SEARCH FOR NARROW BARYONS IN π^-p ELASTIC SCATTERING AT LARGE ANGLESCERN¹-Collège de France²-Ecole Polytechnique³ Collaboration

P. Baillon¹, E. Barrelet³, M. Benayoun², J. Chauveau¹, D. Chew^{3*},
M. Ferro-Luzzi¹, J. Kahane², D. Lellouch³, P. Leruste², P. Liaud³,
F. Moreau³, J.M. Perreau¹, J. Séguinot^{1**}, R. Sené², J. Tocqueville²
and M. Urban³

ABSTRACT

Hoping to find resonant structures in the momentum dependence of π^-p elastic scattering we have measured the differential cross section for this reaction at c.m. angles near 90° . An intense pion beam ($\sim 10^7 \pi/s$) has been used, together with a high incident momentum resolution ($dP/P \approx 2 \cdot 10^{-4}$), to scan the region of laboratory momenta from 5.75 to 13.02 GeV/c (c.m. energy from 3.42 to 5.03 GeV). The sensitivity attained by the experiment is such that signals would have been seen corresponding to the formation of non-strange baryon resonances having width larger than ~ 0.1 MeV and elasticity larger than a few per cent. Within these limits no resonances were sighted.

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(*) Permanent address, LBL, University of California, USA.

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1. INTRODUCTION

In this twilight of the old-fashioned hadron spectroscopy it has occurred to us that the current state of the art still presents an important gap in the knowledge of baryon resonances. The dramatic change in size between, say, the narrower baryon resonances and those of the ψ family emphasizes the existence of an empty region stretching over about two orders of magnitude in the width of these particles. It is not obvious whether this apparent hiatus is real or a simple consequence of experimental difficulties which hamper the detection of such states. For example, any resonance with a width small enough to be below the usual measuring resolution (a few MeV) concurrently handicapped by a feeble coupling to the initial state (an elasticity of a few per cent) was in fact inaccessible to most of the conventional approaches of yesteryear.

The present experiment was conceived with the idea of filling this gap, as regard to non-strange baryon resonances over a conveniently accessible mass range, by pushing to the experimental limit the resonance formation technique. In order to reach the lowest level of resonance coupling, viz. small cross sections, we have aimed at withstanding instantaneous beam fluxes in the region of 10 MHz. In order to be sensitive to narrow widths, we have developed a magnetic focusing spectrometer where the momentum of the incident particles is measured with a resolution of a few parts in 10^4 . Finally, so as to deal with the smallest physical background under the resonant signal, we have chosen a reaction for which the non-resonant contribution is particularly small. The π^-p elastic scattering reaction for c.m. angles near 90° has the desired characteristics: its cross section is several orders of magnitude lower than the forward value, already at a few GeV/c incident momentum, decreasing quickly with increasing momentum. Furthermore, this reaction has the advantage of an easily identifiable configuration requiring a minimum of experimental complications. Lastly, the observation of a signal in this reaction permits a direct measurement of the elastic coupling of the resonance; alternatively, its absence yields unambiguous upper limits to the non-detected resonance.

2. METHOD AND APPARATUS

The experiment was performed at the CERN proton-synchrotron using a negative pion beam of momentum between ~ 6 and ~ 13 GeV/c. This was the

three-stage unseparated P_{17} beam of the East Hall [1]. The first stage of this beam defines the momentum acceptance starting from a 10 cm tungsten target viewed at zero degree over 520 μ sr. The second stage is a transport section, shifting the beam away from the incident protons. The third stage has a configuration symmetrical to that of the first, resulting in an image of the primary target focused onto the experiment target (fig. 1(a)). We have exploited the focusing properties of this third stage in order to momentum-analyze the individual beam particles. A set of conjugate points (H_1 and H_2) was selected along the trajectory of the beam on either side of the Bending Magnets (BM) where the particles position and direction were accurately measured by means of two identical pairs (W_1, W_4 and W_2, W_3) of high resolution proportional wire chambers with 0.5 mm wire spacing. Because of the focusing optics of this stage, the multiple scattering suffered by the particles in the region of the chambers has little effect on the momentum measurement. The accuracy of the latter depends essentially on the knowledge of the magnetic field in the bending magnets and on the wire chambers resolution. The optics used was momentum-compensated at H_2 and had a dispersion of ~ 14 mm per percent of dP/P at H_1 . This dispersion, together with the chambers resolution of ± 0.14 mm, corresponds to a momentum resolution $dP/P = \pm 2 \cdot 10^{-4}$.

