Electron and positron emission in energetic ion-atom collisions

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Motivation

To discuss very briefly a number of collision processes which might be of interest for future experiments at the NESR (GSI, Darmstadt):

i) ionization (single, double, multiple) of atoms by relativistic bare nuclei;

ii) projectile-electron excitation/loss, two-center dielectronic transitions in relativistic ion-atom collisions when the ion initially carries electron(s);

iii) electron-positron pair production;

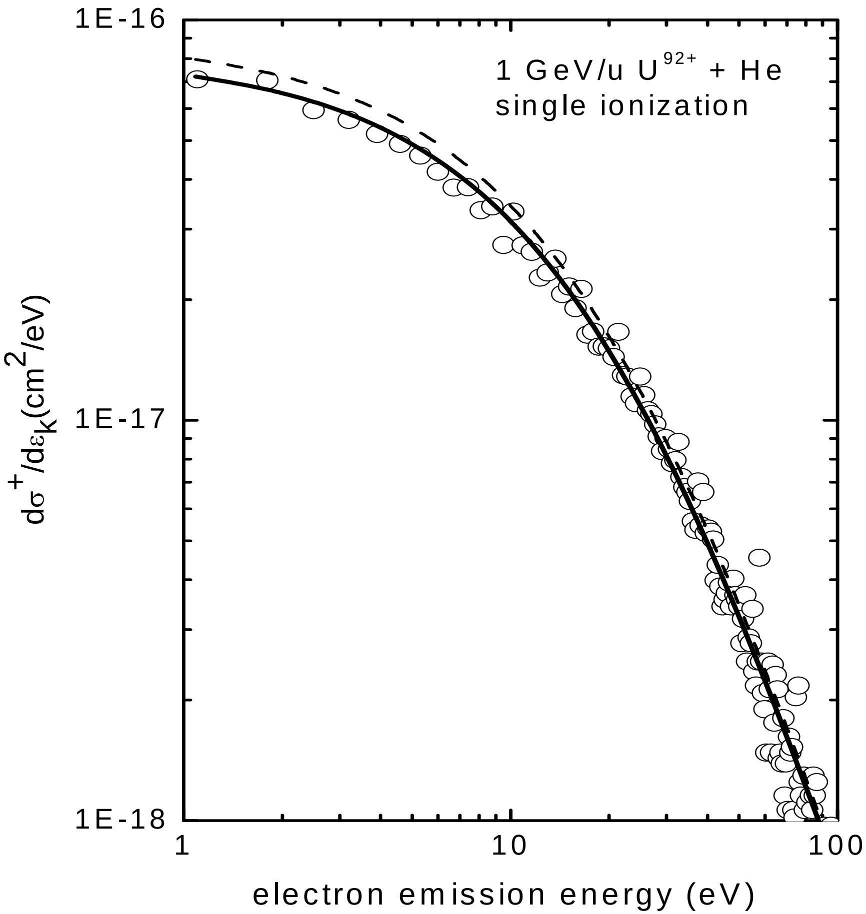
iv) collisions with antiprotons below;

v) resonant electron scattering via nuclear excitation.

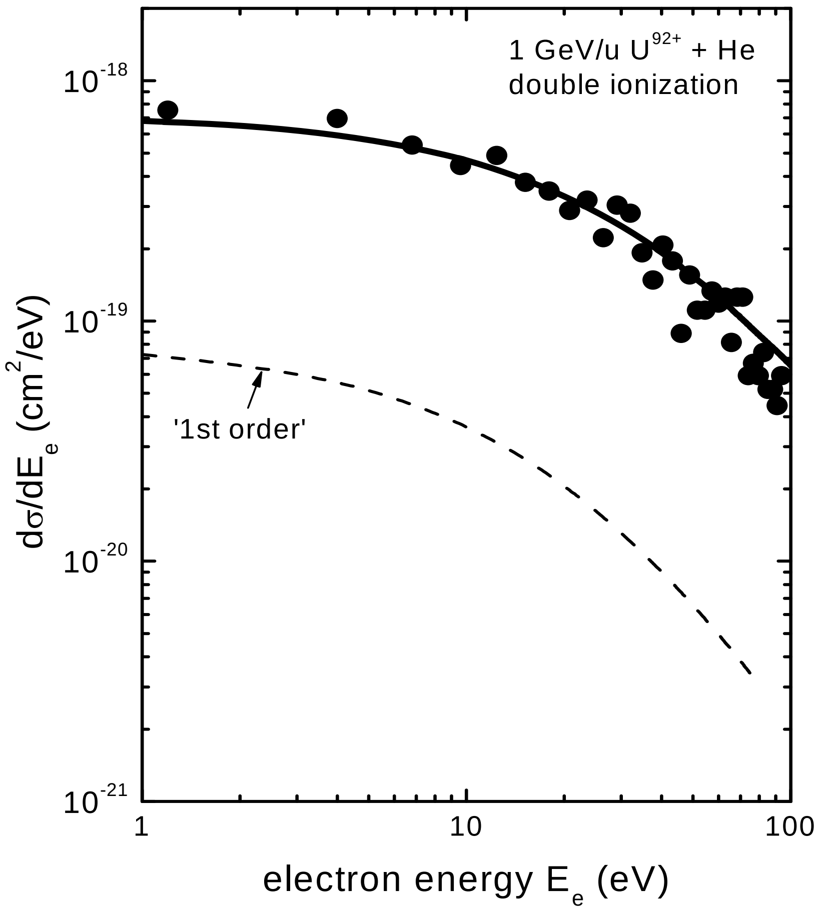
i) Ionization of atoms by relativistic highly charged nuclei

Relativistic and higher order effects, fully resolved collision dynamics.

Examples: $U^{92+} + He \rightarrow U^{92+} + He^{+} + e$



$U^{92+} + He \rightarrow U^{92+} + He^{2+} + 2e$



Exper: Moshammer et al **PRL 79** 3621 (1997).

Calculation: J.Phys. **B 37** 3621 (2004); **B 38** L107 (2005)

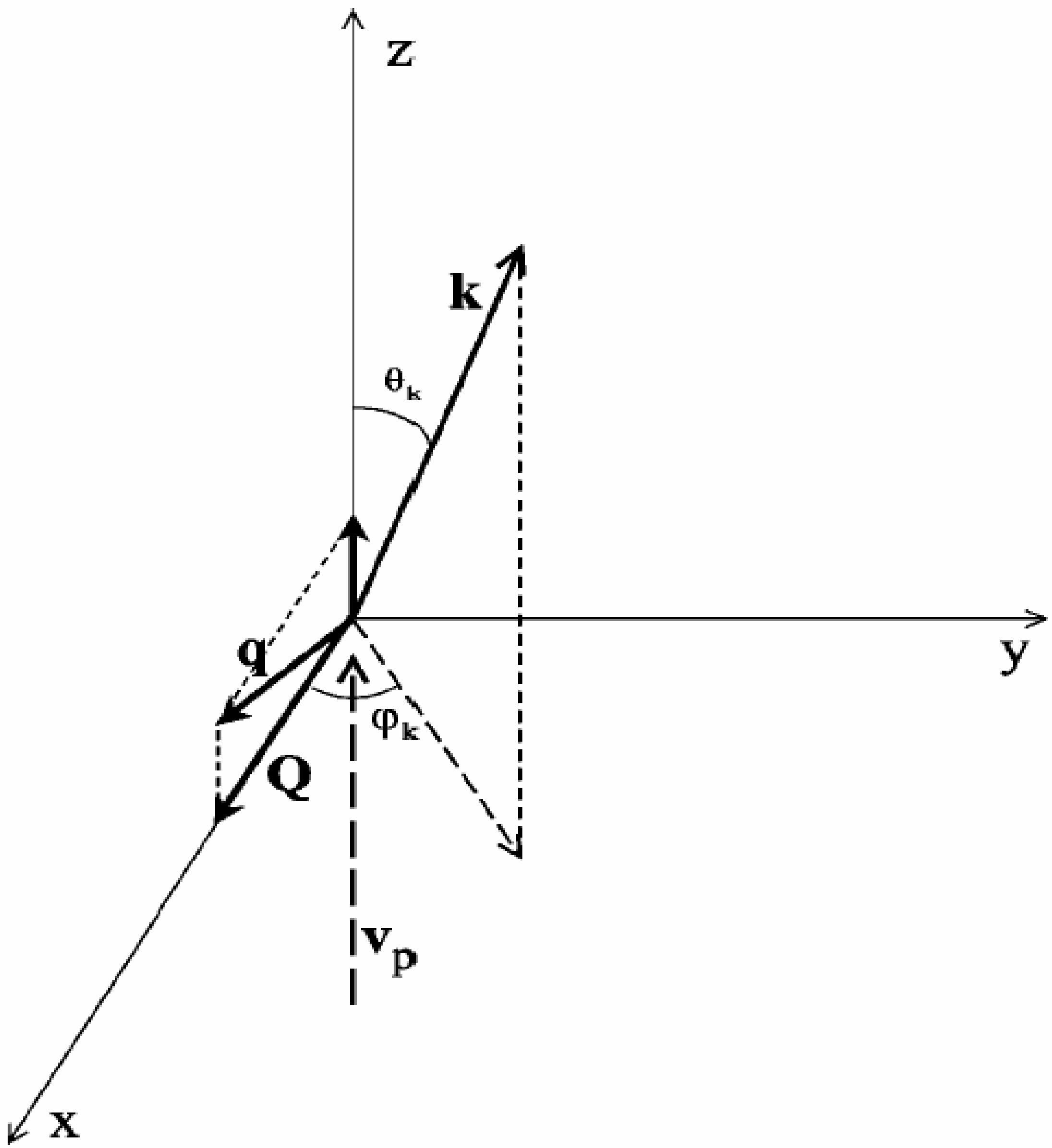
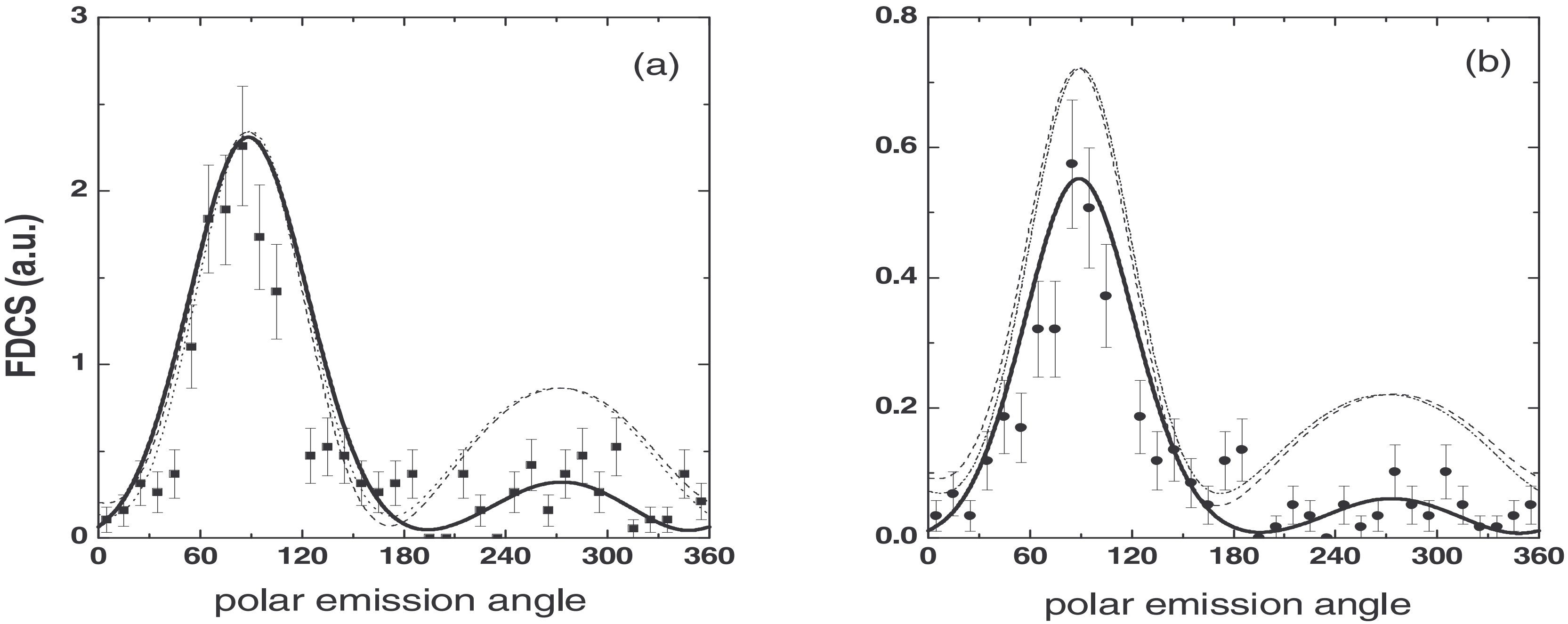


FIG. 1. The collision geometry.

Single ionization



The FDCS for single ionization of helium by 1 GeV/u U^{92+} given as a function of the polar emission angle in the collision plane. The electron emission energy is 4 eV and the total momentum transfer (a) 0.65 a.u. and (b) 1 a.u.. Symbols: experimental data from Moshammer et al. Dot curve: first order model. Dash curve: cdw-eis model without the n-n interaction. Thick solid curve: cdw-eis model model with the n-n interaction.

