ASACUSA collaboration

Recent achievements
Atomic Spectroscopy And Collisions Using Slow Antiprotons

Austria - SMI Vienna
Denmark - University of Aarhus
Germany - Max-Planck Institute for Quantum Optics
Hungary - KFKI Budapest, ATOMKI Debrecen
Italy - INFN Brescia
Japan - University of Tokyo, RIKEN Saitama
United Kingdom - University of Swansea, Queens University of Belfast

Asakusa, Tokyo

7 countries, 10 institutions, 40 researchers
Started in 1997 by merger of PS194, PS205, etc. collaborations.
Members active in CERN’s antiproton programme since >20 years.
We use antiproton beams of various energies to explore fundamental properties and reactions of antimatter.

- **5 MeV** -- Antiproton magnetic moment, Nuclear collisions
- **60 keV** -- Antiproton mass and charge.
- **0.5-10 kV** -- Atomic collisions
- **< 1 eV** -- Antihydrogen

“Musashi” trap
Crucial part of ASACUSA. 
Slows down antiprotons to E<100 keV. 
Delivers >7 million antiprotons every 100 s. 
Beam emittance > 100 pi mm mrad, 
Energy spread > 10 keV.

10-100-fold improvement of many parameters with new ELENA machine.
Goals:

- Two-photon laser spectroscopy of antiprotonic helium:  
  \[ \text{Antiproton mass with } <10^{-10} \text{ precision.} \]

- Microwave spectroscopy of antiprotonic helium (completed):  
  \[ \text{Antiproton magnetic moment with 0.3\% precision} \]

- Microwave spectroscopy of antihydrogen:  
  \[ \text{Ground-state hyperfine structure with } 10^{-6} \text{ precision.} \]
Spectroscopy of antiprotonic helium

- 3-body atom made of antiproton, He, and electron.
- Survives for >10 microseconds.
- >1 billion atoms synthesized per day.
- Amenable to high-precision laser and microwave spectroscopy.
Antiproton mass measurement

\[ p \quad \ \text{1836.15267245(75)} \quad \text{CODATA 2010} \]

\[ \bar{p} \quad \ \text{1836.1526736(23)} \quad \text{Nature 475, 484 (2011).} \]

(Anti)proton to electron mass ratio - 1836.15200 \( / 10^{-5} \)

- Compare laser frequency with 3-body QED calculations.
- Antiproton-to-electron mass ratio measured to 1.3 ppb
Antiproton mass measurement

![Graph showing relative precision over years elapsed from 1995 to 2015. The graph includes markers for LEAR, AD, RFQD, and Two-photon methods. CODATA 98 and CODATA 2010 are also marked. The x-axis represents years elapsed, and the y-axis represents relative precision.](image)
Microwave spectroscopy of antiprotonic helium

- Flip spin of electron in atom by 11-16 GHz microwaves.
- Compare frequency with 3-body QED calculations.
- Antiproton magnetic moment measured to 0.29% precision.

Latest 3He results in
S. Friedrich et. al,
Ground-state hyperfine structure of antihydrogen

- Measured to 0.6 ppt in hydrogen case: \(1.4204057517667(9) \text{ GHz}\).
- Sensitive to magnetic radius and polarizability of antiprotons.
- Classic atomic-beam spectroscopy with polarized antihydrogen beam, microwave cavity, and sextupole magnet.
- Precision 1 part per million (typical for this type of experiment).
Toward production of antihydrogen beams

Y. Enomoto et. al,

Mixed 3 million positrons
0.3 million antiprotons

Typically 70 antihydrogen counts detected per mixing cycle.
Implies 7000 antihydrogens formed.
Antihydrogen in $n=45-50$ Rydberg state.
Atomic collisions with antiprotons

- Collide antiprotons with atoms and molecules at ultra-low energies $E < 10$ keV and measure single and double ionization.

- Even simple observables like total cross section are difficult to predict with advanced theoretical techniques due to quantum-mechanical nature of dynamics.

- Fundamentally new problem compared to proton collisions, since atomic electrons are repelled instead of being attracted and picked up by projectile.
Ionization cross section in He and H2

Atomic H and He: Cross-section relatively constant at velocities 0.2 - 1 a.u.
Molecular hydrogen: Cross-section proportional to antiproton velocity.

→ New mechanism for suppression of single ionization in molecule case?

Collide antiprotons with nuclei at energies $E = 100$ keV to 5 MeV and measure total annihilation cross-section $\sigma$.

C, Ni, Sn, Pt foil targets $\rightarrow$ Simple model suggests $\sigma \propto A^{2/3}$ dependence.

But at low energies $< 1$ MeV, $\sigma$ should deviate from this due to Coulomb interaction which focuses the antiprotons toward the nucleus.

Measurements at 5 MeV completed. 0.1 MeV ongoing.
Cross-sections @ 5 MeV consistent with theoretical expectations.

A. Bianconi et al, *Phys. Lett. B, accepted*
Conclusion: ASACUSA recent achievements

• First sub-Doppler two-photon laser spectroscopy of antiprotonic helium
  → Determined antiproton-to-electron mass ratio to 1.3 ppb.

• Microwave spectroscopy of antiprotonic helium
  → Determined antiproton magnetic moment to 0.3%.

• Produced Rydberg antihydrogen in cusp trap as a first step towards
  ground-state hyperfine structure spectroscopy with ppm-scale precision.

• First measurement of ionization cross-sections of <10 keV antiprotons in H2, He, Ar.

• First measurement of annihilation cross-sections of 5-MeV antiprotons in C, Pt, Sn, Ni.