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FURTHER EVIDENCE FOR NARROW DIBARYON STATES IN dp INTERACTIONS

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INTRODUCTION

The spectroscopy of dibaryon resonances ($\Gamma < 50$ MeV) has been simulated in the last few years by theoretical and experimental studies. This is connected with a search for the effects displaying quark degrees of freedom in nuclear matter. A reliable discovery of these states can throw light on the confinement problem.

The existence of dibaryon states has been predicted in a number of theoretical models, for example: in the MIT bag/1/, joint string/2/, rotational/3/, string-like/4/, and potential nucleon-nucleon/5/ models.

At present there are indications of the existence of narrow dibaryon resonances obtained in the studies of NN–, γd–, πd–, pd– and $p^{3,4}$He-processes. The results of a search for these states in dp and ^{4}Hep interactions are reported in Refs./6–10/. The two-nucleon effective mass spectrum for a deuteron break-up reaction was investigated at LIYAF/11/. A series of narrow states was found for masses, M, of 1959, 2030, 2080 and 2140 MeV/c^2. Studying the two-narrow invariant mass distribution for the $\gamma d \to pp\pi^-$ reaction, a narrow enhancement was observed at $M_{pp} = 2014$ MeV/c^2 /12/. The Saclay data/13/ on the missing mass measured for the ^{3}He(p,d)x reaction are often discussed. The obtained results testify to the observation of series of narrow states for the following masses: $M_x = 1969$, 2124, 2155 and 2192 MeV/c^2.

The ^{3}He($\vec{p}$,d)x process using a polarized proton beam has been recently studied at LAMPF/14/. Narrow structures around $M_x = 2015$, 2054, 2125, 2152 and 2181 MeV/c^2 were obtained by investigating the dependence of the missing mass on the analysing power.

At the same time the deuteron break-up experiments/15,16/ call the observation of narrow structures/6–8/ in question.

The two-proton effective mass spectrum for the $dp \to (pp)n$ charge exchange reaction has been investigated in Ref./15/. In our opinion, the following factors are possible causes of the absence of statistically significant structures.

First, the kinematic conditions for the selection of the charge exchange reaction with two fast protons in a narrow cone are unfavourable. Taking into account the configuration of the experimental setup, our estimates show that more than 30% of charge exchange events are not recorded.

Second, the NN-processes with intermediate Δ-isobar are of great importance for the production of the states observed in the experiments [6,8]. In this case [15] the appearance of peculiarities will be suppressed because of a small value of incident momentum (1140 MeV/c per nucleon).

The deuteron break-up reaction has been studied [16] with the aid of a hydrogen bubble chamber. In this experiment the background of quasi-elastic scatterings was not completely suppressed as indicated by us in [8].

In this report we present a new evidence for the existence of narrow dibaryon states for dp interactions. The results have been obtained using the method which allows one to suppress background processes. The analysis is based on the statistics twice as large as that in Refs. [6-8].

EXPERIMENT

The experiment has been performed using a 1 m hydrogen bubble chamber exposed to a deuteron beam of a 3.33 GeV/c momentum at the Dubna syncrophasotron.

The working material contains about 115 thousand events of dp interactions. To study the two-nucleon effective mass spectrum, the reactions

$dp \to ppn$ - 47298 events, (1)

$dp \to p\pi^+ nn$ - 24124 events (2)

were selected.

It is known that the deuteron break-up reaction (1) can proceed with some change in the charge of the target proton (charge exchange channel) and with its retention (charge retention channel). The set of events, in which the fastest particle in the deuteron rest frame is a neutron, is called charge exchange; and the rest, charge retention. After this separation, we have

39375 charge retention events $(dp \to (pn)p)$ and
7923 charge exchange events $(dp \to (pp)n)$.

Note that for the charge retention channel only those np combinations will be considered which consist of a neutron and the slowest proton in the deuteron rest frame.

