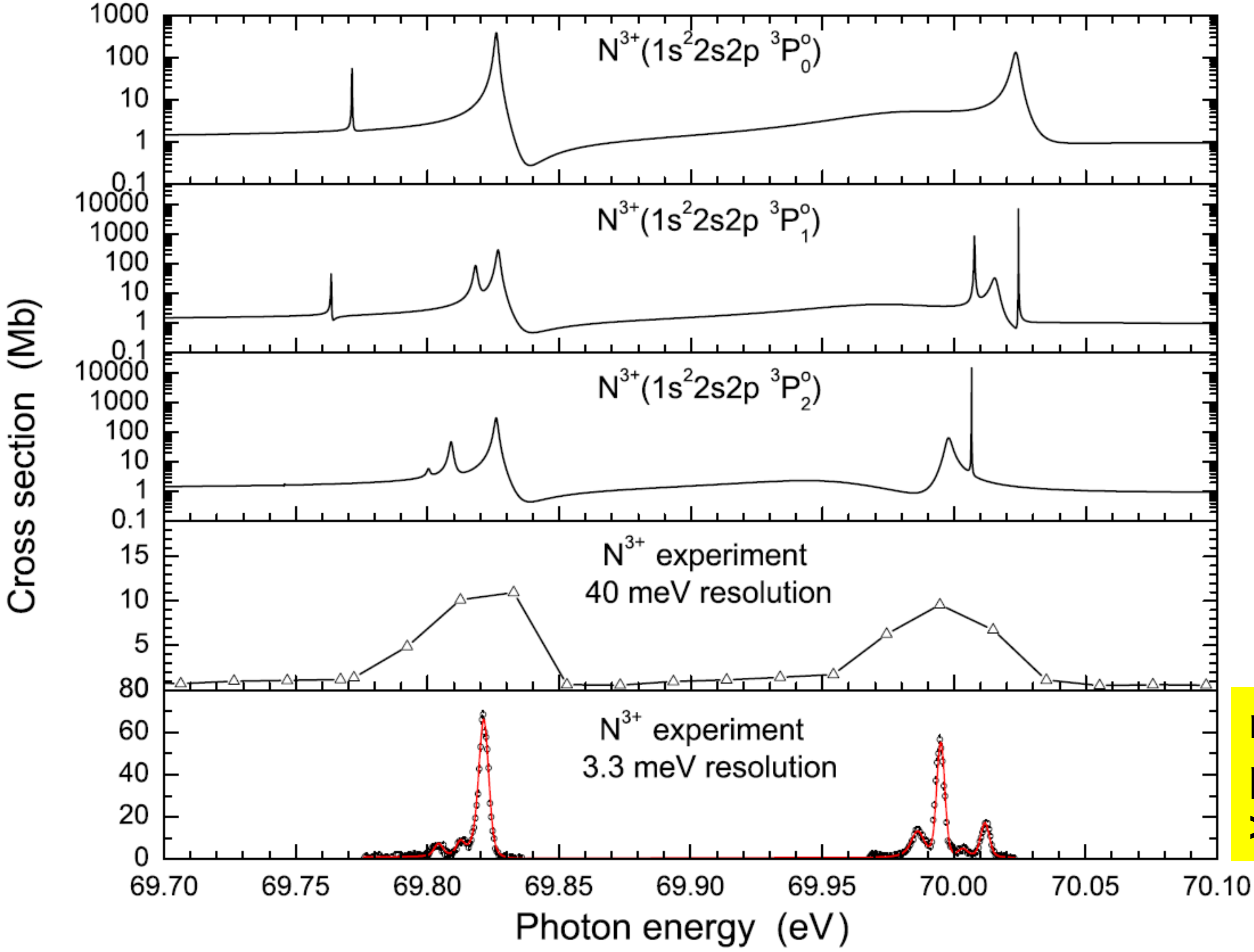
ALS, Müller et al.
JPB **43** (2010) 225201

EBIT, Simon et al.
JPB **43** (2010) 65003

High-Res. Experiment and R-matrix Theory

Breit-Pauli R-matrix (BPRM) theory: <u>Brendan McLaughlin</u>

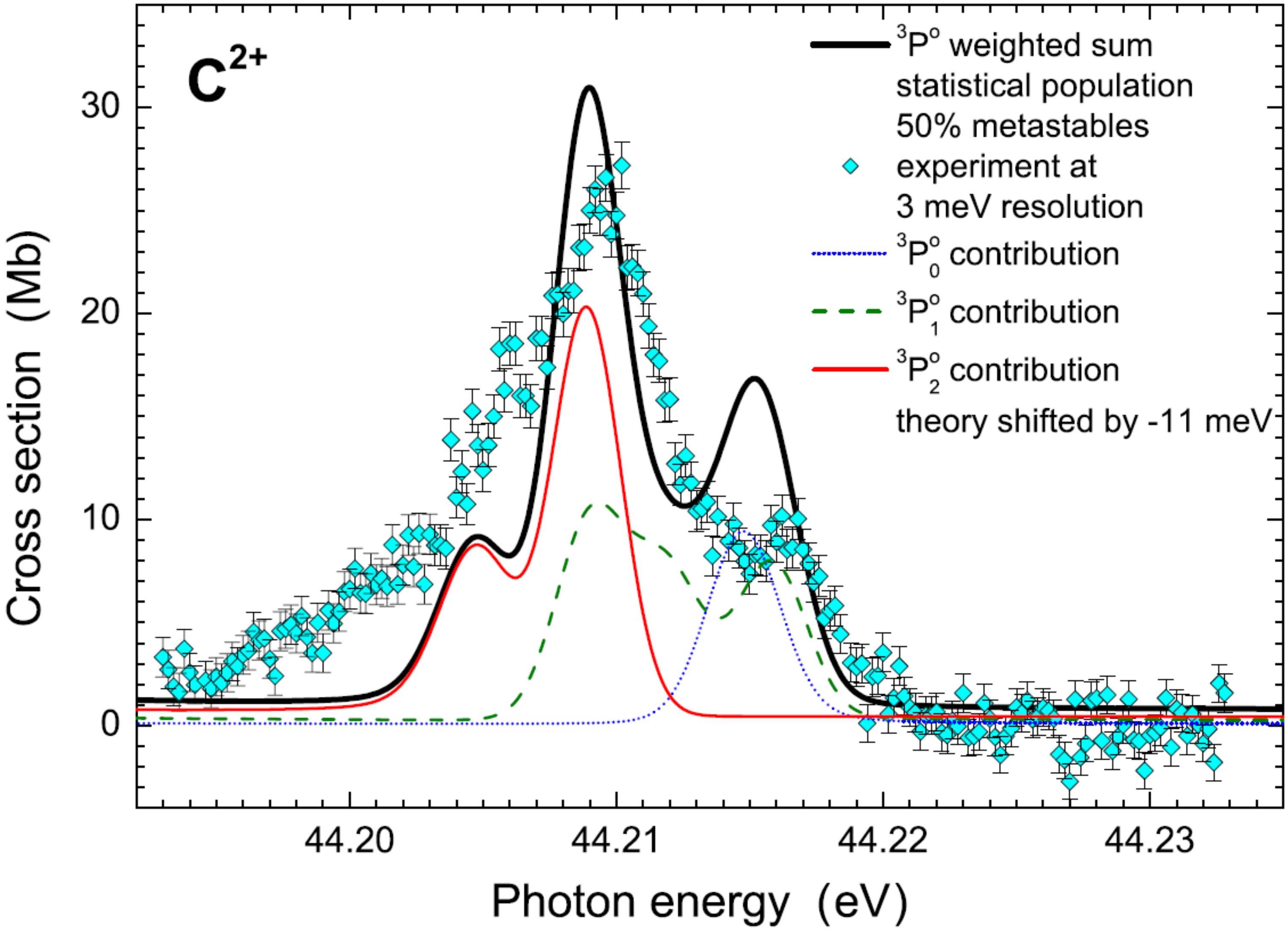
similar calculations by W.-C. Chu et al., JPB **42** (2009) 205003



