Development of Beam Profile Monitor for Antiproton Annihilation Cross Section Measurements by the ASACUSA Collaboration

K. Todoroki¹, T. Kobayashi¹, M. Hori¹,²
¹ Department of Physics, University of Tokyo, Hongo 7-3-1, Bunkyo-ku, Tokyo, Japan
² Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, D-85748 Garching, Germany
E-mail: todoroki@nucl.phys.s.u-tokyo.ac.jp

Abstract. The ASACUSA (the Atomic Spectroscopy And Collisions Using Slow Antiprotons) collaboration has developed various kinds of monitors which both destructively and non-destructively measure the spatial profiles of pulsed antiproton beams at the Antiproton Decelerator (AD) of CERN. These include detectors consisting of foil and wire electrodes based on gas ionization or secondary electron emission, which are compatible with ultra-high vacuum conditions. A new beam profile monitor with a grid of electrode pads fabricated on a normal glass-epoxy circuitboard was adapted for the measurement of antiproton annihilation cross sections. This monitor has an active area of 40 mm × 40 mm and a spatial resolution of 4 mm. It can measure the spatial profile of 40-50-ns-long beam pulses containing > 10⁴ antiprotons striking each anode strip.

1. Introduction
Several groups have previously measured the total cross sections of antiproton annihilations on targets of various mass numbers and antiproton energies of E > 0.6 MeV using the Low Energy Antiproton Ring (LEAR) of CERN[1–6]. The ASACUSA (the Atomic Spectroscopy And Collisions Using Slow Antiprotons) collaboration is planning to measure the cross sections at E ≈ 120–150 keV. No measurement has been carried out before in this energy region, and there are interesting model calculations[7, 8] that use strongly absorptive optical potentials, and predict a saturation of these total cross sections with increasing mass number. This measurement will be carried out using the Antiproton Decelerator (AD) of CERN and a radiofrequency quadrupole decelerator (RFQD) which decelerates antiprotons from E = 5.3 MeV to ∼ 100 keV. An achromatic momentum analyzer will be used to separate decelerated antiprotons from undecelerated ones, and focus these antiprotons on nanometer-thick target foils. This setup of the RFQD and the momentum analyzer were previously developed, and used for the laser spectroscopic measurements of antiprotonic helium atoms (pHe⁺) (Fig.1)[9, 10]. In order to ensure that antiprotons were precisely guided to the target position, we developed the beam profile monitor which we will report here.

The AD was a 188-m-circumference synchrotron which provided a 100–300-ns-long pulsed beam containing ∼ 3 × 10⁷ antiprotons with a kinetic energy of 5.3 MeV, a momentum spread of ∼ 0.2 %, and transverse emittance of ∼ 1.5π mm-mrad at a repetition rate of 0.01 Hz[11].

Published under licence by IOP Publishing Ltd
The RFQD consisted of four electrode rods of length $L = 3.5$ m which produced an average field $E \sim 2$ MV/m at a frequency $f \sim 202.5$ MHz. This decelerated some $\sim 30\%$ of antiprotons extracted from the AD[9, 12]. The energy could be varied between 10 and 120 keV by biasing the electrodes with a dc potential. An energy correction cavity at the upstream end of the RFQD was used to compensate for the changes in the energy of the incident beam resulting from this biasing and variations in the energy of the antiprotons extracted from the AD. The analyzer consisted of two dipole magnets which bent the beam twice at an angle $\theta = 20^\circ$, three 1T solenoids which focused it into a 10-mm-diam spot at the entrance of the experimental target, and three quadrupole magnets (triplet) which transferred the focal plane at the RFQD exit to the position of the target[9].

2. Measurements using the AD and the RFQD

Using the AD, the RFQD, and the achromatic momentum analyzer, the ASACUSA collaboration has previously produced $\bar{p}^4\text{He}^+$ and $\bar{p}^3\text{He}^+$ isotopes, and measured their transition frequencies to fractional precisions of $(9-16) \times 10^{-9}$[10]. By comparing the results with 3-body QED calculations, an antiproton-to-electron mass ratio of $M_{\bar{p}}/m_e = 1836.152674(5)$ was determined. Two-body antiprotonic helium ions $\bar{p}^4\text{He}^{2+}$ and $\bar{p}^3\text{He}^{2+}$ with 100-ns-scale lifetimes were also observed[13]. We will use the beam transport techniques developed in these earlier experiments for the present measurements of antiproton annihilation cross sections.