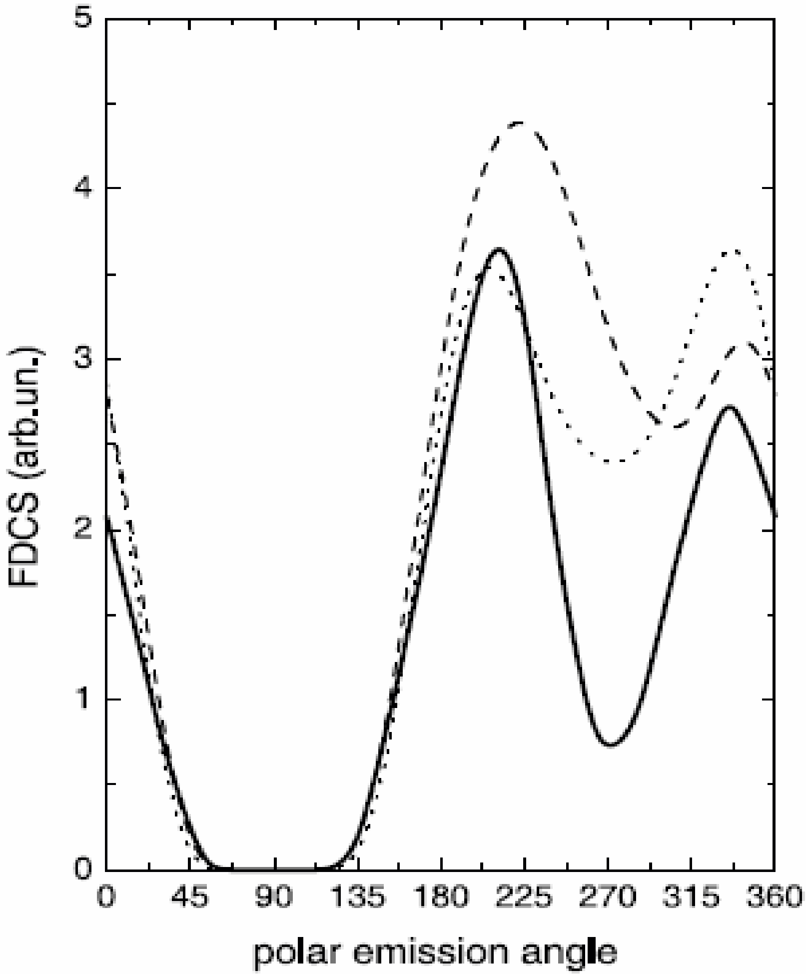
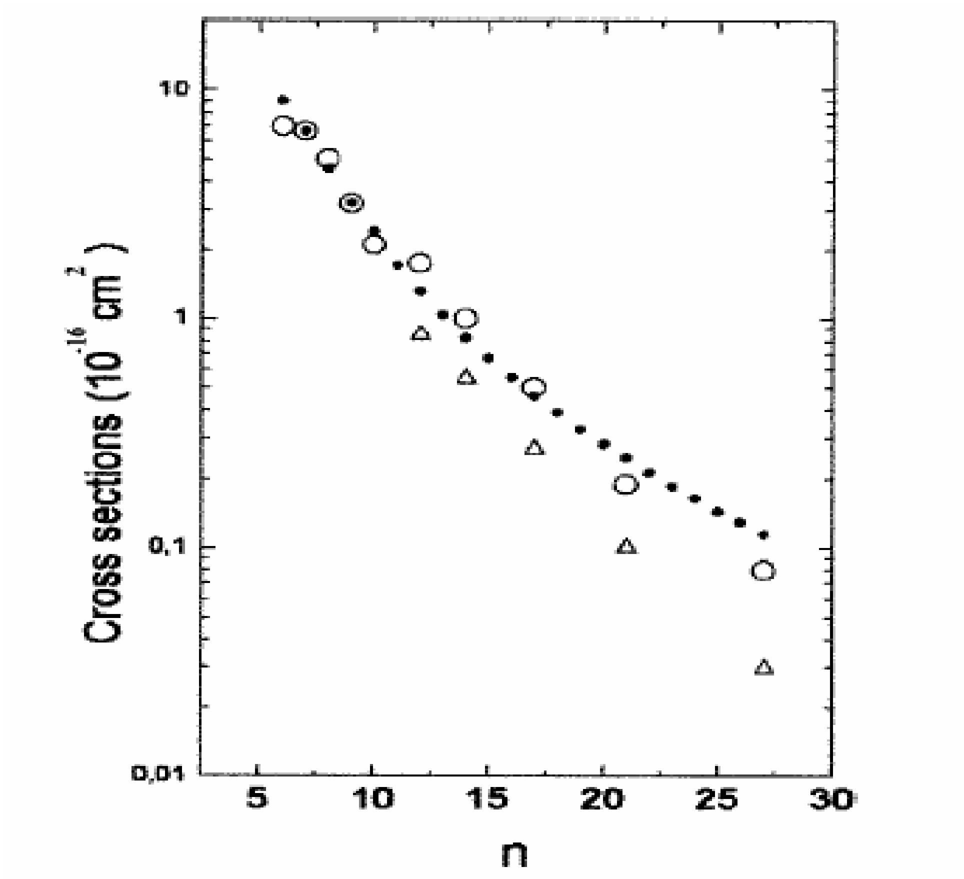


Fig. 1. The FDCS (in a.u.) for double ionization of helium by 1 GeV/u U^{92+} projectiles. The cross section is plotted as a function of the polar emission angle ϑ_1 of the "first" electron, given in the plane defined by $\mathbf{v} = (0, 0, v)$ and $\mathbf{q} = (q_\perp, 0, q_{\min})$. Emission energies $E_1 = E_2 = 10$ eV, azimuthal emission angles $\varphi_1 = \varphi_2 = 0^0$, $q_\perp = 0.25$ a.u., $\vartheta_2 = 90^0$. Solid curve: the symmetric eikonal approximation. Dash curve: the symmetric eikonal approximation without the inter-nuclear interaction. Dot curve: the first order result.

IJMPB 20 1 (2006))

Multiple ionization of atoms by relativistic ion impact



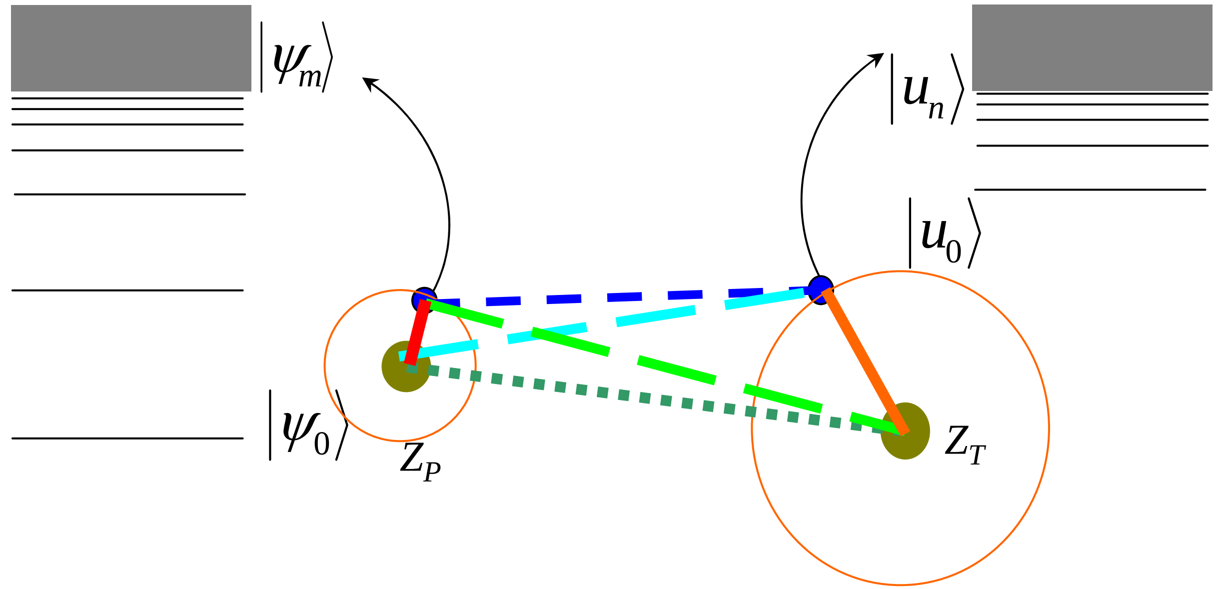
$$\sigma_n = A\frac{Z_p^2}{v^2}\frac{1}{I_n}$$

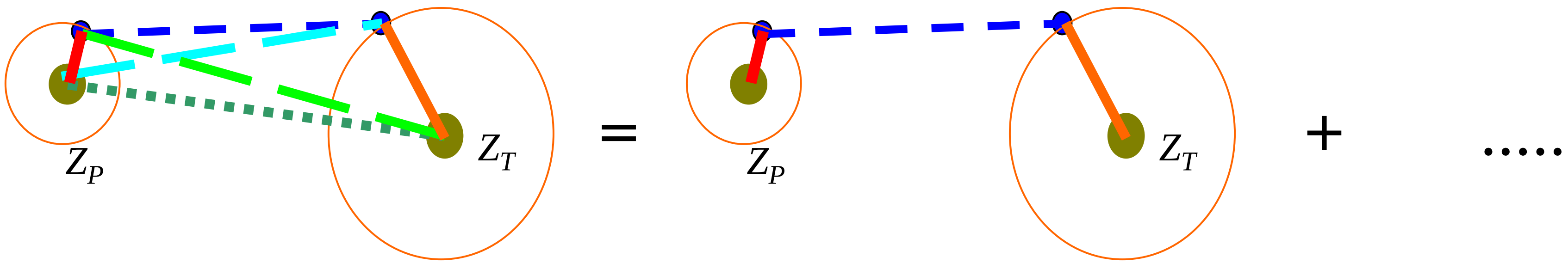
$$Z_p \cong v; n >> 1$$

$$I_n = i_1 + i_2 + \ldots + i_n$$

Multiple ionization of iodine by 420 MeV/u U^{91+} impact. Open circles: experiment (Ullrich et al); triangles: calculations by Horbatch and Dreizler, small solid circles: estimates using the above formula.

