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Antiproton-Proton Total Elastic Cross Sections in the T and U Regions (0.69-2.43 GeV/c)

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1. INTRODUCTION

The antiproton-proton total elastic cross section can provide evidence of meson resonance formation in antinucleon-nucleon interactions and give an estimate of the coupling of such mesons to $\bar{N}N$. This is of particular interest because a number of theoretical models [1] predict states made up from $q\bar{q}q\bar{q}$ which are exotic within the framework of a naive quark model of $q\bar{q}$ for meson states. These exotic states should couple predominantly to $\bar{N}N$ and can be formed in the s-channel in $\bar{N}N$ elastic scattering; indeed it has been suggested [2] that they are dual to the exchange of non-exotic mesons in the t-channel.

In a recent experiment [3] we measured the $\bar{p}p$ elastic differential cross section with very high statistics ($\sim 10^5$ events/incident momentum) and good c.m. angular coverage ($-0.95 \leq \cos \theta^* \leq 0.93$) at 21 incident $\bar{p}$ momenta in the range $0.69 \leq p_{\text{inc}} \leq 2.43$ GeV/c. A full amplitude analysis of this data is made difficult by the large number of amplitudes involved and in any case the data appear to be dominated, even in the backward direction, by diffraction effects [3]. Nonetheless, integration of the differential cross section over the c.m. angular range actually covered by the experiment to form 'partial' elastic cross sections reveals two small but statistically-significant structures when this quantity is plotted as a function of total c.m. energy [3].

Despite the wide angular range and high statistics of this experiment, attempts to use our data alone to deduce $\bar{p}p$ total elastic cross sections yielded disappointingly imprecise results because of uncertainties $\sim \pm 10\%$ in the extrapolated value of the forward elastic cross section. The resulting uncertainty on the total elastic cross section is correspondingly large because the diffraction peak is very steep, so that a large fraction of it lies in the range $0.93 \leq \cos \theta^* \leq 1.0$ not measured by our experiment. This fraction ranges from $\sim 25\%$ at 0.69 GeV/c to $\sim 75\%$ at 2.43 GeV/c.

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Abstract

Antiproton-proton total elastic cross sections at 21 incident momenta in the range 0.69 to 2.43 GeV/c have been deduced by combining $\bar{p}p$ elastic differential cross sections over a c.m. angular range $-0.95 \leq \cos \theta^* \leq 0.93$ with forward elastic cross sections derived from recent real-part measurements and $\bar{p}p$ total cross sections. Two bumps are observed, at $M_1 \approx 2.155$ and $M_2 \approx 2.345$ GeV/c², having widths of $\Gamma_1 \sim 0.135$ and $\Gamma_2 \sim 0.135$ GeV/c². Corresponding structures in other $\bar{p}p$ reaction channels are discussed.

September 1977

2. CALCULATION OF THE FORWARD ELASTIC CROSS SECTION

It has recently become possible to derive independent values for the pp forward elastic differential cross section by combining total cross sections with new measurements of the ratio of the real to imaginary parts of the forward elastic scattering amplitude. Adding these to our data greatly improves the precision of the total elastic cross sections obtained by integrating our differential cross section data because the unmeasured 'hole' in the differential cross section is then filled in by interpolation rather than extrapolation. Making use of the optical theorem, we calculated the pp elastic differential cross section at 0° (in mb/sr) from

$$\frac{d\sigma}{d\Omega}(0^\circ) = \frac{k^2}{\pi Z} \sigma_{\text{tot}}^2 (0.1606)(1 + \rho^2)$$

where k is the c.m. momentum (in GeV/c), σ_{tot} is the pp total cross section (in mb) and ρ is the ratio of real to imaginary parts of the forward elastic scattering amplitude.

The total cross section has been measured accurately at many points in our momentum range by Carroll et al [4] and Abrams et al [5]. Where the two experiments overlap they unfortunately disagree by $\sim 3\%$. This is most likely a problem of overall normalization, but since we cannot know which of the two data sets is correct we have interpolated between them in such a way as to make a smooth transition. The statistical errors on the data are very small and dominated by the overall systematic uncertainty of $\sim 1\%$. Since the disagreement is only just outside the quoted errors we have not increased the errors in the region of overlap. Their results interpolated to our incident momenta are given in table 1.

