Exotic low mass narrow baryons extracted from charge exchange reactions

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Abstract

This paper aims to give further evidence for the existence of low mass exotic baryons. Narrow structures in baryonic missing mass or baryonic invariant mass were observed during the last twelve years. Since their evidence is still under debate, various data, measured with incident hadrons, by different collaborations, are reanalyzed to bring evidence on these narrow exotic baryonic resonances excited in charge-exchange reactions. These structures are clearly exotic as there is no room for them in the qqq configurations [1]: their width is smaller than the widths of "classical" baryonic resonances [2], moreover some of the masses lie below the pion threshold mass.

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I. INTRODUCTION

Already observed since several years, the experimental observation of narrow low-mass baryonic structures is not yet accepted as an evidence. This paper summarizes briefly the experiments where these structures were observed, and reanalyses other data, in order to add information on these narrow baryonic exotic resonances.

Although obtained with different physical motivations, therefore with statistical precision lower than the precision preferable for the present study, these results add information on these structures. We reanalyze here cross-sections data involving only hadrons. Indeed, the narrow structures were associated with multi-quark clusters, which may explain that they are hardly observable in reactions involving incident leptons. Concerning pion charge-exchange reactions, the statistics is too poor for the present study.

Therefore, in the present work, several spectra on baryon charge-exchange reactions are reanalyzed, and plotted as a function of the missing masses even though they were originally published as a function of the energy loss.

II. BRIEF RECALL OF PREVIOUS RESULTS

A. The SPES3 (Saturne) data

Previous experiments, performed at SPES3 (Saturne), which benefit of good resolution and high statistics, exhibit narrow structures at different hadronic masses. Only results concerning baryons are discussed here. In particular, two reactions:

$$p + p \to p + p + X \tag{1}$$

and

$$p + p \to p + \pi^+ + X \tag{2}$$

were studied [3, 4]. Structures were observed in the missing mass M_X of reaction (2), in the invariant mass M_{pX} of reaction (1), and in the invariant masses $M_{p\pi^+}$ and M_{π^+X} of reaction (2).

FIG. 1: Missing mass differential cross-sections for pp \rightarrow p π^+ X reaction for the three lowest angles at T_p=1520 and 1805 MeV, selected for missing masses larger than 960 MeV. Data measured at SPES3 (Saturne) [3]. They have been binned into 5.6 MeV mass intervals, shifted and rescaled in order to present the six angles inside the same figure. Vertical lines indicate the mean position of the structures (α) M=1004 MeV, (β) M=1044 MeV, and (γ) M=1094 MeV.

Narrow structures were observed in different conditions (reaction, incident energy, spectrometer angle, or observable) at the same masses (within ± 3 MeV) which is, in the opinion of the authors, a strong indication of their existence.

A single figure (Fig. 1) is reproduced here, since it corresponds to the first observation of these exotic baryons [3], and since the corresponding masses, narrow and lying below the pion threshold mass, prove directly the exotic nature of these states. We observe three structures very well defined statistically. Several other narrow structure exotic masses were extracted from different studies done at SPES3 (Saturne). They were published in [4–6], showing data in the missing mass range: $1.0 \le M \le 1.46$ GeV, $1.47 \le M \le 1.68$ GeV, and $1.72 \le M \le 1.79$ GeV, respectively.

The values of the observed narrow structures masses are: $1004(\alpha)$, $1044(\beta)$, $1094(\gamma)$, $1136(\delta)$, $1173(\epsilon)$, $1210(\lambda)$, $1249(\eta)$, $1277(\phi)$, $1339(\nu)$, and 1384 MeV. In this work, the greek letters within parenthesis, identify the structures shown in the figures and the vertical arrows show the expected position for these narrow structures on the basis of previous observations. Some narrow structures in the mass range $M_N \leq M \leq 1$ GeV, were also tentatively extracted [7].

Other signatures of narrow baryonic structures, were observed either in dedicated experiments or extracted from cross sections obtained and published by different authors. They are quoted in [4] and will not be recalled here.

III. THE P(D,D')X REACTION

This reaction, like the next one $p(\alpha, \alpha')X$, was studied in order to get information on the Roper resonance excitation. Less precise cross-sections for the p(d,d')X reaction were measured at Saturne (SPES4) [8, 9] using incident deuteron beam with momentum $p_d=2.95 \text{ GeV/c}$, at five laboratory spectrometer angles, from $\theta=6.59^{\circ}$ up to 11.95°. The

model predictions [9, 10] are rather far from the data.

The reanalysis of the two smallest angles: $\theta = 6.59^{\circ}$ and 8.05° , respectively in inserts (a) and (b), is shown in Fig. 2. The broad curve is plotted to drive the eyes through the small triangle points which reproduce the result of the theoretical calculation [10] including the contribution from Δ and Roper excitations. We believe that the significant gap between this calculation and data can be filled by the exotic baryonic structures. For this aim we take the fitting function as a sum of gaussians centered at fixed values quoted above, with a constant width. The only free parameters are the relative normalization. This allows to get a good fit to the data. The expected structure around M=1320 MeV is absent; it will also be the case for other fits shown later on.

