Differential cross sections in collisions of low-energy antiprotons with ions and atoms

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Outline

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- Kinematically complete experiments for ion-impact ionization became feasible within development of the 'reaction microscope' techniques.

- Fully differential cross sections (FDCS) are accessible now, and provide the most stringent test of theoretical models.

- Different types of 'Reaction Microscopes': COLTRIMS, MOTRIMS, advanced MOTRIMS with an alternative optical cooling and trapping scheme.

- For some systems one found large discrepancies at differential level between theory and experiment, as well as between different theories.

- Studying ionization process at detailed level to gain insight into the phenomenon of spontaneous electron-positron pair creation in heavy-ion collisions.

Key aspects of the developed approach

- Semiclassical treatment of the collision.

- Time-dependent Dirac equation for a bare ion projectile colliding with a one-active-electron target atom

$$i\frac{\partial\Psi(\mathbf{r},t)}{\partial t} = [H_{\mathrm{T}} + V_{\mathrm{P}}(t)]\Psi(\mathbf{r},t)\,.$$

- Finite-basis-set expansion of wave function Ψ is used to solve it.

For details: A.I. Bondarev *et al.*, PRA **95**, 052709 (2017).

Antiproton-impact ionization of atomic hydrogen

- A pure three-body system

- Absence of charge-transfer processes in contrast to proton-impact

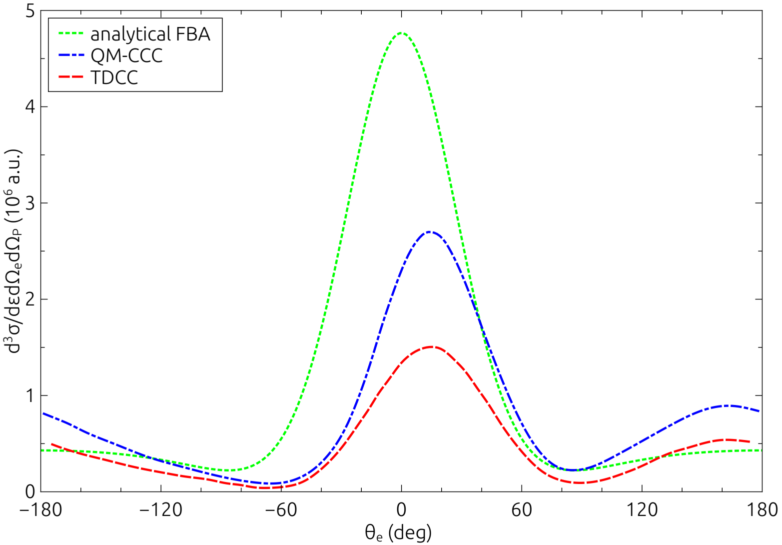
- Absence of correlation effects in contrast to electron-impact

- Discrepancies in the recent predictions of **non-perturbative** approaches:

CP	—	M. McGovern *et al.*, PRA **79**, 042707 (2009),
QM-CCC	—	I.B. Abdurakhmanov *et al.*, JPB **44**, 165203 (2011),
TDCC	—	M.F. Ciappina *et al.*, PRA **88**, 042714 (2013),
WP-CCC	—	I.B. Abdurakhmanov *et al.*, PRA **94**, 022703 (2016).

