Possible indication of narrow baryonic resonances produced in the 1720 - 1790 MeV mass region

B. Tatischeff1*, J. Yonnet1, M. Boivin2, M. P. Comets1, P. Courtat1, R. Gacougnolle1, Y. Le Bornec1, E. Loireleux1, M. MacCormick1, F. Reide1, and N. Willis1

1 Institut de Physique Nucléaire, CNRS/IN2P3, F–91406 Orsay Cedex, France
2 Laboratoire National Saturne, CNRS/IN2P3, F–91191 Gif-sur-Yvette Cedex, France

Signals of two narrow structures at M=1747 MeV and 1772 MeV were observed in the invariant masses $M_{pX}$ and $M_{\pi^+X}$ of the $pp \rightarrow ppX$ and $pp \rightarrow p\pi^+X$ reactions respectively. Many tests were made to see if these structures could have been produced by experimental artefacts. Their small widths and the stability of the extracted masses lead us to conclude that these structures are genuine and may correspond to new exotic baryons. Several attempts to identify them, including the possible “missing baryons” approach, are discussed.

PACS numbers: 12.40.Yx, 13.30.-a, 13.75.Cs, 14.20.Gk

I. INTRODUCTION

Many baryonic states were predicted to exist above 1.5 GeV, first by the non-relativistic QCD inspired quark models [1], but were unobserved in $\pi N$ elastic scattering. They are the so-called ‘missing baryons”. Molecules between baryons and mesons and also gluonic states may exist. Low mass, narrow exotic baryons have already been observed at Saturne [2], the first was in the missing mass of the $pp \rightarrow p\pi^+X$ reaction between the $N$ and the $\Delta(1232)$. Weaker signatures of other narrow baryonic structures have also been observed in different mass ranges [3], but due to their weakness, remain unconfirmed. Structures were also observed at the Moscow Linear Accelerator in the $pd \rightarrow ppX$ reaction [4]. These structures were tentatively associated with colored quark clusters. A recent paper describes, in detail, the experimental set up, the analysis, the checks performed, and the results observed in the baryonic mass range below 1.46 GeV [5].

The results obtained in the higher baryonic mass range above 1.5 GeV do not appear to follow an obvious pattern, and so appear to be somewhat chaotic. These results will not be presented or discussed in this paper. Indeed, this mass range corresponds to a region where many broad and widely excited $\Delta$ and $N^*$ resonances exist and are documented in the Particle Data Group (PDG) records [6]. In this region many observations can result from interferences between different broad resonances, having the same quantum numbers and which overlap. However, considering the two, three and four star broad baryonic resonances as quoted by the Particle Data Group [6], the mass range $1720 \leq N \leq 1900$ MeV is free of any broad resonance and is therefore a more appropriate region for the present studies. It is important

*E-mail: tati@ipno.in2p3.fr
to search for narrow baryonic structures in this mass range since it can shed light on the open question of the missing baryons. The measurements were performed at several incident proton energies [2] [3] [5]. The higher energy \( T_p = 2.1 \text{ GeV} \), gives full access to the interesting region of the invariant masses \( M_{pX} \) and \( M_{\pi^+X} \) of the \( pp \to ppX \) and \( pp \to p\pi^+X \) reactions respectively.

II. EXPERIMENT

A. Experimental set-up

An experiment aimed to look for such exotic states was performed using the Saturne (\( T_p = 2.1 \text{ GeV} \)) polarized proton beam and the SPES3 spectrometer. Figure 1 shows the experimental layout. Briefly, the main properties of the SPES3 spectrometer are the following:
- it is a mean value solid angle spectrometer (\( \pm 50 \text{ mrad} \) in both the horizontal and vertical planes), and
- it is a large momentum range spectrometer \( 600 \leq p_c \leq 1400 \text{ MeV} \).

FIG. 1. The SPES3 spectrometer and the associated detection system.
The experimental conditions were described in detail in a previous paper [5] and will not be repeated here. Its main properties are summarized in the following paragraphs.

The broad momentum acceptance allowed the simultaneous study of a large range of proton and pion energies. The protons were incident on a liquid hydrogen target (393 mg/cm$^2$ thick). The beam varied between $10^8$ particles/burst and $5 \times 10^8$ particles/burst, depending on the spectrometer angle, with the acquisition dead time being less than 10%. The duration of each burst depended on the incident proton energy, and was typically 300 ms for $T_p=2.1$ GeV.

The particle trajectories were determined using drift chambers. The first chamber C1 (‘MIT-type’), was situated on the spectrometer focal plane. Its horizontal spatial and angular resolutions were $\sigma_x = 90 \, \mu$m and $\sigma_\theta = 18$ mrd respectively. Two multidrift chambers noted as C2-C3 in Figure 1, or ‘CERN chambers’, placed perpendicular to the mean particle direction, were designed to obtain trajectories in the horizontal and vertical planes. However, due to the small vertical magnification of the spectrometer ($\approx 0.14$) the $\phi$ resolution at the target was poor. The CERN chambers were used to determine the MIT chamber efficiency by calculating the ratio of three-hit to two-hit coincidences. During the experiment the maximum value of the MIT chamber efficiency was 96% and the variation of this efficiency was monotonous and continuous along the focal plane [5].

