Observation of isovector dibaryon resonance-like states with a mass of 2.2 GeV/c^2

V. Komarov,[1] D. Tsirkov,[1,*] T. Azaryan,[1] Z. Bagdasarian,[2,3] S. Dymov,[1,2] R. Gebel,[2] B. Gou,[4] A. Kacharava,[2] A. Khoukaz,[5] A. Kulikov,[1] V. Kurbatov,[1] B. Lorentz,[2] G. Macharashvili,[1,3] D. Mchedlishvili,[2,3] S. Merzliakov,[2] S. Mikirtytchiants,[2,6] H. Ohm,[2] M. Papenbrock,[5] F. Rathmann,[2] V. Serdyuk,[2] V. Shmakova,[1] H. Ströher,[2] S. Trusov,[2,7] Yu. Uzikov,[1,8] and Yu. Valdau[6,9]

[1]*Laboratory of Nuclear Problems, Joint Institute for Nuclear Research, RU-141980 Dubna, Russia*
[2]*Institut für Kernphysik and Jülich Centre for Hadron Physics, Forschungszentrum Jülich, D-52425 Jülich, Germany*
[3]*High Energy Physics Institute, Tbilisi State University, GE-0186 Tbilisi, Georgia*
[4]*Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China*
[5]*Institut für Kernphysik, Universität Münster, D-48149 Münster, Germany*
[6]*High Energy Physics Department, St. Petersburg Nuclear Physics Institute, RU-188350 Gatchina, Russia*
[7]*Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, RU-119991 Moscow, Russia*
[8]*Department of Physics, M.V. Lomonosov Moscow State University, RU-119991 Moscow, Russia*
[9]*Helmholtz-Institut für Strahlen- und Kernphysik, Universität Bonn, D-53115 Bonn, Germany*

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We report on measurements of the differential cross section $d\sigma/d\Omega$ and the first measurement of the analyzing power A_y in the $\Delta(1232)$ excitation energy region of the reaction $pp \to \{pp\}_s\pi^0$ where $\{pp\}_s$ is a $^1S_0$ proton pair. The experiment has been performed with the ANKE spectrometer at COSY-Jülich. The data reveal a peak in the energy dependence of the forward $\{pp\}_s$ differential cross section, a minimum at zero degree of its angular distribution and a large analyzing power. The results establish a direct manifestation of two dibaryon resonance-like states with $J^P = 2^-$ and 0^- and an invariant mass of 2.2 GeV/c^2.

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The topic of resonances in dibaryon systems has been disputed since many years [1]. It became exciting after the prediction of such a phenomenon in the framework of quarkbag models [2]. The corresponding extensive search for the short-range six-quark systems led to the discovery of resonances in the $^1D_2$, $^3F_3$ and $^3P_2$ states of elastic pp scattering (see [3] and references therein). The corresponding poles at the complex energy plane occurred close to the ΔN branching line and the common response to that was to interpret these poles as conventional states of the ΔN channel [4]. Nevertheless, quark-gluon models employing also π and σ-meson fields were used in the last decades to describe resonance features of dibaryon systems [5–7]. The traditional meson-baryon approach aimed to determine the influence of Δ isobars on the nucleon-nucleon system dynamics also made significant progress [8, 9]. None of the models, however, reproduces the observed resonances with satisfactory accuracy yet.

The corresponding experimental database is also incomplete. It is sufficient to recall a quite unexpected recent observation of an isoscalar dibaryon resonance with a width less than the width of a free $\Delta(1232)$ isobar, in the energy region of double Δ excitation [10, 11]. Because of the lack of convincing evidence in a unique interpretation of the phenomenon, we use here the term “dibaryon resonance system” to indicate a resonant state of a hadron system with the baryon number $B = 2$.

Strong inelasticity of the $^1D_2$, $^3F_3$ and $^3P_2$ resonance states leads to better conditions for their investigation in the inelastic process

$$p + p \to d + \pi^+. \tag{1}$$

The relevant amplitudes ^1D_2p, ^3F_3d, ^3P_2d (small letters denote the pion wave angular momentum) determine the existence of the well-known extensive peak in the energy dependence of the reaction cross section [12]. Separation of the amplitudes can only be obtained by means of a thorough partial wave analysis (PWA) and requires a great amount of experimental data. The situation is rather unsatisfactory for the least intensive ^3P_2d transition being differently reproduced in various PWA solutions [13].

