New evidence for supernarrow dibaryons production in pd interactions

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Abstract. The analysis of new experimental data, obtained at the Proton Linear Accelerator of INR, with the aim to search for supernarrow dibaryons in the $pd \to ppX_1$ and $pd \to pdX_2$ reactions is presented. Narrow peaks with an experimental width of 5 MeV at masses of 1904 ± 2, 1926 ± 2, and 1942 ± 2 MeV have been observed in missing mass M_{pX_1} spectra. In the missing mass M_{X_1} spectra, the peaks at $M_{X_1} = 966 \pm 2$, 986 ± 2, and 1003 ± 2 MeV have been found. The analysis of the data obtained leads to the conclusion that the observed peaks in M_{pX_1} spectra are most likely supernarrow dibaryons, the decay of which into two nucleons is forbidden by the Pauli exclusion principle. An alternative interpretation of the spectra by assuming a decay of the supernarrow dibaryons in "exotic baryon states" with masses M_{X_1} is discussed.

PACS. 13.75.Cs Nucleon-nucleon interactions (including antinucleons, deuterons, etc.) – 14.20.Pt Dibaryons – 12.39.Mk Glueball and nonstandard multi-quark/gluon states

1 Introduction

The experimental search for dibaryons continues since over 20 years (for recent reviews see [1,2]). The dibaryons considered couple usually to two nucleons and reflect their symmetry. Therefore, such dibaryons have estimated decay widths from several MeV up to a few hundreds MeV. However, their production cross-sections in reactions involving nucleons and pions are small and the spectra are dominated by a large background. This has lead to contradictory results and the dibaryons decaying directly into two nucleons are not unequivocally established.

We consider a new class of dibaryons —supernarrow dibaryons (SNDs), the decay of which into two nucleons is forbidden by the Pauli exclusion principle [3–6]. Such dibaryons with masses $M < 2m_N + m_\pi$, where $m_N(m_\pi)$ is the nucleon (pion) mass, can decay into two nucleons, by emitting a third particle, normally a photon. The decay widths of these dibaryons are predicted to be ≤ 1 keV [5].

In the framework of the MIT bag model, Mulders *et al.* [3] calculated the masses of different dibaryons, in particular, NN-decoupled dibaryons. These dibaryons $D(T = 0; J^P = 0^-, 1^-, 2^-; M = 2.11 \text{ GeV})$ and $D(1; 1^-; 2.2 \text{ GeV})$ correspond to the states $^{13}P_J$ and $^{31}P_1$ forbidden in the NN channel. However, the masses of

these dibaryons exceed the pion production threshold. Therefore, these dibaryons can decay into the πNN channel and their decay widths are larger than 1 MeV.

Using the chiral soliton model, Kopeliovich [7] predicted that the masses of $D(T = 1, J^P = 1^+)$ and $D(0, 2^+)$ NN-decoupled dibaryons exceeded the two-nucleon mass by 60 and 90 MeV, respectively. These values are lower than the pion production threshold.

In the framework of the canonically quantized biskyrmion model, Krupovnickas *et al.* [8] obtained an indication of the existence of one dibaryon with $J = T = 0$ and two dibaryons with $J = T = 1$ with masses smaller than $2m_N + m_\pi$.

All these results are model calculations of very limited predictive power and provide just a motivation to look for SNDs. In the following, we summarize the experimental attempts to look for such dibaryons so far.

In ref. [9] dibaryons with exotic quantum numbers were searched for in the process $pp \to pp\gamma\gamma$. The experiment was performed with a proton beam from the JINR phasotron at an energy of about 216 MeV. The energy spectrum of the photons emitted at 90° was measured and showed two peaks. This behavior of the photon energy spectrum was interpreted as a signature of an exotic dibaryon resonance with a mass of about 1956 MeV and possible isospin $T = 2$. However, the results of ref. [10] make the possibility of a production of dibaryons with $T = 2$ in this reaction questionable. So, additional care-

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ful studies of the reaction $pp \to pp\gamma\gamma$ are needed to more correctly understand the nature of the observed state.

