Atomic collision and spectroscopy experiments with ultra-low-energy antiprotons

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Abstract. Antiproton, the antiparticle of proton, is a unique projectile in the study of atomic collision physics, which can be treated theoretically either as a ‘negative proton’ or a ‘heavy electron’. Atomic capture of an antiproton will result in formation of a highly excited exotic atom. Antiprotonic helium atom has been studied intensively by means of precision laser spectroscopy, which has led to a stringent determination of antiproton mass and charge to a level of ppb. Comparison of these values with those of proton gives one of the best tests of CPT invariance, the most fundamental symmetry in physics. However, the dynamic processes of antiproton capture remain unclarified. With an aim to produce an antiproton beam at atomic-physics energies for ‘pure’ collision experiments, we have so far developed techniques to decelerate, cool and confine antiprotons in vacuo, using a sequential combination of the Antiproton Decelerator (AD) at CERN, a Radio-Frequency Quadrupole Decelerator (RFQD), and an electromagnetic trap. Our recent success in stable extraction of monoenergetic ultra-slow antiprotons, about $3 \times 10^5$ in number available every 5 minutes, has opened up the possibility to study ionization and atomic capture processes between an antiproton and an atom under the single collision condition. Our design and strategy of the cross-beam experiments are presented, together with technical challenges in the detection system to identify the rare events with a reaction rate of $10^{-4}$.

1. Introduction
Antiproton is a unique probe for atomic physics researches. Having the same mass as the proton but with opposite charge, it behaves as a “heavy electron” or as a “negative nucleus”, and gives a new test ground for studies of atomic collision dynamics. In fact, it is a “theoreticians’ ideal projectile” because lack of electron capture processes avoids complication in theoretical treatments. In addition to various CTMC (Classical Trajectory Monte Carlo) calculations hitherto available [1], recently semi- and full-quantum treatments have become possible [2, 3]. Yet so far no experiment was possible at energies less than around 5 keV [4].

Experimentally, antiprotons can be produced at accelerator facilities, but only at a huge energy in the GeV range via the reaction $p + p \rightarrow p + p + p + \bar{p}$. The Antiproton Decelerator (AD) at CERN, Geneva, is a unique facility which provides cooled low-energy antiprotons with MeV energies. There, the ASACUSA collaboration has been doing researches on “Atomic Spectroscopy And Collisions Using Slow Antiprotons” [5].

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One branch of our activities is the spectroscopy of metastable antiprotonic helium atom [6]. This three-body atom consisting of a helium nucleus, an electron and an antiproton is a peculiar system, which can be regarded as a mixture of matter and antimatter, and yet shows longevity of a few microseconds at large quantum numbers of \( n \sim 38 \) and \( l \lesssim n \). Laser and microwave spectroscopy has not only revealed the level structure of this exotic atom [7, 8], but also assisted development of calculation techniques for the Coulombic three-body system, in the precision competition between the experiment and the theory [9]. Recent high precision in our laser spectroscopy has reached the level of \( 10^{-9} \) in determination of transition frequencies, and comparison with the theoretical QED calculations now gives one of the most precise values for the antiproton-to-electron mass ratio as well as the antiproton-to-proton mass ratio [10], contributing to the precise determination of the fundamental constant and to the test of CPT invariance theorem.

For the study of dynamic processes of atomic ionization and capture, an antiproton–atom cross-beam experiment would require an ultra-slow antiproton beam at a well-defined energy in the eV to keV range. We the MUSASHI group of the ASACUSA collaboration have developed a system consisting of a Radio-Frequency Quadrupole Decelerator (RFQD), an electromagnetic trap and an extraction beam line at the AD facility, and have recently succeeded in production of ultra-low-energy monoenergetic antiproton beams. These beams are crossed with an atomic gas-jet target, to study ionization and atomic capture processes of an antiproton projectile against various atoms \( \text{"A"} \), \( \bar{p} + \text{A} \rightarrow \text{p} + \text{A}^+ + e^- \) and \( \text{p} + \text{A} \rightarrow (\text{pA}^.)^0 + e^- \) for the first time under the single-collision condition at very low energies. This study will also reveal the properties of exotic antiprotonic atoms formed in vacuo.

### 2. Production of ultra-low-energy antiproton beams

The antiproton beam at 5 MeV from the AD at CERN needs further deceleration for them to be captured in vacuo electrostatically. We developed an RFQ Decelerator in which RF waves were applied to the cavities in such a way as to decelerate microbunches of the antiproton beam at 5.3 MeV down to 110 keV with an efficiency of 30% [11]. The output beam from the RFQD was injected into an electromagnetic trap in a strong magnetic field of 2.5 T produced by a superconducting solenoid. The beam was focused to a diameter of 3–4 mm on a thin Mylar foil used to isolate ultrahigh vacuum of \( 10^{-12} \) mbar inside the trap.

Antiprotons were then captured and confined in the trap, a Multi-Ring Trap (MRT) [12] consisting of 14 cylindrical electrodes, where they were sympathetically cooled by a plasma of typically \( 3 \times 10^6 \) electrons preloaded in the harmonic potential of 50 V depth. The total number of trapped antiprotons can be estimated from the signal counts of antiproton annihilation detected by scintillation track detectors installed beside the trap, with their detection efficiency of \( \varepsilon \sim 5\% \) taken into account. With this trap, we successfully confined \( 1.2 \times 10^6 \) cooled antiprotons until the end of our trap cycle of 1–5 minutes [13]. Typically 1 million antiprotons were trapped for each AD shot. We also demonstrated accumulation of antiprotons for several AD shots. This technique of “stacking” also worked fine, and we trapped \( 1.2 \times 10^7 \) antiprotons simultaneously for stacking of 12 AD shots, the largest number of antiprotons ever accumulated.

