ABC resonance in the $\vec{p}p \to ppX^0$ reaction, or is the *ABC* effect made of colored quark cluster configurations?

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The reaction $\vec{p}p \to ppX$ was studied at two energies ($T_p = 1520$ and 1805 MeV) and at several angles between 0° and 17° in the laboratory. The analyzing powers and cross sections of the *ABC* enhancement production were measured in the missing mass ($M_{\pi^0} \leqslant M_X \leqslant M_\eta$). Several substructures were observed at different angles and both energies. Substructures at $M_X \approx 310$ and 350 MeV were systematically extracted. Substructures in the higher mass range $400 \leqslant M_X \leqslant 500$ MeV were observed but their masses were less stable. These substructure masses have been associated with $q^2-\overline{q}^2$ (and $q^3-\overline{q}^3$) configurations, allowing a new assumption for the *ABC* effect description, as being colored multiquark clusters.

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I. INTRODUCTION

The *ABC* effect was observed for the first time more than 35 years ago in the $pd \to {}^3\mathrm{He}X^0$ reaction [1]. It was associated with isospin 0, since the same large effect close to 320 MeV, was not—at first—observed in the $pd \to {}^3\mathrm{H}\,X^+$ reaction. It was later confirmed by the observation of a similar effect in several other reactions.

This effect consists of a broad and nonsymmetric enhancement inside a two-pion system, between 300 and 500 MeV. Its mass and width vary for different bombarding energies and reaction angles. It is usually accepted that this enhancement is not an intrinsic two-pion property, since there is no resonance structure in the $\pi\pi$ scattering amplitude in this energy region. It is generally believed that such system has to be associated with two nucleons. In other words, the *ABC* effect would be induced by the rescattering of both pions by two nucleons (which must be present) or induced by two elementary $pp \to \pi X$ reactions. The model used by Anjos, Levy, and Santoro [2], the one-pion exchange model, supposed that the production was dominated by two Δ's, produced on both nucleons. The same approch was studied by Risser and co-workers [3,4]. Considering this assumption, it is preferable to perform the measurements at incident kinetic energies larger than the threshold energy of the $pp \to \Delta\Delta$ reaction, which is $T_p = 1359$ MeV.

Several calculations were performed in order to study the *ABC* effect. They were discussed by Barry [5] and other authors. Total cross sections for $NN \to NN\pi\pi$ reactions in the proton energy range $T_p \leqslant 850$ MeV were recently calculated [6]. The authors concluded the necessity to have more complete experimental data near the threshold. A new approach was proposed [7] to describe the results of a $np \to d(\pi\pi)^0$ experiment. The model involves the excitation of the $N^*(1440)$ Roper resonance. In the same way, a theoretical study of the $NN \to NN\pi\pi$ reaction was performed [8]. In this model, at low energy in the $pp \to ppX$ reaction, the isoscalar two-pion state is dominantly excited through $N^*(1440)$ followed by the N^* deexcitation into $N\pi\pi$. Such a picture explains the *ABC* observation in experiments involving only one nucleon. At energies $T_p \geqslant 1300$ MeV, when two nucleons participate in the reaction, the main process is the excitation of two Δ's, one on each nucleon.

In this paper the theoretical studies will not be discussed. To our knowledge, we quote all previous experiments performed to study the meson production in the mass range $300 \leqslant M \leqslant 500$ MeV. We have to notice that a light and broad scalar-isoscalar σ meson—now called $f_0(400\text{–}1200)$ [9]—was often anticipated and used in theoretical calculations as an useful exchange meson. Its mass was extracted through *T*-matrix pole. Different authors found it at different masses centered around 780 MeV. Its width was always found as large as several hundred MeV. The GAMS Collaboration [10], in a study of the effective mass spectrum of π^0 pairs produced in pp central collisions at 450 GeV, gave a mass of 980 MeV for this f_0 meson. These authors observed a large concentration of *S*-wave events below 1 GeV, which interfered destructively with the f_0. It is clear therefore that this f_0 meson does not correspond to the physics of invariant masses in the $300 \leqslant M \leqslant 500$ MeV range discussed in our paper.

Our paper is constructed in the following way. After the Introduction, in Sec. II we will recall the results of several previous experiments. This is essential in order to establish the observed facts and to discuss the conclusions extracted from the observations. In Sec. III our experiment will be described. Section IV will describe the analysis performed in order to obtain the final results. They will be presented in Sec. V. We will also discuss the meaning of our experimental precisions. In Sec. VI, another possible outline of the *ABC* effect will be suggested. Of course it will remain an assumption until it is confirmed, by other experiments and/or calculations. A general discussion of our experimental re-

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sults and the results of our attempt for an interpretation will be presented in Sec. VII. Finally, the last part is devoted to conclusions.

II. PREVIOUS RESULTS

As already noticed, the effect was first observed at Berkeley in $pd \to {}^3\mathrm{He}X^0$ and $pd \to tX^+$ reactions [1]. The $\pi^- p \to \pi^+\pi^- n$ reaction was studied [11] at CERN. The authors concluded that they have not observed the ''anomaly'' around 310 MeV, seen before in $pd \to {}^3\mathrm{He}X^0$ [1]. However, a small bump is not excluded around 325 MeV (see their Fig. 14). The authors said that a two-pion resonance around 380 MeV—or higher—is not excluded by deviation from phase space.

A structure around 310 MeV was observed in the two-pion system in the $\pi^- p \to \pi^0\pi^0 n$ reaction [12]. The presence of this structure, which can have isospin $T=0$ or 1, contradicts the explanation of the ABC effect by a rescattering of both pions by two nucleons.

A structure in the two-pion system was observed in the $K^- p \to K^- p \pi^+\pi^-$ reaction [13]. Its mass and width are $M_{\pi\pi} \approx 410 \pm 20$ MeV ($\Gamma \approx 70 \pm 25$ MeV). It can have isospin 0 or 1. The presence of this structure contradicts the explanation of the ABC effect by a rescattering of both pions by two nucleons.

A structure in the two-pion system around 310 MeV was observed in the $T=0$ channel, at $T_p = 991$ MeV, in the $pn \to d\pi\pi$ reaction [14]. It was obtained by proton scattering on a D_2 target, after subtraction of the $T=1$ contribution studied by $pp \to d\pi\pi$ reaction, in which no structure was observed.

The ABC effect was observed in $dd \to dd\pi^+\pi^-$ [15] in a bubble chamber experiment at Brookhaven. The data confirmed the presence of a broad structure having isospin $T=0$. No significant deviation from phase space was observed in the $dd \to \alpha\pi\pi$ reaction [16] in an experiment showing poor statistical quality data. Note that the low deuton energy ($T_d = 650$ MeV) can explain the ABC effect reduction, as was already observed. The same remarks are valid for the $dd \to \alpha X$ reaction studied [17] 29 MeV above the $2\pi^0$ threshold.