- Experimental data are unavailable at the moment

TDCS @ 200 keV for $\theta_p = 0.2$ mrad and $\varepsilon = 4$ eV



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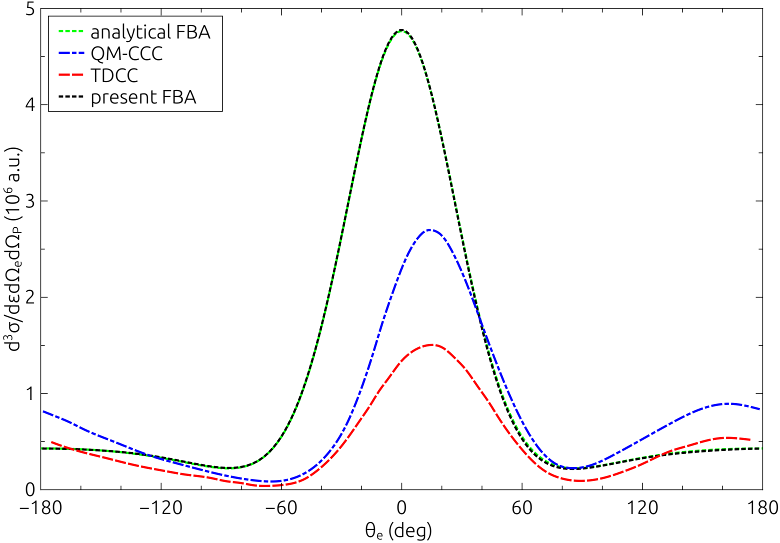

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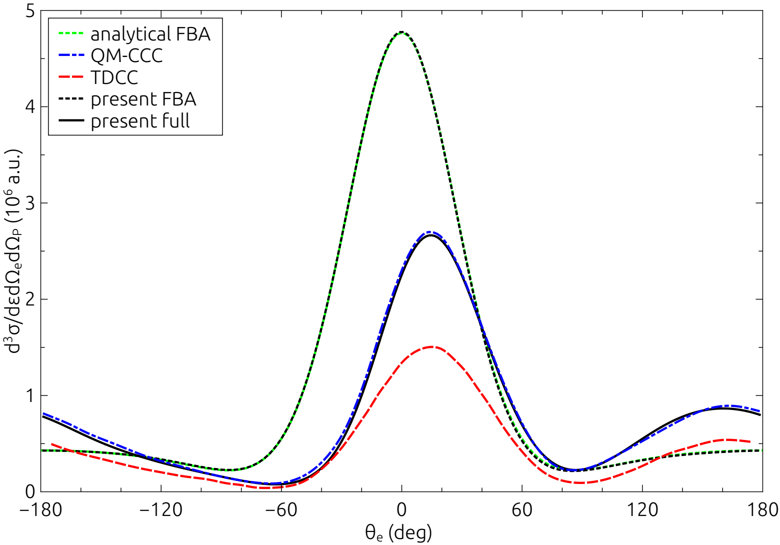

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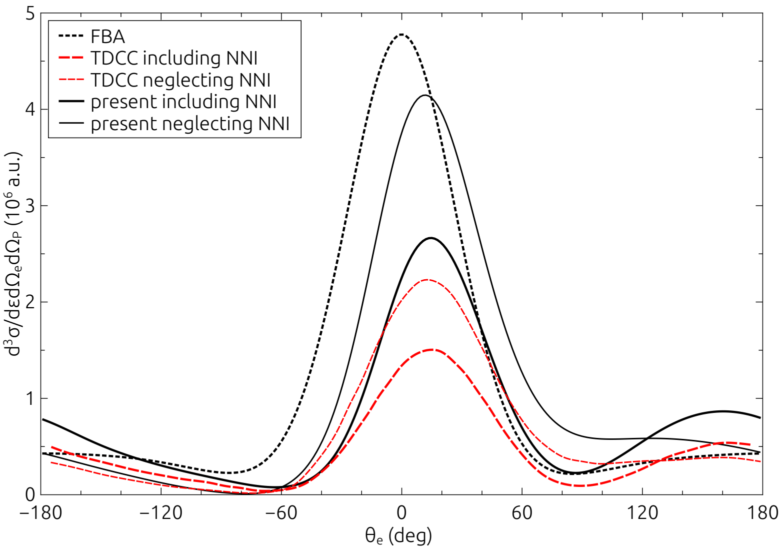
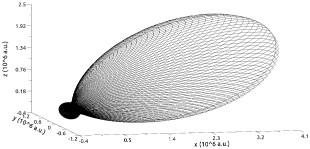
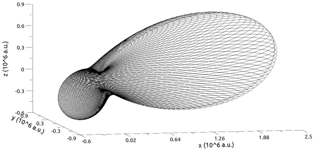


