Electron transtions in high-energy heavy ion-atom collisions

A.B. Voitkiv

Max-Planck-Institut für Kernphysik, D-69117 Heidelberg, Germany

Superstrong fields

Lasers:

State-of-the-art lasers: intensities $\sim 10^{16}$ - 10^{22} W/cm^2

pulse durations $\sim 10^{-12}$ - 10^{-15} s

Relativistic ion-atom collisions:

160 GeV/u Pb^{81+}(1s) on Au: intensities up to 10^{31} - 10^{32} W/cm^2

pulse duration $\sim 10^{-21}$ s

Outline

A. Projectile-electron transitions in ion-atom collisions

I. Low-relativistic domain of the impact energies

I.1 Single loss

I.2 Simultaneous loss-excitation

II. Extreme relativistic impact energies

II.1 Electron loss

II.2 Pair production with capture

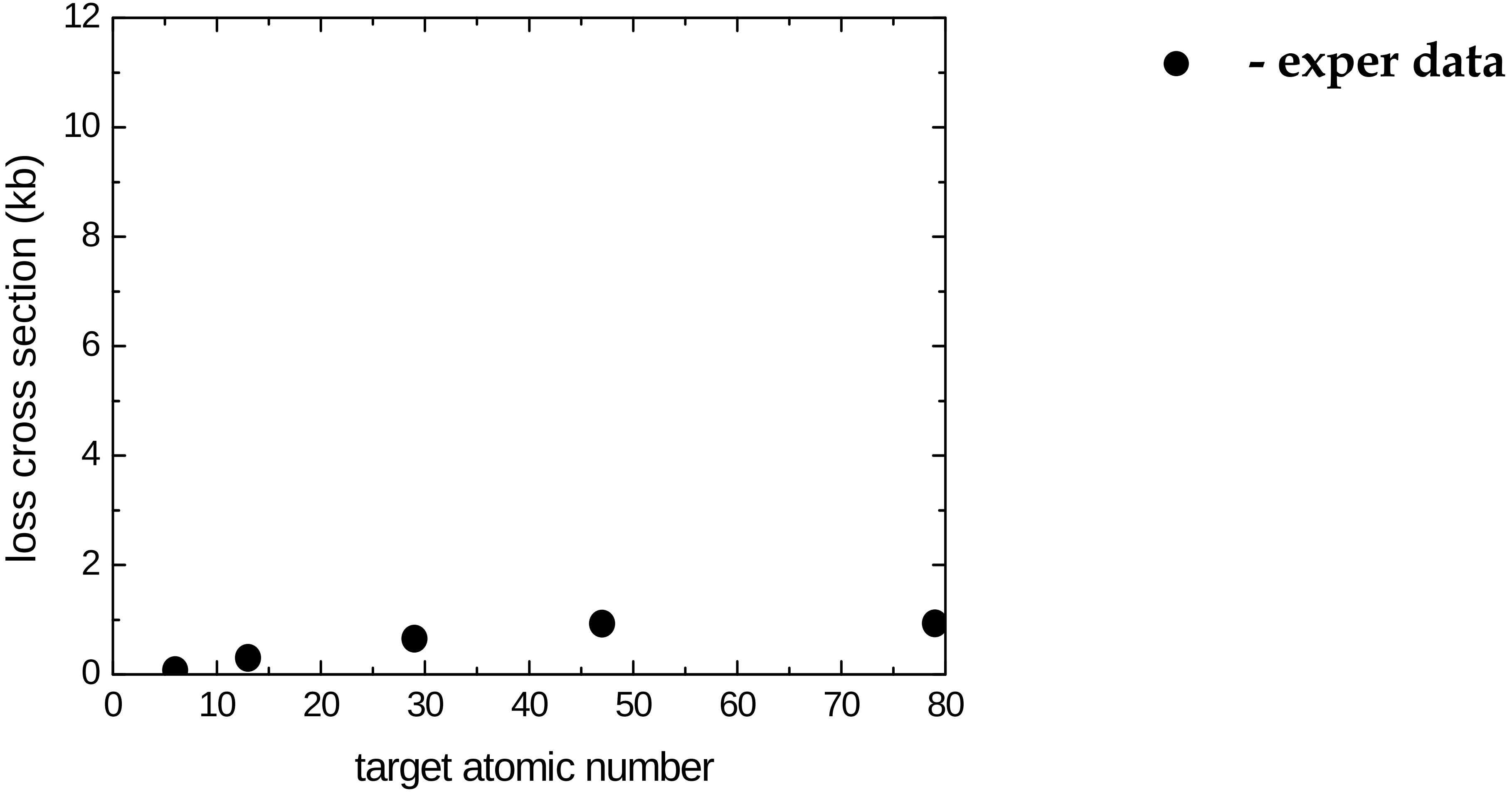
III.3 Multiple-collisions in solids: their influence on the projectile charge states and the electron emission spectra

B. More detailed studies of relativistic ion-atom collisions

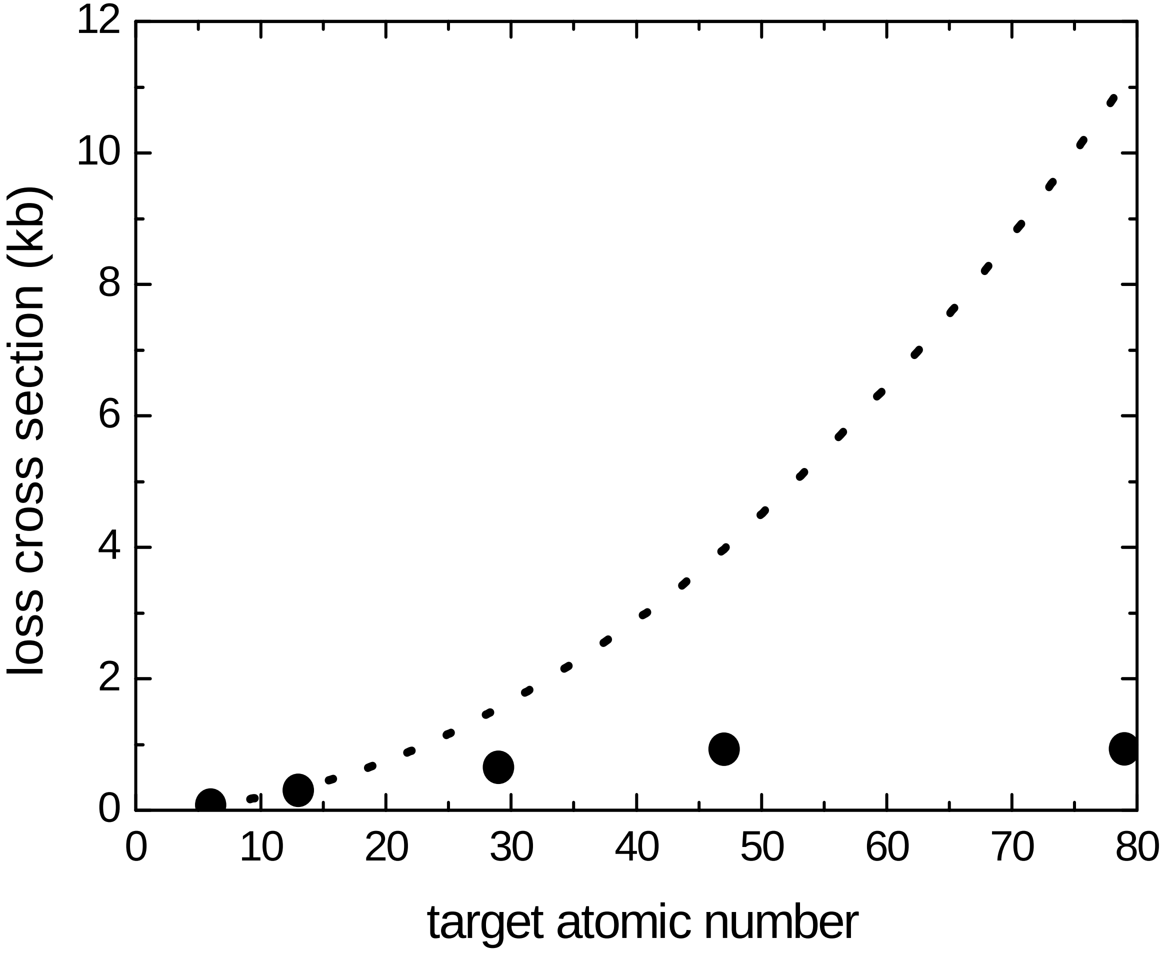
An example: spectra of target recoil ions

C. Outlook

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



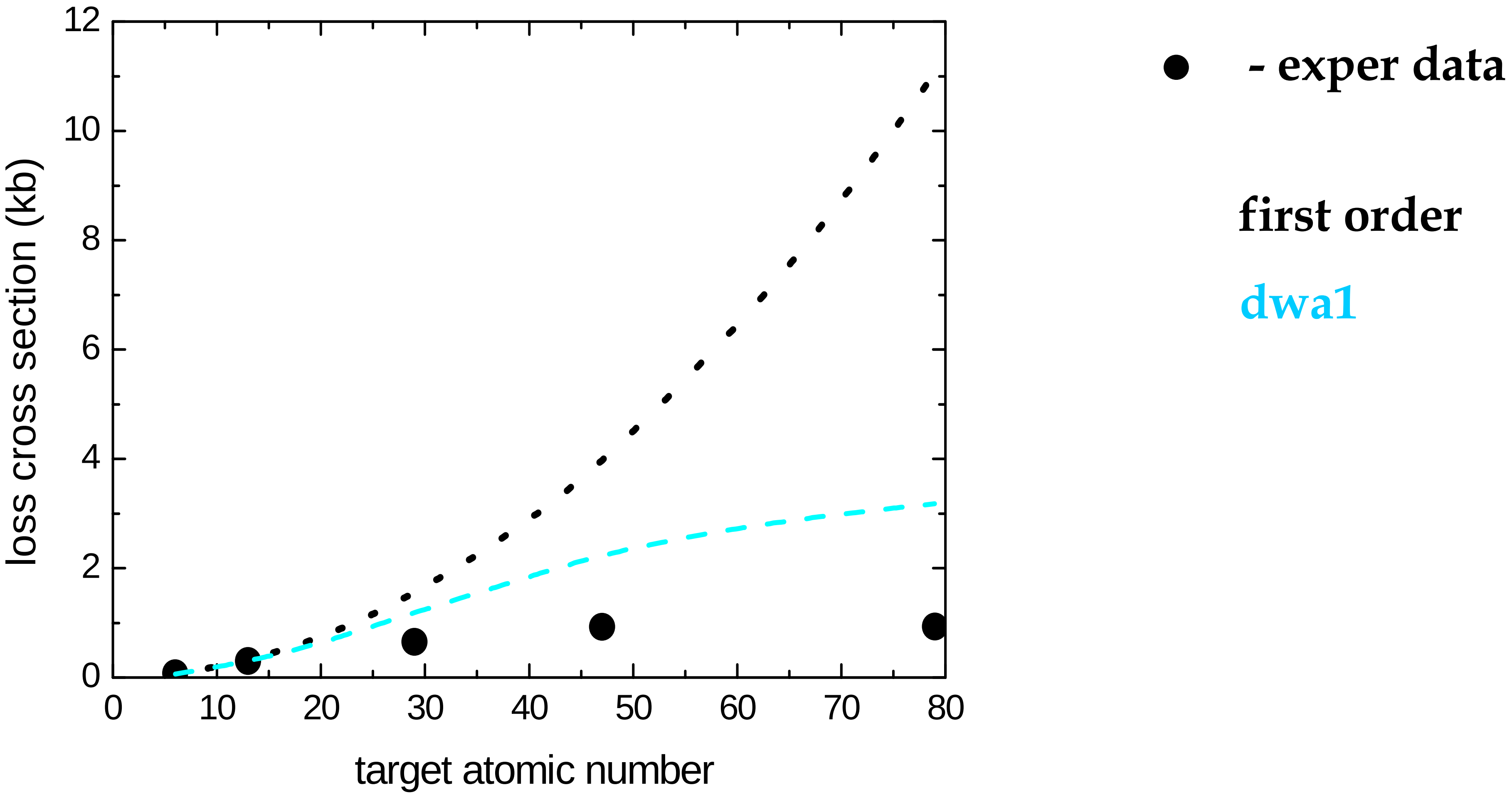
105 MeV/u $U^{90+}(1s^2)$+target → $U^{91+}(1s)+e^- + \ldots$



