Search for narrow six-quark states

The possibility of the existence of multiquark states was predicted by QCD inspired models [1]. These works initiated a lot of experimental searches for six-quark states (dibaryons). Usually one looked for dibaryons in the *NN* channel. Such dibaryons have decay widths from a few up to hundred MeV. Their relative contributions are small enough and the background contribution is big and uncertain as a rule. All this often leads to contradictory results.

L.V. Fil'kov has firstly considered [2] six-quark states with small mass, a decay of which into two nucleons is forbidden by the Pauli exclusion principle. Such states satisfy the following condition:

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

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. Such six-quark states with the masses $M < 2m_N+m_\pi$ (m_N (m_π) 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 < 1keV. Such states were called supernarrow dibaryons (SND). In the works [2,3] the decay widts of such nucleon-nucleon-decoupled dibaryons with the masses $M < 2m_N+m_\pi$ have firstly been estimated. In order to search for such SNDs, different experiments have been proposed in the works [2-6].

The experimental discovery of the SNDs would have important consequences for particle and nuclear physics and astrophysics.
If such states exist it would be necessary to construct an adequate QCD model as the present QCD inspired models do not allow small dibaryon masses to be obtained.
In astrophysics it would give a new information about a possible evolution of compact stars and, in particular, about a new possibility of the quark-gluon plasma (QGP) production in the interior of a neutron star.

As a main contribution to a decay of QGP with a big baryon density is given by particles with the biggest number of degrees of freedom, such a QGP would decay with big probability through SND producing additional photons with small enough energy what could be a specific signal of QGP production.
SNDs are Bose particles, therefore they could fall into the center of nucleus. Estimations [7] showed that in this case the life-time of SND could increase up to 10^{-8} sec and more and dibaryon-nuclei could be produced.

SNDs can be produced in reactions on the deuteron only if the nucleons in the deuteron overlap sufficiently, such that a six-quark state with deuteron quantum numbers can be formed. In this case, an interaction of a photon or a hadron with this state can change its quantum numbers so that a metastable state is formed. Therefore, the probability of the production of such dibaryons is proportional to the probability η of the six-quark state existing in the deuteron. The different estimation showed that $\eta\approx10^{-2}$ or smaller (see [6]).

Since the energy of nucleons, produced in the decay of the SNDs under study with $M<2m_N+m_\pi$, is small, it may be expected that the main contribution to a two nucleon system should come from the $^{31}S_0$ (virtual singlet) state. The results of calculations of the decay widths of the dibaryons $D(T=1,J^P=1^+,S=1)$ and $D(1,1^-,0)$ into γNN on the basis of such assumptions at η=0.01 are listed in Table. As a result of the SND decay through $^{31}S_0$ in the intermediate state, the probability distribution of such a decay over the emitted photon energy ω should be characterized by a narrow peak at the photon energy close to the maximum value $\omega_m=(M^2-4m_N^2)/2M$. Note that the interval of the photon energy from ω_m to (ω_m-1MeV) contains about 75% of the contribution to the width of the decay $D(1,1^{\pm})\rightarrow \gamma NN$. This leads to a very small relative energy of the nucleons from the SND decay (≤1MeV) and these nucleons will be emitted into a narrow angle cone with respect to the direction of the SND 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°.

M(GeV)	1.90	1.91	1.93	1.96	1.98	2.00	2.013
$\Gamma_t(1,1^+)$ (eV)	0.51	1.57	6.7	25.6	48	81	109
$\Gamma_t(1,1^-)$ (eV)	0.13	0.39	1.67	6.4	12	20	27

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

The first experimental investigations of SNDs have been performed in common with Institute of Nuclear Research at the Proton Linear Accelerator of INR with 305 MeV proton beam using the two-arm mass spectrometer TAMS [8,9], where the reactions $pd\rightarrow p+pX_1$ and $pd\rightarrow p+dX_2$ were studied in two experiments. The scattered proton was detected in the left arm of the spectrometer TAMS at the angle θ_L. The second charged particle (either p or d) was detected in the right arm by three telescopes located at different θ_R.

These two experiments mainly differ by the detection angles θ_R. The angles were θ_R=33°, 35° and 37° at θ_L=70° and 72.5° in the first experiment [8] and θ_R=34°, 36°, 38° and θ_L=70° for the second one [9]. In these experiments CD_2 and ^{12}C were used as targets.

According to above, a detection of the scattered proton in coincidence with the proton (or the deuteron) from the decay of SND at correlated angles allows the suppression of the contribution of the background processes and increases 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 themselves by the consideration of an energy interval for the proton from the decay of the pX_1 states, which was determined by the kinematics of the SND decay into γNN channel. Such a cut is very important as it provides a possibility to suppress the contribution from the background reactions and random coincidences essentially.

