SUPERNARROW DIBARYONS PRODUCTION IN $pd$ INTERACTIONS

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Abstract

An analysis of new experimental data, obtained at the Proton Linear Accelerator of INR, is carried out with the aim of searching for supernarrow dibaryons in the $pd \to p + pX_1$ and $pd \to p + dX_2$ reactions. Dibaryons with masses $1904 \pm 2$, $1926 \pm 2$, and $1942 \pm 2$ MeV have been observed in invariant mass $M_{pX_1}$ spectra. In missing mass $M_{X_1}$ spectra, the peaks at $M_{X_1} = 966 \pm 2$, $986 \pm 2$, and $1003 \pm 2$ MeV have been found. The analysis of the data obtained leads to the conclusion that the observed dibaryons are supernarrow dibaryons, the decay of which into two nucleons is forbidden by the Pauli exclusion principle. A possible interpretation of “excited nucleon states” with small masses is suggested.

Key-words: proton, deuteron, dibaryon, interaction

The experimental search for dibaryons is continuing over 20 years (see for review [1, 2]). Usually one looks for NN coupled dibaryons. Such dibaryons have decay widths from a few up to hundred MeV. Their relative contributions are small enough but the background contribution is big and uncertain as a rule. All this leads often to contradictory results.

We consider a new class of dibaryons - supernarrow dibaryons (SNDs), the decay of which into two nucleons is forbidden by the Pauli exclusion principle [3, 4, 5]. Such dibaryons with the mass $M < 2m_N + m_\pi$ ($m_N(m_\pi)$ is the nucleon (pion) mass) can decay into two nucleons, mainly emitting a photon. Decay widths of these dibaryons are $\leq 1$ keV [5].

In Ref. [6, 7, 8, 9], we studied the reaction $pd \to pX$ with the aim of searching for supernarrow dibaryons. The experiment was carried out at the proton beam of the Linear Accelerator of INR using the two-arm spectrometer TAMS. As was shown in Ref. [8, 9], the nucleons and the deuteron from the decay of SND into $\gamma NN$ and $\gamma d$ have to be emitted in a narrow angle cone with respect to the direction of motion of the dibaryon. On the other hand, if a dibaryon decays mainly into two nucleons, then the expected angular cone of emitted nucleons must be more than $50^\circ$. Therefore, a detection of the scattered proton in coincidence with the proton (or the deuteron) from the decay of particle $X$ at correlated angles allowed to suppress essentially the contribution of the background processes and to increase the relative contribution of a possible SND production. As a result, two narrow peaks in missing mass spectra have been observed at $M = 1905$ and $1924$ MeV with widths equal to the experimental resolution (3 MeV). The analysis of the angular distributions of the charged particles ($p$ or $d$) from the decay of particle $X$ showed that the peak found at 1905 MeV most likely corresponds to a SND with isotopic spin equal to 1. In Ref. [9] arguments were presented for the resonance at $M = 1924$ MeV is a SND, too.
In order to argue more convincingly that the states found are really SNDs, an additional experimental investigation was carried out.

In the present paper we give the results of an analysis of new experimental data respecting study of the \(pd \to p + pX_1\) and \(p \to p + dX_2\) processes at the Linear Accelerator of INR with 305 MeV proton beam using the spectrometer TAMS. The properties of this spectrometer are described elsewhere [9]. CD\(_2\) and \(^{12}\)C were used as targets.

In this experiment, the scattered proton was detected in the left arm of the spectrometer TAMS at the angle \(\theta_L = 70^\circ\). The second charged particle (either \(p\) or \(d\)) was detected in the right arm by three telescopes located at \(\theta_R = 34^\circ, 36^\circ,\) and \(38^\circ\). These angles were shifted by 1° in comparison with the conditions of our previous experiment, that allowed to get an additional information about an angular distribution of the charged particles from the decay of the dibaryons in question.

The angle \(\theta_R = 38^\circ\) corresponds to the elastic \(pd\) scattering. A measurement of this effect was used to calibrate the spectrometer.

At first, let us consider the reaction \(pd \to p + pX_1\).