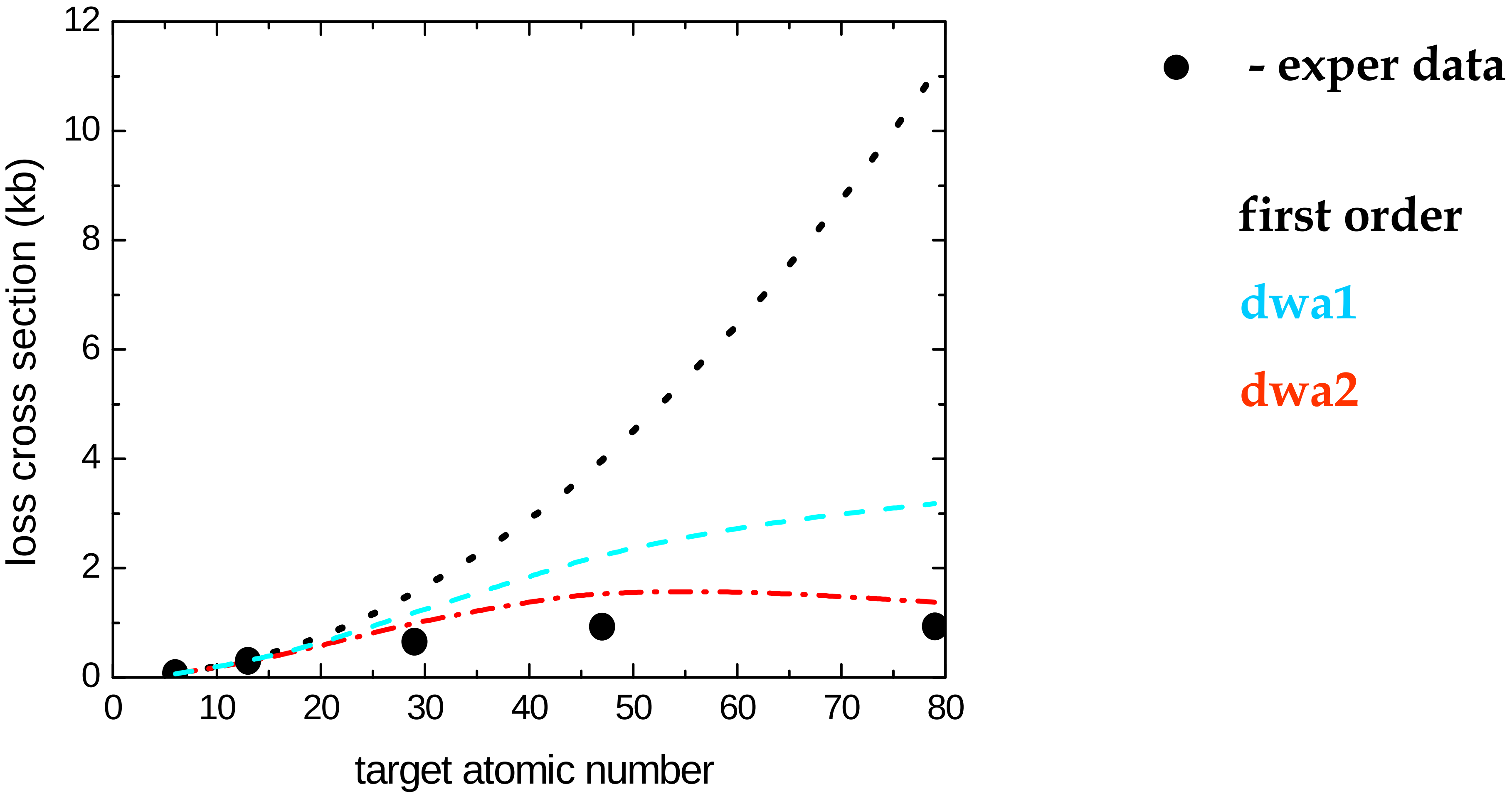
● - exper data

first order

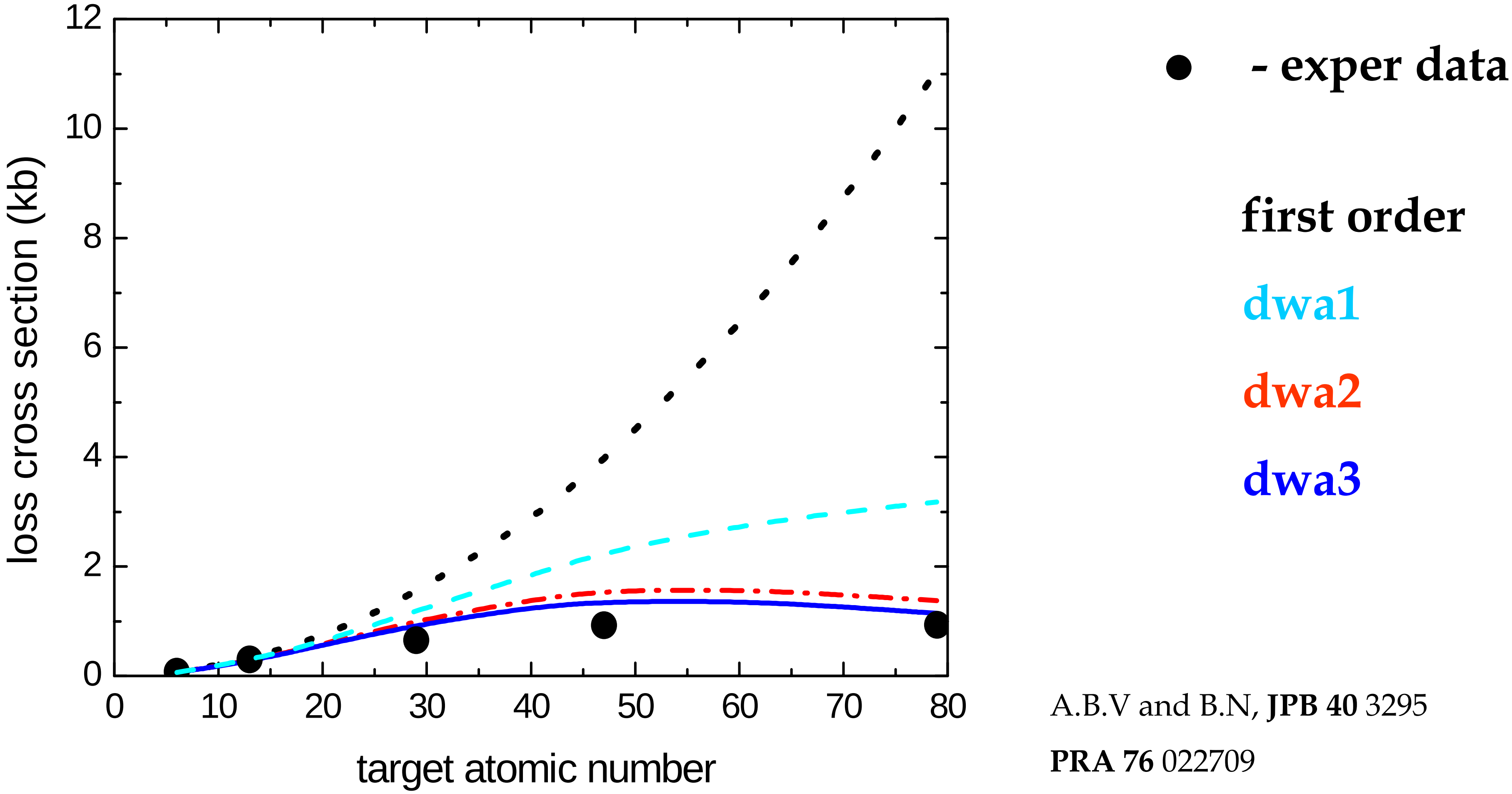
105 MeV/u $U^{90+}(1s^2)$+target → $U^{91+}(1s)+e^- + \ldots$



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



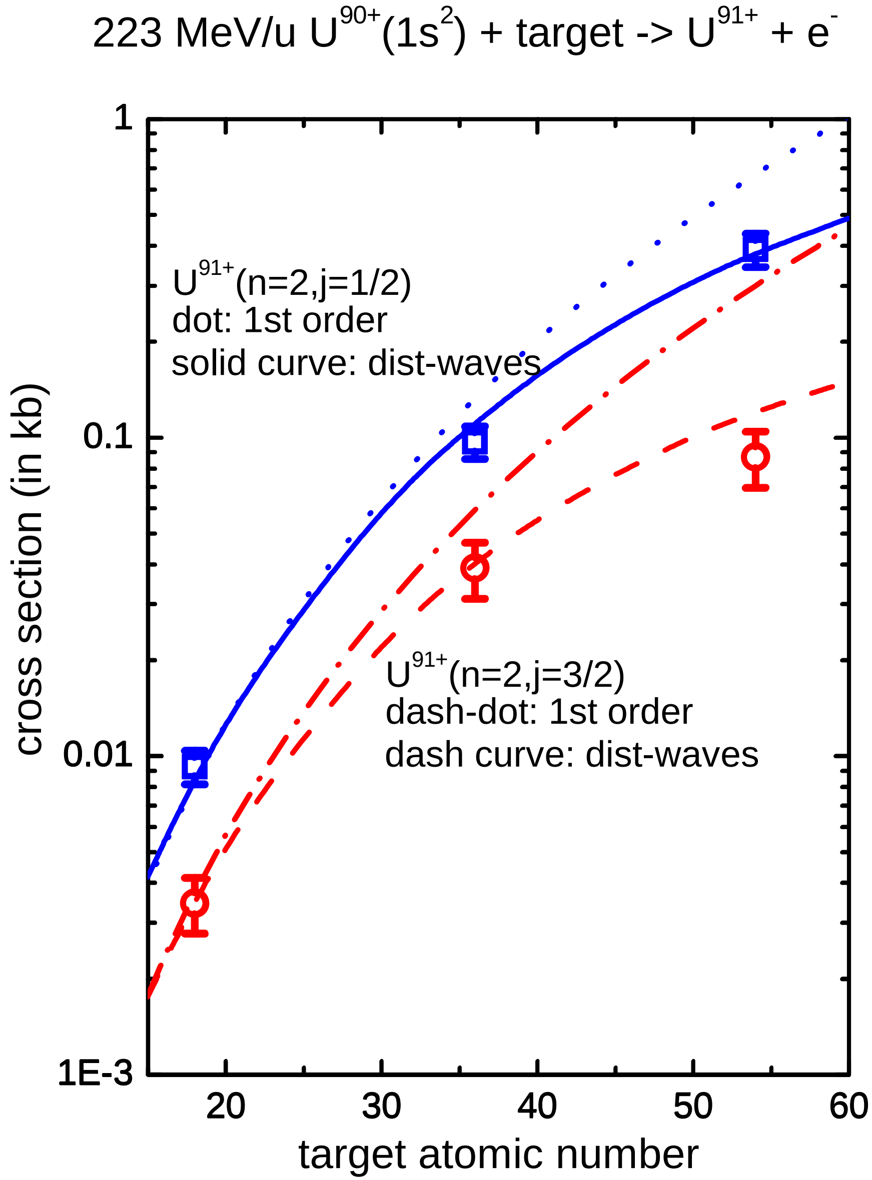
105 MeV/u $U^{90+}(1s^2)$+target $U^{91+}(1s)+e^-$ +…



A.B.V and B.N, **JPB 40** 3295

PRA 76 022709

Simulaneous loss-excitation



Experiment:

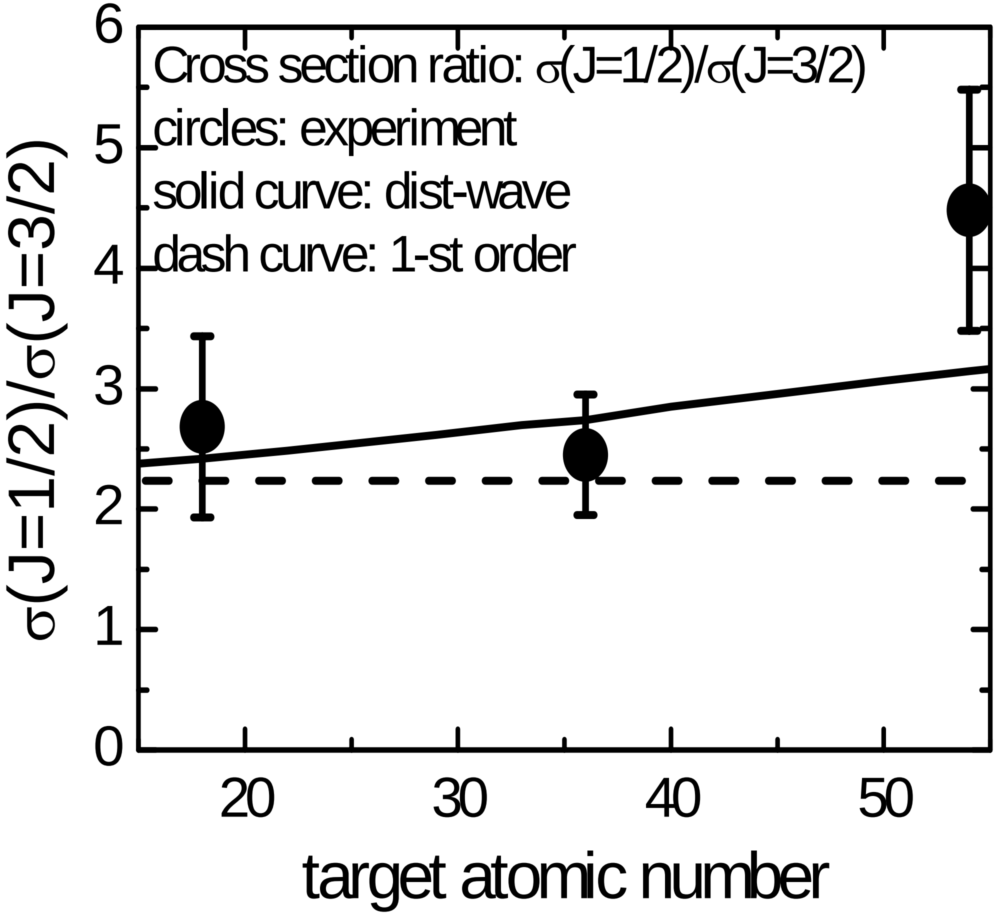
T.Ludziejewsky et al

PRA 61 052706

Calculations: B.Najjari and ABV

JPB 41 115202

223 MeV/u $U^{90+}(1s^2)$ + target -> $U^{91+} + e^-$



Experiment:

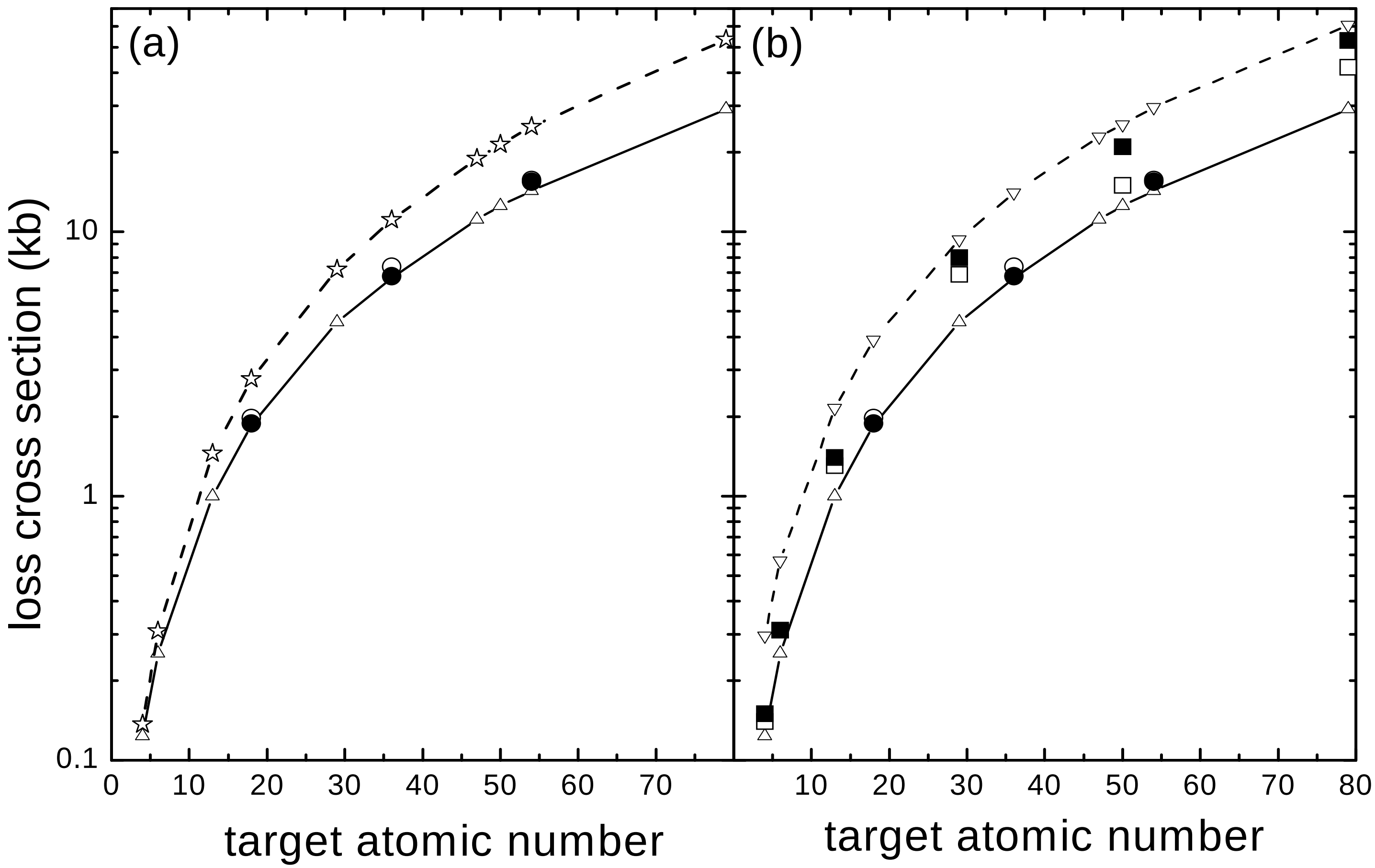
T.Ludziejewsky et al

PRA 61 052706

Calculations: B.Najjari and ABV

JPB 41 115202

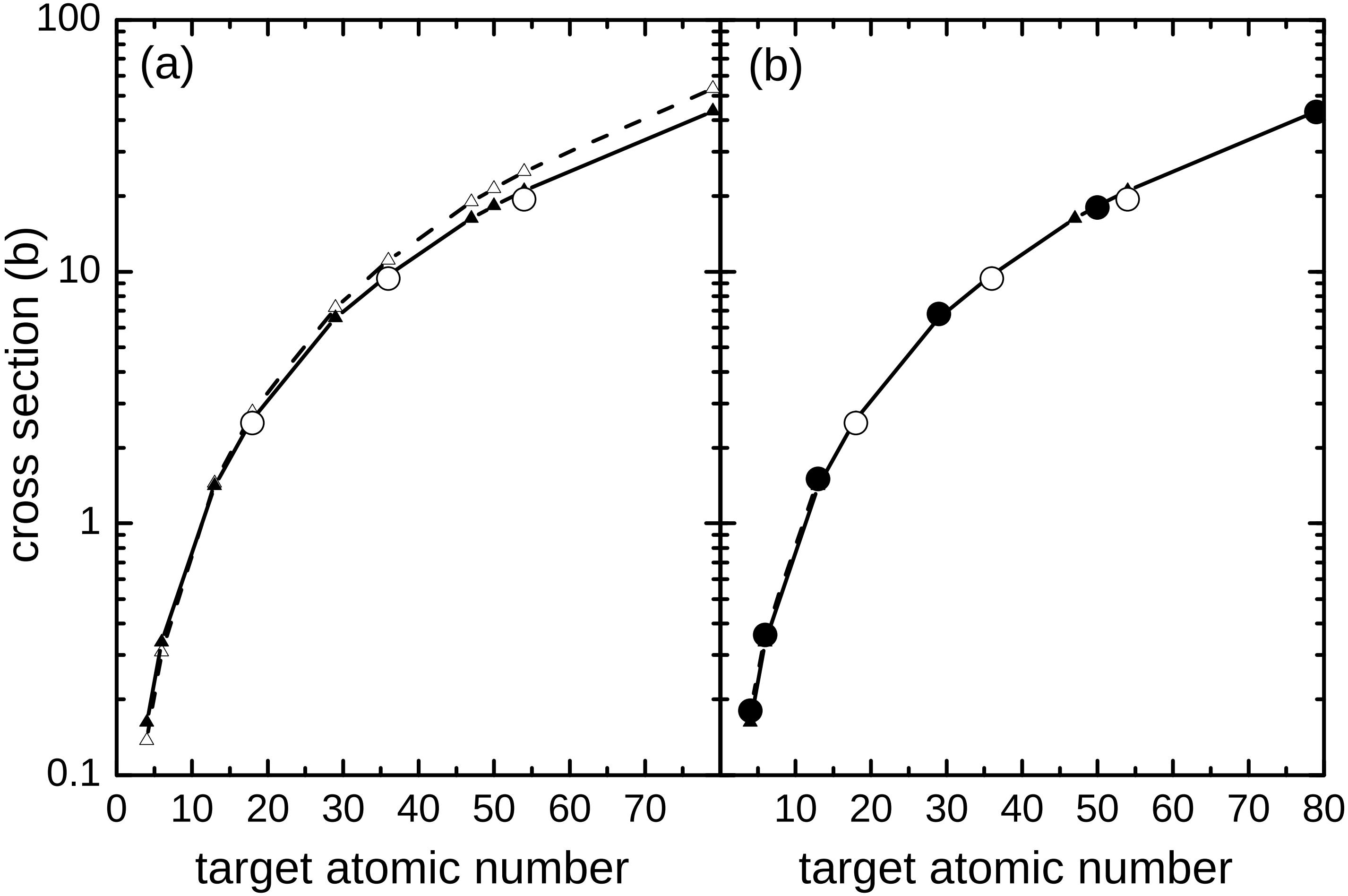
Extreme-relativistic collisions: electron loss from 33 TeV Pb^{81+}(1s).



(a) Circles: experimental data (Krauze et al, 2001) on the electron loss in gas targets (Z_A=18, 36, 54) where the open and solid symbols refer to the 'ionization' and 'capture' experimental scenarios, respectively. Up triangles and stars connected by guiding lines are theory results for collisions wíth neutral atoms and bare atomic nuclei, respectively (Z_A=4, 6, 13, 18, 29, 36, 47, 50, 54 and 79).

