Search for dibaryon production in $^4$He interactions at medium energies

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Abstract

The $^4$He interactions at 2.7 GeV/$c$ and 5 GeV/$c$ initial momenta of $\alpha$-particles are investigated using the 2m liquid hydrogen bubble chamber (the kinetic energies of the initial protons in the nuclear rest frame were $T_p = 220$ MeV and 620 MeV). The effective mass spectrum of two nucleons from the reactions $^4$He$\rightarrow$dp$n$ and $^4$He$\rightarrow$p$p$n$n was analysed. The narrow structure in the 2$p$ mass spectrum from the quasi-elastic reaction $p^4$He$\rightarrow$n$F$(pp)d at $T_p = 620$ MeV (where $n_F$ is the fast neutron in the nuclear rest frame) was found which is the evidence of the existence of dibaryon with a mass $M_{2p} = 2008\pm 13$ MeV and a width $\Gamma_{2p} = 20\pm 5$ MeV. The narrow enhancements were also observed at the masses near the 2$p$ threshold $M_{2p} = 1878\div 1879$ MeV in the reactions $p^4$He$\rightarrow$n$F$(pp)d and $p^4$He$\rightarrow$p$F$(pp)(nn).

1. INTRODUCTION

The question whether the dibaryons exist or not is still the most intricate and contradictory in the nuclear physics. Nowadays there are numerous theoretical as well as experimental papers considering this problem (see, e.g. [1] where the review of the present-day experiments on the search of dibaryons is presented). The overwhelming majority of the evidence for the narrow dibaryons (with the width $\sim 50$ MeV) was first obtained in the experiments with the use of bubble chambers. At the same time the results of some other experiments performed in the same technique [2] as well as the electronic-based ones (see [1]) proved quite the opposite, i.e. they showed no evidence for such objects. Note most of the experiments for hunting the dibaryons have been carried out in the course of investigating the lepton and hadron interactions with the lightest nuclei ($d$, $^3$He, $^4$He). Earlier in the frameworks of the ITEP experiment for the study of nuclear reactions in the few
nucleon systems using liquid-hydrogen bubble chambers (LHBC) there was made a systematic search for the dibaryons in \(^3\)Hp- and \(^3\)Hep- interactions at intermediate energies [3, 4, 5, 6]. The mass spectra for NN and NN\(\Delta\) systems with the different isospin number projections were investigated. In the pp, pn, nn, pn\(\pi^+\)(n\(\Delta^{++}\)) and pp\(\pi^+\)(p\(\Delta^{++}\)) mass spectra for the mass region 1.88 \(\div\) 2.5 GeV there was no evidence for dibaryon production. This paper presents the search for dibaryon production in \(^4\)Hep- interactions using the ITEP 2m LHBC. The momentum of the \(^4\)He nuclei is 2.7 GeV/c (the kinetic energy of initial protons in the nuclear rest frame is \(T_p = 220\) MeV) and 5 GeV/c \((T_p = 620\) MeV). Note the evidence for production of the narrow dibaryons in \(^4\)Hep- interactions became apparent for the first time in the experiment with the JINR 1m LHBC exposed to the \(\alpha\)-particles beam at 8.6 GeV/c initial momentum [7]. Evidently the search for dibaryon in \(^4\)Hep- interactions seems to be more attractive than for proton interactions with other lightest nuclei (d, \(^3\)H, \(^3\)He) due to relatively smaller inter-nucleon ranges and respectively greater probabilities for possible multi-quark bags with hidden color for \(^4\)He.

Earlier during the investigations of the effective mass spectra of two protons in hadron-nucleus and NN interactions the narrow enhancements near the \(2m_p\) threshold were found [8, 9, 10]. They were treated in [9, 10] as the result of the two-proton final state interaction (the so-called Migdal-Watson effect). The \(2p\) mass spectrum near the threshold (similar in this region to the relative momentum distributions) may be useful to obtain the \(2p\) correlation functions in order to measure the space-time range of the interaction region for particles emission in the nuclear reactions [11, 12, 13]. In this paper we analyze in detail the effective mass spectra of two protons near the threshold (for \(^4\)Hep- interactions).

2. EXPERIMENTAL TECHNIQUE

The ITEP 2m LHBC was exposed to separated beam of \(\alpha\)-particles at 2.7 GeV/c and 5 GeV/c. The chamber was situated in a magnetic field of 0.92 T. The primary-beam background particles (mainly deuterons) were easily separated from \(^4\)He nuclei by visual estimation of the track ionisation. About 60,000 pictures on the 2.7 GeV/c beam and about 120,000 pictures on 5 GeV/c beam were obtained with an average of about 5-8 initial particles for the chamber extension. About 18,000-19,000 events were measured at each initial momentum. A more detail description of the experimental and data processing procedure used in the present experiment can be found in [14]. Note the experimental technique applied here permits to analyse the data in \(4\pi\)-geometry.