Quite new possibilities arise from using the spin-isospin partner of reaction (1),

$$p + p \to \{pp\}_s + \pi^0, \tag{2}$$

where $\{pp\}_s$ denotes a pp pair with an excitation energy less than 3 MeV, which ensures the pair to be in the $^1S_0$ state. Full kinematical similarity of the reactions should provide similar behaviour of the reaction amplitudes in the states with the same quantum numbers of the initial proton pair and the final pion in both processes. Spin zero of the final nucleon pair reduces the number of transitions allowed in reaction (2) compared with (1). Only ^3P_2d is kept from the three resonant transitions observed in reaction (1). However, the smaller cross section and the requirement of a high experimental resolution have led to a much smaller amount of data for the reaction. The proton beam energy of $T_p = 425$ MeV in the WASA experiments [14] was the highest for reaction (2) until the ANKE measurements from 353 to 1970 MeV were published [15–17]. The whole $\Delta(1232)$ excitation region has been scarcely explored yet.

In the present paper the first analyzing power data for reaction (2) in the $\Delta(1232)$ excitation region are presented; previous measurements of the differential cross section are complemented by additional points at 500, 550 MeV, and data at 700 and 800 MeV were taken with higher statistics and precision.

The measurements were carried out using the ANKE spectrometer [18] at the COSY-Jülich storage ring. Fast charged particles produced in the interaction of the stored proton beam with a hydrogen cluster-jet target and passing through the analyzing magnetic field were recorded in the forward detector. It includes multiwire gas chambers for tracking and a scintillation counter hodoscope for energy loss and timing measurements.

For identification of reaction 2, proton pairs were selected using the measured momenta p_1, p_2 of the both particles and the difference Δt in their time of flight [15]. The typical resolution in Δt was less than 1 ns (rms), which allowed a clean separation of pp pairs from $p\pi^+$, $d\pi^+$ pairs and the accidental coincidence background of 1% level. The rms resolution in the diproton excitation energy E_{pp} was 0.1–0.6 MeV at $E_{pp} < 3$ MeV and provided a reliable cut in E_{pp}.

The kinematics of the $pp \to \{pp\}_s X$ process was reconstructed on an event-by-event basis to obtain a missing-mass spectrum. The M_X rms resolution of 6–40 MeV/c^2 depending on the T_p value ensured reliable separation of the pion peak from the two-pion continuum and the low-intensity γ peak [19]. The angular acceptance of the setup allowed registration of the diprotons at the forward c. m. s. angles from 0° to 24°–120° at different energies. The rms resolution in the polar angle θ_{pp} ranged from 0.2° to 1°, depending on T_p and θ_{pp}. The registration efficiency was determined by Monte-Carlo simulations with an uncertainty of about 3%.

The integral luminosity was measured with an accuracy of 7% at each energy using pp elastic scattering and the $pp \to d\pi^+$ reaction, both recorded concurrently with the reaction under study. It includes the uncertainty of the SAID [13] differential cross sections used for normalization and the uncertainty of the registration efficiency.

The analyzing power A_y was measured with a transversely polarized beam repeatedly flipping the polarization direction between up and down. For the energies in the 353–700 MeV range the polarization was determined via the measurement of the $pp \to pp$ and $pp \to d\pi^+$ asymmetries normalized by the SAID solutions. The results gave the average value close to 0.68 ± 0.03. For the 800 MeV energy only the $pp \to pp$ channel was used, and the experimental data [21–23] were selected for normalization, resulting in the polarization of 0.57 ± 0.01.

A more detailed description of the setup, measurements and data processing may be found in [15–20]. The only essential change in the data processing was the more careful tuning of the geometry of the setup and the introduction of a kinematical fit into the procedure. It allowed the systematical errors of the cross section to be notably decreased.

