論文内容の要旨

論文題目　A First Attempt to Measure In-flight Antiproton-nucleus Annihilation Cross-sections at 16 MeV/c
(16 MeV/cにおける反陽子・原子核消滅断面積測定の初の試み)

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The Standard Model is currently unable to fully explain the baryon asymmetry in the universe, i.e., the fact that stars, dust, and gas consist exclusively of particles and not antiparticles. One possibility is that local concentrations of matter and antimatter are distributed inhomogeneously in the universe. Intensive work was carried out to search for antimatter clusters by detecting the cosmic gamma-ray background. Since annihilations at the boundaries between matter and antimatter clusters should produce π^0s which decay into two gamma-rays, which contribute to the cosmic gamma-ray background. The cross sections of antiprotons annihilating in-flight on various target nuclei are needed to estimate an upper limit on the ratio between the amount of antimatter and matter from this experimental data. Assuming cross sections of 0.5 - 500 barn which depend on the momentum of the antiproton, the antimatter-matter fraction was constrained as 10^{-5} - 10^{-9}.

Various measurements were carried out previously. The cross sections of antiprotons annihilating in-flight on hydrogen, deuterium, helium-3, helium-4, and neon gas targets have been measured in the momentum region $p > 40$ MeV/c mainly at the Low Energy Antiproton Ring (LEAR) of the European Organization for Nuclear Research (CERN). Most of these experiments measured the annihilations of low-momentum antiprotons which slowed down and came to rest in low-density gas targets. This data was compared with energy loss calculations to determine the annihilation cross sections at low momenta.

The annihilation cross section data for heavier target nuclei measured at LEAR, the National Laboratory for High Energy Physics (KEK), BNL, and the Institute for Theoretical and Experimental Physics was restricted to much higher momenta $p > 500$ MeV/c, because the above tracking methods could not be applied in the case of dense solid targets. In this momentum region, so-called transmission methods were mainly used. The numbers of incident and transmitted antiprotons N_{in} and N_{trans} through target foils were compared using plastic scintillators and multi-wire proportional chambers, and the annihilation cross sections were determined using the equation, N_{in} e^{-$\rho\sigma$} = N_{trans}, where ρ denotes the thickness of the target, and σ the annihilation cross section. Later, the Antiproton Decelerator (AD) of CERN provided 100-MeV/c pulsed antiproton beams. Using this facility, the annihilation cross sections of antiprotons on

Mylar, Ni, Sn, and Pt foil targets at p = 100 MeV/c were measured by the ASACUSA (Atomic Spectroscopy And Collisions Using Slow Antiprotons) collaboration. Tracks of charged particles were reconstructed by scintillation fibers surrounding the targets. The annihilation cross sections were determined by counting the reconstructed vertices which originated from the foils.

The ASACUSA collaboration in this measurement developed a method to measure the in-flight antiproton-nucleus annihilation cross sections at an antiproton momentum p = 16 MeV/c using carbon, palladium, and platinum targets of sub-micron thickness. Such a low momentum region has never been studied before, due to the technical difficulties in obtaining a 16-MeV/c antiproton beam of sufficiently low emittance, and because conventional methods of measuring cross sections could not be used. The difficulty to obtain a 16-MeV/c antiproton beam was solved by using the AD and a radio-frequency quadrupole decelerator which decelerates 100-MeV/c antiprotons to the momentum of 16 MeV/c. The reason why the conventional methods could not be used is the followings. In orde to avoid antiprotons from slowing down, coming to rest in the target foil, and producing an irreducible background, the thickness of the target foils had to be kept extraordinarily small. The range of a 16-MeV/c antiproton in a C target material is only about 3 μm. In fact, the energy loss in a > 100-nm-thick carbon foil is already significant (> 10 keV) compared with the incident beam energy (130 keV). The probability of signal annihilation events occurring in a 100-nm-thick target foil is very low (10^{-5}). The majority of antiprotons (99.999 %) traversed the target foil without contributing to the signal, and instead became a background source by annihilating in the end wall of the apparatus. Elastic Rutherford scattering from these foils also constituted an additional significant background source. In addition, any antiproton annihilating upstream of the experiment generated background from $\pi \rightarrow \mu \rightarrow e$ decay and slow neutrons; these background annihilations were typically 10^5x more than the number of signal events. The experimental methods used for many years to measure the annihilation cross sections with continuous antiproton beams of high momenta p > 500 MeV/c cannot be directly utilized in the case of the 16-MeV/c pulsed beam of the AD. The requirement of using a very thin target foil (100 nm) restricts the types and configurations of detectors that can be used, and makes it difficult to implement any method that involves interception of the beam, such as the transmission method. Vertex reconstruction cannot be easily utilized because the instantaneous flux of the pulsed antiproton beam is too high to reconstruct the many tracks of secondary particles emerging from the target. Sufficient experimental statistics must be collected despite the low repetition rate f = 0.01 Hz of the AD antiproton beam. This implies that we cannot afford to reduce the antiproton beam intensity to a level which would allow normal counting methods to be used.

