Study of the $\pi N$ and $\eta p$ de-excitation channels of the $N^*$ and $\Delta$ baryonic resonances between 1470 MeV and 1680 MeV.

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Two reactions: $pp \rightarrow ppX$ and $pp \rightarrow p\pi^+X$ are used in order to study the $1.47 \leq M \leq 1.680$ GeV baryonic mass range. Three different final states are considered in the invariant masses: $N^*$ or $\Delta^+$, $\pi\pi^+$ or $p\pi^0$, and $p\eta$. The two last channels are defined by software cuts applied to the missing mass of the first reaction. Several narrow structures are extracted with widths $\sigma(T)$ varying between 3 and 9 MeV. Some structures are observed in one channel but not in another. Such non-observation may be due either to the spectrometer momenta limits, or to the physics (for example no such disintegration channel allowed from the narrow state discussed).

We tentatively conclude that the broad PDG baryonic resonances: $N(1520)D_{13}$, $N(1535)S_{11}$, $\Delta(1600)P_{33}$, $N(1650)S_{11}$, and $N(1675)D_{15}$ are collective states built from several narrow and weakly excited resonances, each having a (much) smaller width than the one reported by PDG.

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I. INTRODUCTION

For a number of years partial-wave analysis of baryonic resonances have been extensively studied using mainly $\pi N \rightarrow \pi N$, $\pi N \rightarrow \pi\pi N$, and $\gamma N \rightarrow \pi N$ reactions [1]. The study of the dynamics of the $\pi N \rightarrow \pi\pi N$ reaction [2] is also useful for improving our knowledge about meson production, as well as our knowledge of the baryonic resonances. These resonances have also been studied with $pp \rightarrow pN^*$ reactions [3]. The dispersion of the masses found by different experiments, remains generally less than 20 MeV. However the widths of these resonances, as reported by the various authors, differ by a large amount. For example, the width of the $N(1440)P_{11}$ resonance, extracted from the $\pi N \rightarrow \pi N$ reaction, varies between a lower limit of 135±10 MeV and an upper limit of 545±170 MeV [1]. Moreover, the many theoretical width attributions inside constituent quark models [4] are often much smaller than those reported by the experiments. Such discrepancies between different experimental results and between calculated and experimental widths have sometimes been emphasized, and have been used for example to test [5] whether the $N(1535)S_{11}$ could be a pentaquark $q\bar{q}q$ state. It appears therefore that a study of “low mass” baryon resonances with more precise experiments than those previously performed - with a good resolution, small binning, and large statistics - will be a sensitive test for the many existing models. Another important test to select among the models, would be to measure, with a high precision, the branching ratios for various de-excitation modes. In this respect, a recent theoretical work

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[6] finds a $B_{N\pi}$ ratio for the $S_{11}(1535)$ varying from 29$\pm$1\% up to 67$\pm$1\% depending on the model considered. This question was also studied in different theoretical papers, with the emphasis on positive and negative parity resonances [7], or $J^{\pi}=3/2^-$ resonances [8].

If we exclude some recent experiments performed at JLab, nearly all previous studies in the non-strange sector, were done without any attempt to have a good resolution, and therefore a suitable binning. Now, it is possible to do measurements with a better resolution, and finer binning, than before. Such an experiment was performed at the now defunct Saturne synchrotron, on the SPES3 beam line.

In this paper the data from the $p\; p \rightarrow p\; p\; X$ and $p\; p \rightarrow p\; \pi^+\; X$ reactions studied at two incident proton energies: $T_p=1520$ MeV and $T_p=1805$ MeV are reported. The incident energies open up the $\pi^0 p\; (\pi^+ n)$ and $\eta p$ de-excitation channels of the $N^*$ and $\Delta^+$ baryonic resonances. For the first reaction, $p\; p \rightarrow p\; p\; X$, mass ranges $1470 \leq M_{pX} \leq 1585$ MeV using the lowest incident energy and $1560 \leq M_{pX} \leq 1680$ MeV using the highest incident energy were studied. The second reaction, $p\; p \rightarrow p\; \pi^+\; X$, allows the study of the $n\pi^+\; de-excitation\; channel\; of\; the\; N^*\; and\; \Delta^+\; baryonic\; resonances\; in\; the\; range\; 1470 \leq M_{n\pi^+} \leq 1640$ MeV and with a slight spectrometer angle dependence.

The study of nucleon resonances is clearly connected with the production of mesons either close to threshold or at higher energies. A great number of papers are related to such studies and all these papers cannot be quoted here [9], [10].

In the baryonic mass range studied in this paper, one major problem is to distinguish between genuine quark model states and exotic states. Unlike the situation at low baryonic masses, where new narrow states are clearly exotic, for the mass range discussed in this work the answer is not so simple, since, as already stated, the calculated widths of quark model states are sometimes much smaller than the experimental widths reported by PDG. The situation is further complicated by the possibility of connecting new baryons to the “missing resonances” predicted by the constituent quark model, but, so far, not observed. Clearly, measurements of as many properties as possible of the baryonic resonance excitations and disintegrations, would be useful.

This paper is constructed in the following way: the main properties of the experimental layout are briefly recalled in the second section. The third section describes the analysis, and details the various intermediate results for one given angle and one given missing mass selection. The different ways of subtracting events giving the experimental signal but corresponding to the “uncorrelated” missing mass contribution (hereafter called the physical background), will be considered. Results are presented and discussed in the fourth section, and are compared with many theoretical quark model results. A general discussion then follows and the data for several de-excitation branches are compared. The last section contains a summary of the results and a conclusion.

Our results on narrow baryonic resonances in the mass range $1.0 \leq M \leq 1.46$ GeV were already published in [11], and those in the mass range $1.72 \leq M \leq 1.79$ GeV were previously published in [12].

II. PROPERTIES OF THE MAGNET AND DETECTOR LAYOUT.

A complete description was already published in a previous paper [11]. This description included a presentation of the experimental set up, as well as the performances of the experimental apparatus, the checks performed, the
A simulation code was written in order to check the various properties of the detection system. It reproduces the position and the width of the neutron missing mass peak [11]. The simulation code is used to obtain the contributions of the peaks, by subtraction of the physical smooth uncorrelated invariant masses (see later, section III.B.).

III. DESCRIPTION OF THE ANALYSIS.

In the $p p \rightarrow p p X$ reaction, each invariant mass $M_{pX}$ studied, has two different kinematical solutions corresponding to different transferred momenta. Fig. 2 exhibits the scatterplots of $M_{Xp_i}$ versus $p_j \ (i \neq j)$ at $T_p=1520$ MeV, $\theta = 2^0$. $i$ and $j$ denote the fast (f) and slow (s) detected protons. We see clear cuts, created either by physics or by the momenta limits of the spectrometer: $0.6 \leq p_c \leq 1.4$ GeV. The data must be studied separately for the two branches, otherwise an artificial peak structure will appear in the case of a simple addition. All preliminary spectra, versus $M_{pfX}$ or $M_{psX}$, will therefore be presented as belonging to either the “upper branch” or “lower branch”, depending on whether they are above, or below, the turnback limit in the scatterplots. Here, $M_{pfX}$ or $M_{psX}$ are the invariant masses obtained by using the momenta $p_f$ and $p_s$ of the fast and slow emitted protons respectively. The two branches were separated through software cuts on the momentum of the proton not included in the invariant mass (see Fig. 2). These cuts create narrow invariant mass regions with incomplete efficiencies. These narrow ranges are therefore omitted in the spectra. In a few cases, the sum of the spectra from both branches is performed; the eliminated range due to incomplete efficiency is delimited by vertical lines. The missing masses vary from 0 up to 600 MeV at forward angles and for the lowest incident energy. Such a range of results opens up the study of the de-excitation of the baryonic resonances into $N\pi^0$ and $N\eta$ channels at forward angles (see Fig. 3). This range does not allow the study of the disintegration into heavier and still narrower mesons (and nucleons). For increasing spectrometer angles, the resolution spoils whilst the maximum missing mass decreases. The first effect results from the two terms: $\frac{\partial M_X}{\partial \theta_3}$ and $\frac{\partial M_X}{\partial \theta_4}$, where $\theta_3$ and $\theta_4$ are the laboratory angles of both detected protons. At a given angle, the resolution improves for increasing missing mass; this property is due to the term $dM_X = A/M_X$.

At $T_p=1520$ MeV, the $\eta$ is no longer observable for angles above $9^0$. At this incident energy, the $N\pi^0$ de-excitation
channel is observable at all six angles studied.

At $T_p=1805$ MeV, the missing mass varies from 300 MeV up to 750 MeV at forward angles, and varies from 0 MeV up to 500 MeV at $\theta=17^0$. Therefore only the $N\eta$ de-excitation channel is studied at forward angles, and $N\pi^0$ is studied at backward angles.

The $N\pi^0$ ($N\eta$) de-excitation channel is selected through the following software cuts: $M_X \leq 250$ MeV ($540 \leq M_X \leq 565$ MeV). The range of the invariant masses differs at both incident proton energies: $1470 \leq M \leq 1585$ MeV at $T_p=1520$ MeV and $1560 \leq M \leq 1680$ MeV at $T_p=1805$ MeV. Since these invariant masses are different, the data will be presented and discussed separately in four different subsections.

A. Comparison of momenta and missing masses with simulations

The simulation code was written in the following way: the events were generated using a flat random distribution of fast proton momenta, and of angular distributions: $\theta_{pf}$, $\theta_{ps}$, $\phi_{pf}$, and $\phi_{ps}$. For angles other than forward ones, a variable distribution of $\theta_{pf}$ was introduced between the maximum and minimum possible angles. A Gaussian distribution was introduced for the $\eta$ width. We take into account the width of the incident beam, the spectrometer resolution, and the detection resolution. We do not introduce the description (mass and width) of any baryonic resonance in the invariant $M_{p\pi}$ mass, nor do we introduce a specific disintegration channel for this resonance. Our simulation therefore describes the shape of uncorrelated events. We expect to observe, if any, correlated $p\pi^0$ and correlated $p\eta$ events if these give rise to narrow structures in our invariant mass range. We do not expect to be able to observe the broad PDG baryonic resonances since our mass range is too limited for that and the resonances are mixed. In our relatively small invariant mass range the simulated spectra must be continuous with a slowly varying slope. The measured spectra can display discontinuous shapes, since all reactions studied are exclusive.