An analysis of the Uppsala proton-proton bremsstrahlung data [11] looking for the presence of a dibaryon in the mass range from 1900 to 1960 MeV gave only upper limits of 10 and 3 nb for the dibaryon production cross-section at proton beam energies of 200 and 310 MeV, respectively. This result agrees with the expected values of the cross section obtained at the conditions of this experiment in the framework of the model of dibaryon production and decay suggested in ref. [15] and does not contradict the data of ref. [9].

In our previous studies [12–15] we investigated the reaction $pd \to pX$ in order to search for SNDs. In this process SNDs can be produced only if the nucleons in the deuteron overlap sufficiently, such that a six-quark state with deuteron quantum numbers can be formed. Then, an interaction of a meson or another particle with this state can change its quantum numbers so that a metastable state is formed. 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 refs. [14, 15], the nucleons and the deuteron from the decay of SND into γNN and γd have to be emitted into a narrow angular cone with respect to the direction of the dibaryon. If a dibaryon decays mainly into two nucleons, then the expected angular cone of the emitted nucleons is about 50°. 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 effectively 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) and with 4.8 and 4.9 standard deviations (SDs), respectively. 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 the isotopic spin equal to 1. In ref. [15] arguments were presented that the resonance at $M = 1924$ MeV could be SND, too.

2 Experiment

In this paper we present a new study of the $pd \to pX$ reaction at the Linear Accelerator of INR with 305 MeV proton beam using the spectrometer TAMS where the proton and deuteron from the decays $X \to pX_1$ and $X \to dX_2$ are measured in coincidence with the scattered proton.

In the experiment, CD_2 and ^{12}C were used as targets. The scattered proton was detected in the left arm of the spectrometer TAMS at the angle $\theta_L = 70°$. The second charged particle (either p or d) was detected in the right arm by three telescopes located at $\theta_R = 34°$, $36°$, and $38°$.

A trigger was generated by four-fold coincidences of the two ΔE detector signals of the left arm combined with those of any telescope of the right arm. The events
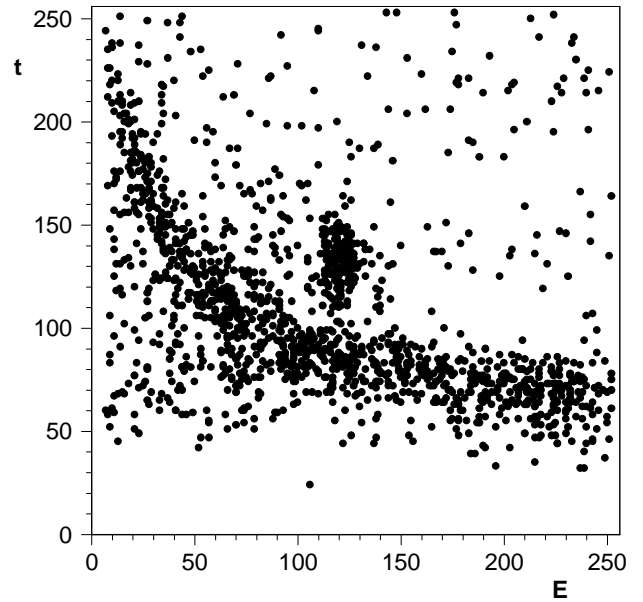

Fig. 1. Energy E against time-of-flight t scatter plots for the right-arm detector at $\theta_R = 38°$.

contained information about time of flights and full energies of two particles detected in coincidence in the left and right arms of the spectrometer. The energy resolution was 4 MeV (7 MeV) for the left (right) arm. A time-of-flight resolution better than 0.5 ns was achieved. Each valid event including two time of flights and two energies were stored event-by-event and then analyzed off-line.

