Sub-Femtosecond Correlated Dynamics Probed with Antiprotons

\[ t = 30 \ldots 6 \ldots 3.5 \text{ fs} \]

\[ I \geq 10^{15} \text{ W/cm}^2 \]

„Attosecond Science“

\[ \tau \approx 150 \text{ attosec.} \]
Sub-Femtosecond Correlated Dynamics Probed with Antiprotons

$I \geq 10^{15} \text{ W/cm}^2$

electrons: sub-threshold

$t = 30 \ldots 6 \ldots 3.5 \text{ fs}$

$t = 5 \text{ fs} \ldots 0.01 \text{ as}$
Sub-Femtosecond Correlated Dynamics Probed with Antiprotons

$I \geq 10^{15} \text{ W/cm}^2$

positive ions: capture

$t = 30 \ldots 6 \ldots 3.5 \text{ fs}$

$t = 5 \text{ fs} \ldots 0.01 \text{ as}$

$\tau \approx 150 \text{ attosec.}$
Sub-Femtosecond Correlated Dynamics Probed with Antiprotons

$I \geq 10^{15} \text{ W/cm}^2$

$\tau \approx 150 \text{ attosec.}$

$t = 30 \ldots 6 \ldots 3.5 \text{ fs}$

$t = 5 \text{ fs} \ldots 0.01\text{ as}$
Why do we care?

Dirac 1929: “The general theory of quantum mechanics is now almost complete…”

“The underlying physical laws necessary for the mathematical theory of a large part of physics and the whole of chemistry are thus completely known,…..“
Why do we care?

Dirac 1929:
Why do we care?

The three-body Coulomb problem solved

- Rescigno, Mc Curdy: Science 1999

- Bray (Stelbovics, Bartschak, Kheifets):
  PRL 91 (2003) 253202
  PRL 89 (2002) 273201
  PRL 76 (1996) 2674

Why do we care? For electron impact!
Why do we care?

Benchmark system for ionization in the presence of correlation

Not understood even for total cross sections!

What about (fully) differential cross sections?
How do we care?

LHC-b

Cloud Chamber for Atomic and Molecular Physics
Outline of the Talk

- Reaction Microscopes
- Single Ionization
- Double Ionization
- Antiproton Capture
- How to do the Experiments?
- Plenty of other Reactions!
Reaction Microscopes

The “Cloud Chambers”

Fragmentation in 3D

Animation: R. Dörner, H. Schmidt-Böcking

Fragmentation in 3D
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Kinematically Complete: Surprise!

At high energies: weak field limit
- all theories converge
- no proton-antiproton difference
He Single Ionization

From the optical limit to 1st Born

1st Born approximation: Dipole limit

\[ d\sigma \propto \left| \langle \phi_f | e^{i\tilde{q} \cdot \vec{r}} | \phi_i \rangle \right|^2 \approx \left| \langle \phi_f | \tilde{q} \cdot \vec{r} | \phi_i \rangle \right|^2 + \left| \langle \phi_f | O(\tilde{q}^2) | \phi_i \rangle \right|^2 \]

Photo-ionization:

\[ d\sigma \propto \left| \langle \phi_f | \hat{e} \cdot \vec{r} | \phi_i \rangle \right|^2 \]
He Single Ionization

Photo-ionization

1st Born:

\[ d\sigma \propto \left| \langle \phi_f | e^{i\mathbf{q} \cdot \mathbf{r}} | \phi_i \rangle \right|^2 \approx \left| \langle \phi_f | q \right|^2 \left| \mathbf{q} \right|^2 \]

\[ d\sigma \propto \left| \langle \phi_f | \hat{e} \cdot \mathbf{r} | \phi_i \rangle \right|^2 \]

D. Madison
**Single ionization**

**Photo-ionization**

- $\cos^2$-distribution
- "Binary"
- $\hat{e}$

**1st Born:**

- Binary peak
- $\vec{q}$

D. Madison
Classical Picture

1st Born:

- binary peak
- recoil peak

D. Madison
“Recoil“:

Explored since about 30 years: “understood”

Theory: Bray, Resigno, Bartschak: “solved”
3-D Imaging

1st Born:

$100 \text{ MeV/u } \text{ C}^6+$

$Z_p / v_p = 0.1$

first experiment: D. Fischer, R. Moshammer, M. Schulz: surprises in 3 dimensions!