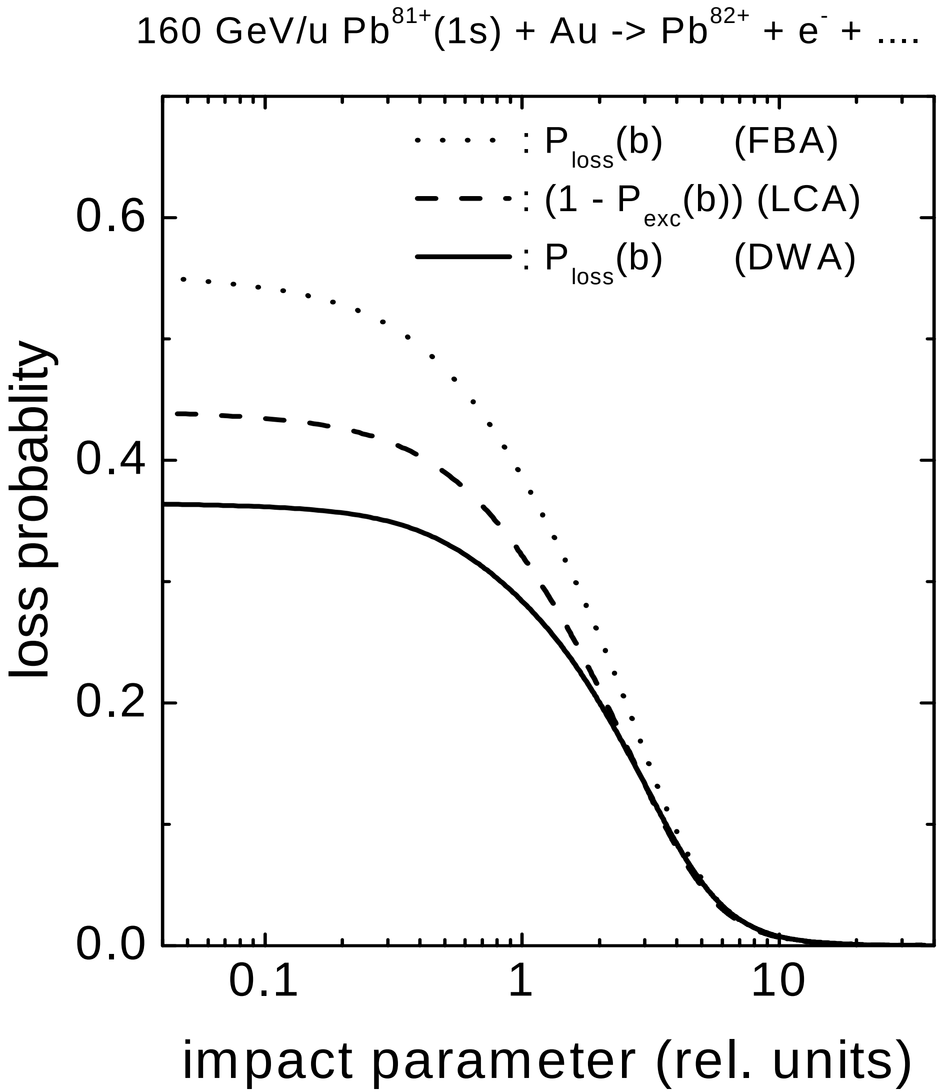
(b) Circles and up triangles: same as in the part (a) of the figure. Squares show the experimental data (Krauze et al, 1998) on the electron loss in solid state targets (Z_A=4, 6, 13, 29, 50 and 79). Down triangles connected by guiding dash line display theoretical results of Anholt and Becker.

Extreme-relativistic collisions: pair production with capture by incident 33 TeV Pb^{82+}.



(a) Open circles are experimental data from Krause et al 2001 for collisions with Ar, Kr and Xe gas targets. Solid triangles connected by solid curve are results of our calculations for collisions with atoms having atomic numbers Z_A=4, 6, 13, 18, 29, 36, 47, 50, 54 and 79. Open triangles connected by dash curve are our results for the pair production in collisions with the bare atomic nuclei. The curves are just to guide the eye.

(b) Open circles and solid triangles connected by solid curve represent the same results as in (a). Solid circles are data from Krause et al 1998 obtained for collisions with solid state targets (Be, C, Al, Cu, Sn and Au).



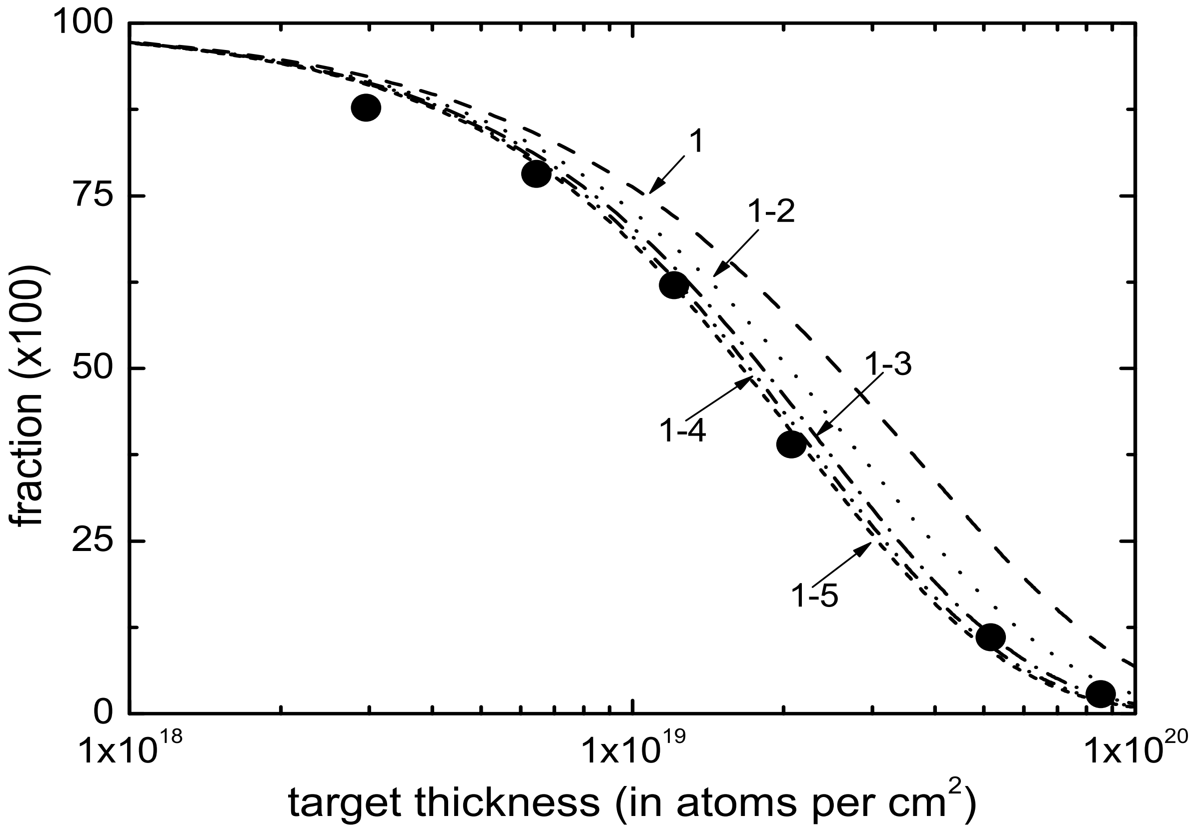
The difference between the dash and solid curves is due to the pair production with capture.

Charge states of 33 TeV Pb projectiles penetrating solids

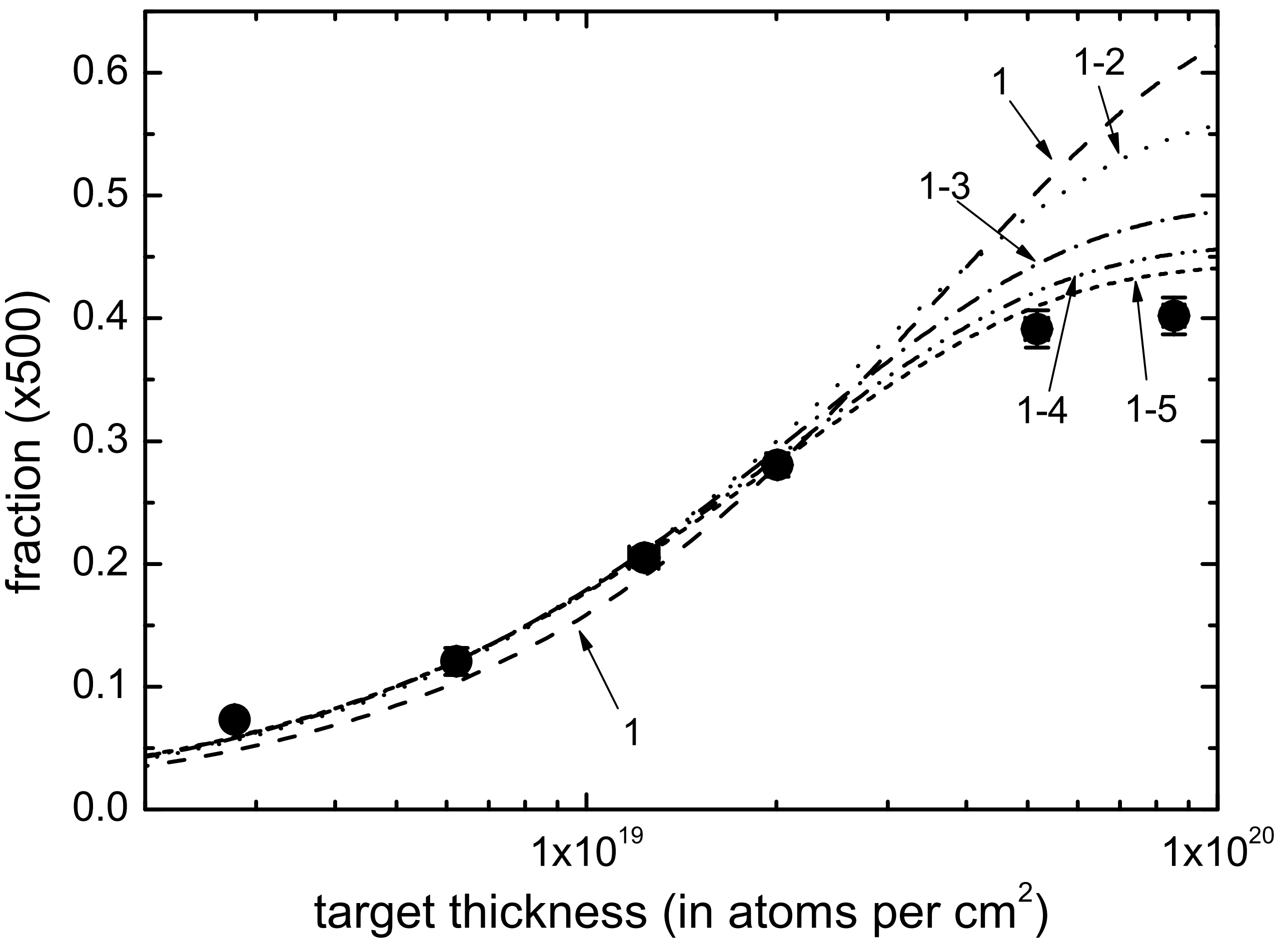
Two-step consideration.

a). The basis of the consideration is represented by calculations of cross sections for: (i) the projectile-electron excitation/de-excitation and loss, (ii) bound-free pair production, (iii) kinematic and radiative capture. Besides, we also calculate rates for the spontaneous decay of excited hydrogen-like lead ions to all possible internal states with lower energies.

b). These cross sections and rates are used to solve the kinetic equations describing the population of the internal states of the ions inside the foil.



