Doubly Inelastic Collisions with Relativistic Heavy Ions and Target Recoil Momentum Spectroscopy

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Outline

- **Introduction**
- **Theoretical approaches**

  - First-Born Approximation: FBA

  - Eikonal Model: EA
- **Results**
- **Conclusions**

Introduction

- $\upsilon_p \ll c$, two point-like charges interact via the Coulomb law.

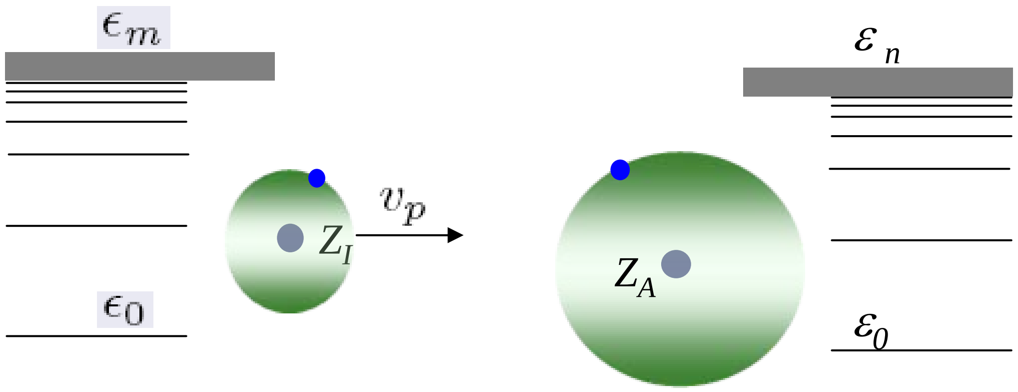
  Despite this law has a very simple form, it is **difficult** to get detailed understanding of the dynamics of atomic collisions involving **more than two** active particles;

- $\upsilon_p \sim c$, the form of the pair-wise EM interaction becomes more complicated.

  - Detailed description of relativistic collisions involving more than two active particles, represents a particularly **strong challenge for theory.**

  - Phenomena occurring in such collisions are **less understood compared to their nonrelativistic counterparts.**

Introduction



Singly inelastic collisions

- Target ionization

$$P^{(Z_I-1)+} + T \rightarrow P^{(Z_I-1)+} + T^+ + e$$

Doubly inelastic collisions

- Mutual P-excitation and T-ionization

$$P^{(Z_I-1)+} + T \rightarrow P^{(Z_I-1)*} + T^+ + e$$

- Mutual P-loss and T-ionization

$$P^{(Z_I-1)+} + T \rightarrow P^{Z_I+} + T^+ + 2\ e$$

Energy-momentum conservation

$$\mathbf{q}_A = (\mathbf{Q}, q^A_{min})$$

$$q^A_{min} = \frac{\varepsilon_n - \varepsilon_0}{v_p} + \frac{\epsilon_m - \epsilon_0}{\gamma v_p},$$

$$\mathbf{q}_I = (-\mathbf{Q}, -q^I_{min})$$

$$q^I_{min} = \frac{\varepsilon_n - \varepsilon_0}{\gamma v_p} + \frac{\epsilon_m - \epsilon_0}{v_p},$$

v_p : collision velocity,

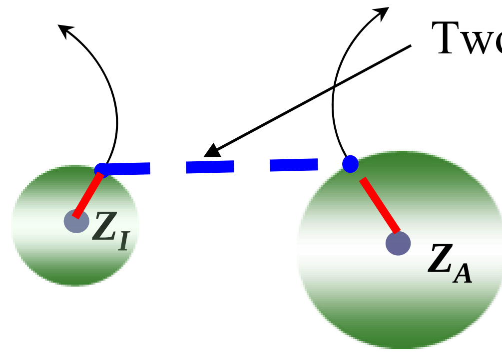
γ : collision Lorentz factor.

$$q^A_{min} = p_{R,||} + k_{||}$$

First-Born approximation

A.B.V. **PR 392**, 191 (2004)

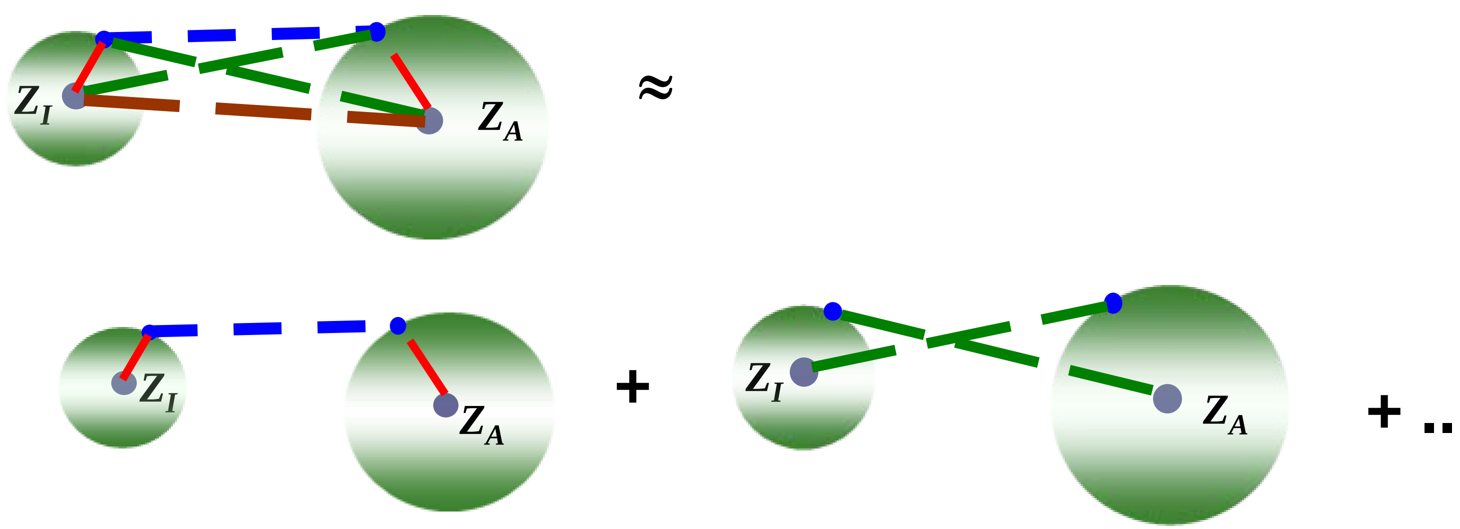
$Z_I / \upsilon_p \ll 1$



A.B.V. et al **PRL 92**, 213202 (2004)

