Search for tribaryon production in alpha-particles interactions with protons at intermediate energies

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Abstract

The analysis of the data on the reactions $^4$He$^+$p + pppn and $^4$He$^+$n + dppn obtained at the 2-m ITEP liquid-hydrogen bubble chamber exposed to beams of $^4$He nuclei with momenta of 2.7 and 5 GeV/c revealed a narrow structures in the effective-mass spectra of the trinucleon system (NNN) at 2.99 GeV (for isospin $T = 3/2$) as well as at 3.04 GeV ($T = 1/2$). The masses of the observed structures are consistent with the masses of low-lying tribaryon resonances predicted by some theoretical models. Possible resonance nature of the structures observed is discussed.

The recent discovery in KEK of the narrow strange ($S = -1$) tribaryons $S^0(3115)$ and $S^+(3140)$ [1] i.e. 9q-resonances as predicted by the quark bag models [2, 3] has given a new impetus to a further search for other similar candidates, $^3B$ resonances with $S = 0$ in particular. Previous indications on possible manifestations of the non-strange tribaryons have been found in some experiments [4, 5] but in some others these states have not been observed [6, 7, 8, 9, 10]. The recent quark bag model calculations [3] predict the low-lying $^3B(S = 0)$ states with the masses as follows: $M_{^3B}=3.1$ GeV (for isospin $T = 3/2$) and 3.04 GeV ($T = 1/2$).

As it was first mentioned in ref.[11] (see also refs.[9, 10]), the tribaryons predicted by the simplest generalization of McGregor’s rotation model for $^2B$ resonances [12] as the rotational excitations of the NNN system can have the following minimum masses (in GeV): 2.96(L=0), 2.99(L=1), 3.04(L=2), 3.12(L=3),... (L− is the orbital angular momentum quantum number of the system). Thus, this simple model also predicts the existence of the low-lying tribaryons with masses below the NN$\Delta$(1232) threshold which is $\sim 3.11$ GeV. In this paper we present the results of the very first attempt to track down such low-lying states by analyzing the mass spectra of 3p and ppp systems produced in alpha-particles interactions with protons at intermediate energies.

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The results presented are based on the data of the reactions

\[ ^4\text{He}p \rightarrow \text{pppnn} \]  

and

\[ ^4\text{He}p \rightarrow \text{dppn} \]  

The isospin of the 3p system from the reaction (1) is evidently \( T = 3/2 \). The reaction (2) is a unique one because, as we may see, the ppn system in this case is in the \( T = 1/2 \) state only. Thus, we have a lucky opportunity to investigate the trinucleon system in two different pure isotopic states.

The data were obtained at the ITEP 2m liquid-hydrogen bubble chamber (LHBC) exposed to separated beam of \( \alpha \)-particles at 2.7 GeV/c and 5 GeV/c (the kinetic energies of primary protons in the rest system of the nucleus are \( T_p = 220 \text{ MeV} \) and 620 MeV respectively). The chamber was placed in a magnetic field of 0.92 T. The primary-beam background particles (mainly deuterons) were easily separated from \( ^4\text{He} \) nuclei by visual estimation of the track ionization. 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 [13, 14]. Note that the experimental technique applied permits to analyze the data on reactions (1) and (2) in \( 4\pi \)-geometry.

The total \( ^4\text{He}p \)- cross section has the standard form [13] and is determined by the account of the number of interactions in the fiducial volume. The total cross section is equal to \( 109.4 \pm 1.8 \) and \( 121.5 \pm 2.9 \) mb at 2.7 and 5 GeV/c respectively (the errors are statistical only). The systematic error in the absolute normalization of the cross section is \( \sim 3\% \).

For particle identification in the case of three-prong events we used the selection procedure which is standard for bubble chamber experiments and which takes into account the secondary track ionization measurements. The events of the reaction (2) with only one neutral particle in the final state make the kinematics balance possible. They are easily separated at 5 GeV/c from the events of the channel \( ^4\text{He}p \rightarrow \text{dppn} \pi^0 \) (see [14]). The events of the reaction (1) with two neutral particles are unbalanced. Note that the pion production in \( ^4\text{He}p \)- interaction is negligible at 2.7 GeV/c \( (T_p = 220 \text{ MeV}) \) below the pion production threshold in the elementary NN process. The channel (1) at 5 GeV/c has some evident admixture of the events of the reaction \( ^4\text{He}p \rightarrow \text{pppnn} \pi^0 \) which we estimate as \( \sim 5\% \).