The beam cross section in the H_1 region was of the order of 3 cm^2 , in the H_2 region 5 cm^2 . Typically, we took data with instantaneous beam fluxes of the order of 10^7 particles per second; this was not far from the maximum rate reachable in this beam with the PS proton sharing in effect during the experiment ($\sim 5 \cdot 10^{11}$ protons per pulse of ~ 300 ms). To help withstanding this rate, the trigger requirement for an incident particle was provided by two sets of scintillator hodoscopes: H_1 at the entry of the spectrometer with five identical vertical fingers each 25 mm wide and H_2 in the neighbourhood of the conjugate point to H_1 with five vertical fingers of which the central three are 5 mm wide and the outer two 10 mm wide. The trigger logic demanded at least one of the 25 H_1 - H_2 scintillator coincidences to be present within the ~ 5 ns time resolution of the electronics. The time resolution of the wire chambers being of the order of 50 ns, we recorded on tape the hodoscope combination for each incident particle in order to resolve the frequent case of coordinate ambiguity during the off-line analysis.

The elastic reactions were produced in a 25 cm liquid hydrogen target (6 cm in diameter) enclosed by a lead scintillator Veto Box (VB) 3.5 radiation lengths thick, open in the forward direction to match the elastic kinematics. The detection of the secondary products was done with the apparatus shown schematically in fig. 1(b). This consists successively of a large three-plane proportional wire chamber W_9 with a 3 mm wire spacing (vertical, horizontal and transverse plane at 26.6°) centred on the beam axis and desensitized over $5 \times 5 \text{ cm}^2$ around the axis, followed by two arms of proportional chambers (W_5-W_6 and W_7-W_8) two in each arm, with a 2 mm wire spacing in the two planes of each chamber (horizontal and vertical). The two arms subtend the angular regions where the scattered pion and the recoil proton are emitted; the W_5-W_6 arm was centred at 22.5° and covered $\pm 12.5^\circ$ around this direction, the W_7-W_8 arm was centred at 30° and covered $\pm 18^\circ$. In each arm a triggering system of vertical and horizontal scintillator hodoscopes (S_2-S_3 and S_4-S_5 in the two arms respectively) was logically connected to require the traversal of one and only one particle per arm. A rough kinematics criterium was also enforced, excluding configurations clearly outside the elastic bounds.

A threshold gas Cherenkov counter filled with isobutane at atmospheric pressure and with a six-cell resolution was placed at the end of the W_5-W_6 arm and matched to the acceptance of this branch. The figure of merit of this counter was measured to be $N_0 = 100$ electrons/cm. The purpose of this counter was to discriminate between protons and pions (the proton threshold was at 17.2 GeV/c, well outside the range explored). The contribution of false signals due to δ -rays from protons in the gas was measured to be $\sim 0.3\%$ at 10 GeV/c. The ADC output of each cell was recorded along with the chamber signal and used in the off-line analysis.

Finally, a system of six scintillator hodoscopes and lead scintillator arrays was positioned around the beam axis and used to anticoincide offbeam particles (T_0), unscattered particles (Tr) and forward emitted charged or neutral particles (T_1-T_4).

The trigger signal to accept and record an event was

$$T_{el} = T_{inc} \cdot \overline{VB} \cdot (S_2 S_3 S_4 S_5) \cdot \overline{Tr} \cdot \overline{T_0} \cdot \overline{T_1} \cdot \overline{T_2} \cdot \overline{T_3} \cdot \overline{T_4} ,$$

where T_{inc} is the incident particle signal from H_1 and H_2 and $S_2 S_3 S_4 S_5$ is the signal combination of the two-arm system satisfying the one-particle constraint mentioned above. The typical trigger rate T_{el}/T_{inc} was of the order of 10^{-6} throughout the momentum region. This rate was kept deliberately large, a factor of ~ 100 to ~ 1000 over the effective elastic rate so as to provide a large rate of checks during data taking (on chambers performance and overall stability of the apparatus) while assuring that no elastic event was lost because of too stringent trigger criteria.

