Forward Electron Spectroscopy at the ESR

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Overview

A. Motivation:

Kinematically complete Ionization Experiments

many-electron continua (2 e^- +1 n)

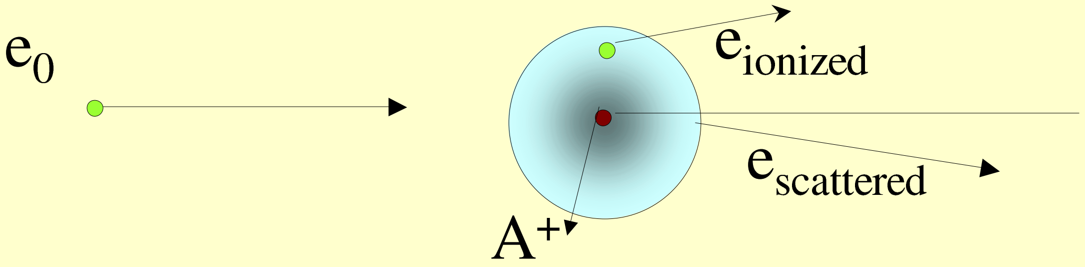
B. A Tool :

Zero Degree Spectroscopy,

from autoionizing Rydberg states to Quasi-Photoionization of Fe XVII

Kinematically Complete Electron – Impact Ionization

Ionization: Fragmentation of Atoms/Ions


e_0
$e_{ionized}$
$e_{scattered}$
A^+

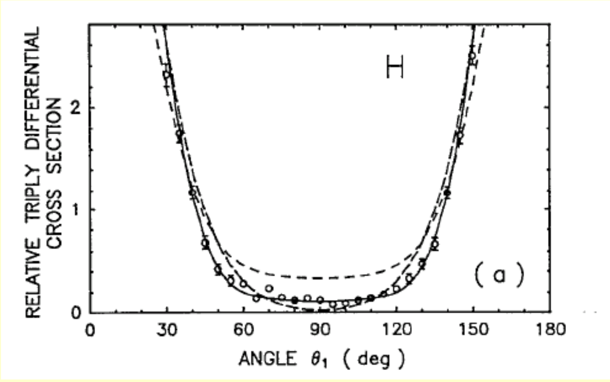
$$\text{e.g.}\quad e^- + H \rightarrow H^+ + e_a + e_b$$

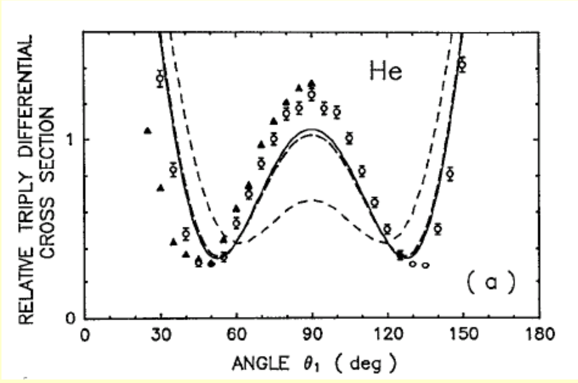
$$e^- + A \rightarrow A^+ + e_a + e_b$$

$$e^- + X^{n+} \rightarrow X^{(n+1)+} + e_a + e_b$$

Comparison of 3-Body - Continua:

(Ehrhardt et al)





