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Evidence against the Narrow $S(1936)$ in a Measurement of $\bar{p}p$ Total Cross Section

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The total $\bar{p}p$ cross section has been measured in the S region by the transmission method with use of a beam-monitoring spectrometer. The result is inconsistent with the existence of the narrow resonance $S(1936)$ with cross sections reported by previous experiments.

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The $S(1936)$ resonance has been attracting special attention since the first observation[1] because of its narrow width[2] and the high branching ratio[3] to the $\bar{p}p$ channel. Theoretically it has been considered to be the best candidate for a baryonium state.[4] Whereas many experimental confirmations[2,3,5] have been reported in the $\bar{p}p$ total and annihilation cross sections, the $S(1936)$ has not been observed in the charge-exchange cross section[6] nor in the backward elastic differential cross section.[7] The present experiment was designed to reexamine the existence of the narrow resonance $S(1936)$ by studying the $\bar{p}p$ total cross section with an improved transmission method.

The experiment was carried out in the low-energy separated beam (K3) of the National Laboratory for High Energy Physics in Japan. The setup (see Fig. 1) was of the transmission type with a fully equipped multiwire proportional-chamber (MWPC) spectrometer system. The incident antiprotons were momentum analyzed to ± 0.3% (full width at half maximum) at the intermediate focus of K3, identified by time of flight and pulse height with a purity of better than 99.98%, and traced by MWPC's. The beam momenta were known to an absolute precision of ± 0.5% and a relative (point-to-point) precision of ± 0.05%, exploiting accurately measured magnetic fields of the bending magnet D3. The target assembly consisted of two identical target cells (86.5 mm long), one filled with liquid hydrogen (full cell) and the other filled with hydrogen gas (empty cell). The temperature of the target assembly was controlled within ± 0.1 °K throughout the experiment. The full-empty cycling was done by bringing either the full cell or the empty cell to the beam center. Our mass resolution for the $\bar{p}p$ system was limited by the energy loss in the full cell and was 1.5 MeV (rms) at 500 MeV/c. The transmitted antiprotons were identified by pulse height in the counter C4 with a purity and efficiency of better than 99.9%, and traced by three MWPC's and a hodoscope (H2). The spectrometer was the key instrument in adjusting and monitoring the antiproton beam and the detectors, and in obtaining various correction factors.

The data-taking run consisted of six data taking weeks. In a typical data-taking week (6–8 days),

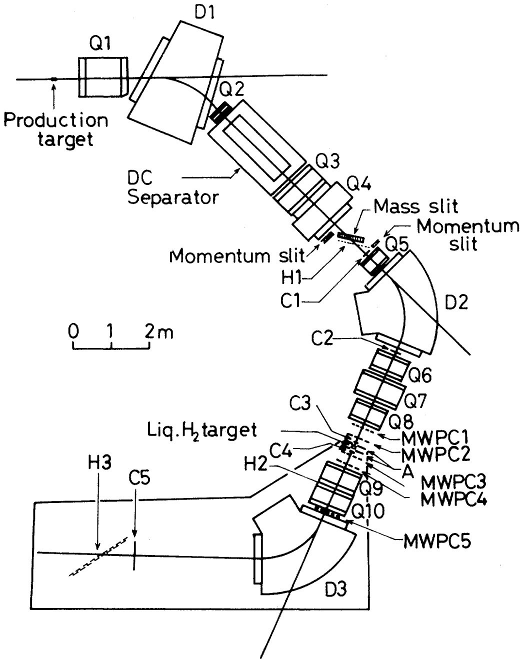

FIG. 1. Plan view of the experimental apparatus. D1–D3, bending magnets; Q1–Q10, quadrupole magnets; C1–C5, scintillation counters; H1–H3, scintillation counter hodoscopes; and MWPC1–MWPC5, multiwire proportional chambers. Scintillation counters A have no relevance to the present Letter.

the full momentum range (400–750 MeV/c was swept in steps of one half ($\Delta p/p = 2\%$) of the K3 acceptance ($\Delta p/p = 4\%$). In each momentum setting, three to four full-empty cycles were repeated. Prior to every new momentum setting, the position, the direction, and the momentum distributions of the antiproton beam were carefully adjusted. The trigger requirement was the threefold coincidence C1•C2•C3 with the C1 threshold set higher than the pion dE/dx peak. For each triggered event the following information was written onto a magnetic tape: time-of-flight and pulse-height information from the scintillation counters C1–C5; coincidence registers for the hodoscopes H1–H3; and anode and cathode coordinates of the MWPC's.

The total cross section was obtained by use of samples of unambiguously reconstructed incoming antiprotons that entered the central part of the target cell (referred to as the "incident antiprotons"). If the pulse height of C4 was consistent with that of an antiproton, the event was classified as "transmitted antiproton (C4)." If the track was successfully reconstructed in MWPC's 3–5 and H2, the event was classified as a "transmitted antiproton" and the scattering angle was calculated. The solid angles covered by C4 and MWPC's 3–5 were 160 and 16 msr, respectively.