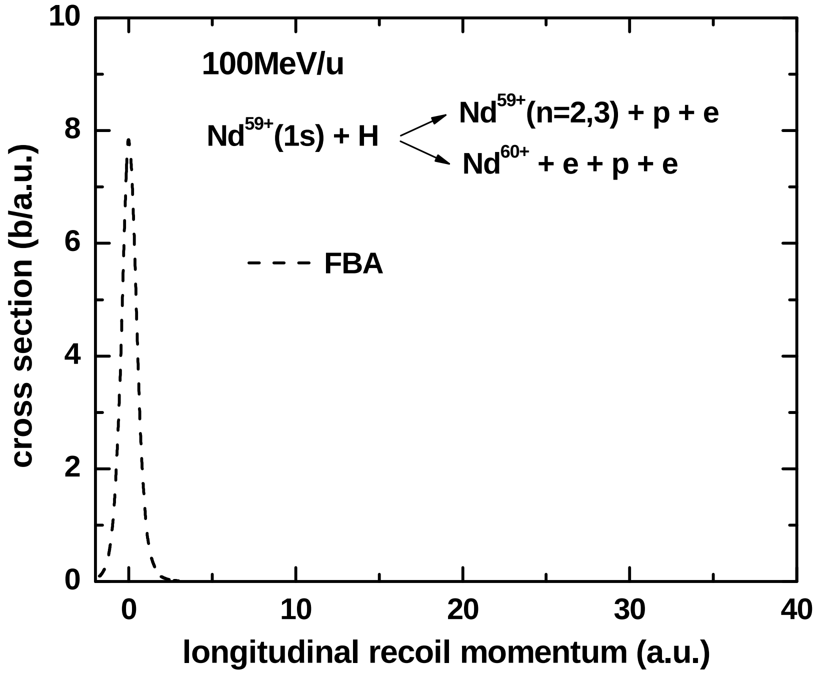
Eikonal model

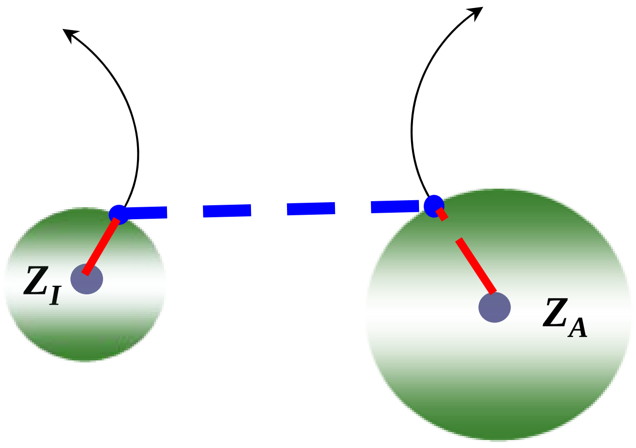
A.B.V. and B.N. **JPB 38**, 3587 and
A.B.V. **PRA 72**, 062705 (2005)