II. Projectile-electron excitation and loss

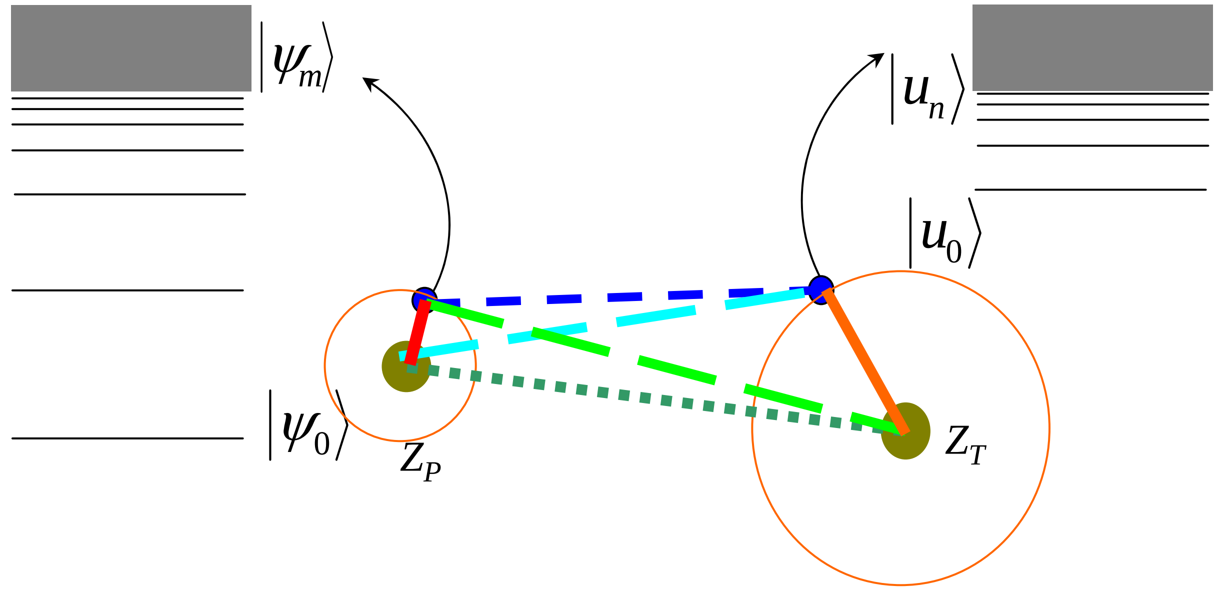


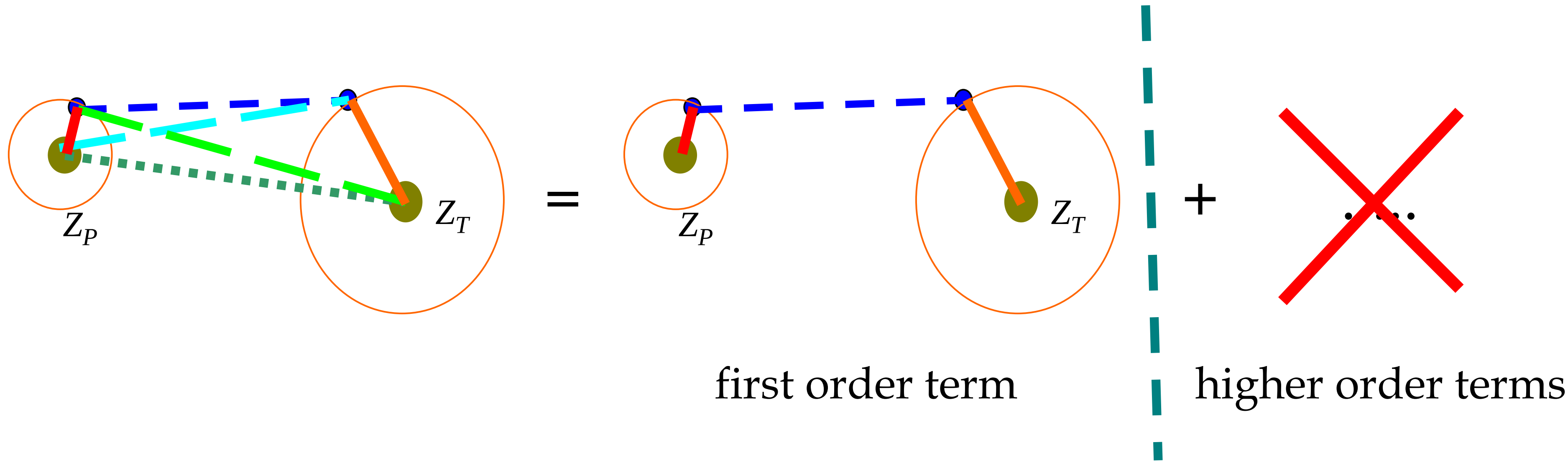


first order term

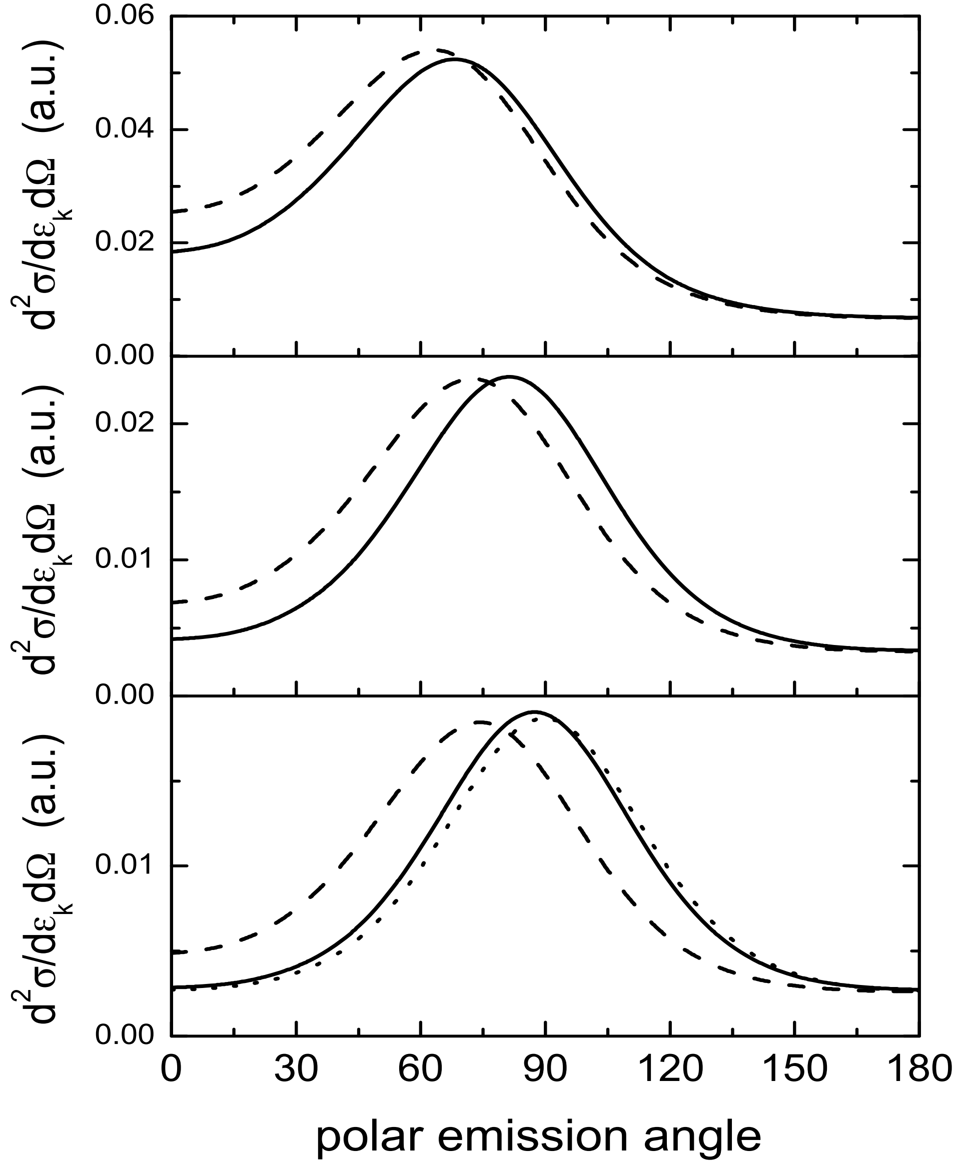
higher order terms

II. Projectile-electron excitation and loss





First order consideration: two-center dielectronic interaction



$N^{6+}(1s)+H(1s) \rightarrow N^{7+} + p^{+} + 2e^{-}$

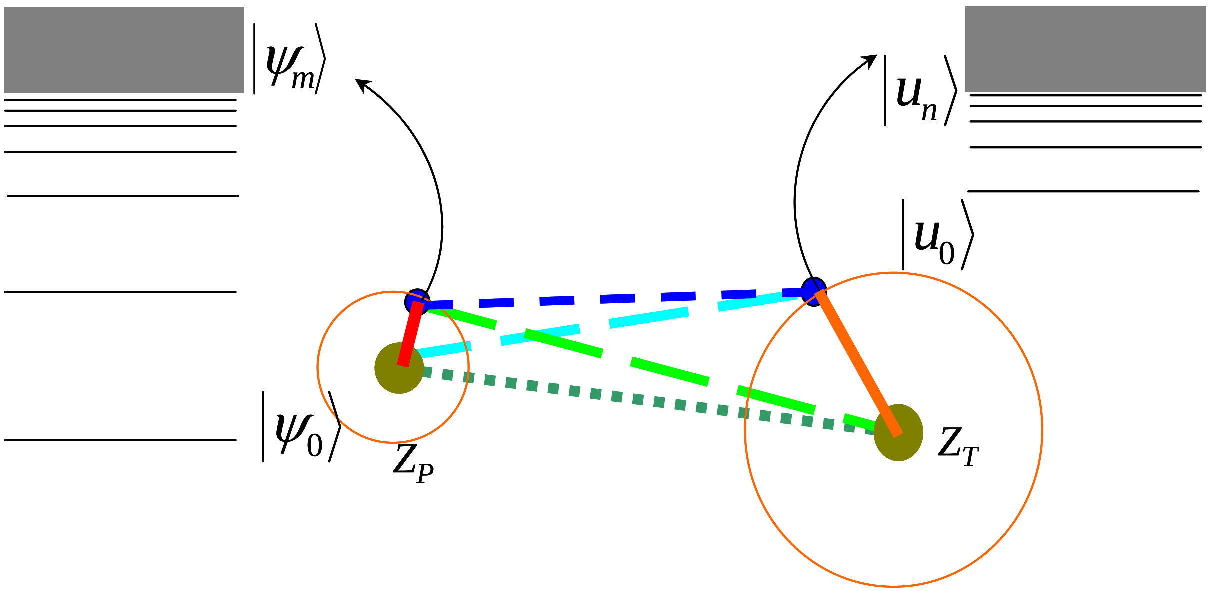
Angular distribution of electrons emitted from the target.

$$\frac{d^2\sigma}{dE\,d\Omega} \qquad E=10\text{ eV}$$

(a) 200 MeV/u; (b) 1 GeV/u; (c) 5 GeV/u.

Results of relativistic (c=137 a.u.) and non-relativistic (c=infty) first order calculations are depicted by solid and dashed curves, respectively. In addition, dot curve in (c) shows the result of relativistic calculation for 1 TeV/u.

Deviations from first order predictions

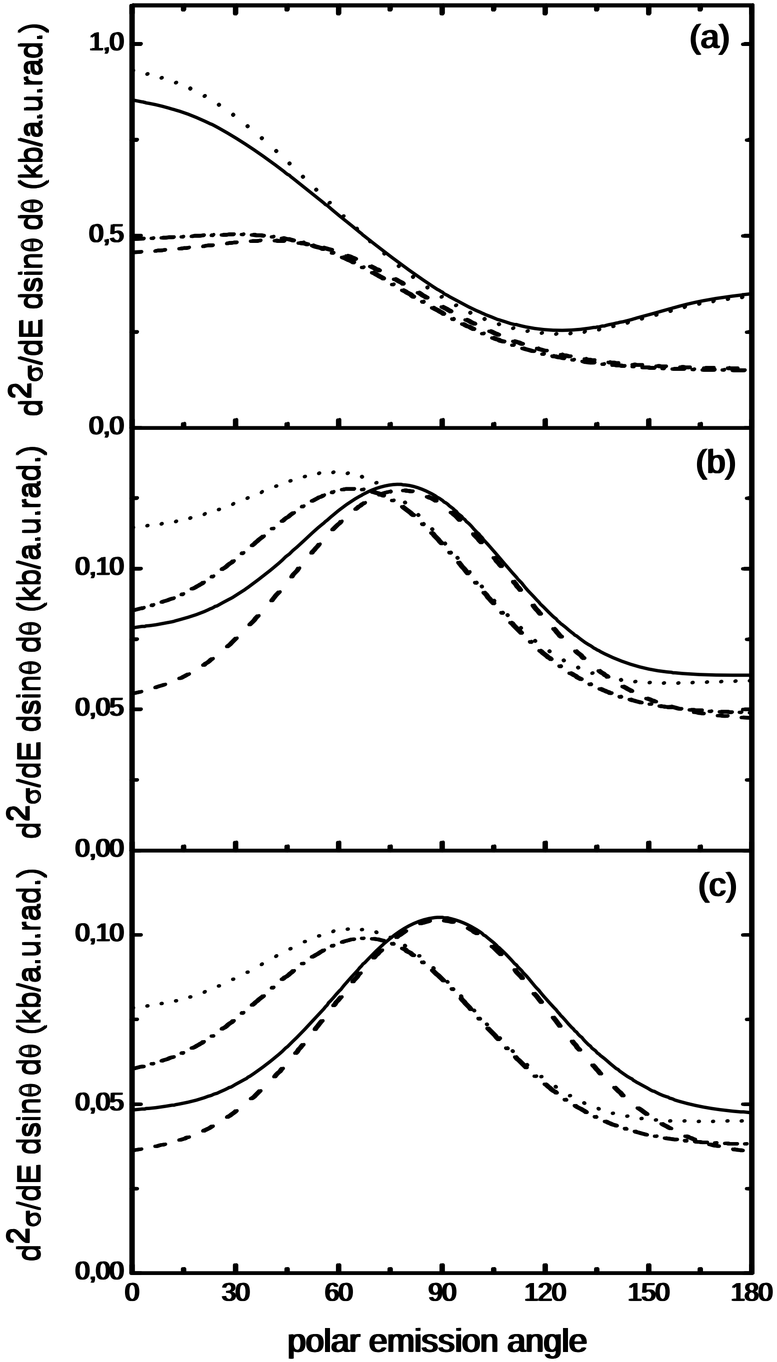


First order consideration: two-center dielectronic interaction

Eikonal model (**JPB 38** 3587; **PRA 73** 062705): two-center dielectronic interaction

+ two-center electron-nucleus interactions

+ nucleus-nucleus interactions



$O^{7+}(1s)+He(1s^2) \rightarrow O^{8+} + He^{+}(1s) + 2e^{-}$;

$$\frac{d^2\sigma}{dEd\Omega}$$

Emission from the target, emission energy E=5 eV

(a) 100 MeV/u ($Z_p/v=0.14$)

(b) 1 GeV/u ($Z_p/v=0.067$)

(c) 30 GeV/u ($Z_p/v=0.058$)

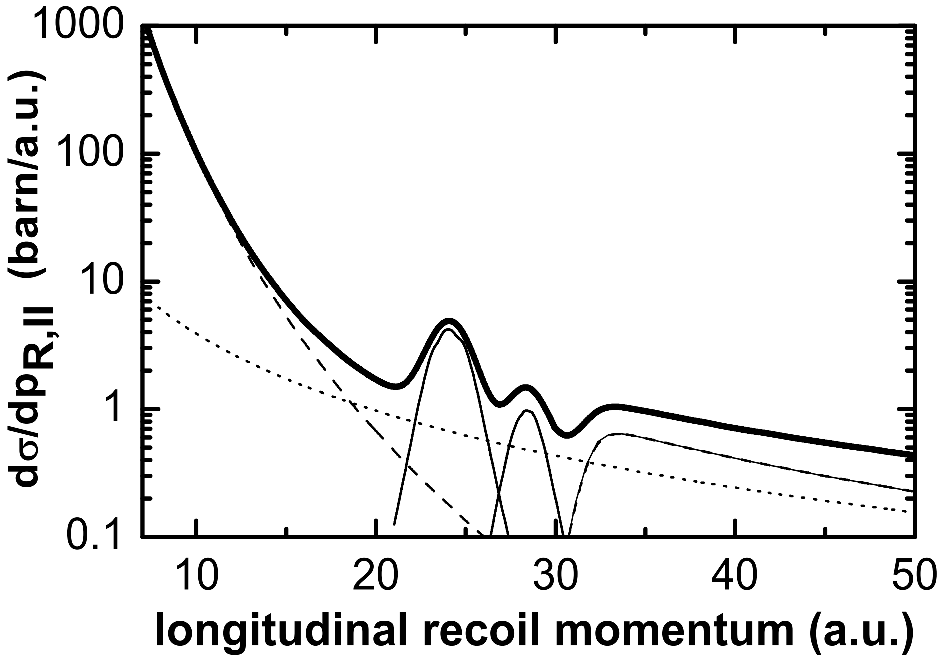
dot-dash: non-relativistic (c=infty) 1-st order

dash: relativistic (c=137 a.u.) 1-st order

dot: non-relativistic (c=infty) eikonal

solid: relativistic eikonal

Collisions between highly charged hydrogen-like ions and simplest atoms.

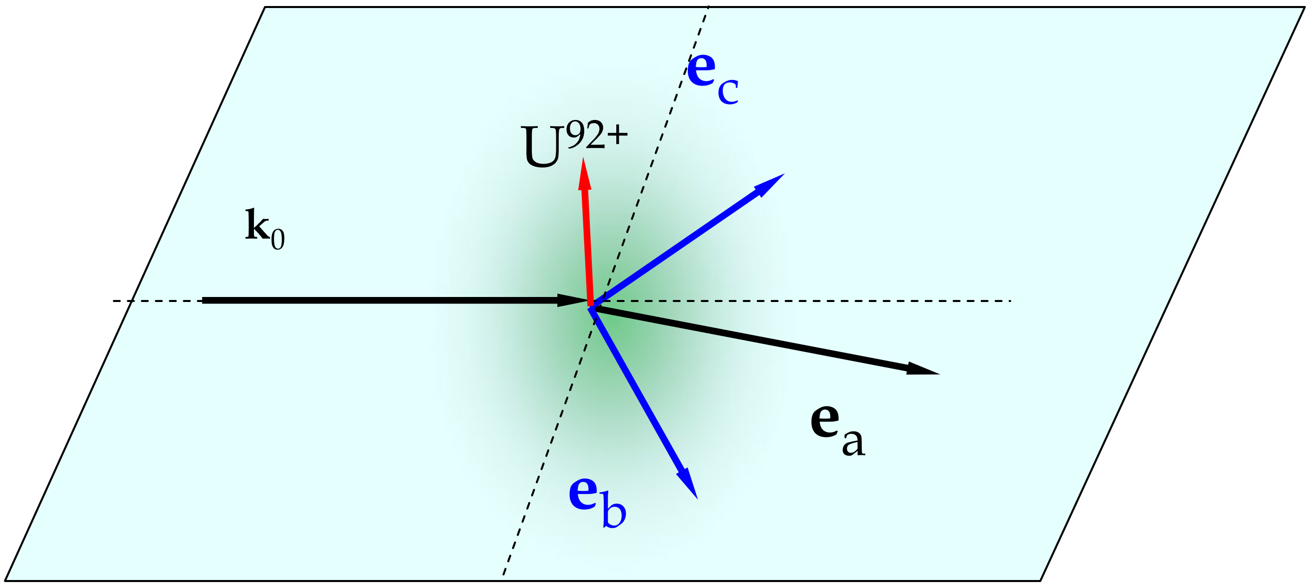


(talk by Bennaceur Najjari)

The longitudinal momentum spectrum of He^{+} recoils produced in 430 MeV/u Th^{89+}(1s)+He collisions.