The total \(^4\)Hep- cross section has the standard form [14] and is determined by the account of the number of interactions in the fiducial volume. The total cross section is equal to \(109.4\pm1.8\) mb and \(121.5\pm2.9\) mb at 2.7 and 5 GeV/c respectively (the errors are statistical only). The systematic error in the absolute normalisation of the cross section is \(\sim 3\%\). The results presented here are based on the data of the reactions.
\( ^4\text{He} \rightarrow \text{dppn} \) \hspace{1cm} (1)
\( ^4\text{He} \rightarrow \text{pppnn} \) \hspace{1cm} (2)

For particle identification in the case of three-prong events we used the selection procedure standard for bubble chamber experiments taking into account the secondary track ionization measurements. The events of the reaction (1) with only one neutral particle in the final state make the kinematics balance possible. The events of the reaction (2) with two neutral particles are unbalanced. Note that at 2.7 GeV/c \( (T_p = 220 \text{ MeV}) \) below the pion production threshold in the elementary NN process the pion production in \(^4\text{He}\)-interaction is negligible.

The missing mass squared \( MM^2 \) distribution for unbalanced events of the reaction (1) as well as the one for the events of the non-fitted reaction \( ^4\text{He} \rightarrow \text{dppn}\pi^0 \) at 5 GeV/c initial momentum is shown in Fig.1 (the distributions presented here are based on the part (~ 80%) of the total statistics). The \( MM^2 \) distribution for the reaction (1) has a gauss shape with the average close to the neutron mass squared \( m_n^2 = 0.88 \text{ GeV}^2 \). The overlap of the events for the channels with and without neutral pion production (which is marked by blacked domain in Fig.1) is ~ 1% of the total number of events of the reaction (1). The channel (2) at 5 GeV/c evidently has some admixture of the events of the reaction \( ^4\text{He} \rightarrow \text{pppnn}\pi^0 \) which is ~ 5% to our estimate.

It is reasonable to sort out the events of the reaction (1) into two classes with the secondary nucleons being the fastest in the nuclear rest frame, i.e. the direct channel (where protons are the fastest) and quasi-elastic charge exchange channel (where neutrons are the fastest). The cross sections and the number of events in each channel for two values of the initial momentum are presented in Table 1 (only statistical errors are indicated). Note that in some events (~ 10%) deuterons are the fastest in the nuclear rest frame. Such events with all the three nucleon-spectators are certainly included in one or another class in the analysis of effective mass distributions.

3. RESULTS AND CONCLUSIONS

Fig.2 shows the effective mass distribution of two nucleon-spectators for the direct channel \( p^3\text{He} \rightarrow p_F(pn)d \) (the upper histograms) and quasi-elastic charge exchange channel \( p^4\text{He} \rightarrow n_F(pp)d \) (the lower histograms), where \( p_F \) (\( n_F \)) is the fast proton (neutron) in the \( ^4\text{He} \) rest frame, at \( T_p = 220 \text{ MeV} \) (a) and \( T_p = 620 \text{ MeV} \) (b).

In the two nucleon spectra for direct channel as well as in the spectrum for charge exchange at \( T_p = 220 \text{ MeV} \) there are no peculiarities. The dotted lines in Fig.2a and Fig.2b correspond to the exponential approximation of the data in the intervals \( 1.88 \text{ GeV} \leq m_{NN} \leq 1.97 \text{ GeV} \) and \( 1.88 \text{ GeV} \leq m_{NN} \leq 2.12 \text{ GeV} \) respectively. In the two nucleon spectrum for charge exchange channel there is a narrow structure (the enhancement is observed at the level of 3.1 standard deviations). The solid line
Figure 1: The missing mass squared $M M^2$ distributions for unbalanced events of the reaction $^4$Hep→dppn (thin histogram) and for the ones of the reaction $^4$Hep→dppn$\pi^0$ (thick histogram) at 5 GeV/c initial momentum.
Figure 2: The effective mass distribution of two nucleon-spectators in the $^4$He rest frame for the direct channel $p^4$He$\rightarrow$F$(pn)d$ (the upper histograms) and quasi-elastic charge exchange channel $p^4$He$\rightarrow$nF$(pp)d$ (the lower histograms), where pF (nF) is the fast proton (neutron) in the $^4$He rest frame, at $T_p = 220$ MeV (a) and $T_p = 620$ MeV (b). The dotted lines correspond to the exponential approximation of the data in the intervals $1.88 \text{ GeV} \leq m_{NN} \leq 1.97 \text{ GeV}$ and $1.88 \text{ GeV} \leq m_{NN} \leq 2.12 \text{ GeV}$ respectively. The solid line shows the fit of the data in the interval $1.88 \text{ GeV} \leq m_{NN} \leq 2.12 \text{ GeV}$ by the sum of Breit-Wigner function with the parameters $M_{2p} = 2008 \text{ MeV}$ and $\Gamma_{2p} = 46 \text{ MeV}$ and the exponential function for phase space (the dotted line in (b) in this case corresponds to the exponential approximation of the data out of the interval $1.96 \text{ GeV} \leq m_{NN} \leq 2.06 \text{ GeV}$).
Table 1: Cross sections of the reactions $^4$He$p\rightarrow$dpn and $^4$He$p\rightarrow$pppnn at 2.7 GeV/c ($T_p = 220$ MeV) and 5 GeV/c ($T_p = 620$ MeV) initial momenta.

