SEARCH FOR A NARROW RESONANCE
IN ANTIPROTON-PROTON ANNIHILATION CROSS-SECTIONS
IN THE BEAM MOMENTUM RANGE BETWEEN 400 AND 600 MeV/c

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ABSTRACT

A measurement of the $\bar{p}p$ annihilation cross-section in the beam momentum region between 400 and 600 MeV/c has been performed with a mass resolution of about 1 MeV/c² and statistical precision generally better than 1%. No evidence for the X(1935) resonance is found. The upper limit at the 90% confidence level is 5 mb·MeV/c² for a width of 2 MeV/c².

(Submitted to Physics Letters B)

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1. INTRODUCTION

Beginning in 1976, several experiments [1-5] reported evidence for a possible resonance around $1935 \text{ MeV}/c^2$ in the $\bar{p}p$ annihilation channel, as listed in Table 1. However, the masses and widths claimed for the resonance differed appreciably, casting serious doubts on the existence of the X(1935) resonance (the S meson). In fact, several other experiments [6-8] saw no evidence of the resonance in the annihilation cross-section. More recently, a measurement of the $\bar{p}p$ total cross-section [9] at the CERN Low-Energy Antiproton Ring (LEAR) also gave a negative result, further reducing the credibility of previous claims for the resonance in the total cross-section [10].

Resonances in the $\bar{p}p$ system are of particular theoretical interest because of speculations regarding the existence of baryonium states (see refs. [11, 12]). These states would consist of two quarks and two antiquarks, and would be excellent examples of exotic quark systems. A summary of the history of these states can be found in ref. [10].

In view of the conflicting experimental results for the annihilation channel and of the great theoretical interest, it seems essential to repeat the measurement of the $\bar{p}p$ annihilation cross-sections in the region around the mass of $1935 \text{ MeV}/c^2$, with improved systematics and higher accuracy than in the old experiments. The $\bar{p}$ beam from LEAR, with a high flux, no pion contamination, and a good energy resolution, makes such an experiment possible.

In the present experiment, the apparatus is optimized to obtain a high mass resolution and to cover a large solid angle. As the resonance could be as narrow as a few MeV/c^2 , a beam momentum resolution of $4 \text{ MeV}/c$ FWHM ($1 \text{ MeV}/c^2$ in mass) is requested at $500 \text{ MeV}/c$. In this experiment, the target is only 2 cm long; therefore we reach the desired mass resolution without vertex reconstruction. This allows the use of a large hodoscope of plastic

scintillators, which covers 73% of the whole solid angle. This combination of good mass resolution and large solid-angle coverage makes the experiment more sensitive to a narrow resonance than was the case in previous experiments, with little bias with respect to multiplicity.

2. EXPERIMENTAL METHODS

The $\bar{p}$ beam extracted from LEAR is first focused 20 m upstream of the target. A 1 mm thick plastic scintillator (F1) and carbon degrader are placed at this intermediate focus point. The degrader consists of two rings, each with 11 carbon cylinders of different thicknesses. Momenta lower than the extracted momentum can be reached by an appropriate combination of the degrader blocks. After the intermediate focus, the beam is momentum-analysed and transported to the target via a beam line consisting of two dipole magnets and two triplet sets of quadrupole magnets.

A cross-section of the apparatus in a vertical plane is shown in fig. 1. Its details are described elsewhere [13]. Two 50 μ m thick plastic scintillators detect the beam before the target. The first, SD, which is 85 cm upstream, is 1.7 cm in diameter and is viewed by two photomultipliers. The second, TD, is 15 cm upstream; it is 0.7 cm in diameter and is viewed by a single photomultiplier. The triple coincidence of F1, SD, and TD defines and counts the beam. One of the SD phototubes defines the timing.

The liquid-hydrogen target consists of a 20 mm diameter, 45 mm high, vertical cylinder with 100 μ m thick Mylar walls. An identical empty target is mounted below the full one, and can be exchanged with it by raising the entire target assembly. This assembly is mounted inside a 1 m diameter aluminium vacuum tank with 1 cm thick walls.

Charged mesons produced from an $\bar{p}$ annihilation are detected in a plastic scintillator hodoscope. The hodoscope is outside the vacuum tank and consists of three different parts: the upper and

lower hodoscopes (UHD and LHD), the backward hodoscope (BHD), and the forward hodoscope (FHD). The upper and lower hodoscopes are each composed of eight trapezoidal slabs of 1 cm thick scintillator. Measured from the vertical axis, they cover angles between 12.6° and 62.8° (upper), and between 117.2° and 167.4° (lower). The centre of each slab is 69 cm from the target. The backward hodoscope consists of eight rectangular slabs, each 27 cm wide and 37 cm high, with the centre 80 cm from the target. Relative to the beam axis, they cover angles between 87.5° and 167.5° , and between -87.5° and -167.5° . The forward hodoscope consists of 32 rectangular plastic scintillators, each 3 mm thick, 5.8 cm wide, and 30 cm high, at a distance of 66 cm from the target. Relative to the beam axis, they cover 2.5° to 82.5° and -2.5° to -82.5° . The fraction of the total solid angle covered by each hodoscope is 54% (U/LHD), 9.6% (FHD), and 9.6% (BHD), for a total of 73% of 4π .