A comparison of detected and simulated proton momenta when the missing mass is selected by software cuts to the $\pi^0$, is shown in Fig. 4. Inserts (a) and (b) show the momenta distributions of the upper branches of $M_{\pi^0pf}$ and $M_{\pi^0ps}$. Full points are data and empty points are the simulation results for $T_p=1520$ MeV and $\theta=2^0$. Both lower branches are empty. Insert (c) shows the missing mass obtained under the same conditions as in insert (a). Fig. 5 shows similar histograms for $T_p=1520$ MeV again, but at $\theta=9^0$.

We observe the same global shape for data and simulation, at all angles, for the three variables shown in Fig. 2. This shapes are smooth for simulated events and quite dispersed, with non-negligible error bars, for data.

B. Subtraction of the simulated uncorrelated events

This subtraction is illustrated in detail for the upper branch of $M_{x^0ps}$ at $T_p=1805$ MeV, $\theta=17^0$. Insert (a) of Fig. 6 shows the data (full points) and the corresponding normalized simulated spectrum (empty points). Over the first half of the range, both distributions nearly coincide, in the second half we observe many more measured events than simulated events. The subtraction between the data and simulated events is shown in insert (b). These events correspond to correlated $p\pi^0$ from narrow $N^*$ or $\Delta^+$. These results will be discussed in the forthcoming section IV.C.2.
Another illustration is shown in Fig. 7 for the baryonic resonance de-excitation into the $\eta n$ channel with $T_p=1520$ MeV and $\theta = 2^0$. We observe, from Fig. 2 that the main statistics will appear from the upper branch of $M_{\chi ps}$, whereas the corresponding lower branch will give rise to only a few events (and will therefore be omitted). Fig. 7(a) shows the data (full circles) and the background from simulation below the $\eta p$ peaks (empty circles). This last spectrum is used for the uncorrelated event description (background). It is normalized to the maximum possible number of events, but the points raised in this paper would not be modified with a smaller selection of uncorrelated events for the background choice. In Fig. 4(b) the difference between the data and the simulated uncorrelated events is shown; it is decomposed into three gaussians, each having the same width (see Table I, first line).

Fig. 8 shows, for three different kinematical conditions, the data minus the normalized simulations for the uncorrelated events, at $T_p=1520$ MeV, $\theta = 2^0$. The three inserts (a), (b), and (c) exhibit respectively the number of events versus $M_{\chi ps}$ when $p_j \geq p_f$ limit, versus $M_{\chi pf}$ when $p_s \geq p_s$ limit, and versus $M_{\chi pf}$ when $p_s \leq p_s$ limit. Here again, $p$ limit is the momentum value of the turnback in the scatterplot of $M_{\chi pi}$ versus $p_j$ where $j \neq i$. Both Fig. 2 and Fig. 8 use the same data, but in the latter the $N\eta$ disintegration channel is selected through software cuts. The reduction in the invariant mass range is particularly important for insert (b) of Fig. 8. When applying the same selection at other angles, namely when we observe $M_{\chi pf}$ with $p_s$ larger than $p_s$ limit, and select the $N\eta$ disintegration channel, we obtain a small increase in the statistics for increasing angles up to $9^0$, followed by a decrease. Given the weak statistics, this last selection of events will not be presented for this disintegration channel at this incident proton energy.

Table II shows that the same mass values and nearly the same widths are obtained from a gaussian fit of the last insert (c) of Fig. 8. The range of insert (b) is too small to allow to a peak to be extracted; the values extracted from inserts (a) and (c) are consistent with the few existing data points.

C. Subtraction of physical uncorrelated events and background processes

The “background” is constructed by a normalized addition of the total invariant $M_{\chi n}$ mass in both parts, below and above the $\eta$ meson mass in the missing mass spectrum. The software cuts chosen are $500 \leq M_X \leq 525$ MeV and $575 \leq M_X \leq 600$ MeV respectively for both ranges. Fig. 9(a) shows the data points with the normalized “background” discussed before, whereas insert (b) shows the subtracted spectrum, with three gaussian fits, as before. In Table I, the last line shows the properties of the extracted peaks, which all have the same mass and the same width as before when the simulated “background” is used. The relative surface of the peaks, obtained with help of both “backgrounds”, moves a little, but has no influence on the discussion which will be presented later. Such an agreement between masses and widths, obtained with help of both choices for the “background”, allows us to keep the simulated “background” for the other data presented later on. When the physical “background” is used, the ranges of background selected on either side of the peak are at least 37.5 MeV away from the central peak. This avoids including an eventual $\eta$ meson tail if it is present. One direct consequence of this is an irregular shape on the high mass side of the background spectrum as shown in Fig. 9.
IV. RESULTS AND DISCUSSION

Different final states will be studied successively: first, the final state without any particular de-excitation channel, then the two final states with the de-excitation into p\(\pi^0\) (n\(\pi^+\)) and p\(\eta\).

A. The \(N^*\) or \(\Delta^+\) final state

Partial results of the reactions studied were already shown in reference [13]. As previously explained, different spectra must be considered that separate upper and lower branches, and the invariant mass constructed with the slow (fast) proton: \(M_{psX}\) (\(M_{pfX}\)).

\textit{IV.A.1 The pp\(\rightarrow pfps\)X reaction at \(T_p=1520\) MeV.}

IV.A.1.(a) Cross sections versus \(M_{psX}\)

The cross sections of the upper branch of the pp\(\rightarrow pfps\)X reaction at \(T_p=1520\) MeV, versus \(M_{psX}\) are shown in Fig. 10. The left-hand part shows the results at four forward spectrometer angles: \(\theta=0^0, 2^0, 5^0, \text{ and } 9^0\). Clear peaks are observed close to 1500 and 1535 MeV, and also, but less clear, close to 1480 MeV (and possibly close to 1575 MeV). The maximum is close to \(M=1535\) MeV, the mass of the first \(S_{11}\) baryonic resonance \(J^P=1/2^-, T=1/2\), but here the observed width \(\Gamma_t \approx 25-40\) MeV, is much smaller than that expected from the PDG where the mean value is as large as 150 MeV. Indeed, PDG reports for \(N^*(1535)\) a width varying from 57 up to 240\(\pm 80\) MeV. Although it is rather difficult to draw a background below the \(M=1535\) MeV peak, we estimate, at \(\theta=0^0\) and \(2^0\), that the maximum of this \(M\approx 1535\) MeV peak amounts to \(\approx 30\%\) of the total excitation at this mass. There is also, at this mass, room for contributions from other PDG baryonic resonances with smaller and larger masses, and also contributions from N\(\pi\) and N\(\pi\pi\) incoherent phase space contributions. It therefore seems highly improbable that these peaks are purely the PDG broad resonances, but are more likely to be simply parts of them. This point will be clarified later. We suggest that the reason for which the PDG data are so wide is due to the lack of experimental precision in previous experiments.

The right-hand part of Fig. 10 shows the effect of looking at the same data but using different binnings. The binning in insert (b), (3.2 MeV/channel), is the same as the one used in the left-hand part of Fig. 10. It corresponds to the experimental resolution. The binning of insert (d), (32 MeV/channel), is close to the one used in \(\pi N\rightarrow \pi N\) and \(\pi N\rightarrow \pi\pi N\) reactions [14] [15]. A more recent energy-dependent and single-energy partial-wave analysis of \(\pi N\) elastic scattering data [16], presents the results binned in steps close to 20 MeV. The amplitudes of the photoproduction data were also presented with a binning close to 18 MeV [17]. Many other papers were published from year to year by the same group [18], testing the sensitivity of different reactions to the pion-nucleon coupling constant [19], or studying the parameter of the multipole analysis in the region of the first \(\Delta\) resonance [20] or in the range of the N(1535) and N(1650) resonances [21].

The cross sections of the lower branch of the pp\(\rightarrow pfps\)X reaction at \(T_p=1520\) MeV, versus \(M_{psX}\) are shown in Fig. 11. The data at the six measured angles are shown. The small range studied in this lower branch, does not
allow a clear observation of narrow structures. However, we observe a narrow peak at M≈1576 MeV at θ=2^0, and at M≈1532 MeV at θ=17^0. Narrow peaks at these two masses were already observed in the upper branch, at the beginning of this paragraph.

IV.A.1.(b) Cross sections versus M_{pfX}

The differential cross sections of the upper branch of the pp→pfpsX reaction at \( T_p = 1520 \) MeV, versus M_{pfX}, are shown in Fig. 12. Several narrow structures are observed at nearly all six spectrometer angles. There are masses close to 1550, 1567, and 1577 MeV at θ=0^0, 1560 MeV at θ=2^0, 1577 MeV at θ=5^0, 1534 MeV at θ=13^0, and 1530 MeV at θ=17^0.

The differential cross sections of the lower branch of the pp→pfpsX reaction at \( T_p = 1520 \) MeV, versus M_{pfX}, are shown in Fig. 13. Here also, as was previously the case in the lower branch of M_{psX}, it is not possible to observe any narrow structure except at M≈1567 MeV, and at only one angle, θ=5^0.

In short, the masses of narrow structures observed at \( T_p = 1520 \) MeV, in the pp→pfpsX reaction, are close to: 1480, 1500, 1533, 1550, 1560, 1567, and 1576 MeV. The masses of the narrow structures extracted from the cross sections of the pp→pfpsX reaction at \( T_p = 1520 \) MeV, versus M_{pfX}, are not as stable, when studied with respect to M_{psX}. They look like “sliding” spectra. Such a behaviour could eventually be the result of interferences between different resonances. An attempt was made to check this assumption and to extract the relative ratio of amplitudes between resonances of the same quantum numbers. The results were not conclusive, and will not be presented here. The small structures observed in these spectra, versus M_{pfX}, are therefore not included in the summary Table VII.

IV.A.2 The pp→pfpsX reaction at \( T_p = 1805 \) MeV.

At this energy, only the upper branch cross-sections are shown, since the lower branches, once again, cover a very small invariant mass range (\( \Delta M \approx 50 \) MeV) and are populated by weak statistics. The left-hand side of Fig. 14 shows the cross sections of the upper part of the pp→pfpsX reaction versus M_{psX}. Narrow peaks are observed close to the following masses, (where the question mark means a weaker definition): M≈(1621 ?), 1635, and 1668 MeV at θ=0.75^0, M≈(1620 ?), 1637, 1669 MeV at θ=3.7^0, M≈1667 MeV at θ=6.7^0, M≈1600 MeV at θ=9^0, and M≈1657 MeV at θ=13^0. However, the last few peaks are small, and will therefore be omitted later on in Table VII.

The right-hand side of Fig. 14 shows the cross sections of the upper part of the pp→pfpsX reaction versus M_{pfX}. A main maximum is observed in the four smallest angles at a mass close to M≈1638-1640 MeV. A small peak is observed close to M≈1660 MeV in the θ=0.75^0, and θ=6.7^0 data.