The trigger consisted of four planes of plastic scintillator hodoscopes. The dimensions of each plastic detector were $12 \times 40$ cm$^2$ for the first plane (A), and $18 \times 80$ cm$^2$ for the last plane (B). Each of these two planes involved 20 scintillators. The time of flight baseline from the first scintillator plane to the last one was 3 m. Particles were identified by their time of flight between the $A_i$ and $B_j$ detectors and also by their energy loss in the $A_i$ plane. This latter measurement was mainly used to discriminate between one and two charged particles. The large horizontal angular magnification of the spectrometer resulted in a wide angular opening (up to $30^\circ$). It resulted in a large number of possible $A_i,B_j$ combinations (125), between the first and last scintillator counter planes. It is important to note that a mean range of 200 MeV/c (25% of the focal plane acceptance) is covered by each $A_i,B_j$ combination. There is therefore a large overlap between many $A_i,B_j$ trigger combinations for each spectrometer momentum. Careful calibrations and efficiency measurements of all the 125 combinations were performed using a system of scintillators that could be automatically displaced. This system was installed in front of the ‘A”-hodoscope and behind the ‘B”-hodoscope. The trigger efficiency mean value was about 95%.

Two particles - either two protons, or a proton and a pion - were identified in the final state using two times of flight. The first time was measured behind the spectrometer, over a 3 m baseline, and allowed a very good separation between p and $\pi^+$, since each scintillator had an intrinsic resolution of $\sigma=180$ ps. The second time measurement was made in the ‘A” plane of scintillators, for the two detected particles over the 6 - 7 m distance from the target. This provided the means to control the random coincidence contribution and to reject the small amount of badly identified reactions. A correction was made to take into account the differences in trajectory lengths, and then a common window of $\pm 2$ ns was used for all the 190 (19x20/2) time of flight channels. The resolution of this distribution is $\sigma \approx 570$ ps. In the analysis, roughly 0.6% of events were eliminated due to a timing mismatch between the trigger and chamber data.

These studies require good resolutions and good statistics for the results to be studied in a sufficiently large number of data bins. This was achieved in this experiment. The typical resolution was $\sigma(M) \approx 3$ MeV (4 MeV) for $\theta=3^\circ$ ($9^\circ$), and the acquired statistics amounted to 1500 counts (after software cuts) per 1 MeV invariant mass bins.
B. Search for experimental artefacts

All elements of the detection system were calibrated. As well as this, the effect of possible inefficient or hot wires in the MIT chamber was studied in detail. All final data (missing masses or invariant masses) were the results of two-particle coincidences. Any possible inefficient or hot wire in the MIT chamber would affect both particles indifferently. The consequence would be a weak - or intense - line over a narrow range in the momentum scatterplots for both detected particles. Given that this paper is devoted to the search for narrow baryonic resonance structures and that this kind of experimental defect could effectively simulate such an effect, it is important to show that this eventuality has been explored in detail.

Each momentum is reconstructed using several (from 3 up to 7) wires in the MIT chamber. The number of wires depends on the trajectory angle. One inefficient wire shifts the reconstructed momenta by an amount less than or equal to one half interwire distance, that is \( \leq 1.14 \text{ MeV/c} \). Since each mass is determined using a combination of large momenta ranges for both detected particles (see figure 2), the effect of one inefficient wire must be small. We illustrate such effect in figure 3. Figure 3(a) shows the

FIG. 2. The \( pp \to p\pi^+n \) reaction at \( T_p = 1520 \text{ MeV}, \theta = 2^\circ \). Comparison between data: inserts (a) and (b), and simulation: inserts (c) and (d).
FIG. 3. Study of the effect of an eventual inefficient wire in the MIT drift chamber (see text). Full squares correspond to the original analysis whereas full circles correspond to partially shifted data.

Figure 3(a) shows the missing mass at $T_p = 1520$ MeV, $\theta = 20^\circ$, and also the same missing mass when a shift of 1.14 MeV/c is performed on both detected momenta in the range $900 \leq p \leq 915$ MeV/c. The applied shift is larger than the real one, since the shift of the momentum is smaller than 1.14 MeV/c when the number of useful wires increases. For such shift, we obtain a missing mass distribution which is difficult to discern from the previous one. Figure 3(b) shows the difference between both missing mass spectra. When applying the inefficient wire effect described previously, the resulting neutron mass, and the $\sigma$ of the gaussian describing the distribution, move by a negligible amount. In the previous example, $\Delta M \approx 4$ keV and $\Delta \sigma \approx 1$ keV respectively.

C. Analysis

The data were normalized using the inefficiency calibrations. They were also normalized using inefficiencies and acceptances obtained using the results of a simulation code which is described in section “Simulation”. The data were normalized by the useful momenta ranges of the two detected particles. The correction function varies as a function of the invariant mass under study and consequently, the final error bars are dominated by the statistics and are not only related to the cross section values.