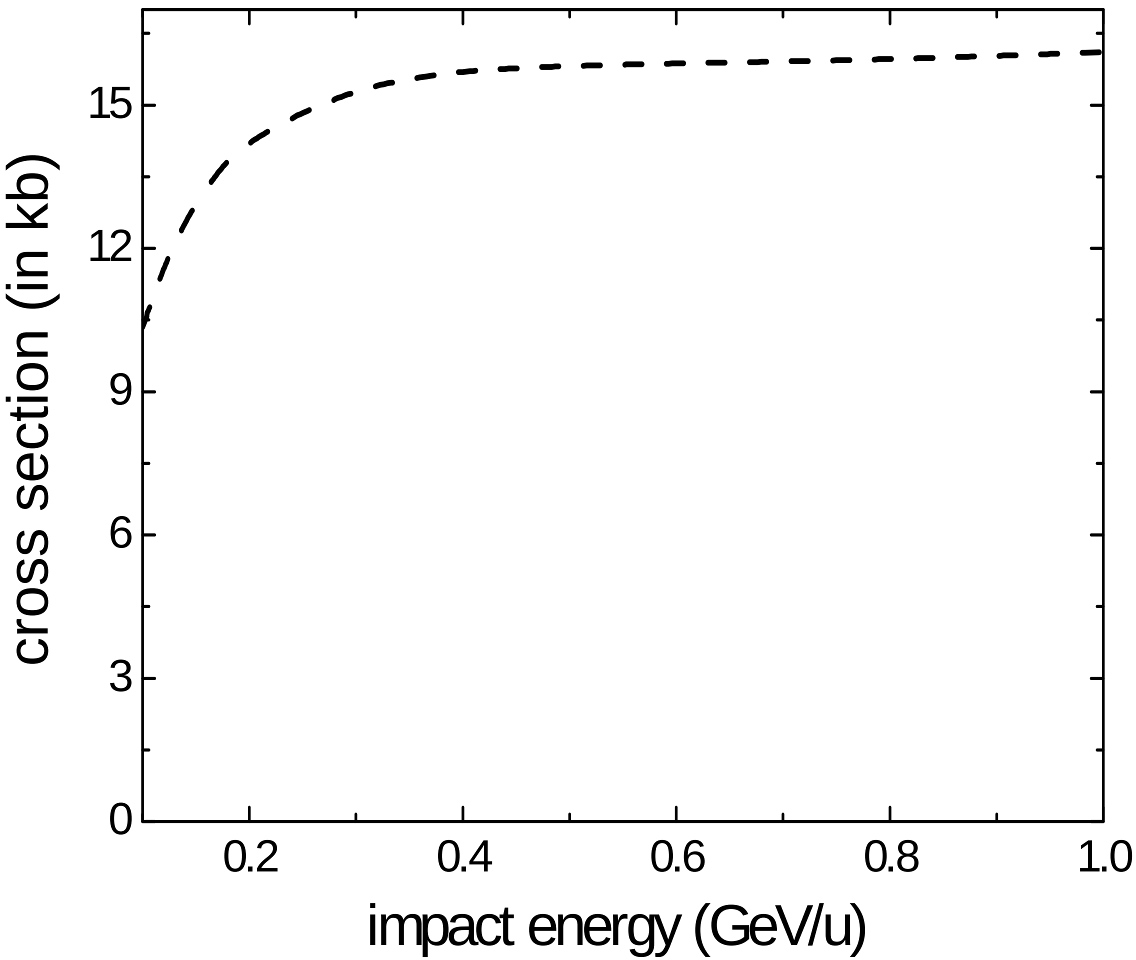
Ion-atom collisions -> e-2e, e-3e on highly charged ions

For the minor part of the reaction phase-space, the electron emitted from the atom in the final state may be influenced mainly by the field of the projectile-ion. Then the problem can be viewed as a bombardment of the ion (in its rest frame) by a (quasi-) free high-energy electron. As a result, one can study e-2e, e-3e on highly charged ions (and perhaps also different types of resonant electron-ion scattering).



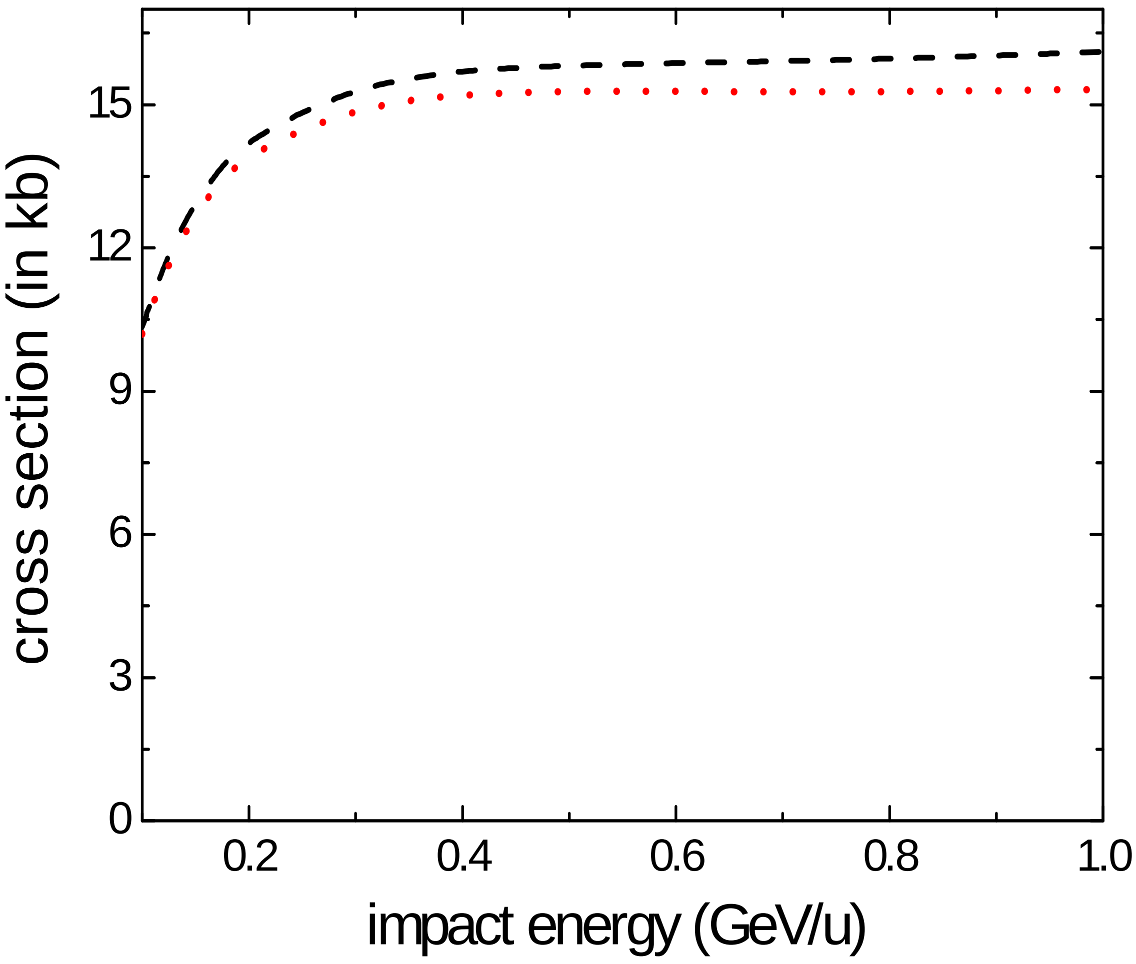
$$e^- + U^{90+}(1s^2) \rightarrow U^{92+} + 3e^-$$

Relativistic few-body problem in heavy ion-heavy atom collisions (exploration of total and differential loss cross sections in the case of strong relativistic interactions)



$U^{91+}(1s)$ + Au -> U^{92+} + e^- + ...

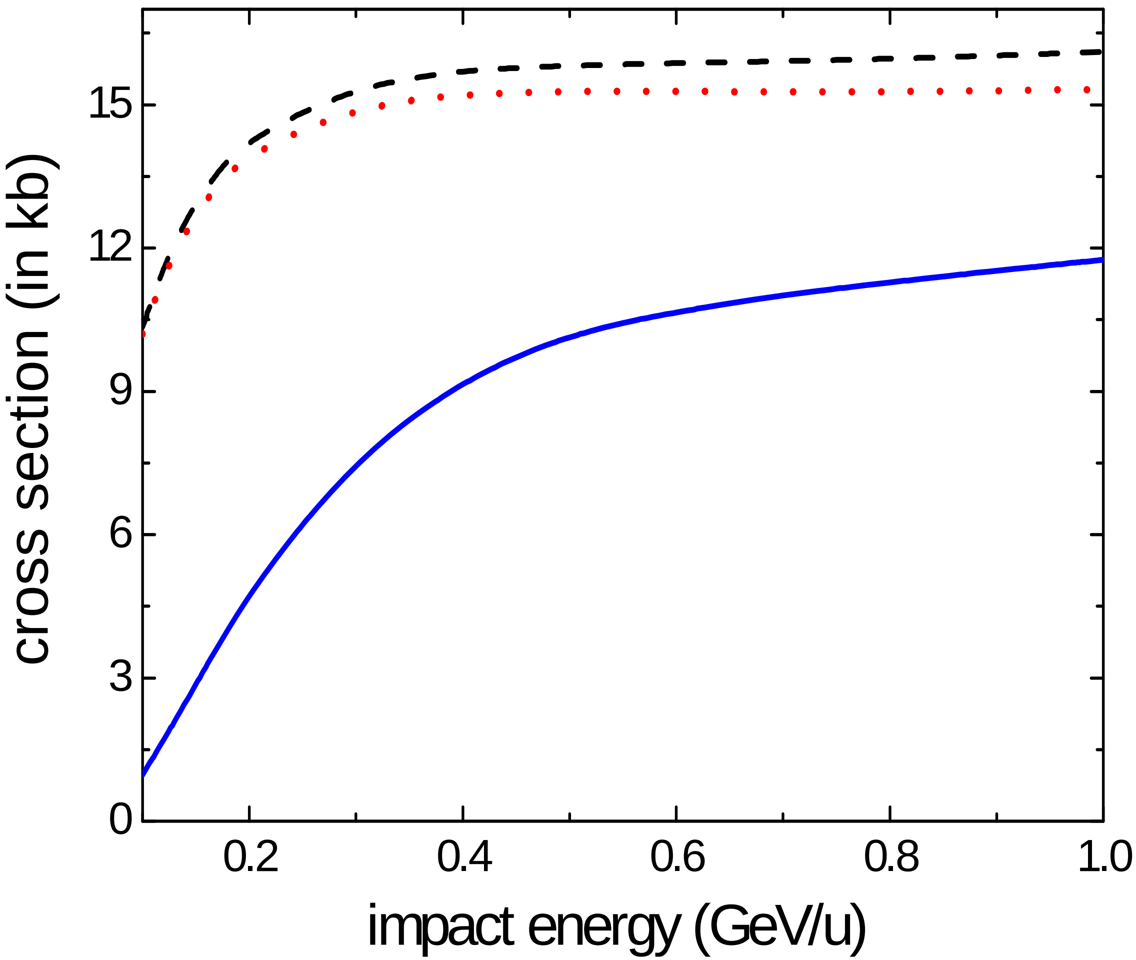
first order without screening



$U^{91+}(1s) + Au \rightarrow U^{92+} + e^{-} + \ldots$

first order without screening

first order with screening



$U^{91+}(1s)$ + Au -> U^{92+} + e^- + ...