In summary, the masses of narrow structures observed at \( T_p = 1805 \) MeV, in the pp→pfpsX reaction, are close to: (1600 ?), (1621 ?), 1639, 1657, 1660, and 1668 MeV. We observe again a shift, \( \Delta M \approx 35 \) MeV, between clear peaks, similar to the observations made at small angles and shown in the left-hand side of Fig. 14. Several broad baryonic resonances are reported by PDG in this mass range; however the widths of the narrow observed peaks are much smaller than the widths reported by PDG.
B. The nπ⁺ final state

The reaction $pp \rightarrow p\pi^+n$ was studied at the same angles and same incident energies as the $pp \rightarrow pfpsX$ reaction. The left-hand part of Fig. 15 shows the cross sections versus the four smallest spectrometer angles obtained at $T_p=1520$ MeV. The maximum, close to $M\approx1506$ MeV, remains steady at the same mass, regardless of the forward angle of observation, and a shoulder is observed at $M_{n\pi^+} \approx 1540$ MeV. The right-hand part of Fig. 15 shows the cross-sections obtained at the two largest angles with maxima close to $1580$ MeV and $1540$ MeV respectively, at $\theta=13^0$ and $\theta=17^0$.

C. The Nπ⁰ de-excitation channel

IV.C.1 The Nπ⁰ de-excitation data from baryonic invariant masses obtained with $T_p=1520$ MeV incident protons

Amongst the four different kinematical conditions shown in Fig. 2, only two at forward angles contribute to the $M_{n\pi^0}$ missing mass. They are the two upper branches for fast and slow detected protons. The $\pi^0$ is not detected in the missing mass for the two lower branches. The results are obtained at the six measured angles: 0⁰, 2⁰, 5⁰, 9⁰, 13⁰, and 17⁰ and are shown in figures 16, 17, 18, 19, 20, and 21 respectively. In these figures the two inserts (a) and (b) present the number of events of the upper branches, versus $M_{XP\pi^0}$ and $M_{XPf}$ respectively. Full circles show the data, empty circles show the normalized simulated uncorrelated spectra, considered to be the ‘background’, and full triangles show the difference between them. In some figures, gaussian peaks are extracted from these last spectra. The quantitative values of these gaussian fits are reported in Table III. Although the number of standard deviations found (S.D.) is large, the definition of the peaks depends strongly on the uncorrelated event distributions, and are therefore poorly defined at $\theta=2^0$ and $\theta=9^0$. At $\theta=13^0$ (Fig. 20) and $\theta=17^0$ (Fig. 21) three peaks are extracted. The extracted masses of these peaks, at both angles, are about the same (see Table III). These patterns may indicate an oscillatory shape. Table III shows a more or less constant mass interval between several peaks ($\Delta M \approx 11$ MeV), since the masses of the extracted peaks are close to $M\approx1479, 1490, 1513, 1520,$ and $1532$ MeV. In this Table R shows the ratio of the peak surfaces (higher mass peak surface divided by lower mass peak surface) where the two peaks are observed under the same kinematical conditions.

At non-forward angles, namely at $\theta=13^0$ and $\theta=17^0$, there are events from the lower branches (see Fig. 2). Fig. 22 shows the number of events versus $M_{\pi^0pf}$ at $\theta=13^0$ (17⁰) in insert (a) ((b)) respectively, at $T_p=1520$ MeV. The statistics are very low when shown as a function of $M_{n\pi^0}$, and the corresponding data were therefore not studied. In the spectra showing the event population versus $M_{\pi^0pf}$, two peaks are extracted at the same masses as for the upper branch (Fig. 13), namely at $M\approx1520$ MeV and $M\approx1531$ MeV (see Table III).

IV.C.2 The Nπ⁰ de-excitation data from baryonic invariant masses obtained with $T_p=1805$ MeV incident protons

The corresponding histograms are empty at forward angles and very few events were accumulated at $\theta=9^0$. The data were studied at the two largest angles: $\theta=13^0$ and $\theta=17^0$. At these angles the number of events is no longer comparable
to the forward angle population since the lower branches are not negligible with respect to the upper branches.

Fig. 23 shows the events at $\theta=13^0$ of the upper branch versus $M_{ps\pi^0}$: data (full points), simulation (empty points) in insert (a) and difference between the two, in full triangles in insert (b). There is a hole close to $M_{ps\pi^0}=1600$ MeV which arises from the region where both $p_f$ and $p_s$ detected proton momenta are similar. In order to avoid such invariant mass ranges with lost events, the following software cuts were applied: all events were suppressed ($M \approx 1600$ MeV), when the difference between both momenta was lower than 50 MeV/c. The mass range $1595 \leq M \leq 1605$ MeV was therefore removed from Fig. 23. The quantitative information is given in Table IV. Fig. 24 shows the corresponding events from the upper branch, versus $M_{pf\pi^0}$. Again, there is a hole in the data close to $M_{pf\pi^0}=1611$ MeV, which corresponds to the region where both proton momenta are equal. However, the simulated results show that the hole is a real physical effect. The data show two peaks described by two gaussians centered at following masses (widths) $M=1605.7$ ($\sigma(\Gamma)=3.4$) MeV and $M=1622$ ($\sigma(\Gamma)=5.4$) MeV, rather than a single gaussian at $M=1616$ ($\sigma(\Gamma)=8.7$) MeV. However, since a (small) ambiguity due to the lost events remains, these results are removed from the general summary and from Tables IV and VII.

A careful detailed analysis was performed at the largest spectrometer angle ($\theta=17^0$). Figures 6 and 25 show the number of events of the upper branches versus the invariant masses $M_{ps\pi^0}$ and $M_{pf\pi^0}$, respectively, at $\theta=17^0$, and $T_p=1805$ MeV. Fig. 26 shows the sum of the data shown in Fig. 6(b) and Fig. 25(b) (i.e. the data minus the simulation of both upper branches). The lower branches contain few events, and Table IV shows that when all upper and lower branches are added (last line of Table IV), the peaks are extracted at the same mass values which were observed before the addition of the lower branches. A check was performed to ascertain that the dip at $M_{p\pi^0} \approx 1607$ MeV was not produced by an instrumental cut or created by a software cut. With this end in view, software cuts were applied to remove the range $1600 \leq M_{p\pi^0} \leq 1610$ MeV in the upper branch data, and the effect on the scatterplot $p_f$ versus $p_s$ was studied. We observe, as shown in Fig. 27, that with this software cut there is an overall reduction in the statistics over the whole scatterplot. This means that the discussed range is not connected to a particular range of momenta. Therefore, the dip is from a physical source as are the two peaks. Quantitative information is given in Table IV.

From these measurements at $T_p=1805$ MeV, five peaks close to the following masses are extracted: 1534 MeV, 1558 MeV, 1582 MeV, 1601 MeV, and 1622 MeV. The three first masses are observed only once, but the last two masses are observed six and four times respectively. The shift between these five masses is more or less constant: $\Delta M \approx 22$ MeV.

D. The $N\eta$ de-excitation channel

IV.D.1 The $N\eta$ de-excitation data from baryonic invariant masses obtained with $T_p=1520$ MeV incident protons

Fig. 28 shows the missing mass $M_X$ at $T_p=1520$ MeV, $\theta=0^0$, for the four kinematical situations. Inserts (a), (b), (c), and (d) correspond to the upper part of $p_s$, the upper part of $p_f$, the lower part of $p_s$, and the lower part of $p_f$ respectively. The $\eta$ is clearly observed in inserts (b) and (c). The data corresponding to the conditions of inserts (a) and (d) will not be studied. The $\eta$ is selected by applying the following software cut: $540 \leq M_X \leq 565$ MeV.
IV.D.1(a) Study of $p_{pf} \geq p_{pf}$ limit data.

The results for the smallest angles, where the $\eta$ meson is observed in our experimental conditions are shown. Figs. 29, 7, 30, and 31 show the number of events of the upper branch of the invariant mass $M_{p\pi\eta}$ for $\theta=0^0, 2^0, 5^0,$ and $9^0$ respectively. The values of the extracted peaks are given in Table V. The peak at $M \approx 1564$ MeV is not well defined, and is only tentatively extracted at $\theta=0^0$ and $5^0$ by analogy with its behaviour at $\theta=2^0$ and $9^0$ where some points remain on the high tail side. Three peaks are extracted at $M_{p\eta} \approx 1502$ MeV, 1519 MeV, and tentatively at 1564 MeV. The $R$ values give the relative angular variation of the surface of the three extracted peaks to the surface of the $M \approx 1564$ MeV peak. They are listed in Table V and are drawn in Fig. 32. This figure shows the relative peak intensities: $M \approx 1505$ MeV peak over $M \approx 1564$ MeV peak (full circles), and $M \approx 1517$ MeV peak over $M \approx 1564$ MeV peak (full triangles). They must be considered as being tentative, since the surfaces are somewhat imprecise. We observe an increase of the second ratio with increasing angles. It is not possible to use this result to discuss the relative spins of both states $M \approx 1517$ MeV and $M \approx 1564$ MeV. Indeed the transferred momenta vary differently for these different final states for increasing angles. The two other ratios are consistent with a constant value.

Three masses are extracted from our spectra, at $M \approx 1502, 1520,$ and 1565 MeV. The second mass is the same as the one extracted with a software selection to $N\pi^0$. The width here is larger, $\sigma(\Gamma) \approx 8$ MeV instead of $\sigma(\Gamma) \approx 4$ MeV. There is a peak at the same mass reported by PDG [1], namely the $D_{13}$, but with a total width $\Gamma \approx 120$ MeV. No peak was extracted at $M \approx 1502$ MeV from the $N\pi^0$ de-excitation data. There is no broad resonance reported at either $M \approx 1502$ MeV, nor at $M \approx 1564$ MeV.

IV.D.1(b) Study of $p_{ps} \leq p_{ps}$ limit data.

Figs. 33, 34, 35, and 36 show the number of events versus the lower branch of $M_{p\eta}$ for angles $\theta=0^0, 2^0, 5^0,$ and $9^0$ respectively, at $T_p=1520$ MeV. For this kinematical configuration, $\theta=9^0$ is again the maximum possible spectrometer angle. The quantitative information is given in Table V. Three peaks are extracted, a peak at $M_{p\eta} \approx 1553$ MeV, seen only once at $\theta=9^0$ and therefore less well defined than the two others, and two peaks close to $M_{p\eta} \approx 1562$ MeV and 1579 MeV. The mass of the first of these two peaks is very close to a mass observed previously in different data, namely the upper part of $M_{p\eta}$, since the mass difference is only $\Delta M \approx 2$ MeV. There is no broad PDG baryon with any of these three masses. Column $R$ in Table V, and Fig. 32 show the relative peak intensities with respect to the $M \approx 1564$ MeV peak. The angular variation of this ratio is flat, and may be considered as being consistent with a value of 1.