A broad structure was observed at 450 MeV in the neutral-meson system X^0 produced in $\pi^- p \to \pi^- p X^0$ at 13.4 GeV/c [18]. Again the presence of this structure contradicts the explanation of the ABC effect by a rescattering of both pions by two nucleons.

However, the most systematic studies of the ABC effect were performed at Saturne. Banaigs *et al.*, using the $dp \to {}^3\mathrm{He}(MM)^0$ reaction at several energies, observed with a better resolution than previously two structures around 315 and 450 MeV [19]. The structure at 450 MeV was called DEF. The same authors observed also a $T=1$ structure in the region close to 390 MeV using a $dp \to {}^3\mathrm{H}(MM)^+$ reaction [20]. This isovector enhancement was observed with a smaller cross section than the isoscalar enhancements quoted before. The same authors studied the $dd \to {}^4\mathrm{He}(MM)^0$ reaction [21,22] for several incident beam energies and production angles. They observed the enhancement whose maximum position moved from 302 up to 352 MeV depending on different kinematical conditions.

The same reaction was studied at Saturne [23] with the emphasis put on spin degrees of freedom (deuteron tensor analyzing power and slope of the vector analyzing power). In this last work, good agreement was found between the data and the calculations performed in a model where each pair of nucleons in the projectile and target undergoes pion production through the $NN \to d\pi$ reaction.

The ABC enhancement was observed in the $np \to dX^0$ reaction through the use of $dp \to dpX^0$ [24]. A 1.88 GeV/c neutron beam at Saturne [25] and a 1.73 GeV/c neutron beam at Dubna [26] were also used. However, the experimental mass resolution in these incident neutron beam experiments was not sufficient to be able to extract structures and measure their masses. A more precise study of the $np \to dX^0$ reaction was performed at LAMPF at $T_n = 796.7$ MeV [27]. In these data there are possible indications for small structures around 305 and 350 MeV, structures not pointed out by the authors.

The $(\pi^+, \pi^+\pi^\pm)$ reactions on several nuclei from ^{2}H up to ^{208}Pb have been studied at TRIUMF [28]. The authors observed a large enhancement in the two-pion invariant mass, around 340 MeV, and an enhancement with increasing A of the $\pi^+\pi^-$ mass distribution in the threshold region. They associate this last enhancement with an effect of the nuclear medium which modifies the $\pi\pi$ interaction. This explanation is qualitatively in agreement with pions rescattering on nucleons. They conclude that the $\pi^+\pi^\pm$ invariant mass distributions display no evidence of strongly interacting pion pairs in either the $I=J=0$ or the $I=2$, $J=0$ channels (see also [29]).

The invariant mass distributions for the $\pi^0\pi^0$ system of the $\gamma p \to p\pi^0\pi^0$ reaction were studied at GRAAL [30] between $E_\gamma = 0.59$ and 1.07 GeV. The author concluded that no resonance was observed although an indication of a narrow structure seemed to appear close to $M_{\pi^0\pi^0} = 0.32$ GeV for the data integrated between 0.59 and 0.65 GeV. In this work, the σ of the invariant $M_{\pi^0\pi^0}$ mass peak equaled 11 MeV, which is four times worse than our resolution. Moreover, their counting rate was lower than that of the experiment described in this paper.

The $pd \to {}^3\mathrm{He}\ \pi^+\pi^-$ and $pd \to {}^3\mathrm{He}K^+K^-$ experiments have been studied at COSY [31], and are presently being analyzed.

A great number of experiments were performed at high energies in order to study the two-pion correlations or eventual exotic mesons, glueballs, or hybrids [32] and more generally to study meson spectroscopy between 1 and 2 GeV. Their invariant two-pion mass resolutions were not accurate enough in order to allow a study as it was done in our work. However, some experiments were performed with attention to $\pi\pi$ invariant mass events below 1 GeV [for example, the DM2 experiment [33] at the Orsay colliding ring (DCI) [34]]. In these data, the bin width—20 MeV—did not allow any substructure extraction, although a slightly oscillating pattern seemed to be sometimes present. A scalar resonance with a mass of 414 MeV was reported, but the authors concluded that ''*the J^P assignement seems to vary with the $\pi\pi$*

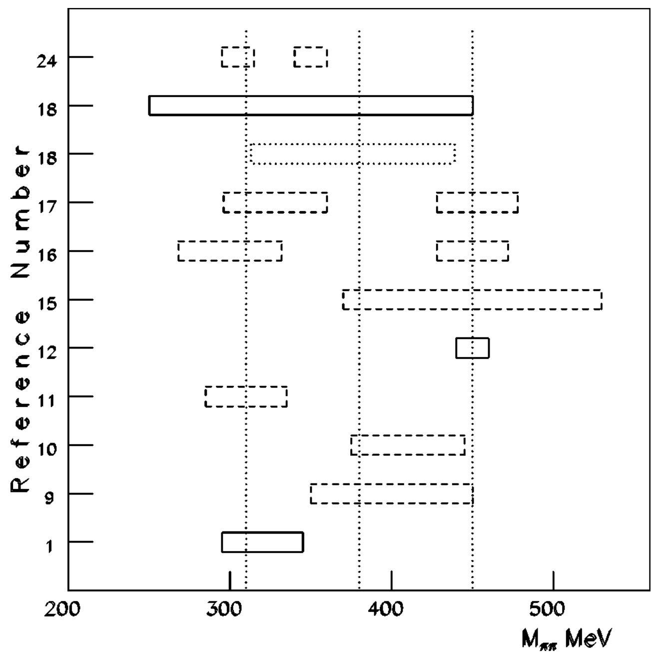

FIG. 1. Distribution of two-pion resonance masses obtained in some previous experiments. When the isospin was defined the line is solid for $T=0$ and dotted for $T=1$. The line is dashed when the isospin was undefined.

mass value, making it difficult to recognize the observed signal as a well-define state.'' In this paper [33], many references were quoted refering to works performed before 1989, which will not be recalled here.

Antiproton annihilation in liquid hydrogen into $\pi^0\pi^0\eta$ was studied [35]. The invariant mass spectra for $\pi^0\pi^0$ events do not display any structure in the threshold up to 500 MeV range, but the resolution and the bin width (20 MeV) were not appropriate for such observation. The study of natural parity resonances in $\eta\pi^+\pi^-$ system was recently performed [36], again with 20 MeV bin width. A small bump is observed (see their Fig. 1) at 500 MeV in $M_{\pi^+\pi^-}$ invariant mass spectra.

In Fig. 1 we have plotted the masses (and widths) of the *ABC* enhancements—when they were observed—resulting from the first generation experiments performed mainly before 1973. The isospin 0 results, which are represented by solid lines, were directly measured by $dd \to ddX$ or $dd \to \alpha X$ reactions or deduced in the other cases. The isospin 1 results (dotted lines) were obtained from the study of the $pd \to tX^+$ reaction. Dashed lines correspond to undefined isospin results.

Several observations can be drawn from these studies.

(i) For increasing resolution and statistical precision, the observed spectra display structures.

(ii) At least two structures at isospin 0 seem to appear around 310 and around 450 MeV, and one structure at isospin 1 around 385 MeV observed with a smaller confidence level.