FIG. 2: (Color online). Cross-section of the p(d,d)X reaction at p_d=2.95 GeV/c, [9] measured at Saturne (SPES4 beam line). Inserts (a) and (b) show respectively the results for $\theta = 6.59^{\circ}$ and 8.05° . The theoretical calculation [10] is shown by the small triangles and the thin curve to drive the eyes.

IV. THE $P(\alpha, \alpha')X$ REACTION

Large statistics spectra of the $p(\alpha, \alpha')X$ reaction were obtained several years ago at SPES4 (Saturne) in order to study the radial excitation of the nucleon in the $P_{11}(1440 \text{ MeV})$ Roper resonance. The experiment was performed with $T_{\alpha}=4.2 \text{ GeV}$. A spectrum measured at $T_{\alpha}=4.2 \text{ GeV}$, $\theta=0.8^{\circ}$ [11] was obtained in the baryonic missing mass range: $1030 \leq M \leq 1490 \text{ MeV}$. Fig. 3 shows these data for the cross-section. A first large peak around $\omega \approx 240 \text{ MeV}$ was associated with the projectile excitation, and a second large peak around $\omega \approx 510 \text{ MeV}$ was associated with the target excitation [11]. Here ω is the energy difference between the incident and the detected α particles.

Above these large peaks lie narrow peaks, clearly observed, defined by a large number of standard deviations [12] (see Fig. 3).

A second spectrum with large statistics was measured at T_{α} =4.2 GeV, θ = 2° [13] which extended up to M=1588 MeV. Fig. 4 shows this data. In both figures, the empty circles,

which correspond to the scale, are the published number of events versus the missing mass. The full circles and full squares show the same data with magnified scale.

The narrow structure masses agree fairly well with the masses of narrow structures for the pp \rightarrow p π^+ and pp \rightarrow ppX reactions studied at SPES3 (Saturne) [4]. Table 1 gives the quantitative information concerning the masses extracted from the previous figures, and the comparison with the masses from SPES3 cross-sections [4]. Nearly all peaks are visible in both experiments. At $\theta = 0.8^{\circ}$, the incident beam enters in the SPES4 spectrometer, preventing a possible confirmation of the lower mass structure at M=1004 MeV. At $\theta = 2^{\circ}$, Fig. 4, several peaks are observed above M=1470 MeV. Fig. 5 shows an enhanced plot of this missing mass range ($\omega \geq 800$ MeV). The same situation, with many structures, is observed in the SPES3 data [5, 6], and the masses observed in both reactions are consistent. The peak at M=1394 MeV, observed in the SPES4 experiment, was not seen in the SPES3 data, since such missing mass range lies between two incident proton energies. The statistical errors of the p(α , α')X cross-sections, could not be larger than a factor of two, calculated from the statistical errors [14]. The error bars are therefore multiplied by a factor of two.

FIG. 3: Cross-section of the $p(\alpha, \alpha')X$ reaction at $T_{\alpha}=4.2$ GeV, $\theta=0.8^{\circ}$ [11]. Full points show magnified data.

FIG. 4: Cross-section of the $p(\alpha, \alpha')X$ reaction at $T_{\alpha}=4.2$ GeV, $\theta=2^{\circ}$ [13]. Full points show magnified data.

We observe a fair agreement between the masses obtained using data originally collected in different experiments, studied with different aims, carried out by different physicists in different reactions with different probes and different experimental equipments.

This agreement is illustrated in Fig. 6 where the points are well aligned along straight lines which correspond to the same masses.

V. NEW REANALYSIS OF VARIOUS DIFFERENT REACTIONS

A large number of charge-exchange reactions were studied in different laboratories, mainly in Saturne (SPES4 beam line) with the aim to study isospin-spin excitations. The corresponding missing mass data range from nucleon up to $\Delta(1232)$. Therefore these data are quite convenient for the present study. An important part of these data is presented in the following paragraphs and figures. Some preliminary reanalysis were previously shown [15]. In the following spectra, we add to the broad $\Delta(1232)$ bump, several narrow gaussians describing the structures observed previously, at the masses previously fixed by the analysis of the cross sections of the $p + p \rightarrow p + \pi^+ + X$ and $p + p \rightarrow p + p + X$ reactions studied at SPES3(Saturne).

FIG. 5: Same caption as in Fig. 4

FIG. 6: (Color online.) Comparison between masses of narrow baryons extracted from SPES3 [3–5] and SPES4 [11, 13] data. Inserts (a) and (b) correspond respectively to $\theta = 0.8^{\circ}$ and $\theta = 2^{\circ}$.