The cross sections and the number of events in each channel (1) and (2) for two values of the initial momentum are presented in Table 1 (only statistical errors are indicated).

Note that the use of the \( ^4\text{He} \) nucleus in the present experiment (as well as in the KEK experiment) looks extremely important since the wave functions of the separate nucleons in this nucleus (the most compact one) are strongly overlapped and possible multi-quark effects (valid for small ranges) are most possible.

Fig.1 provides some examples of the diagrams describing the reactions: \( ^4\text{He}p \rightarrow \text{pppnn} \) (quasi-elastic scattering (a), quasi-elastic charge exchange reaction (b), possible production of tribaryon decaying into 3p (c)) and \( ^4\text{He}p \rightarrow \text{dppn} \) (direct and charge exchange
channel (d), neutron pick-up (e), possible production of tribaryon decaying into ppn (f). Here $p_i$ is the incident proton, $p_F, n_F$, and $d_F$ are the fast (in the nuclear rest frame) secondary proton, neutron, and deuteron respectively.

Fig. 2 shows the effective mass distribution of 3p system $M_{3p}$ for the reaction (1) at 2.7 GeV/c (a-c) and 5 GeV/c (d-f). In the distribution at 2.7 GeV/c without any selections (Fig.2a) there are no statistically confident peaks while at 5 GeV/c there is a narrow structure at $M_{3p} \approx 2.99$ GeV with the statistical significance of $\sim 3.5$ standard deviations from the background (58 events in peak maximum). The significance is defined as the signal enhancement over the background divided by its statistical error taking into account the uncertainty of the background. Evidently, it is a strong function of the assumed background shape. To suppress the background contribution of the diagram 1a in reaction (1) we used the only one selection on the basis of the two-neutron effective mass $M_{2n} > 1.93$ GeV (for 2.7 GeV/c, see Fig.2b) and $M_{2n} > 2.025$ GeV (for 5 GeV/c, Fig.2e). Then the contribution of the diagram 1b is apparently enhanced.

For comparison, Fig.2c,f presents the distributions with selections $M_{2n} < 1.93$ GeV (for 2.7 GeV/c) and $M_{2n} < 2.025$ GeV (for 5 GeV/c). The arrows in Fig.2 show the positions of the tribaryon masses predicted by the model [11]. But again there are no peculiarities in the distribution at 2.7 GeV/c. As seen in Fig.2b the shape of the $M_{3p}$ distribution for proton-spectators (in the nucleus rest frame) is well reproduced by the background distribution received through a random mix of the events (dotted histogram).

At 5 GeV/c the structure observed in the total spectrum at $M_{3p} \approx 2.99$ GeV doesn’t change its position with large 2n mass selection (Fig.2e) and is not reproduced by the background distribution (dotted histogram). Instead of the selection $M_{2n} > M_{max}$ it is possible to use the selections $M_{2n} > M_{ppk}$ and $P_{2n} > P_{ppk}$ to suppress the background contribution of the diagram 1a (here $M_{ppk}, P_{ppk}$ are the effective mass and the total momenta (absolute value in the nucleus rest frame) of the proton pair $p_i p_k$ (i,k =1,2,3) respectively). The number of events selected using the restrictions mentioned above is practically the same: 394 (for $M_{max} = 2.025$ GeV), 403 (for fast $M_{2n}$ selection), and 404 (for fast $P_{2n}$ selection). The structure at $M_{3p} \approx 2.99$ GeV appears under these selections as well.

The position of the maximum revealed in the present experiment is in close agreement with the model predictions [11] for the P-wave ($L = 1$) tribaryon (it is evident that the S-wave 3p state at rest is forbidden by the Pauli exclusion principle). But to make sure of the resonance nature for this structure (see diagram 1c), however, it would be important to have a higher statistics and also to understand better the contribution of the mechanisms with the production of pions in the intermediate state followed by their capture by the correlated NN pair (note that the position of the structure is around the mass of $NN\pi$). And yet, the partial wave analysis of the angular distributions is needed to determine the quantum numbers of the assumed tribaryon.