It is therefore useful to perform a precise experiment in a channel allowing both isospin values for the two-pion system and at an energy larger than 1359 MeV. It is also useful to discuss the assumption that the enhancement is induced by two-proton–pion scatterings. As a matter of fact, there is no calculation with such assumption anticipating the existence of several structures.

An experiment fulfilling such conditions was performed and its results are presented in this paper. The $pp \to ppX^0$ reaction was studied at different angles and energies.

III. EXPERIMENT

The measurements were performed at the Saturne synchrotron, using the SPES3 beam line and detection system. The two energies used, 1520 and 1805 MeV, were both above the energy of the $pp \to \Delta\Delta$ threshold. The details of the experimental properties have already been described [37,38] and they will not be repeated here. Reference [38] presented the results of the same experiment, but was devoted to the study of known meson production, π^0, η, and ω and also production of new narrow structures in the mass range $M_\eta \leqslant M_X \leqslant M_\omega$.

The liquid H_2 target of 393 mg/cm^2 was held in a container with Ti windows having a thickness of 130 μm. External heat shields comprised of 24-μm-thick Al were placed in the beam line on either side of the target. The effects of these windows was checked by regular empty target measurements. The corresponding count rates were small, typically $\leqslant 5\%$. We concluded that the target windows were not a source of noticeable contamination. We concluded also that the data were not contaminated by any hot area of incident beam which could have been scattered by any mechanical structure at the entrance of the spectrometer. The beam flux varied between 10^8/burst and 5×10^8/burst, depending on the spectrometer angle and depending on the incident energy. It was fixed in order to keep the acquisition dead time to less than 10%. It was integrated with help of two scintillation telescopes in direct view from the target and an ionization chamber downstream the beam. The solid angle of the spectrometer was (± 50 mrd) in both the horizontal and vertical planes. The detection acceptances were determined using the spectrometer magnetic field map and the code GEANT [39]. The drift chambers, the trigger, and the acquisition code were conceived in order to detect, to identify, and to measure the properties of two-particle reactions. The time of flight was measured on a 3-m basis, with a resolution for each scintillator equal typically to $\sigma=180$ ps. A particular property due to two particle detection was the second time of flight between both detected protons, used in order to eliminate the random coincidences and possible wrong identification coming from real $pp \to p\pi^+X$ events. Since the reaction was overidentified, a very good identification was obtained, and no parasitic reaction could occur. A small contamination of three charged detected particles was observed, typically $\approx 2\%$. These events were removed.

The experimental mass resolution was determined using the $pp \to pp\pi^0$ reaction. At $T_p=1520$ MeV, at forward angles, the σ of the missing mass peak equals 9 MeV. We deduced therefore that the corresponding values vary from 4 to 2.4 MeV when M_X varies from 300 up to 500 MeV. The resolution deteriorates for increasing angles. The values at

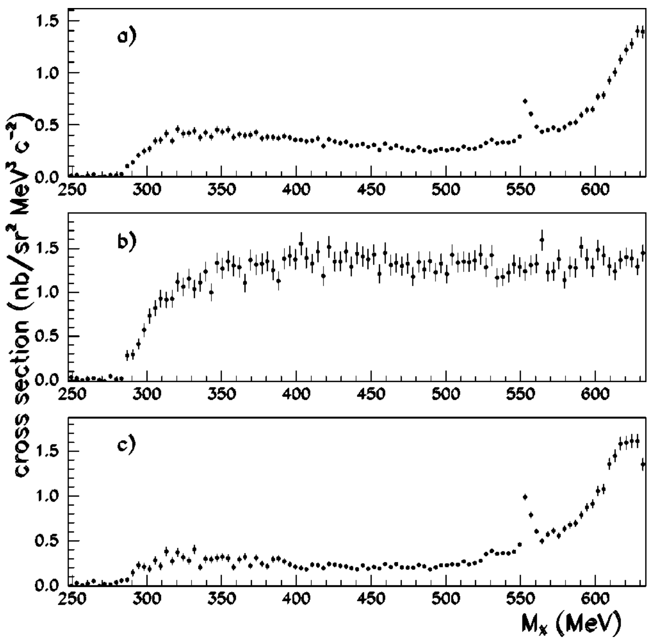

FIG. 2. Typical cross section versus the missing mass, obtained at 1520 MeV and 0° for all the events (a), with a selection for the invariant mass $M_{pp}\leqslant 2M_p+5$ MeV (b), and the complementary part when M_{pp} is $\geqslant 2M_p+5$ MeV (c).

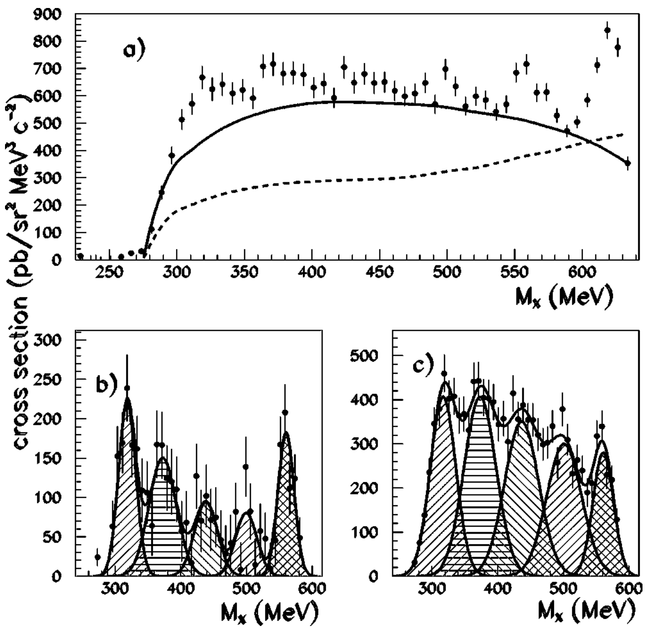

FIG. 3. Cross section at 1520 MeV, 5°, and $M_{pp}\leqslant 2M_p+5$ MeV (a) with two shapes of multipion phase space (see text for explanations). The results of the subtraction of these two phase space contributions are presented in parts (b) and (c) fitted by five Gaussians.

$T_p=1805$ MeV have been extracted from the η width observed from the $pp\rightarrow pp\eta$ reaction, since the $pp\rightarrow pp\pi^0$ reaction was—at that energy and at forward angles—outside the SPES3 experimental acceptance. We deduced that the σ of the missing mass peak for the *ABC* effect, at $T_p=1805$ MeV, varies from 4.9 to 2.9 MeV when M_X varies from 300 up to 500 MeV.

The beam polarizations were 0.78 and 0.74 for both increasing energies. The polarities were reversed between each spill in order to avoid any bias due to slow polarization drift.