VI. THE (P,N) REACTIONS

A. The pp \rightarrow n Δ^{++} reaction.

The cross-sections of the pp \rightarrow n Δ^{++} reaction were measured at different incident energies in different laboratories, and analyzed phenomenologically within the one-pion exchange model [16]. The binning and statistics of these old data are not very precise, therefore only one spectrum is shown. Fig. 7 shows the data at T_p =0.97 GeV [17], the result of the calculation performed [16] (with Λ_{π} =0.63 GeV), and a few gaussians introduced as previously. Adding such gaussians appears to be essential for an accurately the data. These gaussians have all the same width (σ =12 MeV), and their positions are fixed at the masses where narrow exotic baryons were previously observed. The addition to Δ peak of gaussians describing

the baryonic structures found in previous works, allows to get a very good description of the experimental data. The calculation performed in [16, 17] of the Δ^{++} peak alone, is unable to fully describe the data. On the one hand, the statistical significance between data and broad PDG Δ resonance is χ_D^2 =4.7 on the other hand, the statistical significance between data and total spectra including the narrow resonances is χ_{NR}^2 =2.1 (see Table 2).

FIG. 7: (Color online.) Cross-section of the pp $\rightarrow n\Delta^{++}$ reaction at T_p =0.97 GeV $\theta = 0^{\circ}$ [16]

More recent data of the ${}^{1}\mathrm{H}(\mathrm{p,n})\mathrm{X}$ reaction exist at $\mathrm{T}_{p}=790$ MeV, $\theta_{n}=0^{\circ}$, 7.5°, and 15°. The corresponding differential cross-sections $d^{2}\sigma/dE_{n}d\Omega_{n}$ were measured at LAMPF [18]. These data at the two smallest angles are reanalyzed in Fig. 8. The full curves fitting the small empty triangles, describe the theoretical calculations [19] performed with use of an effective projectile-target-nucleon interaction. These curves are reproduced here just as the data; they describe the broad Δ peak. A few points corresponding to the largest energy loss (ω) values are omitted, since they lie over the Jacobian limit, therefore corresponding to decreasing missing masses. The open circles correspond to data integrated by two channels.

SPES3 mass	1004	1044	1094	1136	1173	1249	1277	1339		1384 1479
marker	(α)	(β)	(γ)	(δ)	(ϵ)	(η)	(ϕ)	(ν)		
SPES4 mass 0.8°		1052	1113	1142	1202	1234	1259		1370	1394 1478
SPES4 mass 2°	996	1036	1104	1144	1198	1234		1313	1370	1477
SPES3 mass	1505	1517	1533	1542	(1554)	1564	1577			
SPES4 mass 2°	1507	1517	1530	1543	1557	1569	1580			

TABLE I: Masses (in MeV) of narrow exotic baryons, observed previously in SPES3 data and extracted from previous $p(\alpha, \alpha')X$ spectra measured at SPES4 [11, 13].

A nice fit is obtained after introduction of the narrow resonances, leading to an important decrease of the χ^2 (see Table 2).

FIG. 8: (Color online.) Cross-section of the pp \rightarrow n Δ^{++} reaction at T_p =0.79 GeV [18, 19]. Inserts (a) and (b) correspond respectively to $\theta_n = 0^{\circ}$ and 7.5°.

B. The ${}^{2}H(p,n)X$ reaction

The differential cross-sections $d^2\sigma/dE_n d\Omega_n$ of the $^2\mathrm{H}(\mathrm{p,n})\mathrm{X}$ reaction were also measured at LAMPF [18]. The analysis was performed by the same authors [19], using the distorted-wave impulse approximation. The result of the reanalysis is shown in Fig. 9. Here the width of the structures is fixed at the width extracted from the $\mathrm{pp}{\to}\mathrm{n}\Delta^{++}$ data ($\sigma{=}11\,\mathrm{MeV}$), widen by the Fermi momentum taken to be $\mathrm{p}_F{=}66\,\mathrm{MeV/c}$. Inserts (a), (b), and (c) show the result of the present reanalysis corresponding respectively to $\theta=0^\circ$, 7.5°, and 15°. The data are all integrated by two channels. We observe that the present reanalysis allows to describe quite well the data; the total shapes in the range between the n and the Δ missing masses, are better reproduced after introducing the narrow resonances. The large improvement in χ^2 is visible in Table 2.

The comparison between pp \rightarrow n Δ^{++} and 2 H(p,n) Δ^{++} reanalysis, allows us to favor isospin T=1/2 for the exotic narrow baryons at M=1004 MeV, 1044 MeV, and 1094 MeV, just as the baryonic structure at M=1277 MeV, since here the cross-section on D₂ target is much larger than on H target. The same cross-sections are extracted from both targets for the structures at M=1173 MeV and 1210 MeV, suggesting isospin T=3/2 for both of them. These deductions agree with the isospin values deduced previously [4] with the help of a quark cluster mass formula which will be recalled in Section X.

