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Instrumentation for measurement of in-flight annihilations of 130 keV antiprotons on thin target foils

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ABSTRACT

We describe the instrumentation for an experiment to measure the cross sections of antiprotons with kinetic energies of 130 ± 10 keV annihilating on carbon, palladium, and platinum target foils of sub-100 nm thicknesses. A 120 ns long pulsed beam containing 10^5–10^6 antiprotons was allowed to traverse the foils, and the signal annihilations that resulted from this were isolated using a time-of-flight method. Backgrounds arose from Rutherford scattering of the antiprotons off the target foils, their annihilations in the target chamber walls, and $\pi \to \mu \to e$ decay of the charged pions that emerged from the annihilations. Some antiprotons slowed down and annihilated in the contamination on the target surfaces. This reduced the signal-to-background ratio of the measurement.

1. Introduction

The cross sections σ_A of antiprotons annihilating on various target nuclei have been measured over a wide range of kinetic energies K of the incident antiproton [1]. The data have been used to interpret some observations of the diffuse cosmic gamma-ray background, and to estimate an upper limit on the ratio between the hadronic matter and antimatter in the universe [2,3]. The ASACUSA (Atomic Spectroscopy and Collisions Using Slow Antiprotons) collaboration is currently attempting to measure σ_A for $K = 130$ keV antiprotons annihilating in C, Pd, and Pt target foils [4]. Since the ranges of antiprotons in these foils are a few microns or less, experimental methods employed previously at higher energies cannot be used. This paper presents part of the instrumentation to measure σ_A using the time-of-flight of the slow antiprotons to isolate the signal annihilations that occurred in the foils.

Past experiments at the Low Energy Antiproton Ring (LEAR) of CERN [5] have measured σ_A of H, D, ^{3}He, ^{4}He, and Ne gas targets at antiproton energies $K > 700$ keV. In one experiment, a streamer chamber [6] placed in the continuous antiproton beam of LEAR photographed the tracks of secondary particles emerging from the annihilations. In another measurement, plastic scintillator hodoscopes [7] counted the secondary charged pions produced in a liquid helium target. Other classes of experiments also measured the spatial distributions of the annihilations of the antiprotons as they slowed down and came to rest in low-density gas targets, using spiral projection and jet drift chambers [8–11], or bubble chambers filled with D_2 gas [12,13]. These data were compared with energy loss calculations to determine σ_A.

Until recently, the σ_A–values for heavier nuclei were predominantly measured by transmission methods. The numbers of incident and transmitted antiprotons N_{in} and N_{out} through a target foil were counted using plastic scintillators, multiwire proportional chambers [14–17], or Čerenkov counters [18]. The equation,

$$N_{out} = N_{in}\exp(-\rho\sigma_A), \qquad (1)$$

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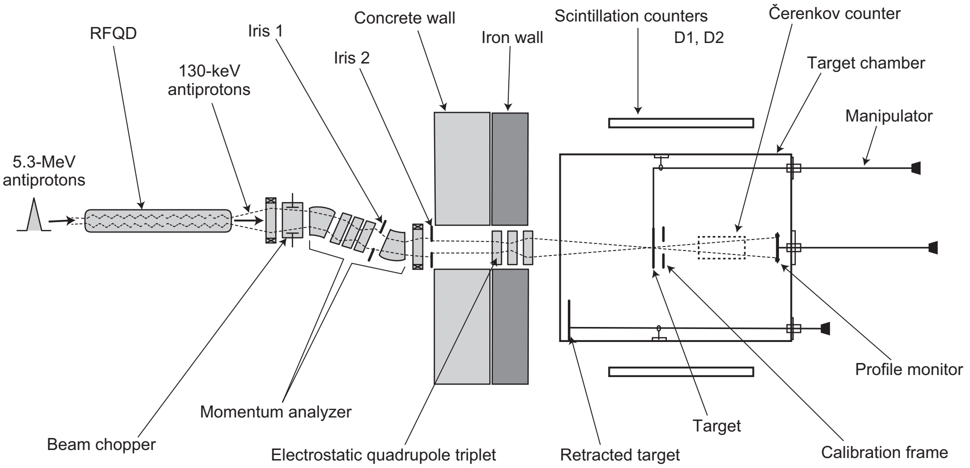

