Recent dibaryon studies at ANKE

D. Tsirkov1,*, V. Komarov1, T. Azaryan1, S. Dymov2, A. Kunsafina1,3,4, V. Kurbatov1, Zh. Kurmanaliyev1,3,4, and Yu. Uzikov1,5,6 for the ANKE Collaboration

1Laboratory of Nuclear Problems, Joint Institute for Nuclear Research, RU-141980 Dubna, Russia
2Institut für Kernphysik, Forschungszentrum Jülich, D-52425 Jülich, Germany
3Al-Farabi Kazakh National University, KZ-050040 Almaty, Kazakhstan
4Institute of Nuclear Physics, KZ-050032 Almaty, Kazakhstan
5Dubna State University, RU-141980 Dubna, Russia
6Department of Physics, Moscow State University, RU-119991 Moscow, Russia

Abstract. The recent results of dibaryon studies at ANKE are being presented, along with our plans concerning further studies on the topic. The $D_0^{3}$ resonance has been observed at ANKE in the coherent $pd \rightarrow pd + (\pi \pi)^0$ channel, accompanied by the ABC effect. An explanation of the ABC effect has been proposed, suggesting to explain it as a kinematic cumulation of the pion pairs in the $D_0^{3} \rightarrow D_{12} + \pi \rightarrow d + (\pi + \pi)_{I=0}$ cascade decay channel due to the predominantly collinear $D_{12}$ decay. Based on this hypothesis, a search for a $D_{21}$ signal in the $pp \rightarrow (pp),\pi\pi$ reaction is suggested. The $p$-wave dibaryon resonances $^3P_2$ and $^3P_0$ have been observed at ANKE; for $^3P_0$ it is the first experimental observation. Preliminary results for a resonance peak in the $pp \rightarrow (pp),\pi^0$ reaction with the mass $m = 2646 \pm 5$ MeV and the width $\Gamma = 132 \pm 14$ MeV are being presented. Also we propose to search for the narrow $NN^*(1535)$ resonance in the $pd \rightarrow pd\eta$ reaction.

1 Introduction

Derivation of the hadron spectroscopy from QCD laws has been an important challenge for decades, but theoretical predictions cannot yet provide a clear set of rules for hadron construction. One of the ways to advance in this field is to study exotic hadrons such as tetra-quarks, penta-quarks, and hexa-quarks. They are allowed by QCD, but convincing experimental observations of tetra-quarks and penta-quarks have been made only recently (see, e.g., [1, 2] and refs. therein). As for hexa-quarks, a search for them has already a long history.

2 SU(6) dibaryon classification

Resonances in two-baryon systems were first considered in [3] and developed in [4] soon after the SU(3) symmetry formulation. In Ref. [4] a classification has been introduced for non-strange two-baryon states as members of an SU(6) unitary multiplet. The members of the multiplet followed the notation $D_{IJ}$, where $I$ is the isospin and $J$ is the angular momentum.

*e-mail: cyrkov@jinr.ru
The lowest states of the multiplet were the deuteron $D_{01}$, and the deuteron virtual singlet state or the $s$-wave proton pair $D_{10}$. The next, higher states, so far unobserved that time, were the $s$-wave $N\Delta(1232)$ resonance $D_{12}$, the $s$-wave $\Delta(1232)\Delta(1232)$ resonance $D_{03}$, the charge-3 $p\Delta^{++}(1232)$ resonance $D_{21}$ and the charge-4 $\Delta^{++}(1232)\Delta^{++}(1232)$ resonance $D_{30}$.

The extensive search for two-baryon states began later after the development of the quarkbag models, that reproduced quite well the spectroscopy of the known hadrons and predicted two-baryon resonances [5, 6]. In these searches, the term “dibaryons” was used to denote “genuine” compact six-quark resonances, and a main criterion of their existence was a small width, $\Gamma \lesssim 100$ MeV [7, 8].