During the raw data analysis, several software cuts were applied at the expense of the statistics but for the benefit of a more stringent selection. The quadratic kinematical equations allow two roots for the invariant baryonic masses studied in this work. The corresponding events must be studied separately for the following reasons:
- due to the momentum limits of the spectrometer, the limits of the invariant masses for both root values are different. A simple sum of both spectra would have created a large shoulder in the result,
- the normalization by the momentum acceptance $\Delta p_1, \Delta p_2$ is different in each case, and,
- the empty region between the two filled regions is not constant but decreases for increasing masses and tends to zero as the kinematics tends to the double value limit.

The events corresponding to both root values were separated by selecting particular proton momenta for the $pp \rightarrow p\pi^+X$ reaction. We will call upper (lower) branch spectra the spectra built from events with momenta larger (smaller) than the upper mass limit momenta. During the study of the $pp \rightarrow ppX$ reaction the two protons were classified as slow or fast momenta protons according to their relative values.

These two reactions are shown in figures 4, 5, and 6 which display the differential cross sections versus the following invariant masses: either $M_{p(slow)X} \equiv M_{psX}$, or $M_{p(fast)X} \equiv M_{pfX}$. Both roots were separated by software cuts keeping forward or backward missing mass C.M. angles. These software cuts were applied to the momenta of the particle not used in the invariant mass combination.

![FIG. 4. Differential cross sections for the reaction $pp \rightarrow pf ps X$ at $T_p=2.1$ GeV, in the laboratory system. Inserts (a), (b), and (c) show the cross sections versus $M_{psX}$ at the following angles $\theta=0.7^0, 3^0$, and $9^0$ respectively. Insert (d) shows the cross sections of the upper branch versus $M_{pfX}$ at $\theta=9^0$. Values are listed in Table 1.](image)

For both reactions, if we write it as $p_1 \times p_2 \rightarrow p_3 \times M_{inv.}$, then the two roots are separated by the $p_3$ momentum and the upper (lower) branch is also the forward (backward) solution for the two particle-reaction.
FIG. 5. Differential cross sections for the reaction $p p \rightarrow p \pi^+ X$ at $T_p=2.1$ GeV, in the laboratory system. Inserts (a), (b), (c), and (d) correspond respectively to $\theta=0.7^0$, $0.7^0$ (with different software cuts), $3^0$, and $9^0$. Values are listed in Table 1.

FIG. 6. Inserts (a), (b), and (c) show the differential cross sections of the reaction $p p \rightarrow p \pi^+ X$, at $T_p=2.1$ GeV, in the laboratory system, at $\theta=0.7^0$, $3^0$, and $9^0$ respectively. Insert (d) shows the analyzing power of the $p p \rightarrow p f_1 p_s X$ reaction, at $T_p=2.1$ GeV, $\theta=3^0$. Values are listed in Table 1.
D. Simulation

The experiment was simulated in order to check several aspects of the detection system, and to evaluate the data normalization for inefficiencies and acceptances. Differential cross sections could then be evaluated. The correction function was smooth for all cross section variables. The simulation describes the detector and the spectrometer magnetic field properties and generates events for a given missing mass distribution and a given angular cross section distribution over the spectrometer horizontal angular range. The code was also used to study the consequences of particles scattered by the target in the vertical plane at angles $50 \leq |\phi| \leq 80$ mrd. No bias corresponding to the appearance of narrow structures was observed in the simulation. Figure 2 illustrates the comparison between the experiment and the simulation for the $pp \rightarrow p\pi^+n$ reaction. Parts 2(a) and (c), showing the pion proton momenta correlation, are in excellent agreement, as are the missing mass distributions shown in parts 2(b) and (d). The variation of the cross section inside the spectrometer solid angle ($\pm 3^0$) in both horizontal and vertical planes does not reproduce exactly the experimental cross section angular dependence inside the spectrometer solid angle. This is not relevant for the present discussion.

We observe that the simulation reproduces the position and the width of the neutron missing mass peak. Indeed in the range $930 \leq M \leq 950$ MeV, the $\sigma$ of the neutron peak in the data (simulation) is equal to 3.4 (3.2) MeV.

E. Controls

Many checks were performed to establish whether or not the observed structures are results of genuine physical phenomena or of experimental artefacts. In the following the various results of the tests will be outlined briefly but can be examined in detail in a previous paper [5].

Different cuts on particle momenta, as well as on emission angles, were performed over a mass range where structures larger than those discussed here were observed [5]. The effect of these cuts, is to reduce the statistics (see figures 11, 12, and 13 of reference [5]) and hamper the interpretation of the data. Nonetheless, the three structures under discussion there, remained in place.

It was also shown in figure 14 of reference [5] that the structures did not depend on the spin state of the incident beam. In figure 15 of the same paper, it is also shown that the structures were not present in accidental coincidences.