After quick kick-out of electrons from the trap, the antiprotons were eventually released as the potential was gradually shallowed, and were extracted as an ultra-slow continuous beam. Since the antiprotons tend to expand in radial direction when they follow the strongly diverging magnetic field line, it was essential that the antiproton cloud be well compressed radially in the trap. To actively compress the antiproton cloud, it was given torque by a rotating electric field, applied to one of the ring electrodes azimuthally segmented into four parts. The antiproton cloud was thus compressed from a radius of 3.4 mm to 0.25 mm in a period of 200 s [14].

The extraction beam line was designed to transport antiproton beams over a length of 3 m, at variable energies ranging from 10 to 1000 eV. The antiproton beams were refocused three
times by sets of Einzel lenses at the position of apertures. These variable apertures of diameter 4–10 mm allowed differential pumping of 6 orders of magnitude along the beam line [15], which was necessary to keep the trap region at an extremely high vacuum better than $10^{-12}$ mbar so as to avoid antiproton annihilation [11, 16].

The MRT, the superconducting solenoid and the transport line for the ultra-slow beam are jointly known as “MUSASHI”, or the Monoenergetic Ultra-Slow Antiproton Source for High-precision Investigations. MUSASHI opens a new research field ranging from atomic physics to nuclear physics including our near-future project of antihydrogen synthesis in a cusp trap [17].

3. Experimental designing of collision experiments

With this unique beam, atomic formation and ionization processes by very-low-energy antiprotons can now be studied under single collision conditions. Since the number of available antiprotons is very much limited, the reaction probability must be maximized for their best use. The number of antiprotonic atoms formed is given by the formula $N_{pA^+} = \sigma n_A L N_p$, where $\sigma$ is the formation cross section, $n_A$ the number density of the atomic target, $L$ the interaction length, and $N_p$ is the number of antiprotons.

Helium atom was chosen for our first target, for technical simplicity and because of the fact that the lifetime of antiprotonic helium atoms are already known from our spectroscopic measurements [18]. Our apparatus has 5 chamber stages in order to achieve good jet collimation and efficient pumping. A supersonic gas jet emerging at a stagnation pressure of 25 bar from a 0.1-mm-diameter nozzle was skimmed by two stages of conically shaped skimmers [19]. The gas jet was collimated to form a target of about 1 cm diameter at the cross point in the main chamber, before being collected at the dump stages. The vacuum in the main chamber was kept to a level of less than $10^{-6}$ mbar. With this setup, we have achieved a gas target density of $n_A = 3 \times 10^{12}$ atoms/cm$^3$. Suppose a beam with $3 \times 10^5$ antiprotons is available every shot per several minutes, we will obtain 10–100 antiprotonic atoms for a reaction cross section of the order of $10^{-16}$–$10^{-17}$ cm$^2$ [1]. The reaction probability is of the order of $10^{-4}$. Rigorous particle identification is necessary in order to assure enough statistical significance for the reaction events to be detected and distinguished from background events.

Antiprotons are extracted as a beam in a slow-extraction mode. This continuous beam allows event-by-event data acquisition associated with each single antiproton extracted. Figure 1 shows

![Figure 1. Schematic setup (left) and a photo image (right) of the modified version of detectors surrounding the collision point of the antiproton beam and the gas-jet target.](image-url)
a schematic layout of the detectors. Two MCP-PSDs were placed inside the gas-jet chamber, one downstream of the cross point along the antiproton beam path for detection of antiprotons hitting it, and another one sideways of the antiproton beam, to selectively detect electrons. They were surrounded by a box of scintillator plates for identification of antiproton annihilation by detecting passage of its annihilation products such as π mesons. A set of electrodes and coils were placed near the collision point to guide electromagnetically the electrons perpendicular to the antiproton beam. The TOF is shorter for electrons than for antiprotons due to the difference in their velocity. Thus a reaction event can be recognized by an electron signal (i.e. side-MCP hit and no scintillator hit) followed by an antiproton signal (i.e. coincidence between downstream-MCP hit and scintillator hit) with an appropriate TOF interval.

4. Summary and Outlook
We have succeeded in production of ultra-low-energy antiproton beams, using a combination of the AD facility, the RFQ Decelerator, the electromagnetic trap and the extraction beam line. This unique beam opens a new research field of atomic physics. We are planning in the future to make measurements in the 100–1000 eV region to reveal the ionization cross section curve which is totally unknown. Even theoretically, no reliable work has been done. A realistic calculation must include diabatic effects, whose methodology is not yet established. Atomic capture process will be studied at lower energies of 10–30 eV. Capture of an antiproton by an atom results in formation of an antiprotonic atom. The cross-beam experiment in vacuo is expected to populate higher-lying states at \( n > 40 \) with a much longer lifetime of 10–100 \( \mu \)s, in contrast to 3 \( \mu \)s in the case of formation at \( n \approx 38 \) in media. Our new measurements are thus expected to clarify the collision dynamics under well-defined single-collision conditions at fixed energies.

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