Supernarrow Dibaryons

L. V. Fil'kov*

Lebedev Physical Institute, Russian Academy of Sciences, Moscow, 119991 Russia
*e-mail: filkov@sci.lebedev.ru

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Abstract—An analysis of the experimental search for supernarrow dibaryons (SNDs) have been performed. The sum rules for SND masses have been constructed. The calculated values of the SND masses are in good agreement with the existing experimental values. It has been shown that the SND decay leads to the formation of \( \Lambda^* \) with small masses. Experimental observations of \( \Lambda^* \) is an additional confirmation of the possibility of the SND existence.

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INTRODUCTION

Supernarrow dibaryons (SNDs) are 6-quark states, a decay of which into two nucleons is forbidden by the Pauli exclusion principle [1–3]. Such states 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. In the \( NN \) channel, these six-quark states would correspond to the following forbidden states: even singlets and odd triplets with the isotopic spin \( T = 0 \) as well as odd singlets and even triplets with \( T = 1 \). These six-quark states 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 metastable six-quark states with the decay widths <1 keV.

The experimental discovery of the SNDs would have important consequences for particle and nuclear physics and astrophysics. This would lead to a deeper understanding of the evolution of compact stars and the new possibility of quark-gluon plasma observation. In nuclear physics there would be a new concept: SND-nuclei.

In the framework of the MIT bag model, Mulders et al. [4] calculated masses of different dibaryons, in particular, masses of \( NN \)-decoupled dibaryons. They predicted dibaryons \( D(T = 0; J^P = 0^+, 1^+, 2^+; M = 2.11 \text{ GeV}) \) and \( D(1;1^+, 2.2 \text{ GeV}) \) corresponding to the forbidden states \( ^{13}P_1 \) and \( ^{31}P_1 \) in the \( NN \) channel. However, the dibaryon masses obtained exceed the pion production threshold. Therefore, these dibaryons preferentially decay into the \( \pi NN \) channel and their decay widths are larger than 1 MeV.

Using the chiral soliton model, Kopeliovich [5] predicted that the masses of \( D(1,1^+) \) and \( D(0,2^+) \) SNDs could exceed 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, Krupnovnickas et al. [6] obtained an indication on possibility of the existence of one dibaryon with \( J = T = 0 \) and two dibaryons with \( J = T = 1 \) with masses smaller than \( 2m_N + m_\pi \).

In the present paper we analyze the experimental search for SNDs, construct and analyze the mass formula for SNDs, and suggest a possible interpretation of exotic narrow baryons with low masses.

SUPERNARROW DIBARYONS

We will consider the following SNDs:

\( D(T = 1; J^P = 1^+, S = 1) \) and \( D(1,1^-,0) \).

It is worth noting, that the state \( (T = 1; J^P = 1^-) \) corresponds to the states \(^{31}P_1 \) and \(^{31}P_1 \) in the \( NN \) channel. The former is forbidden and the latter is allowed for a two-nucleon state. In our work we will study the dibaryon \( D(1,1^-,0) \), a decay of which into two nucleons is forbidden by the Pauli principle (i.e. \(^{31}P_1 \) state).

SNDs can be formed in processes of interaction with the deuteron only if the nucleons in the deuteron overlap sufficiently, such that a 6-quark state with deuteron quantum numbers can be formed. In this case, an interaction of a photon or a meson with this state can change its quantum numbers so that a metastable state can form. Therefore, the probability of the production of such dibaryons is proportional to the
probability $\eta$ of the 6-quark state existing in the deuteron.

The magnitude of $\eta$ can be estimated from the deuteron form factor at large $Q^2$ (see for example [7, 8]). However, the values obtained depend strongly on the model of the form factor of the 6-quark state over a broad region of $Q^2$. Another way to estimate this parameter is to use the discrepancy between the theoretical and experimental values of the deuteron magnetic moment [9–11]. This method is free from the restrictions quoted above and gives $\eta \leq 0.03$ [11].

Since the energy of nucleons, produced in the decay of the SNDs under study with $M < 2m_N + m_\pi$, is small, it is expected that the main contribution to a two nucleon system should come from the $^3S_0$ (virtual singlet) state (Fig. 1).

The results of calculations of the decay widths of the dibaryons into $\gamma NN$ on the basis of such assumptions at $\eta = 0.01$ are listed in Table 1.

