Supernarrow dibaryons and exotic baryons with small masses

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Abstract
A search for supernarrow dibaryons (SND) in $pd$ interactions is reviewed. Narrow peaks at masses 1904, 1926, and 1942 MeV have been observed in the missing mass $M_{pX_1}$ spectra of the reaction $pd \rightarrow p + pX_1$. The analysis of the data obtained leads to the conclusion that these peaks are most likely SNDs. The possible interpretation of the peaks, found in the $M_{X_1}$ mass spectra at 966, 986, and 1003 MeV and in the reaction $pp \rightarrow \pi^+ pX$ at 1004, 1044 MeV, as new exotic baryon states is discussed. The mass formula for the exotic baryons is constructed.

Key-words: baryon, dibaryon, proton, deuteron, mass, dispersion relations

1 Supernarrow dibaryons

In the present paper we will observe the works on a study of supernarrow dibaryons (SNDs), a decay of which into two nucleons is forbidden by the Pauli exclusion principle [1–4]. Such dibaryons satisfy the following condition:

$$(-1)^{T+S}P = +1$$

where $T$ is the isospin, $S$ is the internal spin, and $P$ is the dibaryon parity. These dibaryons with the masses $M < 2m_N + m_\pi$ ($m_N, m_\pi$ is the nucleon (pion) mass) can mainly decay by emitting a photon. This is a new class of dibaryons with the decay widths $\leq 1$keV.

The experimental discovery of such states would have important consequences for particle and nuclear physics and astrophysics. In the following, we summarize the experimental attempts to look for such dibaryons so far.

In ref. [5] the existence of a dibaryon, called $d'$, with quantum numbers $T = even$ and $J^P = 0^-$, which forbid its decay into two nucleons, with the mass $M = 2.06$ GeV, and the decay width $\Gamma_{\pi NN} = 0.5$ MeV, has been postulated to explain the observed resonance-like behavior in the energy dependence of the pionic double charge exchange on nuclei at an energy below the $\Delta$-resonance. This dibaryon has a big mass and can decay into $\pi NN$. However, there is a more conventional interpretation of these data. It was shown [6] in the framework of the distorted-wave impulse approximation that such a peak arises naturally because of the pion propagation in the sequential process, in which pion double charge exchange occurs through two successive $\pi N$ charge exchange reactions on two neutrons.

In ref. [7] dibaryons with exotic quantum numbers were searched for in the process $pp \rightarrow pp\gamma\gamma$. 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. As a result, two peaks have been observed in this spectrum. This behavior of the photon energy spectrum was interpreted as a signature of the exotic dibaryon resonance with
the mass of about 1956 MeV and possible isospin \( T = 2 \). In more details this experiment is considered in the reports of Gerasimov and Khrykin.

On the other hand, an analysis [8] of the Uppsala proton-proton bremsstrahlung data looking for the presence of a dibaryon in the mass range from 1900 to 1960 MeV gave only the 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 estimates of the cross section obtained at the conditions of this experiment in the framework of the dibaryon production model suggested in ref. [9] and does not contradict to the data of ref. [7].

In ref. [9–15], the reactions \( pd \to p + pX_1 \) and \( pd \to p + dX_2 \) were studied with the aim of searching for SND. The experiment was carried out at the Proton Linear Accelerator of INR with 305 MeV proton beam using the two-arm spectrometer TAMS. As was shown in ref. [12,9], 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 the dibaryon motion. 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 the dibaryon at correlated angles allowed the authors to suppress essentially the contribution of the background processes and to increase the relative contribution of a possible SND production.

Several software cuts have been applied to the mass spectra in these works. In particular, the authors limited ourselves by the consideration of an interval of the proton energy from the decay of the \( pX_1 \) states, which was determined by the kinematics of the SND decay into \( \gamma NN \) channel. Such a cut is very important as it provides a possibility to suppress essentially the contribution from the background reactions and random coincidences.

In refs. [13–15], 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 \( \theta_L = 70^\circ \). 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 \( 38^\circ \).