FIG. 9: (Color online.) Cross-section of the ${}^{2}\mathrm{H}(\mathrm{p,n})\Delta^{++}$ reaction at T_{p} =0.79 GeV [18, 19]. Inserts (a), (b), and (c) correspond respectively to $\theta_{n}=0^{\circ}, 7.5^{\circ}, \text{ and } 15^{\circ}.$

VII. THE (D,2P) REACTIONS

A. The $p(d,2p)\Delta^0$ reaction.

The cross-section of the $p(d,2p)\Delta^0$ reaction was measured with the SPES4 spectrometer at Saturne, using 2 GeV and 1.6 GeV incident deuterons, at the following angles: $\theta_{lab.} = 0^{\circ}$, 0.5° , 2.1° , 4.3° , and 7.2° [20–22]. Inserts (a) and (b) of Fig. VII A show the data respectively for θ =0.5° and 4.3°. They exhibit oscillating behaviour in the low part of the Δ missing mass range which are well fitted by the masses of the narrow baryonic structures. Inserts (a) and (b) of Fig. 11 show the cross-sections of the same reaction, for respectively θ = 2.1° and 5.7°. Here again, a nice fit for both angles, is obtained in nearly the whole range, when the narrow structures are added to the broad Δ peak.

FIG. 10: (Color online.) Cross-section of the p(d,2p) Δ^0 reaction at T_d =2 GeV $\theta = 0.5^{\circ}$, and 4.3°, respectively in inserts (a), and (b), [20, 22].

FIG. 11: (Color online.) Cross-section of the p(d,2p) Δ^0 reaction at T_d =2 GeV θ = 2.1°, and 5.7°, respectively in inserts (a), and (b) [20–22].

B. The ${}^{12}C(d,2p)X$ reaction.

Such reaction allows to observe cross-sections corresponding to quasi-free scattering on nucleons in the 12 C target. The narrow peaks, corresponding to excited levels of 12 B, are restricted to the energy loss $\omega \leq 50$ MeV. This value ranges inside the large peak of the left part of Fig. 12. Above this mass, all peaks having total widths smaller than 40 MeV, are attributed to quasi-free production of narrow structures on nucleon targets. The total widths of the narrow baryonic structures are taken as $\Gamma_t \approx 20$ MeV; they are slightly enlarged here, compared to previous reanalyses, due to the Fermi momentum of the target nucleon.

Two small peaks at M \approx 1004 MeV and 1044 MeV in the quasi-free reaction, are introduced in order to improve the fit. They would correspond to $E_{exc.}$ =60 MeV and 80 MeV, if attributed to ¹²B. In Fig. 12, the oscillations are less pronounced than those in Fig. 11. At T_p =2 GeV $\theta = 4.3^{\circ}$, - not illustrated - indications of small structures exist at masses close to M \approx 1004 MeV and 1044 MeV.

FIG. 12: (Color online.) Spectra of the 12 C(d,2p)X reaction at T_p =2 GeV $\theta = 0^{\circ}$ [22]. (No vertical scale in the original paper).

VIII. THE (³HE,T) REACTIONS

A. The $p(^{3}He,t)\Delta^{++}$ reaction.

The cross-section of the $p(^3He,t)\Delta^{++}$ reaction was measured at many incident energies, and spectrometer angles, mostly at the SPES4 spectrometer at Saturne, but also at other places. The data from Dubna [23], at $T_p=2.39$ GeV, 4.53 GeV, and 8.33 GeV are not enough precise since their binning was taken as $\Delta E=25$ MeV. They are not reanalyzed here. The $^3He(p,t)\Delta^{++}$ reaction was studied at SPES1 (Saturne) at forward angle in the laboratory system, with the motivation to reduce the contribution of the direct graph and study the possible (Δ^{++} ,2n) component of the 3He wave function [24]. The beam energy was $T_p=850$ MeV. These data were taken at $\theta_{lab.}=6^{\circ}$, 10° , and 15° ; their cross-sections decrease fast with increasing angle, therefore only the cross-section of the smaller angle is shown here, in Fig. 13.

We observe that indeed oscillations can be seen and are well fitted by the narrow structures (see Table 2) if the data are shifted by Δ M=-9 MeV. This systematic shift may correspond to a possible saturation of the spectrometer magnetic field B, as small as $\delta p/p=6$ 10^{-3} , possibly not taken into account for large triton momenta for the SPES1 spectrometer: $p_t \approx 1.85 \text{ GeV/c}$. The shift may be due also to a bad knowledge of the incident beam energy, since for $M_X=1250 \text{ MeV}$, $\partial M_X/\partial T_p=1.24$ or to a bad knowledge of the spectrometer angle, since here $\partial M_X/\partial \theta_t=-223.6 \text{ MeV/radian}$.