resolving power: > 20 000

Remaining Discrepancies

C^{2+} (2s 2p $^3P \rightarrow$ 2p 5p ^3P) resonances

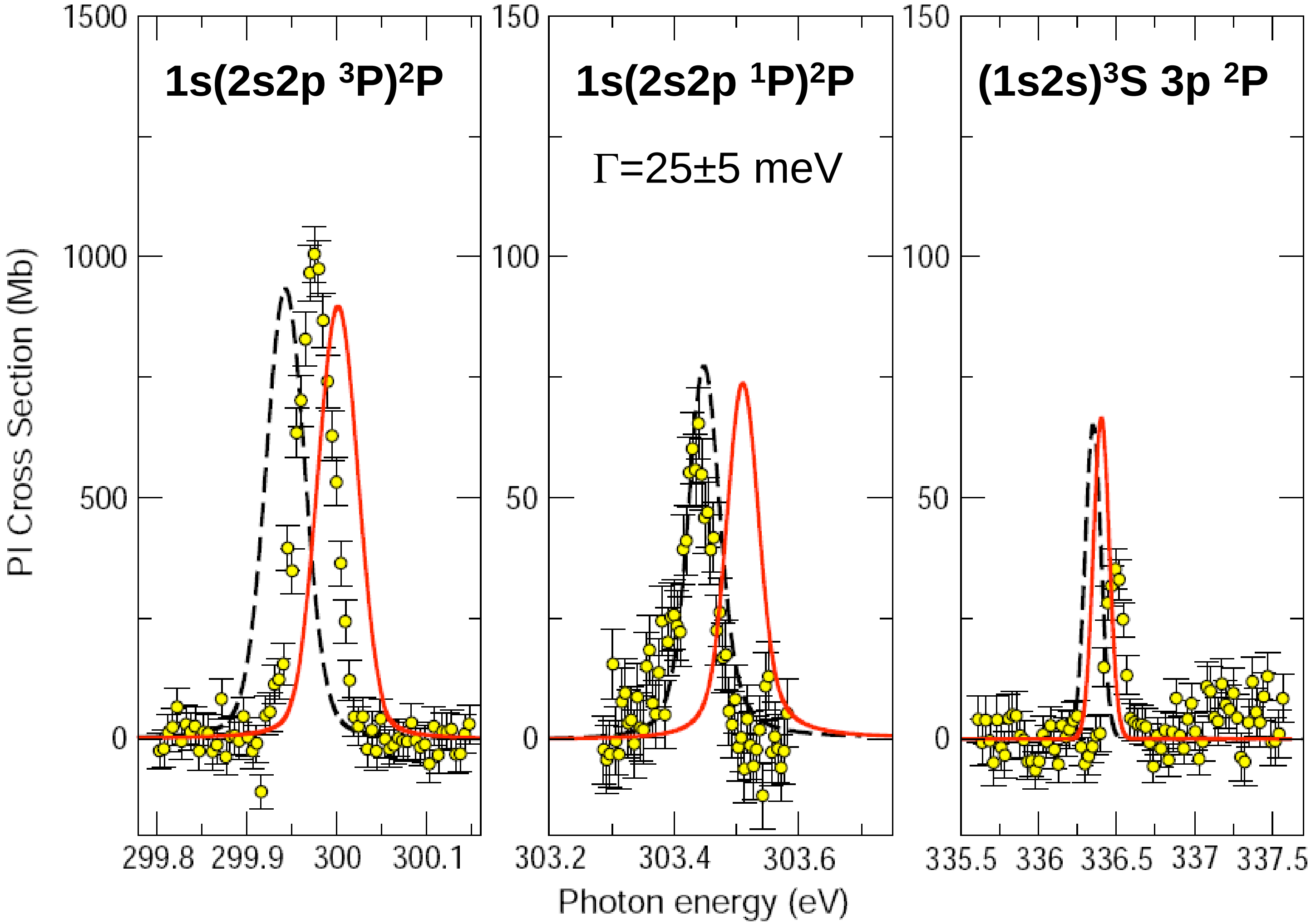


experimental uncertainty < |± 10| meV

K-shell Ionization of Li-like C^{3+}

$h\nu + C^{3+}(1s^2 2s) \rightarrow C^{4+}(1s^2)$

1s 2s nl resonances

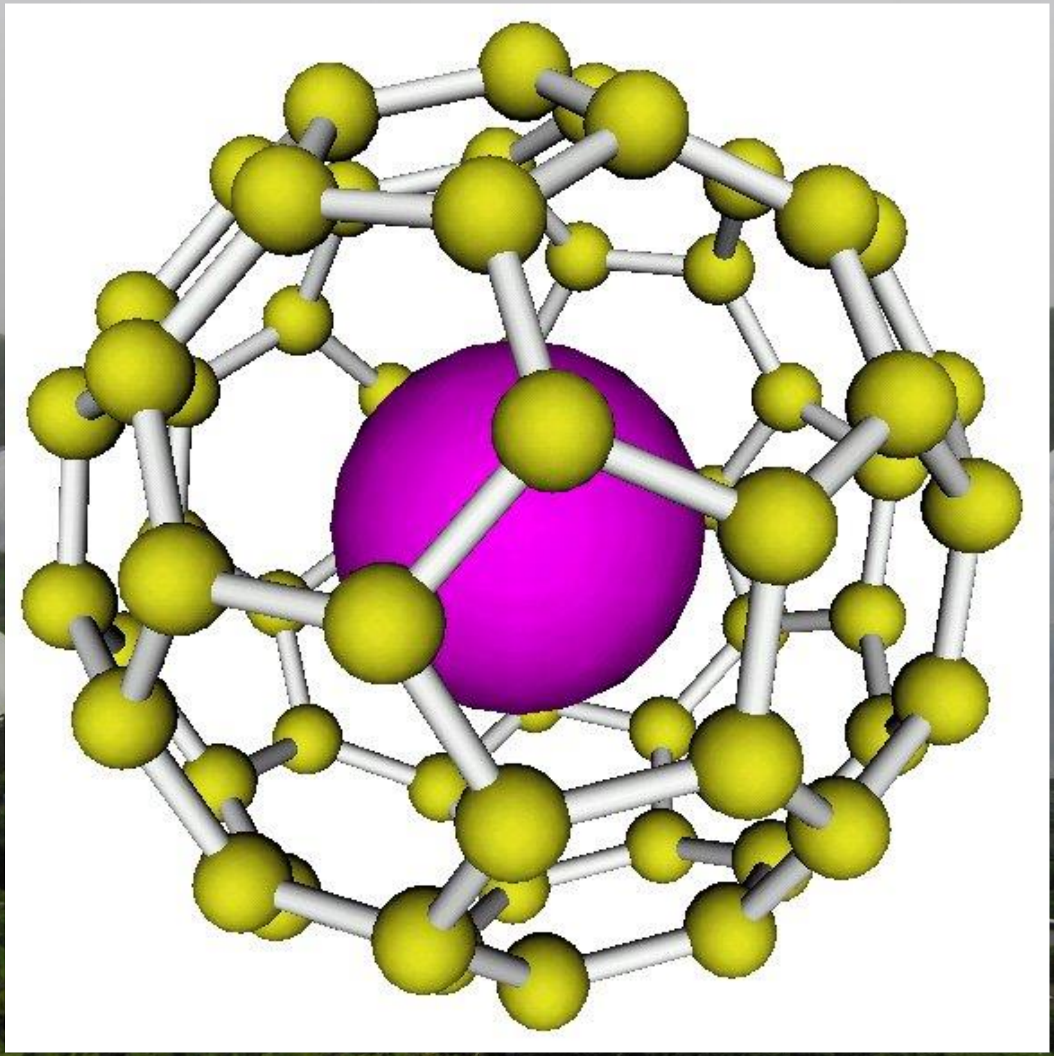


R-Matrix theory

1. **Breit-Pauli intermediate coupling**
2. **LS-coupling**

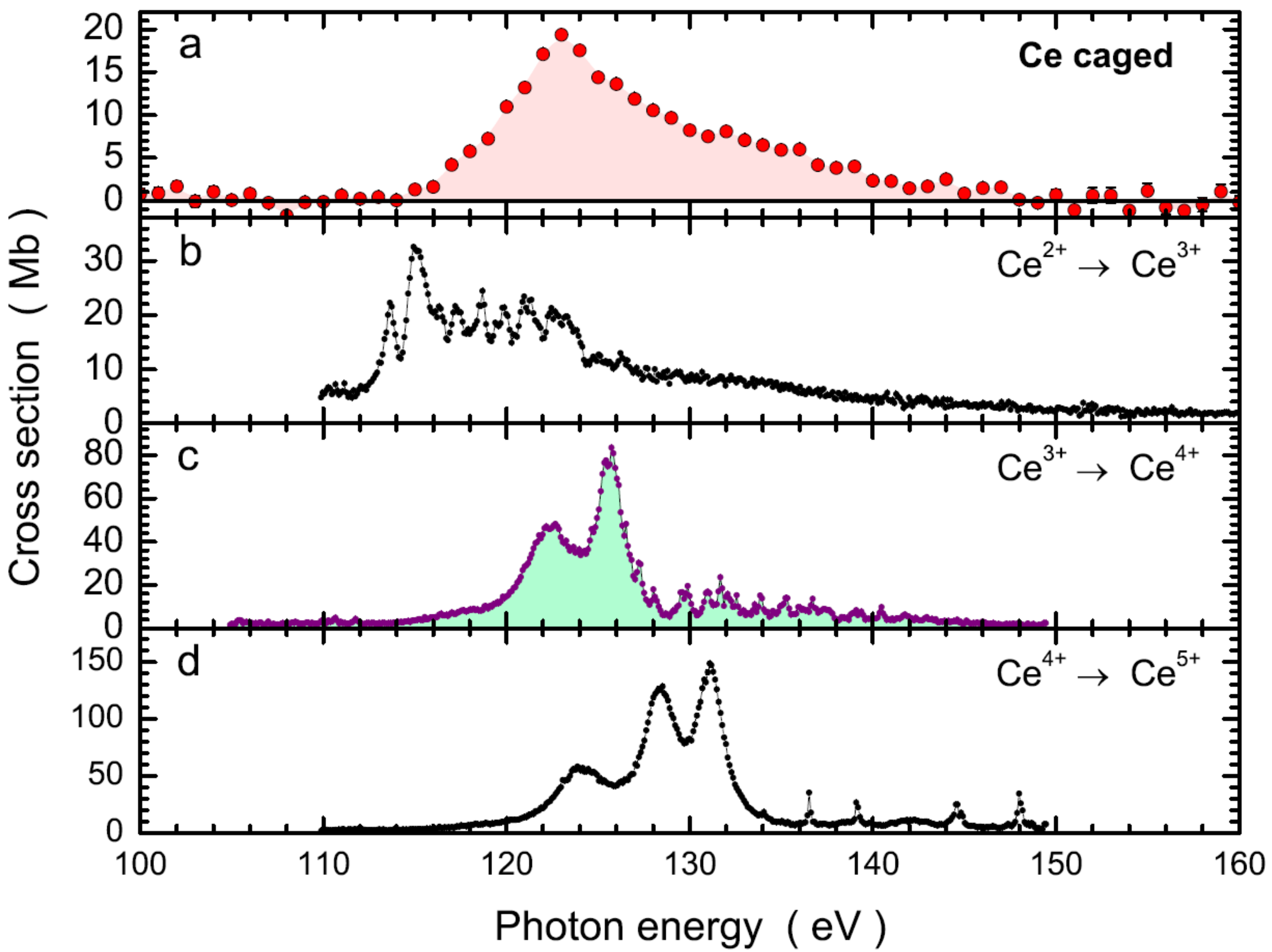
experimental uncertainty of resonance positions: 30 – 100 meV