The applicable method of investigations [17] (a beam of accelerated deuterons and 4π-geometry) allowed the experimental data on these reactions to be obtained almost without losses.

RESULTS

Before analysing the two-nucleon effective mass spectrum for processes (1) and (2), we would like to argue the procedure of selecting the kinematic region, in which the production of two-nucleon systems is expected to be more abundant.

The data on the $dp \to ppn$ reaction [18] show that this process proceeds mainly the participation of one nucleon of the deuteron whereas another is a spectator. In this connection one cannot mark deviations from a smooth distribution of the two-nucleon effective mass. Indeed, as is seen from Fig.1, the effective mass distributions of np and pp combinations do not indicate appreciable features.

Therefore, in order to select the class of interactions where the production of dibaryons is more probable, only those events should be selected in which two nucleons of the nucleus take part in the interaction. In the case of deuteron, this corresponds to the selection of spectatorless events.

The cut of the momentum of the slowest nucleon (spectator) can serve as a selection method of spectatorless events. The substantiation of one possible selection method for such a cut was suggested in Ref. [8], where the class of inelastic events with virtual π-meson production and absorption was selected. The momentum distribution of the slowest nucleon from such groups of inelastic events are presented in Fig. 2 for the charge retention (full line) and charge exchange (dashed line) channels, respectively. Two maxima are seen in the charge retention channel. The first of them corresponds to a part of quasi-elastic NN scattering because of a conditional character of the selection of inelastic events. In is shown [6] that the contribution of high momentum part is much larger in the charge exchange reaction than in the charge retention one. This phenomenon has been explained by the contribution of such inelastic processes as Δ-isobar exchange or virtual π-meson production and absorption taking the corresponding isospin states into account. In connection with the aforesaid, it is not surprising that the first peak was suppressed in the momentum distribution of the slowest protons for the charge exchange channel.

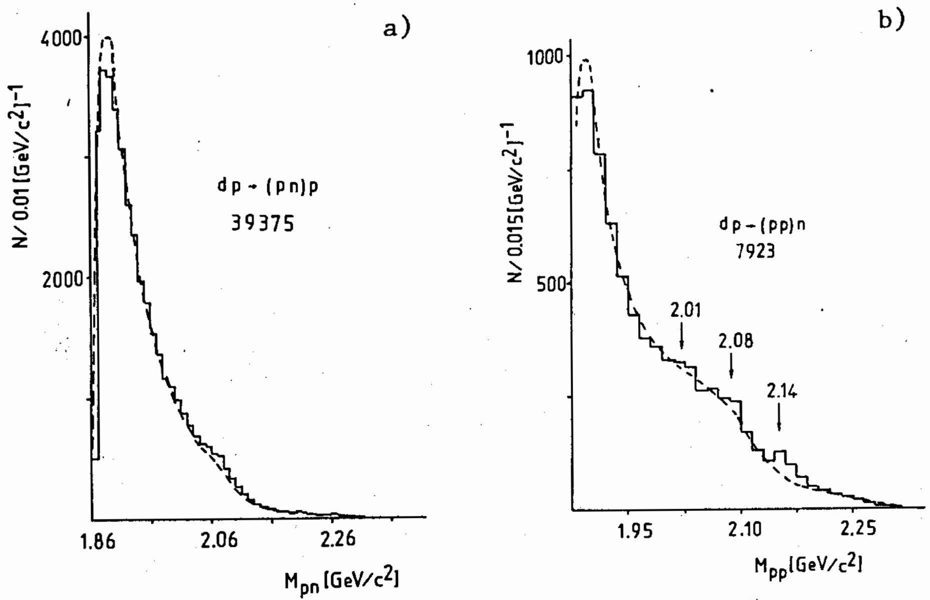

Fig. 1. The effective mass spectrum of the slowest nucleons: a) charge retention and b) charge exchange channels. Curve (---) - background distribution by the "mixing" method.