IV. DATA ANALYSIS

The trigger and drift chamber information was used to identify the particles and to calculate their momenta and emission angles. Then, the missing mass (M_X) and invariant mass (M_{pp}) were computed. A simulation code was written in order to make corrections for lost events. These losses can be generated by the intersection of both trajectories in all detection planes (either an intersection on a drift chamber plane or on a trigger plane). The losses also came from events where the drift chamber trajectory information had no associated information from the trigger. Such trajectories correspond to particles having fringing values in momenta and angles. The spectrometer momenta range was $600\leqslant p\leqslant 1400$ MeV/c, but each proton momentum partially covered this domain, depending on the missing mass, and therefore on the incident energy and scattering angle. In order to study the M_X cross sections, we have to normalize our data by the $\Delta p_1\Delta p_2$ range of the two detected protons. A typical distribution versus M_X is presented in Fig. 2(a).

The theoretical analysis of three particle final states (two protons and $M_{\pi\pi}$ missing mass), is more complicated than it would be for a reaction having two particles in the final state. We have selected in our data such events by introducing soft cuts in order to keep events with $2M_p\leqslant M_{pp}\leqslant 2M_p+5$ MeV [see Fig. 2(b)]. These data correspond to a reaction with a simpler final state: the quasibound two-nucleon $^1S_0$ state and the $M_{\pi\pi}$ missing mass. We can notice that this selection in invariant mass reduces notably the η production. Such a reduction can be associated with the large difference between the incident and the final c.m. momenta (respectively, 844 and 297 MeV/c at $T_p=1520$ MeV). When the two protons have a zero angular momentum ($^1S_0$), the number of partial waves from the incident state which participates to the η production is reduced. For increasing energy, the difference between incident and final c.m. momenta decreases, and so the η peak reappears. We present also the complementary events [Fig. 2(c)] which correspond to $M_{pp}\geqslant 2M_p+5$ MeV. We have to notice that the normalizations on constant $\Delta p_1\Delta p_2$ acceptances were performed for the same cuts as those used to select events. These $\Delta p_1\Delta p_2$ acceptances differ for different cuts. Therefore the cross sections for all data without a cut on M_{pp} are not the sum of the cross sections for $M_{pp}\leqslant 2M_p+5$ MeV and $M_{pp}\geqslant 2M_p+5$ MeV events.

To extract the *ABC* enhancement, we have to remove the two-pion, the three-pion, and eventually the four-pion (at $T_p=1805$ MeV) phase space contributions. In a first stage, the adjustement was done arbitrarily; the maximum contribution of the phase space of two and three pions is illustrated in the Fig. 3(a) by the solid line. Then, doing the subtraction, we obtained the distribution presented in Fig. 3(b). We observe that this distribution displays several oscillations. The next step was to separate the corresponding structures.

To take advantage of the fact that the experiment was

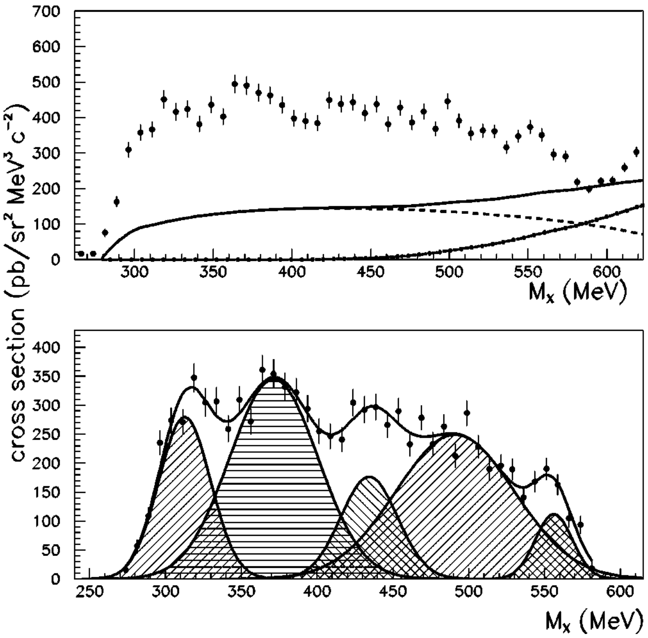

FIG. 4. Phase space of two (dashed line), three (chain-dotted line) pions, and the sum (solid line) applied to the cross section obtained at 1520 MeV, 5°, and $M_{pp} \leqslant 2M_p + 5$ MeV for one state of the polarized beam. In the lower part is the result of the fit after subtraction of the phase space.

done with a polarized beam, in a second stage we analyzed separately the two polarization state data and adjusted the *same* maximun phase space contribution to both distributions (Figs. 4 and 5). Such a choice corresponds to the assumption that the multipion production described by phase space is unpolarized. Such assumption has two consequences: (i) the extracted cross sections values will be minimum, and (ii) the extracted analyzing powers will be maximum.

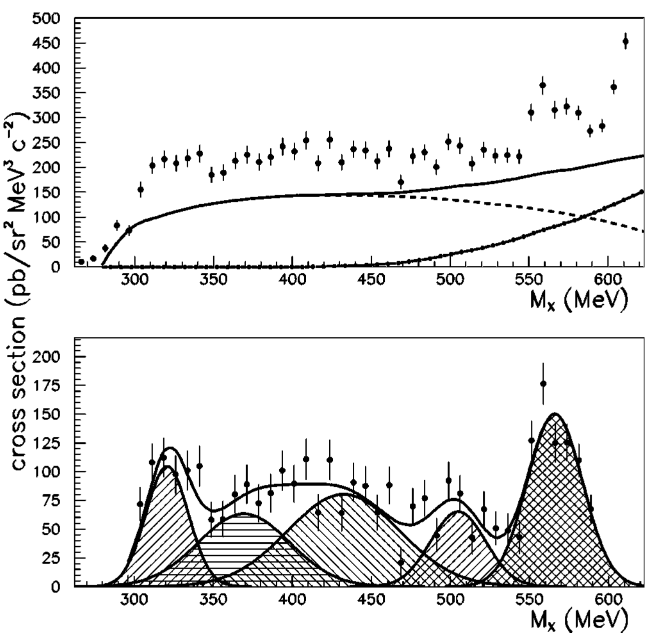

FIG. 5. Same results as those presented in the Fig. 4, but for the other state of the proton beam polarization.

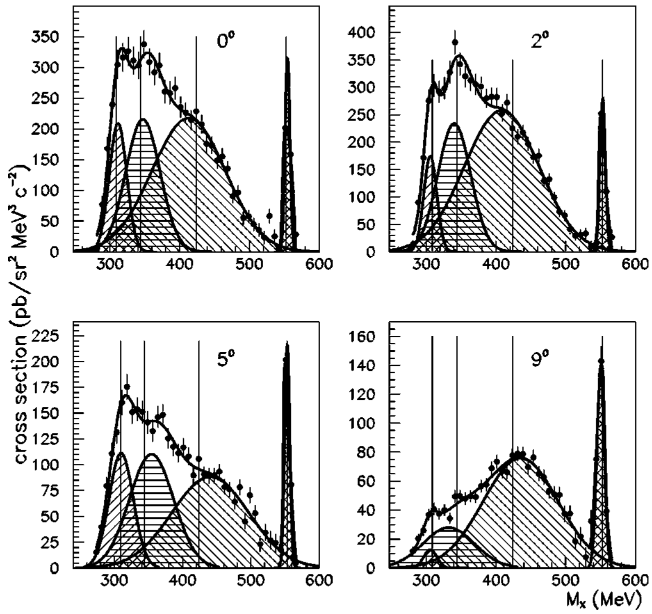

FIG. 6. Results of the minimization after subtraction of the phase space contribution, for $T_p = 1520$ MeV and four laboratory angles. Four vertical lines are fixed at the mean values of the extracted peaks.