Endohedral Fullerenes: Atoms in a Cage



Photoionization of Free and Encaged Ce Ions

Charge of the encaged Ce atom: 3+



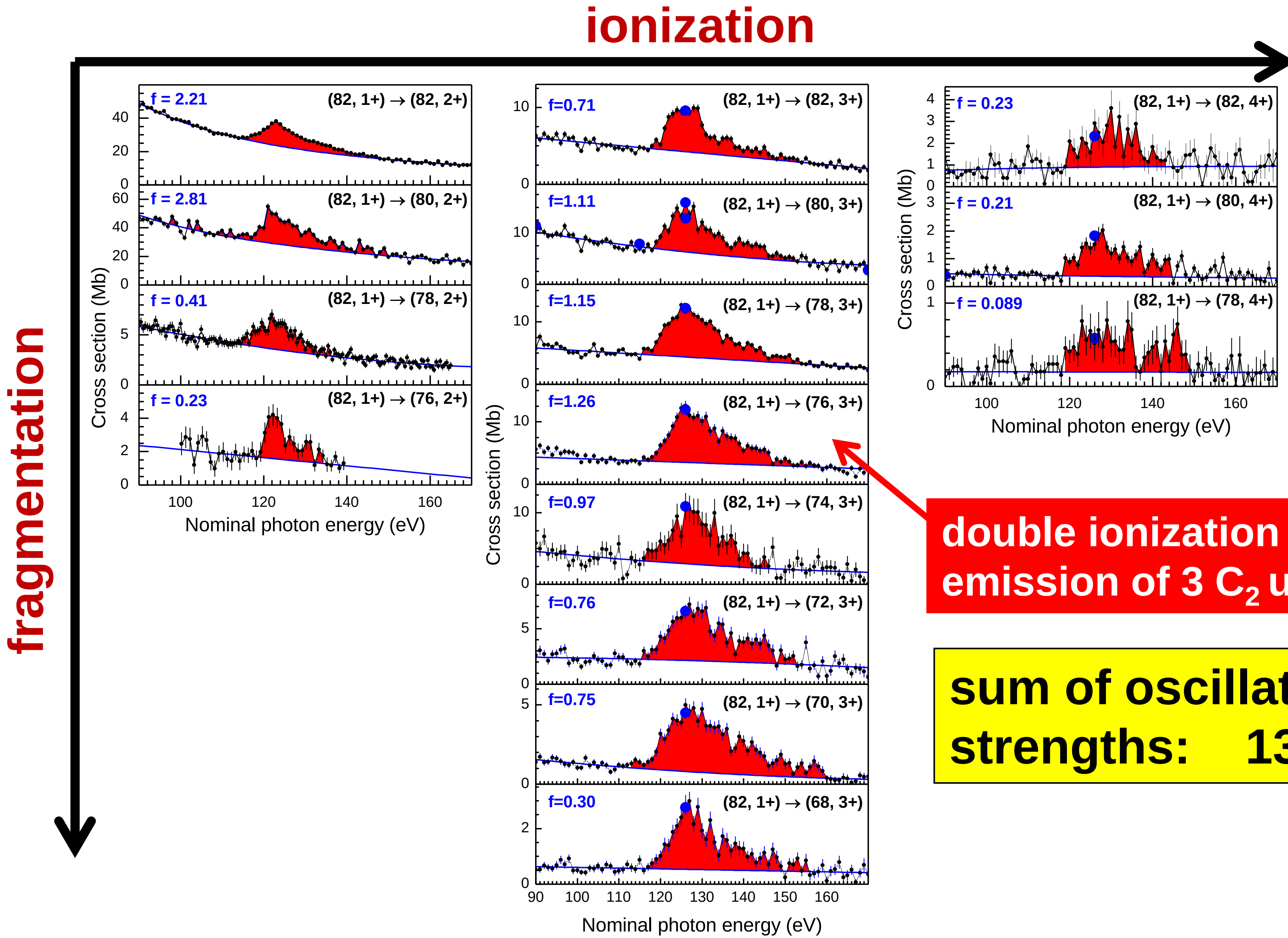
$Ce@C_{82}^{+}$

Ce^{2+}

Ce^{3+}

Ce^{4+}

$Ce@C_{82}^{+}$: Photoionization and –fragmentation

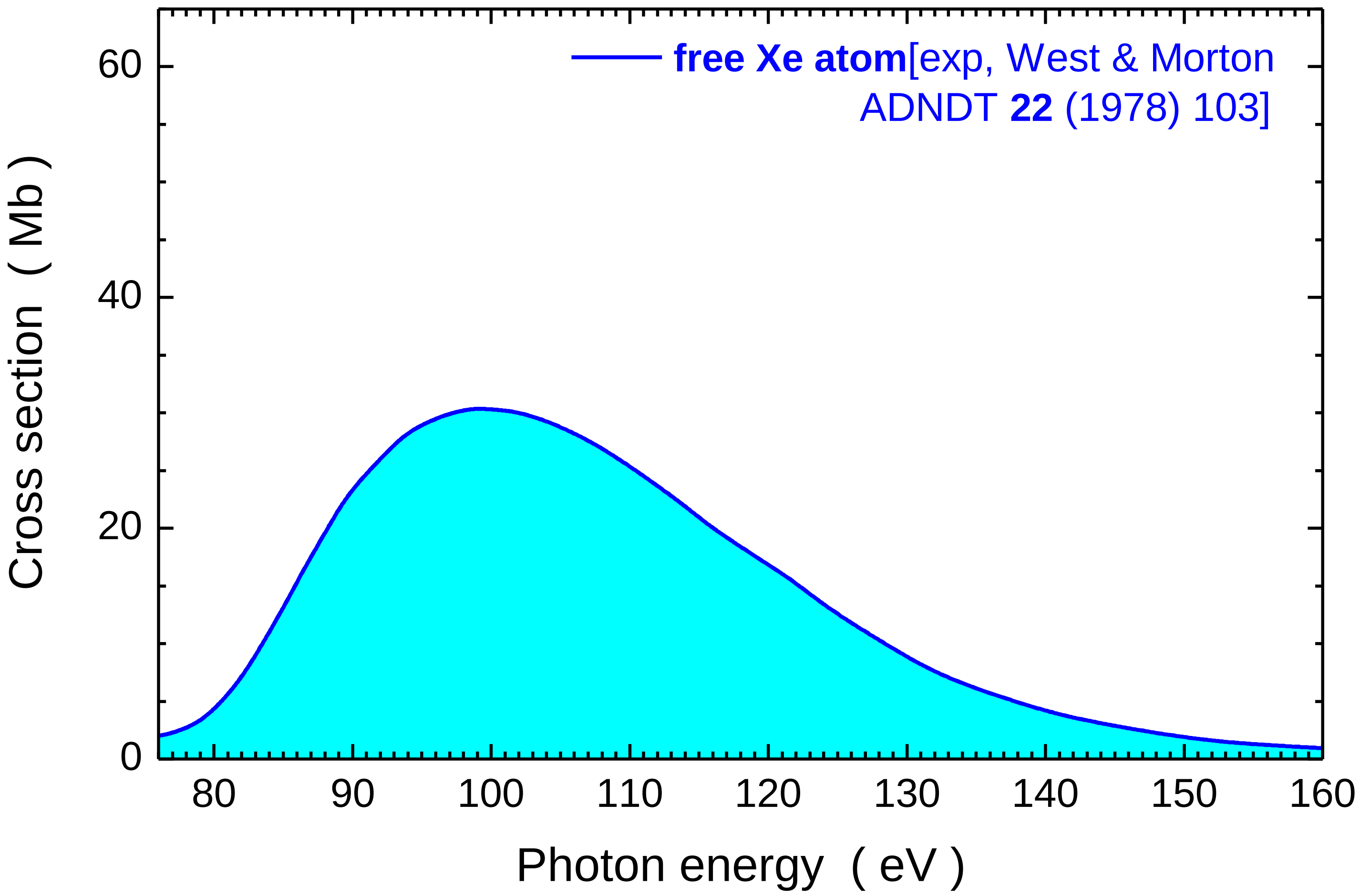


double ionization and emission of 3 C_2 units