“Perpendicular” Plane

not understood at all

100 MeV/u C⁶⁺

\[ Z_P / \nu_P = 0.1 \]

Olson: - interaction with nucleus
       - special trajectories (priv. comm.)

Voitkiv: - interaction with nucleus

Madison: - failure of CCC at small distances

Towards large Perturbations

100 MeV/u C\textsuperscript{6+} 
\(Z_p/N_p = 0.1\) 

2 MeV/u C\textsuperscript{6+} 
\(Z_p/N_p = 0.7\) 

All theoretical predictions fail

Heavy Ions: Capture

Total cross sections correct!

Madison et al., PRL 2003
JPB 2002
Fischer et al., JPB 2002
JPB 2003
PRA 2003
JPB 2004
Schulz et al., JPB 2003
Antiprotons: Kinematically Complete

- ultimate test of strong-field theories
- benchmark: dynamical two-electron correlation

\[ \begin{align*}
\sigma &\text{[10}^{-16}\text{ cm}^2] \\
E_p &\text{[keV]} \\
Z/v & \\
1 \text{ fs} & \ldots 0.3 \text{ fs} \ldots 0.1 \text{ fs} \ldots 30 \text{ as} & \text{time}
\end{align*} \]
The Ultimate Test: $p, \bar{p} + H, He$

500 keV $\bar{p}/p$

Voitkiv and Ullrich PRA 67 (2003) 2591
The Ultimate Test: $p, \bar{p} + H, He$

- 1st order: $\sigma(\bar{p}) = \sigma(p)$
- 2nd order

Voitkiv and Ullrich PRA 67 (2003) 2591
The Ultimate Test: $p, \bar{p} + H, He$

Voitkiv and Ullrich PRA 67 (2003) 2591
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**Double Ionization: \( p \leftrightarrow \bar{p} \)**

1. **Two - Step**
   \[ R \sim q^2/v^2 \]

2. **One - Step**
   \[ R = \text{const.} \]

**Inverse Perturbation:** \( v^2/q^2 \)

**Ratio:** \( \text{He}^{++}/\text{He}^+ \%

**Interference**
- 1st order: \( \sigma \)
- 2nd order: \( \sigma \)

**Antiproton data from**
- LEAR at CERN...

**References:**
- Ullrich et al. PRL (1994); NIM B (1994)
- L. Andersen, H. Knudsen, E. Uggerhoj et al.,
Double Ionization:

- **q**: charge
- **v**: velocity

\[ R \approx \frac{q^2}{v^2} \]

Fully differential cross sections:

- Co-planar
- \[ E_{\text{electron1}} = E_{\text{electron2}} \]

Antiproton data from LEAR at CERN

- L. Andersen, H. Knudsen, E. Uggerhoj et al.,
- Dorn et al., PRL 2000
- Fischer et al., PRL 2002, 2003
Double Ionization: $p \leftrightarrow \bar{p}$

Impact

Proton impact

Forbidden:

$E_{\text{electron}1} = E_{\text{electron}2}$

$\theta_{\text{electron}1} \neq \theta_{\text{electron}2}$

$\rightarrow$ Dipole selection

No theory so far!
The $\bar{p} - p$ difference

Electron impact

Proton impact

In the figure:

- The graph shows the ratio of He$^+$/He$^+$ against $q^2/v^2$ with data points for different charge states.
- The inset graph illustrates the inverse perturbation: $v^2/q^2$.
- The alignment of angles $\theta_e$ and $\theta_p$ for electron and proton impacts, respectively.
- The "Binary Peak" and "Recoil Peak" are highlighted at different energies (4 MeV and 6 MeV).