An off-line identification of different particles was performed by means of their energies E and time of flights t. In this way, protons and other charged particles were identified via characteristic loci observed in two-dimensional diagrams of time of flight *versus* energy. As an example, such an experimental $E - t$ distribution for the right-arm detector at $\theta_R = 38°$ is displayed in fig. 1. This figure shows the band of proton events, presenting the dependence of the proton time of flight on its energy, and a spot corresponding to the deuteron from the elastic pd scattering.

Several software cuts have been applied to the mass spectra. The energy of the scattered proton was limited by an interval of $50 < E_2 < 150$ MeV, that corresponded to the interval of measured dibaryon masses $1980 > M_{pX_1} (M_{dX_2}) > 1860$ MeV/c^2. In order to suppress the background from the reaction p $^{12}C \to dY$, where Y stands for the unobserved particles, in M_{dX_2} spectra, we omitted events with a deuteron energy higher than the energy of the elastically scattered deuteron in the $pd \to pd$ reaction at the given angles. For the M_{pX_1} spectra the energy interval for the proton from the SND decay was determined by the kinematics of the decay of X into the γNN channel. This interval was equal to $50 < E_p < 100$ MeV. Such a cut allows to suppress essentially the contribution from the reaction $pd \to ppn$. The main contribution to this reaction at the energy under consideration is given by one-nucleon pole diagrams when
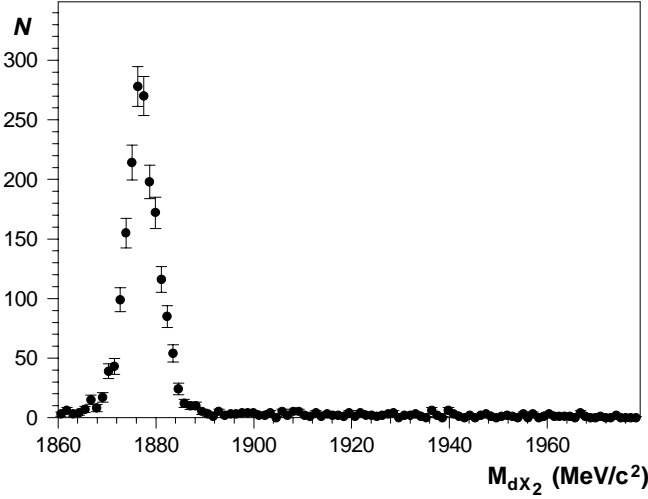
Fig. 2. The missing mass M_{dX_2} spectrum for $\theta_R = 38°$.

one of the nucleons is a spectator. These diagrams give the maximum contribution when the kinetic energy of the spectator nucleon approaches zero.

Missing mass spectra of M_{pX_1} and M_{dX_2} were determined with the expression

$$M^2_{pX_1(dX_2)} = m_d^2 + 2m_p^2 + 2m_d(E_i^t - E_f^t)$$
$$-2E_i^t E_f^t + 2p_i p_f \cos\theta_L \qquad (1)$$

with the additional condition that the proton from the $X \to pX_1$ and the deuteron from the $X \to dX_2$ decay were detected in the right-arm detector of the TAMS spectrometer. In this expression $m_{p(d)}$ is the proton (deuteron) mass, E_i^t and E_f^t are the total energies and p_i and p_f are the momenta of the incident and scattered protons, respectively.

The missing mass M_{dX_2} spectrum of the reaction $pd \to pdX_2$ for the angle $\theta_R = 38°$ (fig. 2) has a peak at the deuteron mass. This peak corresponds to the elastic pd scattering. A measurement of this reaction at different angles of the right and left arms was used to calibrate the spectrometer. The overall mass resolution of the spectrometer was ~ 5 MeV, the angular resolution $\sim 1°$.