IV.D.2 The $N\eta$ de-excitation data from baryonic invariant masses obtained with $T_p=1805$ MeV incident protons

Fig. 37 shows in the missing mass at $T_p=1805$ MeV, $\theta=0.75^0$, clear $M_\eta$ peaks, in inserts (a) and (c), superposed on large backgrounds. Inserts (b) and (d) show the corresponding invariant masses, namely the upper branch of $M_{Xp}\eta$ in insert (a) and the upper branch of $M_{Xps}$ in insert (b). Here the full points correspond to all events and the empty points correspond to events selected by software cuts to choose $p\eta$ disintegrations. In the missing mass at $T_p=1805$ MeV, $\theta=0.75^0$, clear $M_\eta$ peaks are observed, superposed on large backgrounds. The statistics of the lower branch are small and no $\eta$ meson peak is clearly observable in the missing mass spectra. This is illustrated in Fig. 38.
In this figure, insert (a) shows the addition of both upper branch data, to be compared to insert (b) which shows the addition of both lower branch data. Data between both vertical lines are removed since they correspond to the transition region between \( M_{p_f \eta} \) and \( M_{p_s \eta} \) and where some events are lost as the result of the software cuts applied between upper and lower branches. Insert (c) shows the total spectrum of all branches.

Insert (c) of Fig. 38 shows a peak superposed on a background. This background corresponds to uncorrelated events and is studied on Fig. 39 with help of our simulation code. Insert (a) of Fig. 28 shows the renormalized simulated events at \( T_p = 1805 \text{ MeV}, \theta = 0.75^0 \), from the upper branch of \( M_{p_f \eta} \) (empty marks) and from the upper branch of \( M_{p_s \eta} \) (full marks). These simulated data are fitted by two straight lines. Insert (b) shows the same results for \( \theta = 3.7^0 \). The normalized lines fitting the “background” are reported in insert (c) of Fig. 38.

Fig. 40 shows the data for \( \theta = 3.7^0 \) presented in the same way as in Fig. 38 (for \( \theta = 0.75^0 \)). The simulation and data for \( \theta = 6.7^0 \) are shown in Fig. 41 and Fig. 42.

Fig. 43 shows the spectra extracted from the \( pp \rightarrow p_f p_s \eta \) reaction at \( T_p = 1805 \text{ MeV} \) at the three forward angles \( \theta = 0.75^0, 3.7^0, \) and \( 6.7^0 \) corresponding to inserts (a), (b), and (c) respectively. These data came from the subtraction of total events minus uncorrelated simulated events shown in Figs. 38, 40, and 42 for angles \( \theta = 0.75^0, 3.7^0, \) and \( 6.7^0 \) respectively. Two peaks at \( M \approx 1642 \text{ MeV} \) and \( M \approx 1658.5 \text{ MeV} \) are extracted at all three angles. The quantitative information is given in Table VI. The ratio \( R \), shown in Fig. 44, gives the angular distribution of the relative excitation between the \( M \approx 1642 \text{ MeV} \) and the \( M \approx 1658.5 \text{ MeV} \) peaks. The error bars are arbitrarily put to \( \delta R/R = 0.15 \). As previously explained, the different transferred momenta variation, as a function of the angle, prevents drawing any conclusion on the different spins of these two states.

Although the missing mass range is not larger than 70 MeV, the observed shape is not the consequence of a low acceptance due to cuts applied at both edges of the range. These cuts can be clearly seen on both sides of the spectra in Figs. 38(c), 40(c), and 42(c), and affect 4 or 5 channels only on each side.

V. GENERAL DISCUSSION OR COMPARISON BETWEEN BOTH DE-EXCITATION BRANCHES.

Several \( N^* \) and \( \Delta' \)’s are reported in [1] to exist in the mass range \( 1440 \leq M \leq 1700 \text{ MeV} \). They all appear with four stars in the \( N \pi \) de-excitation mode. Two baryonic resonances are reported to have four stars in the \( N \eta \) desexcitation mode: the \( N(1535) \) and \( N(1650) \) both \( S_{11} \). In this channel the observed structures cannot come from any \( \Delta \) resonance.

All our structures have smaller widths than those reported in [1] for the baryonic resonances. They are also weakly excited compared to the excitation of the PDG resonances. It is therefore tempting to associate our narrow structures to the PDG broad ones, providing the latter have a “fine structure”.

By analogy with the nuclear giant resonances, we can argue that the baryonic resonances are so broad, that their lifetime is smaller than \( 10^{-23} \text{s} \). Their de-excitation takes place very quickly, without time for internal reorganizations. Therefore the information on their microscopic structure is conserved. The narrow observed peaks may be signatures of these internal structures.

We observe that interferences between two broad classical baryonic resonances never produce peaks in the middle region between them, but they do produce shifts, usually by \( \pm 10 \) (\( \pm 20 \) MeV of the maximum of the considered
resonance. Therefore, the many narrow observed peaks cannot be the result from interferences.

Table VII shows the quantitative information for the narrow peaks extracted. Some peaks, being too poorly defined, are omitted. The overall data are plotted in Fig. 45, where the channel is defined in Table VII. The dashed areas show the range of study allowed by the physics and the spectrometer momenta acceptance. All broad baryonic PDG resonances have an important $N\pi$ de-excitation channel. We make the assumption that the same is true for the narrow baryonic resonances, even if the spectrometer limits prevent their detection. We observe in Fig. 45 that the many masses of narrow peaks $M\pm\Delta M$, where $\Delta M=3$ MeV, can be brought together into 13 masses shown in the right-hand part of the figure. The full (empty) marks indicate the well (less well) defined peaks.

The mean values of the extracted masses are close to: 1479, 1505, 1517, 1533, 1554, 1564, 1577, 1601, 1622, 1639, 1659, and 1669 MeV. Most observations have been made several times at the same mass, as can be seen in Fig. 45. However, they have different disintegration modes. As previously discussed, the $pp\to pp\pi^0$ and $pp\to p\pi^+n$ reactions are different from the dynamical point of view since in the first one the $\pi^0$ is not detected and has a small momentum, whereas in the second reaction the $\pi^+$ is detected and has therefore a higher momentum ($p_{\pi^+}\geq 600$ MeV/c).

Some masses are seen in both $N\pi$ and $N\eta$ channels, some others are seen in the $N\pi$ channel and not in the $N\eta$ channel. One mass $M=1564$ MeV is seen in the $N\eta$ channel and is not seen in the $N\pi$ channel, although the experimental acceptance allows such an observation. Fig. 46 shows the same results. The left-hand part shows the masses disintegrating through the $N\eta$ channel, and the right-hand part the masses disintegrating through the $N\pi$ channel. The broad dark lines correspond to broad PDG resonances. The vertical lines are dashed when the disintegration mode is not observed, but is likely to exist.

A. Masses disintegrating into $N\pi$ and $N\eta$

Two groups of masses disintegrate through $N\pi$ and $N\eta$ modes. The first one corresponds to the following masses: 1505 MeV, 1517 MeV, 1554 MeV, 1564 MeV, and 1577 MeV. We tentatively associate these five masses to the broad PDG $S_{11}(1535)$ resonance. Indeed, the mean value of our five masses, $\bar{M}\approx 1543$ MeV, is close to the PDG mean mass value: 1535 MeV. The gap between the extreme masses: 72 MeV, fills half of the estimated PDG width: 150 MeV. That several narrow-resonance baryons have an $N\eta$ disintegration channel may, eventually, agree with a calculation of the total the $pp\to pp\eta$ cross section [22]. Ceci et al. [22] “emphasize the fact that a single resonance model, using only $N(1535)$ drastically fails to describe the experimental data. The next $S_{11}$ resonance $N(1650)$ must be included, and the introduction of the third controversial $S_{11} N(2090)$ represents a further improvement”.

The second group of masses which disintegrate through $N\pi$ and $N\eta$ modes, holds two masses, namely $M=1639$ MeV and $M=1659$ MeV. Here $\bar{M}\approx 1649$ MeV is very close to the PDG mass value of the second $S_{11}$ resonance: 1650 MeV. The gap between both masses: 20 MeV is much smaller than the PDG estimated width: 150 MeV.

B. Masses having no $N\eta$ disintegrating channel

Here again, a more or less large gap allows us to tentatively divide the masses of these narrow resonances into two groups. The first one corresponds to the following masses: 1479 MeV, 1533 MeV, and 1542 MeV. Here $\bar{M} \approx 1518$ MeV
and is very close to the PDG mean mass value of the $D_{13}(1520)$ resonance. The gap between extreme masses: 63 MeV corresponds, as it was in the case of $S_{11}(1535)$, to half of the estimated width of the broad PDG resonance.

The second group of masses which do not have the $N\eta$ disintegration mode corresponds to the following masses: $M=1601$ MeV and 1622 MeV. Here $M \approx 1611$ MeV, is close to the PDG mean mass value of the $\Delta P_{33}(1600)$ resonance: 1600 MeV.

It appears therefore that all our masses of narrow baryonic resonances can be associated with PDG resonances, provided the latter can be split into several narrow resonances. Only one, at $M=1669$ MeV, could be a part of the $D_{15}(1675)$ PDG resonance. However, it could also be associated with several hypothetical heavier narrow resonances, which are not observed since their masses lie outside our mass acceptance.

C. Discussion concerning the branching ratios

Since we observe narrow baryonic resonances which disintegrate into $N\pi$ and $N\eta$, it is tempting to compare the ratios of the number of events between both channels.

The comparison between the $p\eta$ final state data (channels $\delta$ to $\nu$ in Fig. 45) and data obtained without final state definition (channels $a$ to $k$ in Fig. 45) is meaningless.

The comparison between the $p\eta$ final state data (channels $\delta$ to $\nu$ in Fig. 45) and $n\pi^+$ final state data (channels l to q in Fig. 45) is again meaningless. Indeed, although we have data at the same angles ($\theta=0^0$ and $2^0$) from the same branch, namely the upper branch, for both reactions, the final states are totally different, since in one case the $\pi^+$ is detected and the neutron is slow, and in the other case, the proton is detected and the $\eta$ is slow.