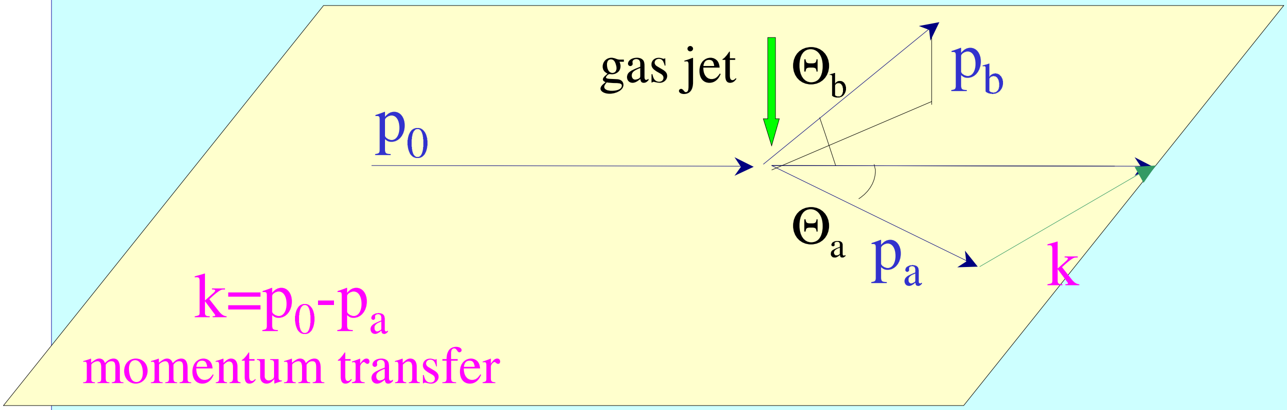
5-fold differential Ionization Cross Section: 5DCS for $e^-(E_0,p_0) + A \rightarrow e^-(E_a,p_a) + e^-(E_b,p_b) + A^+(p_{ion})$

A kinematically complete **measurement**
provides the 5-fold differential cross section

$d^5\sigma(E_0,E_a,\Theta_a,\Theta_b,\varphi_{a,b})$

5DCS : “COMPLETE” information;

➡ most stringent test of theories



peripheral collisions : IA with entire atom- : **k** = small
binary “ : “ single e^- : **k** = large
Quasi-Photoionization for $E_0 \gg E_{bind}$: **k** $\Rightarrow$ 0

5DCS = {ionization-mechanism}⊗{target-structure}

COMPLICATION:

♬ : in some areas of phase space these factors are coupled

What can be derived from Differential Cross Sections ?

DCS = {Ionization -mechanism}⊗{Target-structure}

Test of Theories:
DPW, CCC, ECS;
1. and 2. Order;
Wannier-threshold-law;
WPR for Double-Ionization;
relativistic DW;
Quasi-Photoionization
für k⇒ 0;

1-Electron momentum-density for individual valence-orbitals;
many - body - e-e effects in |i>+ |f> states;
relativistic effects;
momentum dependence of QED-Effects
in
vacuum-polarization,
selfenergy;

Why measure (e,2e) Ionization-cross sections for Ions?

1. study role of e-e interaction (e.g. correlation, polarization) via Z-dependence in DCS for H-, He-like systems

2. “The response of positive ions to ionizing radiation is a dominant process in the universe”

   e^- -, Ion-impact- and Photo-ionization- cross sections for ions are needed recombination for radiative and rates in (see Opacity- project):

   a) Fusionplasma
   b) Astrophysical. Plasma, e.g. in Solar Corona and intra-galact. clusters

.

$$\sigma_{\textbf{Ionization}}\left(\textbf{Electron – Ion}\right)$$

cannot be scaled from

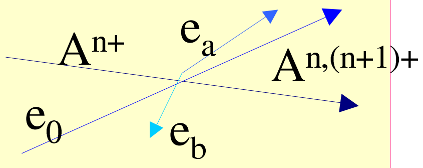
$$\sigma_{\textbf{Ionization}}\left(\textbf{Electron – Atom}\right)$$

(Resonances / channel-couplings etc)

DCS and Inverse Kinematics

“ **crossed electron-ion beam”** experiments

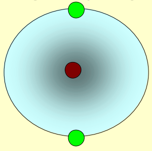
$$e_0 + A^{n+} \rightarrow A^{(n+1)+} + e_a + e_b$$



low target density $\rho \Rightarrow$ low luminosity L

L(e-ion)/L(ion-atom) < 10^{-5}

Inverse kinematics: the incoming ion is ionized by an electron of the He-target :