Therefore, to exclude single-scattering events, different cuts were chosen for the nucleon-spectator momentum: 200 MeV/c and 350 MeV/c for the charge exchange[8] and the charge retention[7] channels, respectively.

For an optimum observation of dibaryon states, such a selection method of the kinematic region is supported by the mechanism of the ^{4}He p → dppn reaction. As is shown in Ref.[20], in this reaction the deuteron in its characteristics is very much alike the residual nucleus which has no influence on the process while the remaining nucleons of the ^{4}He-nucleus take part in the interaction. The two-proton effective mass peculiarities, considered as candidates of dibaryon states[10], were observed just in these interactions without some additional selection criteria.

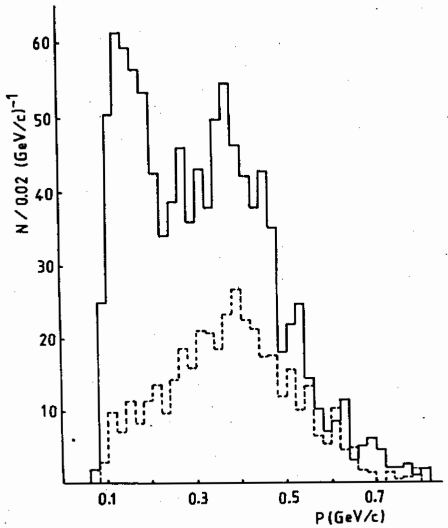

Fig. 2. The momentum distribution of the slowest nucleon in the deuteron rest frame: (——) for the charge retention and (---) charge exchange channels. The events are taken from the "pion absorption region".

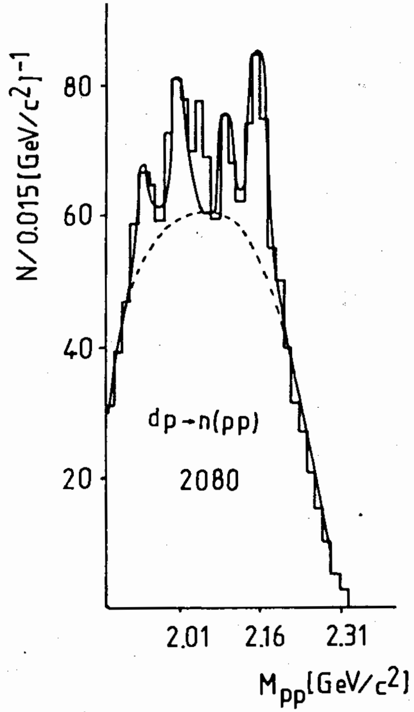

Fig. 3. The pp effective mass distribution for the dp → ppn charge exchange channel where the nucleon-spectator momentum is greater than 200 MeV/c. Histogram - experiment; solid curve - fit.

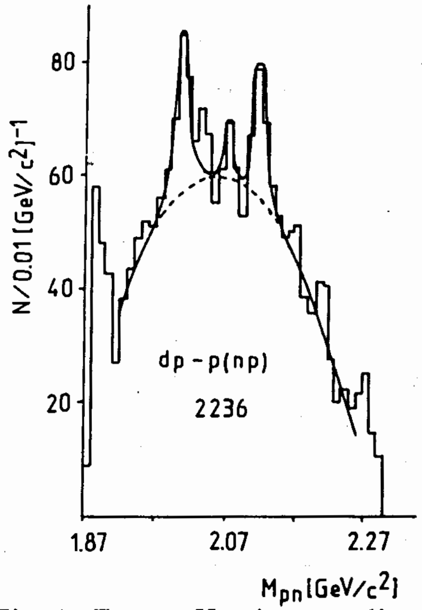

Fig. 4. The np effective mass distribution for the dp → ppn charge retention channel where the nucleon-spectator momentum is greater than 350 MeV/c. Histogram - experiment; solid curve - fit.