The empty target measurements performed as a control and for background subtraction, showed no target contamination (see figure 16 of reference [5]). It is also concluded that, although the measurements were performed at small angles, there was no evidence of any hot area of incident beam which could have been scattered by any mechanical piece at the entrance of the spectrometer.

A detailed discussion was presented that allowed to eliminate contamination from the possible effect of particles emitted outside the spectrometer solid angle but subsequently slowed down (figures 18 and 11 of the same paper).
III. RESULTS

At $T_p=2.1$ GeV this experiment was performed at three spectrometer angles: $\theta_{lab.} = 0^\circ, 3^\circ,$ and $9^\circ$. Peaks were tentatively extracted using low order polynomials for the background and a Gaussian peak for the structure. The channels defining the polynomial and Gaussian peak ranges were given, then all parameters were allowed to vary freely. The following relation was used for the standard deviation (S.D.) evaluation:

\[
S.D. = \left[ \frac{\sum_i (N_{T_i} - N_{B_i})/\Delta\sigma_i^2}{\sum_i (1/\Delta\sigma_i^2)} \right]^{1/2}
\]

where $N_{T_i}$ ($N_{B_i}$) corresponds to the total (background) number of events for the channel $i$, and $\Delta\sigma_i^2 = \Delta\sigma_{T_i}^2 + \Delta\sigma_{B_i}^2 \approx 2 \Delta\sigma_{T_i}^2$. The quantitative information is summarized in Table 1 where we observe small fluctuations of the structure’s masses. The source of these fluctuations, of the order of $\Delta M/M \approx 10^{-3}$, are attributed to three experimental limits. The first limit comes from the mass calibration. Since there is no known reference peak within the experimental acceptance, a high precision mass calibration control cannot be carried out. The second limit is statistical: in order to have enough statistical precision the data are integrated over a large spectrometer angle ($\pm 3^\circ_{lab.}$). The last source of small fluctuations, can be attributed to using a single set of reconstruction parameters over the whole experimental range.

A. The $pp \rightarrow p_s pf X$ reaction

The measured differential mass spectra are shown in figure 4. Structures close to $M=1747$ MeV ($1772$ MeV) are observed with large S.D. in inserts (a), (b), and (d) ((b) and (c)). At $\theta=0.7^\circ$ (insert (a)), no peak was extracted close to $M=1772$ MeV. In this case, the physical background being larger than at $\theta=3^\circ$ (insert (b)) and the statistics lower, a possible peak at $\theta=0.7^\circ$ could have a cross section similar to the one extracted at $\theta=3^\circ$. Well defined peaks are observed at $\theta=3^\circ$ with their cross sections decreasing at $\theta=9^\circ$.

The rapidly increasing shape of the invariant mass data $M_{pfX}$ does not allow any peak extraction at $\theta=0.7^\circ$ or $\theta=3^\circ$. However, at $\theta=9^\circ$, a structure at $M=1747$ MeV was extracted (insert (d)). Here the cut used to define the upper branch is $p_{p_sX} \geq 0.97$ GeV/c.

In Figure 4(d) a single data point close to $M=1758$ MeV, is higher than its neighbours by several S.D. For this reaction and angle, the acceptance spectrum has a peak at this mass. A small shift in mass between the data and the momentum acceptance used for the normalization of the data creates this effect. A careful control was performed in order to check that the physical peaks could not arise from such artefacts.

The experiment was performed using polarized incident protons and the analyzing power (figure 6(d)) shows several discontinuities. These effects are not statistically significant, but they are shown since they appear at the same masses where statistically significant structures are observed in the cross sections. In this case the data are integrated over 3 MeV bins as opposed to 2 MeV bins as in figure 4(b).
B. The \( pp \rightarrow p \pi^+ X \) reaction

For this reaction both root solutions for \( M_{\pi^+X} \) were separated by a software cut on the proton momentum. Figure 5 shows the cross sections of the upper branch where \( p_p \geq 1 \) GeV/c. Figures 6(a), (b), and (c) show the cross sections of the lower branch where \( p_p \leq 0.95 \) GeV/c.

1. The upper branch

The statistics in the upper branch are higher than in the lower branch. However, part of the upper branch statistics included data from the tail of the neutron missing mass, particularly at forward angles. Supplementary software cuts on \( M_X \) were therefore applied in order to suppress the neutron peak contamination. In figures 5 (a) and (b) the invariant mass spectra obtained at \( \theta=0.7^0 \) are shown. Cuts on \( M_X \) at \( M_X \geq 1.15 \) GeV and \( M_X \geq 1.3 \) GeV respectively were applied. When going from 5(a) (2 MeV binning) to (b) (4 MeV binning), the differential cross sections decrease but the peak’s heights are enhanced. The 1747 MeV structure is observed in both binnings. The 1773 MeV structure is observed in figures 5(b), (c), and (d), but is practically absent in figure 5(a). A not excluded lower background in figure 5(a) below \( M=1772 \) MeV will allow a structure extraction at such mass.