| Momentum (GeV/c) | Channel            | Number of events | Cross section (mb) |
|------------------|--------------------|------------------|--------------------|
| 2.7              | Direct $^4$He$p\rightarrow$dpn | 2345             | 3494               | $21.4\pm0.4$         |
|                  | Charge-exchange $^4$He$p\rightarrow$dpn | 1149             |                     |                     |
|                  | Direct $^4$He$p\rightarrow$pppnn      | 1620             |                     | $9.9\pm0.2$         |
| 5                | Direct $^4$He$p\rightarrow$dpn        | 1894             | 2567               | $21.2\pm0.4$         |
|                  | Charge-exchange $^4$He$p\rightarrow$dpn | 673              |                     |                     |
|                  | Direct $^4$He$p\rightarrow$pppnn      | 1394             |                     | $11.5\pm0.3$        |

in Fig.2 shows the fit of the data in the interval $1.88$ GeV $\leq m_{NN} \leq 2.12$ GeV by the sum of Breit-Wigner function with the parameters $M_{2p} = 2008 \pm 7$ MeV and $\Gamma_{2p} = 46\pm14$ MeV and the exponential function for phase space ($\chi^2$/NDF $= 7.6/8$). The dotted line in Fig.2b in this case corresponds to the exponential approximation of the data out of the interval $1.96$ GeV $\leq m_{NN} \leq 2.06$ GeV. Note the fit of the data in the interval $1.88$ GeV $\leq m_{NN} \leq 2.12$ GeV by the exponential function only leads to the value $\chi^2$/NDF $= 21/10$ which does not permit to treat such approximation as statistically significant.

The main results of the analysis of the experimental distributions in Fig.2 are as follows.

1. The position and width of the maximum observed in the 2p mass spectrum in the present experiment are near to the ones from [14] ($M_{2p} = 2007 \pm 15$ MeV, $\Gamma_{2p} = 39 \pm 17$ MeV) and from other experiments as well (see [6]).

2. Comparing the mass spectrum for charge-exchange channel at two energies we may conclude that the observed structure is apparently connected to the manifestation of the non-nucleon degrees of freedom in the reaction considered (it is particularly indicated by the nearness of the peak position to the summed masses of the two nucleons and pion) and is not likely to be described on the basis of the theoretical models considering the nucleon interaction mechanisms only (the multiple scattering model, the pole model and so on).

3. If we assume that the observed structure is caused by the dibaryon excitation with isospin I=1 it is no wonder that similar structures do not appear in the direct channel as the background conditions for charge-exchange reaction look more favorable. To determine the mass and width of the dibaryon itself we use the modification of the usual Breit-Wigner function with the account of the experimental resolution
in the following form (see, i.e. \[15\])

$$BW(m_{2p}) = \frac{1}{\sqrt{2\pi}} \int \frac{BW(m)}{\sigma(m)} \exp\left(-\frac{(m_{2p} - m)^2}{2\sigma^2(m)}\right) dm,$$  \(3\)

where \(\sigma(m)\) is the experimental uncertainty in \(m_{2p}\). Thus we obtain the parameters of the assumed dibaryon: the mass \(M_{2p} = 2008 \pm 13\) MeV and the width \(\Gamma_{2p} = 20 \pm 5\) MeV \((\chi^2/NDF = 7.9/8)\) in an excellent agreement with the results of \[13\] \((M_{2p} = 2009 \pm 15\) MeV and \(\Gamma_{2p} = 16 \pm 19\) MeV\). The dibaryon production cross section is \(\approx 0.45 \pm 0.06\) mb.

In view to search similar structures in other \(^4\)He- interaction channels we investigate the NN mass spectra in reaction (2) where the summarised statistics is sufficient for the analysis. Fig.3 shows the effective mass distribution of two nucleon-spectators for the reaction \(p^4\text{He} \rightarrow p_F(pp)(nn)\) where \(p_F\) is the fast proton in the \(^4\)He rest frame at \(T_p = 220\) MeV (a) and \(T_p = 620\) MeV (b). In the mass spectra there are no peculiarities. A small enhancement of the statistics over the exponential background (the dotted lines in Fig.3) at \(M_{NN} \approx 2008\) MeV (marked by the arrow) is not statistically significant.