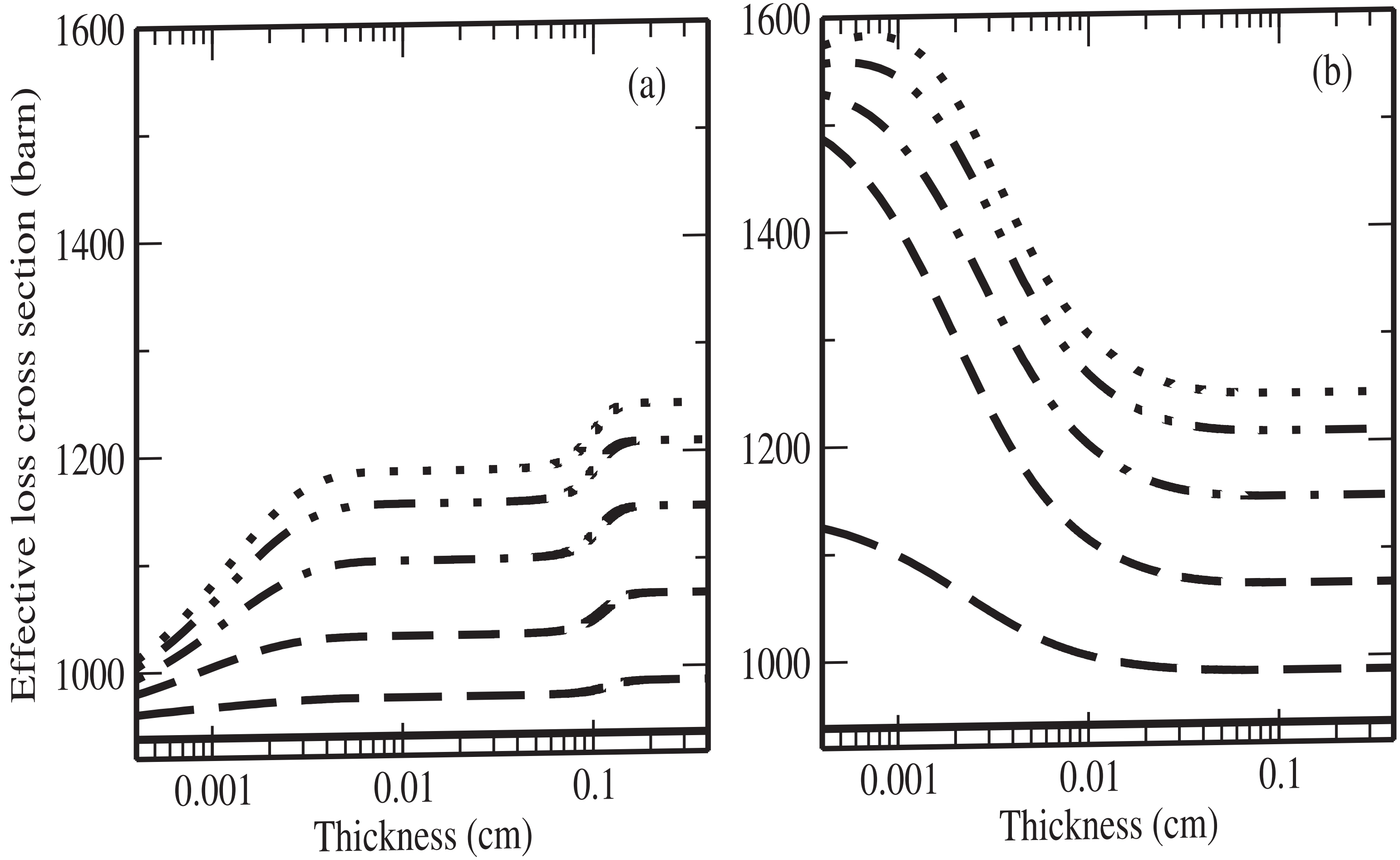
The fraction of hydrogen-like ions given as a function of the target thickness for 33 TeV Pb^{81+}(1s) projectiles incident on a gold foil. The different curves correspond to taking into account different numbers of bound states in the theoretical analysis. Dash curve: only states with the principal quantum number n=1 are included. Dot curve: the states with n=1 and n=2 are included. Dash-dot curve: states with n=1-3 are included. Dash-dot-dot curve: states with n=1-4 are included. Short-dash curve: states with n=1-5 are included. Circles: experimental data from Krause et al, **PRL 80** 1190 . Calculation: ABV, B.Najjari and A.Surzhykov, **JPB 41** 111001



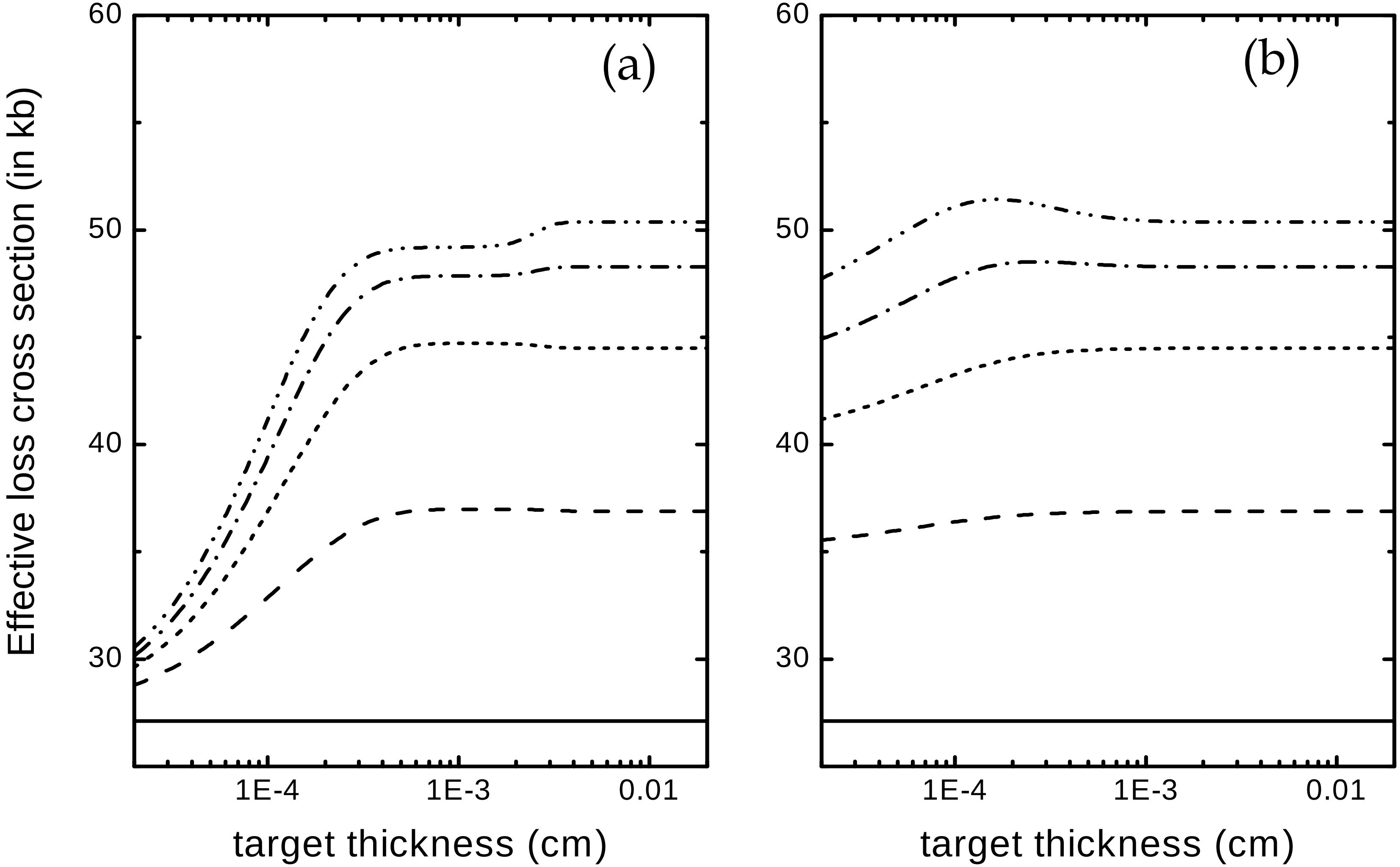
Same as in the previous figure but for the case of incident 33 Pb^{82+} bare nuclei.

Circles: experimental data from Krause et al, **PRL 80** 1190 .

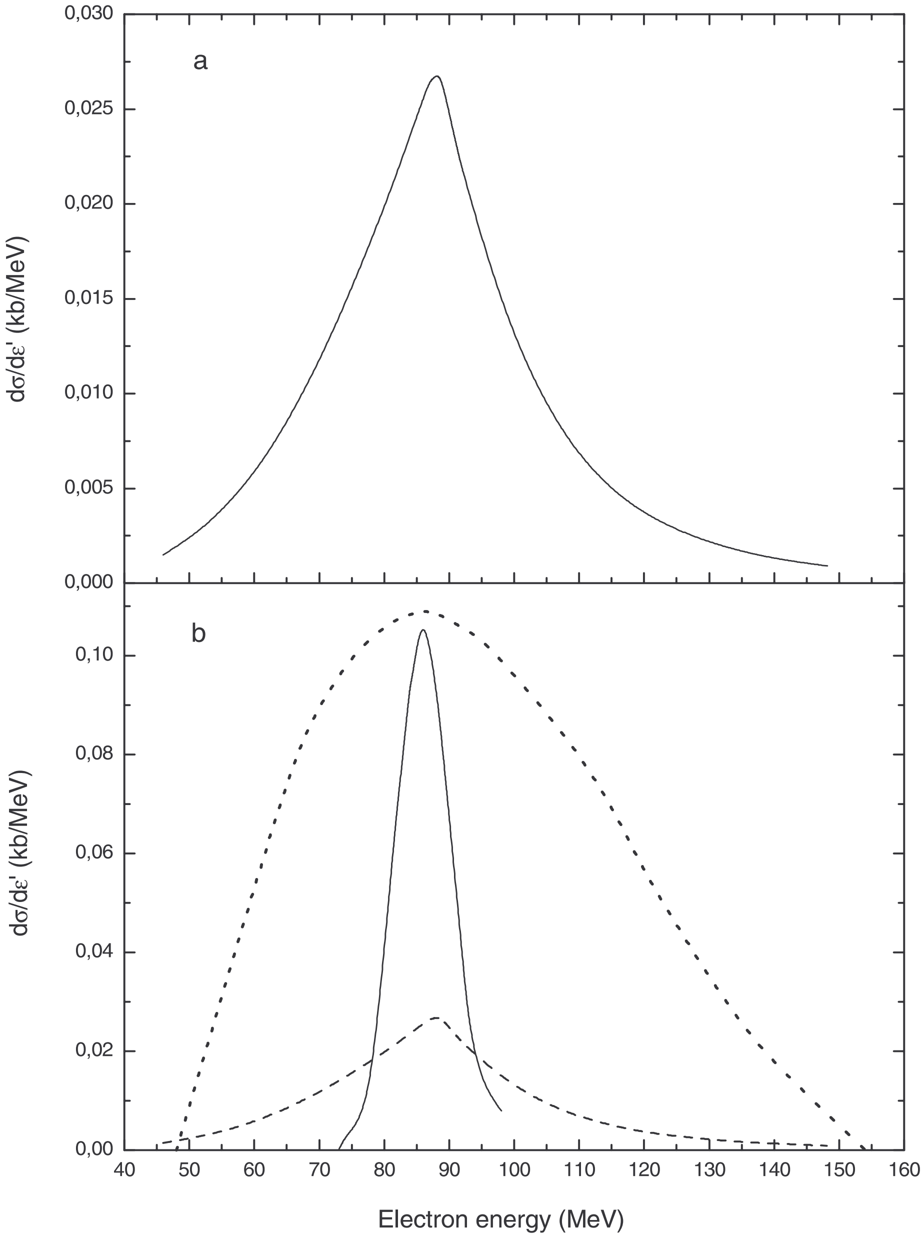
Calculation: ABV, B.Najjari and A.Surzhykov, **JPB 41** 111001



The effective cross section for the electron loss from 33 TeV lead projectiles penetrating an aluminum foil: (a) incident Pb^{81+}(1s) ions; (b) incident Pb^{82+} ions. The cross section is given as a function of the foil thickness. The different curves correspond to taking into account different numbers of bound states in the analysis. Solid curve: bound states with n=1. Dash curve: n=1 and n=2. Short dash curve: n=1-3. Dash dot curve: n=1-4. Dash dot dot curve: n=1-5.Dot curve: n=1-6. (ABV, B.Najjari and A.Surzhykov, **JPB 41** 111001)



Same as in the previous figure but for 33 TeV lead projectiles penetrating a gold foil. (ABV, B.Najjari and A.Surzhykov, **JPB 41** 111001)