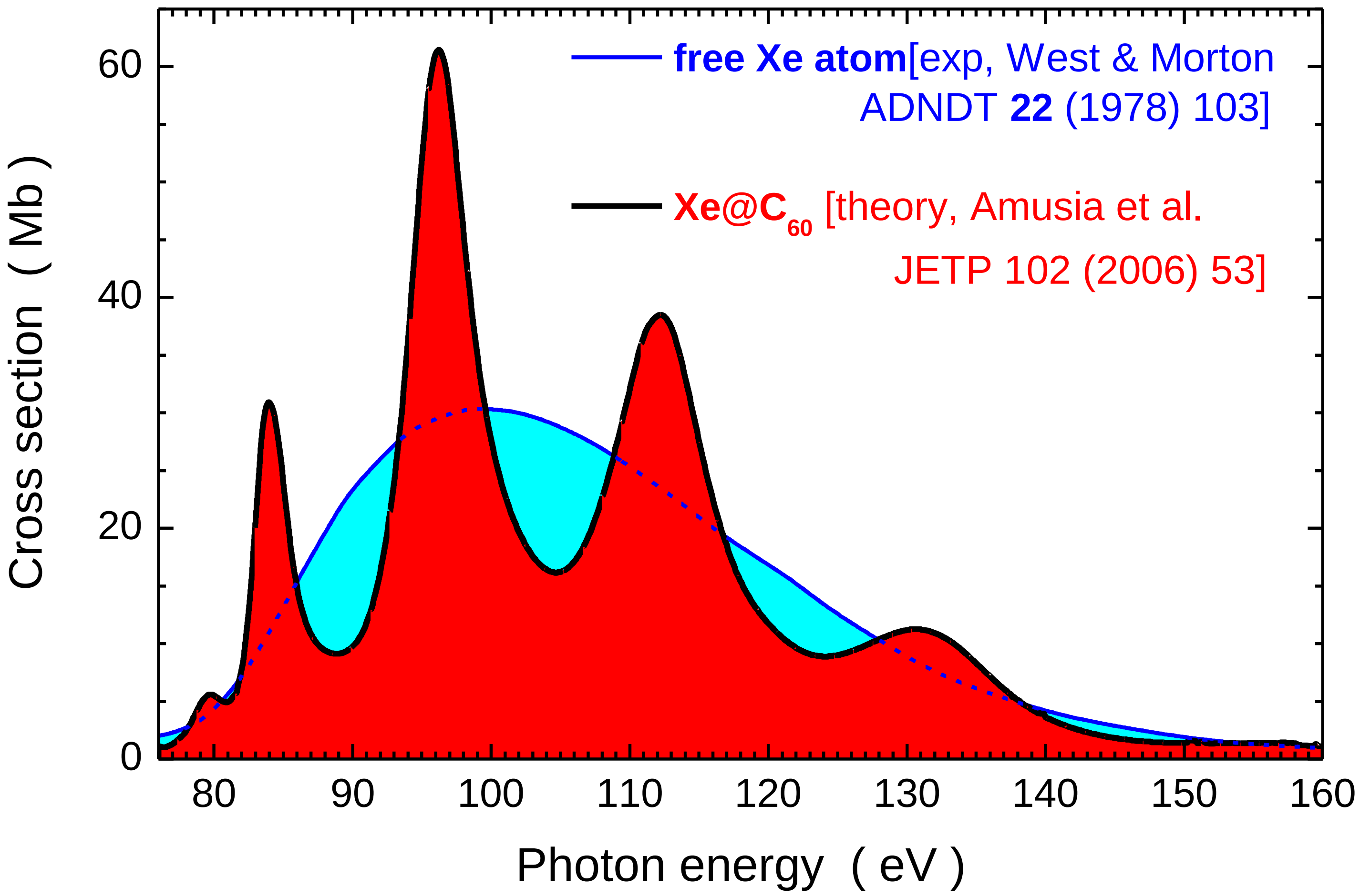
sum of oscillator strengths: 13.2

Giant Atomic Resonance

Photoionization of Xe(4d) shell

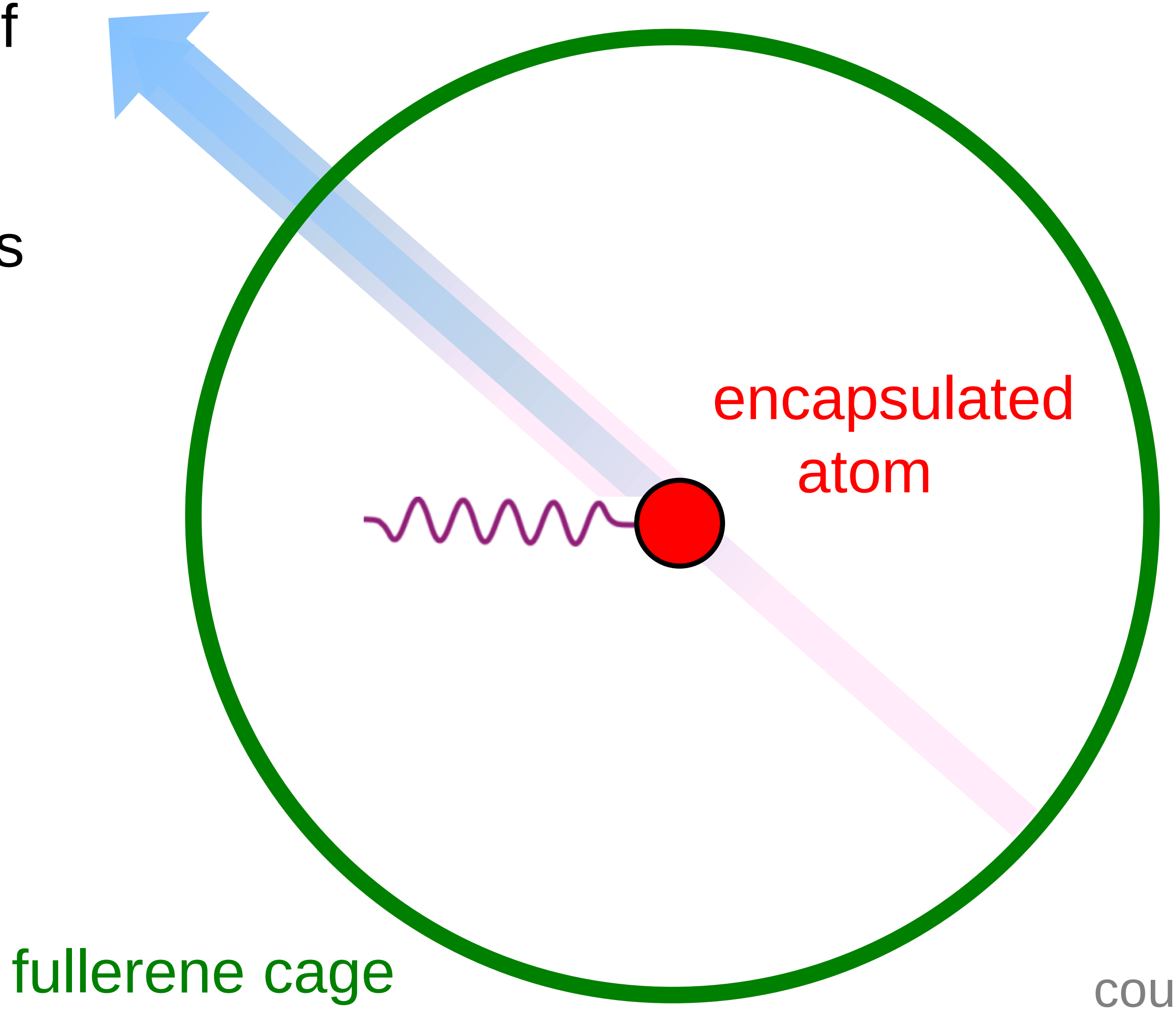


Confinement Resonances



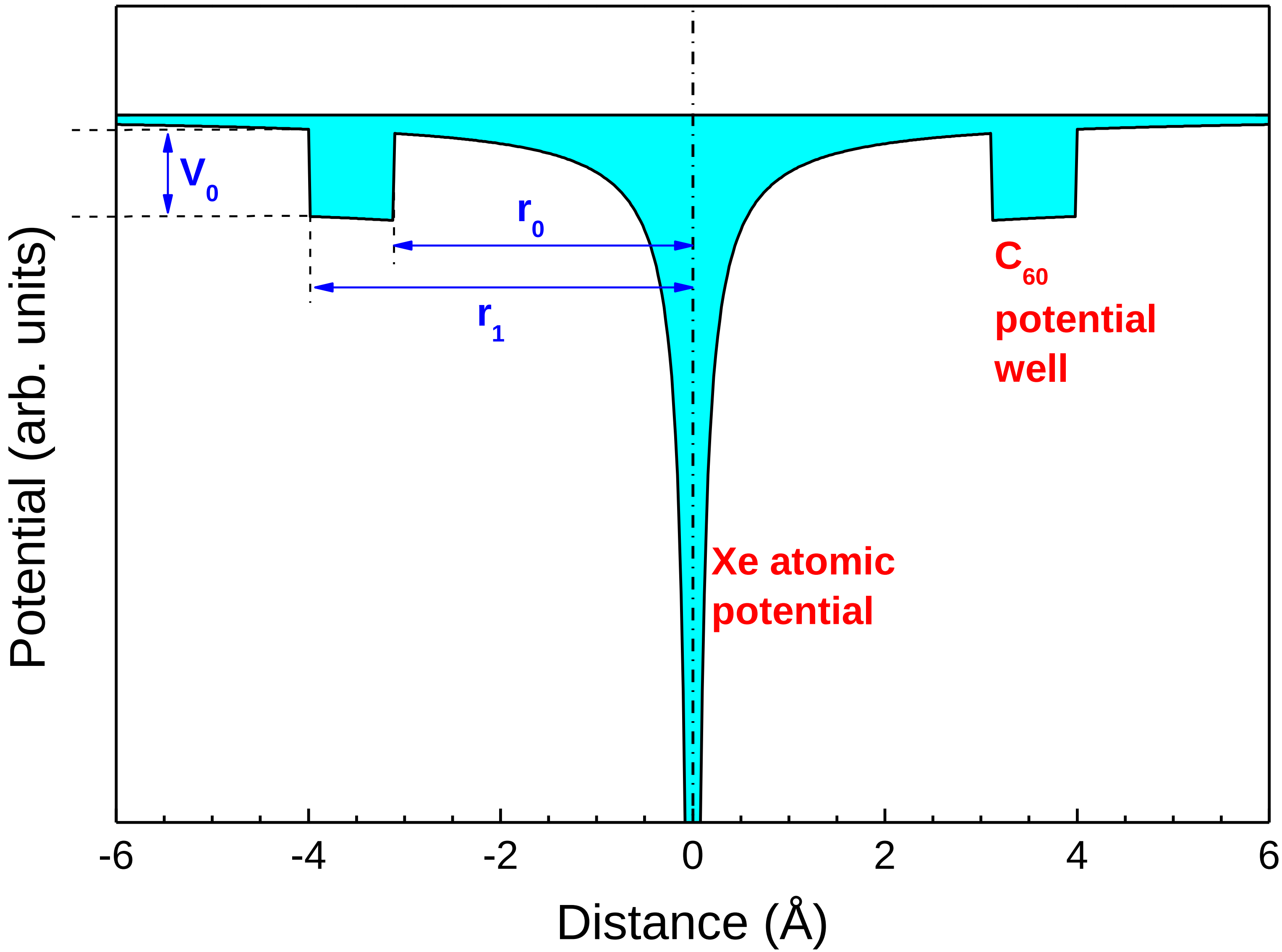
A Quantum Interference Phenomenon

Interference of direct and reflected electron waves