Results: Target-recoil momentum spectra

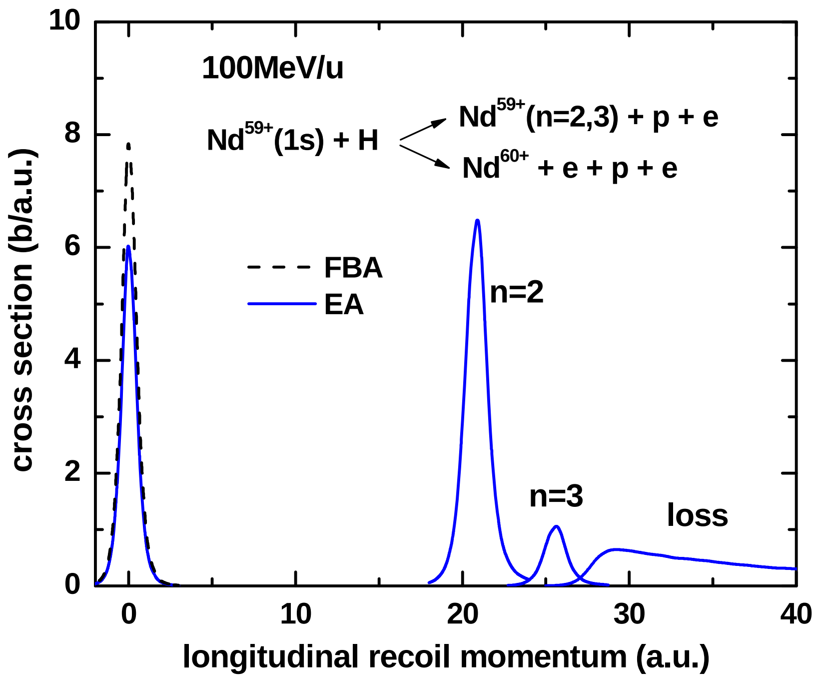
Doubly inelastic collisions

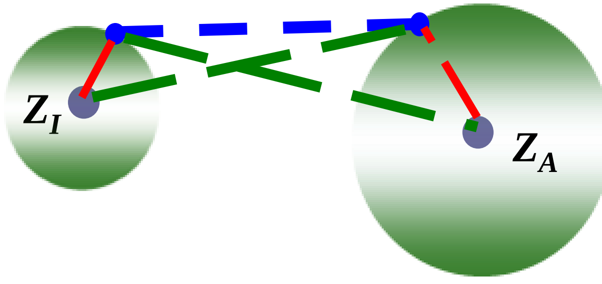




Results: Target-recoil momentum spectra

Doubly inelastic collisions

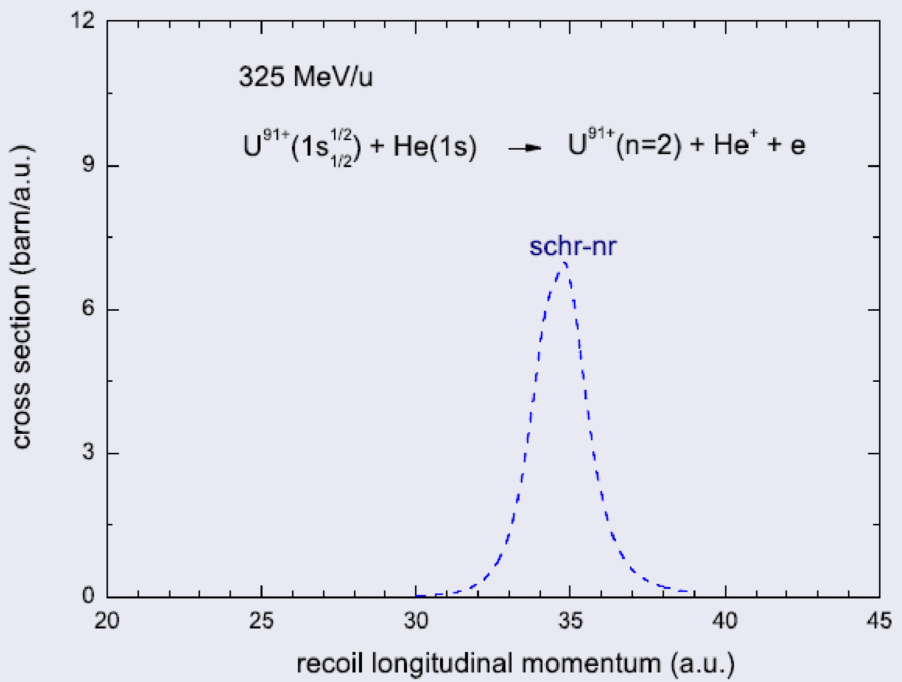




The peaks at large $p_{R,\parallel}$ represent clear signatures of the higher order effects.

Results: Target-recoil momentum spectra

Doubly inelastic collisions



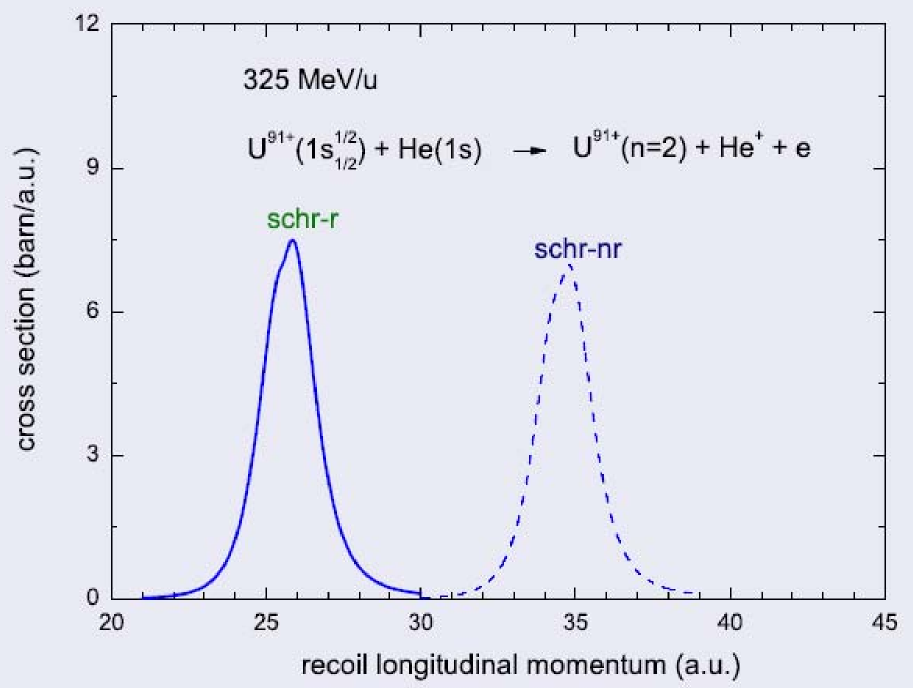
$$c \longrightarrow \infty$$

- in the treatment of the relative ion-atom motion;
- in the description of the internal electron states.

$$q^A_{min} = \frac{\varepsilon'_n - \varepsilon'_0}{v_p} + \frac{\epsilon'_m - \epsilon'_0}{v_p}$$