We then applied this background distribution to the unpolarized cross section [dashed line of Fig. 3(a)], and after subtraction we obtained the final distribution [Fig. 3(c)]. We observe that nearly all spectra display an oscillatory shape, and therefore we decide to analyze all our data in the same way. The difference between these two distributions [Figs. 3(b) and 3(c)] is only in the amplitude; the positions in missing mass M_X of the extracted peaks are the same. The minimization done using several Gaussians gave a χ^2 close to 1. We have to notice that a fit done with a unique Gaussian after the subtraction of these two phase space backgrounds gave, respectively, $\chi^2 = 3.9$ and 7.3.

The plotted vertical bars correspond to statistical errors, before phase space extractions. There is also a systematic error, not plotted, corresponding to uncertainties in two-, three-, and eventually four-pion phase space subtractions. It was estimated to vary between 20% and 40%. These errors have to be understood as possible uncertainties on the data, smoothly varying for increasing $M_{\pi\pi}$. They have little to do with the oscillatory pattern of the subtracted data.

V. RESULTS

The phase space backgrounds were subtracted—using the unpolarized assumption—as explained in the previous section. Since several oscillations appear, the analysis was performed with the aim to extract several substructures. The idea was to look at their stability for different angles and different energies, before deciding whether or not the decomposition has a real meaning. Since our error bars—in this step of the analysis—are rather large, the result of the minimization depends a little on the input data. We have studied the dispersion of the final substructures masses, and found that it may vary between 1 MeV and 6 MeV.

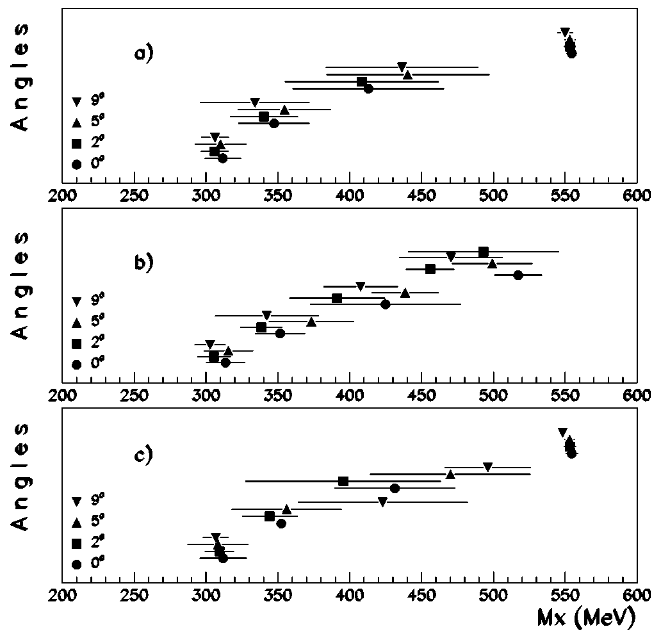

FIG. 7. The position in missing mass and the width (horizontal line) of the decomposition peaks are presented for the four experimental angles at $T_p = 1520$ MeV, for all the events (a), with a selection for the invariant mass $M_{pp} \leqslant 2M_p + 5$ MeV (b), and for the complementary part when M_{pp} is $\geqslant 2M_p + 5$ MeV (c).

A. Cross sections for $T_p = 1520$ MeV

1. All data

Here, we present the cross sections obtained for all our data and for all M_{pp} invariant masses. Figure 6 shows the corresponding decompositions for the four forward angles 0°, 2°, 5°, and 9° in the laboratory. Four substructures were extracted at the following mean masses: 309, 344, 424, and 552.8 MeV. The last one, which was very easy to separate, corresponds to the η meson. We summarize the characteristics (mean value and width) of these peaks in Fig. 7(a). We can see a relative stability of the missing masses whatever the observation angle. The structure at 424 MeV is broader than the others: it is not excluded that it could be produced by the superposition of several substructures that were not extracted.

2. $2M_p \leqslant M_{pp} \leqslant 2M_p + 5$ MeV events

Cuts were put on the M_{pp} invariant mass in order to select the $^1S_0$ state of the two detected protons. The experiment was therefore a two-particle reaction $pp \rightarrow 1S_0[pp]X^0$ which should be more easily computed (using Feynman graphs for instance). The results of the substucture extraction are presented in the Fig. 7(b). The broad peak observed at 424 MeV was separated into two parts. The different substuctures appear at the following masses: 309, 351, 424, and 495 MeV.

3. $M_{pp} \geqslant 2M_p + 5$ MeV events

Figure 7(c) shows the corresponding results obtained for this selection in invariant mass. Here, again, the substructure masses are stable at $M_X = 310$, 350, and 553 MeV.

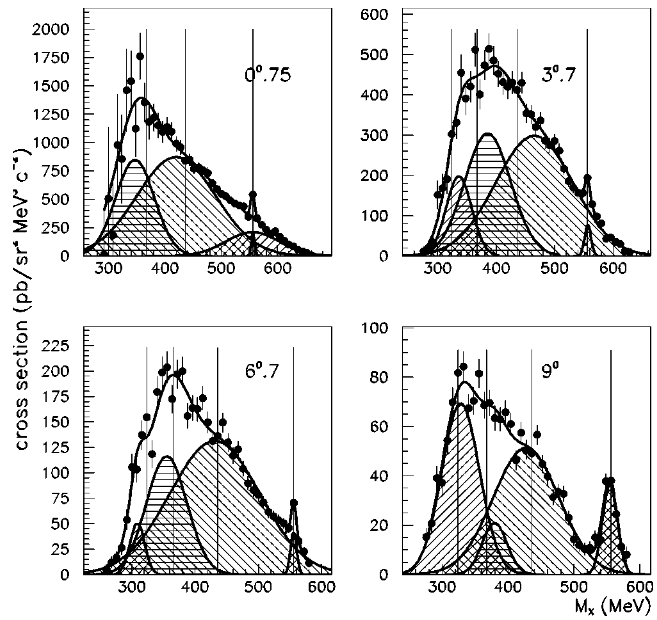

FIG. 8. Results of the minimization obtained at 1805 MeV for four laboratory angles. Vertical lines correspond to the mean value of the peaks.

B. Cross sections for $T_p = 1805$ MeV

1. All data

The same procedure was applied to the all data obtained at this energy. The results are presented in Fig. 8. Vertical lines were drawn at the mean values where the peaks are positioned: 324, 367, 436, and 556 MeV. These values and the widths describing these peaks are summarized in Fig. 9(a).