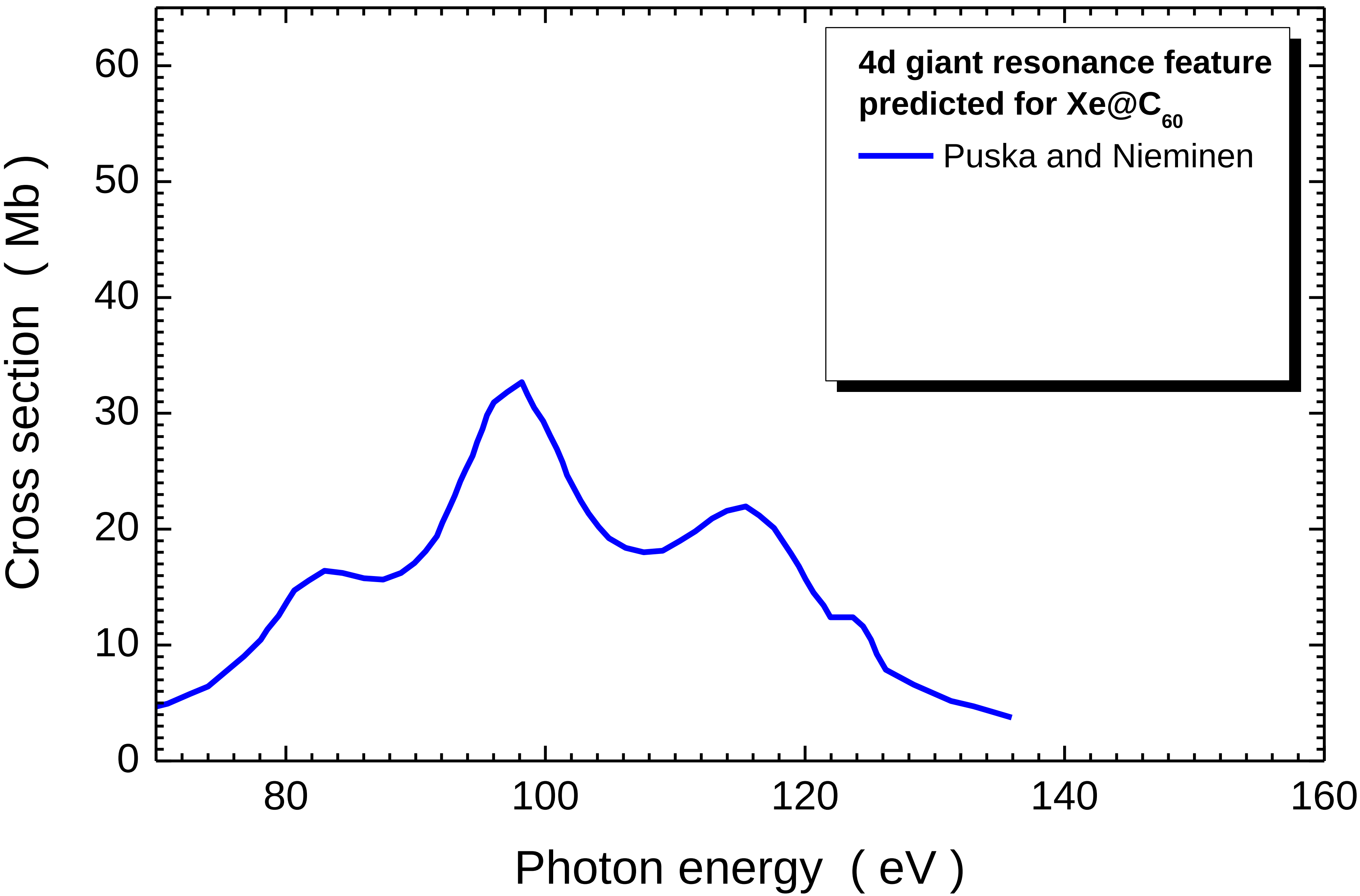


courtesy of A. Müller

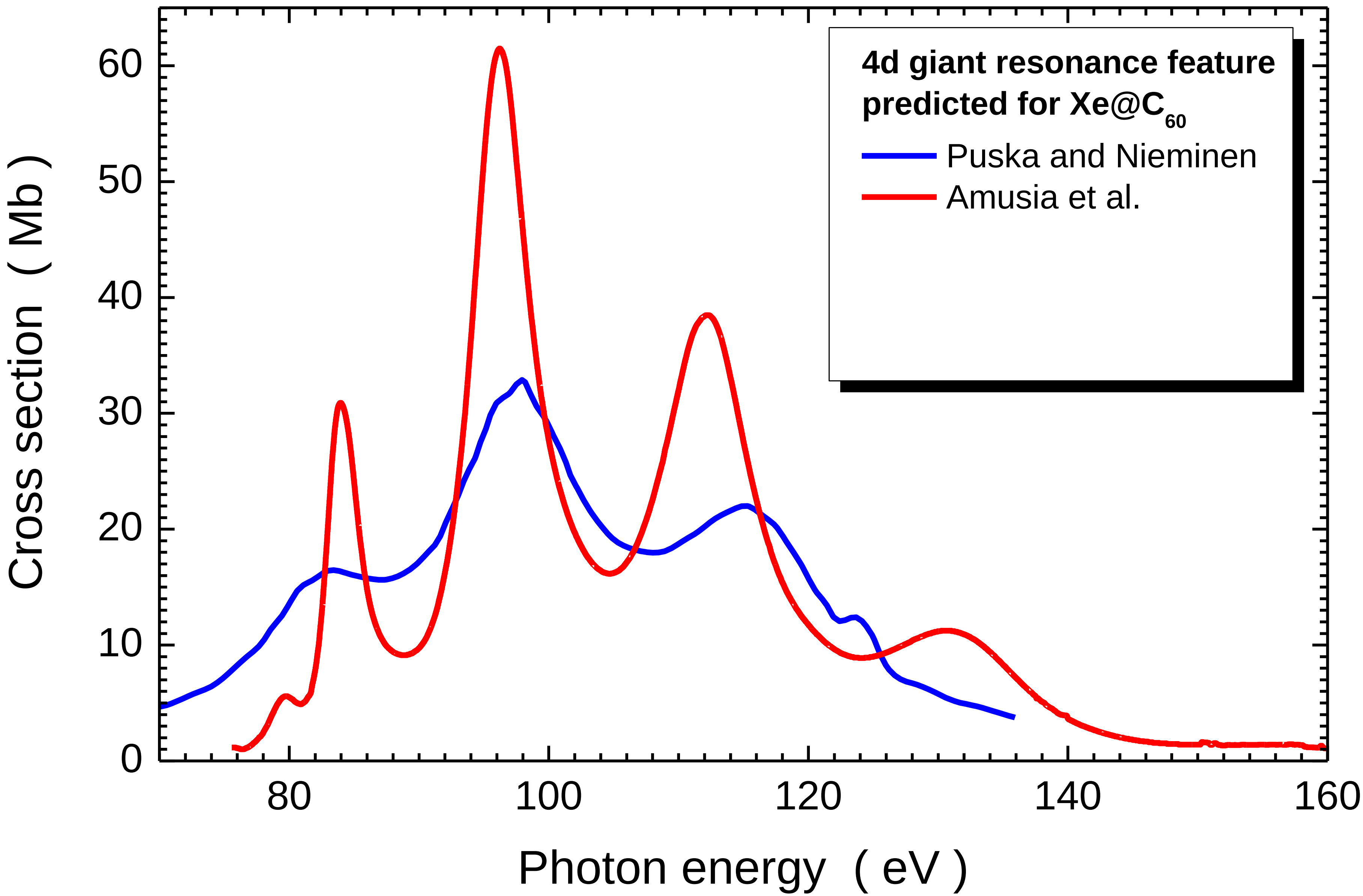
Xe@C_{60} Model Potential



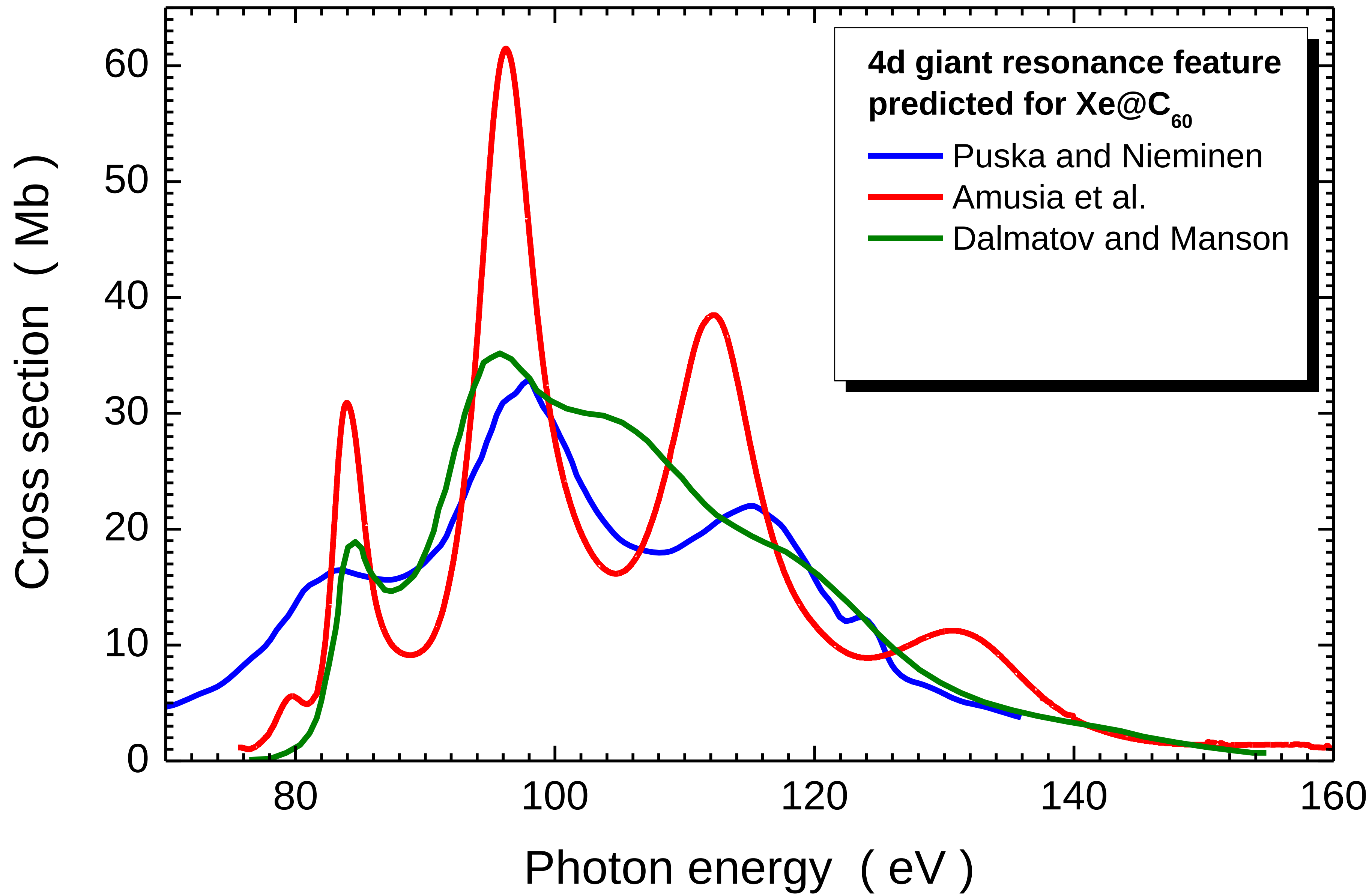
Confinement Resonances in $Xe@C_{60}$:Theory



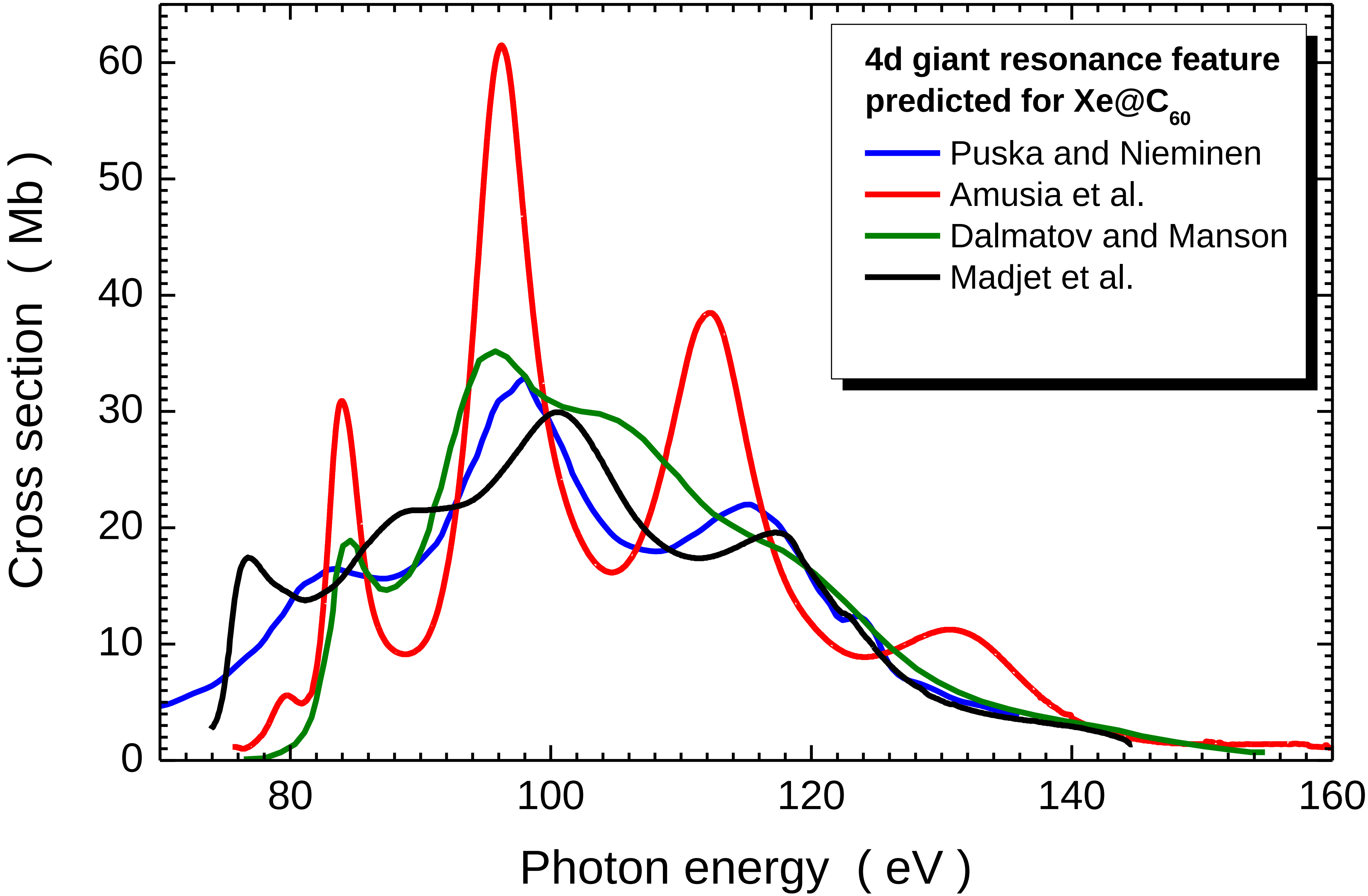
Confinement Resonances in $Xe@C_{60}$:Theory