Figs. 1(a)-1(c) demonstrate the experimental invariant mass \(M_{pX_1}\) spectra obtained with the CD\(_2\) (the points with the statistical errors) and \(^{12}\)C (the bars) targets, where (a), (b), and (c) correspond to a detection of the second proton in the right arm detector at \(\theta_R = 34^\circ, 36^\circ,\) and \(38^\circ\), respectively. Three peaks at \(M_{pX_1} = 1904 \pm 2, 1926 \pm 2,\) and \(1942 \pm 2\) MeV are observed in these spectra. The first two of them confirmed the values of the dibaryon mass obtained by us earlier [6, 7, 8, 9] and the resonance at 1942 MeV is a new one.

The experimental invariant mass spectra obtained with the carbon target are rather smooth. This smoothness is caused by both an essential increase of the contribution of background reactions in the interaction of the proton with the carbon and Fermi motion of nucleons in the nucleus. The latter increases essentially the angular cone size of emitted nucleons. In consequence, it is not possible to see peaks of SNDs in the present experiment on the carbon target.

As the experiment with the carbon target resulted in the rather smooth spectra, all structures, appearing in the experiment with the CD\(_2\) target, may be explained by an interaction of the proton with the deuteron.

The calculation for the isovector SND \(D(T = 1, J^P = 1^\pm)\) with the mass \(M = 1904\) MeV showed that the contributions of such a dibaryon to spectra at the angles 34°, 36°, and 38° must relate as \(1 : 0.92 : 0.42\). For the isoscalar SND \(D(0, 0^\pm)\) we obtained \(1 : 0.95 : 0.67\).

The biggest contribution of the SND with \(M = 1926\) MeV is expected at \(\theta_R = 30^\circ − 34^\circ\). The angles 30° – 33° were not investigated in this work. The calculation of the ratio of the contributions to the invariant mass spectra at the angles 34°, 36°, and 38° gave \(1 : 0.85 : 0.34\) for \(T = 1\) and \(1 : 0.71 : 0.46\) for \(T = 0\).

Nucleons from the decay of the SND with \(M = 1942\) MeV must have a wider angular distribution with maximum in the region of 26° – 32°. In the region of the angles under consideration in this work, the contributions of \(D(1, 1^\pm)\) are expected to be in the ratio of \(1 : 0.6 : 0.2\). For the SND \(D(0, 0^\pm)\) we have \(1 : 0.78 : 0.55\).

All these predictions for the SNDs are in agreement with our experimental data within the errors. However, the analysis of the reaction \(pd \to p + pX_1\) only in the considered angle range does not allow to determine an isotopic spin of the SNDs.

If the observed states are \(NN\)-coupled dibaryons decaying mainly into two nucleons then the expected angular cone size of emitted nucleons must be more than 50°. Therefore,
Figure 1: The invariant mass $M_{pX_1}$ spectra obtained with CD$_2$ (the points with the statistical errors) and $^{12}$C (the bars) targets; (a) – $\theta_R = 34^\circ$, (b) – $\theta_R = 36^\circ$, (c) – $\theta_R = 38^\circ$. 
their contributions to the invariant mass spectra in Fig. 1(a)-1(b), would be nearly the same and would not exceed a few events, even assuming that the dibaryon production cross section is equal to that of elastic pd scattering ($\sim 40\mu b/sr$). Hence, the peaks found most likely correspond to SNDs.

The invariant mass spectrum $M_{dX_2}$ of the reaction $pd \rightarrow p + dX_2$, for the sum of angles $\theta_R = 34^\circ$ and $36^\circ$, is shown in Fig. 2. As seen from this figure, the reaction $pd \rightarrow p + dX_2$ gives very small contribution into the production of the dibaryons under study.

On the other hand, it is expected [8, 9] that isoscalar SNDs contribute mainly into $\gamma d$ channel and isovector SNDs do into $\gamma NN$ one. As the main contribution of the found dibaryons is observed in $pX_1$ channel, it is possible to expect that $X_1 = \gamma + n$, and this is an indication that all the found states are isovector SNDs. The more precise conclusion about the value of the isotopic spin of the observed SNDs could be obtained by the study of the reaction $pd \rightarrow n + X$.

