A NEW MEASUREMENT OF $p\bar{p}$ EXCITATION FUNCTIONS


CERN$^1$-Heidelberg$^2$-Saclay$^3$ Collaboration

Presented at the
Workshop on Physics at LEAR
With Low-Energy Cooled Antiprotons
Erice, Sicily, 9-16 May 1982

1) CERN, Geneva, Switzerland.
3) DPhN/ME, CEN, Saclay, France.
A NEW MEASUREMENT OF $p\bar{p}$ EXCITATION FUNCTIONS


CERN$^1$-Heidelberg$^2$-Saclay$^3$ Collaboration

Presented by Th. Walcher

In a recent experiment at the CERN Proton Synchrotron (PS) the proton-antiproton excitation functions of the annihilation as well as of the elastic channel have been measured in the laboratory momentum range from 370 to 1000 MeV/c. The experiment was characterized by an r.m.s. mass resolution of 0.4 MeV/c$^2$ and a statistical accuracy of 1.2% for the annihilation channel. With this precision a narrow structure, about 4 MeV/c$^2$ wide, at a mass of 1936 MeV/c$^2$ is observed in the annihilation channel.

INTRODUCTION

It is well known that the excitation functions of the $p\bar{p}$ system close to the threshold pose a mysterious problem. In the last ten years there have been about a dozen experiments: half of these claimed to have seen a resonance with a mass of about 1936 MeV/c$^2$, the so-called $S$ meson; the other half could not confirm it. The experimental situation has been reviewed several times$^{1-3}$ in the last two years. These reviews have resulted in a rather pessimistic attitude about the possible existence of narrow states in the $p\bar{p}$ system. However, because of the experimental difficulties with separated $\bar{p}$ beams, the situation is not yet clear, and only new and precise experiments will finally decide.

1) CERN, Geneva, Switzerland.
3) DPhN/ME, CEN, Saclay, France.
In this paper a measurement performed at the CERN PS in the year 1980 is described. This experiment investigated the elastic and the annihilation channels with the best possible precision in statistics and mass resolution offered by today's separated beams. The results presented will be restricted to the annihilation channel, as the analysis for the elastic channel has not yet been finished.

**EXPERIMENTAL SET-UP**

The experiment was performed at the $k_{25}$ separated antiproton beam in the East Hall of the CERN PS. This beam had already been used for two missing-mass experiments and is shown in Fig. 1.

After the production target $P$, there follows the separator stage which gave a $\bar{p}/\pi$ ratio of about 1/15. The second stage is the beam spectrometer in which the $\bar{p}$ were identified by their time of flight between the detectors, $T_{LMR}$ and $T_{BAR}$, and their energy loss in $T_{BAR}$. The momentum of the $\bar{p}$ was determined by measuring the entrance coordinates with a hodoscope EH and the exit coordinates by four planes of wire chambers $W_1$, $W_2$. A fifth wire plane ($W_3$ in Fig. 2), tilted by 45°, resolved the ambiguities of double hits. The imaging properties of this beam were very well known because they were investigated during the missing-mass experiments by means of the high-resolution spectrometer SPES II from Saclay. The over-all resolution,

![Diagram](image)

**Fig. 1.** Separated beam $k_{25}$ in the CERN PS East Hall: $Q_i$, quadrupoles; $M_i$, dipole magnets; $P$, production target; $S$, mass and momentum slits; $T_{LMR}$ and $T_{BAR}$, time-of-flight detectors; $EH$ entrance hodoscope; $W_i$ wire chambers.
Fig. 2. Experimental set-up: $W_i$, wire chambers; $\overline{\tau}$, time-of-flight detector; TH, target hodoscope; FH, forward hodoscope; $SC_i$, scintillators.

including all detector limits and target influences, was $\delta p/p \lesssim 6 \times 10^{-3}$ or 3 MeV/c (FWHM) at 500 MeV/c. Typical $\bar{p}$ intensities are given in Table 1.