first order without screening

first order with screening

3-body distorted-wave approach

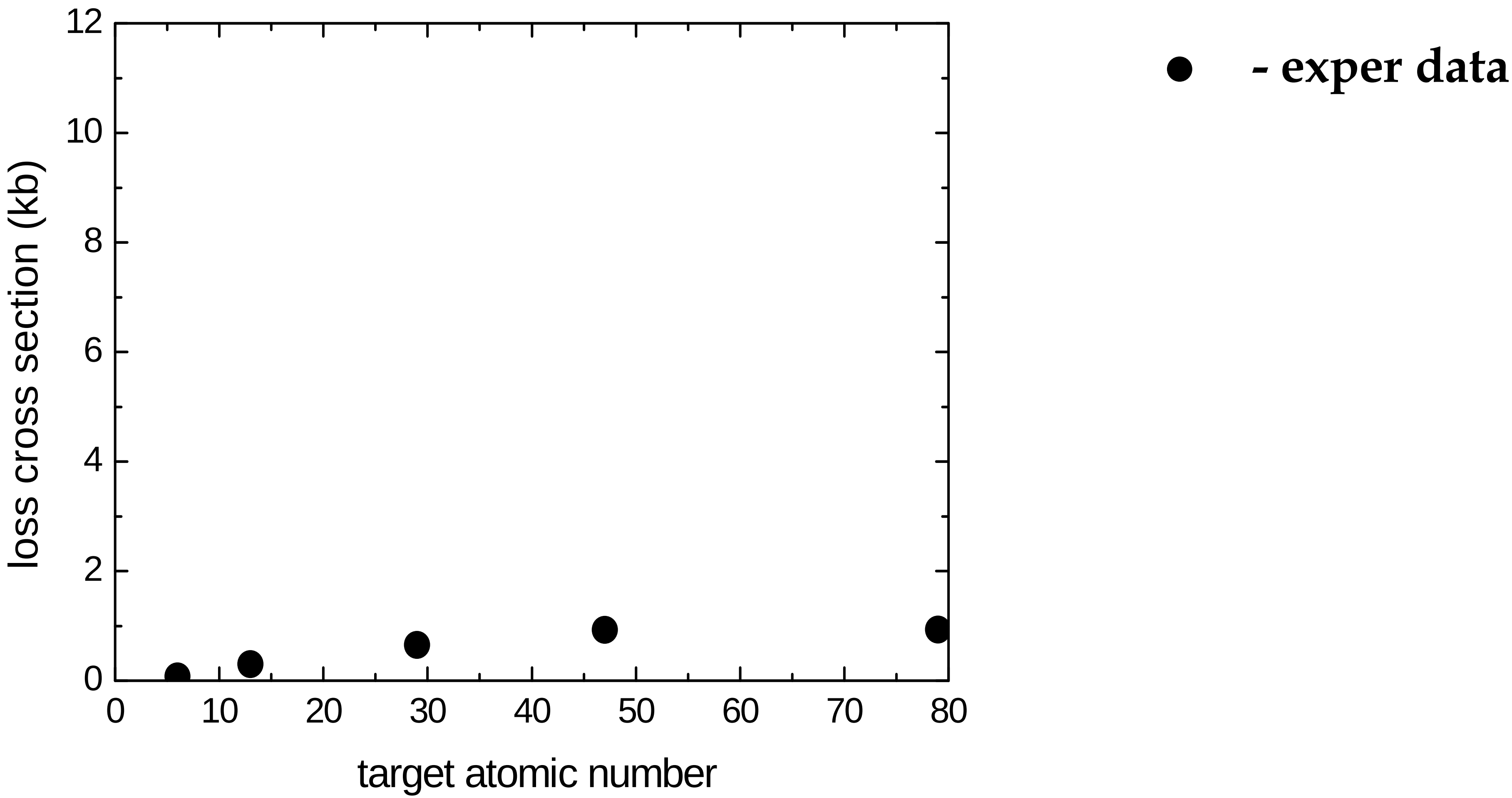
A.B.V and B.N, **JPB**, in press

Projectile-electron excitation and loss in collisions with neutral atoms ->

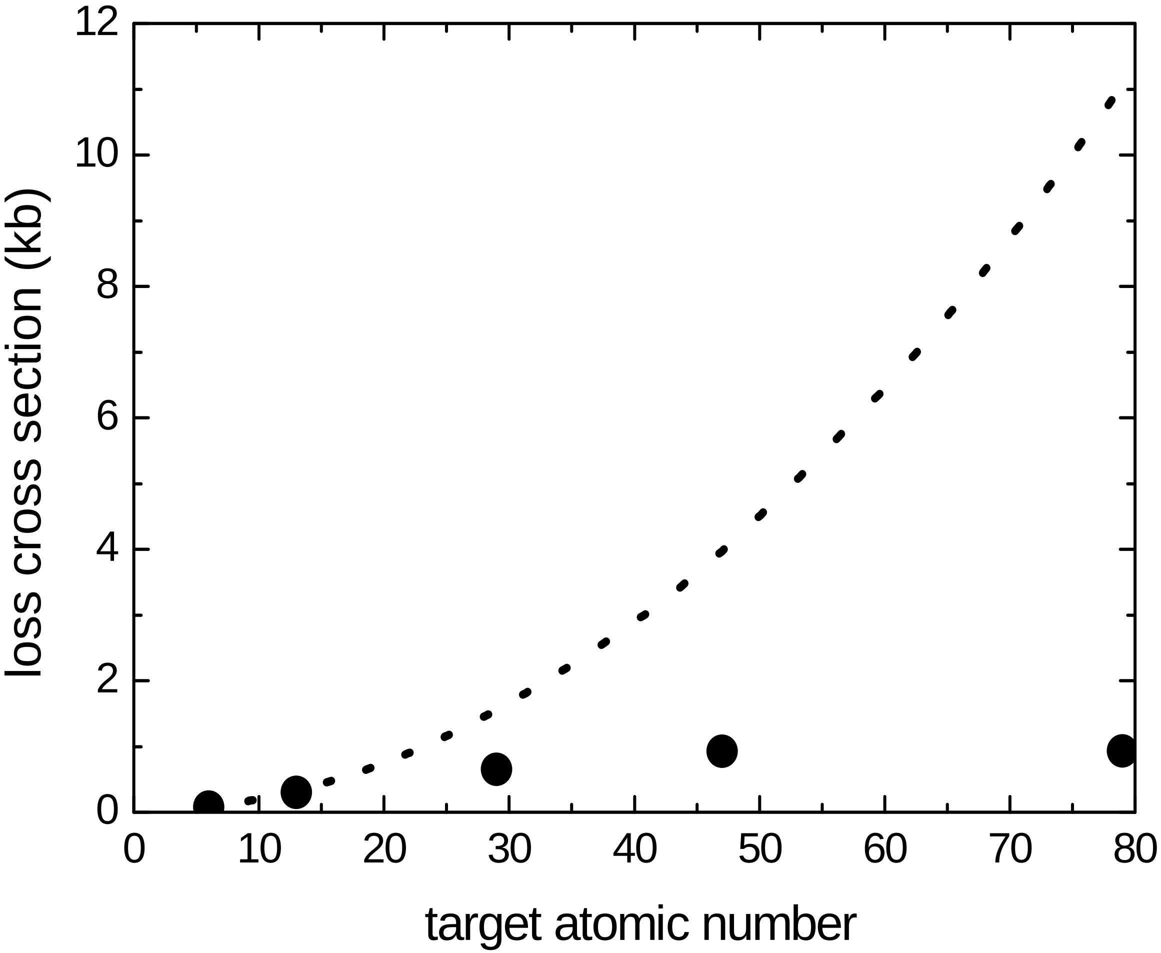
projectile-electron excitation and loss in collisions with atomic nuclei ->

relativistic three-body (few-body) collision models

105 MeV/u $U^{90+}(1s^2)$+target → $U^{91+}(1s)+e^- + \dots$



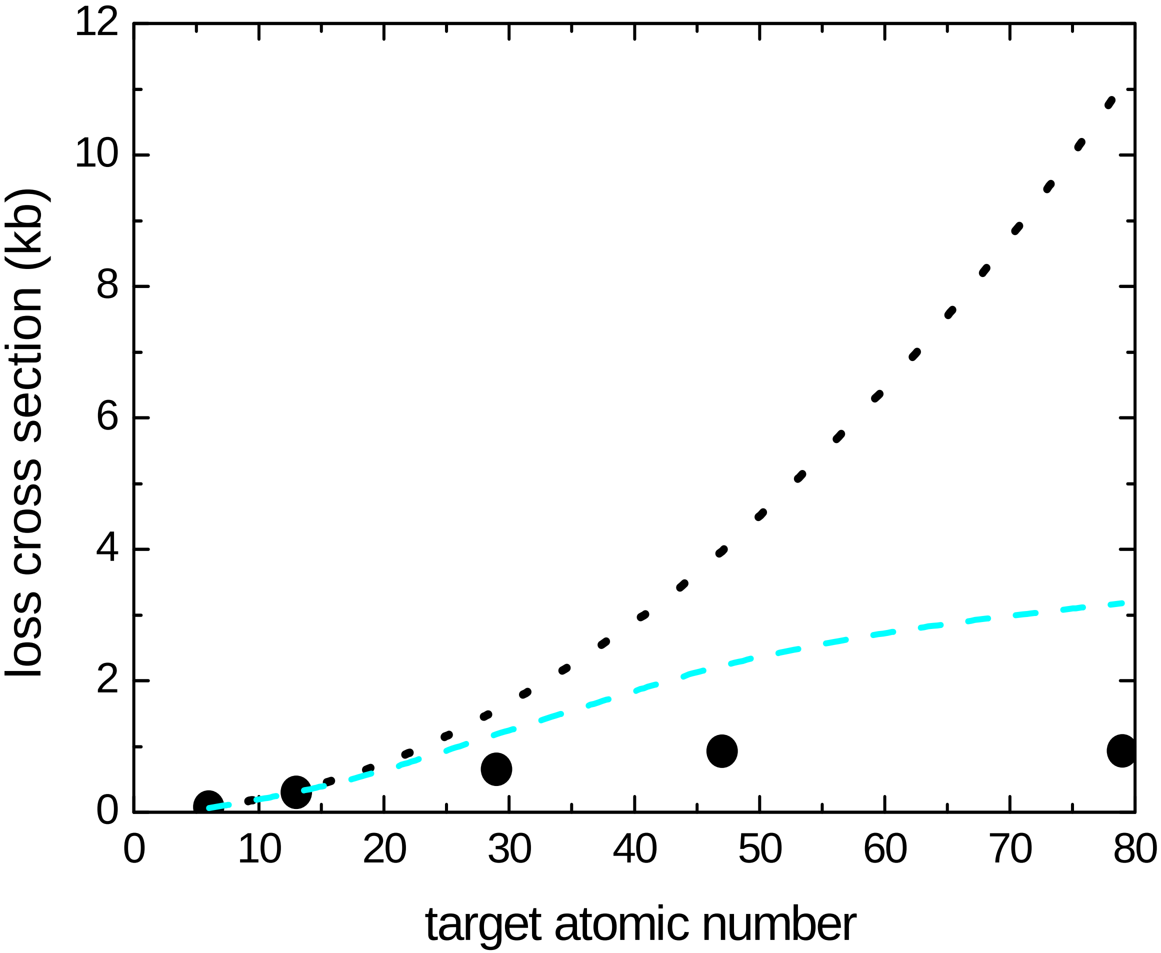
105 MeV/u $U^{90+}(1s^2)$+target → $U^{91+}(1s)+e^- +\ldots$