Results: Target-recoil momentum spectra

Doubly inelastic collisions



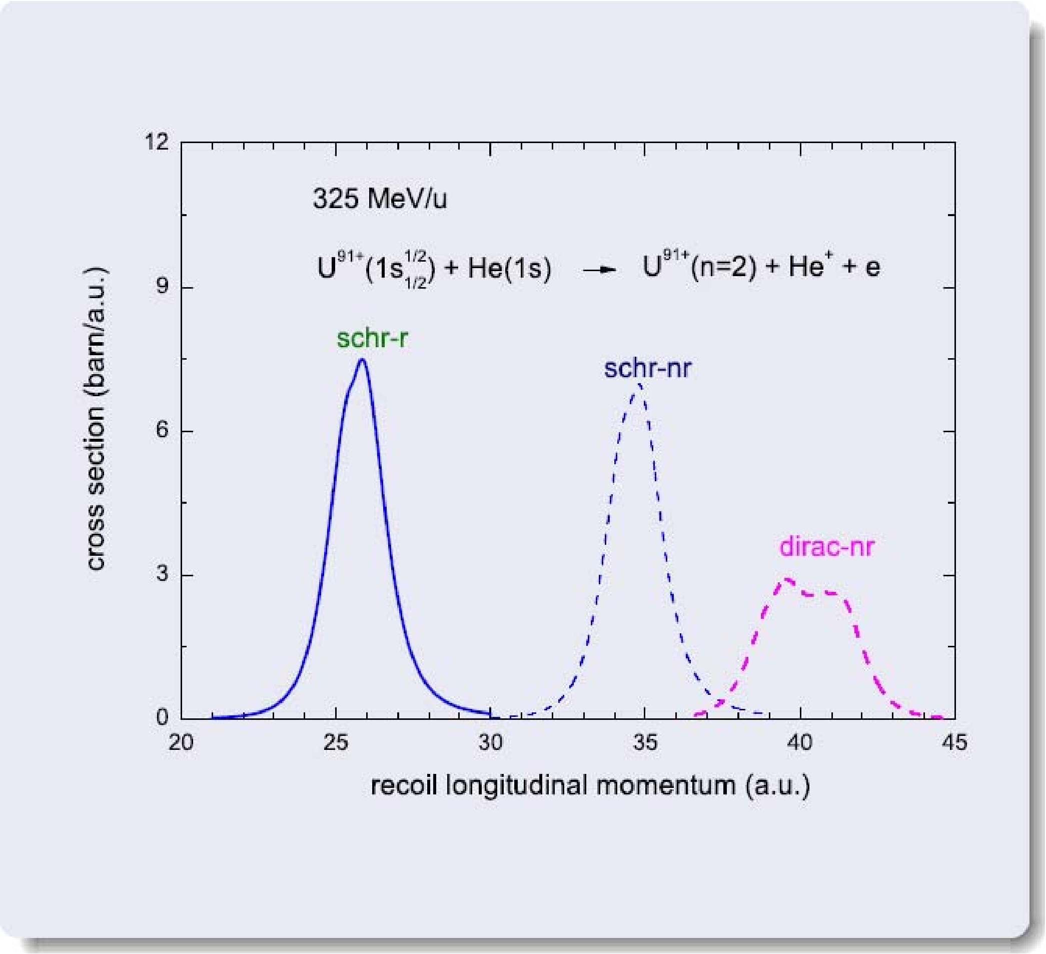
$$c \longrightarrow \infty$$

only in the description of the internal electron states.

$$q^A_{min} = \frac{\varepsilon'_n - \varepsilon'_0}{v_p} + \frac{\epsilon'_m - \epsilon'_0}{\gamma v_p}$$

Results: Target-recoil momentum spectra

Doubly inelastic collisions



$$c \longrightarrow \infty$$

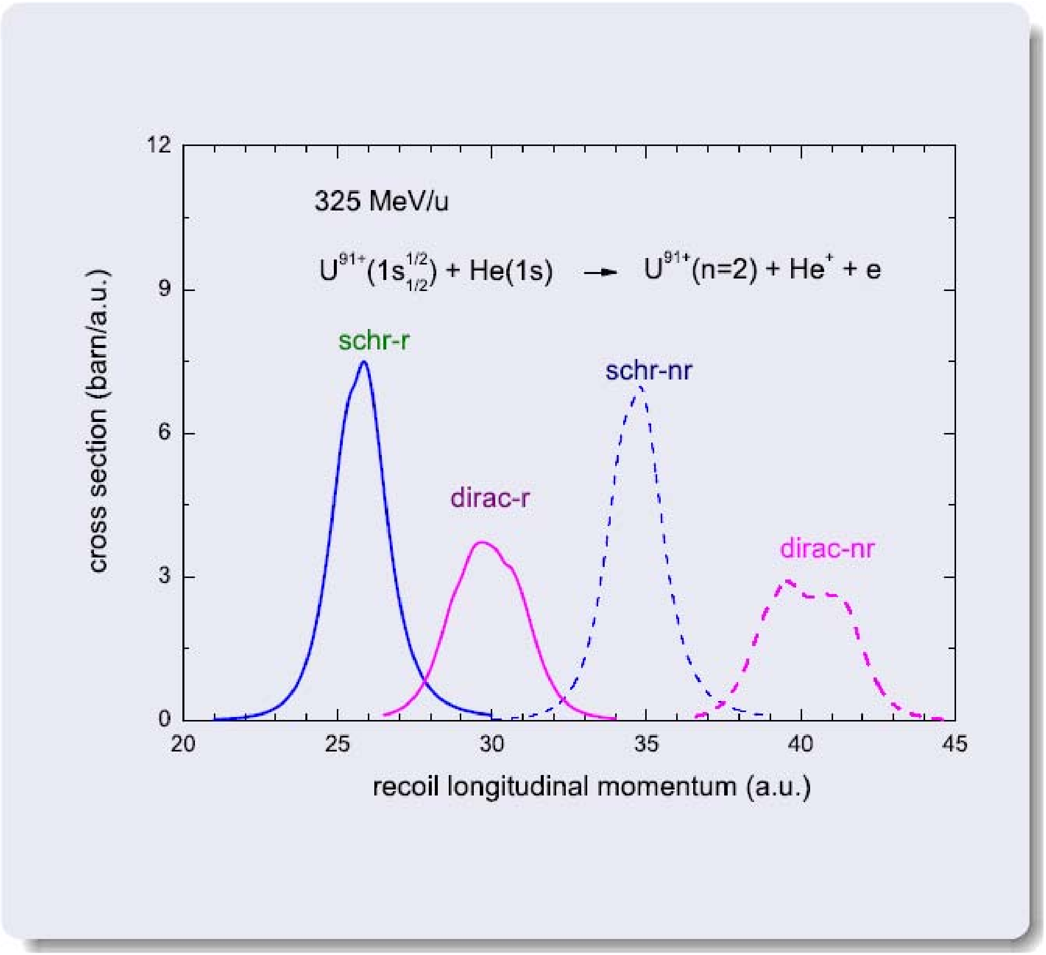
only in the treatment of the relative ion-atom motion.