As a result, three narrow peaks in the missing mass spectra have been observed at \( M_{pX_1} = 1904 \pm 2, 1926 \pm 2, \) and \( 1942 \pm 2 \) MeV with widths equal to the experimental resolution (\( \sim 5 \) MeV) and with numbers of standard deviations (SD) of 6.0, 7.0, and 6.3, respectively. It should be noted that the dibaryon peaks at \( M_{pX_1} = 1904 \) and 1926 MeV had been observed earlier by same authors in ref. [9–12] at somewhat different kinematical conditions. The analysis of the angular distributions of the protons from the decay of the \( pX_1 \) states 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.

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 it is the additional indication that the observed dibaryon is SND.

The simulation of the missing \( M_{X_1} \) mass spectra for the reaction \( pd \to p + pX_1 \) has been performed assuming that the SND decays as \( \text{SND} \to \gamma + ^{31} S_0 \to \gamma pn \) through two nucleon singlet state \( ^{31} S_0 \) [2,9,15]. As a result, three narrow peaks at \( M_{X_1} = 965, 987, \) and 1003 MeV have been predicted. These peaks correspond to the decay of the isovector SNDs with
the masses 1904, 1926, and 1942 MeV, respectively.

In the experimental missing mass $M_{X_1}$ spectrum besides the peak at the neutron mass caused by the process $pd \rightarrow p + pn$, a resonance-like behavior of the spectrum has been 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, we have $X_1 = \gamma + n$ in support of a statement that the dibaryons found are SNDs.

Recently, the reactions $pd \rightarrow pdX_2$ and $pd \rightarrow ppX_1$ have been investigated by Tamii et al. [16] at the Research Center for Nuclear Physics at the proton energy 295 MeV in the mass region of 1896–1914 MeV. They did not observe any narrow structure in this mass region and obtained the upper limit of the production cross section of an NN-decoupled dibaryon is equal to $\sim 2 \mu b/sr$ if the dibaryon decay width $\Gamma_D << 1$ MeV. And if $\Gamma_D \simeq 3$ MeV, the upper limit will be about $3.5 \mu b/sr$. This limits are smaller than the value of the cross section of $8 \pm 4 \mu b/sr$ declared in ref. [9].

However, the latter value was overestimated that was caused by not taking into account angle fluctuations related to a beam position displacement on the CD$_2$ target during the run. As was shown in the next experimental runs, the real value of the cross sections of the production of the SND with the mass 1904 MeV must be smaller by 2–3 times than that was estimated in [9].

On the other hand, the simulation showed that the energy distribution of the protons from the decay of the SND with the mass of 1904 MeV has to be rather narrow with the maximum at $\sim 74$ MeV. This distribution occupies the energy region of 60–90 MeV. In ref. [16] the authors considered the region 74–130 MeV. Moreover, they used a very large acceptance of the spectrometer which detected these protons. As a result, the ratio of the effect to the background in this work is more than 10 times worse than in ref. [9,15]. Very big errors and absence of a proper cut on the energy of the protons from the decay of the $pX_1$ state in ref. [16] did not allow the authors to observe any structure in the $pX_1$ mass spectrum. For example, when the cut at $T_p = 100$ was performed [17], the obtained behavior of this mass spectra would not contradict within the errors the presence of the dibaryon peak in the considered mass region.

It is worth noting that the reaction $pd \rightarrow NX$ was investigated in other works, too (see for example [18]). However, in contrast to the ref. [9,15], the authors of these works did not study either the correlation between the parameters of the scattered proton and the second detected particle or the emission of the photon from the dibaryon decay. Therefore, in these works the relative contribution of the dibaryons under consideration was small, which hampered their observation.

### 2 Exotic baryons

As was shown above, in the missing $M_{X_1}$ mass spectra three peaks at 966, 986, and 1003 MeV were observed. On the other hand, the peak at $M_{X_1} = 1003 \pm$ MeV corresponds to the resonance found in ref. [19] which was attributed to an exotic baryon state $N^*$.

In ref. [19] Tatischeff et al. investigated the reaction $pp \rightarrow \pi^+ X$ at energies of $T_p = 1520, 1805$, and $2100$ MeV and at six angles, for each energy, from $0^\circ$ up to $17^\circ$. Three peaks with widths about 5–8 MeV have been observed in the missing mass spectra of this reaction at $M_X = 1004, 1044$, and 1094 MeV with a statistic significance between 17 and 2 standard deviations. Two of these masses are below the sum of the nucleon and pion masses.
If exotic baryons with anomalously small masses really exist, the peaks observed at 966, 986, and 1003 MeV might be a manifestation of such states. This is not in contradiction with the interpretation of the peaks in the \( M_{pX_1} \) mass spectra of ref. [15] as SNDs, since, in principal, SND could decay into \( NN^* \). In this case the SND decay width could be equal to a few MeV.