● - exper data

first order

105 MeV/u $U^{90+}(1s^2)$+target ➞ $U^{91+}(1s)+e^- +\ldots$

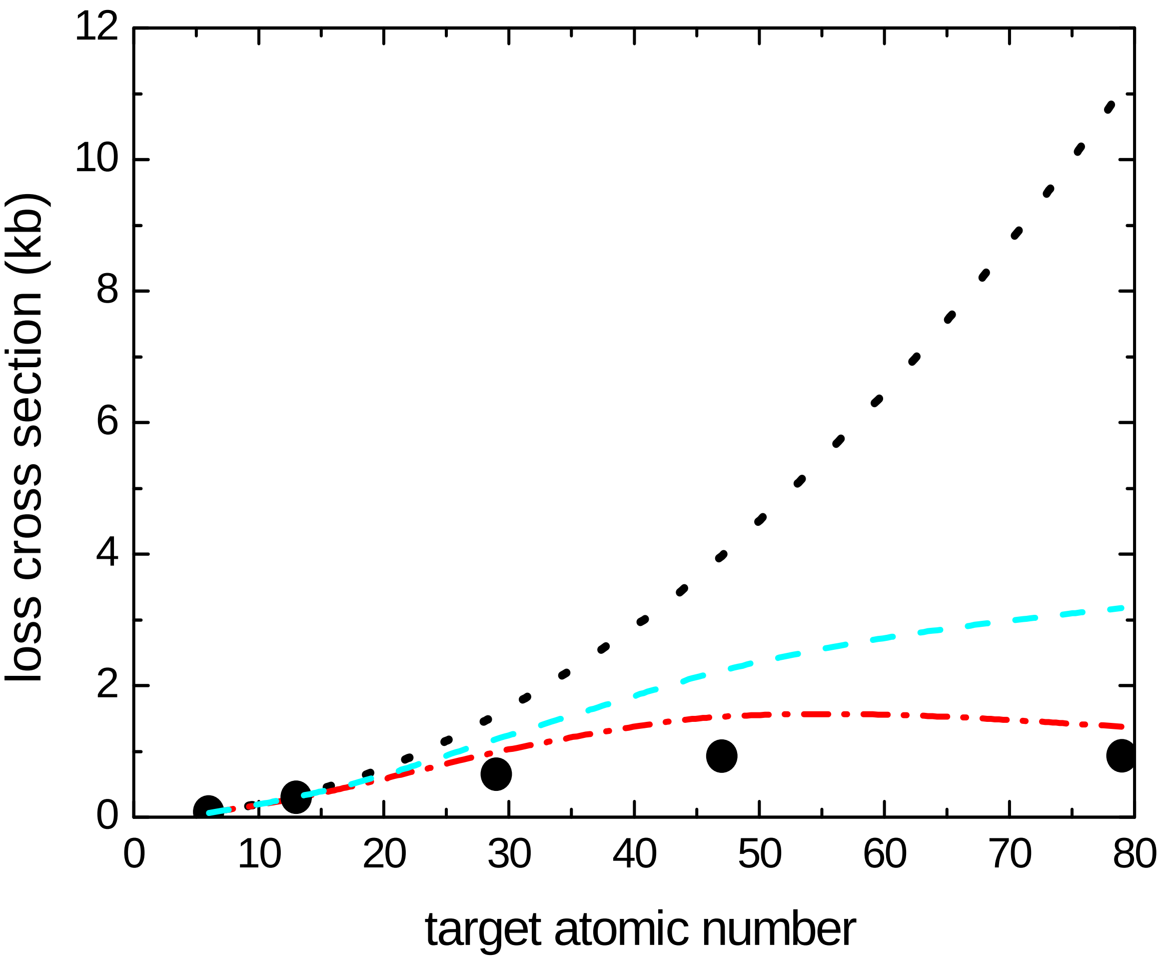


● - exper data

first order

dwa1

105 MeV/u $U^{90+}(1s^2)$+target → $U^{91+}(1s)+e^- + \ldots$



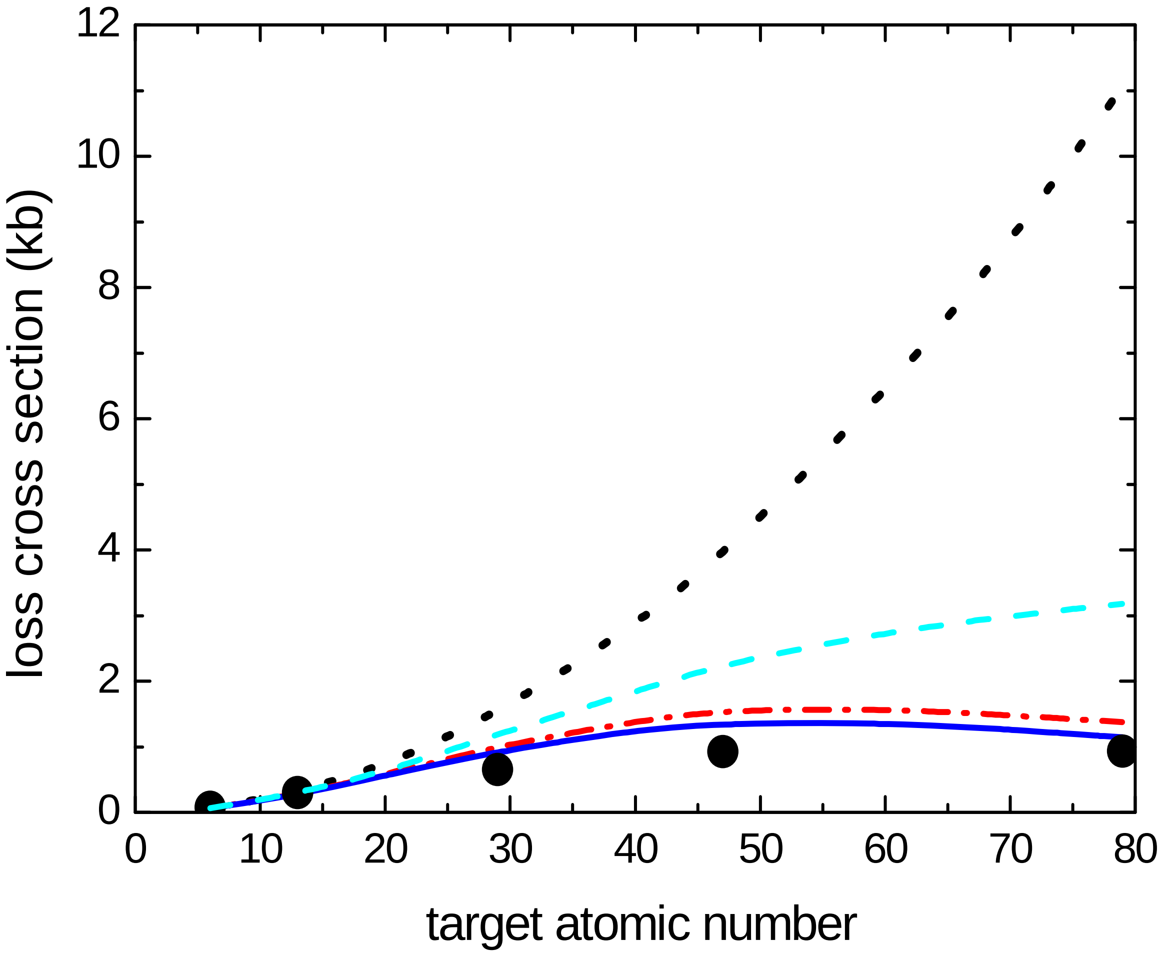
● - **exper data**

first order

dwa1

dwa2

105 MeV/u $U^{90+}(1s^2)$+target $U^{91+}(1s)+e^- + \dots$



● - **exper data**

first order

dwa1

dwa2

dwa3

A.B.V and B.N, **JPB**, in press; PRA, in press

iii) Pair production

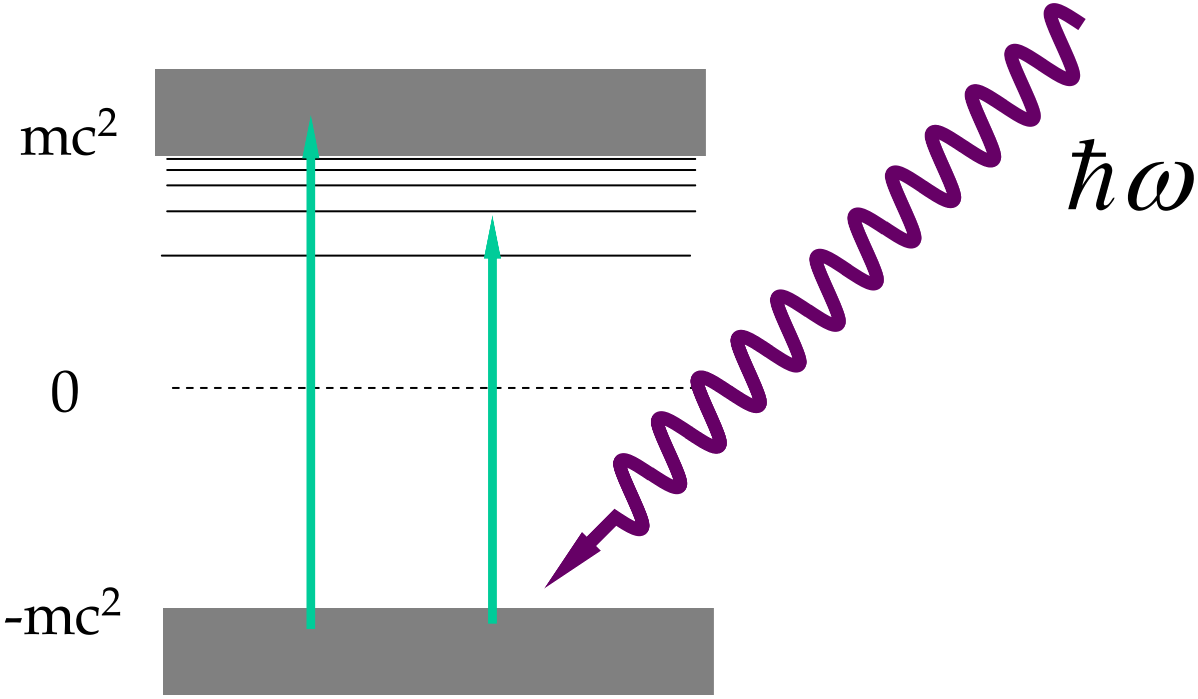
In order to produce electron-positron pairs in reasonable quantities it is necessary to have a sufficient amount of the high-frequency components ($\omega \geq 2mc^2/\hbar$) in the spectrum ("photo-like" pair production)

or (and) to have extremely strong fields ($E \geq E_c = m^2c^3/(\hbar e)$, "tunnelling" from the negative to the positive energy continuum) .

In ion-atom collisions with an impact parameter **b** the spectrum of the electromagnetic field effectively extends to $\omega_{\max} \approx \gamma v/b$.

Estimating typical impact parameters as being of order of the Compton wave we obtain that $\omega_{\max} \approx mc\gamma v/\hbar$. It means that at collision energies accessible at NESR the photo-like pair production will be quite weak and a better option could be to collide very heavy nuclei at relatively low impact energies to produce for a short time a field close to the critical one.

Photo-like pair production



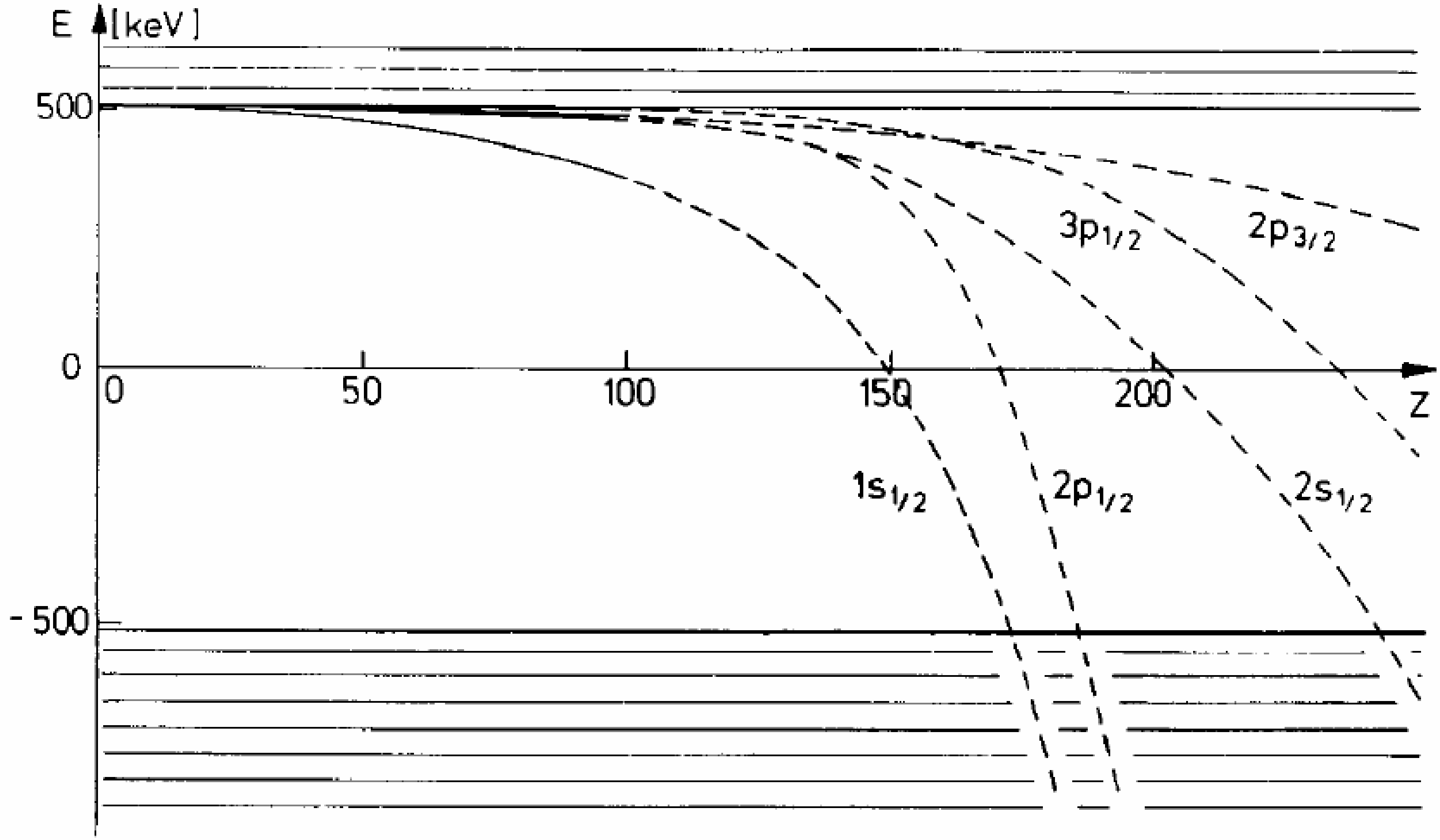


Figure 1 The energies of the lowest atomic states versus the nuclear charge Z. Solid lines give the experimentally known region, dashed lines represent Hartree-Fock-Slater calculations. Observe the critical point for the $1s$, $2p_{1/2}$, and $2s$ states.

(Figure is taken from B.Mueller, **Ann.Rev.Nucl. Sci 26** 351 (1976))

iv) Collisions with antiprotons

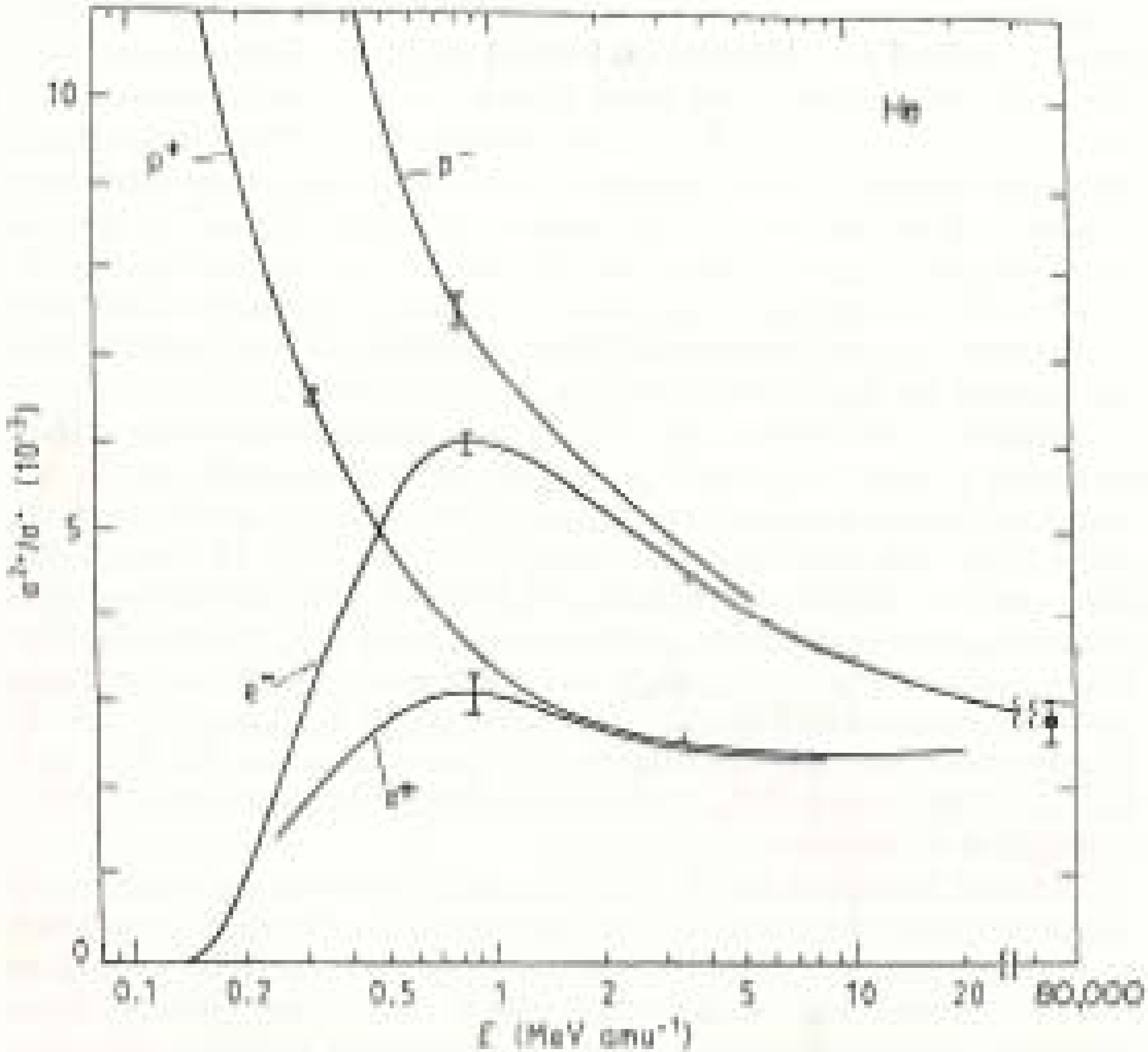


Fig. 7.6. Observed ratios of double to single ionization in helium by protons (p^+), anti-protons (p^-), electrons (e^-), and positrons (e^+) of the same incident velocity [Charlton *et al.*, 1988]. The 80 GeV/amu point is from Müller *et al.* [1983a].