Earlier while studying the two-proton mass spectra in the reaction \(p+n \rightarrow p+p+\pi^-(\text{backward})\) at 1.98 GeV/c momentum near \(2m_p\)-threshold there was observed a narrow enhancement at \(1877.5 \pm 0.5\) MeV with the width \(2 \pm 0.5\) MeV \([11]\). The effective mass distribution of two proton-spectators near \(2m_p\)-threshold for the reaction \(p^4\text{He} \rightarrow n_F(pp)(nn)\) at \(T_p = 220\) MeV (a), \(T_p = 620\) MeV (b) and the reaction \(p^4\text{He} \rightarrow p_F(pp)\) at \(T_p = 220\) MeV (c), \(T_p = 620\) MeV (d) is shown in Fig.4. In the mass region \(1877 \div 1878\) MeV we may observe narrow (with the width \(3 \div 5\) MeV) maxima. The solid curves in Fig.4 correspond to the approximation of the data as the sum of the function \(F_2\) and Breit-Wigner function, where the function \(F_2\) describes the two-particle phase space volume in the following form (see, e.g. \[16\]):

$$F_2(m_{2p}) = \text{const} \cdot (m_{2p} - 2m_p)^{\alpha} (m_{\text{max}} - m_{2p})^\alpha,$$  \(4\)

where for the reaction \([11]\) \(\alpha = 2, m_{\text{max}} = 2.0233\) and 2.3304 at \(T_p = 220\) MeV and \(T_p = 620\) MeV respectively, for the reaction \([12]\) \(\alpha = 7/2, m_{\text{max}} = 2.0211\) and 2.3282 at \(T_p = 220\) MeV and \(T_p = 620\) MeV respectively (only the phase-space contribution \([12]\) is shown by the dotted curves). The best fit of the data presented in Fig.4 in the form indicated above gives the parameters of the observed peculiarity: \(M_{2p} = 1878.8 \pm 0.4\) MeV and \(\Gamma_{2p} = 4 \pm 1\) MeV \((\chi^2/NDF = 13.2/16)\) (see Fig.4c).

As mentioned above the peculiarities observed in the pp mass spectra near threshold may be of use to determine the space-time range of the interaction region for particles emission in the nuclear reactions. We hope to perform such analysis of the data in the future.

The main results of the paper are as follows.

(i) The narrow structure in the 2p-spectator mass spectrum from the quasi-elastic reaction \(p^4\text{He} \rightarrow n_F(pp)\) at \(T_p = 620\) MeV (where \(n_F\) is the fast neutron in
Figure 3: The effective mass distribution of two nucleon-spectators in the $^4$He rest frame for the $^4$He→$p_F(pp)(nn)$ where $p_F$ is the fast proton in the $^4$He rest frame at $T_p = 220$ MeV(a) and $T_p = 620$ MeV(b). The dotted lines correspond to the exponential fit of the data in the intervals $1.88$ GeV ≤ $m_{NN}$ ≤ $1.97$ GeV and $1.88$ GeV ≤ $m_{NN}$ ≤ $2.12$ GeV respectively.
Figure 4: The effective mass distribution of two proton-spectators near 2\(m_p\)-threshold for the reaction \(p^4\text{He} \rightarrow n_F(pp)d\) at \(T_p = 220\) MeV (a), \(T_p = 620\) MeV (b) and the reaction \(p^4\text{He} \rightarrow p_F(pp)(nn)\) at \(T_p = 220\) MeV (c), \(T_p = 620\) MeV (d). The solid curves correspond to the approximation of the data as the sum of the function which describes the two-particle phase-space volume (see the text) and Breit-Wigner function. The phase-space contribution is shown by the dotted curves.
the nuclear rest frame) was seen which is the evidence of the existence of dibaryon with a mass $M_{2p} = 2008 \pm 13$ MeV and a width $\Gamma_{2p} = 20 \pm 5$ MeV. The enhancement is observed at the level of 3.1 standard deviations. The position and width of the maximum observed in the present experiment are near to the ones from ref. \[15\] and from other experiments as well (see \[1\]).

(ii) In the 2p mass spectra for the reactions $p^4\text{He}\rightarrow n_F(p(p)d$ and $p^4\text{He}\rightarrow p_F(p(p)(n)n$ we saw the narrow enhancements at the masses near the 2p threshold $M_{2p} \approx 1878 \div 1879$ MeV which may be useful to get information about the interaction region of the particles emission in the $^4\text{He}$-interaction.

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