X^{n+} + $\rightarrow X^{(n+1)+}$ + He^{1+} + $e_1(\Theta_1)$ + $e_2(\Theta_2)$

⇑Coincidence-⇑-Coincidence⇑

REALM of REACTION-MICROSCOPE

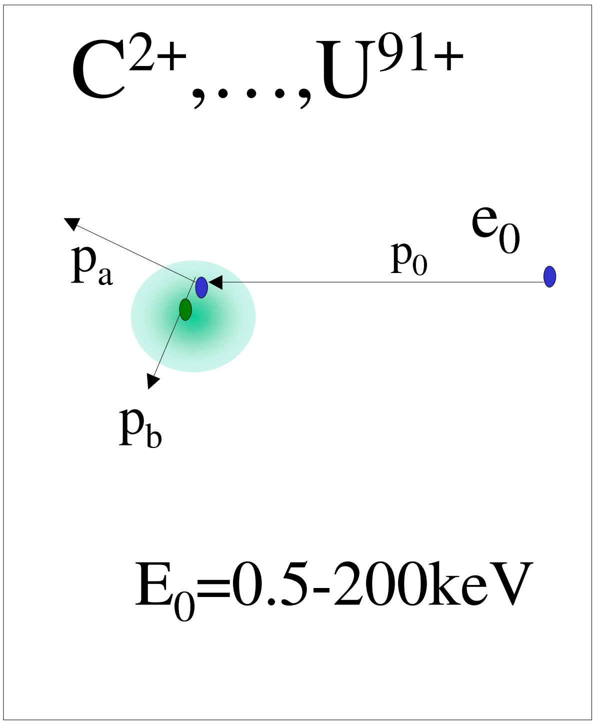
The He-target provides a dense source of quasi-free electrons

However: We must separate contributions:

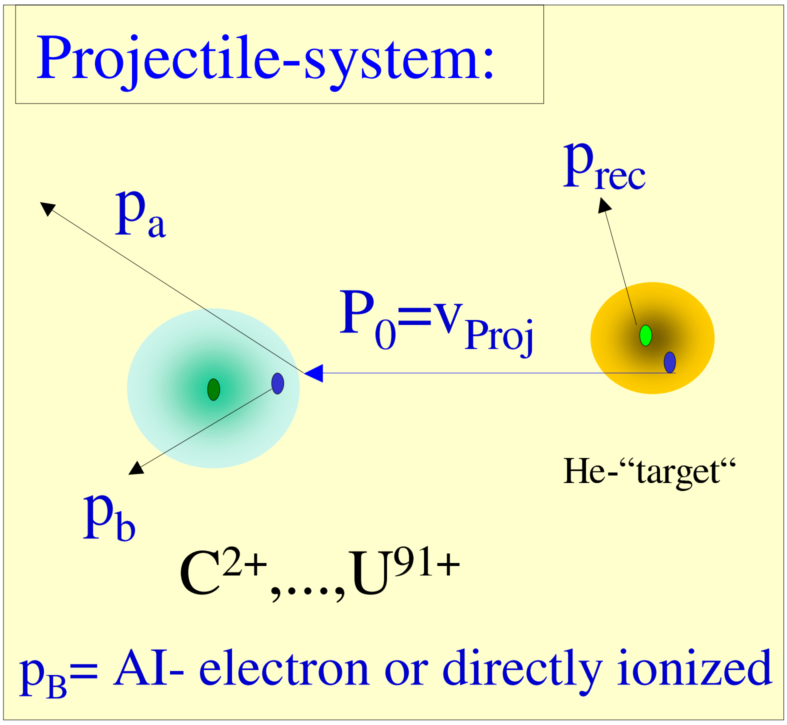
Ionization of X^{n+} by the He-nucleus (e-n)