<table>
<thead>
<tr>
<th>Momentum (MeV/c)</th>
<th>400</th>
<th>500</th>
<th>600</th>
<th>700</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{p}$ per burst</td>
<td>80</td>
<td>430</td>
<td>890</td>
<td>2100</td>
<td>9500</td>
</tr>
</tbody>
</table>
For the measurement of the excitation functions the spectrometer SPES II was moved aside and replaced by the set-up shown in Fig. 2. The wire chambers W1, W2, and W3 as well as the time-of-flight detector T still belong to the beam spectrometer. The set-up consists of three groups of detectors. The first, consisting of the wire chambers W5, W6, W7, and the forward hodoscope FH, was used for the measurement of the elastic scattering. The solid angle covered by these detectors was about 1 sr. The beam was defined by the beam spectrometer and a small detector (not shown in Fig. 2) behind the forward hodoscope. The elastic scattering was defined by the time of flight between T and FH and the energy loss in FH. The chambers W5 (two wire planes), W6, and W7 (one wire plane each) measured the scattering angle and allowed the determination of the differential elastic cross-section. For a measurement of the integrated cross-section for annihilation into charged pions, the target was surrounded by a target hodoscope TH consisting of 10 long scintillator slabs which covered a solid angle of 8 sr. These together with the FH and a scintillator block mounted at the target axis covered 10 sr; this gave a detection probability for charged pions close to 100%. The apparatus was completed by two identical sets of wire chambers, W8, W9 and W10, W11, and scintillators, SCup and SCdown, above and below the target. They suspended a solid angle of 1 sr each. With the aid of these wire chambers the annihilation vertex in the target could be determined for the subsample of events, which had one charged pion in the upper or lower set of detectors. This allowed a correction of the energy loss smearing of the antiproton momentum due to the different positions of annihilation in the target. This smearing contributes about 12 MeV/c (FWHM) for the 6 cm thick H2 target and spoils the good resolution of the beam spectrometer of 3 MeV/c.

The precision of the vertex reconstruction in beam direction was estimated from empty target measurements in which the windows of the target cell could be seen to be better than 1 cm. With this correction the momentum smearing is reduced to less than 2 MeV/c, resulting in an over-all momentum resolution of 3.6 MeV/c (FWHM) for the subsample of events. Furthermore, it is important to note that this subsample is almost free from background.

RESULTS FOR ANNIHILATION

Figure 3 shows the result for the excitation curve into charged pions as measured with the target hodoscope after subtraction of the empty target contribution. The cross-section shown is the sum of all multiplicities. The absolute cross-section is in agreement with the two bubble chamber measurements also shown. The resolution for this spectrum is 5.5 MeV/c (r.m.s.). No statistically significant structure is visible, although a fluctuation occurs just at 500 MeV/c, the momentum of the controversial S meson.
Fig. 3. Cross-section of annihilation into charged pions compared with two bubble chamber measurements.

The spectrum of the subsample seen with the up/down detectors is depicted in Fig. 4. The cross-section has to be multiplied by a factor of 4.3 at 500 MeV/c, which was calculated from the geometry and its efficiency for the different multiplicities using the known branching ratios. However, detailed Monte Carlo calculations were not performed for all momenta. This means that the gross shape of the cross-section is still folded with the efficiency of the geometry. The spectrum of Fig. 4 has not been corrected for momentum smearing in the target, and the resolution is 5.5 MeV/c as for Fig. 3. The fluctuation at about 500 MeV/c persists but is hardly significant. If the momentum smearing correction is switched on, the same data take the form shown in Fig. 5. The resolution is now 1.5 MeV/c (r.m.s.) or about one bin. The fluctuation at 500 MeV/c
Fig. 4. Cross-section measured with the up/down detector arrangements. No correction of momentum loss smearing has been applied.

Fig. 5. Same as Fig. 4 but with momentum smearing correction, giving a resolution of 1.5 MeV/c (r.m.s.).
Fig. 6. Spectrum of Fig. 5 with smooth curve (see text).

now stands out more clearly. In order to test its statistical significance, it is compared in Fig. 6 to a smooth distribution. The form depicted is that given by Hamilton et al.: \( p_{\text{ann}} = \alpha + \sqrt{\beta (p - p_0)^2 + \gamma} \), with \( \alpha = 11167 \pm 68 \), \( \beta = 13.8 \pm 3.6 \), \( \gamma = 1142 \pm 8886 \), and \( p_0 = 444 \pm 8 \), with \( p \) in MeV/c and \( p_{\text{ann}} \) in mb \( (\chi^2/DF = 82/55) \).