3 Results and discussions

We first consider the $pd \to pX \to ppX_1$ reaction. Figures 3a-c depict the experimental missing mass M_{pX_1} spectra obtained with the CD$_2$ and ^{12}C targets, where fig. 3a, b, and c correspond to a detection of the second proton in the right-arm detector at $\theta_R = 34°$, $36°$, and $38°$, respectively. The background in these spectra are interpolated by polynomials. Three peaks at $M_{pX_1} = 1904 \pm 2$, 1926 ± 2, and 1942 ± 2 MeV are clearly visible in these spectra. The first two of them confirm the values of the dibaryon mass obtained by us earlier [12–15], whereas the resonance at 1942 MeV is a new one. This additional resonance is due to the different kinematical coverage of the
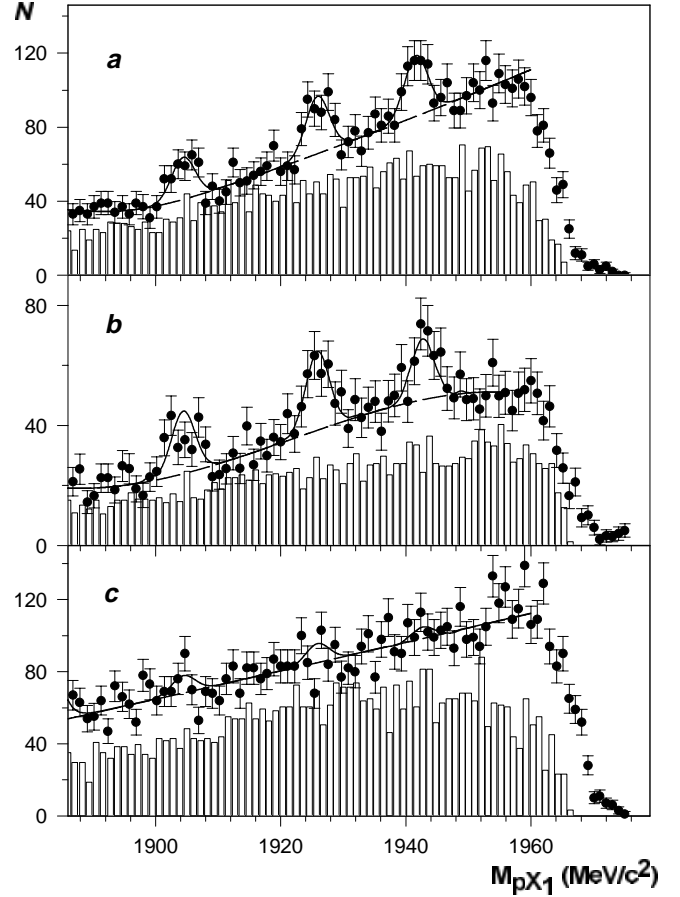

Fig. 3. The missing mass M_{pX_1} spectra obtained with CD$_2$ (the points with the statistical errors) and ^{12}C (the bars) targets; a) $\theta_R = 34°$, b) $\theta_R = 36°$, c) $\theta_R = 38°$. The solid curves are normalized theoretical predictions. The dashed curves correspond to the background interpolated by polynomials.

new experiment. In this experiment we could decrease the detection threshold of the scattered proton down to 50 MeV giving us a broader acceptance in the missing mass.

The experimental missing 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 the Fermi motion of the nucleons in the nucleus. The latter increases essentially the angular cone of the emitted nucleons. In consequence, it is not possible to see peaks of SNDs 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, have to be attributed to an interaction of the proton with the deuteron.