The comparison between the $p\eta$ final state data (channels $\delta$ to $\nu$ in Fig. 45) and the $p\pi^0$ final state data (channels r to $\eta$ in Fig. 45) is more promising. Indeed we have, in both channels, data showing a narrow peak at $M=1517$ MeV at the same incident proton energy ($T_p=1520$ MeV), from the same branch (the upper branch), and using the same slow proton for both reactions. However the $\eta$ is selected at small angles (from $\theta=0^0$ to $2^0$, channels $\delta$ to $\epsilon$ in Fig. 45), when the $\pi^0$ is selected at large angles (from $\theta=13^0$ to $17^0$, channels t to x in Fig. 45). These limitations result from the spectrometer momenta limits.

We conclude that we are unable to give relative branching ratios.

It is worthwhile to point out that a large “background” of 2 pions exist, whose branching ratios cannot be compared with the $N\pi$ or $N\eta$ branching ratios, since our mass (and angular) range is too small.

VI. COMPARISON WITH OTHER RESULTS

Occasionally data, published in order to study different problems, display narrow discontinuities which are not discussed by the authors. These narrow discontinuities are sometimes, but not always, well defined statistically. The authors of such results did not take into account the possibility to associate the discontinuities of their spectra with possible narrow baryonic low mass structures. We present and discuss some such results and limit our discussion to the mass range $1.47 \leq M \leq 1.68$ GeV, which is the range studied in this work.
A. The $p(\alpha, \alpha')X$ reaction

A precise spectra of the $p(\alpha, \alpha')X$ reaction was obtained twelve years ago at SPES4 (Saturne) in order to study the radial excitation of the nucleon in the $P_{11}(1440 \text{ MeV})$ Roper resonance. A spectrum measured at $T_\alpha=4.2 \text{ GeV}, \theta = 0.8^0$ [23] was defined in the baryonic missing mass range: $1030 \leq M \leq 1490 \text{ MeV}$. A peak is extracted at $M=1478 \text{ MeV}$, very close to $M=1479 \text{ MeV}$ where a peak was extracted from our data. Another spectrum was measured at $T_\alpha=4.2 \text{ GeV}, \theta = 2^0$ [24] which extended up to $M=1588 \text{ MeV}$. Fig. 47 shows the part of this spectrum for masses larger than $1470 \text{ MeV}$. The statistical errors could not be larger than a factor of 2 from the those extracted using the given counts [25]. The error bars are therefore multiplied by a factor of 2. The comparison of the masses of the narrow structures extracted from the experiments performed with the SPES4 and SPES3 beam lines is shown in Fig. 48 and Table VIII. The positions of the structures, observed in both experiments, agree to a high extent. This agreement is obtained from published data, originally obtained from experiments with different objectives, carried out by different physicists and using different set-ups, beams, and reactions.

B. Total cross-sections of $\pi N$ reactions

Rather old total cross-sections of $\pi N$ reactions were reported in a CERN compilation [26]. Whereas neither $\sigma_T(\pi^-p)$ nor $\sigma_T(\pi^+p)$ [27] display any narrow peaks, the data from $\sigma_T(\pi p \rightarrow n\pi^0)$ [26] [28], show small narrow and not very precise peaks close to $M=1500 \text{ MeV}$ [1505], 1635 MeV [1639], and 1660 MeV [1659]. Here the numbers between square brackets are the masses extracted in this work.

C. $\eta$ meson photoproduction on the proton

The total cross section of the $\eta$ meson photoproduction on hydrogen was measured near threshold at ELSA (Bonn) [29]. The very small incident photon energy range prevents the possibility of observing baryonic structures. Total and differential cross sections for the $pp \rightarrow pp\eta$ reaction were studied at the internal beam facility at COSY [30]. In this case the total range of $M_{p\eta}$ is also very restricted. The same reaction was also studied at the MAMI accelerator in Mainz [31] [32]. Total cross-section data are plotted in Fig. 49. Three small and narrow peaks (total width $\approx$ a few MeV) can be extracted, even if the definition of the second one (a2) is better than are the definitions of the two other peaks. The masses of these three peaks can be compared to the first three masses in our data, above the threshold of $\eta$ meson photoproduction off the proton. These masses fit accurately with the masses extracted from the SPES3 data, as can be seen in Table IX.

The differential cross section of $\eta$ photoproduction on the proton was also measured at GRAAL (Grenoble) [33]. Here again, the resolution (and binning) is not appropriate for the study of narrow peaks.
D. Near threshold electroproduction of \( \eta \) meson on the proton

The differential cross-section of the \( p(e,e'p)\eta \) reaction was studied at JLab in Hall C [34]. The \( \eta \) electroproduction was also studied at JLab with the CLAS spectrometer [35]. The integrated cross-sections show small peaks in the vicinity of 1561 MeV, 1582 MeV and 1621 MeV. Here again, the binning of 20 MeV prevents a better observation of any eventual narrow peak. However, the masses are close to the those extracted from the SPES3 data.

E. The \( \gamma p \rightarrow n\pi^+ \) reaction

Differential cross sections for the \( \gamma p \rightarrow n\pi^+ \) reaction were measured at the Bonn 2.5 GeV electron synchrotron [36]. The bremsstrahlung beam allows measurements over a wide incident energy range, typically \( 0.31 \leq T_\gamma \leq 2 \) GeV at six angles between \( \theta_\pi=180^0 \) and 95\(^0\). Additional data, in a more limited photon energy range were taken at six outgoing pion angles between \( \theta=85^0 \) and 35\(^0\) [37]. Fig. 50 shows two small peaks extracted at \( \theta=65^0 \) at \( M=1.638 \) GeV \( (\sigma(\Gamma)=10 \) MeV), and at \( M=1.689 \) GeV \( (\sigma(\Gamma)=8 \) MeV). The first of these masses is very close to one of our narrow peak masses \( (M=1639 \) MeV) and the second one is a little higher than our experimental acceptance.

The differential cross section of the reaction \( \gamma p \rightarrow p\pi^0\pi^0 \) was measured with PHOENICS at ELSA (Bonn) over a large range of photon energy: \( 220 \leq E_\gamma \leq 900 \) MeV [38]. However, the wide binning implies that any narrow peak would be washed out, and so, be unobservable.

F. Meson photoproduction on the nucleon

Many cross sections were measured on the proton and neutron, with one or more pions produced. A review article lists the corresponding results [39]. Several other recent experiments were performed with a binning which does not allow to distinguish narrow peaks. In the mass range studied in this work, many recent results exist which have been measured at the CEBAF Large Acceptance spectrometer and at other accelerators at MAMI (Mainz), ELSA (Bonn), GRAAL (Grenoble) [40] to name a few. The resolution (and the binning) of these data are too weak, preventing the possibility of observing narrow structures such as those shown previously. This is typically the case for the \( \gamma p \rightarrow p\pi^0\pi^0 \) total cross section measured at GRAAL.

The cross section for the reaction \( ep \rightarrow e'p\pi^+\pi^- \) was measured at JLab (CLAS) in the resonance region \( 1.4 \leq W \leq 2.1 \) GeV [41]. The authors concluded on the presence of resonant structures that were not visible in previous experiments. The \( \eta \) meson electroproduction cross section was also measured at JLab (CLAS) with the center of mass total energy \( 1.487 \leq W \leq 1.635 \) GeV [42]. The authors concluded on some indication of a \( Q^2 \) dependence of the width of the \( N(1535) S_{11} \) resonance, although the data are not conclusive. They also attributed to an interference between S and P waves, the new structure they observed at \( W \approx 1.65 \) GeV.

Photon and \( \pi^0 \) electroproduction from hydrogen were studied at JLab Hall A [43]. The excitation curves, presented with a binning of 20 MeV, show an oscillatory pattern of possible peaks with widths that would be much smaller than those \( (\Gamma \approx 200 \) MeV) of classical baryonic resonances.
Total photoabsorption cross sections were also measured at MAMI (Mainz) [44] in the photon energy range $200 \leq E_\gamma \leq 800$ MeV, for several target nuclei. In this last data set, the binning is smaller $\approx 8$ MeV, in the region of $M=1.5$ GeV, but the total cross section is not the best channel for observing narrow exotic, and therefore small, effects.

VII. COMPARISON WITH MODELS OF BARYONIC RESONANCES

The classical baryonic spectrum, in the mass region studied here, was analyzed through a partial-wave analysis of pion-nucleon elastic scattering data [16] and partial-wave analyses of single-pion photoproduction data [17] [18]. In both cases, the data were obtained with binnings close to 20 MeV.

The total and differential cross-sections of the baryonic production in nucleon-nucleon reactions, were calculated in the one-boson exchange model [45]. The authors concluded that their model, after adjustment to the elastic nucleon-nucleon scattering, agree with the experiment.

Many models of baryonic resonances were proposed (see ref. [4]). The quark models are restricted to the assumption of $|q^3 >$ wave functions, without considering additional $q\bar{q}$ pairs or gluonic contributions [4], [46], [47]. These calculations are often related to the search for “missing baryons” which possibly couple weakly to the $N\pi$ channel [48]. The low-lying baryon spectrum was calculated within the chiral constituent quark model [49]. The light-baryon spectrum was calculated within a relativistic quark model with instanton-induced quark forces [50]. On the basis of the three-particle Bethe-Salpeter equation, a good description of the overall baryonic mass spectrum up to the highest spin states was obtained [51].

The properties of baryon resonances in the mass range studied in this paper, were calculated [52] using $\pi N$ data and a multichannel unitary model. The authors found “results similar to previous analyses for strongly excited states, but the results can vary considerably when the states are weak”. They emphasize “that the full width of the $S_{11}(1535)$ varies largely, due to the close proximity of the resonance pole to the $\eta N$ threshold”. It is worthwhile to note that the widths found in the calculation of [53] are consistent, for the $S_{11}(1535)$, with our “experimental total” width obtained by combining the shift between the extreme masses: 1505 MeV and 1577 MeV, and the width of each narrow structure. Indeed, the calculated width in [52] for $\eta N$ is $\Gamma=66\pm13$ MeV, and the calculated width for $\pi N$ is $\Gamma=77\pm17$ MeV.

Several recent works investigate the baryon spectroscopy in lattice QCD [54], [55]. The discussion of these results is outside the scope of the present work.

VIII. CONCLUSION

Using the SPES3 spectrometer and detection system at Saturne, the $pp\rightarrow p\pi^+X$ and $pp\rightarrow ppX$ reactions were studied at two incident energies: $T_p=1520$ MeV and 1805 MeV. With the help of software cuts on the missing mass spectra, the following final states were selected: $p\pi^0$, $n\pi^+$, and $p\eta$. The $N\pi\pi$ final state contributed to the physical background. Due to the good resolution and reasonable statistics, we were able to observe in the range $1.47\leq M\leq1.68$ GeV, a large number of narrow and well separated peaks. In some cases the peak to background ratio is not large, therefore a peak
is only considered as a narrow baryonic resonance when several peaks are extracted at the same mass ($\pm 3$ MeV), and in different experimental data sets. The widths of these peaks are low as compared to the widths reported by the PDG.