The data fit in the interval $2.86$ GeV $\leq M_{3p} \leq 3.09$ GeV by the sum of Breit-Wigner function and the polynomial background gives the following parameters (mass and width) of the given structure: $M_X = 2.99 \pm 0.01$ GeV and $\Gamma_X = 0.024 \pm 0.017$ GeV ($\chi^2/\text{NDF} = 0.14$). The solid line in Fig.2d shows the result of the fit (the background is marked by the dash-dotted line). The production cross section of the possible coupled state is $\approx 0.43 \pm 0.22$ mb (only statistical error is indicated). The solid line in Fig.2e shows the
fit of the data in the interval $2.89 \text{ GeV} \leq M_{3p} \leq 3.1 \text{ GeV}$ by the sum of Breit-Wigner function with the parameters $M_X = 2.99 \pm 0.01 \text{ GeV}, \Gamma_X = 0.04 \pm 0.02 \text{ GeV}$ and the exponential approximation (dashed curve) for phase space ($\chi^2$/NDF = 0.43). These fit parameters are in agreement with the ones for the total spectrum within the statistical uncertainties. A random mix of events is shown in Fig.2e by the dotted histogram. In the mass region of interest this background is close to the exponential one (see Fig.2e).

To determine the own (natural) mass and width of the assumed tribaryon we use the modification of the usual Breit-Wigner function with due regard to experimental resolution (see, i.e. [14]). The mean absolute resolution for $M_{3p}$ at 5 GeV/c is $\sigma [M_{3p}] \leq 19 \text{MeV}$ in the region of interest. It is compared to the fitted value of $\Gamma_X$. The fit of the data with the account of the experimental resolution gives almost the same estimation for the width of the assumed tribaryon in the case of total $M_{3p}$ distribution as well as for the spectrum under restriction: $\Gamma_{3p} \leq 66 \text{ MeV} (95\% \text{ C.L.})$. Note that the maximum position doesn’t depend on the uncertainties of the background and its approximation.

Fig.3 shows the effective mass distribution of ppn system $M_{ppn}$ for the reaction (2) at 2.7 GeV/c (a-c) and 5 GeV/c (d-f). The arrows in Fig.3 show the positions of the tribaryon masses predicted by the model [11]. In the distributions without any selections for both initial momenta there are no statistically confident peaks (see Fig.3a,d).

To suppress the background contribution of the diagram 1d in the reaction (2) we used the selections on the deuteron momentum in the $^4\text{He}$ rest frame $P_d > 0.6 \text{ GeV}$ (for 2.7 GeV/c, Fig.3b) and $P_d > 1.1 \text{ GeV}$ (for 5 GeV/c, Fig.3e). Then the contribution of the diagram 1e will be apparently enhanced. For comparison, the distribution with selections $P_d < 0.6 \text{ GeV}$ (for 2.7 GeV/c) and $P_d < 1.1 \text{ GeV}$ (for 5 GeV/c) are presented in Fig.3c and Fig.3f respectively. There are no peculiarities in spectra at 2.7 GeV/c. At 5 GeV/c there is a narrow structure at $M_{ppn} \approx 3.04 \text{ GeV}$ with the statistical significance of $\sim 3.5$ standard deviations from the background (20 events in the peak maximum) which may be the indication of the possible $^3\text{B}$ resonance production in the ppn system (diagram 1f). The cut value choice doesn’t affect the distribution shape at 2.7 GeV/c. At 5 GeV/c, the cut value has been chosen to maximize the effect while having enough statistics.