Fig.	reaction	χ_D^2	χ^2_{NR}	Comment
7	$pp \rightarrow n\Delta^{++}$	4.7	2.1	
8(a)	$pp{\to}n\Delta^{++}$	3.6	0.9	
8(b)	$pp{\to}n\Delta^{++}$	6.8	1.3	
9(a)	d(p,n)X	44.8	2.3	for $M_X \ge 1 \text{ GeV}$
9(b)	d(p,n)X	58.7	1.6	for $M_X \ge 1 \text{ GeV}$
9(c)	d(p,n)X	20.6	0.8	for $M_X \ge 1 \text{ GeV}$
13	$^3{\rm He}(p,\!t)\Delta^{++}$	2.5	1.5	
17(a)	$d(^3{\rm He,t}){\rm X}$	12.1	3.0	
17(b)	$d(^3{\rm He,t}){\rm X}$	17.2	1.1	
18(a)	$d(^3{\rm He,t}){\rm X}$	14.7	2.2	
18(b)	$d(^3{\rm He,t}){\rm X}$	53.0	4.0	

TABLE II: Selection of several statistical significances between data and broad PDG Δ resonance (χ_D^2) on the one hand, and between data and total spectra including the narrow resonances (χ_{NR}^2) on the other hand.

Fig. 14 shows the cross-sections of the p(${}^{3}\text{He,t}$) Δ^{++} reaction [25] measured at Saturne (SPES4 beam line) at $T_{{}^{3}\text{He}}$ =1.5 GeV, θ = 3.5° in insert (a), $T_{{}^{3}\text{He}}$ =2 GeV, θ = 5° in insert (b), and $T_{{}^{3}\text{He}}$ =2 GeV, θ = 0° in insert (c).

The data are well fitted using the masses of narrow baryonic structures. Special attention has to be brought to the low mass spectra. Below $M_X=1100$ MeV, the data in Fig. 14 (empty squares) are rescaled by a factor of five. We observe here negative and positive number resulting from the subtraction of quite poor statistics data obtained with a CH_2 and a C targets.

FIG. 13: (Color online.) Cross-section of the ${}^{3}\text{He}(p,t)\Delta^{++}$ reaction, at $T_{p}=850$ MeV, $\theta_{lab.}=6^{\circ}$ [24] after a $\Delta M=-9$ MeV shift (see text).

The narrow structures in this mass range were predicted to be preferably isoscalar [3, 4], therefore they cannot be excited in the reaction on proton target. The proton missing mass spectra, excited from the neutrons of 12 C and CH₂ targets, are obtained with large statistics, allowing the renormalization and the subtraction. The smaller statistics obtained above the proton missing mass range may explain the observed behaviour. Indeed in inserts (b) and (c) the small bumps agree with the α and β arrows.

Another set of p(3 He,t)X reaction cross section data was also obtained at SPES4 [26] with $T_{{}^{3}He}$ =2 GeV incident beam at the following laboratory angles: $\theta = 0.25^{\circ}$, 1.6°, 2.7°, and 4°. The data are read and reanalyzed in Fig. 15 and 16. The calculation was performed by the authors [26], including the A=3 form factors. The result of this calculation is taken as "background", namely we use the narrow structures to fit the difference between the and the calculation. Fig. 15 shows the results at $\theta = 0.25^{\circ}$ in insert (a) and $\theta = 1.6^{\circ}$ in insert (b). Fig. 16 shows the corresponding results for $\theta = 2.7^{\circ}$ in insert (a) and $\theta = 4^{\circ}$ in insert (b).

The fast decrease of the $\Delta^{++}(1220 \text{ MeV})$ excitation, with increasing angles, allows us to extract narrow baryonic structures. The accuracy between the narrow structure masses extracted here, and those extracted previously, is noteworthy. However in the present case the strutures are broader.

B. The $d(^{3}He,t)X$ reaction

The d(${}^{3}\text{He,t}$)X reaction was studied at SPES4 (Saturne) at $T_{{}^{3}\text{He}}$ =2 GeV and four different angles: $\theta = 0.25^{\circ}$, 1.6°, 2.7°, and 4° [26]. The data are read and reanalyzed in Figs. 17 and 18. The complete calculation was performed by the authors [26], including the quasi-elastic

FIG. 14: (Color online.) Cross-section of the p(3 He,t) Δ^{++} reaction at T_p =1.5 GeV $\theta = 3.5^{\circ}$ insert(a), T_p =2 GeV $\theta = 5^{\circ}$ insert (b), and T_p =2 GeV $\theta = 0^{\circ}$ insert (c) [25].

FIG. 15: Cross-section of the p(3 He,t)X reaction at $T_{{}^{3}He}$ =2 GeV, $\theta = 0.25^{\circ}$ in insert (a) and $\theta = 1.6^{\circ}$ in insert (b) [26]. The small empty circles (blue) describe the theoretical calculation (see text) [26]. Above this calculation the baryonic structures allow to fit the experimental data. The total spectrum is also shown (red curve).

FIG. 16: (Color online) Cross-section of the p(3 He,t)X reaction at T ${}_{^{3}He}$ =2 GeV, θ = 2.7° in insert (a) and θ = 4° in insert (b) [26]. The small empty circles (blue) describe the theoretical calculation (see text) [26]. Above this calculation the baryonic structures allow to fit the experimental data. The total spectrum (red curve) is also shown.