$$\gamma \rightarrow 1$$

$$q^{A}_{min} = \frac{\varepsilon_n - \varepsilon_0}{v_p} + \frac{\epsilon_m - \epsilon_0}{v_p}$$

Results: Target-recoil momentum spectra

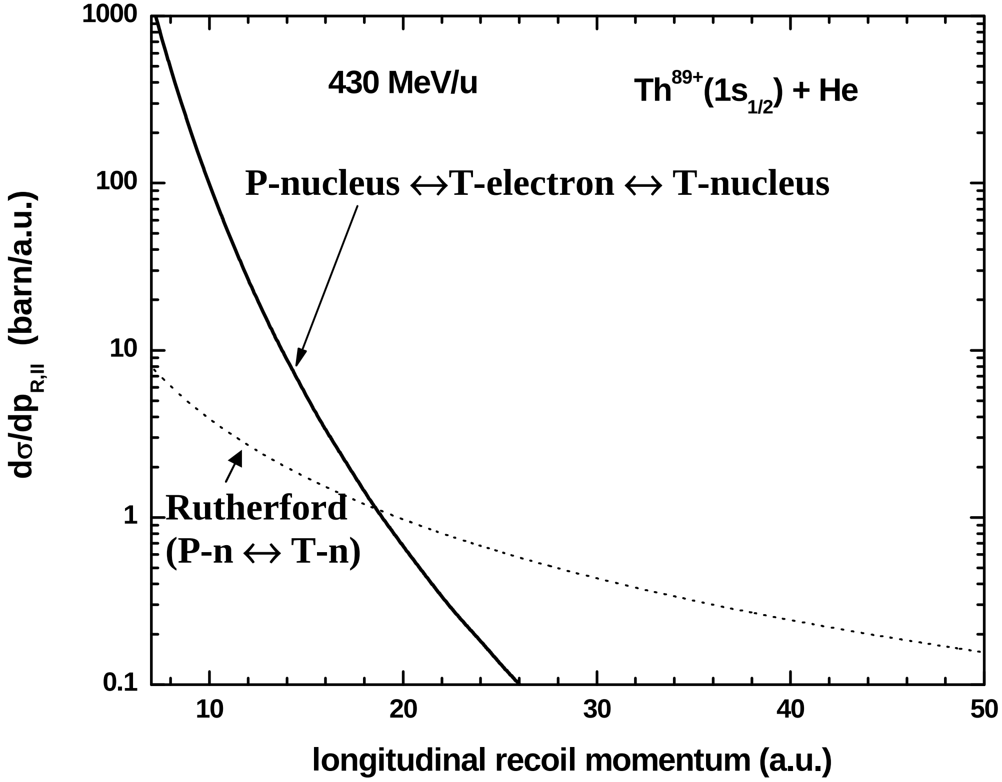
Doubly inelastic collisions

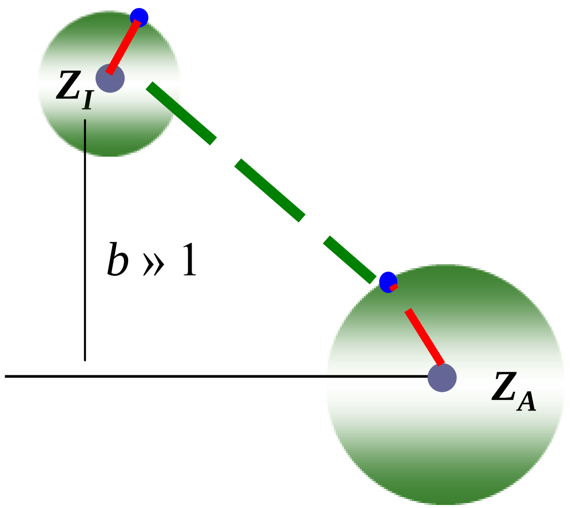


$$q_{min}^{A} = \frac{\varepsilon_n - \varepsilon_0}{v_p} + \frac{\epsilon_m - \epsilon_0}{\gamma v_p}$$