As a result of the SND decay through $^3S_0$ in the intermediate state, the probability distribution of such a decay over the emitted photon energy $\omega$ should be characterized by a narrow peak at the photon energy close to the maximum value $\omega_m = (M^2 - 4m_N^2)/2M$ (Fig. 2). Note that the interval of the photon energy from $\omega_m$ to $\omega_m - 1$ MeV contains about 75% of the contribution to the width of the decay $D(l, l^\pm) \rightarrow \gamma NN$. This leads to a very small relative energy of the nucleons from the SND decay and these nucleons are emitted into a narrow angle cone with respect to the direction of the SND motion. Moreover, the distribution of the SND decay probability over the angle between the final nucleons should be characterized by a narrow angular cone.

The dependence of SND decay probability on the angle between the final nucleons $\theta_\gamma$ is shown in Fig. 3. This figure demonstrates that the nucleons from the decay of SNDs should be mainly emitted in a very narrow angular cone. These dependencies should be taken into account when looking for SNDs.

**PREVIOUS WORKS**

For the first time, SNDs have been searched for in the reactions $pd \rightarrow p + pX_1$ and $pd \rightarrow p + dX_2$ [12–19]. The experiment was carried out at the Proton Linear Accelerator of INR with 305 MeV proton beam using the two-arm mass spectrometer TAMS.

Several software cuts have been applied to the mass spectra in these works. In particular, the authors limited themselves by the consideration of intervals of the proton energy and angles from the decay of the $pX_1$ states, and very narrow angular cone between final nucleons, which were determined by the kinematics of the SND decay into $\gamma NN$ channel. Such cuts are very important as it provides a possibility to suppress the contribution from the background reactions and random coincidences essentially.

In the works [13, 17–19], CD$_3$ and $^{12}$C were used as targets. The scattered proton was detected in the left arm of the spectrometer TAMS at the angle $\theta_\gamma = 70^\circ$. The second charged particle (either $p$ or $d$) was

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**Table 1.** Decay widths of the dibaryons $D(l, l^+, l)$ and $D(l, l^+, 0)$ at various dibaryon masses $M$

| $M$, GeV | 1.904 | 1.926 | 1.942 | 1.965 | 1.985 | 2.006 |
|---------|-------|-------|-------|-------|-------|-------|
| $\Gamma_\ell(l, l^+, l)$, eV | 0.0514 | 0.327 | 0.771 | 1.909 | 3.495 | 5.073 |
| $\Gamma_\ell(l, l^+, 0)$, eV | 0.206 | 1.307 | 3.083 | 7.635 | 13.98 | 23.49 |
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 missing mass spectra have been observed (Fig. 4) 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 $M = 1904$ and $1926$ MeV had been observed earlier by same authors in [12, 14–16] at somewhat different kinematical conditions.

On the other hand, no noticeable signal of the dibaryons has been observed in the missing mass spectra of the reaction $pd \rightarrow p + X_2$. The analysis of the angular distributions of the protons from the decay of $pX_2$ states and the suppression observed of the SND decay into $\gamma d$ 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 has been obtained by studying the missing mass $M_{dX_1}$ spectra of the reaction $pd \rightarrow p + pX_1$. If the state found is a dibaryon decaying mainly into two nucleons then $X_1$ is the 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 the missing mass $M_{pX_1}$ spectra of the reaction $pd \rightarrow ppX_1$ has been performed [13, 17–19] assuming that the SND decays as $D \rightarrow \gamma + ^{31}S_0 \rightarrow \gamma pn$ through two nucleon singlet state $^{31}S_0$ [2, 12, 13]. 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 masses 1904, 1926, and 1942 MeV, respectively.

In the experimental missing mass $M_{X_1}$ spectrum besides the peak at the neutron mass due to 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 [13, 17–19]. These values of $M_{X_1}$ coint-
cide with the ones obtained by the simulation and essentially differ 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 the statement that the dibaryons found are SNDs.

On the other hand, the peak at \( M_{X} = 1003 \pm 2 \) MeV corresponds to the peak found at SPES3 (Saturne) [20] and was attributed to an exotic baryon state \( N^* \) below the \( \pi N \) threshold. In that work the authors investigated the reaction \( pp \to \pi^+ p X \) and have found altogether three such states with masses 1004, 1044, and 1094 MeV with SD \( \approx 10 \). In additional, states with masses close to 966 and 986 MeV were also extracted at SPES3, but from a small number of data [21].