In 2008, a measurement of the total cross sections of antiproton annihilations $\sigma_{\text{tot}}$ was carried out using $E = 5.3$ MeV antiprotons extracted from the AD. The dependence of the cross section on various targets (Mylar, Ni, Sn, Pt) was studied[14]. This measurement contributed to an understanding of the dynamics of the antiproton’s annihilation process. Preliminary results indicate that the data is compatible with the expectation that the annihilation cross section should scale with $A^{3/2}$, where $A$ is the mass number of the target. This suggests that the saturation
effect (where $\sigma_{\text{tot}}$ deviates from $A^{2/3}$) reported for H, D, He targets at lower energies ($E < 1.8$ MeV) by the Obelix collaboration[1–3] is not present for these targets at $E = 5.3$ MeV.

In the planned measurement of the total cross sections of antiproton annihilations at $E \sim 120–150$ keV, the experimental setup will be similar to those of the laser spectroscopic measurements of antiprotonic helium atoms ($\bar{p}\text{He}^+$)[9, 10]. The target foils will be placed instead of the cryogenic helium target (Fig.1). One of the difficulties of this experiment is that antiprotons annihilating on the wall of apparatus or the 10-cm diameter frame of the target produces a large background of charged pions that can saturate the tracker detector. In order to reduce or eliminate this, the pulsed antiproton beam must be finely tuned so that the diameter of the beam on the target would be less than 20 mm. A beam profile monitor operating at the target’s position is therefore needed.

3. Beam profile monitors at the ASACUSA collaboration

The ASACUSA collaboration has so far developed three kinds of beam profile monitors to measure antiprotons of energies $E = 60$ keV–5 MeV[15, 16]. The first of these was a parallel plate ionization chamber (PPIC) which was operated at gas pressure $P = 65$ mbar[15]. The PPIC consisted of three parallel polyester foils of 1.5-mm thickness (an anode foil and two position-sensitive cathodes mounted at a distance of 2 mm) evaporated with layers of segmented gold electrodes. The spatial profile of the beam was obtained by measuring the electric charge induced on the 40 strip electrodes on the two cathode foils, and read out by 40 charge-sensitive preamplifiers.

The second profile monitor was a secondary electron emission detector which was operated in the ultra-high vacuum ($< 10^{-9}$ mbar) of the AD[15]. This monitor consisted of an anode

![Figure 2. Layout of readout electronics of the photocathode wire beam profile monitor. For details see Ref.[16]](image-url)
foil and two position-sensitive cathode foils mounted on either side to provide the X- and Y-projections of the beam with 4-mm spacings between each foil. When antiprotons struck the strip electrodes on the X- and Y- projection cathode foils, secondary electrons were emitted from their surfaces, and accelerated toward the anode foil which was biased at a voltage of 50 – 100 V. The spatial beam profile was obtained by measuring the electric charge ejected from each electrode.

The third monitor was a nondestructive and sensitive detector consisting of photocathode wire grids arranged in an XY configuration[16]. Each grid consisted of 32 gold coated tungsten wires of diameter \( d = 10 \mu m \) stretched over a ceramic frame with a pitch of \( \Delta x = 1 \text{ mm} \) between neighboring wires, active area of 32 mm \( \times \) 32 mm, and optical transmission of \( \sim 98\% \). The photocathode grids which were biased at \(-50 \text{ V}\) were irradiated by the beam, and the photoelectrons or secondary electrons emitted from them were accelerated toward the anode grids which was grounded. The beam profile was obtained measuring the charge ejected from each of the 64 wires on the X- and Y- photocathode grids (Fig.2). Three monitors of this type will be used in the nuclear collision experiment.

We recently adapted a new monitor similar to the secondary electron emission detectors described above to measure destructively the spatial profile at the target’s position with an active area of 40 mm \( \times \) 40 mm, and a resolution of 4 mm. It consisted of cathode micro wires of 20-\( \mu \text{m} \) diameter, and anode pads fabricated on a four-layered electric board of thickness \( t_d = 2 \text{ mm} \) made of an FR4-type glass epoxy (Fig.4). On the first layer (upstream side), there were 400 pads arranged in a checker-board pattern. Rows of 20 neighboring electrodes were electrically connected together by a circuit pattern embedded in the second layer (Fig.3). Columns of 20 neighboring electrodes were similarly connected by a circuit pattern in the third layer. The fourth conductive layer provided electromagnetic shielding. In this way, the X- and Y- projections of the beam profile were measured. Electrical connections between the layers were established by through-hole vertical interconnect accesses (vias) of diameter \( d \sim 500 \mu \text{m} \). These vias were