We have separated the narrow states observed into two classes: those where a de-excitation into a $N\eta$ final state was observed and those where this was not the case. When combining the masses of narrow states seen in both $N\eta$ and $N\pi$ final states, we tentatively identify them as being “fine structures” of $N^*(1535)S_{11}$ and $N^*(1650)S_{11}$. In the same way, the masses not observed in the $N\eta$ final state are tentatively identified as being “fine structures” of $N^*(1520)$ and $\Delta(1600)P_{33}$. Such assumptions give, for each case, a mean mass that is in fairly good agreement with the mass of the broad PDG baryonic resonance. Such a description could also justify the different mean masses sometimes observed when different reactions are used. For example the mass of the $N(1535)S_{11}$ was found at $M=1549\pm 2$ MeV from the $\pi^-p \rightarrow \eta p$ reaction [56] and at $M=1525\pm 10$ MeV from the $\gamma N \rightarrow \pi N$ reaction [17]. Also, the calculated partial widths are generally too small to account for the experimental values of broad PDG baryons [57].

By analogy with nuclear physics, we suggest that the previously broad PDG baryonic resonances, are in fact collective states of several weakly excited and narrow resonances. These resonances, can be single-particles or quasi-particles (from constituent quark) states, with quark structures more complicated than $|q >^3$. We suggest that the reason for which these narrow weakly excited peaks were not observed till now, is due to the lack of experimental precision of previous experiments.

It is clear that these observations - if confirmed by other experiments - would be a milestone in hadron spectroscopy, and would impose a big challenge to hadron theorists. The hadron structure is more rich than has been often though up till now. Its study requires non-pertubative methods in the mass range studied in this paper. It remains to explain the small widths observed. One possibility may be that there exists some “quark tunnelling” from one quark-cluster to another. It is then possible that new theoretical tools will have to be developed. Indeed, a complete description of hadrons should incorporate valence quarks, sea quarks, and gluonic degrees of freedom.

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TABLE I. pp→ppη reaction. Properties (in MeV) of the peaks extracted using different backgrounds at \( T_p=1520 \text{ MeV}, \theta=2^0 \). Insert (a) corresponds to the result of the subtraction of the simulated background, insert (b) corresponds to the subtraction of the experimental background in both parts of the \( \eta \) meson window in the missing range (see text). \( R \) indicates the ratio of the peak surface relative to surface of the 1564 MeV peak.

| Insert | First peak | Second peak | Third peak |
|--------|------------|-------------|------------|
|        | mass \( \sigma(\Gamma) \) | R I | mass \( \sigma(\Gamma) \) | R I | mass \( \sigma(\Gamma) \) | R |
| (a)    | 1502 8 | 1.36 I | 1519 8 | 0.57 I | 1564 7.5 | 1 |
| (b)    | 1502 8 | 1.43 I | 1519 8 | 0.71 I | 1563 7.5 | 1 |

TABLE II. The pp→ppη reaction at \( T_p=1520 \text{ MeV}, \theta=2^0 \). Properties (in MeV) of the peaks extracted in different kinematical conditions. The software cuts select the \( \eta \) meson missing mass region. Inserts (a), (b), and (c) correspond to the result of the subtraction of the simulated background for different kinematical conditions (see text).

| Insert | First peak | Second Peak | Third peak |
|--------|------------|-------------|------------|
|        | M=1502 \( \sigma(\Gamma)=8 \) | M=1519 \( \sigma(\Gamma)=8 \) | M=1564 \( \sigma(\Gamma)=7.5 \) |
| (b)    | consistent with M=1564 \( \sigma(\Gamma)=8 \) | |
| (c)    | M=1564 \( \sigma(\Gamma)=7.5 \) | |

TABLE III. Properties of the peaks extracted at different angles from the pp→ppπ^0 reaction at \( T_p=1520 \text{ MeV} \). Inserts (a) and (b) show the \( M_{X_{ps}} \) and \( M_{X_{pf}} \) data respectively. \( R \) denotes the ratio of peak surfaces (higher mass peak divided by the lower mass peak), where the two peaks are extracted under the same kinematical conditions. S.D. is the number of standard deviations of each extracted peak. The masses \( M \) and widths \( \sigma(\Gamma) \) are in MeV. All figures (except figure 14) show upper branch events.
| $\theta$ | fig. | insert | branch variable | $M$ ($\sigma(\Gamma)$) | $M$ ($\sigma(\Gamma)$) |
|---------|------|--------|----------------|-------------------------|-------------------------|
| 0       | 16   | a      | $M_{\pi^0 ps}$ | 1479 (3.9) | 1490.2 (2.0) |
|         |      | b      | $M_{\pi^0 pf}$ | 1512.0 (2.8) | 1531.9 (2.7) |
| 2       | 17   | a      | $M_{\pi^0 ps}$ | 1513.7 (7.8) | 1531.5 (4.7) |
|         |      | b      | $M_{\pi^0 pf}$ | 1514.2 (9)  | 1530 (5.5)  |
| 5       | 18   | a      | $M_{\pi^0 ps}$ | 1520.5 (3.5) | 1531.5 (4.7) |
|         |      | b      | $M_{\pi^0 pf}$ | 1558 (5)    | 1597.5 (12.5) |
| 13      | 20   | a      | $M_{\pi^0 ps}$ | 1582 (7.7)  | 1622.6 (7.5) |
|         |      | b      | $M_{\pi^0 pf}$ | 1602 (6.4)  | 1620.5 (7.9) |
| 17      | 21   | a      | $M_{\pi^0 ps}$ | 1558 (5)    | 1597.5 (12.5) |
|         |      | b      | $M_{\pi^0 pf}$ | 1601.1 (4.0) | 1622.6 (7.5) |

TABLE IV. Missing mass from the pp→p_fps\pi^0 reaction at $T_p=1805$ MeV, $\theta=13^0$ and $17^0$.

| $\theta$ | fig. | insert | branch variable | $M$ ($\sigma(\Gamma)$) | $M$ ($\sigma(\Gamma)$) |
|---------|------|--------|----------------|-------------------------|-------------------------|
| 23      | (a)  | 13     | $M_{\pi^0 ps}$ | 1558 (5)  | 1582 (7.7) |
|         | (b)  | 13     | $M_{\pi^0 pf}$ | 1600 (7.7) | 1601.1 (4.0) |
| 6       | (a)  | 17     | $M_{\pi^0 ps}$ | 1534.0 (8.0) | 1597.5 (12.5) |
|         | (b)  | 17     | $M_{\pi^0 pf}$ | 1601.1 (4.0) | 1622.6 (7.5) |

TABLE V. Missing mass from the pp→p_fps\eta reaction at $T_p=1520$ MeV. Properties of the peaks extracted at different angles. The software cuts select the $\eta$ meson missing mass region. The masses and widths ($\sigma(\Gamma)$) are in MeV. $R$ denotes the peak surface relative to the peak surface at $M=1564$ MeV. The masses and widths are in MeV.
| Angle | figure | branch | variable | mass   | $\sigma(\Gamma)$ | R  | I    | mass   | $\sigma(\Gamma)$ | R  | I    | mass   | $\sigma(\Gamma)$ |
|-------|--------|--------|----------|--------|-----------------|----|------|--------|-----------------|----|------|--------|-----------------|
| $0^\circ$ | 29 | up    | $M_{p\pi\eta}$ | 1500  | 8    | 1.37 | I    | 1519  | 8    | 0.42 | I    | 1564  | 7.5  | 1    |
| $2^\circ$ | 7    | up    | $M_{p\pi\eta}$ | 1502  | 8    | 1.36 | I    | 1519  | 8    | 0.57 | I    | 1564  | 7.5  | 1    |
| $5^\circ$ | 30   | up    | $M_{p\pi\eta}$ | 1502  | 8.5  | 0.09 | I    | 1520.5 | 9    | 1.08 | I    | 1567  | 8    | 1    |
| $9^\circ$ | 31   | up    | $M_{p\pi\eta}$ | 1502  | 8.5  | 0.09 | I    | 1520.5 | 9    | 1.08 | I    | 1567  | 8    | 1    |
| $0^\circ$ | 33   | lo    | $M_{p\pi\eta}$ | 1561.5 | 6.5  | 1    | I    | 1580  | 6.5  | 0.68 | I    | 1564.2 | 6    | 1    |
| $2^\circ$ | 34   | lo    | $M_{p\pi\eta}$ | 1562.4 | 6    | 1    | I    | 1580.1 | 6    | 1.15 | I    | 1577.2 | 6.1  | 1.08 |
| $5^\circ$ | 35   | lo    | $M_{p\pi\eta}$ | 1561.5 | 6    | 1    | I    | 1576.2 | 6.1  | 1.08 | I    | 1567.0 | 6.3  | 1    |
| $9^\circ$ | 36   | lo    | $M_{p\pi\eta}$ | 1553.1 | 6    | 1    | I    | 1567.0 | 5.3  | 1    | I    | 1567.0 | 5.3  | 1    |

TABLE VI. Missing mass from the pp→p/fp/η reaction at $T_p=1805$ MeV. Properties of the peaks extracted at different angles. The software cuts select the η meson missing mass region. The masses and widths ($\sigma(\Gamma)$) are in MeV. R gives the ratio of the first peak relative to the second peak.

| Insert | Angle | mass  | $\sigma(\Gamma)$ | R  | mass  | $\sigma(\Gamma)$ |
|--------|-------|-------|-----------------|----|-------|-----------------|
| (a)    | $0.75^\circ$ | 1642.5 | 6 | 0.71 | 1656.9 | 6 |
| (b)    | $3.7^\circ$ | 1642.3 | 7.5 | 0.89 | 1658.7 | 7.3 |
| (c)    | $6.7^\circ$ | 1644.2 | 7.8 | 1.45 | 1659.8 | 7.5 |

