2 September 1999

PHYSICS LETTERS B

ELSEVIER

Physics Letters B 461 (1999) 405–412

New measurements of the $\bar{p}p$ annihilation cross section at very low energy

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Received 16 June 1999; accepted 12 July 1999
Editor: L. Montanet

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PII: S0370-2693(99)00827-8

Abstract

The $\bar{p}p$ total annihilation cross section has been measured at four values of the $\bar{p}$ incident momentum, between 70 MeV/c and 38 MeV/c, with the Obelix apparatus at LEAR. The new measurements are in agreement with the trend of previous measurements of the $\bar{p}p$ total annihilation cross section at low energy, performed by the Obelix experiment [A. Bertin et al., Phys. Lett. B 369 (1996) 77; A. Benedettini et al., Nucl. Phys. B (Proc. Suppl.) 56A (1997) 58], as well as with a fit of the latter data based on a low energy expansion of the scattering amplitude [J. Carbonell, K.V. Protasov, A. Zenoni, Phys. Lett. B 397 (1997) 345]. The departure of the annihilation cross section from a smooth behaviour, suggested by a previous measurement of the cross section around 44 MeV/c [A. Bertin et al., Phys. Lett. B 369 (1996) 77], is not confirmed by the new data.

1. Introduction

Measurements of the $\bar{p}p$ total annihilation cross section at low incident momenta, between 175 MeV/c and 44 MeV/c, were performed [1,2] by the Obelix experiment [4] at LEAR. These measurements made possible to see experimentally, for the first time, the $1/v^2$ behaviour of the exothermic reaction cross section in a hadronic system with Coulomb attraction [5] (v being the velocity of the incident particle in the c.m. frame). Moreover, the data were used to obtain information about the low energy parameters of the $\bar{p}p$ system (S-wave scattering length and P-wave scattering volume) [6,3].

In these data [1] it was observed that the cross section measured at the lowest $\bar{p}$ incident momentum (43.6 MeV/c) appeared somewhat in disagreement both with the general trend of the cross section at higher momenta and with theoretical predictions based on a scattering length approximation [3]. To investigate whether this disagreement was due to systematic errors out of control, at this extremely low incident momentum value, or to a real departure of the cross section from a smooth behaviour, a new set of measurements of the $\bar{p}p$ annihilation cross section was performed around 40 MeV/c. In addition, a further measurement was performed at higher momentum, around 70 MeV/c, as a control check of the experimental procedure. An accurate scan of the $\bar{p}p$ annihilation cross section at low energy is, in fact, a matter of primary importance, since both potential [7] and quark models [8] predict the existence of $\bar{N}N$ resonant and/or bound states near threshold.

The data were collected by the Obelix experiment during the 1996 data taking period. The experimental layout and the procedure adopted for the data taking were the same as those ones adopted in the previous measurements of the $\bar{p}p$ annihilation cross section [1,2] and are described in detail in [1].

In summary, the experimental procedure was the following. The 105 MeV/c $\bar{p}$ beam from LEAR was degraded to a selected energy by the beryllium window of the beam pipe (100 μm), the thin scintillator of the beam counting system (80 μm scintillator, plus a 6 μm mylar sheet and a 13 μm aluminized mylar foil) and by a degrader formed by mylar sheets of different thicknesses. The beam entered afterwards a gaseous hydrogen target, contained in a 75 cm long and 30 cm diameter aluminum tank, which was closed by a 23 μm mylar window. The pressure of the target gas could be varied in order to allow the incident $\bar{p}$ beam to stop near or upon the end wall of the target tank. For obtaining average beam momenta, at the entrance of the gaseous target, of about 72 MeV/c, 50 MeV/c, 47 MeV/c and 41 MeV/c, respectively no mylar degrader and three different mylar degraders of 78 μm, 85 μm and 93 μm thickness were used. The corresponding target pressures were respectively: 400 mbar, 150 mbar, 150 mbar and 100 mbar.

The purity of the target gas was better than 40 ppm, the uncertainty in the determination of the gas pressure was about 0.5% and 0.5°C the uncertainty on the gas temperature. The thicknesses indicated for the mylar sheets and the scintillator were the nominal ones. It is worth specifying that this latter uncertainty did not affect the determination of the $\bar{p}$ incident momentum, which was independently determined from the data.