We define the cross section $\sigma(\theta)$ as

$$\sigma(\theta)=n^{-1}\{\ln[N_b^f/N_t^f(\theta)]-\ln[N_b^e/N_t^e(\theta)]\}, \qquad (1)$$

where the superscripts f and e stand for the counts in the full- and empty-cell runs, respectively, N_b is the number of incident antiprotons, $N_t(\theta)$ the number of transmitted antiprotons (MWPC) with the scattering angle less than θ, and n the number of protons per square centimeter in the full cell. To obtain the total cross section σ_{tot}, the following corrections were applied to $\sigma(\theta)$: (i) the correction to account for the difference in the average momenta of interacting antiprotons in the full- and empty-cell runs due to the energy loss in the liquid hydrogen [typically 0.3% in $\sigma(\theta)$]; (ii) the correction for the inefficiency in the track reconstruction in MWPC's 1 and 2 due to the backsplashing of charged pions (smoothly varying from 5.6 ± 1.7 mb at 400 MeV/c to 2.6 ± 0.8 mb at 700 MeV/c); (iii) the correction for the single Coulomb scattering; (iv) the correction for the Coulomb-nuclear interference effect; (v) the correction for the forward elastic scattering.

Some comments are in order. The second correction was necessary because we required the uniqueness of the hits in MWPC's 1 and 2. The correction factors were obtained by carefully examining those events having multiple hits in either MWPC 1 or 2. They were also estimated by a Monte Carlo calculation which gave consistent results. To make the correction for the Coulomb-nuclear interference effect, we used the real-to-imaginary ratio ρ of the forward elastic scattering amplitude measured in the present experiment. The values (preliminary) are $\rho = 0.2$ for the antiproton momentum $p \leq 500$ MeV/c and $\rho = 0.0015p - 0.55$ for $p > 500$ MeV/c. Our value of ρ for $p > 600$ MeV/c is larger than the previously reported value[8] of 0.26 ± 0.05 at 700 MeV/c. In this regard we note that the correction for the interference term is not very sensitive to the value of ρ for $p > 500$ MeV/c and $\theta > 5°$ in Eq. (1), because of the fixed laboratory-angle acceptance cut (the corresponding momentum transfer increases as the beam momentum goes up). Thus the uncertainty in the value of ρ by ± 0.1 causes an uncertainty in σ_{tot} for $\theta = 5°$ by 0.8 and 0.4 mb at 500 and 700 MeV/c, respectively.

The total cross section σ_{tot} was calculated from

TABLE I. Total cross section and cross section σ(C4) in millibarns.

$\bar{p}$ mom. (MeV/c)	$\sigma(5°)$ uncorr.	σ_{tot}(mb)	Stat. Error	σ(C4) uncorr.	σ(C4) corr.	Stat. Error
395.9	194.2	197.8	12.4	165.7	171.0	7.7
407.9	176.5	179.8	4.5	158.6	163.5	2.8
418.9	179.6	183.1	3.2	157.1	161.9	2.0
430.1	173.4	177.2	3.0	154.4	159.2	1.9
441.5	167.3	171.1	3.0	149.1	153.7	1.8
452.9	163.6	167.4	3.0	147.1	151.5	1.8
463.2	158.8	162.8	3.1	145.6	149.9	1.8
475.4	157.4	161.4	3.1	140.7	144.9	1.8
487.1	159.4	163.6	2.9	139.1	143.1	1.7
497.7	154.6	158.7	2.7	138.8	142.8	1.6
509.9	152.1	156.3	2.7	131.9	135.7	1.6
522.0	148.4	152.5	2.9	129.7	133.4	1.6
534.2	148.5	152.6	3.0	128.4	132.0	1.6
547.4	147.0	151.1	3.2	124.8	128.3	1.7
559.2	149.1	153.4	3.2	122.8	126.3	1.7
571.6	143.0	147.0	3.2	118.6	122.0	1.7
584.8	138.5	142.6	3.2	117.9	121.3	1.7
597.5	139.9	144.0	3.3	116.4	119.6	1.7
610.1	134.7	138.8	3.3	116.0	119.2	1.7
624.0	132.6	136.7	4.0	111.9	115.0	2.0
637.7	130.3	134.4	5.3	113.4	116.4	2.5
652.1	126.2	130.3	5.9	105.7	108.7	2.8
664.2	134.1	138.7	5.7	102.4	105.3	2.7
678.6	123.3	127.5	5.6	103.7	106.5	2.6
694.0	121.9	126.1	5.7	103.7	106.5	2.5
707.9	122.4	126.8	6.0	99.8	102.5	2.6
722.6	121.9	126.4	4.6	99.4	102.1	1.9
737.4	121.4	126.2	5.4	100.5	103.2	2.3