FIG. 17: (Color online). Cross-section of the d(${}^{3}\text{He,t}$)X reaction at $T_{{}^{3}\text{He}}$ =2 GeV, $\theta = 0.25^{\circ}$ in insert (a) and $\theta = 1.6^{\circ}$ in insert (b) [26]. The small empty circles describe the theoretical calculation (see text) [26]. Above this calculation the baryonic structures allow to fit the experimental data.

contribution and the final state interaction (Δ -N interaction and Δ N \rightarrow NN process). The result of this calculation is taken as background, namely we fit the difference between data and the calculation with the function summing the gaussians corresponding to the narrow structures. Fig. 17 shows the results at $\theta=0.25^{\circ}$ in insert (a) and $\theta=1.6^{\circ}$ in insert (b). Fig. 18 shows the corresponding results for $\theta=2.7^{\circ}$ in insert (a) and $\theta=4^{\circ}$ in insert (b). Whereas the H(3 He,t)X reaction allows to excite only isospin I=3/2 final states, the d(3 He,t)X reaction allows to excite just as well I=3/2 as I=1/2 final states. The comparison between both reactions shows that, although the reaction on a proton target is favoured versus the reaction on a neutron target by a factor of three due to isospin couplings, the narrow baryonic structures are better excited on the deuterium target. We deduce as above that isospin I=1/2 is favoured for the low mass baryonic structures.

The global fits, after the introduction of the narrow structures in Fig. 17(a), 17(b), 18(a), and 18(b), are very good. Table 2 shows the related quantitative information.

FIG. 18: (Color online.) Same caption as in Fig. 17, for $\theta = 2.7^{\circ}$ in insert (a) and $\theta = 4^{\circ}$ in insert (b) [26].

FIG. 19: (Color online) Angular distributions of some narrow baryonic structures extracted from the d(³He,t)X reaction. M=1044 MeV, full circle, black; M=1094 MeV, full square, red; M=1136 MeV, full triangle, green; M=1213 MeV, full star, blue; M=1247 MeV, empty circle, sky blue; M=1274 MeV, empty square, purple.

Fig. 19 shows the angular distributions at forward angles of six narrow structures: M=1044 MeV, 1094 MeV, 1136 MeV, 1213 MeV, 1247 MeV, and 1274 MeV. The error bars are set arbitrarily to 10%. The cross-sections decrease continuously with increasing angle, more or less parallel to each other. These regular (non oscillating) shapes of the angular distributions, can be considered as an useful argument with respect to the present cross-section reanalysis.

C. The ${}^{12}C({}^{3}\text{He,t})$ reaction

The $^{12}C(^{3}\text{He,t})$ reaction was studied at Saturne (SPES4 beam line) [27–29] at $T_{^{3}He}=2$ GeV, $\theta=0^{\circ}$. Fig. 20 shows the result after adding the narrow structures to the theoretical analysis performed by [28].

FIG. 20: (Color online.) Cross-section of the $^{12}C(^{3}\text{He,t})$ reaction at $T_{^{3}He}=2$ GeV, $\theta=0^{\circ}$. [27] [28]. The text explains the content of the theoretical calculations performed by [28]. Insert (a) shows the double differential cross-section; insert (b) shows the pion coincidence spectrum.

Insert (a) shows the double differential cross-section. The curve passing through the small empty circles is the final result of the calculation [28] within the isobar-hole model. It is obtained including the quasi-free Δ decay, the Δ spreading and the coherent pion production. Insert (b) shows the pion coincidence spectrum [29, 30]. The theoretical curves show the result of the calculations [28] performed with Landau-Migdal parameters: $g_{\Delta\Delta} = 0.33$ (solid curve) and $g_{\Delta\Delta} = 0.4$ (dashed curve). This last curve was renormalized by a factor of 1.5 by the authors. The narrow structures are extracted from the dashed curve. The extraction from the solid curve will change the amplitudes of these structures, but not their position. Here also we find the final fits show a remarkable agreement with the data.

IX. CHARGE EXCHANGE REACTIONS WITH INCIDENT HEAVY ION BEAMS

A. The $p(^{12}C,^{12}N)\Delta^0$ reaction

The p(12 C, 12 N) Δ^0 reaction was studied at SPES4 (Saturne) using a 12 C beam of 1100 MeV/N at the spectrometer angle $\theta = 0^{\circ}$ [32]. The data are read, integrated over three channels and shown as a function of M_X. Fig. 21 shows these data, fitted with the Δ^0 peak and the structures previously observed. The important oscillatory behaviour is very well reproduced by the fit.

FIG. 21: (Color online.) Cross-section of the p(12 C, 12 N) Δ^0 reaction at T_p =1100 MeV/N $\theta=0^{\circ}$ [32].