TABLE VII. Quantitative information concerning the narrow baryonic structures extracted from the following reactions: pp→ppX [1], pp→pπ+ n [2], pp→ppπ^0 [3], and pp→ppη [4]. These informations are used in Fig. 45. The masses are in MeV, the angles are in degrees.
| channel | Fig. | reaction | T   | θ   | variable | branch | 1st mass | 2nd mass | 3rd mass | 4th mass |
|---------|------|----------|-----|-----|----------|--------|----------|----------|----------|----------|
| (a)     | 10   | [1]      | 1520 | 0°  | $M_{\text{ps}X}$ | up     | 1535     |          |          |          |
| (b)     | 10   | [1]      | 1520 | 2°  | $M_{\text{ps}X}$ | up     | 1482     | 1500     | 1535     | 1565     |
| (c)     | 10   | [1]      | 1520 | 5°  | $M_{\text{ps}X}$ | up     | 1476     |          | 1538     |          |
| (d)     | 10   | [1]      | 1520 | 9°  | $M_{\text{ps}X}$ | up     | 1535     |          | 1575     |          |
| (e)     | 14   | [1]      | 1805 | 0.75° | $M_{\text{ps}X}$ | up     | 1635     |          | 1668     |          |
| (f)     | 14   | [1]      | 1805 | 3.7° | $M_{\text{ps}X}$ | up     | 1637     |          | 1669     |          |
| (g)     | 14   | [1]      | 1805 | 6.7° | $M_{\text{ps}X}$ | up     | 1667     |          |          |          |
| (h)     | 14   | [1]      | 1805 | 0.75° | $M_{\text{pf}X}$ | up     | 1636     |          | 1659     |          |
| (i)     | 14   | [1]      | 1805 | 3.7° | $M_{\text{pf}X}$ | up     | 1637     |          |          |          |
| (j)     | 14   | [1]      | 1805 | 6.7° | $M_{\text{pf}X}$ | up     | 1640     |          | 1659     |          |
| (k)     | 14   | [1]      | 1805 | 9°  | $M_{\text{pf}X}$ | up     | 1641     |          |          |          |
| (l)     | 15   | [2]      | 1520 | 0°  | $M_{\text{nx}X}$ | up     | 1505     | 1540     |          |          |
| (m)     | 15   | [2]      | 1520 | 2°  | $M_{\text{nx}X}$ | up     | 1508     | 1545     |          |          |
| (n)     | 15   | [2]      | 1520 | 5°  | $M_{\text{nx}X}$ | up     | 1506     | (1540?)  |          |          |
| (o)     | 15   | [2]      | 1520 | 9°  | $M_{\text{nx}X}$ | up     | 1508     |          |          |          |
| (p)     | 15   | [2]      | 1520 | 13° | $M_{\text{nx}X}$ | up     | 1588     |          |          |          |
| (q)     | 15   | [2]      | 1520 | 17° | $M_{\text{nx}X}$ | up     | (1550?)  |          |          |          |
| (r)     | 17   | [3]      | 1520 | 2°  | $M_{\text{ps}x}^a$ | up     | 1479     | 1490     |          |          |
| (s)     | 19   | [3]      | 1520 | 9°  | $M_{\text{ps}x}^a$ | up     | 1512     |          |          |          |
| (t)     | 20   | [3]      | 1520 | 13° | $M_{\text{ps}x}^a$ | up     | 1513.7   |          |          |          |
| (u)     | 20   | [3]      | 1520 | 13° | $M_{\text{pf}x}^a$ | up     | 1520.5   | 1531.9   |          |          |
| (v)     | 21   | [3]      | 1520 | 17° | $M_{\text{ps}x}^a$ | up     | 1514.2   |          |          |          |
| (w)     | 21   | [3]      | 1520 | 17° | $M_{\text{pf}x}^a$ | up     | 1520     | 1531.5   |          |          |
| (x)     | 22   | [3]      | 1520 | 17° | $M_{\text{pf}x}^a$ | lo     | 1520     | 1531     |          |          |
| (y)     | 23   | [3]      | 1805 | 13° | $M_{\text{ps}x}^a$ | up     | 1558     | 1582     | 1600.3   |          |
| (z)     | 24   | [3]      | 1805 | 13° | $M_{\text{pf}x}^a$ | up     |          |          |          |          |
| (α)     | 6    | [3]      | 1805 | 17° | $M_{\text{ps}x}^a$ | up     | 1534     | 1597.5   |          |          |
| (β)     | 25   | [3]      | 1805 | 17° | $M_{\text{pf}x}^a$ | up     | 1601.1   | 1622.6   |          |          |
| (η)     | 26   | [3]      | 1805 | 17° | $M_{\text{ps}x}^a$ | all    | 1599.5   | 1620.5   |          |          |
| (δ)     | 29   | [4]      | 1520 | 0°  | $M_{\text{ps}η}$ | up     | 1500     | 1519     | 1564     |          |
| (ε)     | 7    | [4]      | 1520 | 2°  | $M_{\text{ps}η}$ | up     | 1502     | 1519.5   | 1564     |          |
| (φ)     | 30   | [4]      | 1520 | 5°  | $M_{\text{ps}η}$ | up     | 1520.5   | 1567     |          |          |
| (γ)     | 31   | [4]      | 1520 | 9°  | $M_{\text{ps}η}$ | up     | 1564.2   |          |          |          |
| (χ)     | 33   | [4]      | 1520 | 0°  | $M_{\text{pf}η}$ | lo     | 1561.5   | 1580     |          |          |
| (ζ)     | 34   | [4]      | 1520 | 2°  | $M_{\text{pf}η}$ | lo     | 1562.4   | 1580.1   |          |          |
| (σ)     | 35   | [4]      | 1520 | 5°  | $M_{\text{pf}η}$ | lo     | 1560.1   | 1576.2   |          |          |
| (κ)     | 36   | [4]      | 1520 | 9°  | $M_{\text{pf}η}$ | lo     | 1553.1   | 1567     |          |          |
| (λ)     | 43   | [4]      | 1805 | 0.75° | $M_{\text{pf}η}$ | all    | 1642.5   | 1656.9   |          |          |
| (µ) | 43 | 1805 | $3.7^0$ | $M_{\eta}$ | all | 1642.3 | 1658.7 |
|-----|----|------|---------|------------|-----|--------|--------|
| (ν) | 43 | 1805 | $6.7^0$ | $M_{\eta}$ | all | 1644.2 | 1659.8 |

**TABLE VIII.** Masses (in MeV) of narrow exotic baryons observed in SPES3 data and extracted from previous $p(\alpha, \alpha')X$ spectra measured at SPES4 [24].

| SPES3 mass | 1479 | 1505 | 1517 | 1533 | 1542 | (1554) | 1564 | 1577 |
|------------|------|------|------|------|------|--------|------|------|
| peak marker | (l)  | (m)  | (n)  | (o)  | (p)  | (q)    | (r)  | (s)  |
| SPES4 mass  | 1492 | 1505 | 1517 | 1530 | 1544 | 1557   | 1569 | 1580 |

**TABLE IX.** Total cross-section of $\eta$ meson photoproduction on the proton. Measurements performed at MAMI [31] [32]. Small peaks (a1), (a2), and (a3) are extracted (see Fig. 49).

| peak | $E_\gamma$ (MeV) | $\sqrt{s}$ (MeV) | SPES3 mass (MeV) |
|------|------------------|------------------|------------------|
| (a1) | 739.8            | 1506             | 1505             |
| (a2) | 757.2            | 1517             | 1517             |
| (a3) | 786.0            | 1534.7           | 1533             |
FIG. 1. Spes3 spectrometer and the associated detection.

FIG. 2. pp→ppX reaction at $T_p=1520$ MeV and $\theta=2^\circ$. Scatterplot of fast proton momenta $p_f$ versus the invariant mass $M_{Xps}$ and slow proton momenta $p_s$ versus $M_{Xpf}$.

FIG. 3. Number of events of the missing mass of the pp→pфpsX scattering. Inserts (a) and (b) show $T_p=1520$ MeV data for the upper branch $p_f \geq p_f$ limit, respectively at $0^\circ$ and $17^\circ$. Inserts (c) and (d) show $T_p=1805$ MeV data for the upper branch $p_s \geq p_s$ limit, respectively at $0.75^\circ$ and $17^\circ$.

FIG. 4. pp→ppπ⁰ reaction at $T_p=1520$ MeV, $\theta=5^\circ$. Inserts (a) (b) shows the number of events versus the momenta of the fast (slow) proton, for the upper branch of $M_{\pi^0ps}$($M_{\pi^0pf}$). The lower branches are empty due to the $M_X \leq 250$ MeV software cut. Insert (c) shows the missing mass under the same conditions as in insert (a). Full points are data and empty points are simulated.

FIG. 5. Same caption as caption of fig. 4, but for $\theta=9^\circ$.

FIG. 6. (a) The number of events of the upper branch of the $M_{\pi^0ps}$ invariant mass from the pp→ppπ⁰ reaction at $T_p=1805$ MeV and $\theta=17^\circ$. Full points are the measured data; empty points are the corresponding normalized simulated events (see text). (b) The difference between data and simulation, representing correlated invariant masses from narrow baryonic resonances.

FIG. 7. pp→pфpфη scattering at $T_p=1520$ MeV and $\theta=2^\circ$. Number of events versus $M_{ps\eta}$ selected by a cut on $p_f$ in order to retain only the upper branch events. In insert (a), the full points are the data and the empty points are the normalized simulated background. In insert (b), the difference between data and background is presented and is fitted by three gaussians (see table 1).

FIG. 8. Data minus normalized simulations for the uncorrelated events at $T_p=1520$ MeV, $\theta =2^\circ$. The three inserts (a), (b), and (c) exhibit respectively the number of events versus $M_{Xps}$ when $p_f \geq p_f$ limit (upper branch), versus $M_{Xpf}$ when $p_s \geq p_s$ limit (upper branch), and versus $M_{Xpf}$ when $p_s \leq p_s$ limit (lower branch).

FIG. 9. Same caption as the one of Fig. 7, except that the normalized background is the physical background obtained by selecting lower and upper part of the missing mass spectrum around the $\eta$ meson mass.

FIG. 10. Upper branch of the pp→ppX cross sections at $T_p=1520$ MeV versus $M_{psX}$. In order to appear clearly in the same figure the data in insert (a) are normalized by factors: 1.7, 2.2, 3.5, and 2.5 for angles $0^\circ$, $2^\circ$, $5^\circ$, and $9^\circ$ respectively. The right-hand part of the figure shows the $\theta =2^\circ$ data with different binnings. The four inserts (a), (b), (c), and (d) correspond respectively to the following binnings: 0.8, 3.2, 19.2, and 32 MeV/channel.