TDCS @ 200 keV for $\theta_p = 0.2$ mrad and $\varepsilon = 5$ eV

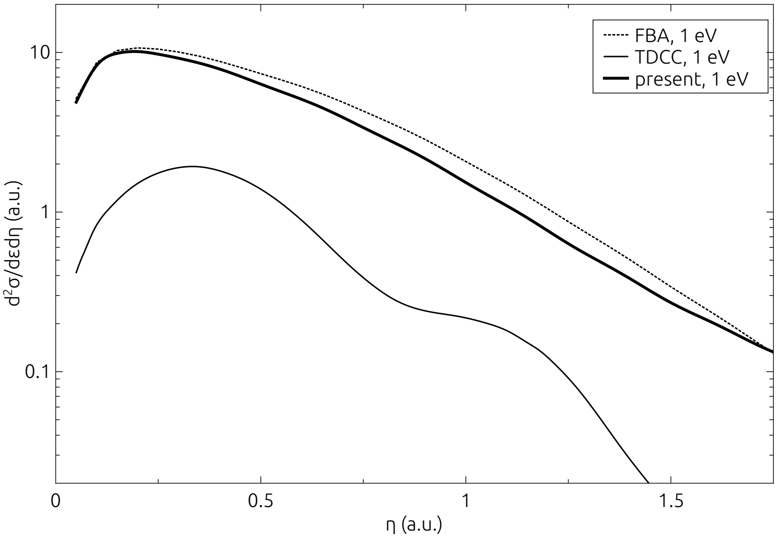


(a) FBA

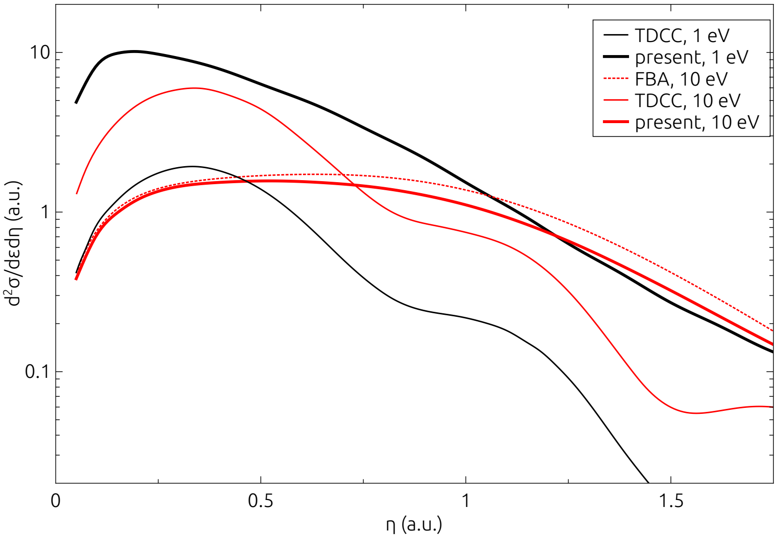


(b) full calculation

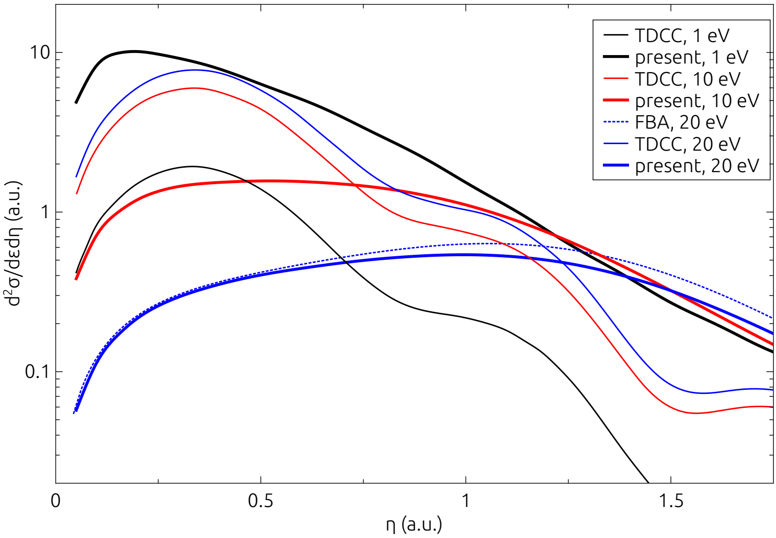
DDCS @ 200 keV for $\varepsilon = 1$ eV



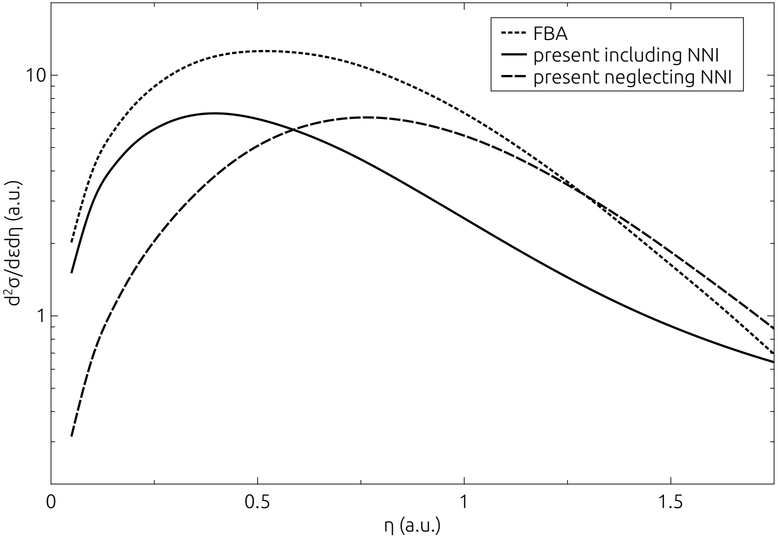
DDCS @ 200 keV for $\varepsilon = 1$ and 10 eV



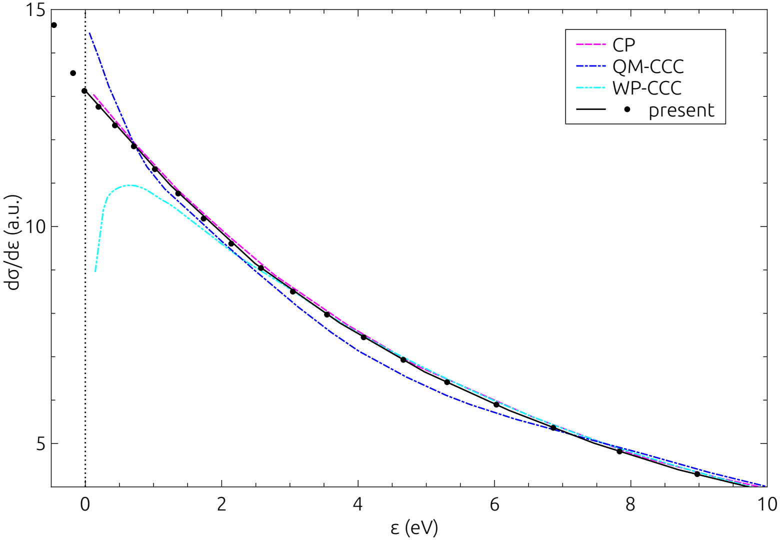
DDCS @ 200 keV for $\varepsilon = 1$, 10 and 20 eV



DDCS @ 30 keV for $\varepsilon = 5$ eV



SDCS @ 30 keV



Total ionization cross sections

Table 1 : Total ionization cross sections (10^{-16} cm^{-2}).

E_{P} (keV)	30.00	200.00	500.00
FBA	2.15	0.77	0.36
present (FBA)	2.16	0.77	0.36
QM-CCC	1.35	0.66	0.34
TDCC	1.46	0.65	0.33
present (full)	1.37	0.68	0.35

Conclusion and Outlook

- Differential cross sections for ionization provide much more stringent test for theory than total ones: fine peculiarities can be smeared in the latter.