Numerous studies have led to the discovery of three resonance states $^1D_{2}$, $^3F_3$, $^3P_2$ in the partial wave analysis (PWA) of the $pp \rightarrow pp$ elastic scattering and then of the $pp \rightarrow d\pi^+$ reaction (see [9–11] and refs. therein). Here the notation follows the PWA standard $^{2S+1}L_J$, where $L$ is the orbital angular momentum, $S$ is the spin, and $J$ is the total angular momentum. The quantum numbers of the $^1D_{2}$ two-baryon resonance state coincide with those of the Dyson’s $D_{12}$ dibaryon, and the predicted $D_{12}$ mass, ~2176 MeV, is close to the $^1D_{2}$ mass, 2120–2150 MeV according to different PWA solutions [12].

However, the dominant interpretation for these resonances was that they are conventional hadron states in the $\Delta N$ channel instead of “genuine” quark dibaryons, since their $S$-matrix poles were found to be close to the $\Delta N$ branching line, and their widths close to that of $\Delta(1232)$. The situation has changed after the observation of an isoscalar two-baryon resonance state in the quasi-free channel $pn \rightarrow p\pi^0\pi^0$, with a mass 2370–2380 MeV and an exceptionally small width $\Gamma \approx 70$ MeV [13–15], that was suggested as a candidate for the “true” dibaryon. The mass and the quantum numbers of this state [14] allowed to associate it with the Dyson’s $D_{03}$ dibaryon.

Calculations within constituent-quark models predicting the $D_{03}$ dibaryon have a long history, and recent development of the model [16, 17] has resulted in the successful calculation of its mass, total width and partial decay widths. It follows from these works that the resonance wave function has a two-component content: a $\Delta \Delta$ part and a dominant hidden-color component, the six-quark exotic state. Nonetheless, the traditional meson-baryon approach to describe this resonance is still up to date. In [18] a general motivation was suggested for the decrease of the $D_{03}$ width compared to that of the free $\Delta(1232)$. The recent work [19, 20] considered the two-component structure of the $D_{03}$ resonance, consisting of a compact $\Delta \Delta$ component and a loose $N\Delta$ near-threshold system, and succeeded in describing its mass, total and partial decay widths. Thus, the resonance behavior of the $pn \rightarrow p\pi^0\pi^0$ cross section can be rather well reproduced by both the meson-baryon and the quark-model approaches. On the basis of that, we would use the term “dibaryon” for any hadronic system with the baryon number two and a resonance-like behavior, without implying its “genuine” quark structure.

Recently, a signal for the $D_{21}$ dibaryon has been observed as well at WASA@COSY [21]. The quasi-free $pp \rightarrow pp\pi^+\pi^-$ reaction has been measured exclusively in $pd$ collisions, allowing to obtain total and differential cross sections for the energy region $\sqrt{s} = 2350–2460$ MeV, which covers $D_{21}$ mass expected from the original predictions [4]. The measured cross sections are significantly underpredicted by the $t$-channel “modified Valencia” calculations ignoring the $D_{21}$ dibaryon, while introducing the one with the mass $m = 2140$ MeV and the width $\Gamma = 110$ MeV to the model allows to get rid of this discrepancy.

### 2.1 ANKE observations

In all the experiments performed so far the $D_{03}$ dibaryon was excited via free or quasi-free collision of fast nucleons. We at ANKE observed $D_{03}$ dibaryon in the coherent $pd \rightarrow pd + (\pi\pi)^0$ channel where both nucleons of the deuteron were excited to $D_{03}$ by the $t$-channel
meson exchange with a fast projectile proton [22]. The reaction $p + d \to p + d + X$ was studied at 0.8–2.0 GeV proton beam energies, and the proton-deuteron pairs emerging with high momenta, 0.6–1.8 GeV/c, were detected at small angles with respect to the proton beam. The invariant mass of the $d\pi\pi$ system in the region of pion-pair production exhibits a resonance-like peak at $m_{d\pi\pi} \approx 2360$ MeV/c$^2$ with the width $\Gamma \approx 100$ MeV/c$^2$, corresponding to the $D_{03}$ excitation.