Therefore, if the exotic baryons with anomalously small masses really exist, the observed peaks at 966, 986, and 1003 MeV might be a manifestation of such states. The existence of such exotic states, if proved to be true, will fundamentally change our understanding of the quark structure of hadrons [22, 23, 25].

However, in experiments on a single nucleon, no any significant structure was observed [26–28]. Therefore, the question about a nature of the peaks observed in [13, 20] remains open at present.

In [29] dibaryons with exotic quantum numbers were searched for in the process \( pp \to pppp \). 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 \( d^0 \), with a mass of about 1956 \( \pm 6 \) stat \( \pm 6 \) syst MeV and possible isospin \( T = 2 \) or \( T = 1 \).

On the other hand, an analysis [30] 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.

However, it is asserted in [31] that a more detailed analysis of the data of [30] gives a confirmation of the existence of \( d^0 \) (1956).

The reactions \( \gamma d \to ppX \) and \( \gamma d \to pdX \) have been studied also in the Research Center for Nuclear Physics at the proton energy 295 MeV over a mass range of 1898 to 1953 MeV [32]. They did not observe any narrow structure in the missing mass spectra of \( pX \), \( dX \), and \( X \).

So, these results are at variance both with the SND in INR and with the results of Tatischeff et al. [20, 21] on the search for exotic baryons. However, exotic baryons were observed in [20] with a sufficiently high accuracy, which leads to a doubt about correctness of the result of RCNP [32].

It is worth noting that the reaction \( \gamma d \to \pi^+ \gamma pn \) investigated in other works, too. However, in contrast to the [12–19], 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 contributions of the dibaryons under consideration were small, which hampered their observation.

On the other hand, the preliminary analysis of the missing mass distributions of the available data on the process \( \gamma d \to \pi^+ \gamma pn \), obtained at MAMI [33], demonstrates three peaks (Fig. 5), which good enough correspond to the values of the SND masses found in INR [12, 13] (red lines). Unfortunately, the statistic is very poor in this case.

In order to argue more convincingly that the states found are really SNDs, an additional experimental investigation of the dibaryon production is needed.

In [3] a search for SNDs in the processes of pions photoproduction by the linearly polarized photon was proposed. The cross section of this process can be written as the following:

\[
\frac{d\sigma}{d\Omega} = A + \frac{q^2}{2}\sin^2\theta \pi B(1 - P \cos 2\alpha),
\]

where \( \alpha \) is the angle of the photon polarization relative to the reaction plane.

The result of calculations of \( \sigma(\alpha = 90^\circ) \sigma(\alpha = 0^\circ) \) for the process \( \gamma d \to \pi^+ D \) at \( M = 1904 \) MeV is shown on Fig. 6 as the function of the polarization degree \( P \).

So, we have a large variation between the differential cross sections of pions propagating parallel to the initial photon polarization and pions propagating perpendicular to the polarization. It is expected that the
cross section for vector SNDs should be substantially larger for mesons emitted parallel to the photon polarization than for mesons emitted perpendicularly. Thus, in the first case, the sensitivity to the contribution of \( D(1,1^-) \) significantly increased.

The calculations showed that \( D(1,1^-) \) gives the main contribution to the amplitude \( B \), and its contribution to \( A \) is less than 1%. The contributions of \( D(1,1^+) \) in \( A \) and \( B \) are almost equal. If we consider the SND masses up to 1960 MeV, then it is expected that when a pion is emitted parallel to the photon polarization, 3 peaks should be observed and only 1, when the pion is emitted perpendicularly.

Such an experiment has been performed at LEGS [34, 35]. They analyzed the reaction \( d(\gamma, \pi^+ n')n \) in the photon energy range 210—340 MeV. The linear polarization of initial photon was approximately 99%. The results of this experiment and their comparison with the data obtained at INR [12, 13] are shown in Fig. 7.

As a result they have observed three peaks in missing mass spectrum when the \( \pi^+ \) was emitted parallel to the polarization of the incident photon \( \gamma \).

The mass values found are very close to the values obtained in INR [12, 13].

The peak at \( M = 1926 \) MeV in the bottom panel corresponds to the expected value. However, this peak is too wide, possibly due to insufficient accuracy in the determination of experimental data in the region of this resonance.