B. The $p(^{20}Ne,^{20}F)\Delta^{++}$ and the $p(^{20}Ne,^{20}Na)\Delta^{0}$ reactions

The p(20 Ne, 20 F) Δ^{++} and the p(20 Ne, 20 Na) Δ^{0} reaction were measured at SPES4 (Saturne) with the 20 Ne beam at 900 MeV/N $\theta = 0^{\circ}$ [32, 33]. The data are read, and shown versus M_X in Fig. 22. The p(20 Ne, 20 F) Δ^{++} cross-sections, (insert (a)), are integrated over two channels. The same width (FWHM=120 MeV), the same mass, and a ratio of three, determined by the isospin Clebsh-Gordan coefficients, are attributed to Δ^{++} and Δ^{0} . Such ratio supposes that the difference between the form factors of the final nuclei 20 F and 20 Na, differ only by a small amount. We observe small contributions of the first narrow baryonic masses -compatible with zero - in insert (a). This result can be explained again by the expected isospin for these masses [3]. In the same way, the large cross-section around M≈1200 MeV in insert (a), agrees with the previous expectation, namely isospin=3/2.

FIG. 22: (Color online.) Cross-section of the $p(^{20}\text{Ne},^{20}F)\Delta^{++}$ reaction (insert (a)), and $p(^{20}\text{Ne},^{20}\text{Na})\Delta^{0}$ reaction (insert (b)) with $T_{^{20}Ne}=18$ GeV, $\theta=0^{\circ}$ [31–33].

C. The 12 C(12 C, 12 B)X reaction

The experiments were performed at SPES4 (Saturne) on 12 C [31] and 208 Pb targets (not shown). The spectra were studied at $\theta=0^{\circ}$, the beam energies being $T_{beam}=900*A$ MeV [32][34]. The reanalysis of the cross-sections on 12 C target are shown in Fig. 23.

FIG. 23: (Color online.) Cross-section of the $^{12}\text{C}(^{12}\text{C},^{12}\text{B})\text{X}$ reaction (insert (a)), $^{12}\text{C}(^{12}\text{C},^{12}\text{N})\text{X}$ reaction (insert (b)), and $^{12}\text{C}(^{20}\text{Ne},^{20}\text{F})\text{X}$ reaction (insert (c)). All three reactions were studied at $\theta = 0^{\circ}$, and $T_{beam} = 900^{\circ}\text{A}$ MeV [31–34].

The three inserts (a), (b), and (c) correspond respectively to the three reactions: $^{12}\text{C}(^{12}\text{C},^{12}\text{B})\text{X}$, $^{12}\text{C}(^{12}\text{C},^{12}\text{N})\text{X}$, and $^{12}\text{C}(^{20}\text{Ne},^{20}\text{F})\text{X}$. In all three cases, we observe the need to introduce the structures, in addition to the Δ peak, to describe the data which are well fitted in that case. We observe small oscillations in the three spectra, at the positions corresponding to the two first masses: M=1004 MeV (α) and M=1044 MeV (β).

D. The ${}^{12}C({}^{14}N, {}^{14}C)X$ reaction

The $^{12}\text{C}(^{14}\text{N},^{14}\text{C})\text{X}$ reaction was studied at SPES4 (Saturne) with ^{14}N incident beam of 880 MeV/A, and θ =0° [35]. The result of our reanalysis is shown in Fig. 24. Again, the experimental oscillations are well reproduced with the narrow structure masses.

FIG. 24: (Color online.) Cross-section of the 12 C(14 N, 14 C)X reaction studied at Saturne (SPES4) at $\theta = 0^{\circ}$, and $T_{beam} = 880^{\circ}$ A MeV. [35].

E. The $p(^{16}O, ^{16}N)X$ and $^{12}C(^{16}O, ^{16}N)X$ reactions

The ¹⁶O, ¹⁶N transfer reactions were studied at Saturne (SPES4) on CH₂ and ¹²C targets [36]. The reanalysis of both spectra is shown in Fig. 25.

FIG. 25: (Color online.) Cross-section of the $p(^{16}O,^{16}N)X$ reaction (insert (a)), and $^{12}C(^{16}O,^{16}N)X$ reaction (insert (b)). Both reactions were studied at $\theta = 0^{\circ}$, and $T_{beam} = 900^{*}A$ MeV. [36].

In the p(16 O, 16 N)X spectra, insert (a), the positions of the central peaks do not correspond so well to the expected masses as the in previous spectra. On the other hand, the agreement in insert (b), describing the 12 C(16 O, 16 N)X reaction is outstanding, since all peaks, including the structures at M=1004 MeV (α) and M=1044 MeV (β) are perfectly reproduced. Here an arbitrary background is introduced in order to simulate the inelastic scattering due to the excitation of 12 C levels.

F. The ²⁷Al(²⁰Ne, ²⁰Na)X and the ²⁷Al(²⁰Ne, ²⁰F)X reactions

The 27 Al(20 Ne, 20 Na)X and the 27 Al(20 Ne, 20 F)X reactions were measured at Saturne (SPES4), using a 20 Ne incident beam of T=950 MeV/A, at $\theta = 0^{\circ}$ [35]. The same analysis is done as above, based on the integration over two channels and the addition of narrow structures over a broad Δ^{++} peak. The result is shown in Fig. 26. Here, again, the oscillations are well reproduced, especially in the region between the nucleon and the Δ missing masses in insert (a).