Before studying the two-nucleon effective mass for reactions (1) and (2), note that a step of histograms was determined by the experimental resolution.

The effective mass distributions of two slowest nucleons with corresponding limitations on spectator momentum are presented in Figs. 3 and 4 for the charge exchange and retention channels, respectively.

As is seen from Fig. 3, two narrow peculiarities are displayed for the spectrum of the protons in addition to the observed states[6-8]. The statistical significance of the peaks for masses of 1940 and 2090 MeV/c^2 is of the order of two standard deviations. The same structure is seen for the spectrum (Fig. 4). Unlike the charge exchange channel, there is a peak near the sum of the masses of two nucleons for the

Table 1. Results of fitting the pp and pn-effective mass spectra for the reaction dp → ppn (M, Γ are the mass and width of the dibaryon state)

M_{pp} (MeV/c^2)	Γ_{pp} (MeV/c^2)	S.D.	M_{pn} (MeV/c^2)	Γ_{pn} (MeV/c^2)	S.D.
1939 ± 15	27 ± 13	2.1			
2007 ± 15	39 ± 17	4.1	2006 ± 10	25 ± 11	5.1
2090 ± 15	10 ± 12	2.0	2080 ± 10	9 ± 12	1.7
2154 ± 15	31 ± 11	5.8	2118 ± 10	15 ± 13	4.3
$\chi^2/N_D = 2.8/10$			$\chi^2/N_D=6.2/16$		

charge retention one. This is due to the neutron-proton final-state interaction[21].

Table 1 present the parameters of the dibaryon states obtained by fitting with the function which represents the sum of background (a polynomial of the second order) and Breit-Wigner functions (Figs. 3 and 4). We use four Breit-Wigner functions for the M_{pp} spectrum and the three-resonance hypothesis for the M_{pn} one. The values of standard deviations (S.D.) for each peak are shown in this Table as well.

The reaction dp → $p\pi^+$(nn) was investigated to search for neutral dibaryon DB^0(nn) as a neutral counterpart for the singly DB^+(pn) and doubly DB^{++}(pp) charged dibaryon states. The analysis of this reaction is somewhat complicated since the momenta of neutrons are unknown. To search for two-neutron coupled peculiarities, it is necessary to exclude the background of single quasi-nucleon-nucleon scatterings by analogy with the pionless break-up reaction. Therefore, we have applied the following selection criteria proposed in Ref.[9]:

1. The events with proton momentum smaller than 300 MeV/c are discarded from further analysis.

2. Assuming that the excitation of a dibaryon takes place more probably in a quasi-two-body reaction, only those events are taken for analysis for which the missing momentum is directed backwards in the CMS.

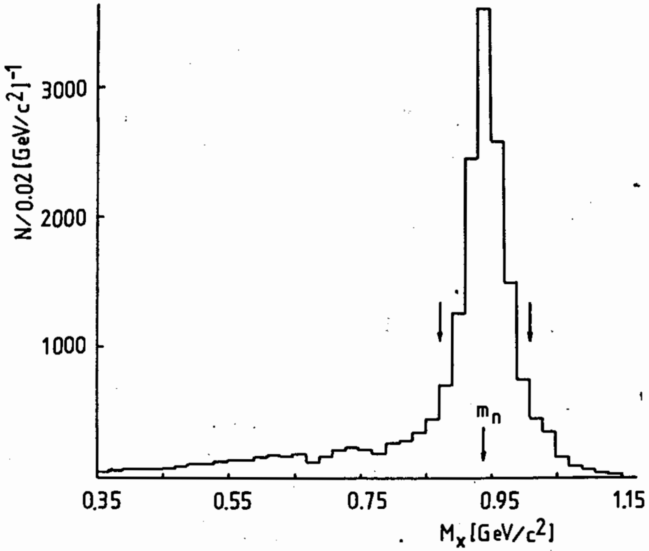

Fig. 5. The mass (M_x) distribution of "active" neutron for the dp → $p\pi^+$ reaction.