The existence of such exotic states, if proved to be true, will fundamentally change our understanding of the quark structure of hadrons.

Exotic baryon states with masses smaller than \( m_N + m_\pi \) can decay mainly with an emission of photons. If they decay into \( \gamma N \) then such states have to contribute to the Compton scattering on the nucleon. However, L’vov and Workman [20] showed that existing experimental data on this process “completely exclude” such exotic baryons as intermediate states in the Compton scattering on the proton. On the other hand, the early Compton scattering data were not accurate enough to rule out these baryon resonances. Moreover, a measurement of the process \( \gamma p \rightarrow \gamma p \) in the photon energy range \( 60 < E_\gamma < 160 \) MeV resulted in a peak at \( M \approx 1048 \) MeV with an experimental resolution of 5 MeV and with 3.5 standard deviations [21]. Unfortunately, the accuracy of this experiment is not enough to do an unambiguous conclusion about the \( N^* \) contribution to the Compton scattering on the nucleon.

In Ref. [22] it was assumed that these states could belong to the totally antisymmetric \( 20 \)-plet of the spin-flavor SU(6)_{FS} symmetry. Such a \( N^* \) can transit into a nucleon only if two quarks from the \( N^* \) participate in the interaction. Then the simplest decay of the exotic baryons with the small masses is \( N^* \rightarrow \gamma \gamma N \).

On the other hand, the \( N^* \)s were produced in ref. [19, 15], more probably, from the decay of 6-quark states, what is supported by the observation of the dibaryon resonances in [15]. Therefore, an exotic quark structure of the \( N^* \) could be arisen which suppressed, in particular, the decay \( N^* \rightarrow \gamma N \) and could be the reason of an unobservation of such states early. In order to clarify the question about an existence of such exotic baryons, different experiments were proposed, in particular, in ref. [23]. In the present work we will assume that such states exist.

In ref. [19] it was shown that values of the masses of the baryon resonances, observed in this work, can be reproduced with good enough accuracy by the mass formula for two colored clusters of quarks at the end of a stretched bag which was derived in terms of color magnetic interactions [24,25]. There are two free parameters in this model which were fixed by requiring the mass of the nucleon and that of the Roper resonance to be reproduced exactly. As a result of the calculations, the following values of the masses and possible isospin \( (I) \) and spin \( (J) \) of these baryons have been obtained:

\[
M(I; J) = 1005(1/2; 1/2, 3/2), \quad 1039(1/2; 3/2).
\]

N. Konno [26] pointed out that the masses of the exotic baryons from the ref. [19] can also be reproduced by the formula of the diquark cluster model [27]. Eight free parameters of this model were fixed using data of baryon masses and the \( \pi d \) phase shift. This model predicted the following values of the masses and \( I, J^P \):

\[
M = 990(I = 1/2(J^P = 1/2^-); 3/2(1/2^-)),
\]

\[
M = 1050(1/2(1/2^-; 3/2^-); 3/2(1/2^-; 3/2^-)), \quad M = 1060(1/2(1/2^-; 3/2^-)).
\]

However, these two models do not reproduce the values of masses: 966 and 986 MeV, obtained in [15].
Th. Walcher [28] noted that the masses taking all experiments together and including the neutron ground state and two additional masses at 1023 and 1069 MeV are equidistant within the errors with an average mass difference of $\Delta M = 21.2 \pm 2.6$ MeV. The author hypothesized the existence of a light Goldstone boson with the mass of 21 MeV consisting of light current quarks. It was assumed that the series of excited states is due to the nucleon in its ground state plus 1, 2, 3, ..., light Goldstone bosons as the quantum of excitation.

In the present paper we construct a model which allows us to calculate the masses of all possible exotic baryon states below the $\pi$ meson production threshold and determine their parities. This model is based on the calculation of the contribution of meson–baryon loops to the exotic baryon mass operator.

