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Search for Structure in the Low-energy $\bar{p}$-p Annihilation Cross Section

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We have measured the relative cross-section for annihilation of antiprotons on hydrogen into one or more charged pions, using a new long-target method which avoids some systematic problems of other electronic techniques. The use of an incident beam momentum of about 600 MeV/c and a one-meter-long target of liquid hydrogen allows the simultaneous detection of annihilation from antiprotons with momenta in the range 600-400 MeV/c. Multiwire proportional chambers detect the charged annihilation products to fix the interaction point, and hence, by the use of the range-energy relation, the momentum at interaction. This removes several problems common to other electronic experiments such as the difficulty of obtaining adequate invariant mass resolution with finite targets and the difficulty of normalizing data taken at many beam momenta.

The measurements were made as part of a search[1] for narrow "baryonium" states in $\bar{p}$N systems (both above and below threshold) using a missing mass technique based on the reaction $\bar{p}d \rightarrow NX$. An important reason for suspecting the existence of such narrow states is that a narrow enhancement, labelled the S(1936), has been reported by several groups[2-6], primarily in the $\bar{p}p$ total cross-section. Although baryonium should decay preferentially through $\bar{N}N$ channels[7], phase space near the $\bar{N}N$ threshold will favor multi-meson decays, and two groups[4,5] have reported a narrow enhancement in the annihilation cross-section at the S mass, with a cross-section of about 26 mb-MeV. However, other searches[8,9] have failed to confirm this structure, and we were therefore motivated to make an independent search. We measured only relative annihilation cross sections, where the charged annihilation products are not forward-going.

Our apparatus is shown in figure 1. We used the LESB II beam at the Brookhaven AGS, a low-energy separated beam with large solid angle and a wide momentum bite (about $\pm$ 1.5% in our experiment). The incident momentum and trajectory of individual beam particles was measured by a system of proportional wire chambers (W_1-W_3 in figure 1). The mean value of the beam momentum at different magnet settings was calibrated using the range of protons in copper at 500 and 600 MeV/c (with the magnets reversed), the time-of-flight of these protons, and the range of 500 MeV/c antiprotons in deuterium of known density; we believe it is accurate to 1% or better. The random error on the momentum of individual particles was better than $\pm$ 0.7%.

Antiprotons were identified (after the electrostatic separation) by time-of-flight over the 3.6 m flight path S_0-S_1 and by energy loss in the counters S_1, S_1' and S_3. An event trigger was an antiproton which was removed from the beam (i.e. no count in S_4) in coincidence with signals from either the top or bottom pion detectors (P_T and W_T or P_B and W_B respectively). Pulse heights and times were recorded for all counters and used in the off-line analysis. The pion detectors covered a solid angle ranging from 0.145sr for the beginning of the target to 2.04sr at a depth of 70 cm; as can be seen from figure 1, the range of angles which were accepted also varied.

Two incident momenta were used in taking data: 604 MeV/c (about 484K triggers) and 586 MeV/c (about 1.24 M triggers). This shift in momentum was made so that any systematic geometrical effects that might produce anomalies in the final mass spectrum would appear at different masses. In the analysis we required that at least one "pion" track, as measured by W_T or W_B, pass within 25 mm of the trajectory defined by W_2W_3; the standard deviation of this distance was 12 mm. Also, the "pion" velocity was calculated (using the calculated time for the antiproton to go from S_1 to the interaction point and the P_TS_1 (or P_BS_1) time difference); it was required to exceed the velocity of a scattered nucleon. These tests enable us to exclude elastic $\bar{p}p$ scattering events from the data sample, and also to reduce the number of double scattering events accepted. After all tests were applied we had 82K events at 604 MeV/c and 234K events at 586 MeV/c. About 5% of these are background events, whose vertex distribution is similar to that of real events. With an incident momentum resolution of $\pm$ 0.7% and and interaction vertex resolution of $\pm$ 10 mm (verified with two-track events) we obtain a resolution of $\pm$ 1.2 MeV at 1950 MeV, $\pm$ 1.5 MeV at 1935 MeV and $\pm$ 1.8 MeV at 1920 MeV.