The results obtained in this experiment, support the possibility of the SND existence. However, these data were limited by the resolution of the pion detection. So, they did not produce a conclusive proof of the SND existence.

\[
\Gamma_{d \rightarrow \pi D(1,1^-)} = \frac{g_1}{M} \sqrt{\eta \Phi_{\mu\nu} G^{\mu\nu}},
\]

\[
\Gamma_{d \rightarrow \pi D(1,1^+)} = \frac{g_2}{M} \sqrt{\eta \Phi_{\mu\nu\lambda\sigma} G^{\mu\nu\lambda\sigma}},
\]

where \( \Phi_{\mu\nu} = r_\mu w_\nu - w_\mu r_\nu \), \( G_{\mu\nu} = p_\mu v_\nu - v_\mu p_\nu \), \( w \) and \( v \) are 4-vectors of the dibaryon and deuteron polarizations, respectively; and \( r \) and \( p_l \) are the dibaryon and deuteron 4-momenta.

It should be noted that SNDs could be produced in the processes under consideration, if a pion is only emitted from the 6-quark state of the deuteron. Therefore the vertexes of \( d \rightarrow \pi D \) can be written as

\[ pd \rightarrow p + pX \]

\[ \gamma d \rightarrow \pi^+ n n' \gamma \] when \( \pi^+ \parallel \gamma \) and \( \pi^+ \perp \gamma \).

The constants \( g_1^2/4\pi \), \( g_2^2/4\pi \), and \( \eta \) are unknown. However, the products of these coupling constants and \( \eta \) can be estimated from the results of work [34].
where the SNDs, were searched for in the process 
\( \gamma d \rightarrow \pi^+ D \rightarrow \gamma \pi^+ n n \).

As a result, we have
\[
\eta_1^2 = 1.4 \times 10^{-4}, \quad \eta_2^2 = 3 \times 10^{-4}.
\] (5)

**MASS FORMULA FOR THE SNDs**

Using the complete Green function of the dibaryons
\[
\Delta(p^2) = \frac{F(p)}{p^2 - m^2 - \delta_p(p^2)},
\]
we determine the SND mass as
\[
M^2 = m^2 + \text{Re} \delta_p(M^2),
\] (6)

where \( \delta_p(M^2) \) is the self energy of the SND under study and \( m \) is the mass of the dibaryon in the intermediate state.

The self energy of the lightest SND will be determined in one loop approximation through the interaction of the pion with the 6-quark state of the deuteron. The self energy of the next SND will be obtained through the interaction of the pion with the lightest SND and so on.

We calculate the SND self energy with the help of the dispersion relations with two subtractions at \( M^2 = m^2 \). Then taking into account (6), we obtain the mass formula for the SNDs [36]
\[
M^2 = m^2 + \text{Re} \delta_p(m^2) + (M^2 - m^2) \left. \frac{d \text{Re} \delta_p(M^2)}{dM^2} \right|_{M^2=m^2} + \frac{(M^2 - m^2)^2}{\pi} \int_{(m+\mu)^2}^\infty \frac{\text{Im} \delta_p(x)dx}{(x-M^2)(x-m^2)^2}.
\] (7)

Since the subtraction is carried out on the mass shell of the dibaryon in the intermediate state, the subtraction function \( \text{Re} \delta_p(m^2) \) is equal to zero. Assuming that this dibaryon is in the ground state, we have \( d \text{Re} \delta_p(M^2)/dM^2 \big|_{M^2=m^2} = 0 \).

Finally, the mass formula for SND can be represented as
\[
\left. \frac{(M^2 - m^2)^2}{\pi} \right|_{(m+\mu)^2}^\infty \int \frac{\text{Im} \delta_p(x)dx}{(x-M^2)(x-m^2)^2} = 1.
\] (8)

Two subtractions in the dispersion relations provide a very good convergence of the integrand in (8). Therefore we restrict ourselves to consideration of one loop approximation only.