from **Ionization of X^{n+} via e-e interaction**

Electron Impact Ionization of Ions in inverse Kinematics

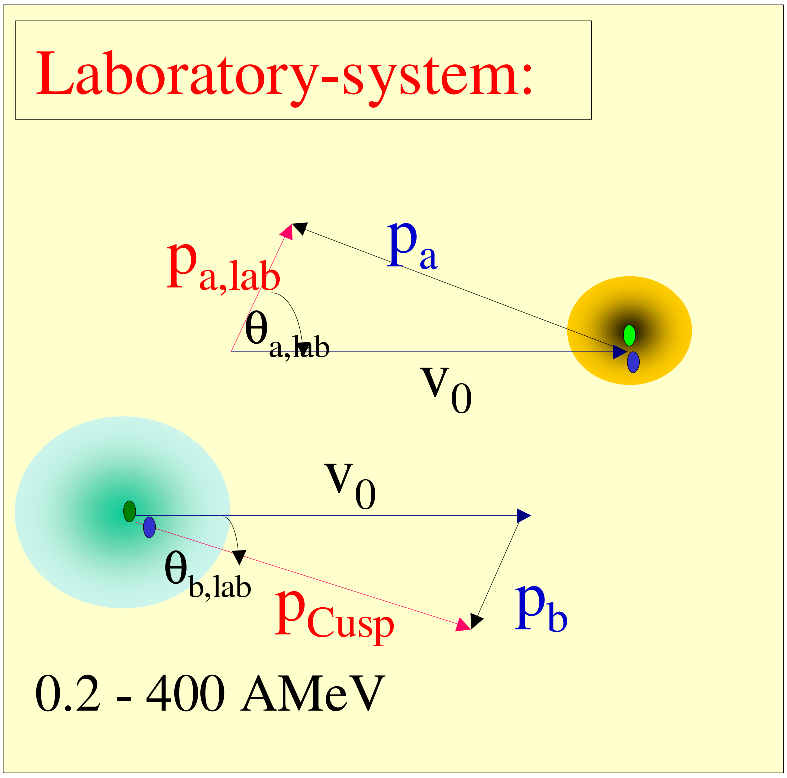

$C^{2+},\ldots,U^{91+}$
p_a
p_0
e_0
p_b

E_0=0.5-200keV


Projectile-system:
p_{rec}
p_a
$P_0 = v_{Proj}$
He-“target“
p_b
$C^{2+},\ldots,U^{91+}$

p_B= AI- electron or directly ionized

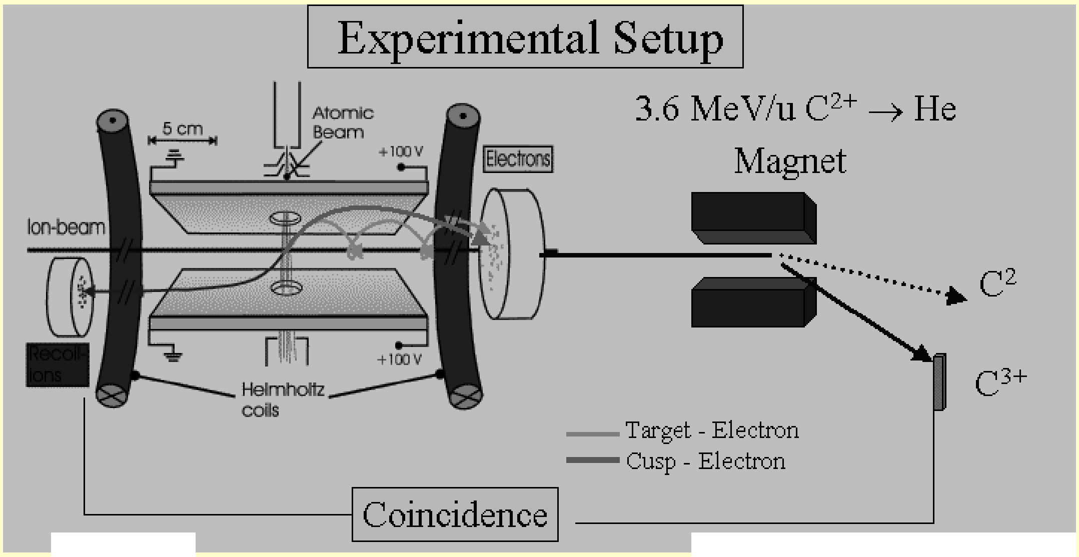
Projectil-sys.	**Labor.-sys.**
$p_{a,gestr,}$ fast	p_a slow
γ_A small	$\theta_{a,lab}$ large
$p_{b,ion}$ slow	$p_b \approx p_{Cusp}$
$0<\gamma_b<360$	$\theta_{b,lab}$ small