Since we are searching only for evidence of narrow structure we have not concerned ourselves with the question of absolute normalization of our data, but only with whether or not there is a smooth variation with invariant mass of the number of events. In this long-target method there is an interaction between total cross-section and other cross-sections which cannot be disentangled: the number of annihilation events occurring at a given depth is a product of the beam intensity at that depth and the annihilation cross-section for the momentum at that point. However, this inability to distinguish variations of the integrated total cross-section from variations of the annihilation cross-section does not significantly affect our ability to find narrow structures. In what follows we are comparing our observed number of events (per unit mass interval) with the numbers expected given the sensitivity of our apparatus. The sensitivity was calculated on the basis of geometrical efficiencies, a simple annihilation model and featureless cross-section models; our data was normalized to the model in the region 1920-1955 MeV. Other experiments provide better absolute values; the value of our technique is that good mass resolution is achieved in an electronic experiment with good statistics; and that a wide range of interaction momentum is scanned at one time.

The geometrical efficiency is given simply by the apertures of the chambers W_T and W_B and the pion counters P_T and P_B.

The model used for $\bar{p}p$ annihilation was a phase-space model in which pions were generated in the two to six body channels according to the appropriate n-body phase space; the weight given to each channel was chosen to fit at-rest annihilation data[10] with an increasing multiplicity at higher energies. For the annihilation cross-section we used a featureless cross section of the form:

$$\sigma_A = A_1 + A_2/P + A_3/P^2$$

where σ_A is the charged annihilation cross-section, P is the momentum, and A_1, A_2, A_3 are constants. We use this quadratic form because we find that misalignments of our apparatus tend to introduce quadratic terms. Since we require a match of the pion track to the antiproton trajectory we use a good-geometry total cross-section for the attenuation of the antiprotons; we used the relation[9]

$$\sigma_T P = 51.4 + 64.0P \text{ mb-GeV/c}$$

Figure 2 shows the fitted cross-sections using combined data from runs at the two momenta. Because the efficiency varies rapidly near the front of the target, and there is background from supporting material at the exit, we have included data from a fiducial region beginning 20 cms from the front and ending 10 cms from the exit. This corresponds to an invariant mass range of 1920-1955 MeV for the 586 MeV/c data and 1927-1960 MeV for the 604 MeV/c data. In the region of overlap the two sets of data agree very well; the quantity χ^2 for the comparison is 0.9 per degree of freedom (d.f.). Data points correspond to 1 MeV bins of invariant mass.

To search for narrow structures, we have tried fitting a quadratic in 1/P plus a Breit-Wigner resonance to the entire range of data, using a variety of starting points. The effect of a resonance in the total cross-section σ_T has been included by assuming various elasticities, typically around 0.5. The effect of a resonance in σ_T is small: one with product $\Gamma\sigma$ of 60 mb-MeV attenuates the beam by only 1%, or the equivalent of about 1 mb in our range. We have not considered a resonance which interferes with the background[11], or multiple resonances[12].

Using a Breit-Wigner resonance of peak cross-section 6.5 mb and fixed width 4 MeV, as would be suggested by Bruckner et al.[5], but allowing the mass to vary, gives a very poor fit (dashed line on Fig. 2), while the simple quadratic in 1/P gives a good fit (full line on Fig. 2). If all the parameters of the resonance are allowed to vary, the best fit, for masses between 1930 and 1942, always has a very small integrated cross-section ($\Gamma\sigma_R$ < 10 mb-Mev, where Γ is the full width and σ_R the cross-section at the peak). If we assume that the non-resonant background is more complex than a quadratic in its dependence on 1/P, we can find a fit to an enhancement with mass 1937 MeV, width $\sim$ 3 MeV, the integrated cross-section (12 $\pm$ 6) mb-MeV. However, we do not feel that the required momentum dependence of the cross-section is a reasonable one, especially in view of the fact that a good fit is found with a simpler dependence and no resonance. Note that in all our attempts at fitting we have assumed narrow resonances, consistent with the narrower values reported for the S meson; use of the quadratic in 1/P when fitting does not allow us to quote useful limits on resonances wider than 4 MeV. Note also that we are measuring a partial charged annihilation cross-section.