Results: Target-recoil momentum spectra

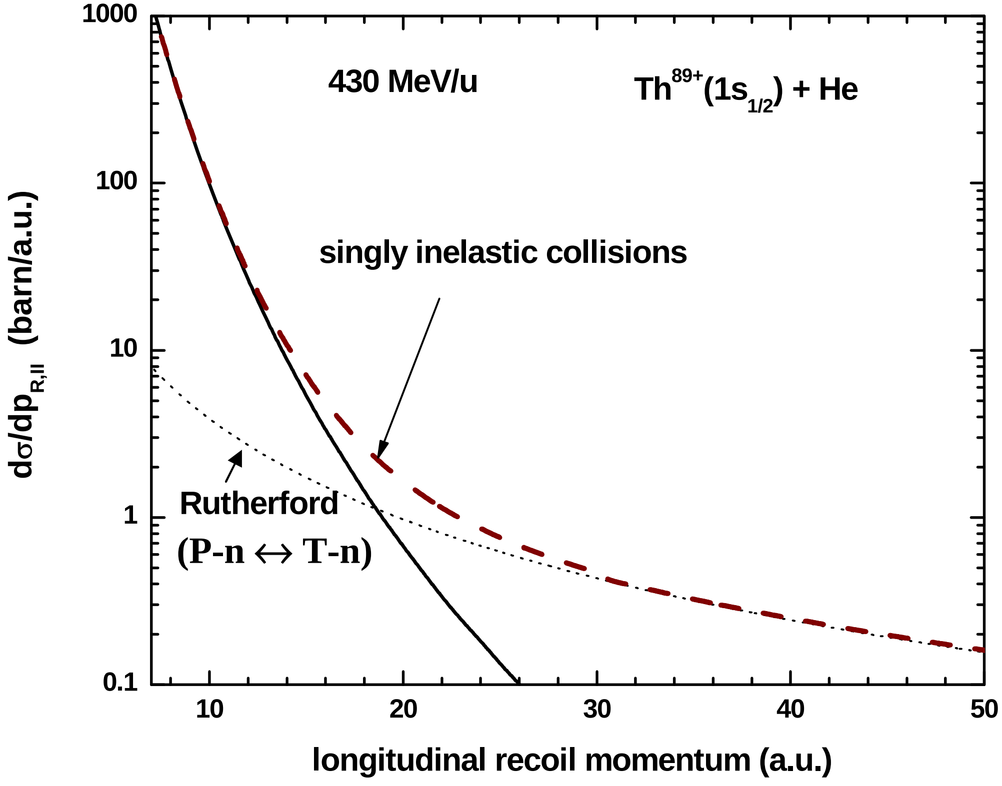
Singly inelastic collisions

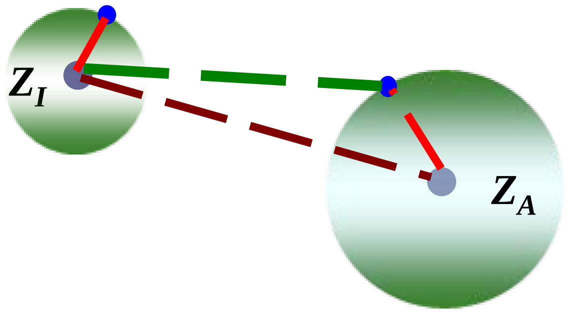




Results: Target-recoil momentum spectra

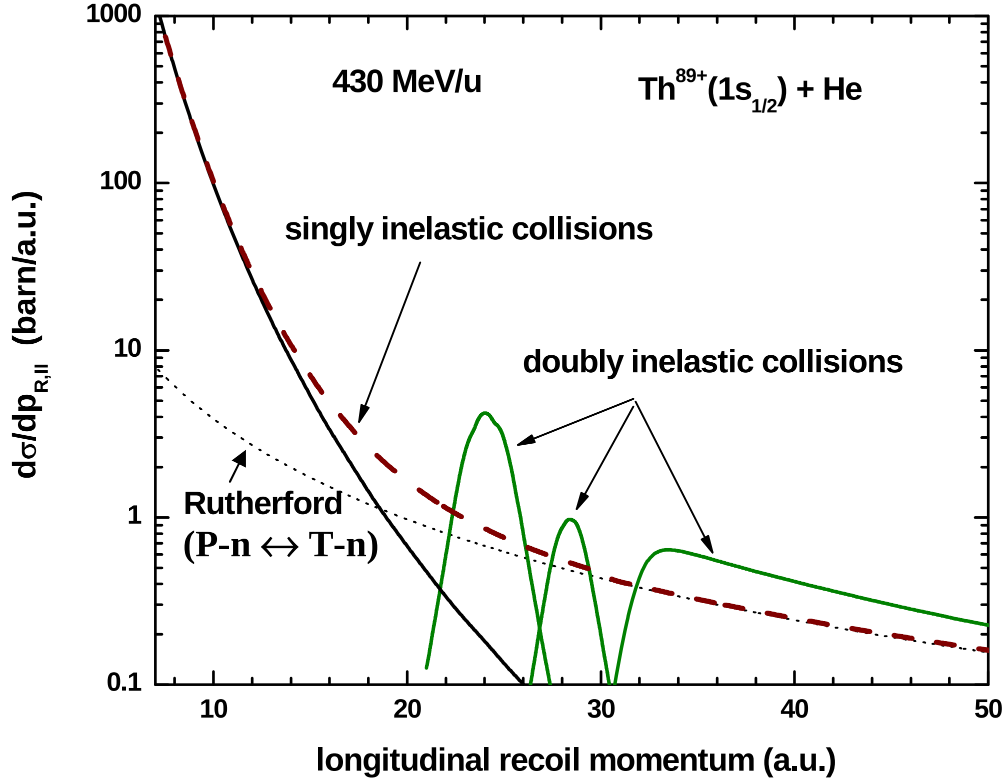
Singly inelastic collisions

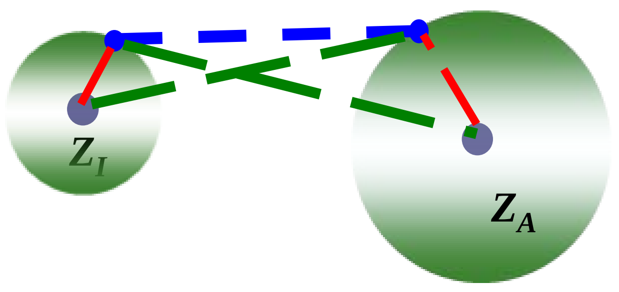




Results: Target-recoil momentum spectra

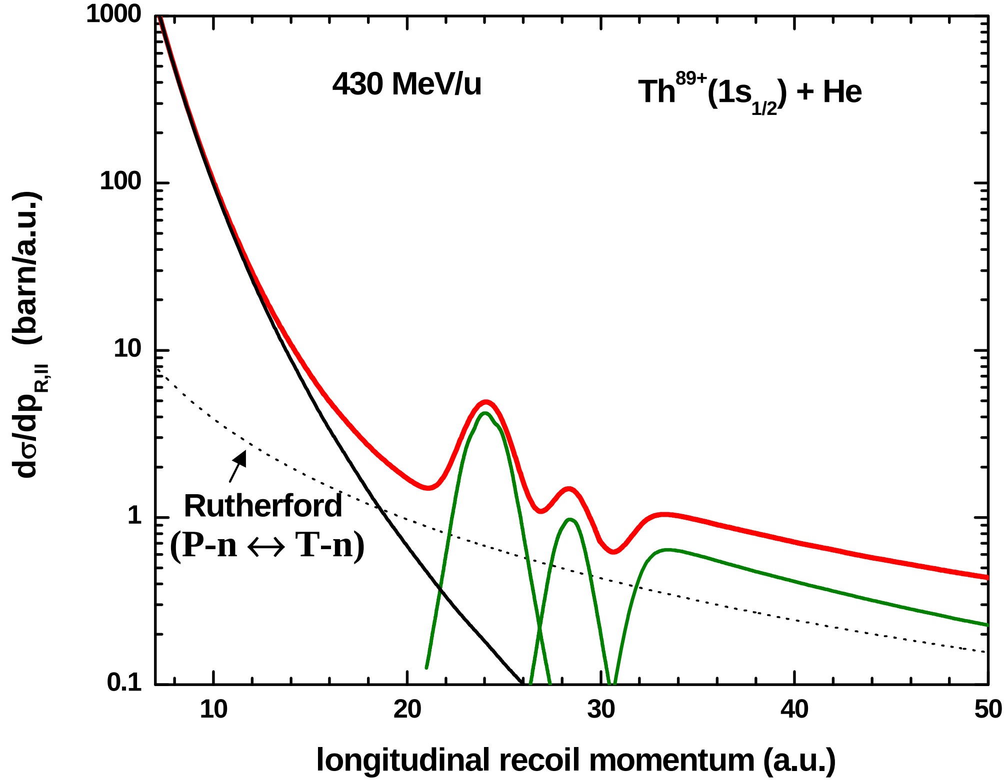
Singly/Doubly inelastic collisions

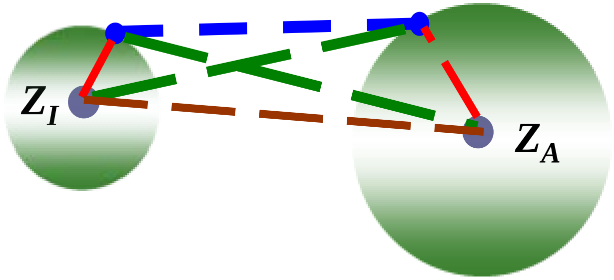




Results

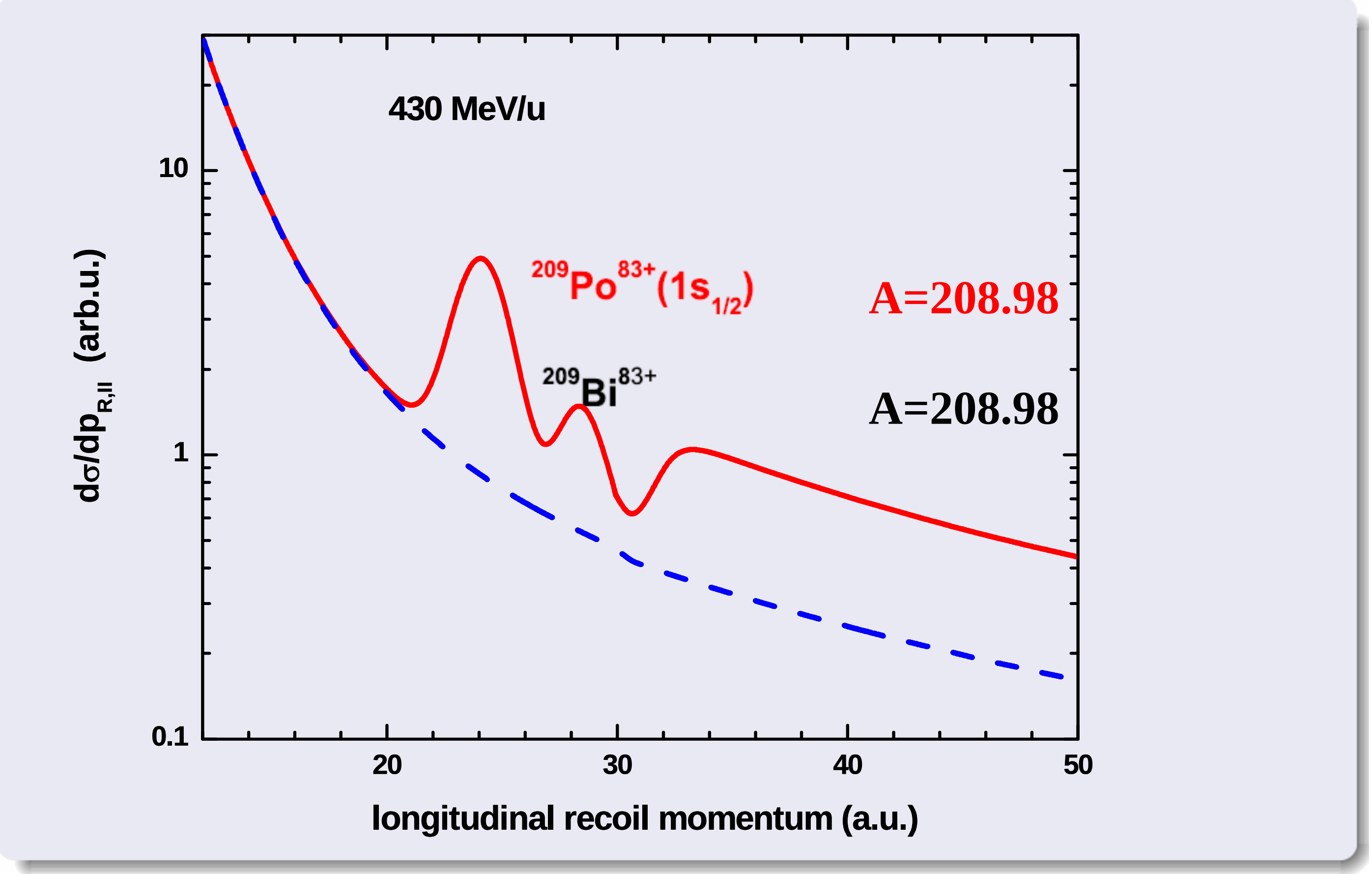
Target-recoil momentum spectra





Results

Target-recoil momentum spectra



Conclusions

Concentrating on the **longitudinal momentum spectrum** of target recoil ions we have considered the **inelastic collisions** of highly charged hydrogen-like ions with the simplest targets. We have shown that:

- the collision **dynamics is strongly influenced** by the **higher order effects** in the projectile-target interaction;
- the relativistic effects, caused both by the **relative ion-atom motion** and the electron motion in the **internal states** of the ion, are clearly manifested;
- the **projectile electron** is very well **visible** in the momentum transfer to the target recoil;