The cross section for $\bar{p}p$ annihilation into charged products was measured by counting the number of annihilations in flight, occurring within a given fiducial volume inside the target, as well as the number of $\bar{p}$'s crossing the target without interactions and annihilating, at rest, near or upon the end wall of the target tank. The coordinates of the vertex of the in flight annihilations were measured by the tracking system of the apparatus [4]. The time at which in flight annihilations occur (relative to the scintillator of the beam counting system) was measured by a barrel of scintillators positioned around the target tank and hit by the charged products of the annihilations. The beam crossing the target and annihilating on its end wall was counted by detecting the signals due to the charged products of the annihilations either in the same scintillator barrel mentioned above, or in an additional scintillator disc positioned close to the end wall of the target tank. Details about the time of flight system of the Obelix apparatus can be found elsewhere [9].

The $\bar{p}p$ annihilation cross section was measured around the following $\bar{p}$ incident momenta: 70 MeV/c, 45 MeV/c, 40 MeV/c and 38 MeV/c. These values were estimated accounting for the energy lost by the incoming beam crossing the target gas between the entrance mylar window and the fiducial volume. The procedure adopted for the accurate determination of the $\bar{p}$ incident momentum at the fiducial volume, from the measurement of the z coordinate of the annihilation vertex and the annihilation time, is described in detail in [1] and will be reviewed in the next section.

Finally, it is worth mentioning that, thanks to the possibility developed in the Obelix apparatus of using gaseous targets at variable pressures [10], it was moreover possible, with a minimal changes, to perform some measurements of $\bar{p}$D and $\bar{p}^4$He annihilation cross sections in the same low momentum range. The results of these measurements were reported in [11] and will be the subject of a forthcoming paper.

2. Evaluation of the $\bar{p}p$ total annihilation cross section

The values of the $\bar{p}p$ total annihilation cross section, at the different momenta of the incident $\bar{p}$'s, were calculated following the formula:

$$\sigma_{\text{ann}}^{T} = \frac{N_{\text{events}}}{2 \cdot N_{\bar{p}} \cdot \rho \cdot \dfrac{N_A}{M} \cdot l \cdot \epsilon} \tag{1}$$

where N_{events} is the number of in flight annihilation events reconstructed inside the given fiducial volume in the target, $N_{\bar{p}}$ is the number of $\bar{p}$'s crossing the fiducial volume and annihilating, at rest, near or upon the end wall of the target tank, ρ is the density of the target gas in g/cm^3, N_A is the Avogadro's number, M is the molecular weight of hydrogen, l is the length of the fiducial volume considered and ϵ is the efficiency of the apparatus for detecting events of $\bar{p}p$ annihilation. This last factor accounts also for the correction relative to the annihilation channels in all neutral particles, which couldn't be detected by the apparatus. The factor 2 accounts for the number of scattering centers in the hydrogen molecule.

The number of in flight annihilations (N_{events}) was evaluated considering those events whose reconstructed vertices were within a given fiducial volume inside the target, that is within a cylinder of 10 cm radius and 4 cm length (l in formula (1)) around the beam axis, positioned at a suitable distance from the entrance mylar window. In addition, since the incoming beam was degraded and, consequently, its momentum distribution was spread by energy straggling, it was necessary to recognize the annihilations (inside the fiducial volume) that were originated by the different momentum components of the incoming beam. For this reason the data had to be analyzed in a plot representing the annihilation time versus the z coordinate of the vertex [3]. Moreover, as it will be illustrated in the following, the analysis of the data in the plots of annihilation time versus z coordinate allowed for an accurate evaluation of the incident momentum of the $\bar{p}$ at the fiducial volume.

Such plots are shown in Fig. 1 for the two extreme experimental conditions. The 70 MeV/c sample (a), where the momentum degradation of the beam was minimal and the 38 MeV/c sample (b) where, on the contrary, the incident beam was

[3] It is worth reminding that the uncertainty on the determination of the z coordinate of the vertex of an annihilation event was 1.0 cm and the uncertainty on the annihilation time was 1.0 ns.