Our new technique uses the timing information of the antiproton annihilation signals to distinguish the in-flight annihilation events that occur in the target from backgrounds caused by the $\pi \rightarrow \mu \rightarrow e$ decay, Rutherford scattering, and annihilations in the surrounding experimental apparatus. Of the antiprotons that were directed at the target foil, a small fraction (~ 10^{-5}) annihilated in the target, whereas the remainder transversed it and reached the end wall of the target chamber after a time-of-flight of ~ 200 ns. We detected the charged pions from all these annihilations using scintillation counters, recorded the analog waveforms of the scintillator signals, and counted the number of peaks N_{hit} in the waveforms which corresponded to the pion hits. The timing of the pion hits provided a spatial map of the positions of the annihilations along the beamline, since the velocity of the antiprotons were sufficiently low (v/c ~ 0.014) compared to the size of the apparatus, and the charged pions (v/c ~ 1) whose contribution to the total time-of-flight could be neglected. Using this timing information, we selected hits corresponding to timings when antiprotons struck the target, and rejected backgrounds caused by antiprotons which transversed the target and annihilated on the lateral and end walls of the target chamber.

In order to focus a 120-ns-long pulsed beam of 16-MeV/c momentum on the foil target, a beam profile monitor, beam chopper, and electrostatic quadrupole triplet were developed. The beam profile monitor which was based on the secondary electron emission was placed at the target position. It had an active area of 40 mm x 40 mm and a spatial resolution of 4 mm. The monitor consisted of cathode micro wires of 20-μm diameter, and anode pads fabricated on a four-layered electric board of thickness t_d = 2 mm made of an FR4-type (Flame Retardant Type 4) glass epoxy. Generally, ceramic boards would provide ultra-high vacuum compatibility, but the glass epoxy was chosen because this experiment was carried out in a relatively modest vacuum of 10^{-7} mbar. It also had the advantages of being lightweight and low cost. On the first layer (upstream side) of the electric board, 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. 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 vertical and horizontal projections of the beam profile were measured. Electrical connections between the layers were established by through-hole vertical interconnect accesses (vias) of diameter d ~ 500 μm. These vias were filled by epoxy. The epoxy surfaces were then electrolytically plated with copper, nickel, and gold layers of respective thicknesses t_d = 40 μm, 1 μm, and 70 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 with a purity of 99.5 %.

The electrostatic quadruple triplet consisted of four stainless-steel cylindrical electrodes of radius R = 57.5 mm, which were radially spaced to obtain an aperture radius A = 50 mm. The ratio R/A = 1.15 produced a nearly ideal electrostatic quadrupole field near the axis of the triplet lens. The inner and outer quadrupoles of the triplet were 200 and 100 mm in length, respectively. They were biased at ± 5.0 and

± 4.5 kV. The lengths and applied voltages of the electrodes were optimized using the software package SIMION.

The beam chopper consisted of two rectangular electrodes of size 100 mm x 130 mm made of oxygen-free high conductivity copper placed parallel to each other with a gap of 20 mm. The electrodes were suspended within a CF 160 vacuum chamber using ceramic spacers. A 20-mm-diameter iris was placed 1.5 m downstream at the center of the momentum analyzer. The chopper worked in the following way. (i) A voltage pulse with an amplitude of + 3 kV was initially applied to the upper electrode, while the lower electrode was maintained at 0 kV. The antiprotons were deflected at an angle of ~ 0.08 radians by the transverse electric field $E_{chopper}$ = 150 kV/m. The iris cut the antiprotons which were deflected > 100 mm upward at its position. (ii) The voltage on the upper electrode rapidly returned to 0 kV in a stepwise manner, so that the antiproton were no longer deflected, and were instead transmitted to the experimental target. (iii) Finally, a - 3 kV pulse was applied to the lower plate, so that the antiprotons were again deflected upwards, and allowed to annihilate on the iris.

By making use of this new experimental apparatus, we succeeded in observing in-flight annihilation signals as a clear peak in the time spectra for the first time, and found a new, previously unreported systematic error which became important only because of the extremely low momentum of the antiproton beam. This anomalous background annihilations, presumably due to microscopic dust on the target surfaces, prevented us from measuring accurate values for the cross sections. We were able to deduce the upper limits of the cross sections for carbon, palladium, and platinum targets as σ(C) < 30 barn, σ(Pd) < 200 barn, and σ(Pt) < 500 barn, respectively. The bounds on these limits are within factor 2 - 3 of the theoretical values calculated by the modified black-disk model and the 'tρ' potential model based on past experimental data at higher momenta and X-ray spectroscopy of antiprotonic atoms. The method has now been established, and can be extended to measurements of antiproton annihilation cross sections over unexplored regions in the future with the Extra Low Energy Antiproton ring which will provide much smaller beam (~ 2 mm) than the AD.