We assume that the SND under study and the dibaryon in the intermediate state have opposite parities. Then the vertex \( D'(1^+) \rightarrow \pi + D(1^+) \) can be written as
\[
\Gamma^{(\pi)} = \frac{\bar{g}_3}{M} G_{\mu\nu} \Phi^{\mu\nu}. \] (9)

### Table 2. The masses and \( J^P \) of the SNDs

| No | \( J^P \) | Model \( M \), MeV | Experiment \( M \), MeV | Experimental works |
|----|--------|-----------------|-----------------|-------------------|
| 1  | 1−     | 1904            | 1904 ± 2        | [13]              |
| 2  | 1+     | 1925            | 1926 ± 2        | [13]              |
| 3  | 1−     | 1945            | 1942 ± 2        | [13]              |
| 4  | 1+     | 1965            | 1956 ± 6        | [29]              |
| 5  | 1−     | 1985            | 1982            | Predicted [13, 20]|
| 6  | 1+     | 2006            |                 |                   |

As a result of calculations we have got the following expression for the imaginary part of \( \delta_p(x) \):
\[
\text{Im} \delta_p(x) = \left( \frac{2}{4\pi} \right) \left[ q(x + m^2 - \mu^2)^2 + 2m^2 x \right],
\] (9)

where \( q \) is the pion momentum equal to \( q = [(x - (m + \mu)^2)(x - (m - \mu)^2)]^{1/2}/2x^{1/2} \).

The coupling constant \( g_3/4\pi \) in the vertex for transition of the 6-quark state of the deuteron \((D(0, 1^+))\) plus the pion to the SND \( D(1, 1^-) \) has been fixed by requiring a reproduction of the mass \( M = 1904 \) MeV. It results in
\[
\frac{\bar{g}_3}{4\pi} = 26.5888.
\] (11)

Calculations within the framework of the present model yielded very close values of the SND masses found in channels with \( \pi^0 \) and \( \pi^\pm \) mesons. Therefore, we take them equal one to another.

In order to calculate the mass of the next SND \( D(1, 1^+) \), we take in the intermediate state the SND \( D(1, 1^-) \) with \( m = 1904 \) MeV and the pion. To calculate the mass of the next \( D(1, 1^-) \), we consider SND \( D(1, 1^+) \) with \( m = 1925 \) MeV and pion in the intermediate state and so on.

The coupling constant \( \bar{g}_3/4\pi \) in the vertex \( D(1, 1^+) \rightarrow D(1, 1^-) + \pi \) differs from \( \bar{g}_1 \). Due to the isospin invariance, we have \( \bar{g}_3^2/4\pi = 3/4(\bar{g}_1^2/4\pi) \).

The results of the calculations of the masses and \( J^P \) of the SNDs are listed in Table 2.

As can be seen from the table, the values of the SND masses obtained are in good agreement with available experimental data. The existence of the SND with the mass \( M = 1982 \) MeV was predicted in [13, 20]
as a consequence of the observation of the peak in the missing mass spectrum of the reaction $pp \to \pi^+ pX$ [37] at $M_X = 1044$ MeV.

An analysis of the probability of SND decay shows that due to the smallness of the angle $\theta_{12}$ and difference in the energies of the final nucleons, resonance-like states with masses $(p_1 + k)^2 = (p_2 + k)^2 = M_{N^*}^2$ appear. Table 3 presents the values of $M_{N^*}$ for various SND masses.

As the SNDs observed in [12, 13] decay into $NN^*$ with the small relative momentum between $N$ and $N^*$, the SND parity has to be determined by the parity of the $N^*$. As seen from Tables 2 and 3, the SND parities found here agree with the results obtained for the $N^*$ states.

Thus, the formation of $N^*$ is uniquely determined by the existence of SNDs. $N^*$ is not a new particle. This is a kinematic effect associated with the SND decay form. Consequently, the experimental observation of $N^*$s can be an additional indication of the possibility of the existence of SNDs.

### SUMMARY

The main properties of SNDs have been considered. A number of experiments [12, 13, 29, 33, 34], where evidence was obtained for the existence of SNDs, has been analyzed.

Negative results obtained in RCNP [32] are at variance both with the observation of SNDs in INR [12, 13] and with the result of B. Tatischeff et al. [20] on search for exotic baryons. On the other hand, the latter was observed in [20] with sufficiently high accuracy, which leads to doubt about correctness of the result of RCNP [32].

The sum rules for the SND masses have been constructed. The values of the SND masses obtained by means of the sum rules agree very well with the experimental data [13, 20].

The decay of SNDs leads to the formation of resonance-like states $N^*$s. The predicted values of the masses of $N^*$ are in good agreement with available experimental data.

The experimental observation of $N^*$s is an additional confirmation of the possibility of the SND existence.

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