Fischer et al., PRL 90 (2003)

Dorn et al., PRL 2004

$E_{e1,2} < 25$ eV

$\Delta E_e < 2.5$ eV

Coplanar

"Binary Peak"
Outline of the Talk

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Questions:
- capture cross section
- few-particle dynamics at 10 to 100 fs time-scale
- n,l distributions
- spectroscopy of states

Exp.: no single collision conditions
"\bar{p}\textsuperscript{–}Capture: Structure & Dynamics"

\[ \Delta p_p \]

\[ p_p^f \]

\[ p_p^i \]

\[ v_p = 0.35 \text{ a.u.} \]

\[ \text{Ne}^{6+} \]

\[ \text{He}^{1+} \]

\[ \text{Ne}^{7+} \]

\[ \text{Highly-Charged Ions} \]

\[ \text{Antiprotons} \]

\[ \bar{p}\textsuperscript{–}\text{He}^{1+} \]

\[ \text{electron momentum} \]

\[ \text{He}^{1+} \text{ momentum} \]
$\bar{p}$–Capture: Structure & Dynamics

$n,l$ distributions for
- antiprotonic atoms
- protonium

precision spectroscopy?
- all states that are formed
- $\Delta \lambda/\lambda \approx \ldots 10^{-6}$
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Experimental Needs

• High Luminosity: ...$10^{-21}$ cm$^2$...
FLAIR: Cold Antiprotons

Cryring

USR

30 MeV – 300 keV

300 – 20 keV

cEV ... eV

10^5 times: antiprotons/second in the ring
The USR: Design

Challenges:
- 2 ns beam bunching
- antiproton deceleration
- electron cooling at 10 eV
- in-ring reaction microscope

atomic jet + reaction-microscope

electron cooler
- photocathode
- $\Delta E \sim 1$ meV

injection
The In-Ring Reaction Microscope

- zero degree spectrometer
- supersonic jet
- ESR-beam
- reaction-microscope
- Helmholtz-coils
The In-Ring Reaction Microscope

- successfully tested
- ESR: end of 2005
- K. Küne: USR design
The USR: Design

Challenges:
- 2 ns beam bunching
- antiproton deceleration
- electron cooling at 10 eV
- in-ring reaction microscope

atomic jet + reaction-microscope

electron cooler
- photocathode
- $\Delta E \sim 1$ meV
TSR: ultra-cold e- target

A. Wolf
D. Orlov
U. Weigel
F. Sprenger
M. Lestinsky
The USR: Design

Challenges:
- 2 ns beam bunching
- antiproton deceleration
- electron cooling at 10 eV
- in-ring reaction microscope

atomic jet + reaction-microscope

a prototyp at MPI-K

CSR

electron cooler
- photocathode
- $\Delta E \sim 1 \text{ meV}$

injection
Space for the CSR

~75 % funded!
Summary:

• Reaction Microscope + USR: “Cloud Chamber” + high luminosity

• Sub-fs Correlated Dynamics
  Single, double multiple ionization
  Antiproton Capture …..

• Plenty of other Reactions?
Ultra-Low Energy Antiproton Storage Ring

Electron Cooler: 10 eV – 150 eV

Positron Cooler Storage Ring

Recombination; Laser assisted

Supersonic Jet Target

Recombination

Supersonic Jet Target

Electron Cooler: 10 eV – 150 eV

Laser-Beam

Laser Beam

E+ E- spectrometer

Reaction Microscope

PP, PHe+, Antiprotonic Atom Beam

Single, Double, Multiple Ionization Dynamics

Antiprotonic Atom Formation n,l Distributions, Spectroscopy

Re-injection: eV-20 keV

Recombination

Injection from ISR: 300 keV; ~10^8 pbar, 0.1 Hz

Laser Precision Spectroscopy

Microwave HFS Spectroscopy

Low Energy H-Beam

1 eV – 100 eV

Ultra-Low Energy p-Beam

Ultra-Low Energy p-Beam

Buncher

deceleration

Nested Trap