Table 1 lists our upper limit for the formation of a narrow resonance as a function of mass and width, along with data from previous experiments. Tripp et al.[9] have not given cross-sections for the formation of narrow resonances; their measured annihilation and total cross-sections vary smoothly through our momentum range. We find good agreement with their variation with momentum of σ_A and σ_T; in quoting absolute cross-sections we have therefore normalized to their measurements.

We conclude that we do not confirm the structures reported by Chaloupka et al.[4] and Brückner et al[5] (assuming that these are narrow); this lack of agreement may conceivably be due to a multiplicity or angular distribution of the decay products of the S very different from those of normal annihilations, although no such anomalous distributions have been reported.

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Table I - Cross-sections for formation of narrow resonances in the S region. In the table σ_T denotes the total and σ_A the charged annihilation cross-section, Γ the Breit-Wigner width measured or assumed, and σ_R the peak production cross-section.

Author	Cross-section	Mass MeV	Width, Γ MeV	σ_R mb	$\Gamma\sigma_R$ mb-MeV
Carroll et al.[a]	σ_T	1932 ± 2	9^{+4}_{-3}	18^{+6}_{-3}	160
Chaloupka et al.[b]	σ_T	1935.9 ± 1.0	$8.8^{+4.3}_{-3.2}$	10.6 ± 2.4	93 ± 21
	σ_T	1935.9	8.8	3.2 ± 1.8	28 ± 16
Brückner et al.[c]	σ_A	1939 ± 3	< 4	--	26 ± 6
Sakamoto[d]	σ_T	$1935.6^{+0.5}_{-0.2}$	2.8 ± 1.0	15 ± 4[e]	42 ± 11[e]
This work	σ_T	1930-1942	≤ 4	--	< 12

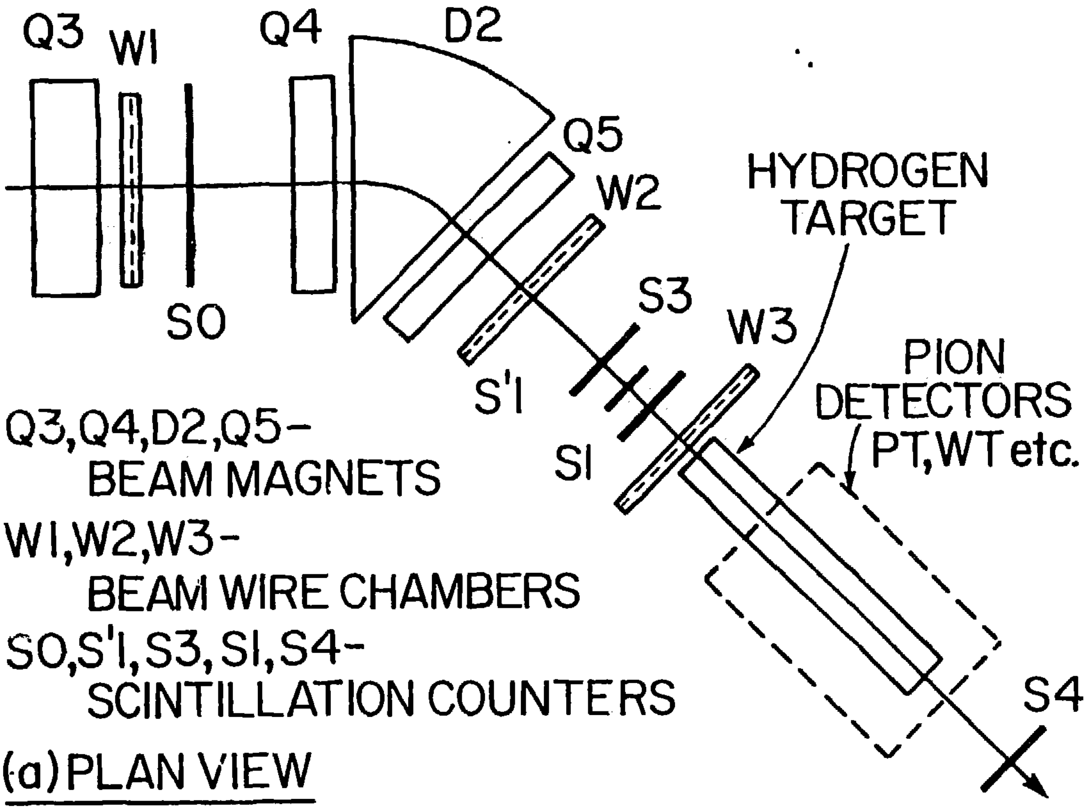
[a]Reference 3. [b]Reference 4. [c]Reference 5. [d]Reference 6.