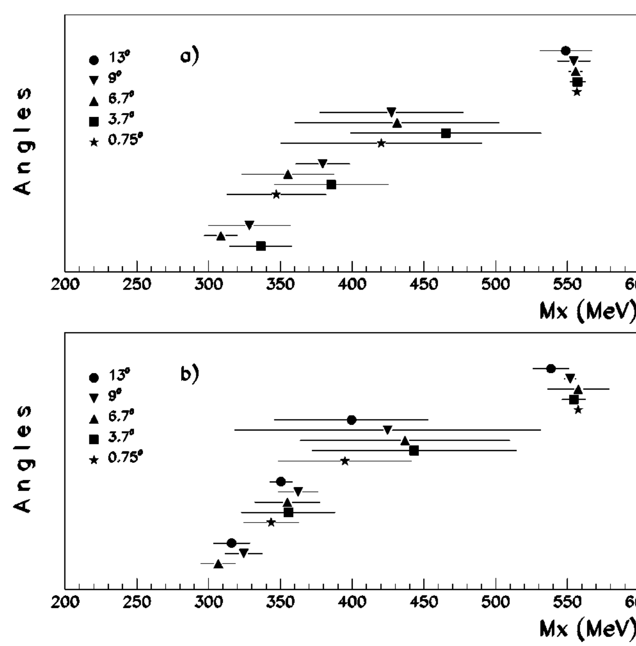

FIG. 9. Position in missing mass and width (horizontal bar) of the decomposition peaks obtained at $T_p = 1805$ MeV for all data (a) and with a selection in $M_{pp} \leqslant 2M_p + 5$ MeV (b).

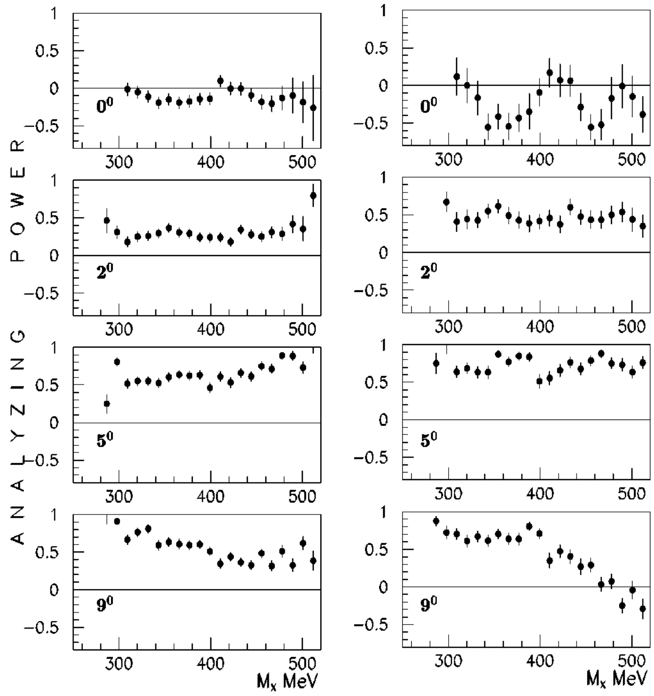

FIG. 10. Analyzing power versus the missing mass obtained at $T_p = 1520$ MeV and at the four experimental angles. On the left side the results are presented for all the data, on the right side a selection of events with $M_{pp} \leqslant 2M_p + 5$ MeV was made.

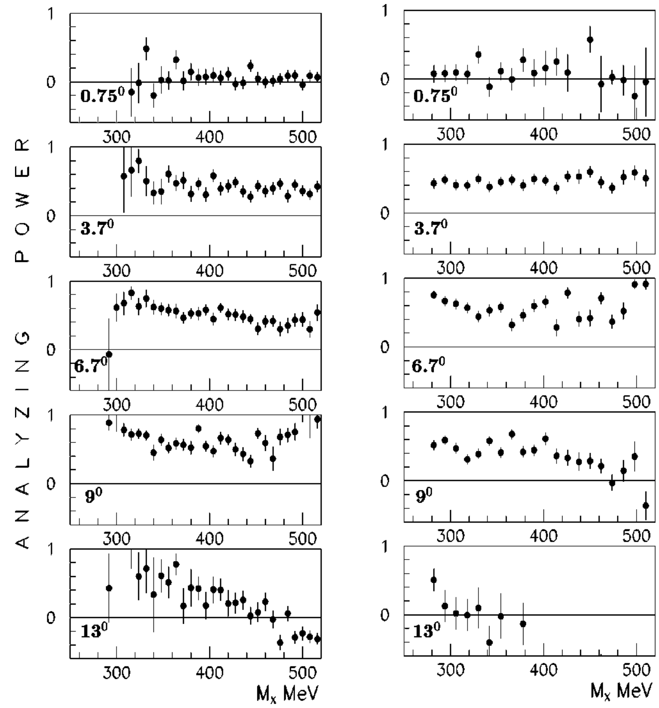

FIG. 11. Analyzing power for $T_p = 1805$ MeV and five laboratory angles. All data were used for the results presented in the left part, and only events with $M_{pp} \leqslant 2M_p + 5$ MeV were used for the right hand distributions.

2. $2M_p \leqslant M_{pp} \leqslant 2M_p + 5$ MeV events

Using the same selection conditions as for the invariant mass M_{pp}, the peaks which describe the cross section have masses and widths summarized in Fig. 9(b). We can notice that the masses are relatively close to those obtained for the same condition at lower incident energy. These masses are 316 compared to 309, 353 to 351, 420 to 424, and 552 to 560 MeV for the η meson.

C. Analyzing power

As the beam was polarized, it was possible to extract the analyzing powers corresponding to the missing mass. The method of subtraction of two- and three- (or four-) pion phase space was explained in the data analysis section (unpolarized background assumption).

The results are presented versus the missing mass M_X in Fig. 10 for 1520 MeV and in Fig. 11 for 1805 MeV. The nonzero mean value at 0° is related to a small shift of the spectrometer angle. The real laboratory angle is smaller than the nominal one by several 1/10 degrees. The analyzing power is negative for all angles but crosses the zero axis with the increasing missing mass M_X for the largest observation angle.

The oscillatory pattern of the analyzing power shows the presence of some—more than one—production processes. Their variation with missing mass can be considered as an argument strengthening our decomposition of the *ABC* effect on some distinct states corresponding to our substuctures. Indeed, we do not expect the different ''classical'' *N-N* amplitudes to vary so fast with mass.