The ratio ρ has been measured by Jenni et al [6] at 1.2, 1.4, 1.8 and 2.6 GeV/c and by Kaseno et al [7] at 0.7 GeV/c. We have chosen to use the results from their fits which neglected spin-dependent terms. Interpolation between these points is not unambiguous; the values we used are given in table 1. Below 1.2 GeV/c there is an additional problem - the determination of ρ at 0.7 GeV/c is in serious disagreement with dispersion

relation predictions [8]. Since the low point at 0.7 GeV/c receives some support from the point of Jenni et al at 1.2 GeV/c we have selected values of ρ from an eyeball fit, based mainly on the data. We have not increased the error on ρ to take account of this problem of choice; the resulting extra uncertainty on the total elastic cross section is $<1\%$.

Our calculated values of $d\sigma/d\Omega(0^\circ)$ are given in table 1. The quoted errors combine systematic errors on σ_{tot} and the errors on ρ in quadrature.

3. CALCULATION OF TOTAL ELASTIC CROSS SECTIONS

The forward cross sections described in sect. 2 were fitted along with the differential cross sections [3] at each incident momentum, and the resulting fits integrated to obtain total elastic cross sections. As explained in ref. [3] we found exponential fits unsatisfactory because complicated forms were needed to fit at angles outside the forward diffraction peak, and the results depended strongly on the range of angles covered. Because of this we fitted the data with Legendre polynomial series. The order of fit was chosen by observing the $\chi^2/\text{d.f.}$ as a function of order, and stopping when it reached a plateau at $\chi^2/\text{d.f.} \sim 1$. The orders needed ranged from 6 at 0.69 GeV/c to 16 at 2.43 GeV/c. The values of $\sigma_{\text{el}} = 4\pi a_0$ obtained are given in table 1.

The errors on σ_{el} are difficult to estimate. The diagonal error on a_0 implies errors ~ 0.5 mb in most cases and somewhat more below 1 GeV/c. These errors are a combination of statistical errors on our differential cross sections and overall errors on $d\sigma/d\Omega(0^\circ)$. The overall normalization uncertainty on our differential cross sections is about $\pm 4\%$; if our data were to shift while the forward point remains fixed σ_{el} will change by less than 4% , the actual amount depending on incident momentum. There is also an unknown error due to our choice of a particular functional form (Legendre polynomials) for filling in the 'hole' in the data. Taking the various uncertainties into account we assign a total error of $\sim \pm 4\%$ to our values of σ_{el} .

The results for σ_{el} are shown in fig. 1a, plotted against total c.m. energy. The error bars are only the diagonal errors on a_0 , without the full normalization uncertainty. We have also plotted some of the more precise earlier bubble-chamber results [9] for comparison; the agreement is excellent.

4. STRUCTURE IN THE TOTAL ELASTIC CROSS SECTIONS

Examination of fig. 1a reveals the presence of two broad bumps in the data. These were first seen in the 'partial' elastic cross sections and discussed in ref. 3. We have performed new resonance fits to the total elastic cross section data using a procedure somewhat different from that used in ref. 3 so that the same method could also be applied to other reactions (see also sect. 5).

The data were fitted with an incoherent sum of two Breit-Wigner resonances, σ_T and σ_U , and a background σ_B :

$$\sigma_{el} = \sigma_T + \sigma_U + \sigma_B,$$

where the two resonances have the form

$$\sigma_{T,U} = \frac{1}{k^2} \frac{h_{T,U}^2}{1 + \epsilon^2}$$

$$\epsilon = \frac{2(E_{T,U} - E_{cm})}{\Gamma_{T,U}}$$

with

$E_{T,U}$, $\Gamma_{T,U}$ and $h_{T,U}$ are the mass, width and height, respectively, of the resonances. The background form is not known a priori, so it was represented by a polynomial in p_{inc} :

$$\sigma_B = a + b/p_{inc}^2 + c/p_{inc}^3 + d/p_{inc}^4.$$

A cubic sufficed to give good fits to the data.

4.

A problem in doing the fits is the relatively large number of free parameters, 10, compared to the number of data points, 21. To arrive at good starting values we inserted values for E_T , E_U , Γ_T , Γ_U and performed linear least squares fits to find h_T , h_U , a , b , c , d . We then used the program MINUIT to minimize and improve our values for E_T , E_U , Γ_T , Γ_U , finding the other parameters again from a linear fit. The results obtained are shown in figs. 1a and 2. The errors given are only approximate, since one finds very strong correlations between the height and width of each resonance and fairly strong correlations between the other parameters. We also tried other forms for the background which give good fits; these affect the heights in particular. Because of this the value for σ_T and σ_U must be considered to be only approximate. The use of more complicated, energy-dependent widths can shift the masses somewhat. We used constant widths.