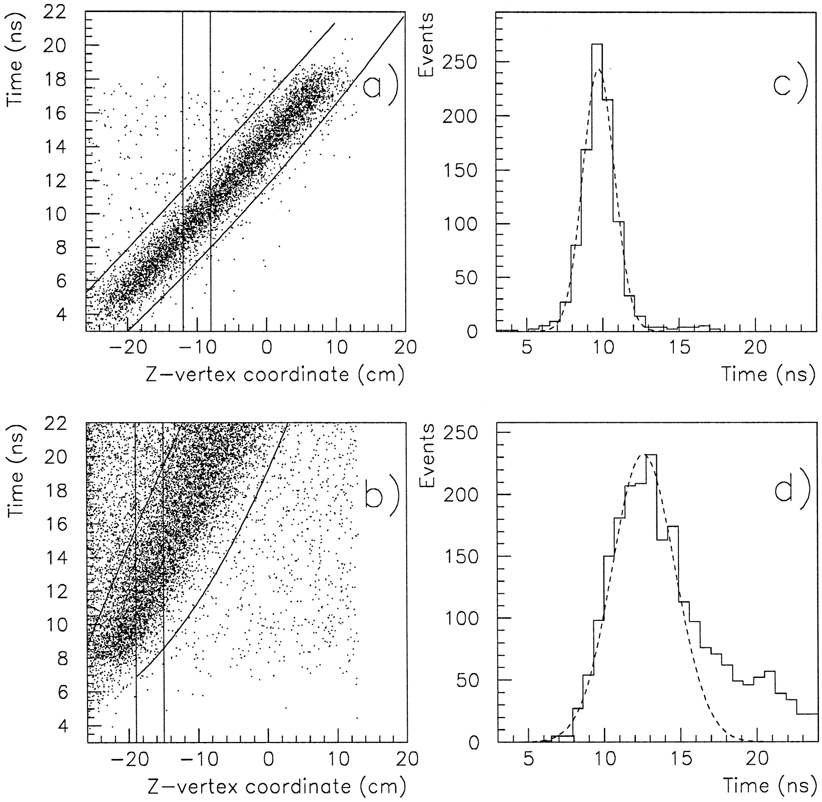

Fig. 1. Scatter plot of annihilation time versus z coordinate of the vertex for the sample at 70 MeV/c (a) and for the sample at 38 MeV/c (b). The vertical lines represent the z coordinate limits of the fiducial volumes. The time projections of the corresponding z slices are shown in (c) and (d). The inclined curves represent the chosen limits for the accumulation bands of the in flight annihilations.

strongly degraded and spread in momentum. In the two scatter plots the bands of accumulation due to in flight annihilations are clearly recognized. The events above these accumulation bands are originated by annihilations in flight at energies lower than the average beam energy. Due to the greater momentum degradation of the beam, the fraction of these events for the lower momentum samples (45 MeV/c, 40 MeV/c, 38 MeV/c) is much higher with respect to the 70 MeV/c sample. Events falling in other zones of the plots are due to inefficiencies of the timing system.

In conclusion, the number of annihilations (N_{events}) was counted not only considering those events whose vertices were comprised within the given geometrical limits in z coordinate and radius, but also requiring that they belonged to the accumulation bands of in flight events. The limits of the accumulation bands were determined considering all the different z slices, 1.0 cm thick, along the target and fitting the time distributions of the corresponding events to Gaussians. The limits at 3 σ's of these Gaussian distributions were connected with smooth curves that were taken as the limits of the accumulation bands (see Fig. 1(a) and (b)).

As shown in Fig. 1(c), in the 70 MeV/c sample, the time projection of the z slice corresponding to the chosen limits of the fiducial volume is well fitted by a Gaussian. On the contrary, as shown in Fig. 1(d), in the 38 MeV/c sample, the time projection of the z slice is rather asymmetric, due to the annihilations in flight at momenta lower than the average beam momentum. For the samples at lower momentum, the incident beam corresponding to the in flight annihilations not comprised within the previous limits had to be evaluated and subtracted from the total beam counting. This evaluation was performed both by considering the ratio between in flight events comprised or not in the given limits, in the annihilation time versus z coordinate plots, and by a Monte Carlo simulation of the beam transport and momentum degradation.