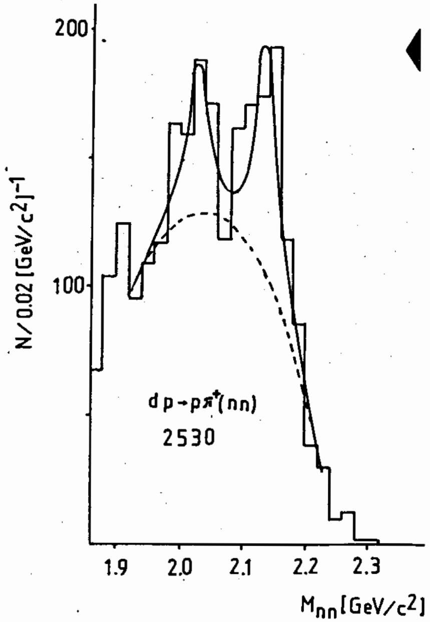

Fig. 6. The two-neutron effective mass distribution for the dp → $p\pi^+$nn reaction. Histogram - experiment; solid curve - fit.

3. To enrich the analysed set with neutron-spectator events, the mass of the "active" neutron calculated as

$$M_x^2 = [M_{miss}^2 - 2 \cdot E_{miss} E_s + 2(\vec{P}_{miss} \cdot \vec{P}_s) + M_n^2],$$

where E_{miss}, P_{miss}, E_s, P_s are the energy and momentum of the missing mass and neutron-spectator, was taken within the regions $M_x < 0.87$ and $M_x > 1.0$ GeV/c^2.

(The M_x distribution for the reaction (2) is shown in Fig.5). Such selection is confirmed by the behaviour of M_x calculated for two random protons for the reaction dp → $ppp\pi^-$ when one of them is a spectator. In this case the above M_x ranges turn out to contain approximately one half the events with proton-spectator momentum greater than 300 MeV/c.

Figure 6 presents the two-nucleon effective mass distribution for the events satisfying these selection criteria. Two peaks are seen at the same masses (M_{nn} = 2020 and 2140 MeV/c^2) as in Ref./9/ .

To determine more precisely the parameters of the statistically significant states, all the effective mass M_{pp}, M_{pn}, M_{nn} spectra were fitted by two Breit-Wigner functions and background as a polynomial of the second order. The Breit-Wigner function distortion connected with the experimental resolution of measuring the effective masses was taken into account as follows:

$$BW(M) = \frac{1}{\sqrt{2\pi}} \int BW(m) \cdot \frac{1}{\sigma_i(m)} \cdot \exp[-\frac{(M-m)^2}{2\sigma_i^2(m)}]\,dm,$$

$\sigma_i(m)$ is an experimental error at a given mass. The results are presented in Table 2.

Table 2

Reaction	Z	M (MeV/c^2)	Γ (MeV/c^2)	S.D.	M (MeV/c^2)	Γ (MeV/c^2)	S.D.	χ^2/N_D
$dp \to (pp)n$	++	2009±15	16±19	4.1	2153±15	7±11	5.8	9.6/21
$dp \to (pn)p$	+	2007±10	8±12	5.1	2118±10	6±9	4.3	6.2/33
$dp \to (nn)\pi^+p$	o	2027±20	16±18	5.3	2137±20	17±9	8.2	21.2/14

As is seen from Table 2, two peaks with a good statistical significance are observed in the two-nucleon effective mass spectra for different reactions and isospin states.