The experimental spectra in figs. 3a-c are compared with the prediction of the theoretical model of SNDs $D(T = 1, J^P = 1^\pm)$ production constructed in the one-meson exchange approach [15] and normalized to the values of the peaks in fig. 3a. Our 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 the
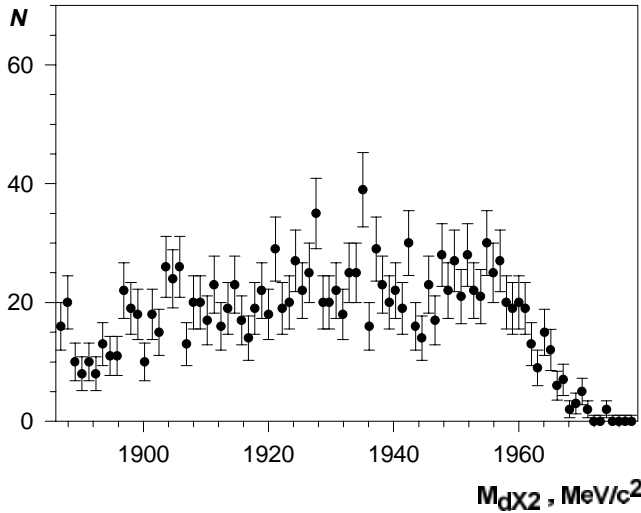
Fig. 4. The sum of missing mass M_{dX_2} spectra for the reaction $pd \rightarrow pX \rightarrow pdX_2$ for the angles $\theta_R = 34°$ and $36°$.

spectra at angles $34°$, $36°$, and $38°$ must relate as $1 : 0.92 : 0.42$. For the isoscalar SND $D(0, 0^{\pm})$, one obtains $1 : 0.95 : 0.67$. The biggest contribution of the SND with $M = 1926$ MeV is expected at $\theta_R = 30°$–$34°$. However, the angles $30°$–$33°$ were not investigated in this work. The calculation of the ratio of the contributions to the missing 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 have a wider angular distribution due to the the higher mass and consequently the higher transverse momenta in the decay $X \rightarrow pX_1$ according to the calculations with a maximum in the region of $26°$–$32°$. In the region of the angles under consideration here, the contributions of the $D(1, 1^{\pm})$ are expected to behave as $1 : 0.6 : 0.2$. 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 $pd \rightarrow ppX_1$ only in the considered angular 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, their contributions to the missing mass spectra in fig. 3a-c would be nearly constant 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 missing mass M_{dX_2} spectrum of the reaction $pd \rightarrow pX \rightarrow pdX_2$, for the sum of angles $\theta_R = 34°$ and $36°$ is shown in fig. 4. As seen from this figure, the reaction $pd \rightarrow pdX_2$ gives a very small contribution to the production of the dibaryons under study.

On the other hand, it is expected [14,15] that isoscalar SNDs contribute mainly in the γd and isovector SNDs in the γNN channels. As the main contribution of the in-

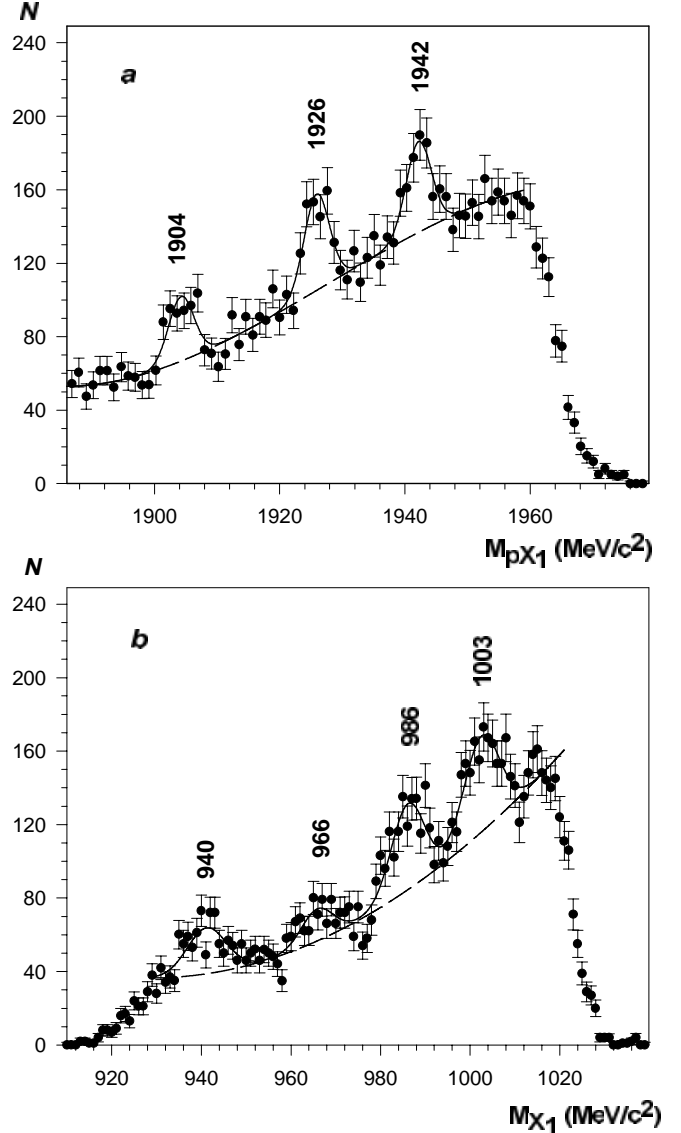**Fig. 5.** The sum of missing mass M_{pX_1} (a) and M_{X_1} (b) spectra for the angles $\theta_R = 34°$ and $\theta_R = 36°$. The dashed and solid curves are results of a fit by polynomials for the background and Gaussians for the peaks, respectively.