We recall that all data are normalized by the momentum phase space \( \Delta p_p \times \Delta p_\pi \). Consequently the relative comparison of different cross sections cannot be made when different cuts are applied. In figures 5(c) and (d) the

| TABLE I. Properties of the tentatively extracted narrow peaks in the 1720-1790 MeV baryonic mass region as observed in \( pp \rightarrow p\pi^+X \) and \( pp \rightarrow ppX \) reactions at \( T_p=2100 \) MeV. |
|-----------------|---|---|---|---|---|---|---|
| M (MeV)        | Fig | Mass | obs. width | SD | reaction | \( \theta \) | cuts |
| 1747           | 4(a) | 1745.1 M_{p,X} | 1.3 | 11.7 | \( pp \rightarrow ppX \) | 0.7° | upper branch |
| 1747           | 4(b) | 1745.9 M_{p,X} | 2.5 | 9.1 | \( pp \rightarrow ppX \) | 3° | upper branch |
| 1747           | 4(d) | 1747.0 M_{p,X} | 4.5 | 3.4 | \( pp \rightarrow ppX \) | 9° | upper branch |
| 1747           | 5(a) | 1746.6 M_{\pi^+X} | 1.5 | 3.6 | \( pp \rightarrow pp\pi^+X \) | 0.7° | (see text) |
| 1747           | 5(b) | 1747.9 M_{\pi^+X} | 2.1 | 2.5 | \( pp \rightarrow pp\pi^+X \) | 0.7° | (see text) |
| 1747           | 6(c) | 1751.9 M_{\pi^+X} | 4.2 | 4.3 | \( pp \rightarrow pp\pi^+X \) | 9° | lower branch |
| 1772           | 4(c) | 1770.6 M_{p,X} | 2.0 | 3.8 | \( pp \rightarrow ppX \) | 3° | upper branch |
| 1772           | 5(b) | 1771.5 M_{\pi^+X} | 2.1 | 4.7 | \( pp \rightarrow pp\pi^+X \) | 0.7° | (see text) |
| 1772           | 5(c) | 1773.5 M_{\pi^+X} | 4.9 | 10.5 | \( pp \rightarrow pp\pi^+X \) | 3° | upper branch |
| 1772           | 5(d) | 1773.6 M_{\pi^+X} | 3.4 | 5.8 | \( pp \rightarrow pp\pi^+X \) | 9° | upper branch |
| 1772           | 6(b) | 1769.1 M_{\pi^+X} | 5.3 | 7.8 | \( pp \rightarrow pp\pi^+X \) | 3° | lower branch |
| 1772           | 6(d) | 1772.9 M_{\pi^+X} | 6.2 | 8.2 | \( pp \rightarrow pp\pi^+X \) | 3° | lower branch |
peaks extracted at $\theta = 3^0$ ($M_X \geq 1.15 \text{ GeV}$) and $\theta = 9^0$ ($M_X \geq 0.98 \text{ GeV}$) are shown respectively.

2. The lower branch

In figures 6(a), (b), and (c) the differential cross sections of the $M_{X\pi^+}$ missing mass are shown for the $pp \rightarrow p\pi^+X$ reaction. Low branch events are defined by the condition that $p_p \leq 0.95 \text{ GeV/c}$. The data are shown for $\theta=0.7^0$, $3^0$, and $9^0$ respectively. The error bars are too large at $\theta = 0.7^0$ to allow a peak to be extracted around $M=1747 \text{ MeV}$. In all cases, the available statistics are poor.

C. Differential cross sections

The differential cross sections were obtained for all peaks extracted. Since they are not well defined they are not included in Table 1. Their variation versus the spectrometer angle is only meaningful when all cuts are the same. In this case, we observe that the cross section decreases by a factor $\approx 2.5$ when the spectrometer angle increases from $\theta=0.7^0$ up to $\theta=3^0$ and decreases by a further factor $\approx 7$ as the spectrometer angle increases from $\theta=3^0$ up to $\theta=9^0$.

D. Other spectra - not presented.

In Table 2, a summary of the overall situation is given. In this table there are references to spectra shown in this paper as well as other spectra, which are not shown since there were no structures observed.

As a complement to figures 4, 5, and 6, there was also a study of the forward kinematical branch of the $pp \rightarrow ppX$ reaction at $\theta = 0.7^0$ and $\theta = 3^0$. No peak or structure was observed in the $M_{p_f}$ missing mass spectra.

The lower branch of the $pp \rightarrow ppX$ reaction was also studied. Both the $M_{p_sX}$ and $M_{p_fX}$ missing masses were displayed along with their differential cross sections. The spectra had similar shapes, both having low statistics and a rapid rise in the cross section as a function of the missing mass. The statistics were only sufficient for a more detailed study for the $M_{p_sX}$ data, inside a very narrow invariant mass range, between $M=1782 \text{ MeV}$ and $M=1791 \text{ MeV}$.