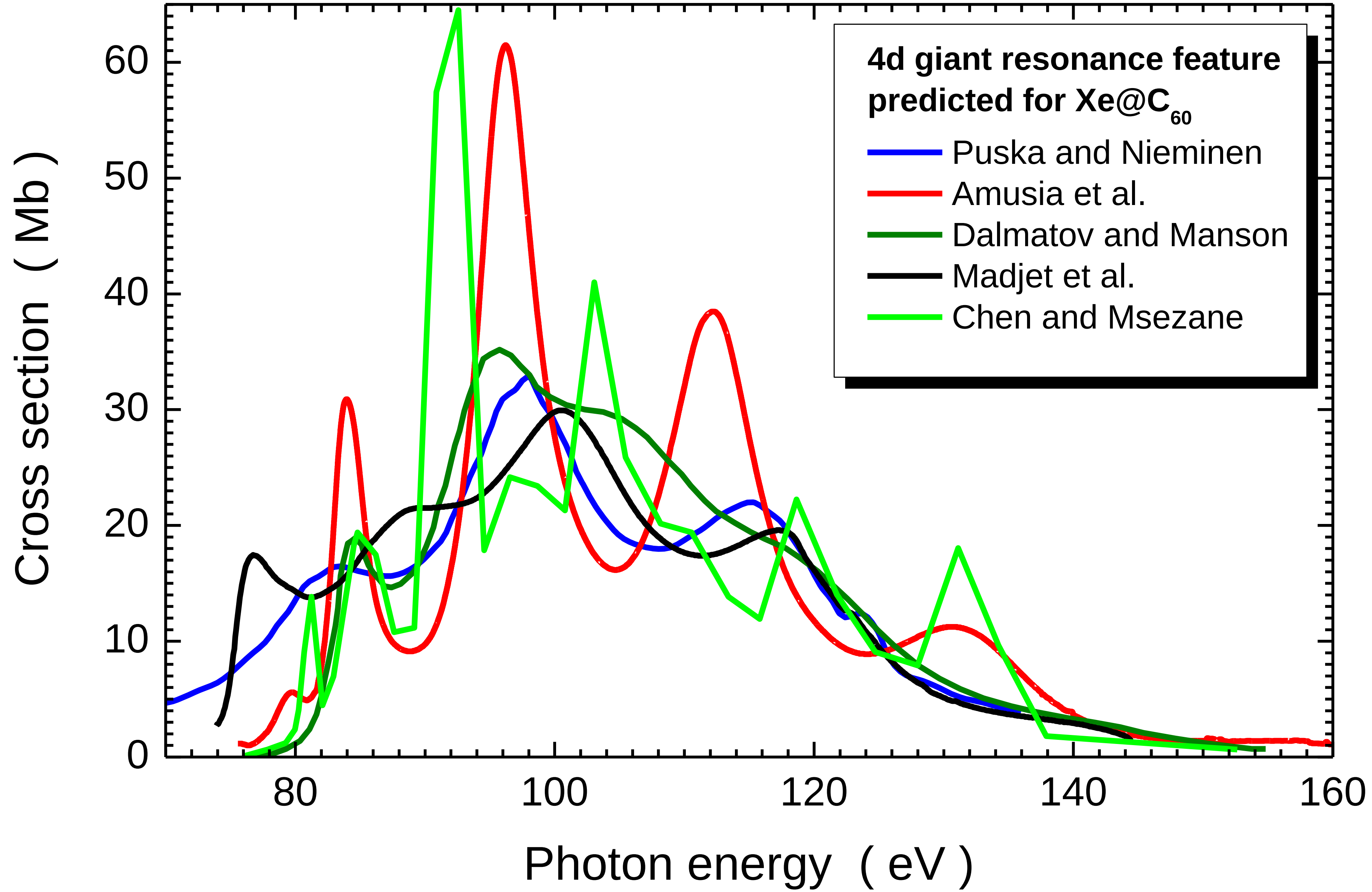
Confinement Resonances in $Xe@C_{60}$:Theory



Confinement Resonances in Xe@C_{60}:Theory

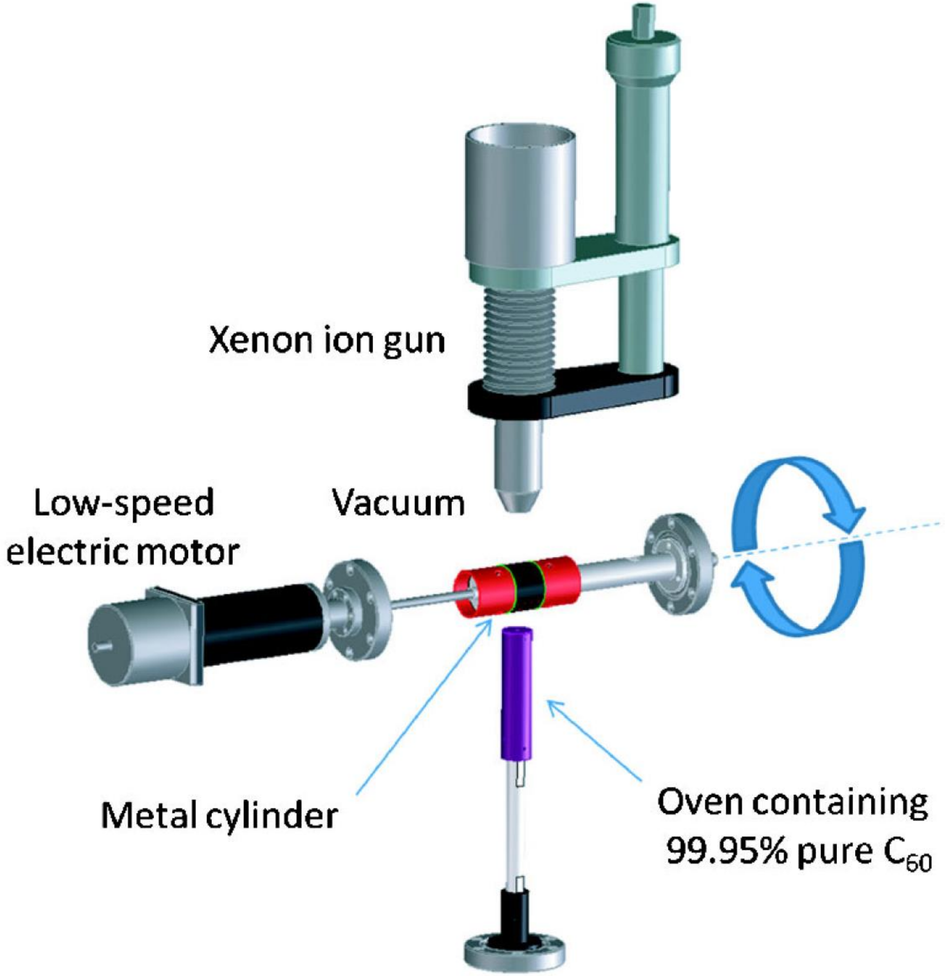


Confinement Resonances in Xe@C_{60}:Theory



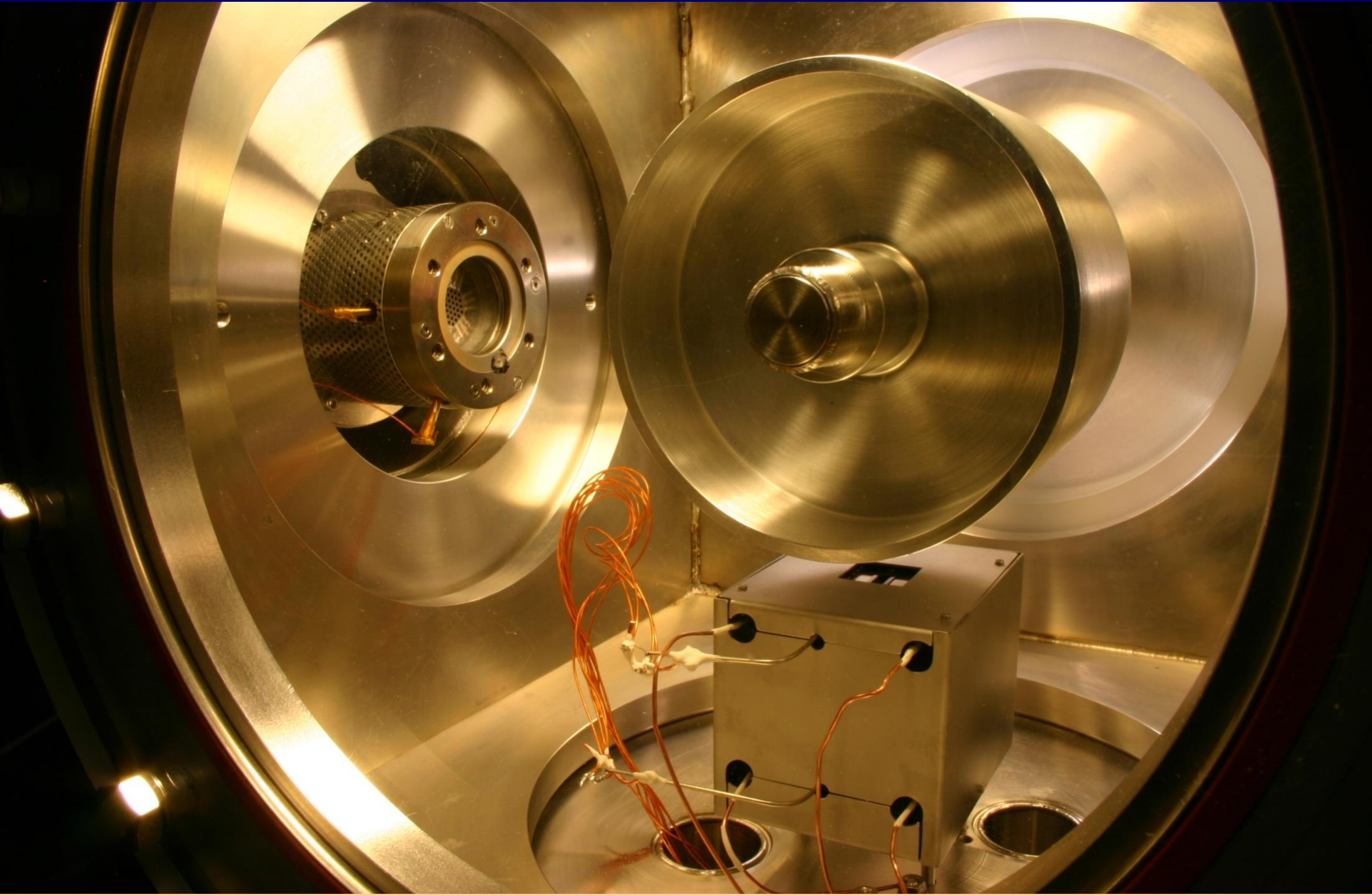
How to Make Xe@C_{60}?