Fig. 1. Experimental layout. Whole beamline was evacuated to avoid energy loss of the antiprotons. A 200 ns long pulsed beam of antiprotons with a kinetic energy $K=5.3$ MeV were extracted from the AD. It was decelerated by a radiofrequency quadrupole decelerator (RFQD) to $K \sim 130$ keV. A beam chopper reduced the pulse length of the beam to $\Delta t \sim 120$ ns. The beam was transported by a momentum analyzer, and focused on a <100 nm thick target foil positioned within a vacuum chamber. Signal annihilations in the foil were detected by two types of scintillation counters D1 and D2. For some of the measurements, a calibration ring frame positioned downstream of the target intercepted the antiprotons that underwent Rutherford scattering in the target. The relative intensity of each antiproton pulse was measured by detecting the flux of secondary particles emerging from the annihilations in the end wall of the target chamber using a Čerenkov counter. Concrete and iron walls reduced the flux of background particles striking the scintillation counters. Drawing not to scale. See text.

was then used to determine σ_A, where ρ denotes the target thickness. Since it was difficult to adapt this method to very slow antiprotons, the σ_A-data for heavier target nuclei were restricted to energies $K > 130$ MeV.

The 5.3 MeV pulsed antiproton beam provided by the Antiproton Decelerator (AD) of CERN was recently employed [19,20] to measure σ_A of Mylar, Ni, Sn, and Pt targets. Scintillation fibers were used to reconstruct the annihilation vertices by measuring the tracks of secondary charged particles emerging from the target foils.

The results of all these measurements of σ_A are consistent with the predictions of a modified black-disk model [21,22]. The model implies that the antiprotons are strongly absorbed at the nuclear surface, i.e., that the imaginary part of the optical potential of the antiproton–nucleus system is larger than the real part. We attempted to expand the σ_A-measurements to low-energy regions where experimental data were not available.

2. Experimental methods

We used thin ($t_d < 100$ nm) target foils to prevent the incoming antiprotons from slowing down and stopping in them, and thus producing an irreducible background. C targets much thicker than $t_d = 100$ nm would cause an intolerably large ($\Delta K \gg 10$ keV) energy loss to a traversing 130 keV antiproton. This makes it difficult to utilize any technique that involves the interception of the beam by a counter to measure σ_A. Vertex reconstruction could not be easily used because the instantaneous flux of the pulsed antiproton beam was too high to efficiently reconstruct the many tracks of secondary particles emerging from the annihilations in the target. Since sufficient experimental statistics had to be collected despite the low repetition rate $f_r = 0.01$ Hz of the AD beam, its instantaneous flux could not be further reduced.

We therefore devised a time-of-flight method involving the use of a pulsed antiproton beam of short ($\Delta t = 120$ ns) duration. A small fraction ($\sim 10^{-5}$) of the antiprotons directed to the target foil annihilated in it, whereas the remainder transversed it and reached the end wall of the target chamber after a time-of-flight of ~200 ns. Scintillation counters detected the charged pions from all these annihilations. Depending on the variety of nuclei on which an antiproton annihilated, about 2–3 charged pions with an average momentum of a few hundred MeV momentum emerged. The timing of the scintillator hits provided a map of the longitudinal positions of the annihilations along the beamline, since the antiprotons were slow ($\beta \sim 0.017$) and the duration of the pulsed antiproton beam was short compared to the size of the apparatus. The intervals between the pions emerging from the annihilations and their arrival at the scintillators made only small contributions to the total time-of-flights.

We selected hits with the correct timings of antiprotons striking the target, and rejected backgrounds caused by annihilations on the lateral and end walls that occurred at later times. We determined σ_A by counting the number of such signal annihilations, and normalizing this against the number of antiprotons that underwent elastic scattering in the target foil, before annihilating in a calibration ring frame positioned downstream of the target (see Section 5). We assume that the elastic scattering follows a simple Rutherford formula. As the same scintillation detectors were used to measure the in-flight annihilation and elastic scattering signals, this normalization method is relatively insensitive to the systematic uncertainties of estimating the absolute number of antiprotons in the beam or the detection efficiency of the scintillators.

3. Experimental setup

The experimental layout is shown in Fig. 1. The entire experimental beamline was evacuated to a pressure of $<10^{-5}$ Pa to prevent energy loss of the antiprotons. A pulsed beam containing 2×10^7 antiprotons of energy $K=5.3$ MeV was extracted from the AD at a repetition rate $f_r = 0.01$ Hz [23]. A radiofrequency quadrupole decelerator (RFQD) was used to decelerate ~20% of the antiprotons to $K \sim 130$ keV [24]. The physical emittance of the beam increased as its velocity was reduced. An achromatic momentum analyzer separated the 130 keV antiprotons from the beam that was not fully decelerated, and transported them to the position of the target foil [25,26]. An adjustable iris placed after the analyzer (indicated as "Iris 2" in Fig. 1) removed the spatial halo in the beam. An electrostatic quadrupole triplet [26] then focused the beam on the target. The beam had an energy spread of ± 10 keV, and a transverse emittance of $>50\pi$ mm mrad. The quadruple triplet of aperture $d = 100$ mm consisted of twelve cylindrical electrodes