The $D_{03}$ is known to have an association to the ABC effect—a significant near-threshold enhancement in the spectrum of the pion pair invariant mass $m_{\pi\pi}$, observed in the reactions with production of the isoscalar pion pair accompanied by the bound light nucleus, at the position $m_{\pi\pi} \approx 300$ MeV/c$^2$ with a surprisingly small width about 40 MeV/c$^2$ [23]. At ANKE, the invariant mass of the pion pair $m_{\pi\pi}$ also reveals a local enhancement with a structure of a narrow bump placed above a smooth continuum, specific to the ABC effect.

The explanation of the ABC effect, especially a rather narrow width of the enhancement, has puzzled science for decades. Various explanations have been proposed (see, e.g., [23, 24]). The one that seemed promising for us was the cascade decay channel

$$D_{03} \to D_{12} + \pi \to d + (\pi + \pi)_{l=0}, \quad (1)$$

proposed in [24]. That work suggested that the effect could arise from the interference between (1) and another $D_{03}$ decay channel,

$$D_{03} \to d + \sigma \to d + (\pi + \pi)_{l=0}, \quad (2)$$

with the mass and the width of the $\sigma$ meson equal to $m_\sigma = 300$ MeV and $\Gamma_\sigma = 100$ MeV due to the hypothetical chiral symmetry restoration in the hot and dense quark matter composing the $D_{03}$ dibaryon. Since such restoration in the case of the $D_{03}$ resonance decay does not seem to have enough confirmations to us, we have proposed a hypothesis that the ABC effect is a kinematic effect of pion-pair cumulation near the specific excitation energy in channel (1) due to the binary character of the reactions composing the cascade and predominantly collinear decay of the intermediate $D_{12}$ dibaryon [22]. At the extreme case of zero dibaryon widths and exactly collinear decay, the position of the ABC enhancement would be the $\delta$ function at $m_{\pi\pi} = 271$ MeV/c$^2$ for $\pi^0\pi^0$. Both receding from the collinear kinematics and dispersion of the resonance masses cause the peak smearing, but a simple simulation with the standard dibaryon masses and a $\cos \theta$ angular distribution for the $D_{12}$ decay gives a peak position similar to that of the ABC one [22]. One more argument in favor of the collinear character of the $D_{12}$ decay is the concentration of fast deuterons, $^3$He, $^4$He nuclei near 0° and 180° angles in the experiments where the narrow ABC enhancement was observed [13, 22, 25].

One of the common reactions where it is suggested to search for the $D_{21}$ dibaryon is the $pp \to D_{21}\pi^- \to pp\pi^+\pi^-$ channel [4, 21]. The effect of the pion-pair cumulation could take place in this reaction as well if we select final proton pairs with a small excitation energy, which would lead to a quasi-binary kinematics in the second step of the cascade. A simple calculation, done for the case of zero dibaryon width and exactly collinear decay, shows that the position of the two-pion peak would depend on the initial energy (see Fig. 1), though in the beam energy region $T_p = 1–2$ GeV it would be close to the threshold, resulting in the ABC-like peak.

Fortunately, these are ANKE data on the $pp \to (pp)_s + (\pi\pi)^0$ reaction at $T_p = 1.1$ and 1.4 GeV [26], that show a prominent near-threshold enhancement. The model describing the data proposed in that paper describes the data well in the whole $\pi\pi$ mass range except the region near the threshold, where the data seem to show some excess over the model predictions. We suggest to estimate the near-threshold enhancement numerically and to consider, whether it could be a sign for the ABC-like effect associated with the $D_{21}$ production.
3 Dibaryons outside the SU(6) scheme