dicated dibaryons is observed in pX_1 channel, it is possible to suppose that $X_1 \rightarrow \gamma n$ and all found states are isovector SNDs. A more precise conclusion about the value of the isotopic spin of the observed SNDs could be obtained by the study of the reaction $pd \rightarrow npX_1$. The experiment on the SND photoproduction in the process $\vec{\gamma}d \rightarrow \pi^{\pm}D$ with polarized photons could separate the $D(T = 1, J^P = 1^+, S = 1)$ and $D(1, 1^-, 0)$ states [16] where S is the spin of the SND.

The sum of the missing mass spectra of the reaction $pd \rightarrow ppX_1$ over angles $\theta_R = 34°$ and $36°$, where the contribution of the SNDs is maximum, is presented in fig. 5a. This spectrum was fitted by a polynomial for the background plus Gaussians for the peaks. The number of standard deviations (SDs) is then determined from this
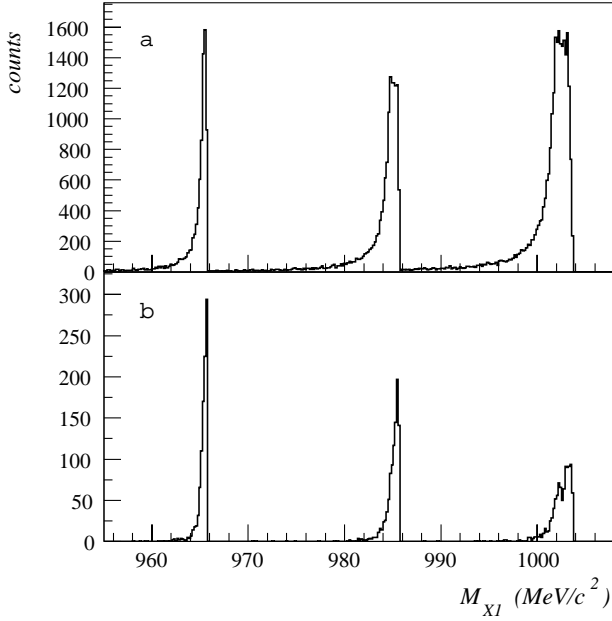
Fig. 6. The result of the simulation of the missing M_{X_1} mass spectra; a) the proton from the decay $X \to pX_1$ is emitted in the whole allowed angular region, b) this proton is detected at $\theta_R = 34°$ and $\theta_R = 36°$.

spectrum as

$$\frac{N_{\text{eff}}}{\sqrt{N_{\text{eff}} + N_{\text{back}}}} , \qquad (2)$$

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 SDs for the resonances at 1904, 1926, and 1942 MeV, respectively. The widths of these resonances are equal to the experimental resolution of $\sim$ 5 MeV.