5. COMPARISON WITH OTHER REACTIONS

The two bumps we observe in elastic scattering are almost certainly related to features observed in other antiproton interactions. In this section we will summarize these.

5.1 Total cross sections

The structures known as T and U were first observed in the $\bar{p}p$ and $\bar{p}d$ total cross sections and originally fitted in the decomposition into pure isospin 0 and 1 cross sections [5]. However, here for comparison with elastic scattering it is more appropriate to use the $\bar{p}p$ total cross section. To avoid problems due to fitting with different parametrizations we have not used an earlier fit [10] but have refitted the data ourselves using the same procedure described in sect. 4. The results obtained are given in fig. 2. The major difference with the elastic results is that the mass of the T bump is significantly higher in the total cross section. The heights of the bumps in the elastic channel are of the same order as in the total cross section, which implies either that they have $J=0$ or that there are strong interference effects present. This is discussed further in ref. 3. We also give in fig. 2 the results of fits to the

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pure $I=0$ and $I=1$ cross sections; to be consistent we have again used our own fits. The results are similar to those in ref. 5.

5.2 Charge-exchange

The cross section for the reaction $\bar{p}p \rightarrow \bar{n}n$ has been measured in this energy range by two experiments [11,12]. The data are in serious disagreement on both overall normalization and the presence or absence of resonance-like structure. The data of Curtis et al [11] exhibits structure at c.m. energies near the T and U bumps. We have therefore fitted their data, again using the procedure described in sect. 4. The results are presented in fig. 2 and plotted along with their data in fig. 1b. The masses and widths obtained are entirely consistent with what we find in the elastic channel, but the heights, which one would expect to be about the same as those in the elastic data, are very much smaller. Experimentally, one therefore finds a situation in the three mass regions S(1935), T and U where the peak in the elastic channel is larger than would be predicted by reasonable assumptions for values of J and elasticities, and the peak in the charge-exchange smaller than expected. One possible explanation is strong interference effects with the background, already alluded to in sect. 5.1; this is discussed in a review by Eisenhandler [13].

5.3 $\bar{p}p \rightarrow \pi^+ \pi^-$

An amplitude analysis of this channel has been carried out by Carter et al [14]. Three resonances were found, with masses and widths as given in fig. 2. The first of these (2150) has the same mass as the structures in the elastic and charge-exchange cross sections, and the same isospin, 1, as the T in the total cross section. The second (2310) is somewhat lower in mass than the U peaks in the other channels, but this shift could be due to interference effects. The third resonance (2480) is only partly inside the mass range of our elastic experiment. It is broad and so the fact that a clear bump does not appear in the elastic data is not surprising. The U peak derived from the total cross section has two components, one with $I=0$ and another with $I=1$ [5]; this matches the second and third resonances seen in the $\pi^+ \pi^-$ channel. However, a

very large mass difference of $130 \text{ MeV}/c^2$ is observed for the third resonance if it is associated with the $I=1$ structure in the total cross section. It therefore remains an open question as to whether the $\pi^+ \pi^-$ features are related to the others.

5.4 Backward production by baryon exchange in $\bar{p}p$ interactions

An experiment on the reaction $\bar{p}p \rightarrow p_f \bar{p} \pi^-$ [15], where p_f is a fast forward-going proton, has published mass spectra obtained after cuts to isolate $\bar{p}p \rightarrow \Delta^0(1232) \bar{p}p$ and $\bar{p}p \rightarrow N^0(1520) \bar{p}p$. These processes appear to be dominated by baryon exchange which could imply that one is seeing virtual $\bar{p}p$ elastic scattering. Two narrow peaks appear in the $\bar{p}p$ mass spectra. The lower of the two, at $2020 \text{ MeV}/c^2$, does not seem to correspond to any structure observed previously, but is in a mass region where detailed searches have not been made in formation experiments. The second peak, at $2204 \text{ MeV}/c^2$ has a mass consistent with that of the T state in the total cross section. However, its mass and very narrow width are inconsistent with what we observe in on-shell elastic scattering. It is therefore unclear whether or not this is the same object which we have observed. In the U region the acceptance of the backward production experiment is not sufficiently high.