- **general picture has emerged** for the formation of the longitudinal momentum spectrum of the target recoil ion;
- at *moderate* γ's, a **great deal** of **information** about the **doubly inelastic collisions** could be **obtained in experiment** by measuring just the longitudinal momentum spectrum of the target recoil ions.

Thank you !

$$S_{fi}(\mathbf{Q}) = -\frac{2i}{v}\int d^2\mathbf{p}_1 \int d^2\mathbf{p}_2 \int d^2\boldsymbol{\kappa}$$
$$\frac{f(p_1,\nu)\, f(p_2,\nu)\, f(\kappa,-\eta)}{(\mathbf{q}^A + \boldsymbol{\kappa} - \mathbf{p}_1 - \mathbf{p}_2)^2 - \frac{(\varepsilon_n - \varepsilon_0)^2}{c^2}}$$
$$\times\Phi^A_\mu\left(n0;\mathbf{q}^A + \boldsymbol{\kappa} - \mathbf{p}_1 - \mathbf{p}_2;\mathbf{p}_1;\mathbf{p}_2\right)$$
$$\gamma^{-1}\,\Lambda^\mu_\alpha\, F^\alpha_I\left(m0;\mathbf{q}^I - \boldsymbol{\kappa} + \mathbf{p}_1 + \mathbf{p}_2\right)\Big)$$

$$f(a,\tau) = \frac{\Gamma(1-i\tau)\Gamma(1/2+i\tau)}{2\pi\Gamma(1/2)\Gamma(2i\tau)} a^{\delta-2+2i\tau}$$

$$\Phi^A_\mu\,\gamma^{-1}\,\Lambda^\mu_\alpha\, F^\alpha_I = \left(\Phi^A_0 + \frac{v}{c}\Phi^A_3\right)\left(F^0_I + \frac{v}{c}F^3_I\right) + \frac{\Phi^A_3 F^3_I}{\gamma^2} + \frac{\Phi^A_1 F^1_I + \Phi^A_2 F^2_I}{\gamma}$$

$$
\begin{aligned}