Concerning possible systematic errors in the counting of (N_{events}), the error arising from the cut in radius of the fiducial volume was corrected by Monte Carlo simulation. The error arising from the uncertainty in the measurement of the z coordinate of the vertex was not accounted for, since it was compensated by the contribution of the target volumes neighbouring the selected fiducial volume.

Possible sources of background in the evaluation of (N_{events}) arose from the annihilations occurring at rest on the target walls and whose vertex were reconstructed inside the fiducial volume and from the background due to inefficiencies of the timing system. Both sources of background were taken into account and the relative correction applied. The former contamination was evaluated using a sample of data recorded with an empty target; the latter one was evaluated from the background counted, in the plots of annihilation time versus z coordinate, below the accumulation band of in flight annihilations. This latter correction proved to be quite small, less than 1%.

The number of $\bar{p}$'s $(N_{\bar{p}})$ crossing the target was obtained from the number of annihilations counted by the beam counting system and corrected for its efficiency. This last correction was evaluated with a Monte Carlo simulation and also measured from the data [1]. As mentioned before, the number of $\bar{p}$'s $(N_{\bar{p}})$ was corrected to take into account annihilations in flight at momenta lower than the average beam momentum and not comprised within the limits of Fig. 1. This correction was negligible for the 70 MeV/c sample and increased with the lowering of the beam energy.

The efficiency (ϵ) for the detection of annihilation events was calculated with a Monte Carlo simulation of the apparatus. The simulation took into account the shape of the vertex distribution, the average beam energy, the geometrical structure of the detectors and their detection efficiencies. In addition, the contribution for annihilation channels into all neutral particles was accounted for. The total amount of all neutral channels considered was 4.1%. This assumption is justified by the value of the fraction of all neutral channels measured at rest in liquid hydrogen [12] $(4.1^{+0.2}_{-0.6})$%. In fact, in flight annihilations at very low energy and annihilations at rest in liquid hydrogen should be similar as regards the annihilation fractions since, in both cases, S-wave annihilations are dominant [3,13].

Finally, for what concerns the determination of the values of the $\bar{p}$ incident momentum, the adopted procedure was the following [1]. The curvature of the accumulation band of the in flight annihilations is the effect of the slowing down of the $\bar{p}$'s in the gaseous target, the slope at each point being the average velocity of the $\bar{p}$'s at the corresponding position in the target. The average momentum of the beam, as a function of the z coordinate, was obtained by fitting the curvature of the accumulation band of the in flight annihilations with the proper time versus space relationship. This last relationship was based on the stopping power in gaseous hydrogen for low energy $\bar{p}$'s, measured by the Obelix experiment [14]. This procedure allowed both the value of the average beam momentum at the entrance of the target and the value of the $\bar{p}$ incident momentum at the center of the fiducial volume to be accurately determined. A Monte Carlo calculation of the beam transport along the line provided expected values of the beam momentum, at the entrance of the target, in agreement within 2% with the values obtained, independently, from the fitting of the data.

In Table 1 the momentum setting of the LEAR beam, the target pressures, the average beam momentum at the entrance of the target and the $\bar{p}$ incident momentum at center of the fiducial volume are reported for the different samples. The uncertainty on the average beam momentum at the entrance of the target was determined from the maximum uncertainty in the z coordinate at the entrance mylar window. The uncertainty on the $\bar{p}$ incident momentum at the center of the fiducial volume accounts both for the thickness of the fiducial volume and for the spread of the beam momentum distribution due to the degradation of the beam. This last uncertainty was evaluated by a Monte Carlo simulation of the beam transport.

In the same table the values of the total annihilation cross section at the different incident momenta

Table 1
Values of the $\bar{p}p$ total annihilation cross section, reported in the present work, multiplied by the velocity β of the $\bar{p}$'s and the respective $\bar{p}$ incident momenta. In addition to the statistical and systematic errors, an overall normalization error of 2.5% has to be considered. Corresponding LEAR beam momentum settings, target pressures and average beam momenta, at the entrance of the gaseous target, are reported too.

