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SEARCH FOR NARROW STRUCTURE IN PROTON-ANTIPROTON ANNIHILATION
CROSS SECTIONS FROM 1900 TO 1960 MEV*

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ABSTRACT

The $\bar{p}p$ annihilation cross section has been measured with good resolution (~ 2 MeV rms) in the mass range 1900-1960 MeV. No narrow structures are seen, the 90% confidence level upper limit being 8-12 mb-MeV for the integrated area of a resonance in this mass range. However, we do not rule out a very narrow bump-dip structure seen in an earlier experiment in the 1935-1941 MeV mass interval. The data also do not support the existence of a broad structure previously reported at 1937 MeV.

In the past ten years several $\bar{p}p$ formation experiments have reported evidence for a narrow structure in the total and annihilation cross sections in the S(1936) region, while other experiments have found their data to be inconsistent with the existence of such a state. These conflicting results in the total cross sections are summarized in Fig. 1, taken from recent papers of Nakamura et al [1] and Clough et al [2]. The annihilation cross sections which are equally conflicting are summarized in Table 1 where the properties of the reported signals [3-6] as well as the upper limits for the negative results are given [7,8], and plotted in Fig. 2.

We report here our measurement of the $\bar{p}p$ annihilation cross

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Fig. 1: Total cross section from (a) Ref. 1, (b) Ref. 2.

Fig. 2: Annihilation cross sections from Refs. 4-8 and from this experiment.

sections with at least one charged particle in the mass range 1920-1960 MeV with good mass resolution (~ 2 MeV rms). In addition we have been able to explore the 1900-1920 MeV region, heretofore unexplored. We report that our data are inconsistent with the existence of narrow structure between 1910-1950 MeV with smaller upper limit than previously reported negative results. These new results are also plotted in Fig. 2 for purposes of comparison and completeness.

The experiment was performed in the low energy separated beam at the Brookhaven National Laboratory AGS with an existing spectrometer and represents a continuation and improvement over a previous measurement [8]: wider mass range, significant increase in statistics and a modest improvement in resolution. In the beam transport system (Fig. 3) individual antiprotons were identified and momentum analyzed by time-of-flight (TOF) and magnetic optics, utilizing scintillation counter S_2 , a new scintillation counter hodoscope BH 468 cm upstream of S_2 and improved drift chambers BDC1 and BDC2 (9 and 6 sense planes respectively). The beam was then allowed to

Table 1: $\bar{p}p$ annihilation experiments in the S(1936) region.

Experiment	Ref.	Mass (MeV)	Γ (MeV)	$\sigma\Gamma$ (mb-MeV)	Mass Resolution at 1936 (MeV)
Chaloupka et al	3	1936	9	28 ± 20	1.5 rms
Bruckner et al	4	1939	≤ 4	26 ± 6	4 FWHM
Hamilton et al	5	1937	21	225 ± 127	1.5 rms
Ansler et al	6	1935-1941 (bump-dip)			0.4 rms
Jastrzemski et al	7	upper limit		12 (90% CL for $\Gamma \leq 4$)	1.5 rms
Lowenstein et al	8	upper limit		16 (90% CL for $\Gamma \leq 4$)	2.5 rms
This experiment		1910-1940 upper limit		8 (90% CL for $\Gamma \leq 4$)	2.0 rms
		1940-1960 upper limit		8-12 (90% CL for $\Gamma \leq 4$)	2.6 rms

interact in a 50 cm long, 20 cm diameter liquid hydrogen target, surrounded by a cylindrical drift chamber (CDC) consisting of two axial and two stereo ($\pm 16^\circ$) cylinders of sense wires. To one side of the target and CDC were placed a large six-plane drift chamber (3x,3y) and a single plane (u,10°) drift chamber (UDC). The annihilation vertex was determined by the intersection of the beam trajectory, as measured by BDC2, and a produced secondary particle trajectory, as measured by the combination of the CDC, UDC and RDC.