\Phi_0^A(n0;\mathbf{k};\mathbf{p}_1;\mathbf{p}_2) = \quad & \langle \varphi_n \mid Z_A \exp(i\mathbf{p}_1\cdot\mathbf{r}_1 + i\mathbf{p}_2\cdot\mathbf{r}_2) \\
& - \exp(i\mathbf{p}_1\cdot\mathbf{r}_1 + i\mathbf{p}_2\cdot\mathbf{r}_2) \times \\
& (\exp(i\mathbf{k}\cdot\mathbf{r}_1) + \exp(i\mathbf{k}\cdot\mathbf{r}_2)) \mid \varphi_0 \rangle
\end{aligned}
$$

$$
\begin{aligned}
\Phi_l^A(n0;\mathbf{k};\mathbf{p}_1;\mathbf{p}_2) = \quad & \langle \varphi_n \mid \exp(i\mathbf{p}_1\cdot\mathbf{r}_1 + i\mathbf{p}_2\cdot\mathbf{r}_2) \times \\
& (\alpha_{l,1} \exp(i\mathbf{k}\cdot\mathbf{r}_1) \\
& +\alpha_{l,2} \exp(\imath\mathbf{k}\cdot\mathbf{r}_2)) \mid \varphi_0 \rangle,
\end{aligned}
$$

$$
\begin{aligned}
F_0^I(m0;\mathbf{k}) &= -\langle \chi_m \mid \exp(i\mathbf{k}\cdot\boldsymbol{\xi}) \mid \chi_0 \rangle \\
F_l^I(m0;\mathbf{k}) &= \langle \chi_m \mid \alpha_l \exp(i\mathbf{k}\cdot\boldsymbol{\xi}) \mid \chi_0 \rangle
\end{aligned}
$$

γ

$$q^A_{min} = \frac{\varepsilon'_n - \varepsilon'_0}{v_p} + \frac{\epsilon'_m - \epsilon'_0}{v_p}$$

$$q^A_{min} = \frac{\varepsilon'_n - \varepsilon'_0}{v_p} + \frac{\epsilon'_m - \epsilon'_0}{\gamma v_p}$$

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