The vacuum tank has a $\pm 80^\circ$, 40 cm high window, covered by 250 μm Mylar in the forward direction. A cylindrical multiwire proportional chamber (MWPC) covering angles between $\pm 74^\circ$ is located between the vacuum tank and FHD. The angular resolution of this chamber is 0.2° in the horizontal direction and 0.9° in the vertical direction. A $10 \times 10 \text{ cm}^2$ MWPC with a resolution of 0.05° is located 123 cm from the target on the beam axis. The two MWPCs are used to monitor the beam profile.

A 3 cm square, 3 mm thick scintillation counter (BA) is located on the beam axis 70 cm downstream from the target. This counter is used as a fast veto of antiprotons which did not interact in the target. The data are taken in two different trigger modes: i) the 'beam trigger', which requires only the coincidence of F1, SD, and TD, and which is used to monitor the beam profile; and ii) the 'reaction trigger', which requires additionally that there be no hit in BA.

The scan of the beam momentum is performed over the following ranges: (I: 605,537), (II: 547,475), (III: 527,468), and (IV:

467,411), the first figure indicating the extraction momentum and the second the lowest degraded momentum. Regions I and IV are scanned once, region II twice, and region III three times. Momentum steps of 5 MeV/c are used near 500 MeV/c, and 10 MeV/c elsewhere.

The intensity at the intermediate focus point is typically 2×10^5 $\bar{p}$ per second. The transmission from F1 to SD varies between 80% and 10%, depending on the degrader thickness. The transmission from SD to TD is typically 70%. One spill of the beam from LEAR, which lasts about one hour, is used for a measurement at one momentum. Runs with the four combinations of full and empty target and beam and reaction trigger are made for each momentum.

3. RESULTS

In the off-line analysis, effects of the beam quality on the cross-sections are first studied. It has been observed that the transmission rate of antiprotons in the beam line varies from spill to spill and also during a spill. This is due to the instability of the magnets in the beam line and to the variations of the beam extraction conditions at LEAR. In the following analysis, we take the data from only those runs in which the beam centre on the second MWPC deviates less than 3 mm horizontally and 1.5 mm vertically from the beam-line axis, the transmission from TD to SD differs by less than 10% from the expected value, and the transmission from TD to BA is more than 80%.

In order to evaluate annihilation cross-sections, the cross-sections from empty-target runs are first subtracted. Cross-sections from the empty target are typically 7% of those from the full target.

Next, corrections are made for a) the efficiency of time-of-flight (TOF) cut and b) solid-angle acceptance. The charged mesons from the antiproton annihilation in the target are identified by a 2 ns wide cut in the spectra of the forward hodoscope, and by a 3 ns wide cut in the other hodoscopes. The efficiency of identi-

fying charged annihilation events with these cuts is estimated to be $90.6 \pm 1.0\%$ by a Monte Carlo simulation, using the charged-meson multiplicity distribution [14] and the actual detector acceptance.

Finally, a correction for c) neutral channels, such as $\pi^0\pi^0$, is made. Gamma rays from π^0 decay are partially converted to electron-positron pairs in the target vessel and the vacuum tank wall. Therefore, a part of the neutral channels, 1.5 mb out of 4 mb at 500 MeV/c, is detected by the hodoscope. Using the data of these channels in ref. [14], the correction is made so as to obtain total annihilation cross-sections including the neutral channels.

The corrections for (a), (b), and (c) are $+13.4 \pm 1.5\%$ in total at 500 MeV/c. Figure 2 shows the total annihilation cross-section after these corrections, with statistical errors only. Since these corrections are smooth functions of the beam momentum, the errors associated with them are not added to the statistical ones.

Non-statistical variations of the cross-sections from the accepted data set are studied by comparing cross-sections from different runs. From this analysis, the systematic fluctuation of the cross-sections is deduced to be 0.6% (one standard deviation). This variation is added in quadrature to the statistical one when making fits in the next section.

The mass resolution for beam momenta near 500 MeV/c is determined to be $1.0 \text{ MeV}/c^2$ FWHM ($0.4 \text{ MeV}/c^2$ r.m.s.) as follows. The momentum smearing due to energy loss in the target gives a rectangular distribution with a width of 4 MeV/c at 500 MeV/c. The intrinsic momentum distribution of the beam is determined to be a Gaussian shape with a σ of 2 MeV/c as measured by TOF between F1 and SD. The folding of these two distributions gives a total FWHM of 4 MeV/c, which corresponds to $1 \text{ MeV}/c^2$ in mass.

4. DISCUSSION OF THE EXPERIMENTAL RESULTS

The annihilation cross-sections are fitted using the empirical formula

$$\sigma_{\text{annih.}} = a + b/p , \quad (1)$$

giving $\chi^2 = 44.1$ for 42 data points with $a = 29.43 \pm 1.83$ mb and $b = 32.00 \pm 0.92$ mb·GeV/c, where p is the beam momentum in GeV/c. In this fit, the systematic error of 0.6% evaluated in the previous section is added quadratically to the statistical errors. The relatively large errors in a and b are due to the correlation between a and b . However, the value of eq. (1) is well determined with a precision of 0.1 mb near 500 MeV/c. Figure 3 shows the difference between the results of this experiment and the cross-section given by eq. (1), along with fits to the results of three earlier experiments. There is no evidence of a resonance-like structure. The bump-dip structure reported in ref. [4] is inconsistent with the present result.