The fit of the data in the interval $2.9 \text{ GeV} \leq M_{ppn} \leq 3.09 \text{ GeV}$ by the sum of Breit-Wigner function and the exponential background gives the mass and the width of the observed structure $M_Y = 3.039 \pm 0.005 \text{ GeV}$ and $\Gamma_Y = 0.035 \pm 0.008 \text{ GeV}$ ($\chi^2$/NDF = 0.18). The solid line in Fig.3e shows the result of the fit (the background is marked by the dash-dotted line). Note, the fit of the data in the same interval by the exponential function only leads to the value $\chi^2$/NDF = 2.1, which does not permit to treat this approximation as statistically significant. The position of the maximum is in close agreement with the simple model predictions [11] for the D-wave ($L = 2$) tribaryon as well as with the quark bag model calculations [3] for $T = 1/2$ tribaryon. The production cross section of the possible coupled state is $\approx 0.25 \pm 0.08 \text{ mb}$ (only statistical error is indicated). The mean absolute resolution for $M_{ppn}$ at 5 GeV/c in the region of interest is $\sigma [M_{ppn}] \leq 31 \text{ MeV}$ which gives the estimated width of the assumed tribaryon: $\Gamma_{3p^-} \leq 60 \text{ MeV} (95\% \text{ C.L.})$.

The main results of the paper are as follows.

The narrow structures were seen in the trinucleon mass spectra in the reactions $^4\text{He} \rightarrow \text{pppn}$ and $^4\text{He} \rightarrow \text{dpn}$. The positions of the observed structures are in a very good agreement with the simple rotation model predictions for low-lying non-strange tribaryons
where they are interpreted as the rotation excitations of the NNNπ system. Furthermore, the position of the structure for $T = 1/2$ is also consistent with 9q quark bag model calculations. But to make sure of the resonance nature for these structures it is necessary to understand better the contribution of the mechanisms with the production of pions and deltas in the intermediate state.

It looks rewarding in the future to investigate the trinucleon mass spectra in the reactions (1) and (2) in the same mass region but at greater initial energies and with a higher statistics. It might appear promising as well to study the possible decay mode into the NNNπ in the mass region of (3Nπ, NNΔ).

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Figure 1: Some of possible diagrams describing the reactions: $^4\text{He} \rightarrow \text{pppnn}$ (quasi-elastic scattering (a), quasi-elastic charge exchange reaction (b), possible production of tribaryon decaying into $3p$ (c)) and $^4\text{He} \rightarrow \text{dppn}$ (direct and charge exchange channel (d), neutron pick-up (e), possible production of tribaryon decaying into $\text{ppn}$ (f)).
Figure 2: The effective mass distribution of 3p system $M_{3p}$ for the reaction $^4$He$p \rightarrow$ pp$n n$ at $^4$He momentum of 2.7 GeV/c (all events - (a), the events selected by two-neutron effective mass: $M_{2n} > 1.93$ GeV - (b), $M_{2n} < 1.93$ GeV - (c)) and 5 GeV/c (all events - (d), the events selected by two-neutron effective mass: $M_{2n} > 2.025$ GeV - (e), $M_{2n} < 2.025$ GeV- (f)). Solid curves represent the fit for experimental data as a sum of the background (dash-dotted curve in figure (d) and dashed – on figure (e)) and Breit-Wigner function (see text). Dotted histograms correspond to the experimental background distribution received through a random mix of the events.
Figure 3: The effective mass distribution of ppn system $M_{ppn}$ for the reaction $^4$He$p \rightarrow dppn$ at $^4$He momentum of 2.7 GeV/c (all events - (a), the events selected by deuteron momentum in the nucleus rest frame: $P_d > 0.6$ GeV/c - (b), $P_d < 0.6$ GeV/c - (c)) and 5 GeV/c (all events - (d), the events selected by deuteron momentum in the nucleus rest frame: $P_d > 1.1$ GeV/c - (e), $P_d < 1.1$ GeV/c - (f)). Solid curve represents the fit for experimental data as a sum of the background (dashed curve) and Breit-Wigner function (see text). Dotted histograms correspond to the experimental background distribution received through a random mix of the events.
Table 1: Cross sections of the reactions (1) and (2) 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             | $^4$HeP→dppn  | 3474             | 21.4±0.4          |
|                 | $^3$HeP→pppnn | 1620             | 9.9±0.2           |
| 5               | $^4$HeP→dppn  | 2567             | 21.2±0.4          |
|                 | $^3$HeP→pppnn | 1394             | 11.5±0.3          |