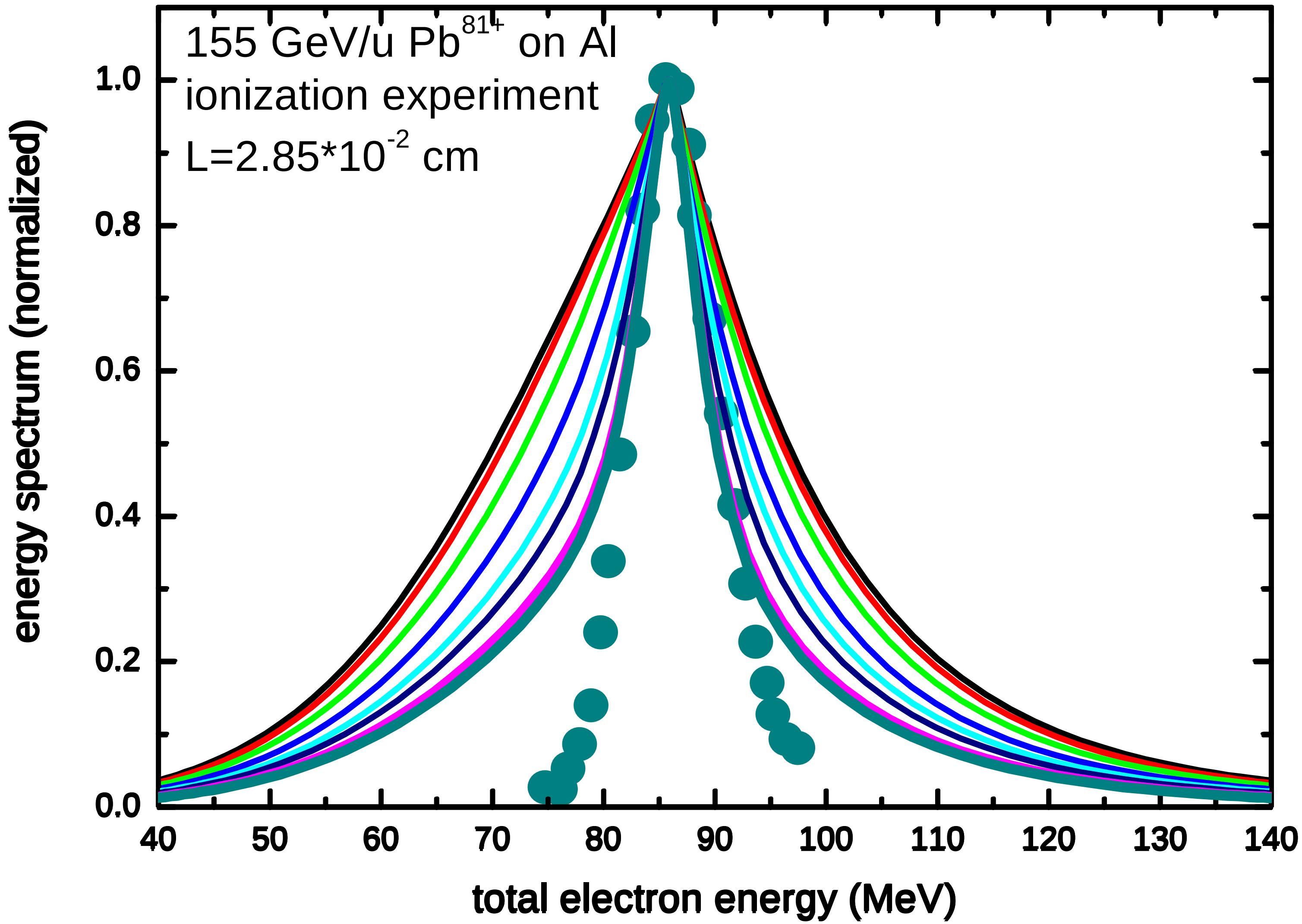
Cross section differential in energy for the electron loss from 33 TeV Pb^{81+}(1s) colliding with Al atoms. The cross section is given in the laboratory frame.

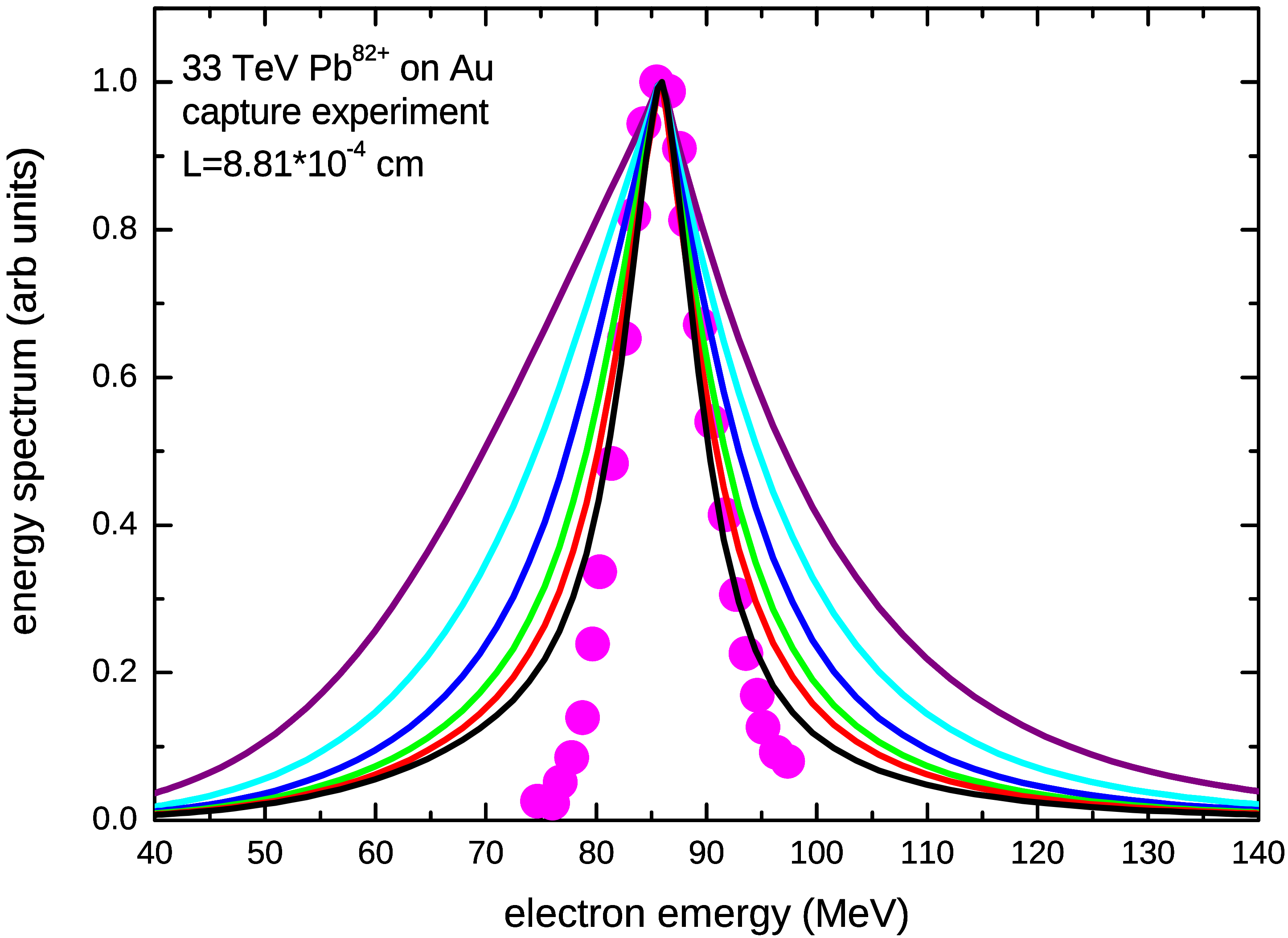
a) Calculations by ABV and N.Gruen (**JPB** 2001).

b) Full curve: experimental results of Vane et al (2000) for collisions with Al solid target. Dashed curve: same as in (a); dotted curve: the Compton profile of Pb^{81+}(1s) mapped into the laboratory frame (Vane et al 2000).