An analysis of the mass shifts of experimentally well-known baryons due to meson–baryon loops was carried out in a set of works (see for references [29]). In these works, the self energy of a baryon was calculated, as a rule, in the framework of a time-ordered perturbation theory. In this case, an underintegral expression diverges strongly and additional assumptions about a behavior of baryon-baryon-meson vertices are required.

We will calculate the masses of exotic baryons with help of dispersion relations with two subtractions for the mass operator. The mass operator is determined as

$$\hat{p} - M = \hat{p} - m - \Sigma(M), \quad \Sigma = a\hat{p} + b$$

(2)

where $M$ and $p$ are the mass and the 4-momentum of the $N^*$ under consideration, $m$ is the mass of the baryon in the intermediate state. The mass of the $N^*$ is equal to

$$M = m + \delta$$

(3)

where

$$\delta = \bar{u}(p)\Sigma u(p) = \bar{u}(p)(aM + b)u(p).$$

(4)

In order to find $\delta$ we construct the dispersion relations over $M^2$ for $\delta(M)$ with two subtractions at $M^2 = m^2$. Then taking into account eq.(3) we obtain the following nonlinear integral equation for the mass $M$

$$M = m + \text{Re} \delta(m) + (M^2 - m^2) \frac{d \text{Re} \delta(M)}{d M^2} \bigg|_{M=m} + \frac{(M^2 - m^2)^2}{\pi} \int_{(m+\mu)^2}^{\infty} \frac{\text{Im} \delta(x) \, dx}{(x - M^2)(x - m^2)^2}.$$  

(5)

We will consider here only baryon with the spin equal to $1/2$. Then the function $\text{Im} \delta$ for the baryon-pion loop can be written as

$$\bar{u}(p)\text{Im} \delta(M)u(p) = \bar{u}(p)\text{Im} \Sigma(M)u(p) = N\bar{u}(p)(\mp\hat{p}_1 + m)u(p)$$

(6)

where $N = 1/2(g^2/4\pi)\left|p_1\right|/M$, $p_1$ is the 4-momentum of the baryon in the intermediate state. The sign minus (plus) at $\hat{p}_1$ corresponds to the same (opposed) parities of the final baryon and the baryon in the intermediate state. Multiplying these expressions by $u(p)$ from the left and by $\bar{u}(p)$ from right and using the condition $u(p)\bar{u}(p) = (\hat{p} + M)/2M$ we have

$$(\hat{p} + M)\text{Im} \delta(M)(\hat{p} + M) = N(\hat{p} + M)(\mp\hat{p}_1 + m)(\hat{p} + M).$$

(7)

Calculating traces in the left and the right parts of this expression we obtain:

$$\text{Im} \delta(M) = \frac{N}{2M^2}[\mp 2(pp_1)M + (p^2 + M^2)m].$$

(8)
Table 1: The masses and $J^P$ of the exotic baryon resonances

<table>
<thead>
<tr>
<th>$N^*$</th>
<th>$J^P$</th>
<th>Model $M$ (MeV)</th>
<th>Experiment $M$ (MeV)</th>
<th>Experimental works</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$\frac{1}{2}^-$</td>
<td>963.4</td>
<td>966 ± 2</td>
<td>[15]</td>
</tr>
<tr>
<td>2</td>
<td>$\frac{1}{2}^+$</td>
<td>987</td>
<td>986 ± 2</td>
<td>[15]</td>
</tr>
<tr>
<td>3</td>
<td>$\frac{1}{2}^-$</td>
<td>1010</td>
<td>1004 ± 2</td>
<td>[19,15]</td>
</tr>
<tr>
<td>4</td>
<td>$\frac{1}{2}^+$</td>
<td>1033</td>
<td>?</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>$\frac{1}{2}^-$</td>
<td>1056</td>
<td>1044 ± 2</td>
<td>[19]</td>
</tr>
<tr>
<td>6</td>
<td>$\frac{1}{2}^+$</td>
<td>1079</td>
<td>?</td>
<td></td>
</tr>
</tbody>
</table>

Taking into account that $p^2 = M^2$, $2(p p_1) = M^2 + m^2 - \mu^2 = 2M E(M)$ we have

$$Im\delta(M) = \frac{1}{2} \frac{g^2}{4\pi} |p_1| (m \mp E),$$

(9)

here $|p_1| = \sqrt{E^2 - m^2}$.