In the first experiment [8] two dibaryon peaks at M=1905 and 1924 MeV with the widths less than 3 MeV have been observed. The analysis of the angular distributions of the protons from the decay of the dibaryons indicated that these dibaryons observed could be SNDs with the isospin equal to 1.

In the second experiment [9] three narrow peaks in the missing mass spectra have been observed (Fig. 1a) at M_{pX1}=1904± 2, 1926± 2, and 1942± 2 MeV with the widths equal to the experimental resolution (~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 coincided very well with the results obtained in the first experiment [8] at somewhat different kinematical conditions. On the other hand, no noticeable signal of the dibaryons has been observed in the missing mass M_{dX2} spectra of the reaction $pd\rightarrow p+dX_2$. The analysis of the angular distributions of the protons from the decay of pX_1 states and the suppression observed of the SND decay into γd 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_{X1} 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 the neutron and the mass M_{X1} is equal to the neutron mass m_n. If the value of M_{X1}, 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 the SND.

The simulation of the missing mass M_{X1} spectra of the reaction $pd\to ppX_1$ has been performed [9] assuming that the SND decays as $D\to\gamma+{}^{31}S_0\to\gamma\, pn$ through two nucleon singlet state ${}^{31}S_0$. As a result, three narrow peaks at MX_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_{X1} spectrum, besides the peak at the neutron mass caused by the process $pd\to p+pn$, a resonance-like behavior of the spectrum has been observed at 966± 2, 986± 2, and 1003± 2 MeV [9]. These values of M_{X1} coincide 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_{X1}=1003± 2 MeV corresponds to the peak found in ref. [10] and was attributed to an exotic baryon state N^* below the πN threshold. In that work the authors investigated the reaction $pp\to\pi^+pX$ and have found altogether three such states with masses 1004, 1044, and 1094 MeV. Therefore, if the exotic baryons with anomalously small masses really exist, the observed peaks

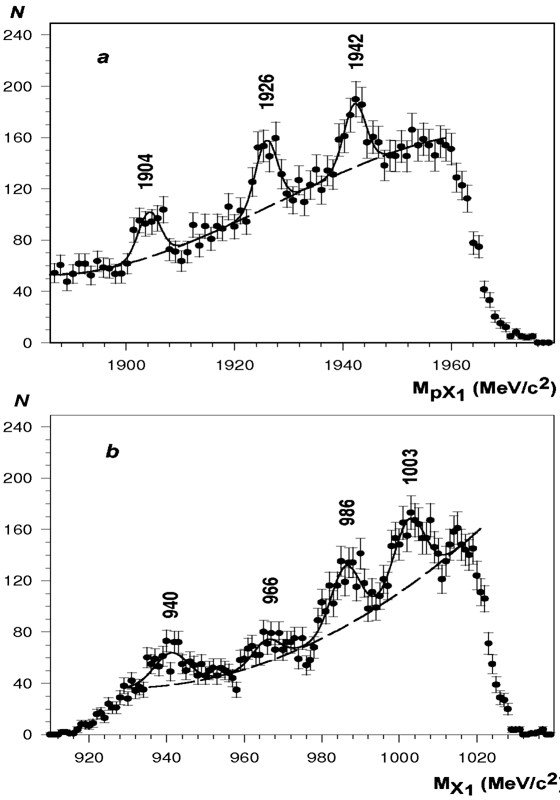

Figure 1: The missing mass M_{pX1} (a) and M_{X1} (b) spectra of the reaction $pd\to p+pX_1$ for the sum of angles of θ_R=34° and θ_R=36°. The dashed and solid curves are results of interpolation by polynomials (for the background) and Gaussian (for the peaks), respectively.

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 [11-14].

However, the experiments on single nucleon have not observed any significant structure. Therefore, the question about a nature of peaks observed in [9,10] is open at present.

The reactions $pd \rightarrow pdX$ and $pd \rightarrow ppX$ have been also investigated at the Research Center for Nuclear Physics (Japan) at the proton energy 295 MeV in the mass regions of 1896--1914 [15] MeV and 1898 - 1953 MeV [16]. They did not observe any narrow structure in this mass regions. However, they worked at a wrong kinematics in the first work and at a very high beam intensity in the second one, which was more than two orders of magnitude higher than that used in INR. The small value of the intensity was a necessary conditions which allowed authors of work [8,9] to suppress a background and to observe SNDs. Moreover, the authors of works [15,16] did not observe any narrow structure in the missing mass spectrum of X too. It contradicts not only work [18] but the result of B. Tatscheff *et al*. [10] where the resonance like structure had been obtained at M_X=1004 MeV with a good statistic.

However, in order to argue more convincingly that states found are really SNDs and to search for their properties, an additional experimental investigation of the narrow dibaryon production is needed. Such experiments are scheduled [6].

The authors of the investigation "Study supernarrow dibaryons in pd-interactions at the linear accelerator INR RAS " were awarded the second prize at the jubilee competition of scientific works of INR RAS in 2000.

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