Known dibaryons are not limited to the Dyson’s classification. The resonance states $^3P_2$ and $^3F_3$ have long been known from PWA of the $pp$ scattering [9–11]. According to the $D_{IJ}$ notation, $^3P_2$ would correspond to $D_{12}$ with negative parity, $D_{12}^-$ (all SU(6) dibaryons have positive one), and $^3F_3$ would be $D_{13}^-$. Since $^3P_2$ is the least intensive resonance of the ones obtained from PWA, uncertainties in its parameters are rather large. New opportunities to study this resonance are offered by the channel (here diproton $\{pp\}_s$ is a proton pair in $^1S_0$ state), since the intensive ones $^1D_2, ^3F_3$ are forbidden in it. At ANKE we have measured for the first time the differential cross section $d\sigma/d\Omega$ and the analyzing power $A_y$ in the $\Delta(1232)$ excitation energy region of the reaction (3) (see [27] and refs. therein). The data exhibited the following features: a prominent peak in the energy dependence of the forward differential cross section in the region of $\Delta(1232)$ excitation, the anomalous dip for the differential cross section at zero angle, and the significant analyzing power. A simple PWA of the ANKE results together with the data from [28] has been performed, taking into account only the transitions $^3P_0 \rightarrow ^1S_0 s$ and $^3P_2 \rightarrow ^1S_0 d$, since the other ones are known to be small from the PWA of the $pp \rightarrow pp$ and $pp \rightarrow d\pi^+$ reactions. This allowed to explain the aforementioned features observed for the data as a result of the interference for the $^3P_2$ and $^3P_0$ resonances.

The PWA results also allowed specify the parameters of the $^3P_2$ resonance, that turned out to be $m = 2195 \pm 8$ MeV/$c^2$ and $\Gamma = 134 \pm 22$ MeV/$c^2$. Besides, a $^3P_0$ was observed experimentally for the first time, and PWA gave its mass $m = 2199 \pm 5$ MeV/$c^2$ and width $\Gamma = 94 \pm 11$ MeV/$c^2$. In the $D_{IJ}$ notation the $^3P_0$ resonance would be $D_{10}^-$, that could be treated as an excited state of the s-wave diproton / virtual singlet deuteron $D_{10}^-$. Both $^3P_2$ and $^3P_0$ resonances belong to the new family of $p$-wave dibaryons, as opposed to the $s$-wave dibaryons considered earlier.

One of the first ANKE studies of the $pp \rightarrow \{pp\}_s \pi^0$ reaction [29] suggested the following feature of the energy spectrum of the forward cross section: after reaching a minimum at $T_p = 1.4$ GeV, it increased again for $T_p = 2.0$ GeV, while its angular slope changed the sign. That suggested the existence of the second peak in the cross section spectrum at the energies $T_p > 1.4$ GeV. We have preliminarily analyzed the data on this reaction at several energies in the $T_p = 1–3$ GeV range, which revealed the clear second peak with the mass $m = 2646 \pm 5$ MeV and the width $\Gamma = 132 \pm 14$ MeV. Whether this peak could be interpreted as a sign for some dibaryon resonance, for example $N\Delta(1700)$ or $\Delta(1232)N^*(1440)$, is subject to further studies.
The observation of the $D_{03}$ resonance has been performed at ANKE in the coherent $pd \rightarrow pd + (\pi\pi)^0$ channel [22], accompanied by the ABC effect.

We proposed an explanation of the ABC effect as a result of kinematic cumulation of the pion pairs in the $D_{03} \rightarrow D_{12} + \pi \rightarrow d + (\pi + \pi)_{l=0}$ decay channel due to the predominantly collinear $D_{12}$ decay.

We suggest to extract a signal for $D_{21}$ from the $pp \rightarrow \{pp\},\pi\pi$ data [26] supposing the ABC “cumulation” hypothesis.

The parameters of the $^3P_2$ dibaryon resonance have been specified at ANKE, and the $^3P_0$ dibaryon resonance has been observed for the first time in the $pp \rightarrow \{pp\},\pi^0$ reaction [27].
• Preliminary results have been obtained for the resonance peak in the $pp \rightarrow \{pp\},\pi^0$ reaction with the mass $m = 2646 \pm 5$ MeV and the width $\Gamma = 132 \pm 14$ MeV.

• Preliminary data suggest an existence of the $NN'(1535)$ resonance in the $pd \rightarrow pd\eta$ reaction. Further analysis of the data on this reaction is planned.

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