3. DATA ACQUISITION AND ANALYSIS

The momentum region to be scanned was chosen from ~ 6 to ~ 13 GeV/c because of the favourable particle flux over this region. The flux varied from $\sim 10^6$ to $\sim 5 \cdot 10^6$ particles per PS burst of ~ 300 ms. The total momentum bite for a given setting being $\sim 4\%$, we subdivided the momentum region into a series of 22 partly overlapping momentum settings. At each setting we took data until a total of $\sim 5 \cdot 10^{11}$ incident particles was reached. With the apparatus acceptance of the order of 8% of the total solid angle this flux corresponds to a sensitivity of ~ 40 events per nb over each setting; over the fine bins into which we then subdivided the total momentum bite ($dP/P = 5 \cdot 10^{-4}$) this sensitivity decreases to ~ 0.4 events/nb. On the average, each setting took ~ 10 days of running. Table 1 lists the momenta and the amount of data taken at each setting.

In parallel to a sample on-line analysis of the data, tapes were filled at the rate of about one every few hours; in these we recorded, beside the chamber signals, a variety of information such as the hodoscope configuration, the Cherenkov output and a regular monitoring of the magnetic field in BM via two sets of NMR cells.

The field map of the BM magnets had been carefully measured prior to the experiment with an accuracy of one part over $\sim 10^5$. The expected momentum resolution, dP/P , calculable on the basis of the element positions in the third stage of the beam and of the geometrical resolution of the W_1 - W_4 chambers, was $\pm 1.7 \cdot 10^{-4}$ at 10 GeV/c. The internal consistency checks of the track reconstruction procedure (only five coordinate planes

are necessary among the eight available) allowed a confirmation of the above estimate. We used a polynomial expansion of the second order to reconstruct the particle trajectory [2]. All eligible five-plane combinations were used, employing the redundant coordinates plus the extrapolation of the trajectory to the primary target and to the momentum slit as constraint checks.

In view of the importance of this essential feature, a direct measurement of the incident momentum resolution was also performed. For this, we assembled a second spectrometer downstream of the third stage of the beam so as to obtain an independent measurement of the particles momentum. The second spectrometer was of the conventional non-focusing type. The particle direction at the exit of the third stage was measured before and after the deflection through an additional magnet. The multiple scattering (of consequence in this case) was reduced to the minimum, at the cost of a reduced acceptance, by using a chamber with only one plane of vertical wires and two mylar windows 5 mm thick supported by a rigid venetian-blind steel grid. Particles traversing the grid elements were identified and excluded from the analysis. The momentum resolution was calculated to be $dP/P = \pm 4 \cdot 10^{-4}$ at 6 GeV/c, of which about one half coming from multiple scattering. A series of runs was then performed where the momentum measurement of the focusing spectrometer was compared to that of the second spectrometer. From the resulting distributions it appeared that the spread of the momentum difference was mainly due to the multiple scattering in the second spectrometer, hence confirming the original calculation of the focusing spectrometer resolution.

The incident particle analysis in the focusing spectrometer, averaged over all the data taken, resulted in a successful reconstruction in $\sim 80\%$ of the cases. The failures were due to accidental triggers or faulty coordinate associations for a variety of reasons such as multiple hits, delta rays, chambers inefficiency, interaction in the materials, etc.

The secondary particles reconstruction was achieved by demanding a straight and unambiguous track in the horizontal and vertical plane of each arm. The measurement sets are overconstrained, with three horizontal, three vertical and one transverse coordinate per arm. The overall successful reconstruction rate in the secondary branches was of the order of 20%

throughout the experiment, reflecting essentially the loose criteria of the downstream trigger plus the presence of a non-negligible contribution of false triggers due to beam halo and secondary interactions on the chamber supports close to the incident beam. A study of the chambers efficiency showed that the loss of elastic events due to an insufficient number of coordinates along the tracks was less than a few per cent.

Finally, the incident and secondary tracks were constrained to have a common vertex and to satisfy coplanarity and elastic kinematics. The elastic events are clearly identifiable against the inelastic background as shown on the plots in fig. 2 which represent a sample of distributions for the coplanarity and the elastic kinematics correlation. The background level under the elastic peak is important only for the case where the proton is in the Cherenkov branch where it varies from 10% at the lowest momentum to $\sim 50\%$ at the highest. The response of the Cherenkov counter was used to solve the ambiguities occurring when proton and pion can be interchanged in the two arms without altering the kinematics. A small fraction of the events (less than 3%) turned out to have a contradictory Cherenkov signal; this is probably due to delta ray emission or particle interaction (or decay) on its way to the Cherenkov.