The parametrization \( \sigma_{\text{ann}} = \alpha + \beta/p^2 \) with \( \alpha = 12.55 \pm 0.13 \) and \( \beta = (252.7 \pm 3.3) \times 10^6 \) gives almost the same \( \chi^2/DF = 84/57 \), whereas the form \( \sigma_{\text{ann}} = \alpha + \beta/p \) with \( \alpha = 2.80 \pm 0.25 \) and \( \beta = (100.4 \pm 1.3) \times 10^2 \) reproduces our data much worse \( (\chi^2/DF = 99/57) \). The contribution to the \( \chi^2 \) of the structure at 500 MeV/c for 6 bins is 33 (see Table 2). If this is subtracted the smooth curves give a good

<table>
<thead>
<tr>
<th>( \chi^2 )</th>
<th>DF</th>
<th>St. dev.</th>
<th>P(( \chi^2 ),DF)</th>
<th>( \Phi )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bump</td>
<td>16.2</td>
<td>2</td>
<td>3.6</td>
<td>3 \times 10^{-9}</td>
</tr>
<tr>
<td>Dip</td>
<td>16.8</td>
<td>2</td>
<td>3.6</td>
<td>3 \times 10^{-9}</td>
</tr>
<tr>
<td>Bump + dip</td>
<td>33.0</td>
<td>5</td>
<td>5.7</td>
<td>6 \times 10^{-6}</td>
</tr>
</tbody>
</table>
description of the data ($\chi^2/DF = 51/51$). It is interesting to note that the data seem to show a break at about 500 MeV/c. As will be seen later, this is a common feature of the measurements done by several groups.

In comparison with the smooth curve of Fig. 6, the structure at 500 MeV/c exhibits a bump and a dip side by side. As will be discussed, there could be physical reasons for such a structure, the shape of which is difficult to predict. It is therefore reasonable to calculate the significance of the bump and the dip separately without hypothesizing a special shape. The significance of the width which is suggested by the data of 15 MeV/c (3 bins) or about 4 MeV/c$^2$ (FWHM) in mass is shown in Table 2, where $DF$ is the degrees of freedom, St. dev. the standard deviations, $P(\chi^2,DF)$ the $\chi^2$ probability for one interval of 3 bins, and $\Theta$ are the odds against the occurrence of the structure in the measured momentum range from 375 to 665 MeV/c.

Quite a few tests have been made to exclude systematic errors as the cause for this structure. First of all, the dependence of the structure on the momentum smearing correction shows that it comes from the target, i.e. is a function of the antiproton momentum. In order to exclude unknown problems with this correction, the known coordinates of the subsample events were used to cut out, by software, a slice of ±2 cm around the centre of the target without applying any further corrections. Figure 7 shows the result,

![Fig. 7. Spectrum for a slice of ±2 cm around the target centre.]

- 8 -
and again demonstrates that the structure depends on the resolution, i.e. the target thickness. A further check was that the structure occurred in two independent measurements, about one month apart. The structure is also seen in the spectra due to the up and down detectors separately. All these tests have not revealed any experimental problem.

Although there may still be doubts about the statistical significance of the structure, it is remarkable that it occurs at a momentum of 495 MeV/c$^2$ or 1936 MeV/c$^2$, which is just the value of the S meson. In Fig. 8 a comparison of the new result (spectrum E)