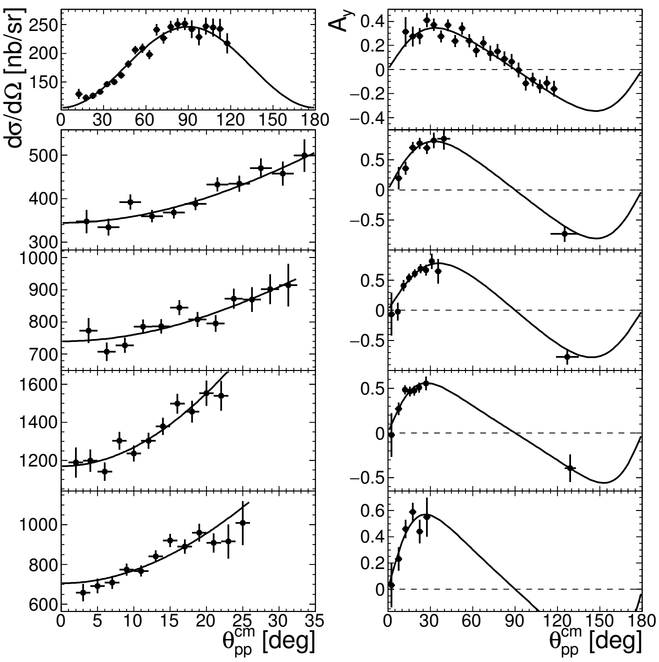

FIG. 1: Angular dependences of the differential cross section $d\sigma/d\Omega$ (left) and the analyzing power A_y (right) at the beam energies T_p equal to 353, 500, 550, 700, 800 MeV (top to bottom). The errors shown are purely statistical. The A_y values at 353 MeV are from [17], the $d\sigma/d\Omega$ ones at 353 (800) MeV are the new and [17] ([16]) data combined. The 800 MeV data published in [16] were re-analyzed using the improved procedure described in the text.

Figure 1 shows the data obtained in the 353–800 MeV region. The curves are a simultaneous fit of the relations

$$\begin{aligned} \frac{d\sigma}{d\Omega} &= \frac{k}{4p}\left(a_0 + a_2\cos^2\theta_{pp}\right), \\ A_y\frac{d\sigma}{d\Omega} &= \frac{k}{4p}\, b_2 \sin\theta_{pp}\cos\theta_{pp}, \end{aligned} \tag{3}$$

to the data at each energy. Here p is the incident c. m. s. momentum and k is the momentum of the produced pion. The relations are valid for the pion angular momentum ℓ equal to 0 and 2 [17]. The χ^2/ndf values of the fit are in the 0.5–1.5 range.

No contribution of the next higher angular momentum, $\ell = 4$, is visible within the experimental errors because of the rather narrow angular acceptance of ANKE. Therefore the main justification of the restriction $\ell < 4$ may be obtained from a comparison of reactions (1) and (2). Indeed, in reaction (1), the ratio of the amplitudes squared for the ^3H_4g, ^3F_3g transitions to that for ^3P_2d is less than

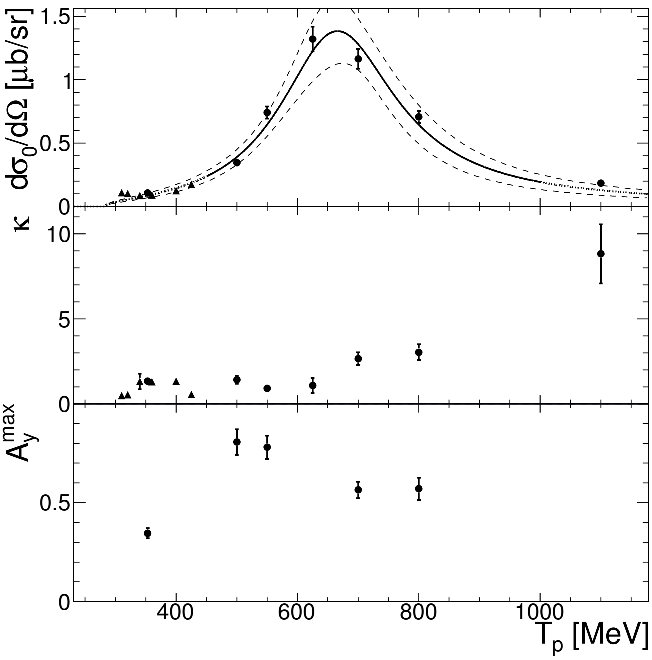

FIG. 2: Energy dependences of the parameters fitted for $d\sigma/d\Omega$ and A_y (top to bottom): forward cross section $d\sigma_0/d\Omega$, slope parameter κ, maximal analyzing power $A_y^{\max}$. • — ANKE data (combined analysis of [16, 17] and present work), ▲ — WASA data [14]. The errors include statistical and systematic uncertainties from the normalization used to find luminosity and polarization. The curve approximating $d\sigma_0/d\Omega$ is the Breit-Wigner fit in the range where the line is solid. The corridor shows the 68% confidence interval.