LEAR beam (MeV/c)	Target pressure (mbar)	Entrance momentum (MeV/c)	$\bar{p}$ incident momentum (MeV/c)	$\beta\sigma_{\rm ann}^T$ (mbarn)
105	400	72.3 ± 0.2	69.5 ± 1.5	$42.4 \pm 1.6\,(\text{stat}) \pm 1.2\,(\text{sys})$
105	150	49.8 ± 0.2	45.4 ± 3.4	$50.2 \pm 1.0\,(\text{stat}) \pm 3.9\,(\text{sys})$
105	150	46.8 ± 0.2	40.1 ± 3.9	$51.8 \pm 1.0\,(\text{stat}) \pm 5.1\,(\text{sys})$
105	100	41.2 ± 0.2	37.6 ± 5.1	$54.4 \pm 1.2\,(\text{stat}) \pm 7.4\,(\text{sys})$

(as obtained from the formula (1)), multiplied by the velocity β of the incoming $\bar{p}$, are reported. The systematic errors on the $\beta\sigma_{\rm ann}^T$ values are obtained as the quadratic addition of the possible systematic uncertainties: uncertainty on the determination of the $\bar{p}$ incident momentum, on the number of annihilation

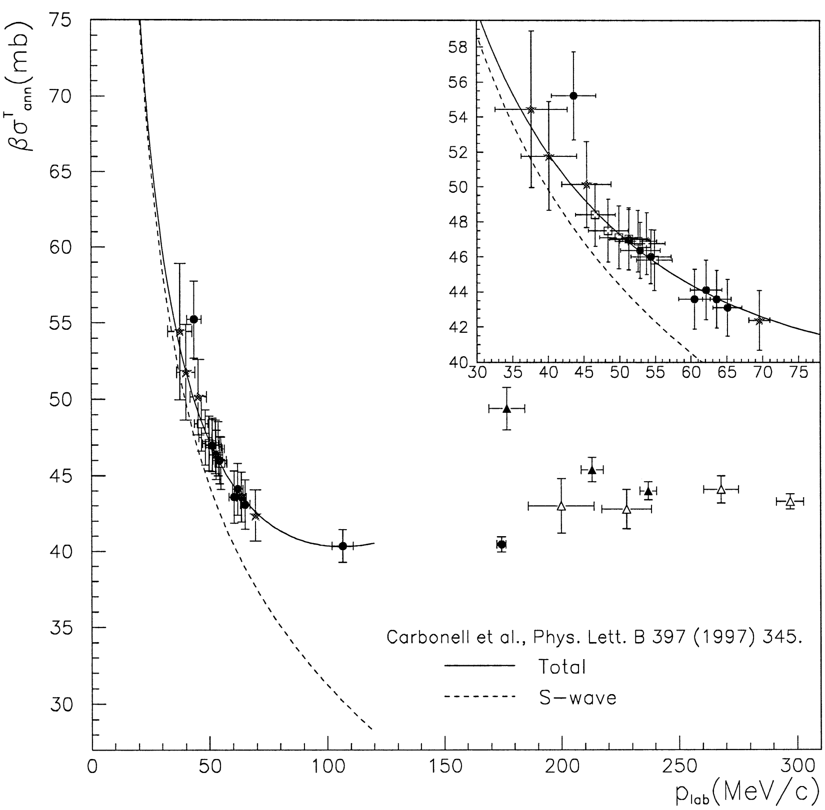

Fig. 2. Values of the total $\bar{p}p$ annihilation cross section at low energy, multiplied by the incoming beam velocity, as a function of the $\bar{p}$ incident momentum. This work (★). Measurements from Brückner et al. [15] (▲ thin target, △ thick target). Previous measurements from Obelix [1] (●) [2] (□). Theoretical curves are from Carbonell et al. [3]. The full line is the total annihilation cross section, the dashed line represents the S-wave contribution. In the inset the low energy region is magnified.

events occurring inside the fiducial volume, on the beam correction due to annihilations in flight at momenta lower than the average beam momentum. The dominant effect on the systematic error of $\beta\sigma_{ann}^{T}$ is determined by the uncertainty on the $\bar{p}$ incident momentum.

In addition to the systematic error, an overall normalization error of 2.5% has to be considered. It arises from the quadratic addition of the uncertainties on different corrections that may affect all the values of the cross section to the same extent: the Monte Carlo correction for apparatus efficiency, the correction for annihilations in all neutral particles as well as the correction for the beam counting efficiency. The possible uncertainty in the determination of the gas density is accounted too in the overall normalization factor.