Laboratory-system:
$p_{a,lab}$
p_a
$\theta_{a,lab}$
v_0
v_0
$\theta_{b,lab}$
p_{Cusp}
p_b

0.2 - 400 AMeV

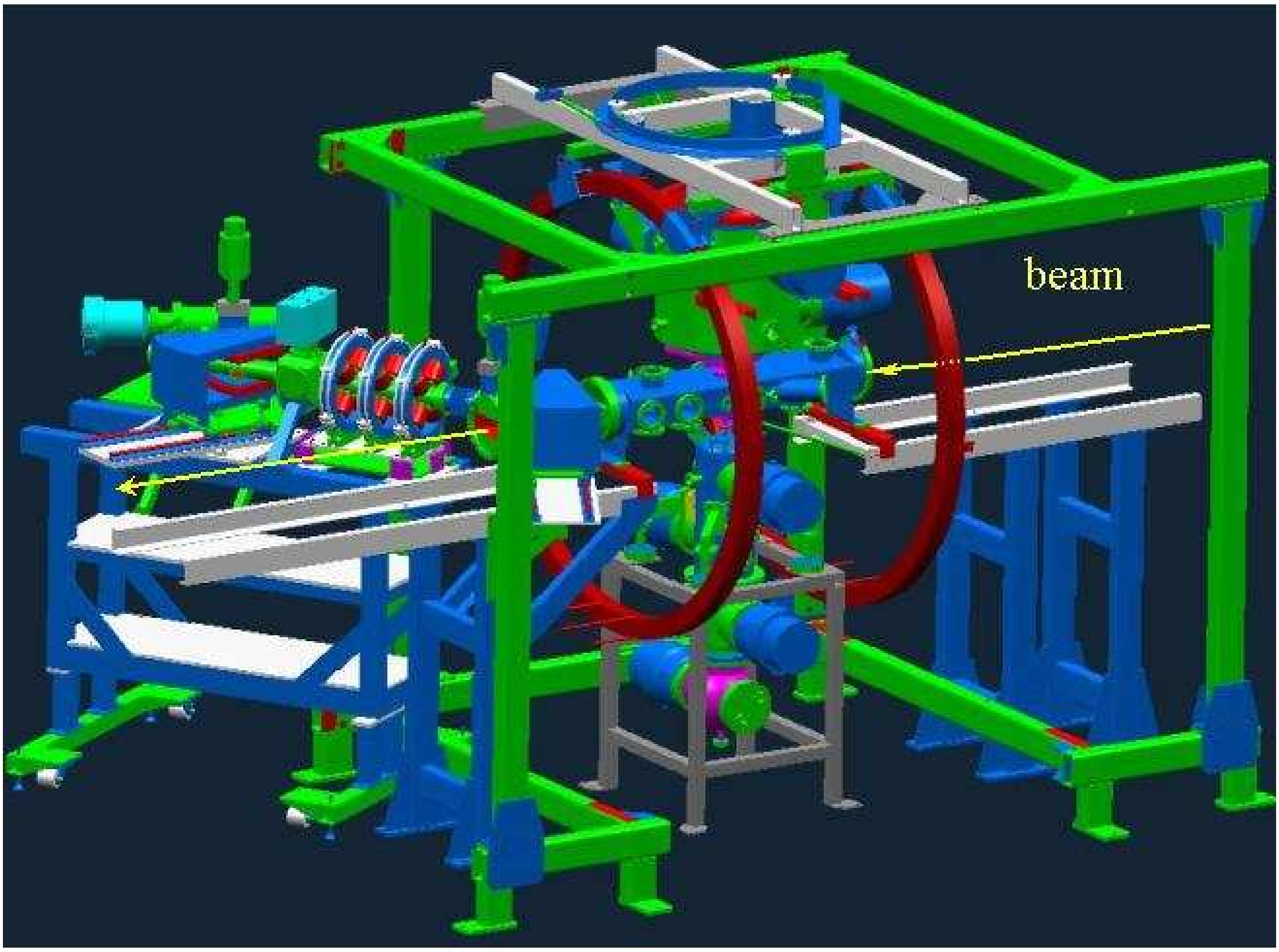
⇒ projectile electron spectroscopy

Reaction microscope


Experimental Setup
3.6 MeV/u C2+ → He
Magnet
Atomic Beam
5 cm
+100 V
Electrons
Ion-beam
Recoil-Ions
Helmholtz coils
+100 V
C2
C3+
Target - Electron
Cusp - Electron
Coincidence