Antiprotons entering the target were triggered by the counter logic $\bar{p} \equiv BH \cdot S_2 \cdot TOF(S_2 - BH) \leq 20 \text{ ns} \cdot PH(S_2) \leq 3 \text{ x min.}$, where $PH \equiv$ pulse height. The target was surrounded by a twelve element barrel-slat hodoscope (M_{1-12}), with M_{3-6} facing the RDC. In addition, the front face of the RDC was covered by a hodoscope of eight vertical counters (R_{1-8}). Annihilation events were triggered by the sequence $A \equiv \bar{p} \cdot (M_{3-6}) \cdot (R_{2-7})$. Typically, the intensity of the untriggered beam was 500 $\bar{p}$ /sec and $2 \times 10^5 \pi^-$ /sec. The $\bar{p}$ trigger resulted in a pion rejection factor of better than $10^5:1$. Nine in-flight beam momenta were chosen to give the desired mass acceptance from 1900 to 1960 MeV: 455, 475, 495, 520, 540, 560, 580, 600 and 620 MeV/c. In addition, carbon degraders were used periodically to stop the beam in the target for the purpose of absolute momentum calibration, and a 400 MeV/c beam was stopped directly in the target without the use of degraders.

In Fig. 4 we show the longitudinal profile of vertices for three representative in-flight runs, as well as the 400 MeV/c stopping run.

Fig. 3: Schematic layout of experiment.

The S₂ counter (3 mm thick) is clearly seen in all the runs. Fits to a gaussian peak plus a smooth background (due to the nearby presence of insulation and a vacuum window in the target assembly) give an rms width of 1.75 ± 0.20 cm, which determines the vertex resolution for events in the target. Due to the momentum-dependent energy loss of the beam in the liquid hydrogen,

Fig. 4: Longitudinal profile of annihilation vertices for 400, 455, 520 and 580 MeV/c runs.

Fig. 5: Measured TOF for beam antiprotons, referenced to 468 cm/ $\langle\beta c\rangle$, for the nine in-flight runs.

this vertex resolution introduces an rms uncertainty to the momentum of the antiproton at its point of interaction which varies from 3.9% (1900 MeV) to 0.4% (1960 MeV). The width of the 400 MeV/c stopping peak (2.9 ± 0.2 cm rms) is a convolution of this vertex resolution with contributions from the momentum spread in the beam (2.1 cm rms) and calculated range straggling (0.8 cm rms) effects.

The momentum of individual interacting antiprotons was determined by two independent methods: TOF and magnetic optics. In Fig. 5 we show TOF measurements, referenced to their average value of 468 cm/ $\langle\beta c\rangle$. All nine sets of in-flight data are consistent with an rms resolution of 780 ps. The resolution has been limited by the small size (3x25x32 mm) of the BH scintillators and long lightguides (100 cm), and hence low light output. The resultant rms momentum uncertainty due to TOF alone varies from 1.6% (1900 MeV) to 2.7% (1960 MeV), when data are limited to $|\Delta\text{TOF}| < 3$ ns. For further improvement of momentum measurement we utilize the momentum dispersion vis-a-vis transverse horizontal coordinate at the position of the 9H12 magnet (Fig. 3) by studying the correlation of momentum (determined from range in liquid hydrogen) versus the horizontal coordinate of the stopping runs. The results are shown in Fig. 6 for four representative momenta. An average dispersion of $0.24 \pm 0.03\%/cm$ is observed in agreement with the expected value of 0.28%/cm from beam-line Monte Carlo calculations. Thus we are able to improve individual particle momentum values by measuring the transverse coordinate at the 9H12 which provides a position dependent correction to the value determined by TOF.

Fig. 6: Correlation of momentum as obtained from vertex measurement versus the transverse horizontal position at the center of the 9H12 magnet at 455, 495, 560 and 600 MeV/c.

Fig. 7: (a) The rms errors in $\bar{p}p$ mass as a function of mass. Also shown are momentum errors due to various contributions; (b) the percentage difference of two independently determined average momenta of stopping runs and in-flight runs.