FIG. 26: (Color online.) Cross-section of the 27 Al(20 Ne, 20 Na)X reaction (insert (a)), and 27 Al(20 Ne, 20 F)X reaction (insert (b)). Both reactions were studied at $\theta = 0^{\circ}$, and $T_{beam} = 950^{\circ}$ A MeV. [35].

X. CONCLUSION

This work analyses different cross-sections measured with incident hadrons, in order to increase the experimental signatures for the excitation of low mass narrow baryons previously observed. A large improvement is obtained in the description of the data by a fit, which takes narrow structures into account. The corresponding χ^2 values, which show such improvement,

have been reported in Table 2. Most of the data were shown without preselecting those which present the most pronounced oscillations, well fitted by the exotic baryonic structure masses.

This paper does not pretend to give an exhaustive outline of all existing data.

These structures were associated with quark clusters [3] [4]. This can explain the fact that reactions performed with incident leptons, which in principle allow similar observations [37], lead to smaller signals than reactions performed with incident hadrons. In this case the number of quarks involved in the reactions are reduced.

All reactions reanalyzed here were measured in view of another physical goal, therefore the binning and the statistics were not optimized for the present study. So, there is here no attempt to study the mass range $950 \le M \le 1000$ MeV, although several spectra exhibit an excess of counting over the fits. Moreover, this missing mass region, when composite targets are concerned, corresponds also to possible excitation of nuclei excited states.

In almost all spectra, clear structures are however observed, mainly in the mass region $1000 \le M \le 1130$ MeV before the region where the Δ starts to dominate the countings. This mass range concerns the structures at M=1004 and 1044 MeV, particularly interesting since they are both located at masses lower than the threshold of possible pion-nucleon disintegration. The narrow baryonic resonances are observed in almost all missing mass range studied. The most noteworthy spectra, are those showing notable oscillations well fitted by the narrow structures. This concerns a large part of the reactions discussed previously, namely the spectra corresponding to the pp $\rightarrow p\pi^+X$, (d,2p)X, (p,t)X, $d(^3He,t)X$, $p(^{12}C,^{12}N)X$, $^{12}C(^{16}O,^{16}N)X$, $(^{20}Ne,^{20}F)X$, and $(^{20}Ne,^{20}Na)X$ reactions.

The comparison between final states with isospin T=1/2 and T=3/2 leads us to favor isospin T=1/2 for the lower narrow structure masses. These structures are more easily observed in reactions using isoscalar scattered particles such as α or deutons. We notice however that the overall results suggest possible isospin degeneracy.

In order to reproduce the masses of exotic, narrow, and weakly excited baryons, we use a phenomenological relation wich describe them by a configuration adding one (or more) $q\bar{q}$ pairs to the classical qqq configuration. Such approach was justified theoretically [38] in a paper which discussed the existence of the pentaquark: In fact the Skyrme model is in accordance with quarks but it is in one way better as it allows baryons to be made of N_c quarks, plus an indefinite number of $Q\bar{Q}$ pairs.

Although theoretical studies must be carried out to describe these observations, it is useful

to remind the nice mass spectra obtained with help of the phenomenological mass relation [39] obtained within the assumption of two clusters of quarks at the ends of a stretched bag in terms of color magnetic interactions:

$$M = M_0 + M_1[i_1(i_1+1) + i_2(i_2+1) + (1/3)s_1(s_1+1) + (3)$$

$$(1/3)s_2(s_2+1)] (4)$$

Here i and s are isospins and spins of the two clusters. Notice that the formula involves degeneracy. We adjust the two parameters M_0 =838.2 MeV and M_1 =100.3 MeV in order to reproduce the masses, spins and isospins of the nucleon and of the Roper resonnace: $N^*(1440)$. Then we calculate the masses of the other structures without any free parameter. These masses, possible spins and isospins, quark configurations, and parities if only s wave are considered, are shown in Fig. 27. Notice that the parity of the Roper N*(1440) is positive if a P wave between (qqq) and $q\bar{q}$ quark clusters is assumed.

FIG. 27: (Color online.) Calculated properties of narrow exotic baryonic structures, using the phenomenological mass formula [39]: parity for s wave clusters, configurations as indicated, masses, possible spins and isospins. The right column shows the experimental masses.

Note also the attribution of isospin I=1/2 to the three lightest structure masses.

We conclude that the growing number of coherent indications reinforces the evidence for the genuine existence of these structures. These structures are clearly exotic since there is no room for them in the qqq configurations [1], since their width is smaller than the widths of "classical" PDG [2] baryonic resonances, and also since some masses lie below the pion threshold mass. They are naturally associated with precursor quark deconfinement and may show that the quark and gluon degrees of freedom are effective even at very low energy and must be taken into account.

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