---

Fig. 8. Comparison of several recent annihilation spectra: A (Ref. 7), B (Ref. 8), C (Ref. 6), D (Ref. 5), E (this work). The spectra have been shifted by: A, +20 mb; B, +10 mb; C, 0 mb; D, -10 mb; E, -20 mb. The spectrum E is the same as in Fig. 5 multiplied by a factor of 4.3 (see text).
with the most significant measurement of recent years is presented. The bar at each spectrum indicates the resolution of the different experiments. The agreement between spectrum C (Brückner et al.\textsuperscript{6}) and spectrum E is excellent as far as the cross-section and the width are concerned. The small shift in momentum can be explained by a less well known absolute momentum calibration of C against E. The measurement D of Hamilton et al.\textsuperscript{5} is characterized by good statistics but a poorer resolution of 1.5 MeV/c\textsuperscript{2} (r.m.s.). This group did not find a narrow resonance, but a wide one of 20 MeV/c\textsuperscript{2} width at a mass of 1937 ± 2 MeV/c\textsuperscript{2}. The integrated cross-section found by them was (82 ± 41) mb MeV/c\textsuperscript{2}, which has to be compared with the (26 ± 6) mb MeV/c\textsuperscript{2} of Brückner et al. It is difficult to reconcile these two results. The most optimistic possibility is that there are two different resonances at the same mass. A more realistic possibility is that in Ref. 5 a low background was chosen, and consequently the integrated cross-section and the width came out large. The measurements A (Lowenstein et al.\textsuperscript{7}) and B (Jastrzembski et al.\textsuperscript{8}) have about the same statistical precision and resolution. Neither group claims any structure; however, it is surprising that their largest statistical fluctuations occur just in accordance with the structure of C and E. As already mentioned, all spectra seem to have the feature of a break at 500 MeV/c, i.e. the slope changes quickly as it passes 500 MeV/c.

The spectrum of annihilation into charged pions for the momentum range from 650 to 1000 MeV/c is depicted in Fig. 9. It has

![Graph](image)

**Fig. 9.** Cross-section for annihilation in the momentum range from 650 to 1000 MeV/c. The empty target effect has not been subtracted.
been measured with the target hodoscope TH. The empty target effect has not been subtracted. For the resonance claimed at 2020 MeV/c² (see Ref. 2) with a width of 24 MeV/c² (FWHM), the 3 σ limit is 60 mb MeV/c². For a narrow structure of 4 MeV/c² width this limit is 15 mb MeV/c².

RESULTS FOR THE ELASTIC CHANNEL

A necessary confirmation (if this structure is a resonance) has to come from the elastic channel. The analysis of this channel has not yet produced final results. The spectrum of the integrated elastic cross-section in Fig. 10 is therefore preliminary. It has been produced by integrating dσ/dt in the range 0.002 ≤ t ≤ 0.026 (GeV/c)² for each momentum setting of the beam spectrometer. This means that the momentum of the antiprotons has not been determined from the coordinates but is integrated over the momentum bite of the beam of 1% (r.m.s.). The resolution, including the target contribution, is consequently about 1.8 MeV/c² (r.m.s.) and cannot be corrected for the energy loss smearing because the vertex cannot be reconstructed with sufficient accuracy for forward-scattered antiprotons. The statistical fluctuations are not inconsistent with a bump at about 500 MeV/c and a width given by the experimental resolution.

![Graph](image)

Fig. 10. Elastic cross-section integrated between 0.002 ≤ t ≤ 0.026 (GeV/c)² for full and empty targets.
DISCUSSION AND CONCLUSIONS

The physical parameters such as the cross-section and the shape of the narrow structure seen in this experiment depend on the choice of background. If the smooth form of Fig. 6 is accepted, an interference pattern in the annihilation channel is suggested. There are several physical possibilities that could explain such a pattern, for example some kind of Ericson fluctuations of two adjacent resonances. One possibility, which is particularly related to the idea of baryonium, has been pointed out by Dosch\(^3\). He considers in the K-matrix formalism a schematic model in which a resonance in the elastic channel is due to a bound state in another channel which is not open at the resonance energy. He shows that the unitarity constraints implied by the K-matrix formalism can lead to the forms of the resonance in the elastic and inelastic channels given in Fig. 11. The phase factor can be changed to correspond to the experimental situation.

The evidence presented for a structure at 1936 MeV/c\(^2\) is not significant enough to establish the S meson. However, the question of its existence is open. It is unlikely that this final answer can be given without the drastic improvement of experiments that could be brought about by LEAR.

![Graph showing elastic and inelastic channels](image)

**Fig. 11.** Result of a schematic model for an elastic resonance in a closed channel (Ref. 9); \(y\) is a normalized mass coordinate.
REFERENCES