≈3% in the whole energy region of interest [12, 13].

Formulas (3) can be rewritten in other parametrization:

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_0}{d\Omega}\left(1+\kappa\sin^2\theta_{pp}\right), \qquad A_y = \frac{A_y^{\max}\sqrt{1+\kappa}\sin 2\theta_{pp}}{1+\kappa\sin^2\theta_{pp}}, \tag{4}$$

where $d\sigma_0/d\Omega$ means $d\sigma/d\Omega$ at the zero angle, $\kappa = a_2/a_0$ is a slope parameter and $A_y^{\max}$ is the maximal value of A_y, acquired when $\sin^2\theta = 1/(2+\kappa)$. The energy dependences of those parameters are shown in Fig. 2, where the $d\sigma_0/d\Omega$ and κ values from the earlier published data [14, 16] are included as well.

The cross section $d\sigma_0/d\Omega$ reveals a clean peak around 660 MeV, caused by the ΔN intermediate state, with a low background. The main part of the peak was fitted by the simplest Breit-Wigner form with the phase space correction: the mean value $E_P = 2182 \pm 2$ MeV/c^2, the width $\Gamma_P = 101 \pm 7$ MeV/c^2. The width is close to that for a free $\Delta(1232)$, 117 ± 3 MeV/c^2 [24].

The angular dependence of the differential cross section has a dip at zero degree. It is compatible with the WASA results [14] at low energies, where the dip was explained as a result of the s and d pion wave interference. A prominent feature of our data is the existence of this dip at all energies. The angular slope parameter varies slowly from the near-threshold region up to 800 MeV. It may indicate the presence of the s-d interference effect in the whole energy region studied. Another remarkable feature of the data is a significant analyzing power reaching a value of 0.8 for the energies of 500 and 550 MeV.

The lowest initial proton states for reaction (2) are $^3P_0$, $^3P_2$ and $^3F_2$. The states of angular momenta $L \geq 5$ can be neglected, again in similarity with reaction (1) as was pointed out above. Consequently only three possible transitions contribute: $^3P_0 \to {}^1S_0 s$ ($J^P = 0^-$), $^3P_2 \to {}^1S_0 d$ (2^-) and $^3F_2 \to {}^1S_0 d$ (2^-) with the corresponding amplitudes denoted as M_s^P, M_d^P and M_d^F.

The $M_d^F(2^-)$ amplitude may be assumed to be considerably smaller than $M_d^P(2^-)$ and non-resonant. It is justified by the relative smallness of this amplitude at 353 MeV where the PWA [17] resulted in $|M_s^P|^2 = 3271$ nb/sr, $|M_d^P|^2 = 794$ nb/sr and $|M_d^F|^2 = 36$ nb/sr. Again, the $pp \to d\pi^+$ reaction shows: the $^3F_2 d$ amplitude is significantly smaller there than $^3P_2 d$ and varies weakly in the entire $\Delta(1232)$ region [12]. Therefore, it is reasonable to restrict reaction (2) in this region to only two considerable amplitudes, M_s^P and M_d^P. Then, following [17] one gets

$$\begin{aligned} \frac{d\sigma}{d\Omega} &= \frac{k}{4p} \\ &\times\Bigg[\left(\left|M_s^P\right|^2 + \frac{4}{3}\left|M_s^P\right|\left|M_d^P\right|\cos\phi + \frac{4}{9}\left|M_d^P\right|^2\right) \\ &+\left(-2\left|M_s^P\right|\left|M_d^P\right|\cos\phi - \frac{1}{3}\left|M_d^P\right|^2\right)\sin^2\theta_{pp}\Bigg], \\ A_y\frac{d\sigma}{d\Omega} &= \frac{k}{4p}\left|M_s^P\right|\left|M_d^P\right|\sin\phi\sin 2\theta_{pp}, \end{aligned} \tag{5}$$