VI. ATTEMPT FOR AN INTERPRETATION

We showed in previous papers that narrow structures exist in *baryonic states* [40] and in *dibaryonic states* [37]. The same papers showed that it was possible to find a good agreement between the experimental masses and a very simple phenomenological mass relation. This mass formula was derived some years ago in terms of color magnetic interactions [41], for two quark clusters at the end of a stretched bag:

$$M = M_0 + M_1[i_1(i_1+1) + i_2(i_2+1) + (1/3)s_1(s_1+1) + (1/3)s_2(s_2+1)], \quad (1)$$

where M_0 and M_1 are parameters deduced from mesonic and baryonic mass spectra and $i_1(i_2)$ and $s_1(s_2)$ are isospin and spin of the first (second) quark cluster.

Here, we will also associate the observed substructures to colored quark clusters. We make the assumption that the clusters are $q^2 - \overline{q^2}$ or $q^3 - \overline{q^3}$. We choose for our two parameters M_0 and M_1, the values found during the analysis of the higher mass range [38] $M_\eta \leqslant M_X \leqslant M_\omega$. Therefore, although our formula can be considered as being a phenomenological one, we use it without any free parameter. These values $M_0 = 310$ MeV and $M_1 = 30$ MeV allow us to obtain the calculated mass spectra shown in Fig. 12. The figure is divided into three parts: from left to right, the experimental masses found at $T_p = 1520$ MeV, the masses found by calculation using the previous formula, and the experimental masses found at $T_p = 1805$ MeV. As before, here (a), (b), and

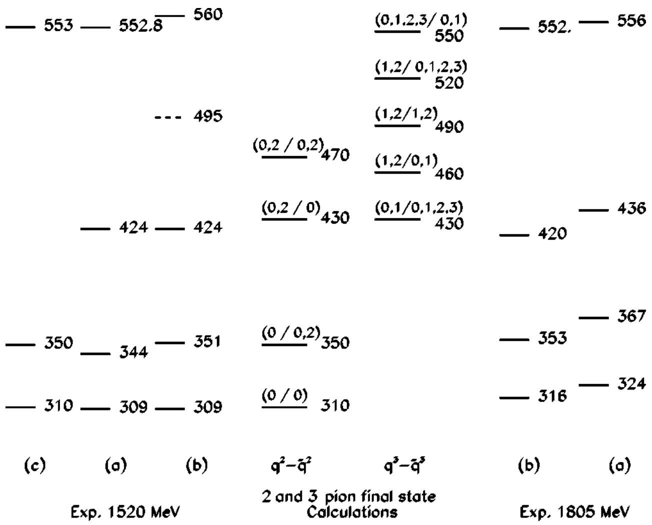

FIG. 12. Experimental and calculated masses for two- and three-pion substructures in the *ABC* range (see text). The quantum numbers for calculated levels are (I/S).

(c) correspond, respectively, to all events, events with $M_{pp} \leqslant 2M_p + 5$ MeV, and events with $M_{pp} \geqslant 2M_p + 5$ MeV. In the center of the figure, the calculated masses are displayed in two columns corresponding to $q^2-\overline{q}^2$ and $q^3-\overline{q}^3$ clusters. The quantum numbers (I/S) are given for two-pion disintegration ($q^2-\overline{q}^2$ configurations) and for three pion disintegration ($q^3-\overline{q}^3$ configurations). With our M_0 and M_1 values, the $q^2-\overline{q}^2$ configurations predict levels between 310 and 470 MeV. The $q^3-\overline{q}^3$ configurations predict levels between 370 and 610 MeV when the $q^4-\overline{q}^4$ configurations (not shown in the figure) predict levels up to 790 MeV. Two states at 370 and 400 MeV predicted by $q^3-\overline{q}^3$ configurations are not drawn since their masses are lower than the three pion mass. The 430 MeV state can be either $q^2-\overline{q}^2$ or $q^3-\overline{q}^3$ clusters, depending on its parity. The state found at 550 MeV can have $I=S=0$—that is, the mass and quantum numbers of the η meson. Also its parity is negative, as it must be for the η meson.

We limited our discussion to $l=0$ orbital momenta between both quark clusters since our missing mass range is limitated to less than 300 MeV. We have therefore positive total parity for all substructures in the case of two-pion disintegration. We need therefore an even orbital momentum between both pions. Then the total two-pion isospin must be even, since they obey Bose-Einstein statistics. All states with odd isospin or spin vanish and four states survive: $I=0$ or 2 and $S=0$ or 2. This is no longer true for three-pion disintegration which is allowed for $M_X \geqslant 410$ MeV. We found the possibility to have an isovector enhancement in the *ABC* effect at masses larger than 410 MeV. This is somewhat more than the experimental result of [20]. Below 410 MeV, only two-pion disintegration is allowed, and such a disintegration is forbidden by Bose-Einstein statistics, inside the scope of our model.

Therefore our four levels, from bottom to top, can have different quantum numbers (I/S), (0,0), (0,2), (2,0), and (2,2), justifying *a posteriori* our incoherant extractions.

VII. DISCUSSION

Our separation of the measured cross sections into several peaks was justified by the following considerations.

(i) Some spectra display an oscillatory pattern (see Fig. 3).

(ii) The total spectra shape varies with angle (see Fig. 6).

(iii) The analyzing power display an oscillatory pattern (see Figs. 10 and 11).

This separation was *a posteriori* justified by the stability of the masses extracted from different data.

Our level spacing, experimental as well as calculated, is of the order of 30–40 MeV. The error bars extracted for different substructure masses are rather large. This is mainly due to the phase space background lying below the *ABC* enhancement and to the separation between overlapping states. We cannot exclude that some states would have the same quantum numbers. The justification of the assumption made implicitly that there is no interference between the different states (incoherent sum of cross sections) lies with the fact that the quark cluster substructures can be different.

The widths extracted are of the order of $\sigma \approx 20$ MeV. They are even less precise than the masses. It is possible that other smaller states were not extracted in the range studied.

The level scheme found does not contradict any previous experiment. The previous studies have all been performed with less precision (resolution and/or statistics). A special comment must be made concerning the $T=1$ *ABC* enhancement observed in the $dp \rightarrow {}^3\mathrm{H}(MM)^+$ reaction [20]. Our calculations predict possible $T=1$ levels for masses larger than those observed with a small contribution in [20]. The authors commented on their results in the following way: ‘‘*The low mass bump ... could indicate a small I =1 contribution to the ABC effect. However it is much wider, centered around 400 MeV, and could also indicate a deviation from phase space of another sort.*’’

The presence of isospin 1 or 2 levels can be confirmed by precise comparisons of data from $pp \rightarrow ppX$ and $dd \rightarrow ddX$ reactions. The old $dd \rightarrow ddX$ experiment [15] from Brookhaven had very small statistics and very large data bins (50 MeV). The presence of eventual isospin 1 levels can be studied using $pp \rightarrow dX$ reactions. Such an experiment was performed 30 years ago at Birmingham. No deviation from $T=1$ phase space was observed, which is in agreement with our analysis. No analysis has been done which could produce pure $T=2$ mesonic final states. An experiment like $pp \rightarrow nnX^{++}$ would be imprecise.