It is quite natural to observe higher statistics in the $M_{p_sX}$ upper branch, as compared to the lower branch. This is because the selection is made on the fast proton and there are more events in the upper branch of the fast proton than in the lower branch. Symmetrically, we would expect to have the $M_{p_fX}$ lower branch favoured relative to the upper branch, but such a comparison must be put alongside the observation that, with our experimental kinematical conditions, there are naturally many more events in the upper branch than in the lower branch. For example, if we study the kinematics of the two particle reaction: $p p \rightarrow p_3 N_4 X$ with the mass $M(N_4 X)=1760 \text{ MeV}$, at $\theta = 1^0$, the forward solution corresponds to $p_3=1310 \text{ MeV/c}$, and the momentum transfer $q=4.0 \text{ fm}^{-1}$, whereas the backward solution corresponds to $p_3=720 \text{ MeV/c}$, and the momentum transfer $q=6.1 \text{ fm}^{-1}$. This larger value of $q$ also explains the difficulty in observing small structures. The spectrum of $M_{\pi^+X}$ at $\theta=0.7^0$, from the $pp \rightarrow p\pi^+X$ reaction (lower
branch), is not shown. Here the statistics are close to 300 events/MeV at $M_{e^+X} = 1970$ MeV and are even lower for smaller masses. The same argument as before concerning the transfer momenta values between forward and backward solutions holds here.

**E. Comparison Between Data And Simulation**

Two structures were extracted at 1747 MeV and 1772 MeV. All the peaks - except one - were extracted with S.D. $\geq 3.3$. They are shown graphically in figures 4, 5, and 6, and numerically in Table 1.

In figure 7 the comparison between data and simulation is made for the $pp \rightarrow ppX$ reaction at $T_p = 2.1$ GeV and $\theta = 3^\circ$ (upper branch). It corresponds to the data shown in Figure 4(b) (see also Table 1). Apart from the extremities, we observe a similar shape with a small excess in narrow ranges of data. These excesses occur at the same masses where the possibility of a peak was observed.

**FIG. 7.** Comparison between data (full points) and simulation (empty points) for the $pp \rightarrow ppX$ reaction at $T_p = 2.1$ GeV and $\theta = 3^\circ$ (upper branch). The experimental data are the same as those shown in figure 4(a).

**IV. DISCUSSION**

Since the two structures extracted at $M=1747$ MeV and $M=1772$ MeV are both narrow and are excited at stable masses regardless of the reaction or the angle, then it is not unreasonable to suggest that they may be exotic baryons. Their widths are narrow, and therefore the structures may be associated with genuine baryonic states as opposed to being from some dynamical rescattering effects between final state particles. The mean extracted widths for $\theta = 0.7^\circ$, $3^\circ$, and $9^\circ$ are $\sigma = 1.8$ MeV, 3.9 MeV, and 3.1 MeV respectively. Although the precision is low, these values agree with the experimentally simulated resolutions.

In the $pp \rightarrow ppX$ reaction, the missing mass range $640 \leq M_X \leq 840$ MeV, corresponds mainly to two-pion phase space [7] and $\rho^0$ and $\omega$ mesons. Therefore, these structures may couple to $\Delta \pi$, $p\pi\pi$, $p\rho^0$, or $p\omega$ final states.
The coupling of these potentially new narrow baryons to $N\pi$ cannot be easily studied. Indeed, if the $pp\rightarrow p\pi^+ n$ reaction allows us to study such a coupling, the software cuts due to the experimental acceptance and the need to eliminate the range $1746 \leq M_{\pi^n} \leq 1763$ MeV, which corresponds to a region of lost events where $p_p \approx p_{\pi^+}$, prevents us from getting a clear answer. Nonetheless, our results do not contradict a twenty-year old theoretical statement [8] that the missing baryons couple weakly to $N\pi$.

Several broad baryons, in the $1700 \leq M \leq 1800$ MeV mass range, quoted by PDG [6] with at least two $\star$'s, are $N(1700)D_{13}$, $N(1710)P_{11}$, $N(1720)P_{13}$ and $\Delta(1700)D_{33}$. They all have full widths $\geq 100$ MeV and a predominant decay mode to $N\pi\pi$. Interferences between broad baryons located on both sides of the range $1700 \leq M \leq 1800$ MeV may be relevant. A simulation was performed using Breit Wigner shapes with physical masses and widths given in PDG and arbitrary amplitudes (a). Figure 8 shows the results of the simulation for three different spin and isospin states.

The masses, widths and arbitrary amplitudes are presented in Table 3. In Figure 8 the light lines correspond to the same calculation, but in this case the amplitude of the second baryon is taken as being negative. We observe that in all cases, a narrow, resonance-like structure cannot be created by an interference between broad baryons. Their main effect is to shift, by a small amount, the position of the maximum, which remains broad anyway. So, the very different masses and widths arising from possible interferences between broad baryons, and those observed in our data, preclude any common identification.