An additional information about the nature of the observed states has been obtained by studying the missing mass M_{X_1} spectra of the reaction $pd \to ppX_1$. 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 $X_1 \to \gamma n$ and we have the additional indication that the observed dibaryon is SND.

The simulation of the missing M_{X_1} mass spectra for the reaction $pd \to ppX_1$ has been performed assuming that the SND decayed as $\text{SND} \to \gamma d(^{31}S_0) \to \gamma pn$ through the two-nucleon singlet state $^{31}S_0$ [5,15]. Such a decay is characterized in the rest frame by a narrow peak near the maximum photon energy in the probability distribution of the dibaryon decay over an emitted photon energy. As a result of this simulation, in the missing M_{X_1} spectra three narrow peaks at $M_{X_1} = 965$, 987, and 1003 MeV have been predicted. These peaks correspond to the isovector SNDs with the masses 1904, 1926, and 1942 MeV, respectively. The result of this simulation without the influence of the detector resolution is shown in fig. 6. Figure 6a shows the M_{X_1} mass spectrum when the proton from the

SND decay $\text{SND} \to \gamma pn$ is emitted into the whole allowed angular region. The acceptance of the detectors cuts into the widths of these peaks. The missing M_{X_1} mass spectra, taking into account the acceptance of the detectors at the angles 34° and 36°, is presented in fig. 6b. The experimental resolutions widen these peaks to 6–8 MeV.

Figure 5b depicts the sum of the missing mass M_{X_1} spectra for the angles $\theta_R = 34°$ and 36°. As is seen from this figure, besides the peak at the neutron mass, which is caused by the process $pd \to ppn$, peaks are observed at 966 ± 2, 986 ± 2, and 1003 ± 2 MeV. Hence, for all states under study, we have $X_1 \to \gamma n$ in support of the assumption that the dibaryons found are SNDs.

It should be noted that the peak at $M_{X_1} = 1003 \pm 2$ MeV corresponds to the resonance found in ref. [17] and was attributed to an exotic baryon state N^* below the πN threshold. In that work, the authors found altogether three such states with masses 1004, 1044, and 1094 MeV. This is not in contradiction to our interpretation, since in principle SND could decay according to $X \to pN^*$. The possibility of the production of NN^*-coupled dibaryons was considered in [2].

If the exotic baryon states decay into $N^* \to \gamma N$ then they would contribute to the Compton scattering on the nucleon. However, the analysis [18] of the existing experimental data on this process excludes N^* as intermediate states in the Compton scattering on the nucleon.

In ref. [19] it was assumed that these states belong to totally antisymmetric 20-plet of the spin-flavor $SU(6)_{\text{FS}}$ group. Such a N^* can transit into a nucleon only if two quarks from the N^* participate in the interaction [20]. Then the simplest decay of N^* with the masses 1004 and 1044 MeV would be $N^* \to \gamma\gamma N$. This conjecture could be checked, in particular, by studying the reactions $\gamma p \to \gamma X$ or $\gamma p \to \pi X$ at a photon energy close to 800 MeV.

Taking into account the mentioned connection between the SNDs and the resonance-like states X_1, it is possible to assume that the peaks, observed in [17] at 1004 and 1044 MeV, are not exotic baryons, but they are the resonance-like states $X_1 \to \gamma n$ caused by the existence and decay of the SNDs with the masses 1942 and 1982 MeV, respectively. Such X_1 would be not real resonances and cannot give contribution to the Compton scattering on the nucleon.

4 Conclusions

The result of the study of the reaction $pd \to ppX_1$ is that three narrow peaks at 1904, 1926, and 1942 MeV have been observed in the missing mass M_{pX_1} spectra. The analysis of the angular distributions of the protons from the decay of the pX_1 states and the data of the reaction $pd \to pX \to pdX_2$ 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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