Experiment: Vane et al, ICPEAC Proceedings, APS 1999

Calculation: B.Najjari,A.Surzhykov, ABV, **PRA77** 042714

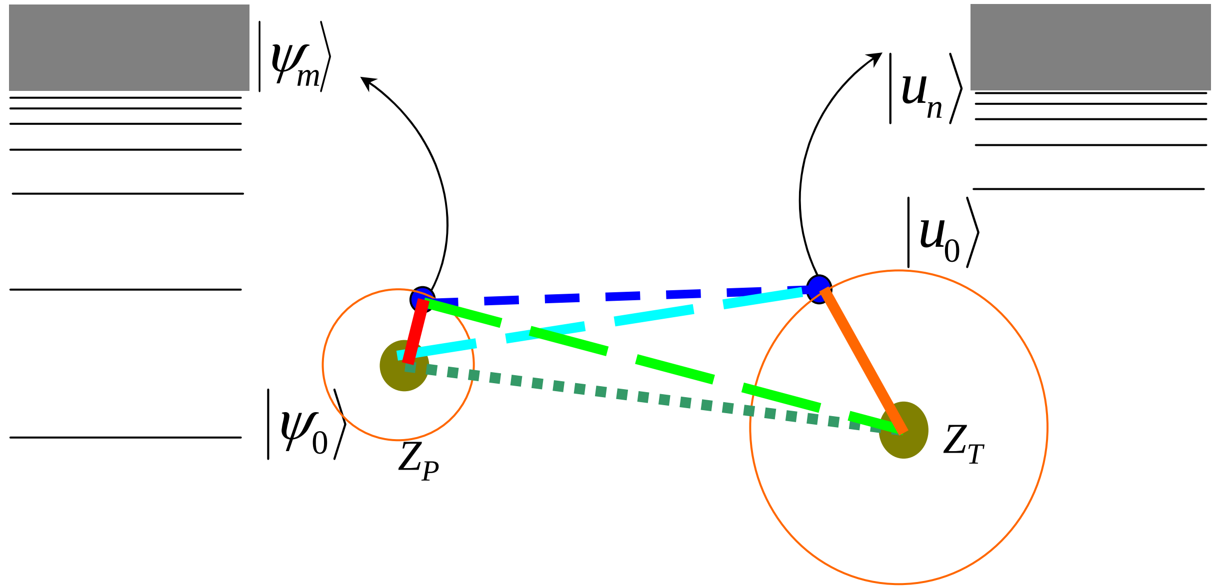


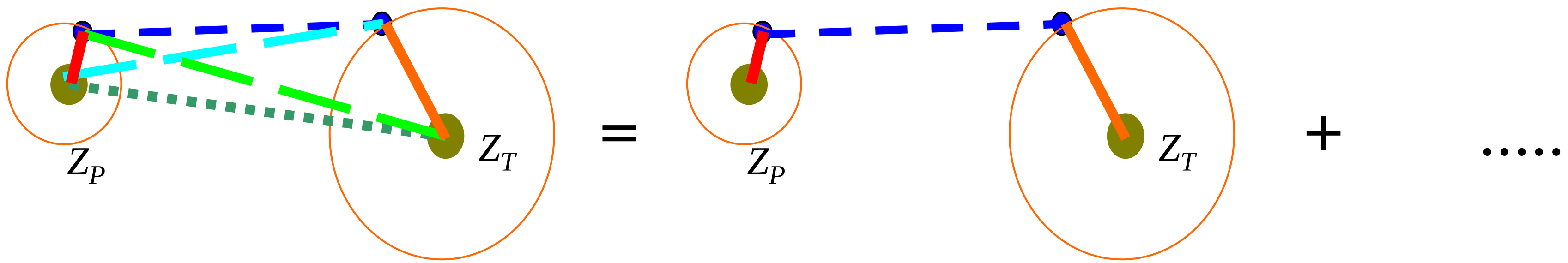


Experiment: Vane et al, ICPEAC-1999 Proceedings, APS 2000

Calculation: B.Najjari,A.Surzhykov and ABV, **PRA77** 042714

More detailed studies of ion-atom collisions



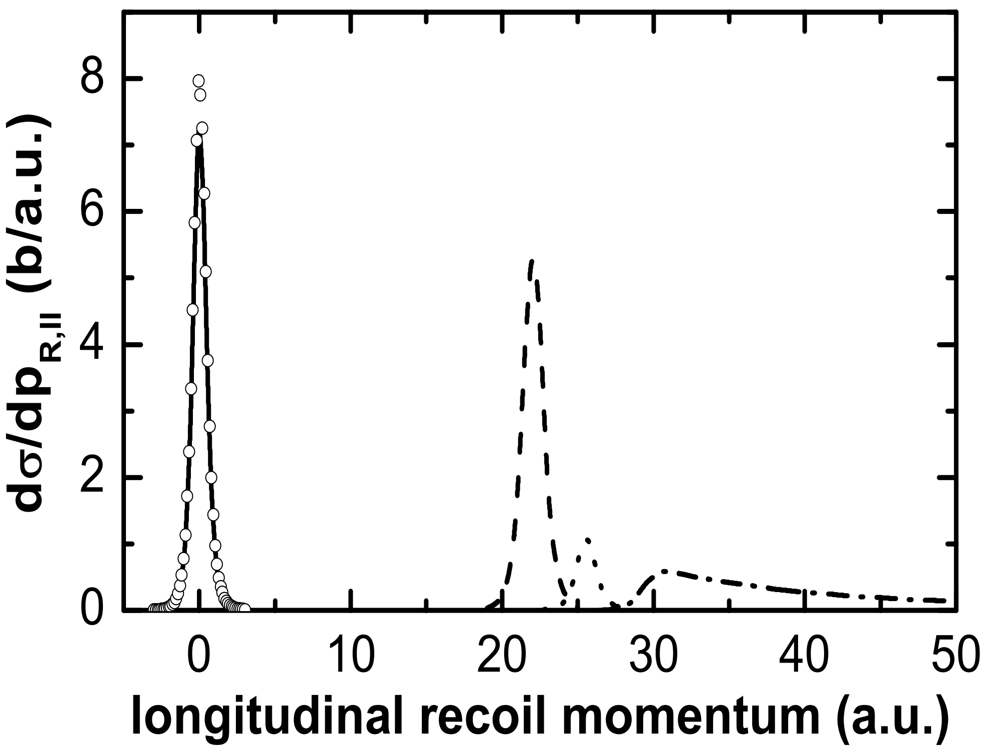


first order term

higher order terms

Longitudinal momentum spectrum of H^+ recoil ions produced in

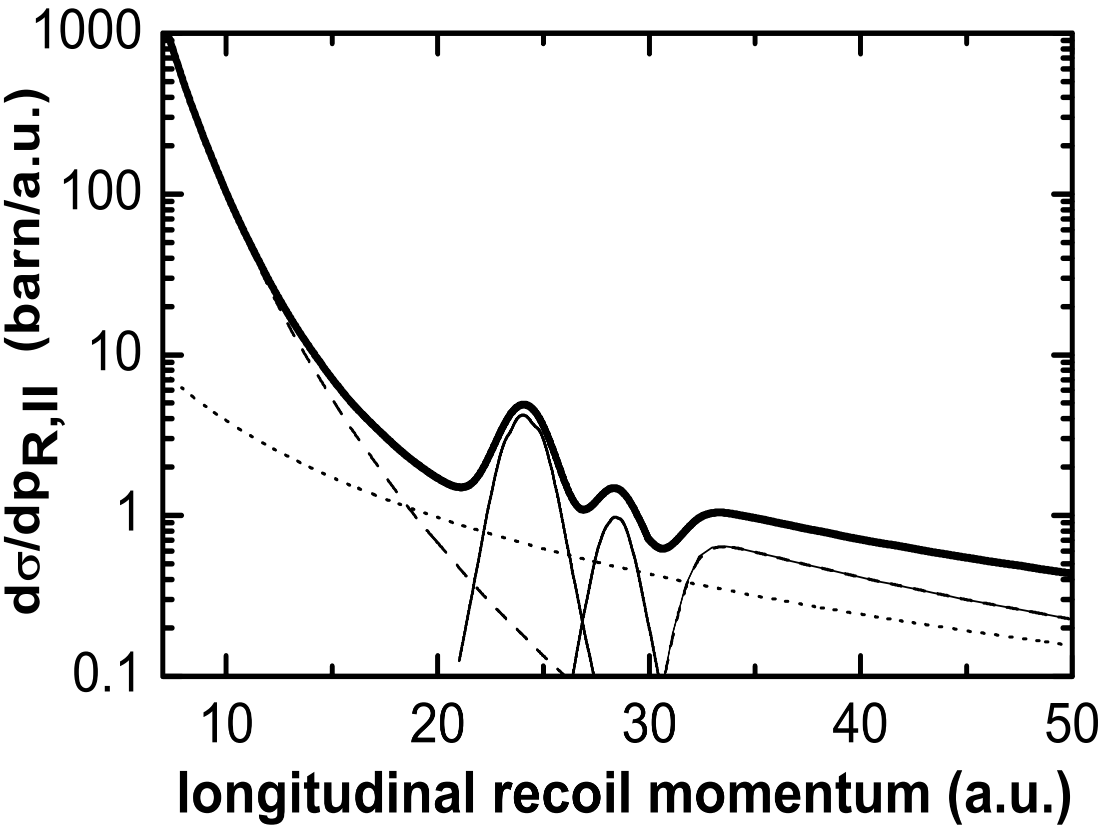
100 MeV/u Ne^{59+}(1s)+H(1s) -> Ne^{59+}(n=2,3 and continuum)+…. collisions.



ABV, B.Najjari and J.Ullrich,

PRL 99 193201

The longitudinal momentum spectrum of He^{+} recoils produced in 430 MeV/u $Th^{89+}(1s)+He(1s^2)$ collisions.



ABV, B.Najjari and J.Ullrich, **PRL 99** 193201

Outlook

I. Projectile-electron transitions (without paying attention to what happens with the target)

Total and differential cross sections: studies of the influence of higher order effects and the role of atomic electrons (screening) in projectile-electron(s) transitions.

(i) Low impact energies (below 1 GeV/u): strong higher-order effects and weak screening.

(ii) High impact energies (ten(s) of GeV/u and higher): strong screening and weak higher-order effects.

(iii) **"Intermediate" impact energies (~ 1 – 15-30 GeV/u):** higher-order and screening effects may be of comparable importance.

II. More detailed studies (scrutinizing both the projectile and the target):

few-body quantum dynamics, higher-order effects, elastic and inelastic target modes, two-center dielectronic transitions, the interaction with the radiation field, e^- - e^+ pair production (as a particular case of projectile-electron transitions), kinematically complete studies, ….

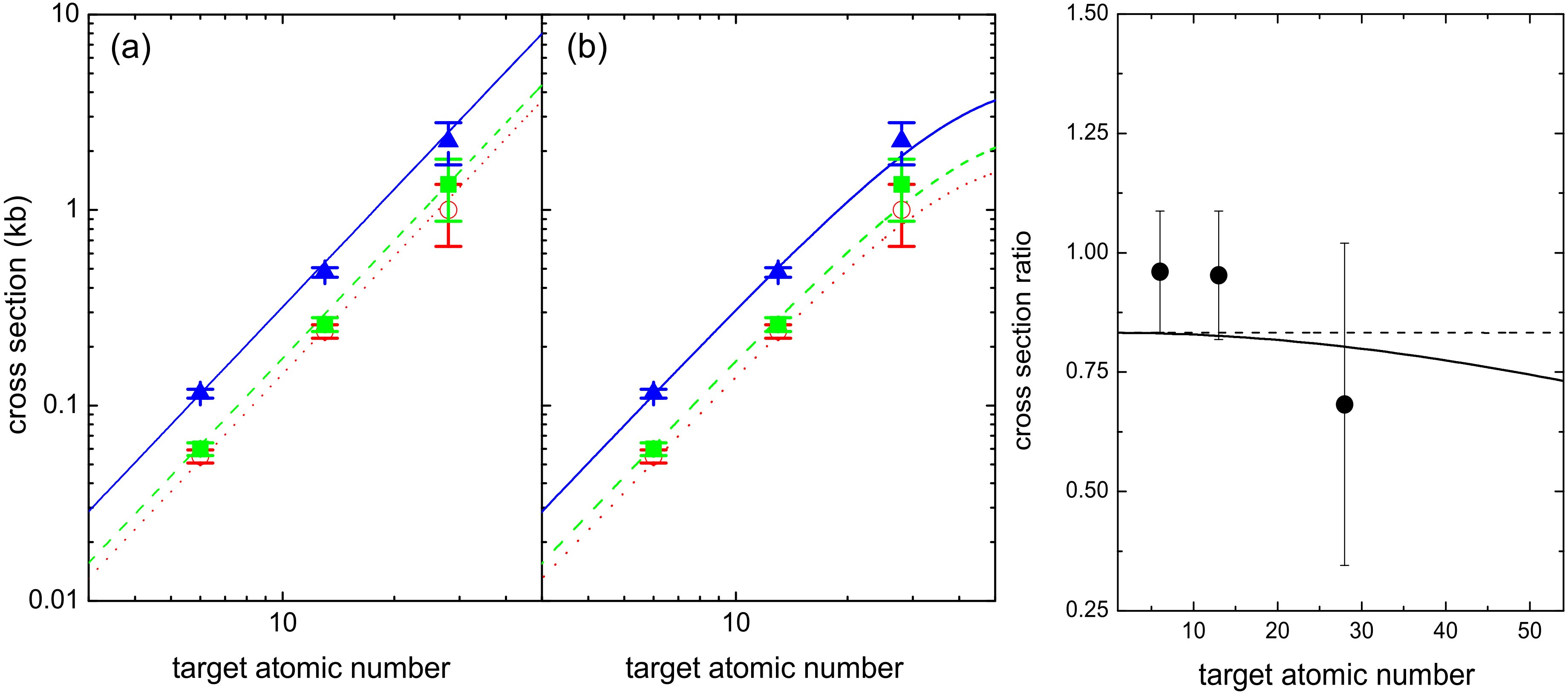
Collaboration:

B. Najjari (MPI-K, Heidelberg)

A. Surzhykov (Uni-Heidelberg)

J. Ullrich (MPI-K, Heidelberg)

119 Bi^{82+}(1s) + atomic target -> Bi^{82+}(n=2) + ……



Experimental data: T. Stöhlker et al, **PRA 57** 845

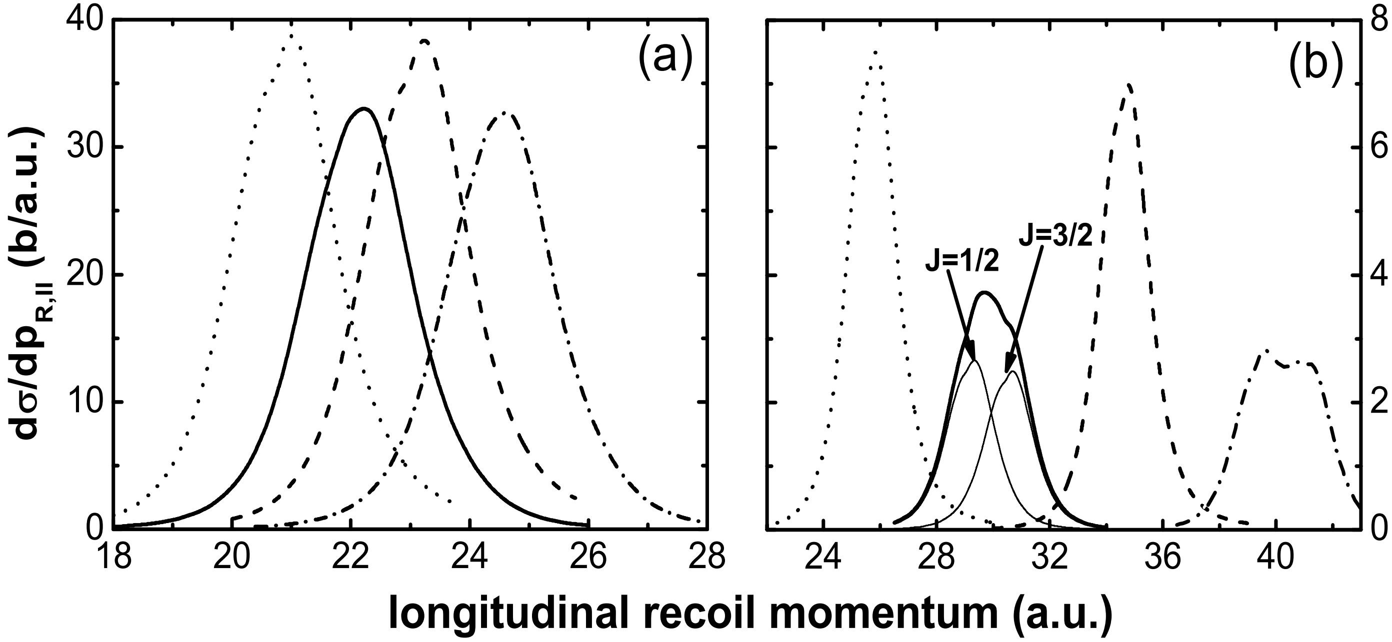
Calculations: (a) FBA; (b) DWA

(ABV et al, **PRA 75** 062716)

Longitudinal momentum spectrum of He^+ recoil ions produced in

(a) 100 MeV/u $Ne^{59+}(1s) + He(1s^2) \to Ne^{59+}(n=2)+He^+ + \ldots$ collisions

(b) 325 MeV/u $U^{91+}(1s) + He(1s^2) \to U^{91+}(n=2)+ He^+ + \ldots$ collisions.