- Antiprotons at low and medium energies are interesting objects to be used as projectiles in kinematically complete experiments.

- Our recently developed approach can compete with prominent non-perturbative techniques.

- Further improvement and application of the approach to experimentally investigated collisions of heavy ions with atoms.

Outline

Analogy with classical mechanics

- In classical mechanics (the result of the Mie theory for scattering of light is similar) DCS is given by

$$\frac{d\sigma}{d\Omega} = \frac{b}{\sin\theta}\left|\frac{db}{d\theta}\right|$$

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- Two types of singularities: the rainbow and glory

Solar glory from an airplane

[www.wikipedia.org]

Timeline

- 1984 Yu.N. Demkov and co-workers found special behavior of the DCS for backward scattering in screened Coulomb attractive potential and named it the Coulomb glory. At some energies of the incident particle there is a prominent maximum of the DCS in the backward direction;

- 2001 Quasi-classical calculations of the Coulomb glory phenomenon in antiproton-xenon collisions:
Yu.N. Demkov and V.N. Ostrovsky, J. Phys. B **34** L595 (2001).

- 2007 – 2010 Quantum-mechanical relativistic calculations of the Coulomb glory in antiproton-uranium collisions:
A.V. Maiorova et al., Phys. Rev. A **76**, 032709 (2007);
A.V. Maiorova et al., J. Phys. B **41**, 245203 (2008);
A.V. Maiorova et al., J. Phys. B **43**, 205006 (2010).

Scaled differential cross section

- For pure Coulomb potential DCS is given by the Rutherford formula

$$\frac{d\sigma_{\mathrm{C}}}{d\Omega} = \left(\frac{Z}{4E}\right)^2 \frac{1}{\sin^4(\theta/2)},$$

and has a minimum at $\theta = \pi$.

- To describe the Coulomb glory quantitatively, let us introduce the scaled DCS,

$$\frac{d\sigma'}{d\Omega} = \left(\frac{4E}{Z}\right)^2 \frac{d\sigma}{d\Omega},$$

so that

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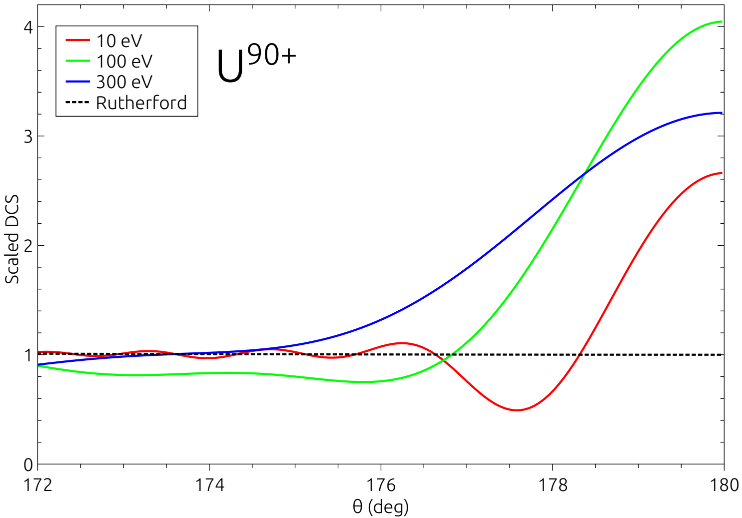
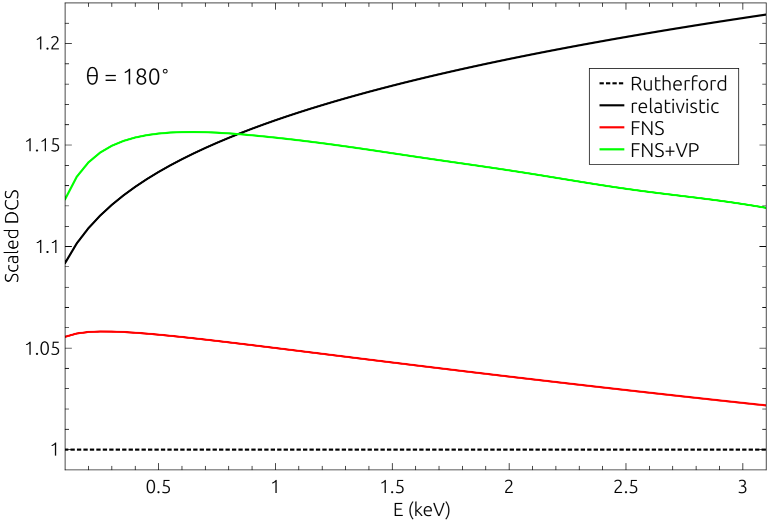
Scaled DCS for antiproton scattering on uranium ions