6. CONCLUSIONS

Accurate values of the $\bar{p}p$ total elastic cross section covering the momentum range 0.69 to $2.43 \text{ GeV}/c$ have been deduced.

There are two resonance-like bumps in the data, at masses of 2155 and $2345 \text{ MeV}/c^2$. Both have widths $\sim 135 \text{ MeV}/c$. They appear to correspond to the T and U bumps in the $\bar{p}p$ total cross section and to possible bumps in the $\bar{p}p$ charge-exchange cross section. The relative sizes of the structures in these three reactions suggest the existence of strong interference effects with the background.

It is not at all clear how the narrow peak recently observed at $2204 \text{ MeV}/c^2$ in the production experiment fits into the pattern observed

in the elastic scattering. The nearest state in mass is the $\tau(2190)$ in the total cross section, but the widths differ considerably.

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Table 1
 $\bar{p}p$ total elastic cross sections and quantities
 used in their calculation

p_{inc} (GeV/c)	E_{cm} (GeV)	ρ	σ_{tot} (mb)	$\frac{d\sigma(0^\circ)}{d\Omega}el$ (mb/sr)	σ_{el} (mb)
0.69	1.986	0.33 ± 0.04	137.4	36.2 ± 1.2	53.4 ± 2.1
0.79	2.015	0.32 ± 0.04	128.0	39.8 ± 1.3	49.3 ± 2.0
0.86	2.037	0.31 ± 0.04	123.0	42.3 ± 1.3	47.2 ± 1.9
0.99	2.078	0.29 ± 0.04	115.6	47.1 ± 1.4	44.5 ± 1.8
1.09	2.112	0.28 ± 0.04	111.9	51.5 ± 1.5	44.2 ± 1.8
1.14	2.129	0.27 ± 0.04	110.3	53.5 ± 1.6	43.8 ± 1.8
1.23	2.159	0.255 ± 0.04	108.3	57.9 ± 1.7	42.1 ± 1.7
1.30	2.184	0.245 ± 0.04	106.5	61.1 ± 1.7	41.3 ± 1.7
1.36	2.205	0.235 ± 0.04	104.8	63.2 ± 1.7	40.1 ± 1.6
1.43	2.229	0.225 ± 0.04	101.8	64.2 ± 1.8	38.7 ± 1.6
1.50	2.254	0.21 ± 0.04	100.0	66.1 ± 1.8	37.5 ± 1.5
1.60	2.289	0.19 ± 0.04	97.8	69.4 ± 1.8	37.6 ± 1.5
1.71	2.328	0.164 ± 0.04	96.2	73.3 ± 1.8	37.0 ± 1.5
1.81	2.363	0.135 ± 0.04	94.5	76.3 ± 1.8	35.7 ± 1.4
1.86	2.381	0.13 ± 0.04	93.3	77.4 ± 1.8	35.2 ± 1.4
1.91	2.399	0.12 ± 0.04	92.2	78.3 ± 1.8	33.9 ± 1.4
2.01	2.434	0.105 ± 0.05	90.0	80.0 ± 1.9	32.4 ± 1.3
2.12	2.472	0.09 ± 0.05	87.9	82.1 ± 1.9	31.8 ± 1.3
2.23	2.510	0.08 ± 0.05	86.1	84.3 ± 1.9	30.4 ± 1.2
2.33	2.544	0.065 ± 0.06	84.6	86.3 ± 2.0	29.8 ± 1.2
2.43	2.578	0.055 ± 0.06	83.2	88.3 ± 2.0	28.6 ± 1.1

FIGURE CAPTIONS

- (a) $\bar{p}p$ total elastic cross sections from our experiment and from a sample of bubble chamber experiments.

(b) Cross sections for $\bar{p}p + \bar{n}n$ from [12].

In both parts the upper curve is the two-resonance fit described in the text. The lower curve is the background contribution to it.
- Resonance parameters from fits to various $\bar{N}N$ interactions. Mass values (in MeV/c^2) are given above the lines, widths and resonant cross sections below. Cross sections are accurate to no better than 25%. First 4 columns are from our own fits, last 2 from [14] and [15].

FIGURE 1

FIGURE 2