(The figure is taken from "Electron correlation dynamics…" by J.McGuire (p.167))

Antiprotons/protons on helium: single ionization

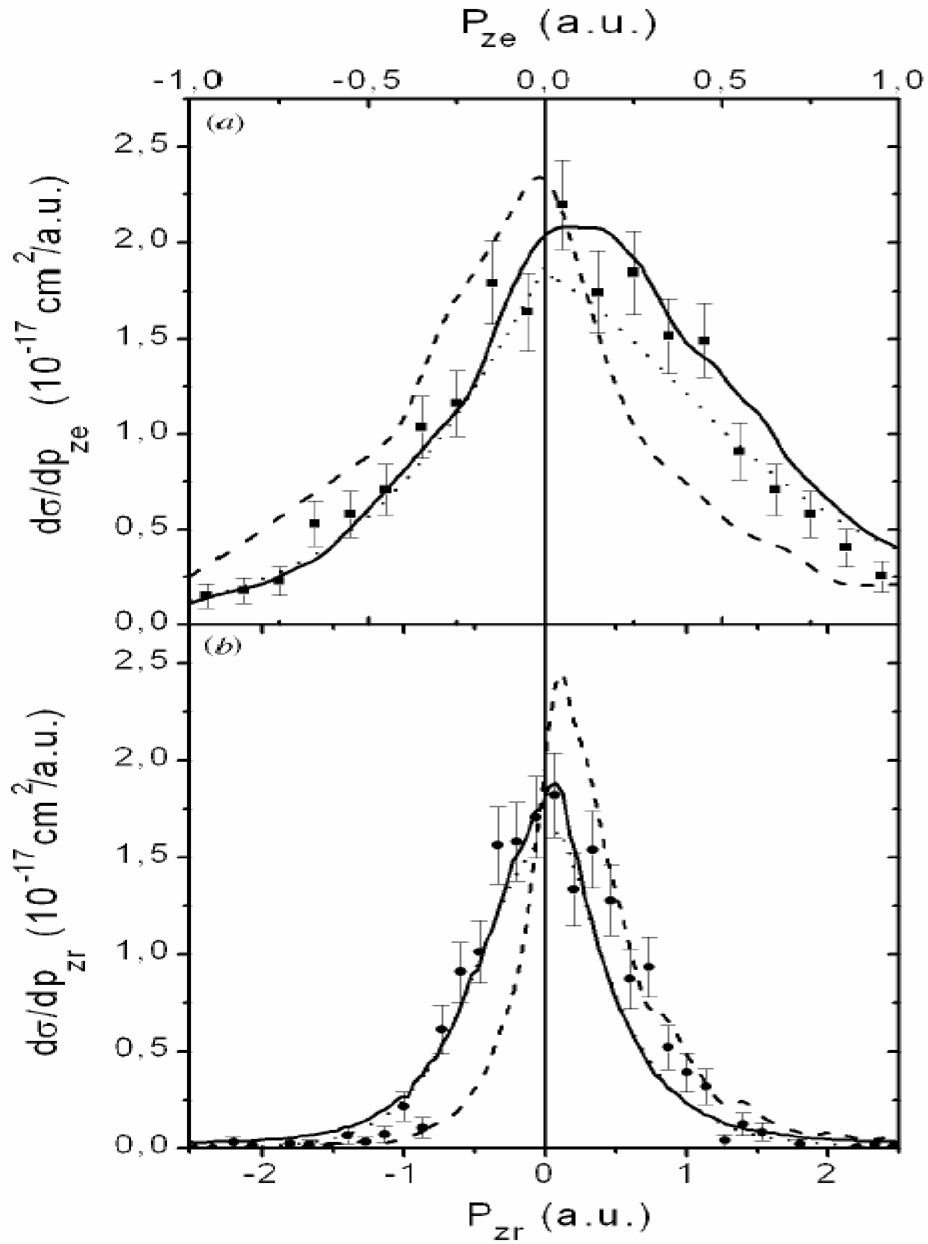
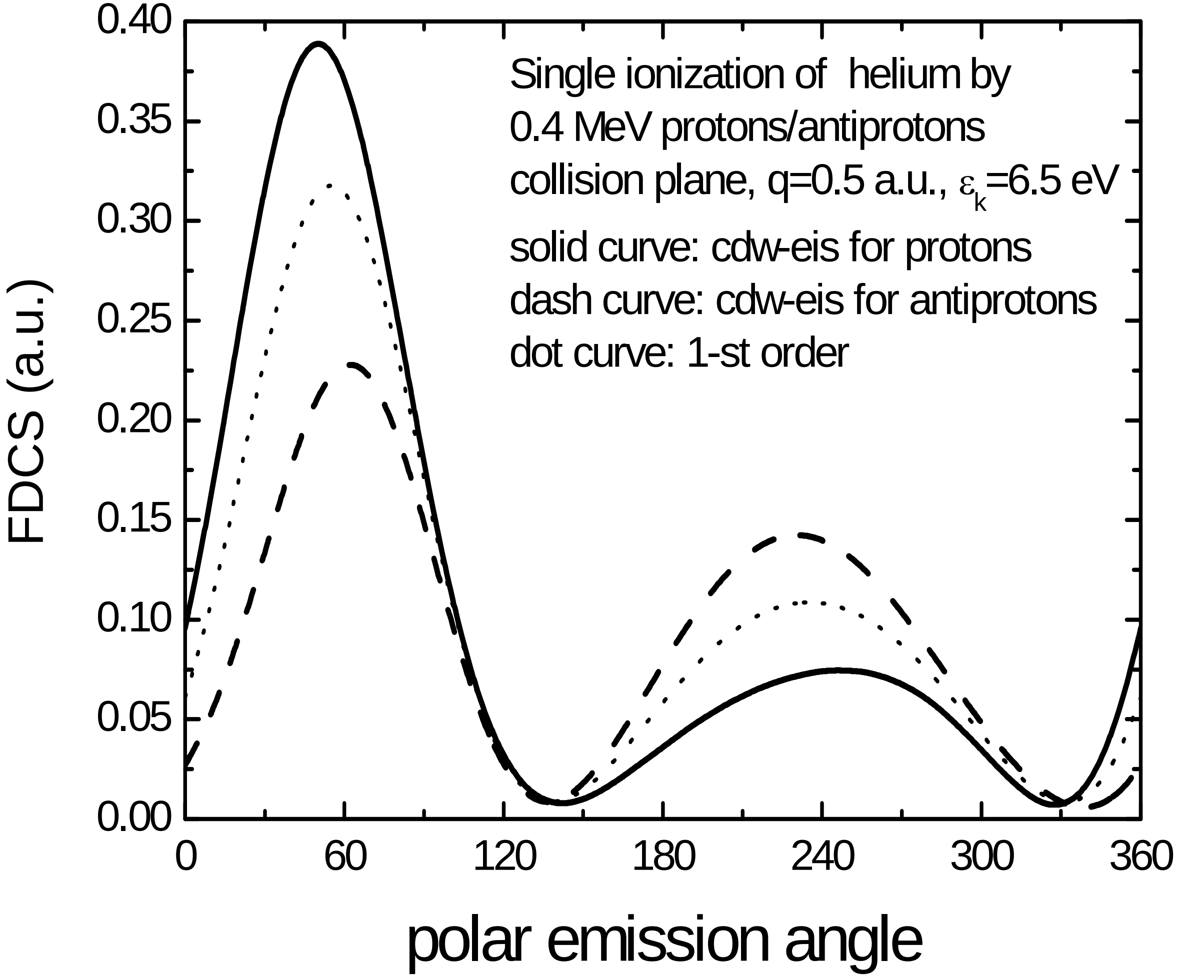


Figure 2. Longitudinal momentum distribution for single ionization of helium by 945 keV antiproton (data points) in comparison with proton collision (full curve). ($_a$) Electron momentum data; ($_b$) recoil-ion data. The theoretical calculations represent antiproton collision: dotted curve, CDW result; broken curve, CTMC result.

Khayyat et al,

J.Phys. **B32** L73 (1999)



Single ionization of helium by
0.4 MeV protons/antiprotons
collision plane, q=0.5 a.u., ε_k=6.5 eV
solid curve: cdw-eis for protons
dash curve: cdw-eis for antiprotons
dot curve: 1-st order
FDCS (a.u.)
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0
60
120
180
240
300
360
polar emission angle

Ionization of hydrogen by proton/antiproton impact

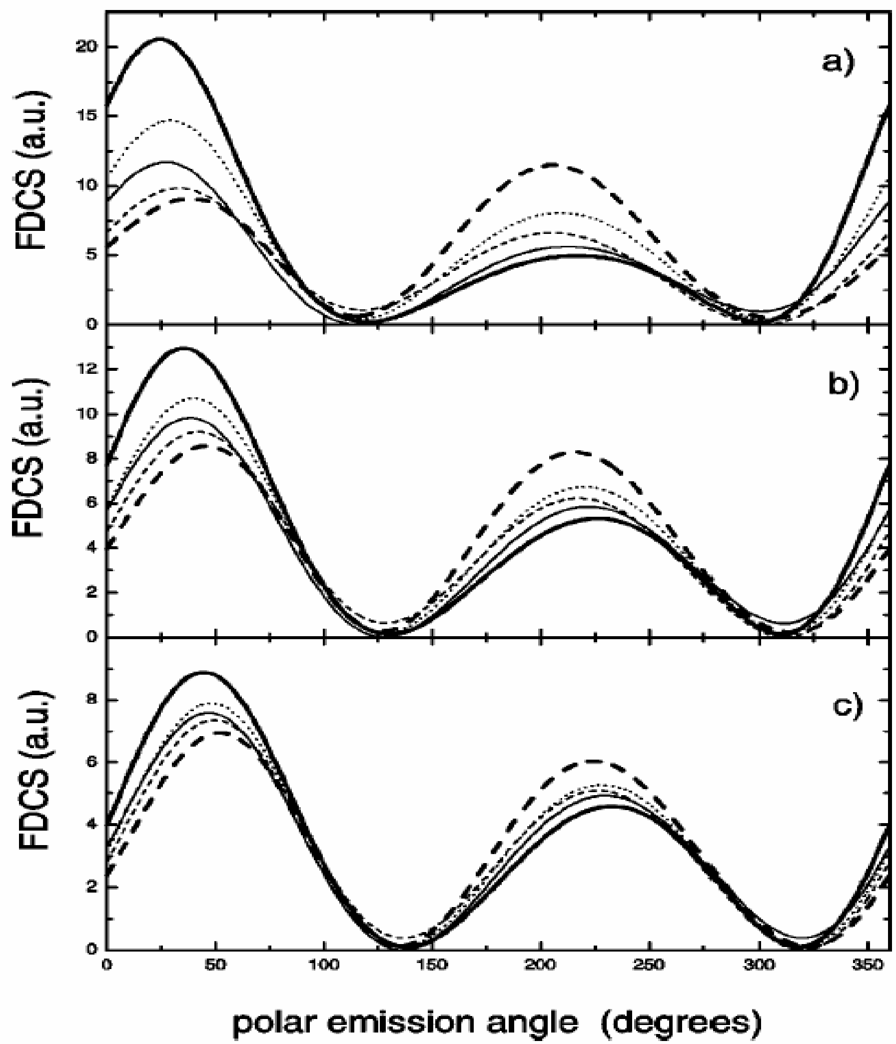
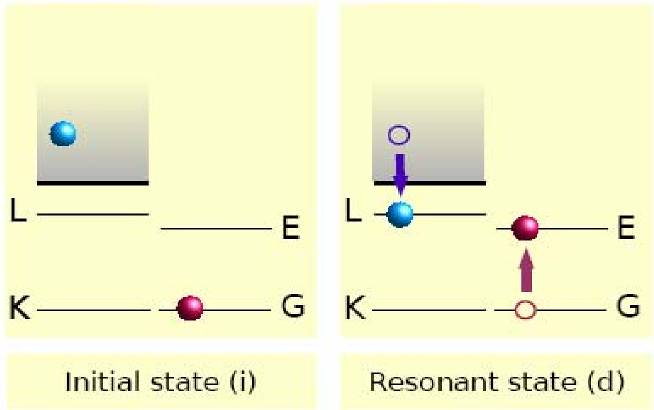


FIG. 2. Fully differential cross section (FDCS) in the collision plane. Collision parameters: $v_p = 3$ (a), 4.5 (b), and 6 (c); $E_k = 1$ eV, $Q = 0.1$ a.u., and $\varphi_k = 0°$. Thick solid curve: CDW-EIS results for a proton impact; the p-n interaction is included. Thin solid curve: CDW-EIS results for a proton impact; the p-n interaction is ignored. Thick dashed curve: CDW-EIS results for an antiproton impact; the p-n interaction is included. Thin dashed curve: CDW-EIS results for an antiproton impact; the p-n interaction is ignored. Dotted curve: first Born results.