In order to determine the upper limit for a narrow resonance of a Breit-Wigner type, the cross-section is fitted with the form

$$\sigma_{\text{annih.}} = \sigma_0 / \{1 + [2(E-E_0)/\Gamma]^2\} + a + b/p , \quad (2)$$

where Γ is the fixed width and E_0 is the fixed mass of the resonance. The values of a and b are first determined by fitting the cross-sections in the mass region below $E_0 - 2\Gamma$ and above $E_0 + 2\Gamma$. The σ_0 is then increased from zero until the total χ^2 increases by 2.7, the 90% confidence level for the fit with a single parameter. The systematic error of 0.6% and the beam momentum width are taken into account. This fit is repeated by varying E_0 in the mass region from 1927 to 1952 MeV/c². The results with $\Gamma = 2$ and 4 MeV/c² are plotted in fig. 4. The upper limits of $\sigma_0 \Gamma$ are 5 and 6 mb·MeV/c² for Γ of 2 and 4 MeV/c², respectively. The results reported in refs. [1] and [2] (curves A and B in fig. 3) are inconsistent with the present result. The resonance cross-section of

6^{+6}_{-1} mb·MeV/c² ($\Gamma < 3$ MeV/c²) reported in ref. [5] is close to the present upper limit.

5. CONCLUSION

A measurement of antiproton-proton annihilation cross-section has been performed with a large-acceptance detector. An energy resolution of 1.0 MeV/c² FWHM and a statistical precision generally better than 1% have been achieved. No evidence for the X(1935) resonance was found. The upper limit of a Breit-Wigner-type resonance in the annihilation cross-section was found to be 5 mb·MeV/c² for $\Gamma = 2$ MeV/c², and 6 mb·MeV/c² for $\Gamma = 4$ MeV/c², at 90% confidence level. No evidence for a bump-dip structure was found.

Acknowledgements

We wish to thank the LEAR machine group for producing the high-quality beam of low-energy antiprotons at several momenta. The design and manufacturing of the liquid-hydrogen target was performed skilfully by the CERN cryotarget group. The support of our technicians Z. Kenesei and J. Zimmer is gratefully acknowledged.

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Table 1

List of experimental results on $X(1935)$
in the $\bar{p}p$ annihilation cross-section

Reference	$\sigma_0 \Gamma$ (mb·MeV/c ²)	Γ (MeV/c ²)	Mass resolution (MeV/c ²)
a) Resonance cross-sections from positive results ^{a)} :			
[1] Chaloupka et al.	28 ± 20	9	1.5 r.m.s.
[2] Brückner et al.	26 ± 6	< 4	4 FWHM
[3] Hamilton et al.	50	20	1.5 r.m.s.
[4] Amsler et al.	bump-dip		0.4 r.m.s.
[5] Franklin	6^{+6}_{-1}	< 3	1.5 r.m.s.
b) Upper limits from negative results (90% cl):			
[6] Jastrzembski et al.	12	< 4	1.5 r.m.s.
[7] Lowenstein et al.	16	< 4	2.5 r.m.s.
[8] Brando et al.	8	< 4	2.0 r.m.s.
	(mass: 1910 - 1940)		
	8-12	< 4	2.6 r.m.s.
	(mass: 1940 - 1960)		
Present experiment	5	< 2 ^{b)}	0.4 r.m.s.
	6	4 ^{b)}	0.4 r.m.s.

a) An enhancement of the cross-section was seen also in F. Sai, S. Sakamoto and S.S. Yamamoto, Nucl. Phys. B213 (1983) 371.

b) The upper limit at 90% confidence level is defined to be the σ_0 value which corresponds to a χ^2 increase of 2.7.

Figure captions

- Fig. 1 : The apparatus in the vertical plane. Annihilation events are detected with the upper and lower hodoscopes (UHD, LHD), the forward hodoscope (FHD), and the backward hodoscope (BHD). The antineutron calorimeter (ANC) and the lead-glass detector (Pb G) are not used in the present analysis.
- Fig. 2 : Antiproton-proton annihilation cross-sections. The errors shown are only statistical.
- Fig. 3 : Antiproton-proton annihilation cross-sections after the subtraction of a smooth background of the $(a + b/p)$ type. The errors shown are only statistical. The curves are from: A) Chaloupka et al. [1]; B) Brückner et al. [2]; and C) Hamilton et al. [3]. A width of $4 \text{ MeV}/c^2$ is assumed in (B).
- Fig. 4 : The upper limit of a Breit-Wigner-type resonance at 90% confidence level. The solid line is for the width of $2 \text{ MeV}/c^2$, and the dashed line for $4 \text{ MeV}/c^2$.

Fig. 1

Fig. 2

Fig. 3

Fig. 4