Two subtractions in the dispersion relations provide a very good convergence of the underintegral expression in eq.(5). Therefore, we restrict ourselves to a consideration only one baryon and the pion in the intermediate state. The calculations showed that the contribution of the $\sigma$ meson is negligible. Therefore, it is expected that the contribution of other heavy mesons in the mass region under consideration is negligible too. However, these contributions could be important in the mass region higher than the $\pi N$ production threshold.

As the subtraction is performed at the mass shell of the baryon in the intermediate state, the subtraction constant $Re\delta(m)$ is equal to zero. We assume also that $dRe\delta(M)/dM^2|_m = 0$. This assumption corresponds to a supposition that the baryon with the mass $m$ is in the ground state. It should be noted that if one takes into account a few different baryons in the intermediate state, the subtraction constants could not be equal to zero because in this case the mass $m$ does not coincide with the mass shell for some of these baryons.

In our calculations we assumed that all baryons under consideration have the isotopic spin and the spin equal to $1/2$. Then eq.(5) has a solution in the mass region lower than the $\pi N$ production threshold only if the final baryon with the mass $M$ and the baryon in the intermediate state have opposite parities.

Taking the nucleon plus the pion ($\pi^+$ and $\pi^0$) in the intermediate state, we find for the first exotic baryon state the mass $M = 963.4$ MeV and $J^P = 1/2^-$. Then taking the first exotic baryon with $m = 963.4$ MeV, $J^P = 1/2^-$ and the $\pi$ meson in the intermediate state we obtain for the second exotic baryon state $M = 987.0$ MeV and $J^P = 1/2^+$. Continuing the same procedure, six possible exotic states of baryons have been found. The obtained states are listed in Table 1 where the experimental data are also given.

As seen from this table, the results of calculations are in a good agreement with the experimental data. The mass values of two unobserved still states at 1033 and 1079 MeV are close to the ones predicted in [28].

At the calculation we assumed that the coupling constant $g^2/4\pi$ in the vertices $NN^*\pi$ and $N^*N^*\pi$ is same for all $N^*$ and equal to the coupling constant of the $\pi NN$ interaction ($g_{pp\pi}^2/4\pi = 14.6$). So, an increase of the difference between the model predictions for the masses and experimental data with a rise of the mass could be caused, in particular, by this
assumption. Therefore, it is expected that a real value of the mass for the unobserved state #6 is smaller by \( \sim 10 \) MeV and so it has to be below the pion production threshold.

As follows from the table, the odd parity has been predicted for all baryon states observed in [19]. It agrees with the comment of Th. Walcher [28] and is due to the kinematics of the experiment [19]. This experiment detected \( \pi^+ \) and \( p \) from the reaction \( pp \rightarrow \pi^+ + pX \) in coincidence in one spectrometer at small angles. Since the \( N^* \) states were observed mainly in the forward direction with respect to the beam (\( \theta \approx 5^\circ \)), this means that the outgoing \( \pi \) and \( p \) carry no angular momentum and only the odd parity state of \( N^* \) can be observed in this experiment. But the baryons with the odd parity cannot belong to the total antisymmetric 20-plet [22].

It is worth noting that eq.(5) has additionally solutions. But all of them are essentially higher than \( \pi N \) production threshold. However, to get more reliable information about values of the masses obtained in this mass region, we should take into account the contribution of the \( \sigma, \omega \), and other mesons.

3 Conclusion

As a result of the study of the reaction \( pd \rightarrow p + pX_1 \), three narrow peaks at \( M_{pX_1} = 1904, 1926, \) and 1942 MeV have been observed. The analysis of the angular distributions of the protons from the decay of the \( pX_1 \) states 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, 986, and 1003 MeV is an additional indication that the dibaryons found are the SNDs.

On the other hand, these peaks in \( M_{X_1} \) mass spectra and peaks observed in [19] in the reaction \( pp \rightarrow \pi^+ pX \) could be consider as the new exotic baryon states with small masses. However, additional experiments are necessary to understand the real nature of these peaks. In the present paper, the mass equation has been constructed which was used to calculate the masses and determine parities of the exotic baryons. The obtained values of the masses are in a good agreement with the experimental data [15,19]. Two new exotic baryon states bellow the \( \pi \) production threshold have been predicted.

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References