[e]Read from figure in Ref. 6.

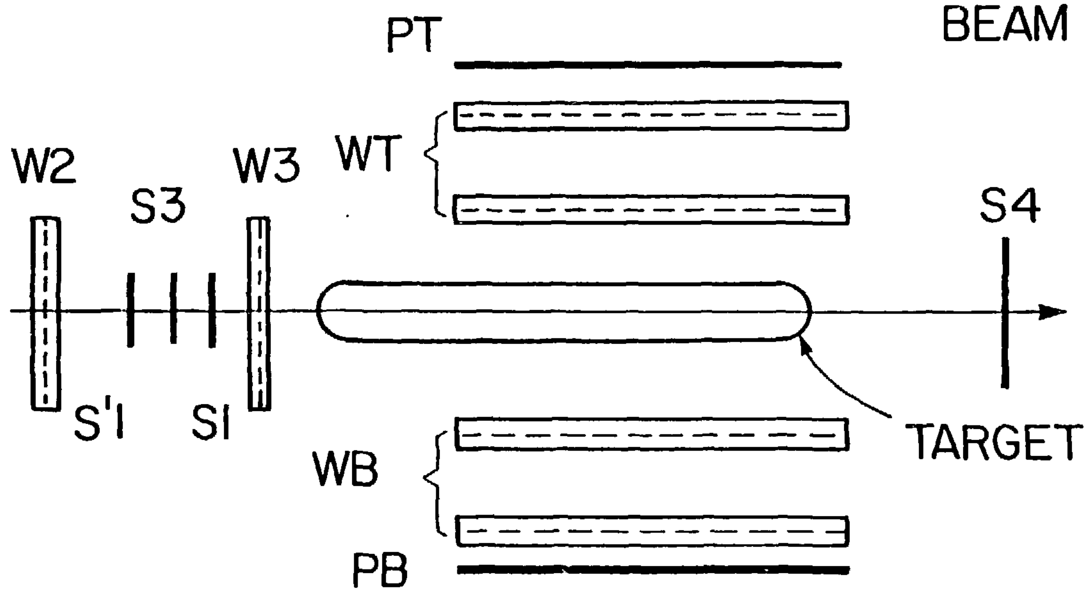
Figure Captions

Figure 1 Sketch of beam and apparatus; not to scale.

Figure 2 Observed relative cross-sections as a function of momentum for the two runs combined. The data points correspond to 1 MeV bins of invariant mass; they range from 1920-1960 MeV. The dashed line shows the effect expected from an enhancement at 1937.5 MeV with a width of 4 MeV and an integrated cross-section of 26 mb-MeV (χ^2 = 1.56 per degree of freedom); the full line is a fit with no resonance (χ^2 = 1.06/d.f.)