ABV, B.Najjari and J.Ullrich,

PRL 99 193201

Summary

1. There is a good agreement between theoretical “atomic“ cross sections and experimental results obtained for gas targets.
2. There is a satisfactory agreement between the experiment involving solid targets and theory concerning the fraction of the hydrogen-like lead ions.
3. Because the effective loss cross section depends strongly on the target thickness and the initial conditions (“ionization“ or “capture“ scenario), the data reported by Krauze et al 1998 should be taken with reservation.
4. Certain progress has been achieved in the understanding of the form of the electron spectra emitted when 33 TeV lead ions penetrate thin foils. However, in order to a really satisfactory understanding of them, more theoretical (and perhaps experimental) work is needed.
5. Repetition of the CERN experiment seems to be unlikely. One could think about the “scaling“ of its parameters to those which, while yielding similar physics, would be accessible at the future GSI.

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:

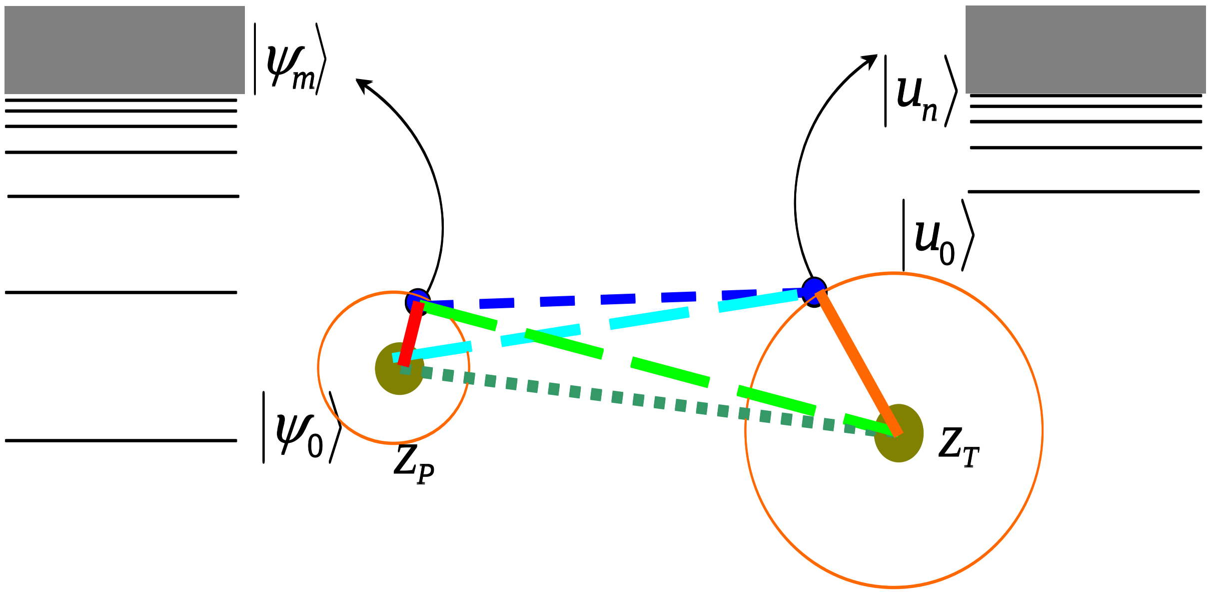
spectra of emitted electrons, target recoil ions, etc (collision dynamics resolved as fully as possible)

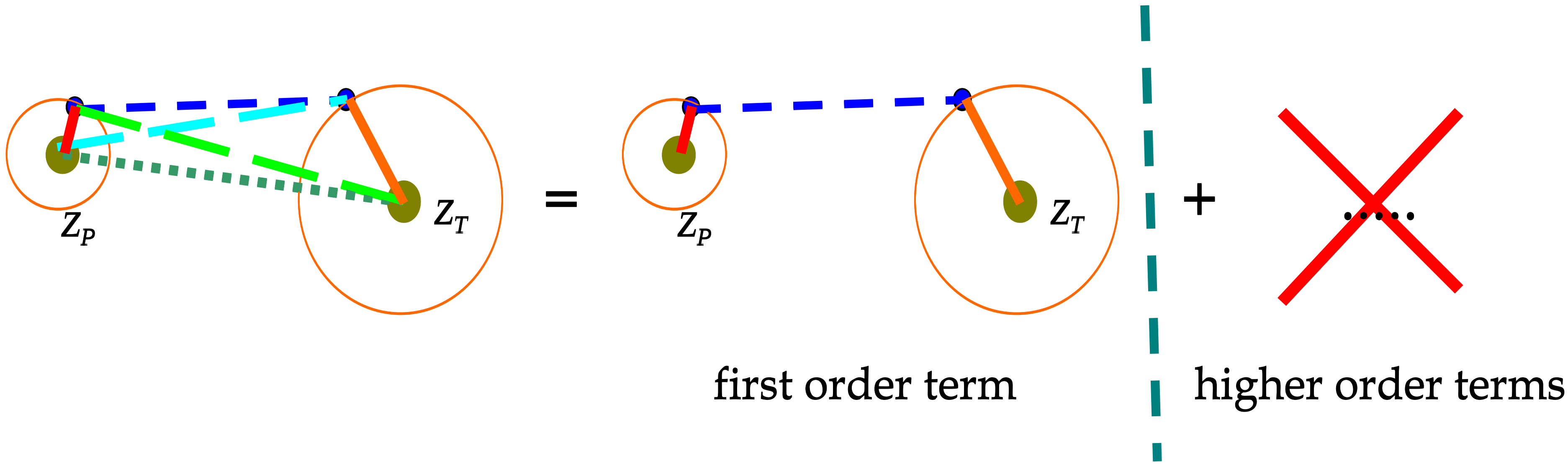
3. Projectile-electron excitation and loss at low-relativistic impact energies (below 1 GeV/u) in collisions with atoms having large atomic numbers .

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.

More detailed studies of ion-atom collisions





Rate equations for the populations

$$\frac{dP_0}{dt} = -\frac{P_0}{\tau^{capt}} + \sum_{j=1}^{N_{max}} \frac{P_j}{\tau_j^{loss}},$$

$$\frac{dP_j}{dt} = \frac{P_0}{\tau_j^{capt}} - \frac{P_j}{\tau_j^{loss}} - P_j \sum_{i=1}^{i\leq j} \frac{1}{\tau_{j\to i}^{sp}}$$

$$-P_j \sum_{i=1(i\neq j)}^{N_{max}} \frac{1}{\tau_{j\to i}} + \sum_{i=1(i\neq j)}^{N_{max}} \frac{P_i}{\tau_{i\to j}}.$$

where, for instance,

$$\tau_j^{capt} = \frac{1}{n_a v \sigma_j^{capt}}; \tau_j^{loss} = \frac{1}{n_a v \sigma_j^{loss}}$$

The system of the rate equations can formally be reduced just to two equations:

$$\frac{dP_0}{dt} = -\frac{P_0}{\tau^{capt}} + \frac{P_h}{\tau_{eff}^{loss}}$$

$$\frac{dP_h}{dt} = \frac{P_0}{\tau^{capt}} - \frac{P_h}{\tau_{eff}^{loss}}.$$

Here, $P_h = \sum_{j=1}^{N_{\max}} P_j$ is the total population of the hydrogen-like ions,

$\tau_{eff}^{loss} = \frac{1}{n_a \sigma_{eff}^{loss} v}$ and $\sigma_{eff}^{loss} = \frac{\sum_{j=1}^{N_{\max}} P_j \sigma_j^{loss}}{\sum_{j=1}^{N_{\max}} P_j \sigma_j^{loss}}$ is the effective loss cross section.

The model includes the following three steps.

1. Calculations of spontaneous decay rates and cross sections for excitation/de-excitation, loss and capture (kinematic, radiative and via pair production);

2. Solving the rate equations for the populations and calculating the ‘preliminary‘ electron emission spectrum.

3. Consideration of the propagation of the emitted electrons inside the foils.

2. Rate equations

$$\frac{dP_0}{dt} = -\frac{P_0}{\tau^{capt}} + \sum_{j=1}^{N_{\max}} \frac{P_j}{\tau_j^{loss}}$$

$$\frac{dP_j}{dt} = \frac{P_0}{\tau_j^{capt}} - \frac{P_j}{\tau_j^{loss}} - P_j \sum_{i=1}^{i\leq j} \frac{1}{\tau_{j\to i}^{sp}} - P_j \sum_{i=1(i\neq j)}^{N_{\max}} \frac{1}{\tau_{j\to i}} + \sum_{i=1(i\neq j)}^{N_{\max}} \frac{P_i}{\tau_{i\to j}}.$$

‘Preliminary‘ emission spectra

$$\frac{dn_e}{d\varepsilon_p} = n_a \sum_{j=1}^{N_{\max}} \frac{d\sigma_j^{loss}}{d\varepsilon_p} \int_0^L dz P_j(z)$$

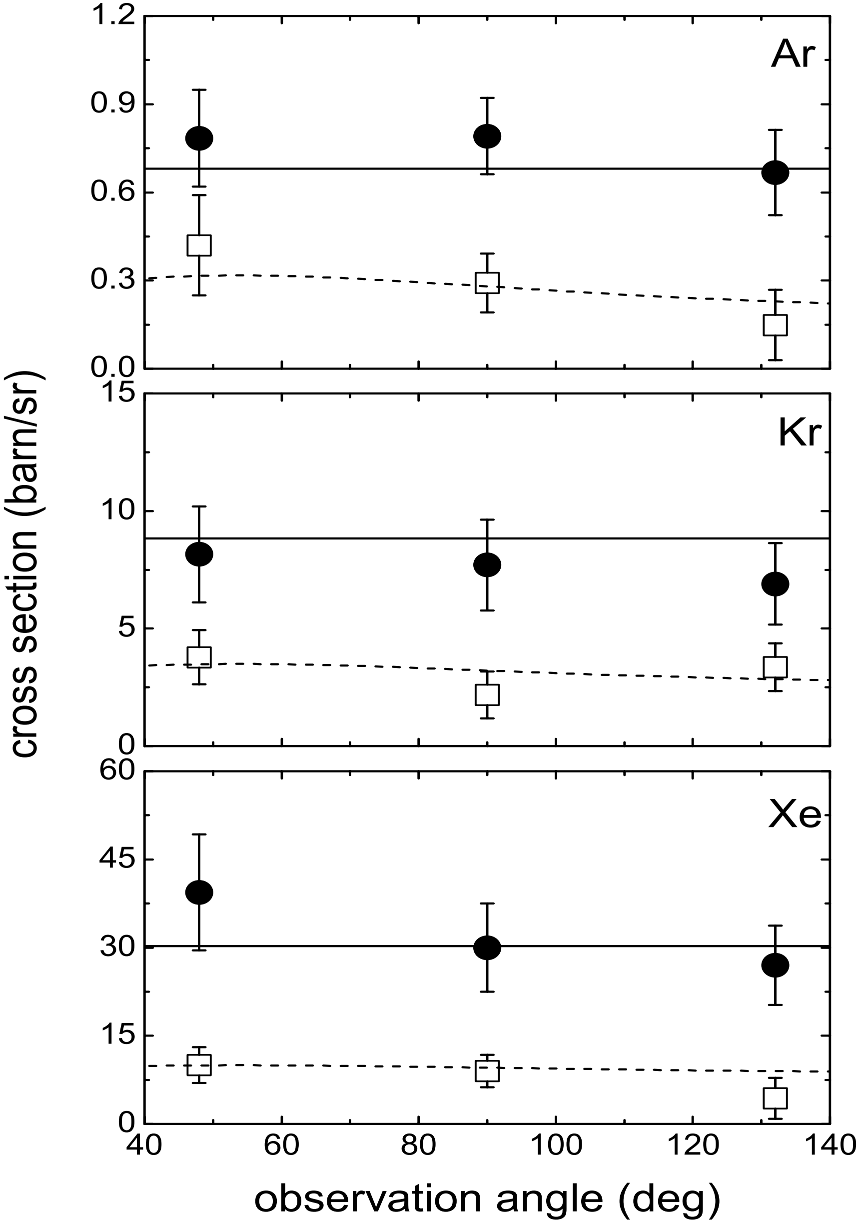
3. Propagation of the electrons inside the foil.

Energy losses:

(i) Energy transfer to ions and electrons of the foil;

(ii) Emission of the electromagnetic radiation (bremsstrahlung).

Spreading of the electron momentum distribution in the transverse direction.



cross section (barn/sr)
observation angle (deg)
Ar
Kr
Xe
1.2
0.9
0.6
0.3
0.0
15
10
5
0
60
45
30
15
0
40
60
80
100
120
140