FIG. 11. Lower branch of the pp→ppX differential cross section at $T_p=1520$ MeV versus $M_{psX}$. In order to appear clearly in the same figure the data are normalized by the following factors: 1.5, 1.5, 0.8, 0.3, 0.1, and 0.1 for angles $0^\circ$, $2^\circ$, $5^\circ$, $9^\circ$, $13^\circ$, and $17^\circ$, respectively.
FIG. 12. Upper branch of the \( pp \rightarrow ppX \) differential cross section at \( T_p=1520 \) MeV versus \( M_{p_X} \). In order to appear clearly in the same figure the data are normalized by the following factors: 1.0, 0.4, 0.5, 0.3, 0.1, and 0.1 for angles 0°, 2°, 5°, 9°, 13°, and 17°, respectively.

FIG. 13. Lower branch of the \( pp \rightarrow ppX \) cross sections at \( T_p=1520 \) MeV versus \( M_{p_X} \). In order to appear clearly in the same figure the data are normalized by the following factors: 1, 0.4, 0.6, 0.5, 0.4, and 0.7 for angles 0°, 2°, 5°, 9°, 13°, and 17°, respectively.

FIG. 14. Cross sections of the upper branch of the \( pp \rightarrow ppX \) reaction at \( T_p=1805 \) MeV. The left-hand part of the figure shows the results from the upper branch versus \( M_{psX} \). In order to appear clearly in the same figure the data are normalized by the following factors: 3.6, 7.5, 10.0, 7.5 and 10.0 for angles 0°, 7.5°, 3.7°, 6.7°, 9°, and 13°, respectively. The right-hand part of the figure shows the results from the upper branch versus \( M_{pfX} \). In order to appear clearly in the same figure the data are normalized by the following factors: 1, 2.5, 4, 4, and 5 for angles 0°, 7.5°, 3.7°, 6.7°, 9°, and 13°, respectively.

FIG. 15. The left-hand part of the figure shows the differential cross sections of the \( pp \rightarrow p\pi^+n \) reaction versus \( M_{\pi^+n} \), at forward angles and at \( T_p=1520 \) MeV. In order to appear clearly in the same figure, the data, going from top to bottom, are normalized by factors: 1.0 at 0° (empty squares), 1.5 at 2° (full circles), 4.4 at 5° (full triangles), and 12. at 9° (empty stars). The right-hand part of the figure shows the same differential cross sections at \( T_p=1805 \) MeV, at the two largest measured angles. In order to appear clearly in the same figure, the data are normalized by factors: 1.0 at 13° (full triangles) and 2.0 at 17° (empty triangles).

FIG. 16. \( pp \rightarrow pp\pi^0 \) reaction at \( T_p=1520 \) MeV and \( \theta=0^0 \). Both inserts show the number of events of the upper branch versus \( M_{\pi^0ps} \) (insert (a)), and versus \( M_{\pi^0pf} \) (insert (b)). Full circles show the data and empty circles show the normalized simulated background (see text for more details).

FIG. 17. \( pp \rightarrow pp\pi^0 \) reaction at \( T_p=1520 \) MeV and \( \theta=2^0 \). Both inserts show the number of events of the upper branch versus \( M_{\pi^0ps} \) (insert (a)), and versus \( M_{\pi^0pf} \) (insert (b)). Full circles show the data and empty circles show the normalized simulated background. Full triangles show the difference between data and simulation. The curves show two gaussians tentatively extracted from the full triangles spectrum. (see text for more details).

FIG. 18. Same caption as for Fig. 17, but at \( \theta=5^0 \).

FIG. 19. Same caption as for Fig. 10, but at \( \theta=9^0 \).

FIG. 20. Same caption as for Fig. 10, but at \( \theta=13^0 \).

FIG. 21. Same caption as for Fig. 10, but at \( \theta=17^0 \).
FIG. 22. pp→ppπ⁰ reaction at T_p=1520 MeV and θ=13⁰ (insert (a)) and θ=17⁰ (insert (b)). Number of events of the lower branch versus M_{pfπ⁰}. Full circles show the data, empty circles show the normalized simulated background, and full triangles show the difference between measured and simulated data. See text for more details, and table 3 for quantitative information.

FIG. 23. pp→ppπ⁰ reaction at T_p=1805 MeV and θ=13⁰. Number of events of the upper branch, versus M_{psπ⁰}. Insert (a) shows the data (full points) and simulated uncorrelated events (empty points). Insert (b) shows the difference between both (full triangles) and an attempt to extract three gaussians from the spectrum.

FIG. 24. Same caption as for Fig. 15, but versus M_{pfπ⁰}. Two different possible descriptions of the data, with one or two gaussians, are shown, although the description with two gaussians is preferred (see text).

FIG. 25. Same caption as for Fig. 3, but versus M_{pfπ⁰}.

FIG. 26. The pp→ppπ⁰ reaction at T_p=1805 MeV and θ=17⁰. Addition of data from both upper branches. The quantitative information is given in table 4.

FIG. 27. The upper branch data corresponding to the pp→ppπ⁰ reaction at T_p=1805 MeV and θ=17⁰. Insert (a) shows the scatterplot of the fast versus the slow detected proton momenta. Insert (b) shows the same scatterplot after a software selection vetoing the range 1600≤M_{psπ⁰}≤1610 MeV. Insert (c) shows the scatterplot of these data corresponding to the range 1600≤M_{psπ⁰}≤1610 MeV.

FIG. 28. The pp→ppX reaction at T_p=1520 MeV and θ=0⁰. Inserts (a), (b), (c), and (d) show the missing mass M_X for p_s≥p_s limit, p_f≥p_f limit, p_s≤p_s limit, and p_f≤p_f limit respectively.

FIG. 29. The pp→ppη data, selected by software cuts, at T_p=1520 MeV and θ=0⁰. Insert (a) shows the data of the upper branch (full points), and the corresponding normalized simulated background (empty points), versus M_{psη}. Insert (b) shows the data minus background spectrum, and the extracted gaussians.

FIG. 30. Same caption as in Fig. 20, but for θ=5⁰.

FIG. 31. Same caption as in Fig. 20, but for θ=9⁰.

FIG. 32. pp→ppη data selected by software cuts at T_p=1520 MeV. Relative intensities R, versus the spectrometer angle (see text). In spectra versus M_{psη}, full circles show the ratio of the M≈1505 MeV peak over the M≈1564 MeV peak, full triangles show the ratio of the M≈1517 MeV peak over the M=1564 MeV peak. In the spectra versus M_{pfη}, full stars show the ratio of the M≈1577 MeV peak over the M≈1564 MeV peak.
FIG. 33. Number of events of the lower branch of the \( pp \rightarrow pp\eta \) reaction, selected by software cuts, at \( T_p=1520 \) MeV and \( \theta=0^0 \). Insert (a) shows the data (full points) and the normalized simulated background (empty points) versus \( M_{ pf \eta} \). Insert (b) shows the data minus background, and the extracted gaussians.

FIG. 34. Same caption as in Fig. 23, but for \( \theta=2^0 \).

FIG. 35. Same caption as in Fig. 23, but for \( \theta=5^0 \).

FIG. 36. Same caption as in Fig. 23, but for \( \theta=9^0 \).

FIG. 37. The \( pp \rightarrow pp\eta \) reaction at \( T_p=1805 \) MeV and \( \theta=0.75^0 \). Insert (a) and (c) show the missing mass events corresponding to the upper branch of \( M_{X pf} \) and to the upper branch of the \( M_{X ps} \) spectra. Inserts (b) and (d) show the corresponding invariant masses. Full points are data without cuts on the missing mass, and empty points show the number of events after applying software cuts to retain the \( \eta \) meson in the missing mass.

FIG. 38. The \( pp \rightarrow pp\eta \) reaction at \( T_p=1805 \) MeV and \( \theta=0.75^0 \). Inserts (a), (b), and (c) show both the two upper branch data, both lower branch data, and data from all four branches respectively. The simulated background is reported by two straight lines.

FIG. 39. The \( pp \rightarrow pp\eta \) reaction at \( T_p=1805 \) MeV. Insert (a) shows the simulated events at \( \theta=0.75^0 \), from the upper branch of \( M_{ pf \eta} \) (empty symbols) and from the upper branch of \( M_{ ps \eta} \) (filled symbols). This simulated data is fitted by two straight lines. Insert (b) shows the same results for \( \theta=3.7^0 \).

FIG. 40. Same caption as in Fig. 27 but for \( \theta=3.7^0 \).

FIG. 41. Same caption as Fig. 28, but for \( \theta=6.7^0 \).

FIG. 42. Same caption as in Fig. 29, but for \( \theta=6.7^0 \).

FIG. 43. The \( pp \rightarrow pp\eta \) reaction at \( T_p=1805 \) MeV. The points show the total data minus the normalized uncorrelated background simulated data. Inserts (a), (b), and (c) are for \( \theta=0.75^0, 3.7^0, \) and \( 6.7^0 \) respectively.

FIG. 44. The \( pp \rightarrow pp\eta \) reaction at \( T_p=1805 \) MeV. The ratio \( R \) shows the relative excitation between the \( M \approx 1639 \) MeV and the \( M \approx 1659 \) MeV peaks at three forward angles, where both peaks were extracted.
FIG. 45. Masses (in MeV) of the narrow structures extracted from pp→ppX and pp→pπ+n reactions in the mass range 1470≤M≤1680 MeV. Full (empty) circles correspond to well (less well) defined peaks. Each column correspond to a particular experimental situation (reaction, incident energy, angle, upper or lower branch, and invariant mass reconstructed using the slow (fast) proton). The mass ranges studied differ with different reactions; they are indicated by a dashed area. The mass values of these areas are defined in the following way: the mean value of several masses of narrow peaks is kept as being a narrow peak mass, and the area is drawn with ±3 MeV range. The quantitative information is given in table VII.

FIG. 46. The figure shows the disintegration channels of the narrow baryonic resonances experimentally observed, and an attempt to associate them with broad PDG resonances.

FIG. 47. The p(α, α′)X spectrum at T_α=4.2 GeV, θ=20°, measured at SPES4 (Saturne) [24]. Only the part of the spectrum corresponding to the baryonic mass range studied here: 1470≤M≤1680 MeV is shown.

FIG. 48. Comparison of narrow mass structures observed in the SPES3 data with those extracted from the p(α, α′)X spectrum at T_α=4.2 GeV, θ=20°, measured at SPES4 (Saturne) [24]. Only part of the spectrum, corresponding to the baryonic mass range studied here: 1470≤M≤1680 MeV, is shown.

FIG. 49. Near threshold photoproduction of the η meson on the proton. The data were taken at MAMI (Mainz) [31] [32]. The quantitative information of the extracted peaks is given in table IX.

FIG. 50. Differential cross section at θ = 65° of the γp→π+n reaction measured at Bonn [36].
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