method by Shimshi et al. (1997)

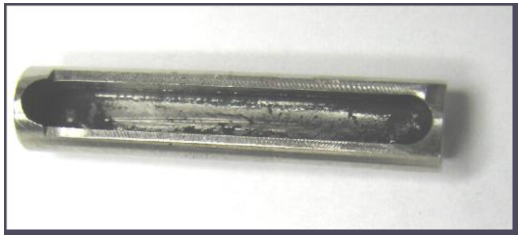


Kilcoyne et al., PRL **105** (2010) 213001

Gießen $Xe@C_{60}$ Production Plant

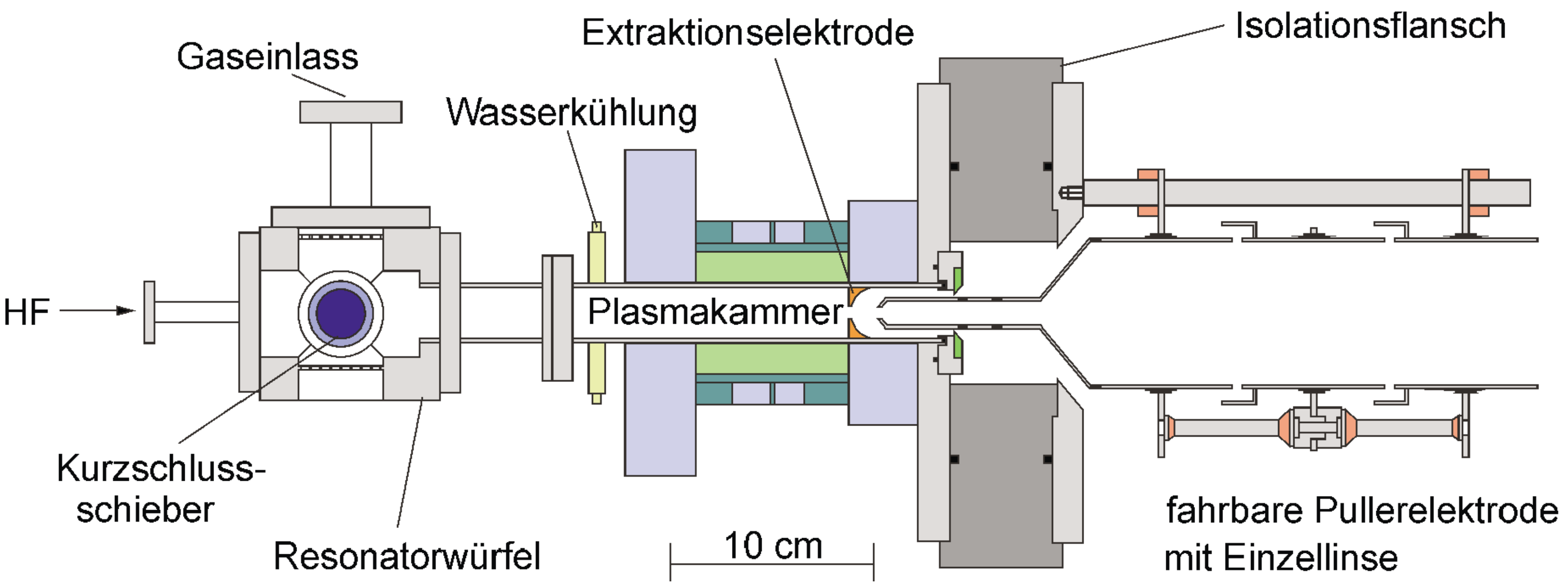


Xe@C_{60}^{+} Ion-Beam Production

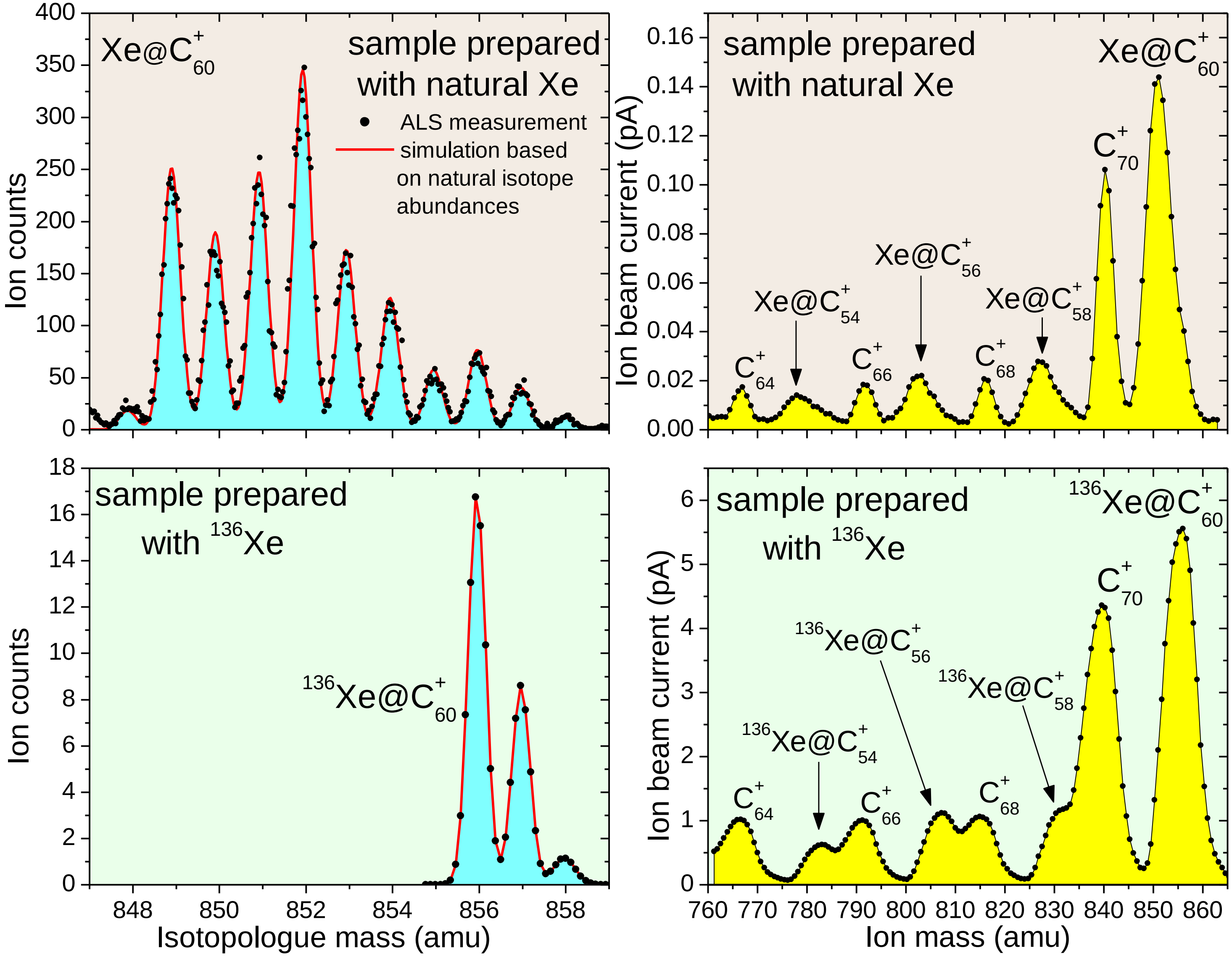


"boat" containing home made powder

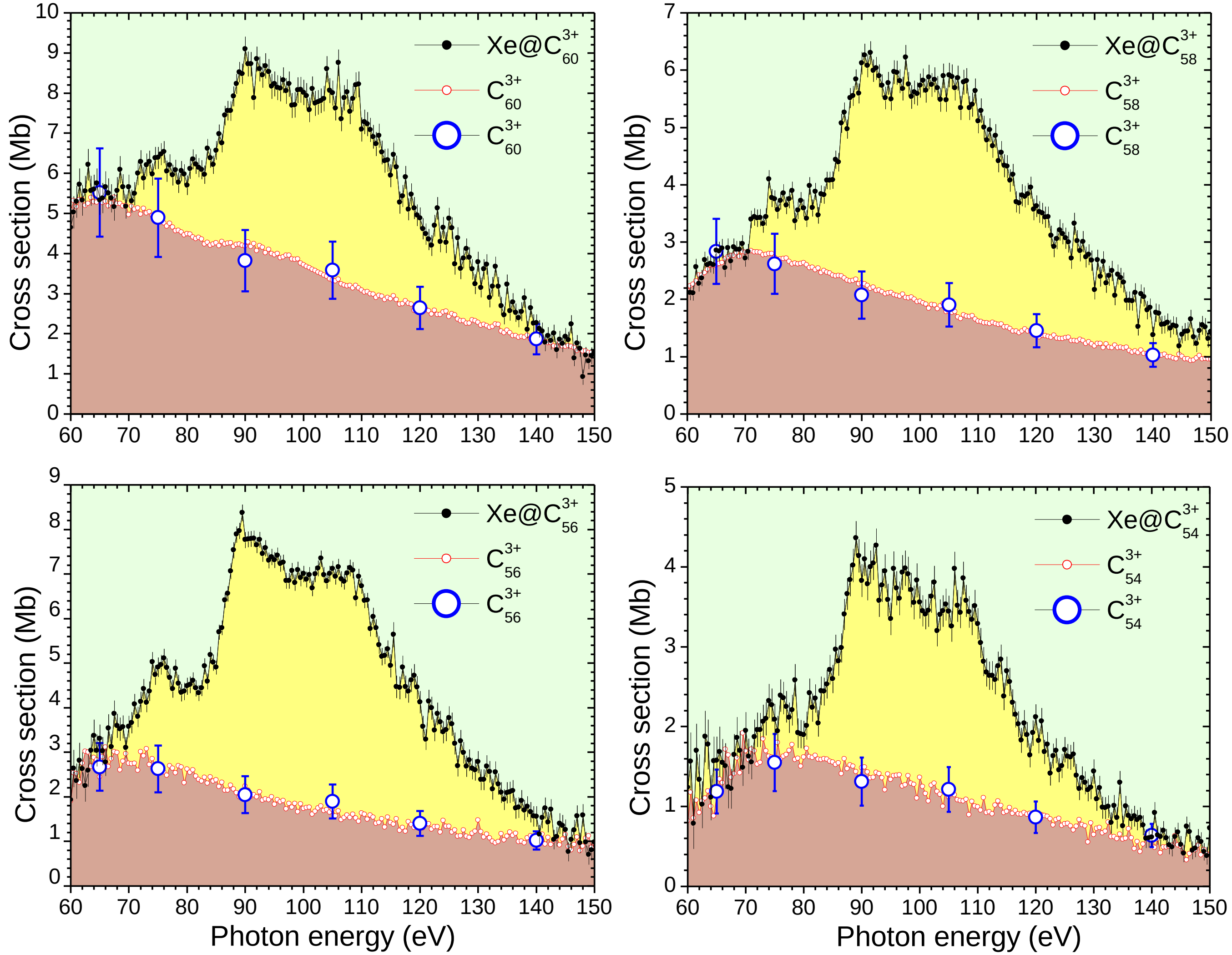
Giessen-type ECR ion source



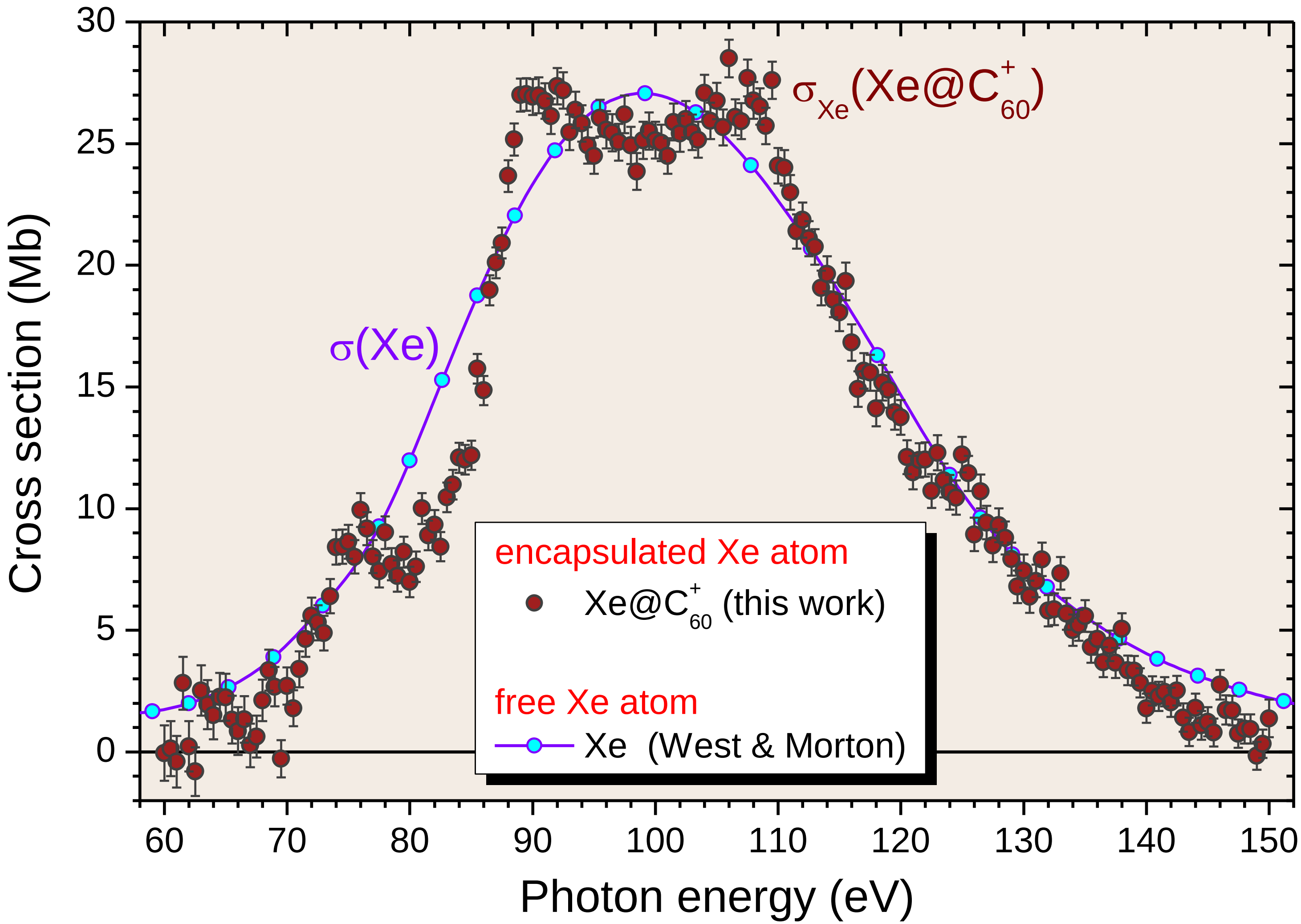
Mass Spectra of Home Made Xe@C_{60}



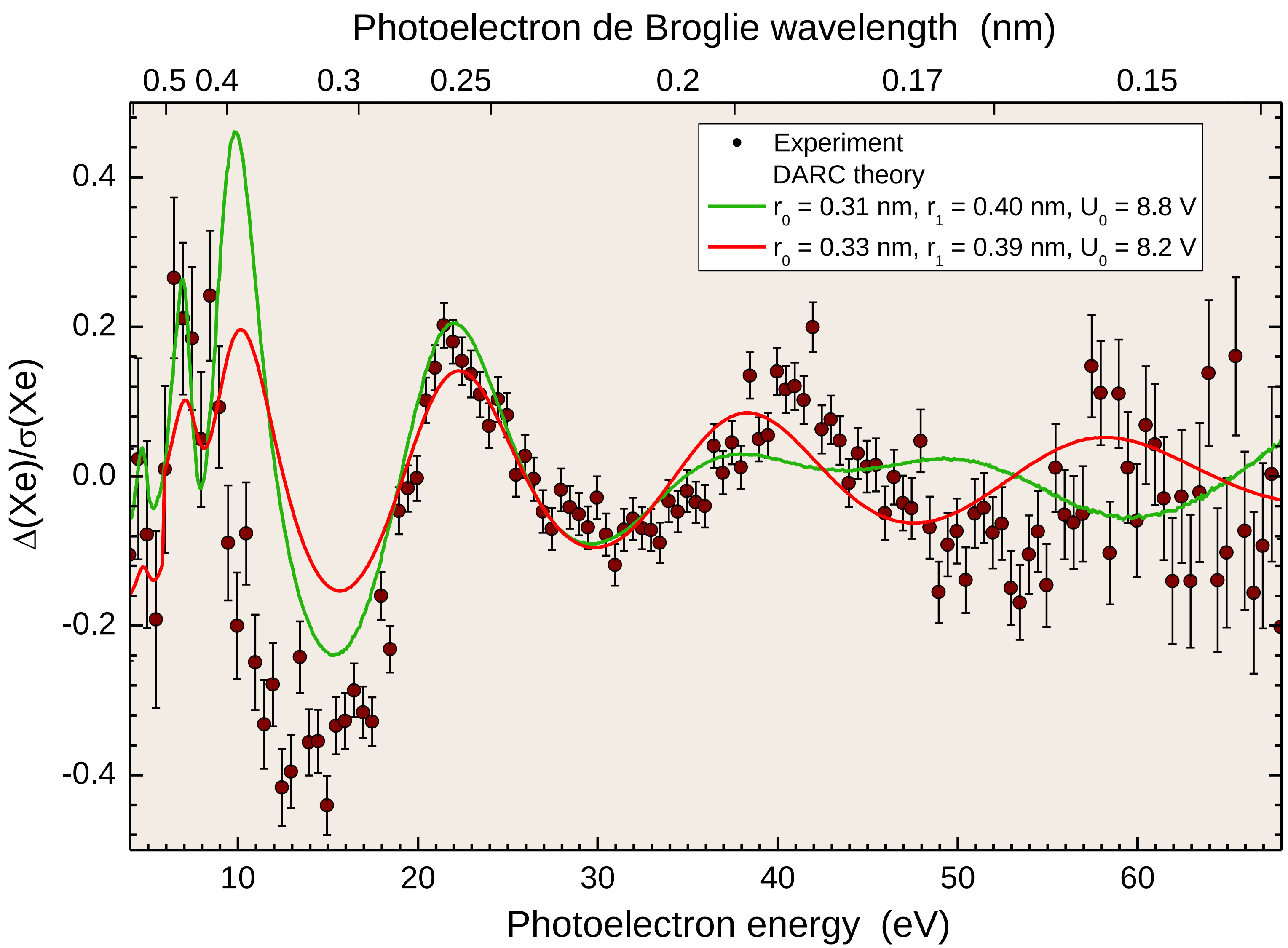
Photoionization + Fragmentation of Empty and Filled C_{60}^{+}



Xe 4d Excess Cross Section in $Xe@C_{60}^{+}$



Oscillations Magnified



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Selected References (2002-2014)

Li^{+}:	Scully et al.,	JPB **39** (2006) 3957
B^{+} valence shell:	Schippers et al.,	JPB **36** (2003) 3371
B^{+} K-shell:	Müller et al.,	JPB **47** (2014) 135201
B^{2+} K-shell:	Müller et al.,	JPB **43** (2010) 135602
C^{2+} K-shell:	Scully et al.,	JPB **38** (2005) 1967
C^{3+} K-shell:	Müller et al.,	JPB **42** (2009) 235602