DISCUSSION OF RESULTS

We tried to explain the nature of the observed structure without using the dibaryon hypothesis. In particular, considering the fact that the first of the observed states has a mass close to the sum of two nucleons and a π-meson and the second state to the sum of a nucleon and a Δ-isobar, the two-proton effective mass spectrum was calculated taking into account the transverse cross section behaviour of the $\pi^+ d \to pp$ reaction/8/. The obtained positions of the peaks in the spectrum do not contradict the experimental ones. However, to describe the first state, one has to advance an additional assumption of the presence of a peculiarity in the behaviour of the off-energy shell amplitude for the $\pi^+ d \to pp$ reaction near the threshold. Moreover, the width of the second peak was somewhat greater (80-100 MeV) than that observed in the experiment.

Thus, one failed in describing the found structures within the frame of the above assumptions. This allowed one to interpret them as a display of multi-quark states.

Table 3 shows the data on narrow dibaryon states obtained by us in this paper and the experiments /10-14/ along with

Table 3

Lab.	Reaction	M_{NN}	1	2	3	4	5	6
DUBNA	(this work) $dp \to ppn$	M_{pp}	1939 ± 15*	2009 ± 15	2090 ± 15*		2153 ± 15	
		M_{pn}		2007 ± 10	2080 ± 10*	2118 ± 10		
	(this work) $dp \to p\pi^+nn$	M_{nn}		2027 ± 20			2137 ± 20	
	$^4He\,p \to dppn$ /10/			2035 ± 15			2137 ± 15	
	$^4He\,p \to pppp\pi^-n$ /10/			2036 ± 15			2126 ± 15	
LIYAF	$pd \to ppn$ /11/	M_{pp}	1948 ± 9	2033 ± 9			2136 ± 10	
		M_{pn}	1953 ± 3	2024 ± 5	2078 ± 3		2144 ± 3	
BONN	$\gamma d \to pp\pi^-$ /12/	M_{pp}		2014 ± 2				
SACLAY	$^3He(p,d)x$ /13/	M_x	1969 ± 2			2124 ± 3	2155 ± 3	2192 ± 5
LAMPF	$^3He(\vec{p},d)x$ /14/	M_x		2015 ± 5	2054 ± 4	2125 ± 5	2152 ± 4	2181 ± 5
Predictions	Rotation /8/	$M_{I=1}$		2015	2052	2124	2155	2192
		$M_{I=0}$	1940		2080	2128	2152	
	String-Like /4/	$M_{I=1}$			2090			2190
		$M_{I=0}$	1950		2050			

the theoretical predictions of the rotational [3] and string-like [4] models. The statistically insignificant peculiarities (S.D. ≈ 2) are denoted by (*). The structures found by us in dp and ^{4}Hep interactions within the experimental errors are grouped in a region, M_{NN}, of (2010-2020) MeV/c^2 (see column 2). These states were also observed in the other experiments presented in the same column. They agree with the prediction [3] at M = 2015 MeV/c^2 for isospin I = 1. Note that we observe all charge configuration of the dibaryon as a two-nucleon system. It is not excluded that they are members of one isotriplet.

The peculiarities in the mass region M_{NN} = (2140 - 2150) MeV/c^2 (see column 5) are observed in a number of experiments [10,11,13,14] and predicted at $M_{I=1}$ = 2155 and $M_{I=0}$ = = 2125 MeV/c^2 [3]. Moreover, the state M_{pn} = (2118 ± 10) MeV/c^2 may be out of this scheme and agrees better with $M_{I=1}$ = 2124 and $M_{I=0}$ = 2128 MeV/c^2 [3].

Note that our statistically insignificant states (*) have been found in the experiments [11,13,14] and predicted by the models [3,4].

CONCLUSION

(i) The narrow structures with a high statistical significance are observed in deuteron-proton interactions in the two-nucleon effective mass spectrum around M_{NN}= (2010-2020) and (2140-2150) MeV/c^2.

(ii) All the charged configurations of dibaryon state are observed in both mass regions.

(iii) The analogous structures are found by us in ^{4}Hep interactions and confirmed by other experiments.

(iiii) The observed dibaryon states agree with the prediction of the rotational model.

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