3. Results and discussion

In Fig. 2 the values of $\beta\sigma_{ann}^{T}$ from Table 1 are plotted versus the $\bar{p}$ incident momentum. The reported error bars represent the quadratic addition of the statistical error and the systematic error interval divided by $\sqrt{12}$. The values of $\beta\sigma_{ann}^{T}$ measured by Brückner et al. at higher energies [15] and by the Obelix experiment [1,2], in the same energy region, are reported too for comparison. In Table 2 these latter values of the $\bar{p}p$ annihilation cross section are reported for the sake of completeness. The theoretical curves are the result of the fit to the previous data from the Obelix experiment [1,2] in terms of S-wave and P-wave scattering lengths [3].

The value of the annihilation cross section measured at 70 MeV/c incident momentum is well in agreement both with the trend of the previous data and with the theoretical predictions [3]. Around 40 MeV/c incident momentum, in spite of the larger systematic errors, the values of the cross section appear in agreement both with the trend of the measurements of the cross section at higher momentum and with the theoretical predictions. The possible departure of the annihilation cross section from a smooth behaviour, suggested by the previous measurement at 43.6 MeV/c, is not confirmed by the new data.

The good agreement of the new measurement of the $\bar{p}p$ annihilation cross section with the theoretical predictions of Carbonell et al. [3], down to 38 MeV/c, gives further support to the values of the $\bar{p}p$ low energy parameters obtained from the quoted analysis: Im $a_{sc} = -0.69 \pm 0.01(\text{stat}) \pm 0.03(\text{sys})$ fm, Im $A_{sc} = -0.76 \pm 0.05(\text{stat}) \pm 0.04(\text{sys})$ fm^3. These values are in very good agreement with the values of the same parameters obtained from the analysis of the data of the X-rays emitted from antiprotonic atoms [13,16]: Im $a_{sc} = -0.71 \pm 0.05$ fm, Im $A_{sc} = -0.71 \pm 0.07$ fm^3, taken from Ref. [3].

Table 2
Previous measurement of the $\bar{p}p$ total annihilation cross section, multiplied by the velocity β of the $\bar{p}$'s, performed by the Obelix experiment [1,2]. In addition to the statistical and systematic error an overall normalization error of 3.4% has to be considered.

Ref.	$\bar{p}$ incident momentum (MeV/c)	$\beta\sigma_{ann}^{T}$ (mbarn)
[1]	174.4 ± 2.0	40.5 ± 0.5(stat) ± 0.5(sys)
	106.6 ± 4.5	40.4 ± 0.5(stat) ± 1.7(sys)
	65.1 ± 2.0	43.1 ± 0.7(stat) ± 2.5(sys)
	63.6 ± 2.0	43.6 ± 0.7(stat) ± 2.6(sys)
	62.1 ± 2.2	44.1 ± 0.7(stat) ± 2.7(sys)
	60.5 ± 2.2	43.6 ± 0.7(stat) ± 2.7(sys)
	54.4 ± 2.8	46.0 ± 0.7(stat) ± 2.4(sys)
	52.9 ± 2.8	46.4 ± 0.7(stat) ± 2.5(sys)
	51.3 ± 2.9	47.0 ± 0.8(stat) ± 2.7(sys)
	43.6 ± 3.1	55.2 ± 0.9(stat) ± 4.1(sys)
[2]	54.9 ± 2.5	45.8 ± 0.9(stat) ± 2.5(sys)
	53.8 ± 2.6	46.8 ± 0.9(stat) ± 2.6(sys)
	52.6 ± 2.6	46.9 ± 0.9(stat) ± 2.6(sys)
	51.3 ± 2.7	47.0 ± 0.9(stat) ± 2.6(sys)
	49.9 ± 2.7	47.1 ± 0.9(stat) ± 2.7(sys)
	48.4 ± 2.8	47.5 ± 0.9(stat) ± 2.7(sys)
	46.6 ± 2.8	48.4 ± 0.9(stat) ± 2.7(sys)

Acknowledgements

The technical support of the staff of the LEAR machine group is gratefully acknowledged.

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