The same baryonic mass region was previously studied for other purposes with a lesser resolution and (or) weaker statistics and larger data bins. However, some recent results show some narrow structures, although these are not pointed out by the authors (usually due to statistical reasoning). For example, in the $ep \rightarrow e'p\eta$ cross sections measured at CEBAF [9], a sharp structure was observed at $W \approx 1.7$ GeV and was shown to originate from an interference between S and P waves, in terms of known resonances. Its width is about one order of magnitude larger than the width of the structures presented in this paper, and so in this case, the source of the peak is well understood. In the raw asymmetry data measured with CLAS at JLAB at $T_e=2.6$ GeV in an inclusive $\bar{e}N\bar{H}_3 \rightarrow eX$ scattering experiment [10], a peak at

| reaction | selection          | variable | figures or comments            |
|----------|--------------------|----------|-------------------------------|
| $pp \rightarrow ppX$ | upper branch       | $M_{p_{pX}}$ | $0.7^0$: Figure 4(a), $3^0$: Figure 4(b) |
|          |                    |          | $9^0$: Figure 4(c)            |
|          | lower branch       | $M_{p_{pX}}$ | $9^0$: Figure 4(d)            |
| $pp \rightarrow p\pi^+ X$ | upper branch       | $M_{p_{\pi^n X}}$ | $0.7^0$: Figure 5(a), $3^0$: Figure 5(c) |
|          |                    |          | $9^0$: Figure 5(d)            |
|          | lower branch       | $M_{p_{\pi^n X}}$ | $3^0$: Figure 6(b), $9^0$: Figure 6(c) |
FIG. 8. Search for possible narrow structures created by interferences between broad baryons quoted by PDG [6]. Table 3 lists the masses, widths and amplitudes used.

M≈1780 MeV (σ≈10 MeV) was also observed. This peak was not discussed by the authors, although its S.D. ≈ 3 MeV. Many channel data, ep→eX and ep→eΔ++π− were recorded simultaneously using CLAS at JLAB [11]. In these data, the rather large binning precludes the observation of eventual narrow structures.

The various models of the baryon spectra predicted in the symmetric | q^3 > model were described in a review article by Capstick and Roberts [12]. This article contains an important list of references. In the mass range close to the one discussed in this paper, several baryons

TABLE III. Description of the broad baryon’s used for the simulation of possible narrow bumps through interferences. Masses and widths are in MeV.

| J^P  | T | M_1  | (Γ_1) | a_1 | M_2  | Γ_2 | a_2 | M_3  | (Γ_3) | a_3 |
|------|---|------|-------|-----|------|-----|-----|------|-------|-----|
| 3/2^+| 3/2 | 1600 | (350) | 2   | 1920 | (200)| 1   |       |       |     |
| 1/2^-| 3/2 | 1620 | (150) | 2   | 1900 | (200)| 1   |       |       |     |
| 3/2^-| 1/2 | 1520 | (120) | 2   | 1700 | (100)| 1   | 2080 | (300) | 2   |
were predicted. Many of them may be associated with known PDG baryonic resonances with the same quantum numbers. However, some have no experimental equivalence if we only associate each known PDG resonance with a single calculated baryonic mass. The non-relativistic QCD model [13] predicted several states, all of which have a broad PDG baryon counterpart. In the quark model using chromodynamics [14] [15] [16], one level N(1870)P_{13} has no PDG counterpart. The relativized quark model [17] [18] predicts one baryon \( \Delta_{\frac{1}{2}^+} \) at 1835 MeV without having any PDG counterpart, but with a large partial width in the \( \Delta\pi \) channel. Within the extended Goldstone-Boson-Exchange Constituent Quark Model [19] [20], four levels are found between \( M \approx 1700 \) and 1780 MeV, all of which have a known PDG baryon counterpart if we accept identifications with a difference as large as 100 MeV between calculated and experimental masses. The collective algebraic model [21] [22], predicted several levels, among which four have no PDG counterpart, namely one \( N_{\frac{1}{2}^+} \) state at \( M \approx 1725 \), two \( N_{\frac{3}{2}^+} \) states at \( M \approx 1740 \) MeV and \( M \approx 1810 \) MeV, and one \( \Delta_{\frac{3}{2}^+} \) baryon at \( M \approx 1910 \) MeV. There are no missing baryons in the mass range considered in the semi-relativistic flux-tube model [23] [24]. There are no missing states for masses lower than 2.4 GeV within the framework of the relativistic covariant quark model with instanton-induced quark forces [25].

Among this multitude of predicted baryons, only those having a small calculated width can be compared to our narrow structures. Our \( pp \rightarrow p\pi^+X \) reaction selects mainly the \( \Delta\pi \) invariant mass, whereas the \( pp \rightarrow ppX \) reaction selects \( \Delta\pi \), \( N\pi\pi \), and \( N\pi\pi\pi \) invariant masses. Therefore, the small experimental widths can be close to total widths. Although the calculated partial widths of the missing baryons are sometimes small, even in the \( \Delta\pi \) channel, it is unlikely that the total widths would remain so small for \( |q^3> \) baryons.