4. RESULTS

The number of elastic events at each momentum setting is listed in table 1 along with the incident flux. The determination of the absolute cross section is discussed in a separate publication [3]. What is relevant here is only the shape of the differential cross section because it enables the selection of the most convenient region of angles where to search for narrow structures. Four regions were chosen, all having (a) small absolute value of the differential cross section, (b) small angular variation within the region and (c) a width large enough to encompass a reasonable number of events. The intervals of $\cos\theta^*$, where θ^* is the pion c.m. angle, are: -0.4 to -0.2, -0.2 to 0, 0 to 0.2 and 0.2 to 0.4. Within each interval of $\cos\theta^*$ we have examined the cross section as a function of momentum, subdividing the 4% momentum bite into bins of $dP/P = 5 \cdot 10^{-4}$. We used the incident momentum spectrum of each setting to apportion the total incident flux among the fine momentum bins and derive cross sections for

each bin. In order to show the different momentum settings into one continuous and uniformly spaced display covering the entire momentum region from ~ 5 to ~ 13 GeV/c, we have plotted in fig. 3 the individual cross sections as a function of the logarithm of the incident momentum (the overlapping portions of the different settings have been averaged). It is on this plot that we expect resonances to manifest themselves as structures standing up over a smooth background. None appears.

In order to give a quantitative basis to this conclusion we have carried out a statistical analysis of these data. The number of events for each point in fig. 3 becomes quite small in the upper half of the momentum range; we have therefore assumed a Poisson law for the distribution of the events around an average value which was calculated over intervals spaced closely enough not to be appreciably affected by the cross section fall off with momentum. The observed and expected distributions were then compared and examined for disagreements. The conclusion was that the events follow reasonably well the Poisson distribution without significant resonant-like deviations.

The search having turned out negative, we next try to set an upper limit on the parameters of the narrow resonances which may have been missed because of the finite sensitivity of the experiment. For this, we have combined the lowest two $\cos\theta^*$ bins of fig. 3 where the cross section is at its minimum and, correspondingly, the resonance sensitivity is highest. We first performed an exponential fit to these data; the residuals of the fit are shown in fig. 4(a) and confirm that, as already mentioned, no anomalous deviations occur. We then calculate the limits on the resonance parameters consistent with these data. If the total width of the resonance is Γ and its elasticity $x = \Gamma_{el}/\Gamma$ where Γ_{el} is the elastic width, then for each value J of the resonance spin the experiment sensitivity can be conveniently expressed by a minimum detectable product $\Gamma x^{2(*)}$. Let us assume, conservatively, that a resonant structure would be clearly seen if

(*) The limit on Γx^2 has been obtained on the basis of the enhancement expected from the resonant amplitude alone. If the resonance interferes with the background one may expect a contribution proportional to Γx . This enhancement could well be much larger than the one considered above. However, it would depend on the specific size and shape of the background amplitudes and we have preferred to remain on the safe side by giving the higher limit based on the resonant amplitude alone.

standing above the background by more than six standard deviations. The minimum detectable value is then given by

$$(\Gamma x^2)_{\min} = 6\delta \Delta E \Delta \cos\theta^* / (\Delta A 2\pi^2 \lambda^2),$$

where δ is the measurement error on $d\sigma/d\Omega$, ΔE the energy bin of the measurement (wherein the resonance is assumed to be fully contained), $\Delta \cos\theta^*$ the $\cos\theta^*$ interval, A the fraction of resonant angular distribution accepted in the $\cos\theta^*$ bin, λ the reduced wave length of the incident pion. The plot in fig. 4(b) shows $(\Gamma x^2)_{\min}$ as a function of the incident momentum for the $J = 1/2$ case. Larger values of J yield smaller values of $(\Gamma x^2)_{\min}$; for the $\cos\theta^*$ interval considered and large values of J , this decrease is well approximated by a $3/(1 + 2J)$ factor. The plot of fig. 4(b) shows that the experiment sensitivity improves with increasing momentum (because of the decreasing level of the cross section).

As an illustration of what our results imply on the state of non-strange baryon resonances we have plotted in fig. 4(c) the known particles [4] as a function of Γ and x . On the same graph we show, as dotted lines, the upper limits set by our experiment (at 10 GeV/c) on the parameters of resonances which would have escaped detection.