The absolute cross sections for the first three separated peaks ($M=310$, 350, and 430 MeV) were extracted within the assumption of the maximum nonpolarized pion phase space distributions. They are imprecise since the multipion phase space is poorly defined, and therefore they are not shown. The relative variations of these cross sections versus the angle are different. Such behavior explains the moving position and width of the total enhancement observed in old experiments. It can also explain the observation [42] of the ''*isotropy within 10% –20% of the low-mass $\pi\pi$ production, compatible with neither the double-baryon-excitation model nor the baryon-exchange model.*''

Narrow structures in two-pion invariant masses have been studied at Dubna [43] using $np \rightarrow np\pi^+\pi^+\pi^-\pi^-$ and $np \rightarrow pp\pi^+\pi^-\pi^-\pi^0$ reactions. In spite of poor statistics, the authors insist that some separated peaks were extracted. Among these masses, several are close to those we found in a completely different experiment. Those which were more clearly extracted in this two-pion invariant mass experiment were at 388 and 479 MeV in the $\pi^-\pi^-$ invariant mass system and at 388 and 652 MeV in the $\pi^+\pi^-$ invariant mass system. The structures observed in the quoted work were narrower than our structures.

A measurement of the yield of the $\pi^-A \rightarrow \pi^+\pi^-\pi^-A$ reaction was performed at Protvino [44]. The invariant masses of two charged pions were extracted inside a 10 MeV binning and with a low statistical precision. The $M_{\pi^-\pi^-}$ spectra do not display any structure (which would have corresponded to isospin 2). The $M_{\pi^+\pi^-}$ spectra display a structure around 450 MeV with a width (σ) close to 10 MeV.

The $\pi\pi$ scattering states, with $I=0$ or 2, like the meson spectroscopy, are steadily studied in many places inside various collaborations: among them, at CERN (Crystal Barrel Collaboration, GAMS, OBELIX, DELPHI, L3, ALEPH, OPAL, and others), at Brookhaven, Fermilab, Novosibirsk, BES, IHEP, Stanford, Cornell, and others. This is a very rich field of particle physics entirely concentrated to the study of the meson mass range larger than 750 MeV. This field of research is related to the study of meson spectroscopy with special attention to the search of exotic mesons, scalar, and tensor glueballs, hybrids, and multiquark states [45]. The discussion of the related results is clearly outside the scope of the present work. The results—up to August 1997—can be found in [46,47]. Several papers have been published since that time, [32,48] for instance. Our interpretation of the substructures observed between threshold and 550 MeV (mass of the η meson), interpretation tentatively associated with $q^2\overline{q}^2$ configurations, assumes that such states are already present at masses lower than the usual assumption at around 1.5 GeV.

A natural question arises: why are these states relatively narrow? It is of course possible to think of non-normal quantum numbers J^{PC} for $q\overline{q}$ states. However, the approximate mean width $\sigma \approx 20$ MeV of our structures is only 2.5 times lower than the corresponding width of the Δ and it may be possible to speculate on such factor due to $q^2\overline{q}^2$ nature of the states. These widths are physical since the contribution of the experimental width is small.

VIII. CONCLUSION

Our study of the *ABC* enhancement, more precise than experiments performed before, allowed us to observe spectra displaying oscillations. In a few cases, these oscillations allow the extraction of structures with a large number of standard deviations (s.d.) (up to 6.77). In other cases, the extracted structures have a small s.d. However, since nearly all spectra display an oscillatory shape, we extended our approach to all our data, even if in a few cases the total spectrum does not exhibit any oscillation. Is is noteworthy, by looking at Figs. 7 and 9, that the masses of the first two *ABC* substructures were found—at all angles—at masses close to 310 and 350 MeV. Such a stability justifies *a posteriori* our approach. After two- and three-pion phase space subtraction, the spectra have been analyzed with the superposition of several Gaussians. The stability of the masses found allows us to conclude the existence of several peaks, the masses of which are given below. Using the previous observations obtained by various authors, and recalled in Sec. II of this paper, it is possible to suggest the following isospin values: $M \approx 310$ MeV($T=0$), $M \approx 350$ MeV ($T=0$), $M \approx 430$ MeV, and $M \approx 550$ MeV (η meson).

The superposition of these peaks, excited with variable cross sections for different reactions, different incident energies or angles, leads to the previously observed result of the nonstability of mass and width for the *ABC* enhancement.

Further states could, of course, have been omitted. For masses larger than 550 MeV, the four-pion phase space and the lower tail of the ρ meson contribute, and the same analysis will be more difficult. The relative smallness of the structures and the experimental resolution make it impossible to observe eventual doubling of the peaks due to both possible invariant $M_{\pi^0\pi^0}$ and $M_{\pi^+\pi^-}$ masses which differ by 10 MeV.

Within our assumption for these *ABC* substructures, the consistency between observations and explanation is noteworthy. This consistency is emphasized by the fact that it was obtained without any adjustable parameter. The $q^2-\overline{q}^2$ configurations predict levels between 310 and 470 MeV while $q^3-\overline{q}^3$ predict levels between 370 and 610 MeV and $q^4-\overline{q}^4$ predict levels between 370 and 790 MeV. The first two masses at 310 and 350 MeV are well separated from the others and they are also experimentally observed close to these positions in all cases—see Figs. 7 and 9. A structure around 430 MeV is observed at both proton energies. Such mass is close to the ''excitation mass'' ($M_e = 411$ MeV) between the three lightest pseudoscalar mesons π, η, and η'. Above 430 MeV, where more levels are predicted by different configurations, the experimental situation is more chaotic.

Now let us try to comment on the usual assumption used to describe the *ABC* enhancement. As long as physicists believed in the presence of *one enhancement*, since its position and width vary with kinematical conditions, one had to introduce a dynamical explanation which was naturally two-pion production on two nucleons. Now, since we associate the nonstability of the mass and width of the total enhancement with the presence of *several substructures*, the previous description is no longer essential. Does it mean that it is not correct? Our work does not say anything about the production mechanism. The common production mechanism allowed a good description of several observables. For example, this was the case in a recent analysis of the $dd \rightarrow \alpha X$ reaction [49] described by two parallel $NN \rightarrow d\pi$ reactions (double-Δ model). However, since the *ABC* enhancement was also observed in reactions implying only one nucleon, this reaction mechanism may be important, but in no way it can be the only one.

The π-π phase shifts for masses $M_{\pi\pi} \leqslant 500$ MeV were obtained [50] by the analysis of K_{e4} branching ratio. They are scarce, imprecise, and cannot be used to confirm or infirm our interpretation.

It is not unnecessary to disentangle the different problems in nuclear physics, studied with two-pion interactions, but corresponding to different space-time correlations. The precise lifetime measurement of $\pi^+\pi^-$ atoms to test low energy QCD predictions [51] concern lifetimes of the order of 3×10^{-15} s, and therefore large atomic interaction distances ≈ 1 μm. Two-pion interferometry, used to study the interaction dimensions, concerns distances of the order of 1 fm, $\Delta E \approx 200$ MeV. These are the characteristic dimensions of excited baryons and mesons. The states observed in our work have smaller widths, and therefore somewhat larger lifetimes.

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