V. CONCLUSION

Due to the good resolution of our experimental set-up, previously unobserved narrow structures were identified. An indication for narrow baryonic structures at \( M = 1747 \) MeV and 1772 MeV were observed in the invariant mass spectra \( M_{pX} (M_{\pi^+X}) \) of the \( pp \rightarrow ppX \) (\( pp \rightarrow p\pi^+X \)) reaction. These structures were extracted from several spectra, each with a large number of standard deviations. A careful comparison of our data to simulated spectra allow to conclude that these structures are not simply experimental artefacts. Their small widths exclude the possibility of associating these structures with interference effects between final state particles. Considering the stability of the masses extracted from various reactions at various angles, and with different filters applied, it is reasonable to suppose that these structures are genuine baryonic states. Their masses and widths are compared to the masses and widths of the missing baryon model calculations, and it is concluded that such an identification is unlikely. These possible baryons could be more exotic than the three-quark broad baryons. The name ‘exotic” is usually associated with meson production [26], where angular distributions are measured and the extracted quantum numbers forbid simple \( q\bar{q} \) configurations. In the present work, no spin assignment could be made since no angular distributions are available. The name ‘exotic” is supported by the small observed widths and the impossibility to associate them with any classical \( q^3 \) configuration.

The small spacing \( \approx 25 \) MeV between the observed masses suggests that many narrow and weakly excited states
could exist within the baryonic spectra, and are superimposed on the classical broad baryons. The small widths of the states observed in the present work suggest that the wave functions of these possible baryons could be more complicated than the wave functions of $|q^3>$ baryons.

REFERENCES

[1] E.S. Smith, JLAB-PHY-99-27 (1999).

[2] B. Tatischeff, J. Yonnet, N. Willis, M. Boivin, M.P. Comets, P. Courtat, R. Gacougnolle, Y. Le Bornec, E. Loireleux, and F. Reide, Phys. Rev. Lett. 79, 601 (1997).

[3] B. Tatischeff, 2001 Proceedings of the IX Int. Conf. on Hadron Spectroscopy (Protvino) edited by D. Amelin and A.M. Zaitsev, AIP Conf. Proc. 619, 765 (2001).

[4] L.V. Fil’kov, V.L. Kashevarov, E.S. Konobeevski, M.V. Mordovskoy, S.I. Potashev, V.A. Simonov, V.M. Skorkin, and S.V. Zuev, Eur. Phys. J. A 12, 369 (2001).

[5] B. Tatischeff, J. Yonnet, M. Boivin, M.P. Comets, P. Courtat, R. Gacougnolle, Y. Le Bornec, E. Loireleux, M. MacCormick, F. Reide, and N. Willis, Eur. Phys. Jour. A 17, 245 (2003).

[6] D.E. Groom et al., (Particle Data Group) Eur. Phys. Jour. C 15, 1 (2000).

[7] J. Yonnet, B. Tatischeff, M. Boivin, M.P. Comets, P. Courtat, R. Gacougnolle, Y. Le Bornec, E. Loireleux, F. Reide, and N. Willis, Phys. Rev. C 63, 014001 (2001).

[8] R. Koniuk and N. Isgur, Phys. Rev. D 21, 1868 (1980).

[9] R. Thompson, et al. Phys. Rev. Lett. 86, 1702 (2001).

[10] V.D. Burkert, Prog. Part. Nucl. Phys. 44, 273 (2000).

[11] V.D. Burkert, Nucl. Phys. A 684, 16c (2001).

[12] S. Capstick and W. Roberts, Prog. Part. Nucl. Phys. 45, S241 (2000).

[13] N. Isgur and G. Karl, Phys Rev. D 19, 2653 (1979).

[14] R. Koniuk and N. Isgur, Phys.Rev. D 21, 1868 (1980).

[15] R. Koniuk and N. Isgur, Phys. Rev. Lett. 44, 845 (1982).

[16] R. Koniuk, Nucl. Phys. B195, 452 (1982).

[17] S. Capstick and W. Roberts, Phys. Rev. D 47, 1994 (1993).

[18] S. Capstick and W. Roberts, Phys. Rev. D 49, 4570 (1994).
[19] L.Ya. Glozman, Nucl. Phys. A 663&664, 103c (2000).

[20] R.F. Wagenbrun et al., Nucl. Phys. A 663&664, 703c (2000).

[21] R. Bijker, F. Iachello, and A. Leviatan, Ann.Phys. 236, 69 (1994).

[22] R. Bijker, F. Iachello, and A. Leviatan, Phys. Rev. D 55, 2862 (1997).

[23] P. Stassart and F. Stancu, Phys. Rev. D 42, 1521 (1990).

[24] P. Stassart and F. Stancu, Zeit. Phys. A 351, 77 (1995).

[25] Y. L¨oring, B.Ch. Metsch, and H.R. Petry, 2001 Eur. Phys. J. A 10, 395 (2001).

[26] K.K. Seth, Nucl. Phys. A 684, 89c (2001).