Our conclusions are, first, that we have not seen narrow baryon resonances in $\pi^- p$ large angle elastic scattering with mass between 3.4 and 5.0 GeV, second, that we can exclude the existence of such resonances as long as the product of their width times the elasticity squared is larger than the values given as a function of the mass in fig. 4(b). Down to a few keV in width and a few percent in elasticity the non-strange baryon spectrum seems to be a desert.

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TABLE 1

Lab. momentum (GeV/c)	Number of triggers (10 ⁶)	Incident flux (10 ¹¹)	Number of elastic events (10 ³)
5.90	4.85	2.28	14.47
6.10	4.36	2.34	14.51
6.35	2.54	3.60	15.57
6.60	2.10	3.28	12.43
6.85	2.20	4.40	13.48
7.10	2.69	5.05	13.11
7.35	2.76	5.38	9.68
7.65	3.39	4.70	8.87
7.95	2.96	4.74	6.41
8.25	1.64	6.94	3.50
8.55	1.21	6.25	1.77
8.90	1.04	6.09	1.25
9.20	0.45	4.05	0.43
9.60	0.59	4.94	0.47
10.00	1.94	9.01	2.94
10.35	0.70	5.75	1.71
10.70	0.81	6.38	1.92
11.10	0.75	7.47	1.50
11.50	0.53	6.26	0.90
11.90	0.44	5.47	0.72
12.30	0.33	4.18	0.37
12.70	0.39	4.91	0.37

FIGURE CAPTIONS

Fig. 1 Experimental layout:

- (a) The third stage of the P_{17} beam at the CERN PS. The quadrupoles (Q) are each 2 m long. The bending magnets (BM) are each 1 m long; the bending angle of each BM element is 74 mrad; at 10 GeV/c the BM field was 11.30 kG. H_1 and H_2 are in approximately conjugate positions and represent the scintillation hodoscopes described in the text. W_1 to W_4 are multiwire proportional chambers.
- (b) The elastic scattering detection apparatus. The liquid hydrogen target centre is at the focus of the beam. W_5 to W_9 are multiwire proportional chambers, S_2 to S_5 are scintillation hodoscopes, T_0 , Tr and T_1 are scintillation counters, VB, T_2 , T_3 and T_4 are lead-scintillator arrays. The Cherenkov is described in the text. An example of the tracks from an elastic reaction is shown by the dotted lines.

Fig. 2 Identification of the elastic events:

- (a) The coplanarity distribution at the momenta indicated in GeV/c on each plot. The estimator is $C = \hat{\pi}_{in} \times \hat{P} \cdot \hat{\pi}_{out}$ where the unit vectors represent the direction of the incident pion, the recoil proton and the scattered pion respectively. The cut around the peak of coplanar events has been chosen at each momentum taking into account the experimental resolution.
- (b) The elastic-angle correlation for the same momenta as above. $\Delta\theta$ represents the difference between the measured and expected proton scattering angle for the events in the coplanarity peaks. These distributions are shown separately for the events where the proton or the pion is in the Cherenkov arm.

FIGURE CAPTIONS (Cont'd)

Fig. 3 Differential cross sections $d\sigma/d\Omega$ in nb/sr for π^-p elastic scattering at the values of the c.m. cosine indicated above each set. The cross sections are given for 1700 values of the incident laboratory momentum P spaced at equal intervals of $dP/P = 5 \cdot 10^{-4}$. The error bars represent only the statistical uncertainty.

Fig. 4 Results of the experiment:

- (a) Distribution of the residuals of the fit $d\sigma/d\Omega = a_1 + \exp[a_2 + a_3 \ln P + a_4 (\ln P)^2]$ to the differential cross section averaged over $\cos^*$ between -0.4 and 0. Resonances would appear as large positive residuals.
- (b) Minimum detectable value of Γx^2 as a function of laboratory momentum; the elasticity x refers to the specific $\pi^-p \rightarrow \pi^-p$ mode examined here.
- (c) State of nucleon resonances on an "elasticity vs. width" plot. The elasticity x is here the total elastic decay mode of the resonance. Lines of constant Γx^2 are drawn in steps of powers of 10. The dashed lines represent the lower limits established by this experiment in the region of 10 GeV/c: $\Gamma x^2 = 2300$ for Δ 's and $\Gamma x^2 = 600$ for N 's, with Γ in keV and x in percent.

Fig. 1

(b) ANGULAR CORRELATION

(a) COPLANARITY

$$C = \hat{\pi}_{in} \times \hat{p} \cdot \hat{\pi}_{out}$$

Fig. 2

Fig. 3

Fig. 4