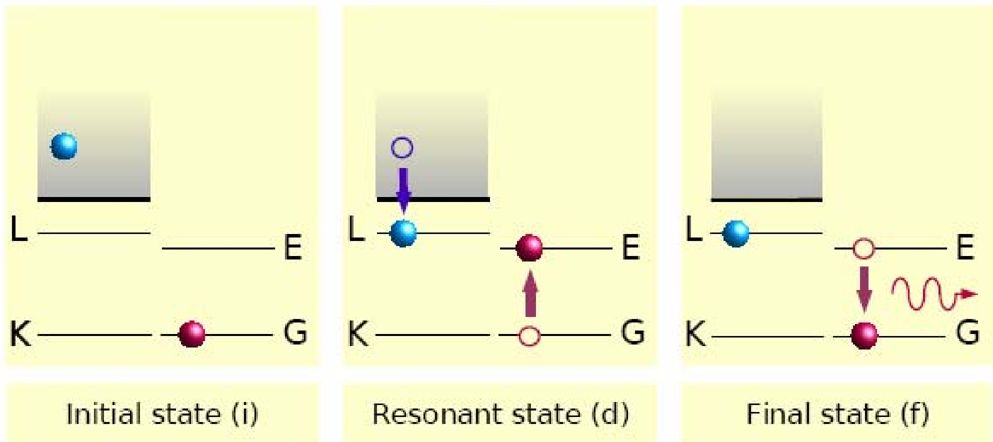
PRA 67 062703 (2003)

v) Resonant electron-nucleus scattering via nuclear excitation

A.Pallfy, Z.Harman and W.Scheid

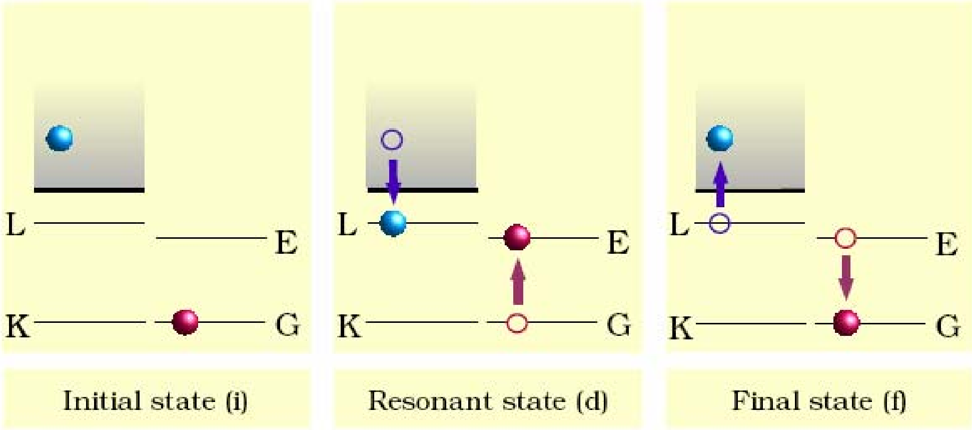


nuclear excitation by electron capture into the L shell of an initially bare ion

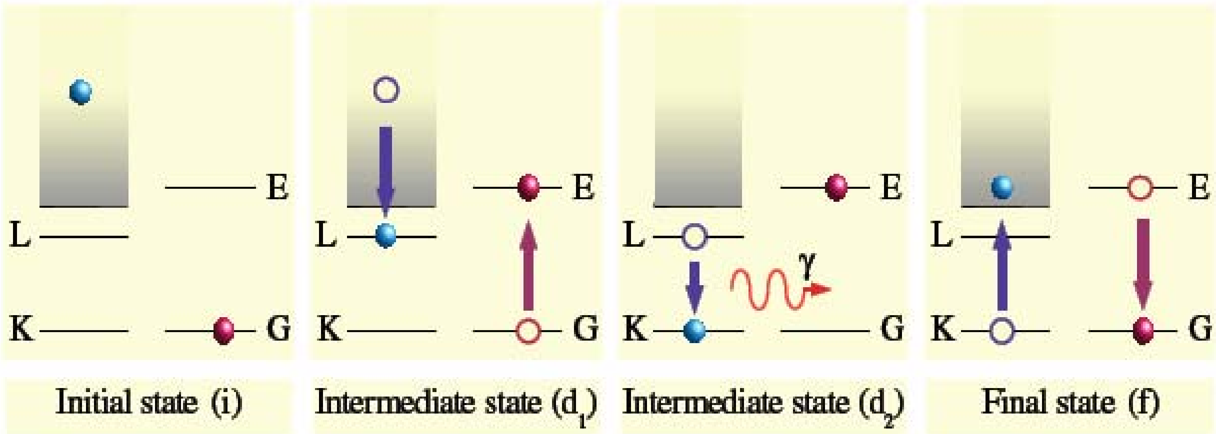


NEEC followed by the radiative decay of the nucleus

(figures are courtesy of A.Pallfy)



NEEC followed by internal conversion



(figures are courtesy of A.Pallfy)

Thank you for attention !

Experimental results which we would like to see:

1. Single, double and multiple ionization by highly charged nuclei:

   relativistic and higher order effects, total and differential cross sections, fully resolved quantum dynamics (for instance, besides one experiment with not very good statistics, no results on the fully differential cross sections).

2. Singly and doubly inelastic collisions between multiply and highly charged (hydrogen-like) ions and simplest atoms/moleculas:

   spectra of emitted electrons, target recoil ions, etc (collision dynamics resolved as fully as possible)

3. Projectile-electron excitation and loss at low-relativistic impact energies (below 1 GeV/u) in collisions with atoms having large atomic numbers .

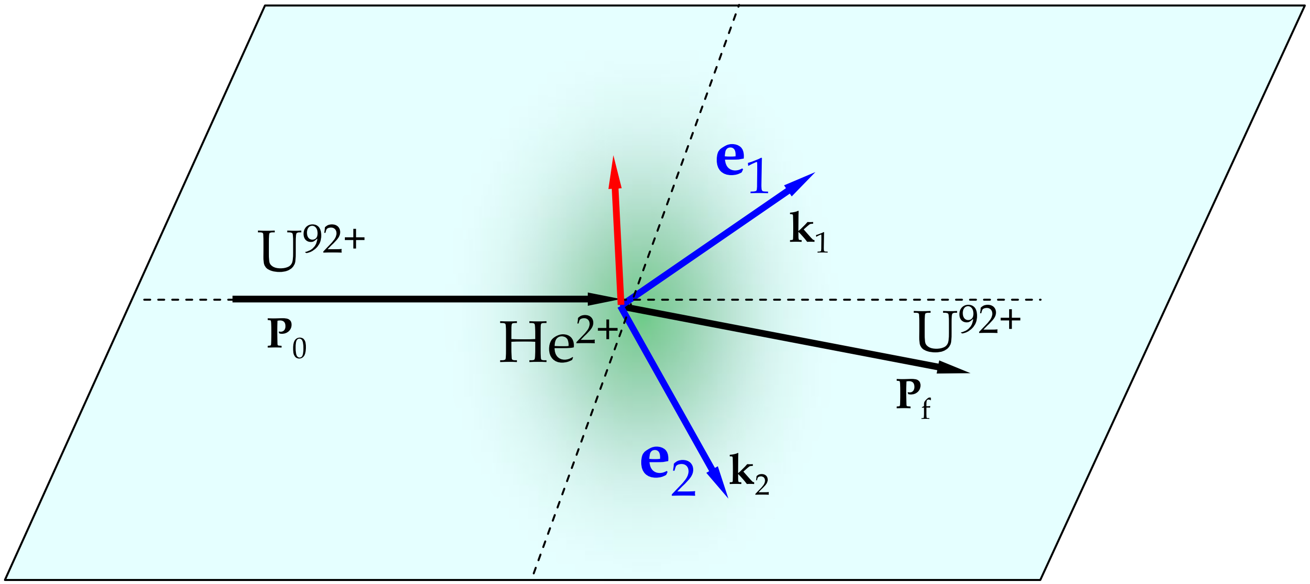
4. Projectile-electron excitation and loss at high impact energies (role of solid state effects in experimental observables).

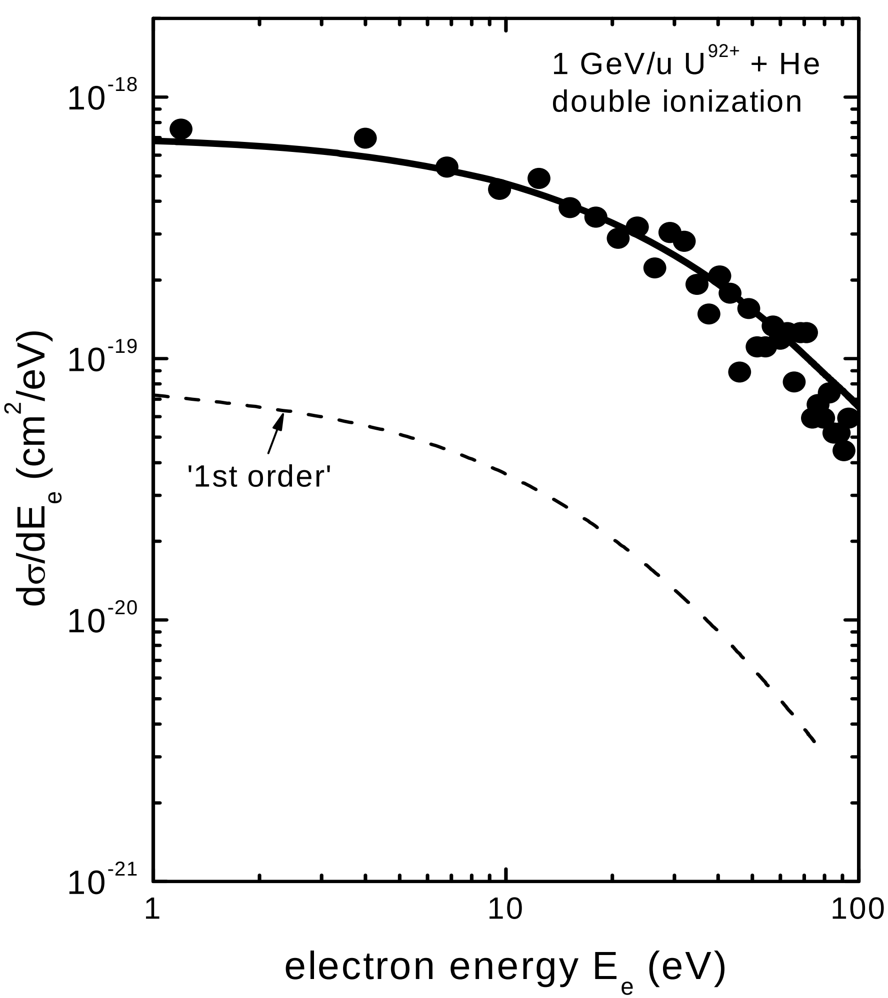
The future experimental facility will provide an unique opportunity to study these processes but some of them seem to be possible to study with tools already existing at GSI.

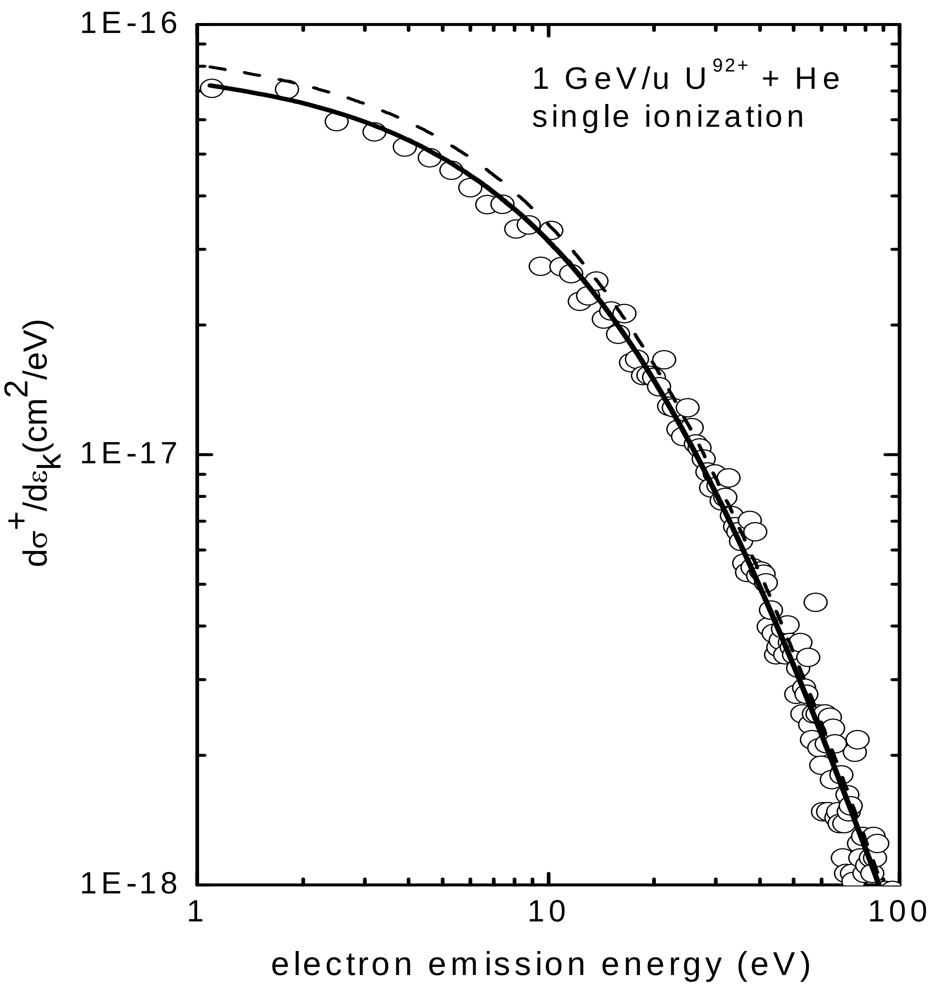
i) Ionization of atoms by relativistic highly charged nuclei

Relativistic and higher order effects, fully resolved collision dynamics, photo-like collisions.

An example: $U^{92+} + He \rightarrow U^{92+} + \ldots$







Circles: experimental data from Moshammer et al **PRL 79** 3621 (1997).

J.Phys. **B 38** L107 (2005)

J.Phys. **B 37** 3621 (2004)