where ϕ is the relative phase of the two amplitudes. To estimate compliance of the two-amplitude approach with the experimental data we checked the contribution of the unaccounted amplitudes by variation of the used ones within the limits relying on the mentioned above data for reaction (1). For this we obtain at 700 MeV energy a change of $d\sigma_0/d\Omega$ less than 12%, of κ less than 26% and of $A_y^{\max}$ less than 21%. A fit of relations (5) to the $d\sigma/d\Omega$ and A_y experimental data results in $\left|M_d^P\right|^2$, $\left|M_s^P\right|^2$ and ϕ values presented in Fig. 3. At several energies below 425 MeV the cross sections [14] were used in the fit and, since at these energies A_y has not been measured, the $\left|M_d^P\right|^2$, $\left|M_s^P\right|^2$ values were found by fixing the relative phase ϕ to that of the $pp \to pp$ scattering, in accordance with the Watson theorem [25]. The pp-elastic transition phases were taken from the SAID code [13]. At the energy of 625 MeV the analyzing power has also not been measured, so it was obtained by interpolating the results at adjacent energies, $A_y^{\max} = 0.69 \pm 0.03$. The points at

400 and 425 MeV remarkably deviate from the smooth energy dependence, which can be explained by the evident non-applicability of the Watson theorem far from the reaction threshold. For this reason these points were not used in the subsequent analysis.

Figure 3 shows that both amplitudes are of a similar size and have resonance-like behaviour. The M_d^P amplitude corresponds to the known $^3P_2d(2^-)$ resonance and should have a fast change of its phase in the resonance region. The relative phase ϕ changes rather little (121°–148°) in the 450–800 MeV region, so the $^3P_0s(0^-)$ amplitude is correlated with the $^3P_2d(2^-)$ and should also have a rapid resonance-like phase change. Therefore, the observed peak in the reaction differential cross section and the zero degree dip in the angular distributions are the result of the coherent contribution of these two resonant amplitudes.

In order to describe the resonance feature of the transitions in the dibaryon system under study we used the Breit-Wigner expression modified due to the proximity to the reaction energy threshold:

$$|M|^2 = \frac{N\varGamma}{(E-E_R)^2+\varGamma^2/4},$$
$$\varGamma = \varGamma_R\left(\frac{k}{k_R}\right)^{2\ell+1}\frac{B_\ell(k_R)}{B_\ell(k)}, \qquad (6)$$

where N is a normalization factor, E is the c. m. s. energy, E_R is the mass of the dibaryon system resonance and $\varGamma$ is the energy-dependent width. The centrifugal barrier effect was employed by the Blatt-Weisskopf penetration factor model [26, 27] for a pion orbital momentum ℓ, a c. m. s. momentum k and a characteristic radius of the pion emission volume r. Here $B_2(k) = 9+3(kr)^2+(kr)^4$, $B_0(k) = 1$ and $\varGamma_R$, $B_\ell(k_R)$ and k_R are the values of $\varGamma$, $B_\ell(k)$ and k at $E = E_R$. The results depend on the factor r, unknown from an independent source and treated here as a free parameter. The $|M_s^P|^2$ distribution has a small background assumed to be constant.

A fit of the energy dependences of the amplitude squared resulted in: $E_R(2^-) = 2195 \pm 8$ MeV/c^2, $\varGamma_R(2^-) = 134 \pm 22$ MeV/c^2, $r = 5.6 \pm 0.8$ fm with χ^2/ndf $= 8/6$; $E_R(0^-) = 2199 \pm 5$ MeV/c^2, $\varGamma_R(0^-) = 94 \pm 11$ MeV/c^2 with χ^2/ndf $= 6.5/6$. The obtained parameters of the ^3P_2d resonance coincide with those found in SAID solution S96 for reaction (1): $E_R(2-)|_{d\pi^+} = 2192$ MeV/c^2, $\varGamma_R(2^-)|_{d\pi^+} = 127$ MeV/c^2. The $^3P_0s(0^-)$ resonance has not been observed earlier: the relevant transition is forbidden in reaction (1) and the $pp \to pp$ database most likely has not enough sensitivity to this resonance because of its small branching ratio into the elastic channel. However, a recent analysis [28] of several realistic NN interactions has indicated possible existence of the $^3P_0$ resonance alongside with the known $^1D_2$, $^3F_3$ and $^3P_2$ resonances.