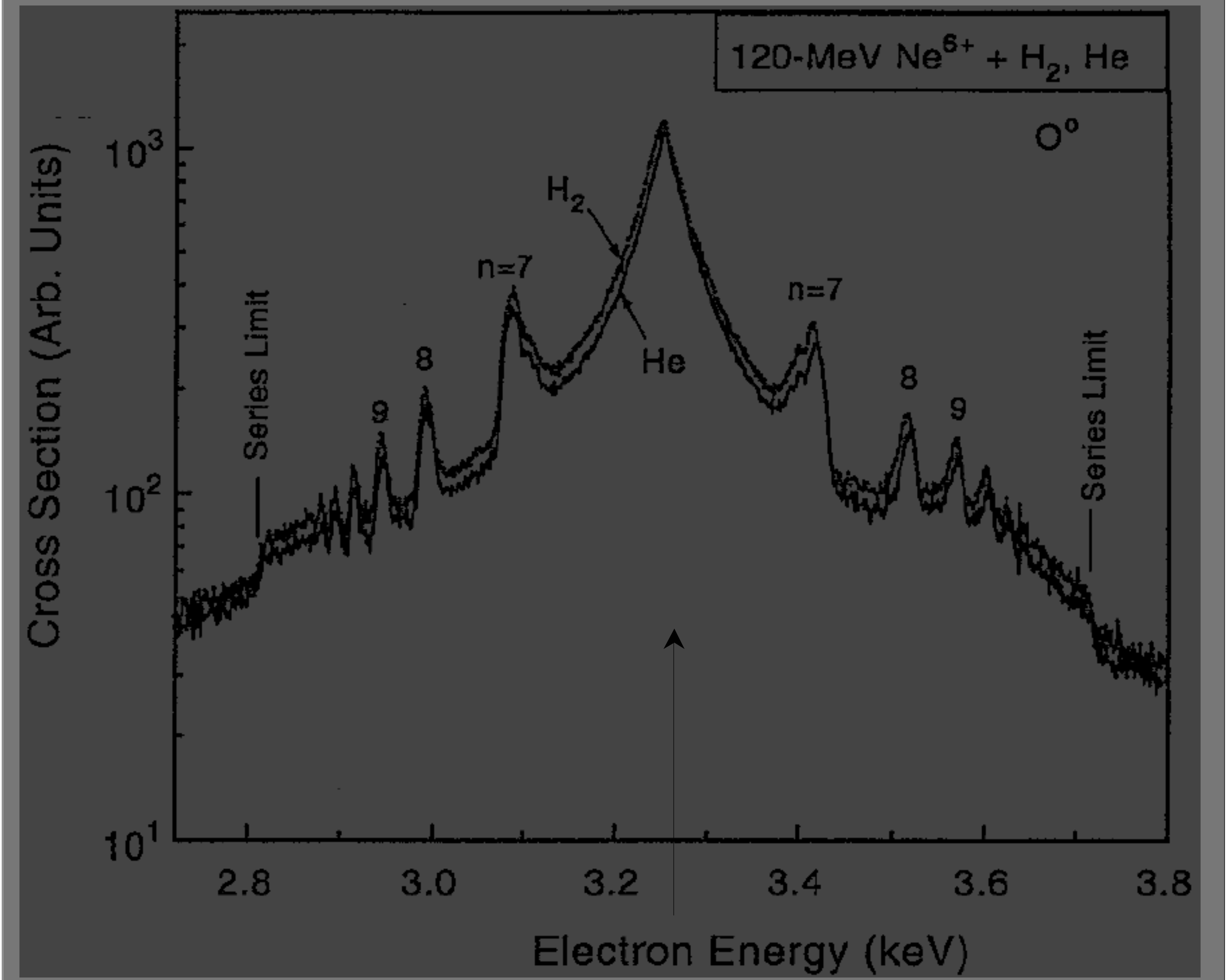
- For $v_{\mathrm{Proj}} < 10$ a.u. both e^- can be mapped onto 2D position sensitive electron detector