C^{2+},N^{3+},O^{4+} valence shell:	Müller et al.,	JPB **43** (2010) 225201
Sc^{2+} :	Schippers et al.,	PRL **89** (2002) 193002
Sc^{2+} :	Schippers et al.,	PRA **67** (2003) 03270
Ti^{3+} :	Schippers et al.,	JPB **37** (2004) L209
Kr^{5+} :	Lu et al.,	PRA **74** (2006) 012703
$Xe^{1+ - 5+}$ 3d-shell @ PIPE:	Schippers et al.,	JPB **47** (2014) 115602
Xe^{7+} :	Müller et al.,	JPB **47** (2014) 215202
C_{60}^{+}:	Scully et al.,	PRL **94** (2005) 065503
Ce@C_{82}^{+}:	Müller et al.,	PRL **101** (2008) 133001
Xe@C_{60}^{+}:	Kilcoyne et al.,	PRL **105** (2010) 213001
Xe@C_{60}^{+}:	Phaneuf et al.,	PRA **88** (2013) 052403

Summary – Photoionization of Ions

- **Photon-ion merged-beams technique at synchrotron light sources**
- **Selected results from the ALS and from the new PIPE-setup at PETRA III**
- **Valence and inner-shell ionization of atomic ions**
- **Absolute cross sections for astrophysics**
- **Endohedral fullerenes, first observation of confinement resonances**
- **Investigations are possible with different types of ions (atoms, molecules, clusters, biomolecules …)**