The energy position of the resonances observed in the

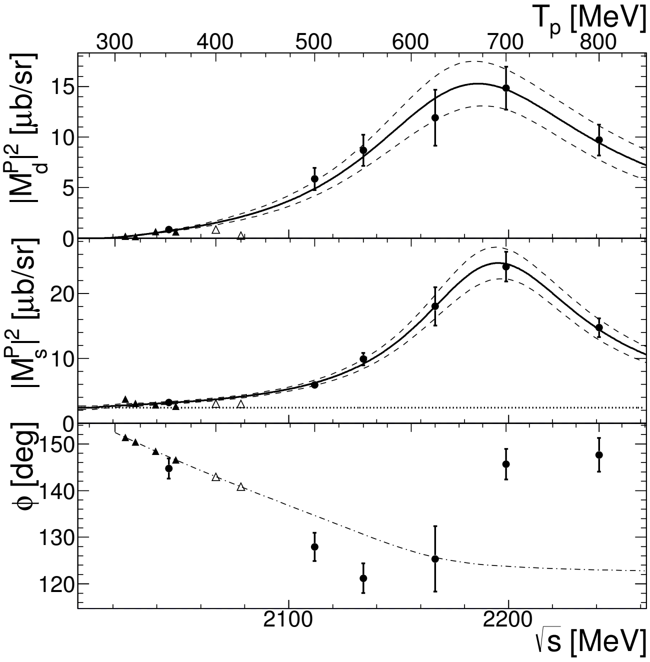

FIG. 3: Energy dependences of the found amplitudes squared of the transitions $^3P_2 \to {}^1S_0d$, $^3P_0 \to {}^1S_0s$ and their relative phase ϕ (top to bottom). The curves approximating the $|M_d^P|^2$, $|M_s^P|^2$ values are described in the text. The corridors show the 68% confidence interval. The experimental data are marked as in Fig. 2. Empty triangles are excluded from the fit for the reason described in the text. The sources of errors are the same as in Fig. 2. The dashed curve in the bottom panel shows the relative phase of the $^3P_0$ and $^3P_2$ amplitudes in the $pp \to pp$ scattering.

dibaryon system can be qualitatively interpreted assuming a resonance in the P-wave state of the $\varDelta N$ pair. In the absence of the $\varDelta N$ interaction and relative motion its mass is the sum of the $\varDelta$ and nucleon masses, which amounts to 2170 MeV/c^2. The orbital P-wave motion should increase the invariant mass by about 60 ± 7 MeV/c^2 as it takes place for P- and S-wave $\varDelta N$ resonances in reaction (1) [12, 13]. Thus, the mass should be 2230 ± 7 MeV/c^2. The difference, about 35 ± 9 MeV/c^2, between this value and the observed ones indicates the strength of the attraction in the $\varDelta N$ pair. A quantitative description of the results requires relevant model calculations employing hadronic or QCD degrees of freedom, as well as an interplay of both of them [7, 9, 29], to advance elucidation of the physical nature of dibaryon resonance states.

Summary. The measured differential cross section of the $^1S_0$ diproton forward production reveals a clean peak in the $\varDelta(1232)$ excitation energy region. The angular dependence of the pair emission has a minimal value at the zero degree through the whole energy region studied. The analyzing power is significant, its maximum varies from 0.3 to 0.8 at different energies.

A simple model assuming significant contributions of only two amplitudes, M_s^P and M_d^P, allows to describe all of the data, in particular the strong enhancement of the both amplitudes in the Δ excitation region. The energy dependence of the amplitudes squared is well reproduced by the Breit-Wigner distribution modified by the Blatt-Weisskopf penetration factor. The found parameters of the ^3P_2d resonance coincide with those known for the $pp \to d\pi^+$ reaction. The parameters of the new resonance ^3P_0s are close to them. The position of the resonances indicates a noticeable attraction in the P-wave state of the intermediate ΔN pair. Our study also suggests that the diproton formation may be similarly used in the reaction $pp \to \{pp\}_s\pi\pi$ [30] as a tool for search of isovector dibaryon resonances above the ΔN region [29].

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* Electronic address: cyrkov@jinr.ru

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