![diagram](image.png)

**Figure 3.** Layout of the first layer of the anode pads (left) and the second layer of the circuit pattern (right, see text) of the profile monitor. Each row connects 40 through-hole vias (indicated with red color) and a through-hole via connecting to a readout cable. The first layer of anode pads and the second layer of rows are connected by through-hole vias (indicated with red color).
filled by epoxy. The epoxy surfaces were then electrolytically plated with copper, nickel, and gold layers of respective thicknesses $t_d = 40 \mu m$, $1 \mu m$, and $70 \text{ nm}$. All other surfaces of the circuit board were similarly plated and grounded to avoid charge up, and minimize outgassing in vacuum. The insulators separating the anodes and cathodes were made of alumina of purity 99.5%. This nuclear collision experiment will be carried out in a relatively modest vacuum of $10^{-7} \text{ mbar}$. On the other hand, the detector is required to be lightweight (in this case $\sim 80$ g) so that it can be mounted on a delicate manipulation arm in the experimental target. Generally, ceramic boards would provide a better ultra-high vacuum compatibility, but we decided to use glass epoxy due to the above reasons, as well as its lower cost and faster delivery.

As in our previous detectors, the spatial profile of the beam will be obtained by measuring the charge which is induced by antiprotons hitting the segmented anode and releasing electrons which are collected by the cathode micro wires biased at 50 V. The charge is transmitted by a 2-m-long ribbon cable with Kapton insulation and a vacuum feedthrough to the outside of the experimental apparatus. The signal is measured by charge-sensitive preamplifiers with a charge-to-voltage conversion ratio of $\sim 1 \text{ V/pC}$ (Fig.2). The capacitance of the 2-m-long cable is relatively large ($\sim 50 \text{ pF/m}$) and this limits the sensitivity of the detector. We estimate the equivalent noise charge[16] to be around 1000 electrons. Based on our experience with our previous profile monitors[15,16], we expect that this monitor would be sensitive to pulsed beams containing $>10^4$ antiprotons. We initially planned to place a microchannel plate (MCP) in front of anode pads to provide higher sensitivity. The profile would be obtained by measuring secondary electrons which were produced by antiprotons striking the MCP, multiplied by it, and collected by the anode pads. However, preliminary measurements using pulsed antiproton beams have shown that a MCP is unnecessary to produce a strong signal in the nuclear collision experiment.

Despite the simplicity and low cost of this monitor, it is sensitive enough to measure the profiles of antiproton beams containing $>10^4$ antiprotons. We can finely tune a pulsed

![Figure 4](image-url)
antiproton beam using this and our previous profile monitors.

Acknowledgments
The authors are grateful to R. S. Hayano, E. Lodi Rizzini, M. Corradini, M. Leali, V. Mascagna, M. Mitani, A. Soter, L. Venturelli, N. Zurlo and ASACUSA collaborators. The development of the profile monitor was supported by the Grant-in-Aid for Specially Promoted Research (20002003) of MEXT, Japan, the European Science Foundation, and the Munich Advanced Photonics Cluster of the Deutsche Forschungsgemeinschaft (DFG).

References
[1] Bertin A et al. 1996 Phys. Lett. B 369 77
[2] Zenoni A et al. 1999 Phys. Lett. B 461 405
[3] Zenoni A et al. 1999 Phys. Lett. B 461 413
[4] Brückner W et al. 1990 Z. Phys. A 335 217
[5] Bianconi A et al. 2000 Phys. Lett. B 481 194
[6] Bianconi A et al. 2000 Phys. Lett. B 492 254
[7] Gal A et al. 2000 Phys. Lett. B 491 219
[8] Batty C J et al. 2001 Nucl. Phys. A 689 721
[9] Hori M et al. 2003 Phys. Rev. Lett. 91 123401
[10] Hori M et al. 2005 Phys. Rev. Lett. 94 063401
[11] Belochitskii P 2007 Proc. of COOL 2007 Bad Kreuznach Germany
[12] Pirkl W, Lombardi A M and Bylinsky Y 2001 Proc. of the 2001 Particle Accelerator Conf. Chicago p 585
[13] Hori M et al. 2006 Phys. Rev. Lett. 96 243401
[14] Corradini M et al. 2009 Hyperf. Interact. 194 305
[15] Hori M 2004 Nucl. Instr. Meth. A 522 420
[16] Hori M 2005 Rev. Sci. Instr. 76 113303