The summary spectrum of the reaction $pd \rightarrow p + pX_1$ over angles $\theta_R = 34^\circ$ and $36^\circ$, where the contribution of the SNDs is maximum, is presented in Fig. 3(a). This spectrum was interpolated by a second order polynomial (for the background) plus Gaussians (for the peaks). The number of standard deviations (SD) is determined as

$$
\frac{N_{eff}}{\sqrt{N_{eff} + N_{back}}}
$$

where $N_{eff}$ is the number of events above the background curve and $N_{back}$ is the number of events below this curve. Taking nine points for each peak, we have 6.0, 7.0, and 6.3 SD for the resonances at 1904, 1926, and 1942 MeV, respectively. The widths of these resonances are equal to the experimental resolution of $\sim 4$ MeV.
Figure 3: The invariant mass $M_{pX_1}$ (a) and the missing mass $M_{X_1}$ (b) spectra for the sum of angles of $\theta_R = 34^\circ$ and $\theta_R = 36^\circ$. 
An additional information about the nature of the observed states was obtained by studying the missing mass $M_{X_1}$ spectra of the reaction $pd \to p + pX_1$. If the state found is a dibaryon decaying mainly into two nucleons then $X_1$ is a neutron and the mass $M_{X_1}$ is equal to the neutron mass $m_n$. If the value of $M_{X_1}$, obtained from the experiment, differs essentially from $m_n$ then $X_1 = \gamma + n$ and we have the additional indication that the observed dibaryon is SND.

The simulation of missing mass spectra for the reaction $pd \to p + pX_1$, where $pX_1$ are decay products of the SNDs with the masses 1904, 1926, and 1942 MeV, gave peaks at $M_{X_1} = 965$, 987, and 1003 MeV, respectively. Fig. 3(b) demonstrates the missing mass $M_{X_1}$ spectrum obtained from the experiment for the sum of the angles $\theta_R = 34^\circ$ and $36^\circ$. As is seen from this figure, besides the peak at neutron mass, which caused by the process $pd \to p + pn$, a resonancelike behavior of the spectrum is observed at $966 \pm 2$, $986 \pm 2$, and $1003 \pm 2$ MeV. These values of $M_{X_1}$ coincide with the ones obtained from the simulation and differ essentially from the value of the neutron mass (939.6 MeV). Hence, for all states under study, $X_1 = \gamma + n$ and the dibaryons found with the masses 1904, 1926, and 1942 MeV are really SNDs.

It should be noted that the peak at $M_{X_1} = 1003 \pm 2$ MeV corresponds to the resonance found in [10] and attributed to an excited nucleon state $N^*$. In this work, the authors brought out three such states with masses 1004, 1044, and 1094 MeV. In principle, SND could decay into $NN^*$. A possibility of the production of $NN^*$-coupled dibaryons was considered in [6].

If these excited nucleon states decay into $\gamma N$ then they would contribute to the Compton scattering on the nucleon. However, the analysis [11] of the experimental data on this process completely excludes $N^*$ as intermediate state in the Compton scattering on the nucleon.

In Ref. [12] it was assumed that these states belong to totally antisymmetric 20-plet of the spin-flavor $SU(6)_{FS}$ group. Such a $N^*$ can transit into nucleon only if two quarks from the $N^*$ participate in the interaction [13]. Then the simplest decay of $N^*$ with the masses 1004 and 1044 MeV would be $N^* \to \gamma\gamma N$. This assumption could be checked, in particular, by studying the reactions $\gamma p \to \gamma X$ or $\gamma p \to \pi X$ at the photon energy close to 800 MeV.

Taking into account the found connection between the SNDs and the resonancelike states $X_1$, it is possible to assume that the peaks, observed in [10] at 1004 and 1044 MeV, are not excited nucleons, but they are the resonancelike states $X_1 = \gamma + n$ caused by possible existence and decay of the SNDs with the masses 1942 and 1982 MeV, respectively. Such $X_1$ are not real resonances and cannot give contribution to the Compton scattering on the nucleon.

The following conclusion can be made. As a result of the study of the reaction $pd \to p + pX_1$ three narrow peaks at 1904, 1926, and 1942 MeV have been observed in the invariant mass $M_{pX_1}$ spectra. The analysis of the angular distributions of the protons from decay of $pX_1$ states and the data on the reaction $pd \to p + dX_2$ showed that the peaks found can be explained as a manifestation of the isovector SNDs, the decay of which into two nucleons is forbidden by the Pauli exclusion principle. The observation of the peaks in the missing mass $M_{X_1}$ spectra at 966, 985, and 1003 MeV is an additional confirmation that the dibaryons found are the SNDs.

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