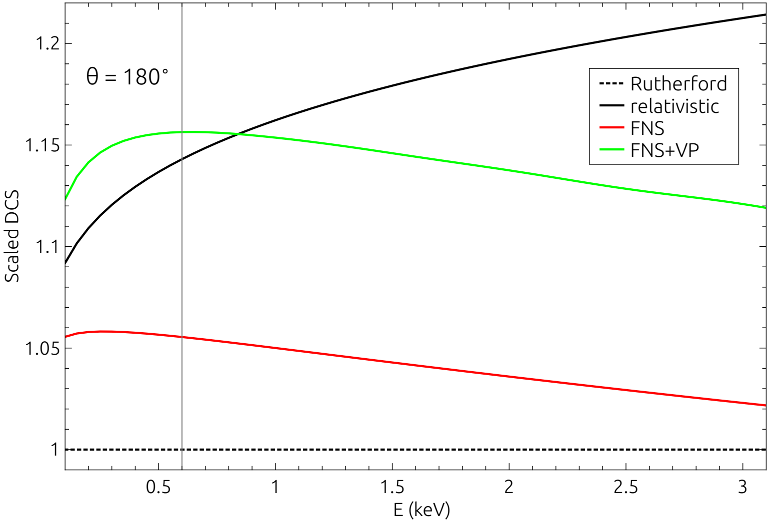


Maximal enhancement is 90 at $E = 300$ eV and 680 at $E = 1.8$ keV for U^{82+} and U^{64+} ions, respectively.

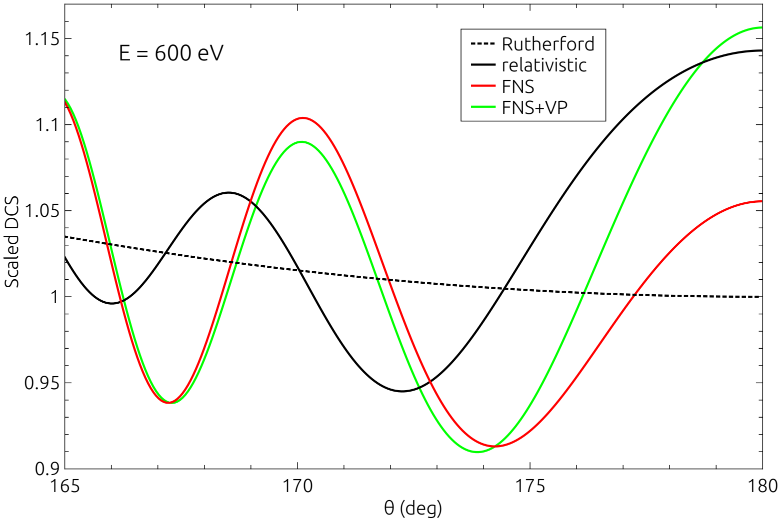
Scaled DCS for antiproton scattering on bare uranium



Scaled DCS for antiproton scattering on bare uranium



Scaled DCS for antiproton scattering on bare uranium



Summary

- The backward scattering of antiprotons by ions is very sensitive to the screening potential. It provides a tool to study screening properties of the vacuum polarization potential in dynamical processes.

- The role of inelastic processes such as radiative recombination and antiproton annihilation has also been estimated. It is found that they should not mask the Coulomb glory phenomenon.

Summary

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Thank you for your attention!