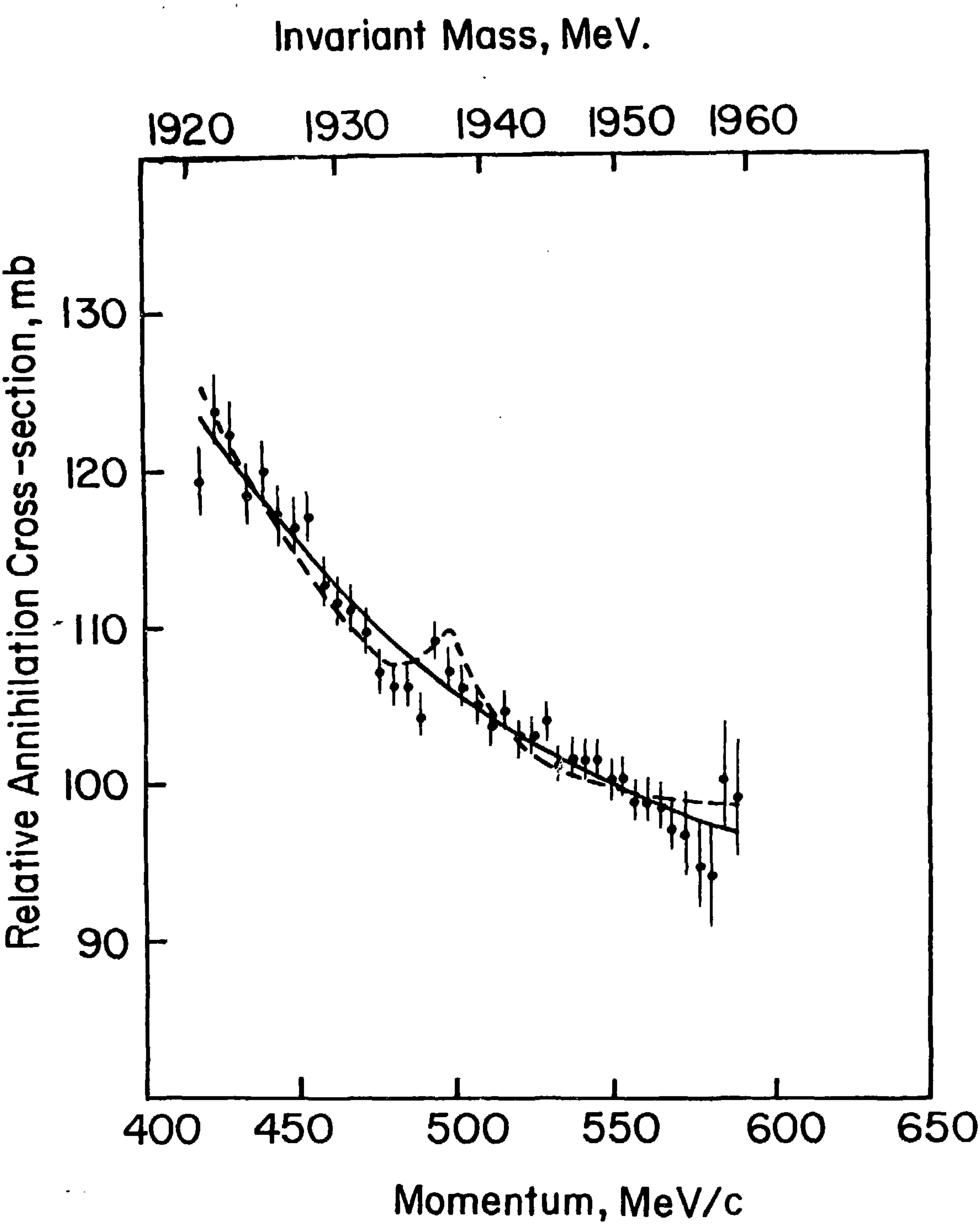


(a) PLAN VIEW



PB, PT-PION SCINTILLATORS
WB, WT-PION WIRE CHAMBERS

(b) ELEVATION



Invariant Mass, MeV.
1920
1930
1940
1950
1960
Relative Annihilation Cross-section, mb
130
120
110
100
90
400
450
500
550
600
650
Momentum, MeV/c