$\sigma(\theta)$ for $\theta = 3°$, 4°, 5°, and 6° in 1% bins of the beam momentum. The fact that the σ_{tot} thus obtained did not depend on the choice of θ confirmed the correctness of our corrections. For the presentation of the data, we combined two bins into one (2% in the beam momentum) considering our mass resolution at 500 MeV/c. We checked that there was no obvious binning effect by examining the results of the two different combination methods. The results for $\theta = 5°$ are listed in Table I, where errors are statistical only. The total systematic uncertainties due to the corrections (i)-(v) are less than 1%. There is an additional normalization uncertainty of ± 0.8% arising from the uncertainty in the absolute length of the liquid hydrogen target. In Table I, we also list the cross section σ(C4) defined as

$$\sigma(\mathrm{C4}) = n^{-1}\{\ln[N_b{}^f/N_t{}^f(\mathrm{C4})] - \ln[N_b{}^e/N_t{}^e(\mathrm{C4})]\}, \tag{2}$$

where N_t(C4) is the number of transmitted antiprotons (C4). The corrections (i), (ii), and (iii) were applied. The σ(C4) is the total cross section minus a small portion of forward elastic cross section covered by C4. Thus any s-channel effect in the total cross section is expected to be retained in σ(C4). The statistical errors are substantially smaller for σ(C4) than for $\sigma(5°)$ since C4 does not contribute to the loss of antiprotons in obtaining σ(C4). The percentage losses of the antiprotons, $\ln(N_b/N_t)$, were 5.9% and 0.8% at 497.7 MeV/c for the full- and empty-cell runs, respectively, in obtaining σ(C4), while they were 8.8% and 3.2% in obtaining $\sigma(5°)$.

The total cross section and σ(C4) are plotted in Fig. 2 and compared with the results of the measurements by Carroll *et al.*[1] and Sakamoto *et al.*[2] In either σ_{tot} or σ(C4), we do not see any significant structure around the beam momentum of 500 MeV/c. In fact σ_{tot} and σ(C4) can be fitted well by the smooth functional form of $a + b/p$. For σ_{tot}, we obtain $a = 54.3 \pm 4.6$ mb and $b = 52.2 \pm 2.4$ mb • GeV/c with χ^2 per degree of freedom (DF) = 14.4/26. For σ(C4), we obtain $a = 19.5 \pm 2.4$ mb and $b = 59.8 \pm 1.3$ mb • GeV/c with χ^2/DF = 16.4/26. We obtain the following upper limits (90% confidence level) for a resonance cross section

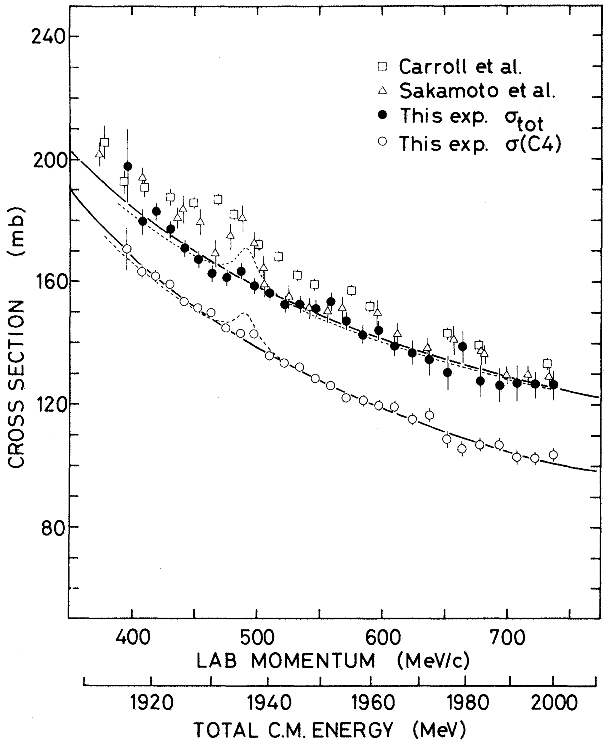

FIG. 2. The total cross section (filled circles) are plotted together with previous data (open squares, Carroll *et al.*, Ref. 1; open triangles, Sakamoto *et al.*, Ref. 2). The open circles are σ(C4) obtained in the present experiment. The solid curves are the results of the fits with the form $a + b/p$ to σ_{tot} and σ(C4) obtained in the present experiment. The dashed curves correspond to the 90%-confidence-level upper limits with a narrow (Γ = 5 MeV) resonance at 1936 MeV.

at 1936 MeV based on σ_{tot} and its statistical errors: 17.1 mb for the width $\Gamma = 3$ MeV; 12.6 mb for $\Gamma = 5$ MeV; 9.8 mb for $\Gamma = 10$ MeV. Based on σ(C4), the same upper limits improve: 13 mb for $\Gamma = 3$ MeV; 10.2 mb for $\Gamma = 5$ MeV; 8.5 mb for $\Gamma = 10$ MeV. They are inconsistent with the resonance cross sections and widths given by Carroll *et al.*[1] The upper limit based on σ(C4) is inconsistent with the results given by Chaloupka *et al.*[3] The results given by Sakamoto *et al.*[2] are not inconsistent with our 90%-confidence-level upper limit if one considers their statistical uncertainty. However, their results may be regarded as consistent with absence of the S(1936), since their fit without the resonance gave a high confidence level of 49.3%.

In conclusion, our results do not support the existence of the narrow S(1936) resonance at the level of the two of the previously reported integrated cross sections.[1,3]

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