Forward Electron Spectrometer and Reaction Microscope



For high v_{Proj} the fast electron is analyzed with a separate spectrometer

Advantage of Fast Projectile Spectroscopy: Autoionization Spectra from Projectile Rydberg States

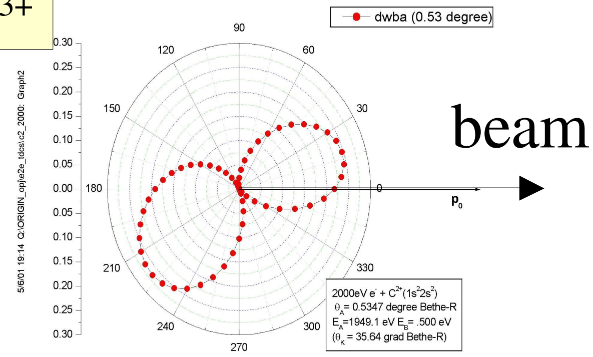


Stolterfoht et al

Electrons ionized into Projectile Continua

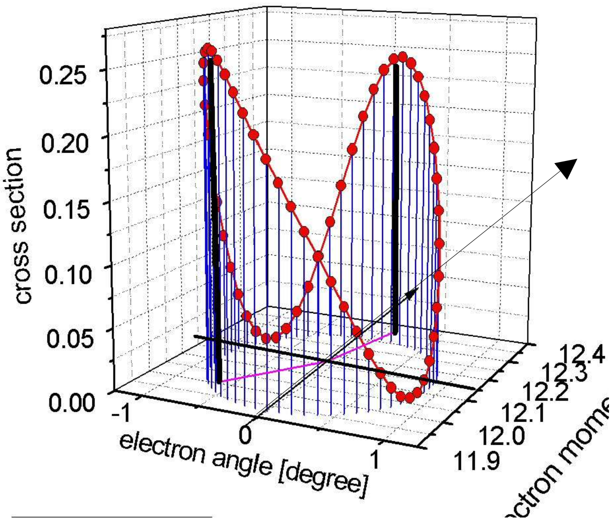
$e^- + C^{2+} \Rightarrow e_{scatt.} + e_{ionized} + C^{3+}$

Projectile frame



Theory: I. McCarthy

Laboratory frame



Forward e^- Spectrometer

- 60^0 Dipol-QT-60^0 Dipol ,r=200mm, with aperture 100mm x250mm, for electrons with 20-200 keV, emitted into a narrow forward cone $2\Theta \leq 3^0$ around the beam axis:
- In telescope mode maps electrons from the target zone onto 2D-position sensitive detector with magnification $|M_x| = |M_y| = 1$; **reconstruction** of **scattering plane** and primordial direction of emission following momentum analysis, variable momentum resolution modes
- In high resolution mode $p/\Delta p = 1600$

First Experiments at JRM :
5DCS at threshold in
$\Theta_{a,b}$= constant geometry

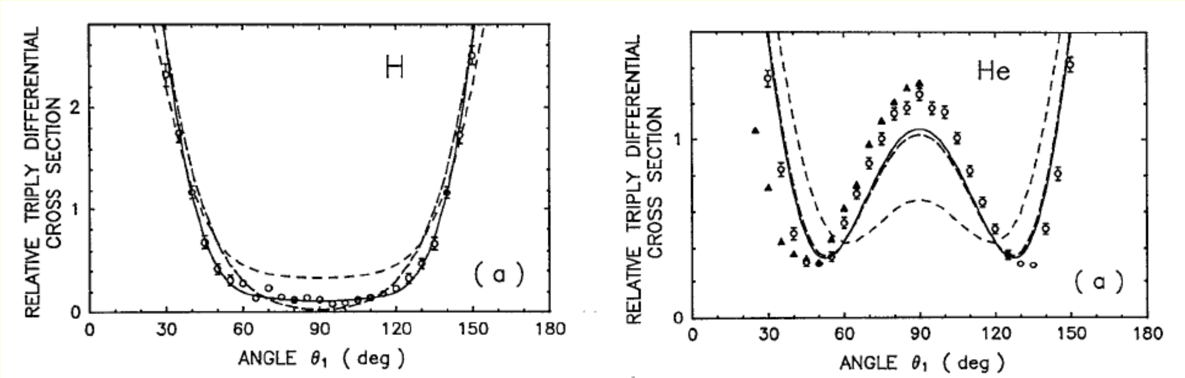
for $E_0 \geq \varepsilon_{Bind}$, close to threshold:

3-body- effects in entrance channel: (polarization of the targets via incoming electron) and PCI cannot be distinguished in asymmetric geometry;

for Θ_{ab}= const. and E_a=E_b the effect from the entrance channel can be isolated:

e.g. : E_a=E_b= 2eV

Ehrhardt et al.



Quasi-Photo-ionization of FeXVII: Opacity Project for Stellar Atmospheres

- Goal: determine the Equation of State for stellar atmospheres for $T \leq 10^7$ K
- EOS must reliably predict the optical properties of the plasma (current models derive from the observed spectra widely varying T-distributions)
- To improve models:
- Reliable input-data are missing :
- a) Ionization- Rekombination over a wide q-range
- b) Photoionization of ions
- c) Dielectronic Recombination

(e,2e) at the ESR: Photoionization of Fe XVII via Electron-Electron-Coincidences

Motivation: Opacity-Project

Knowledge of Fe ion distribution is of fundamental importance in modeling stellar atmospheres (and intra-Cluster clouds)

Fe is dominant source of opacity over a wide range of high temperatures in stellar atmospheres.

Photoionization contributes ≈50% or more for opacity of the Fe .

Hibbert et al. pointed to large discrepancies between non-relativistic and relativistic Photoionization cross sections for Fe XVII (PRA57,3489(1998))

below the $2s^22p^5$ ($^2P_{1/2}$)

threshold ,where a large

fraction of the oscillator-strength is.

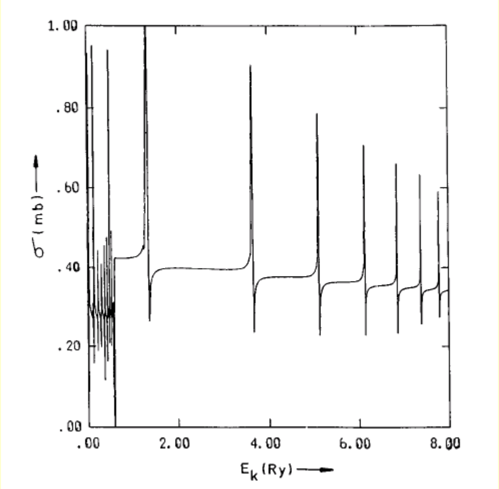


Photo-Ionization via Electron-Electron Coincidence

- For swift, peripheral collisions and small momentum transfer ΔK:

- DCS (e^- + Atom) =DCS(hν + Atom)
  the interaction of a swift electron with an atom is equivalent to the interaction with an incident photon, the target electron experiencing a force along the polarization vector of the light ; [provided that $E_{inc} \gg E_{bind}$] :

  $$E_{loss} = E_0 - E_a = E_{h\nu}$$

- For small ΔK the generalized oscillator – strength for ionization is given by the optical oscillator strength (Bethe)

Photo-ionization of Fe XVII via Electron-Electron Coincidence

•Fe^{16+} + He → $e^-(E_a,p_a)$ + $e^-(E_b,p_b)$ + Fe^{17+} + He^+

Coincidences between outgoing products e_{fast},e_{slow}, He^+ und Fe^{17+} for $E_{proj} \geq 100$ AMeV .

•Using the new combined reaction-microscope ⊕ magnetic 0^0 -degree electron-spectrometer

$$E_{0,inc} - E_{scatt} = E_{h\nu}$$

→ Energy of the equivalent incident photon;

E_b ,Θ_b [e_{fast}] around 0^0Cusp --> complete angular distribution for photo-electrons on 2D position sensitive electron-detector