This procedure of beam momentum determination plus the vertex uncertainty discussed above produces rms errors (δW) in $\bar{p}p$ mass as a function of mass (W) as shown in Fig. 7(a). Also shown are the fractional momentum errors due to various contributions. Note that the δW vary between 1.8 (at 1900) and 2.6 MeV (at 1960 MeV), the value in the S(1936) region being 2 MeV. For the purpose of absolute momentum calibrations, we compare in Fig. 7(b) the fractional difference of two independently determined average momenta of (i) stopping runs (based on the range in the liquid hydrogen and energy loss in the beam channel) and (ii) in-flight runs (based on the TOF data, improved with the momentum dispersion). We find that for all runs these average momenta agree better than 0.3%, thereby establishing a limit on systematic errors for the momentum measurement in this experiment.

To obtain annihilation cross sections, we have compared our data with a detailed Monte Carlo acceptance calculation that includes geometry, apparatus inefficiencies, energy loss and beam attenuation in the target due to elastic, charge-exchange and all-neutral annihilation processes. The momentum distributions of produced particles were assumed to be given by phase space alone, and angular distributions of particles were assumed to be isotropic in the C.M. Multiplicities were taken from previous measurements [9]. Ratios of data yield to Monte Carlo yield versus $\bar{p}p$ mass are shown in Fig. 8 and

Fig. 8: Ratio of data to Monte Carlo yields for the nine in-flight runs.

while above this mass range the limit rises to 12 mb-MeV (see Table 1).

The results of Amsler *et al* [6] are unique among those which have reported narrow structures near the $S(1936)$ because their resolution is exceptionally good (0.4 MeV rms) and they have reported an unusual bump-dip structure for 6 data points between 1935-1941 MeV. In an attempt to test the sensitivity of the present experiment to this effect, we have smeared their data with our resolution function (2 MeV rms) in the interval 1916-1960 MeV, using the same statistics as in the present experiment. We have fitted this distribution with a smooth $A+B/p^2$ form as suggested by Amsler *et al*. Whereas the χ^2 contribution for the six points between 1935 and 1941 is 33 for the original data, it is only 9 for the same six points in the smeared data. Therefore, we must conclude that the present experiment is not sensitive to the bump-dip structure. We have also attempted to fit our data to a broad structure as reported by Hamilton *et al* [5]. We find no significant structure near 1937 MeV. Our 90% confidence level upper limit of 156 mb-MeV for σ_T is to be compared with 225 ± 127 mb-MeV for the signal of Hamilton *et al*. These two results appear to be inconsistent.

In summary, our data are inconsistent with the existence of narrow structures between 1910 and 1960 MeV, and give smaller upper

correspond to a total event sample of 0.9×10^6 events. By design there is a considerable overlap of data points between adjacent beam momenta. A fit to all 210 data points between 1900 and 1960 MeV to a straight line gives a $\chi^2/DF = 261/201$, demonstrating excellent consistency of the data from run-to-run. The annihilation cross sections shown in Figs. 2,9 were obtained by combining and averaging the data of Fig. 8 with an absolute normalization based on published annihilation cross sections [3-5]. Specifically, we have normalized to an average cross section of 90 mb at 500 MeV/c.

Over the entire mass range we observe no statistically significant structures. The data are fit satisfactorily ($\chi^2/DF = 65/58$) with an $A+B/p$ momentum-dependent cross section ($A = 8.5 \pm 2.5$ mb, $B = 40.7 \pm 1.3$ mb-GeV/c). For a narrow resonance with mass between 1910 and 1940 MeV, we find a 90% confidence level upper limit of 8 mb-MeV for σ_T ,

limits than previously reported negative results. However, the experiment is not sensitive to any previously reported narrow bump-dip structures. No broad structures are seen, with a 90% confidence level upper limit of 156 mb·MeV at 1937 MeV.

Fig. 9: Annihilation cross sections from this experiment. The curve is a fit to the form $A+B/p$ (see text for details).

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