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# ON EVIDENCE FOR EXOTIC DIBARYON $d_1^*(1956)$ IN SELECTED TWO-NUCLEON-TWO-PHOTON REACTIONS

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The narrow $NN$-decoupled dibaryon resonance with a mass about 1956 MeV was reported in 2000 by DIB2$\gamma$ Collaboration (JINR, Dubna) on the basis of the measurement of the two-photon energy spectrum in the reaction $pp \to pp2\gamma$ at 216 MeV. The most probable quantum numbers $J^P = 1^+$ prevent the resonance from decaying into two protons due to the exclusion principle, while the pionic decays are impossible energetically. The significance of this resonance (called $d_1^*(1956)$) for the interpretation of a few other exclusive and inclusive reactions connected with the photon(s) production in nucleon collisions with nucleons and nuclei at different energies is discussed. The importance is stressed of on-going and planned studies of the elastic and inelastic Compton scattering on the lightest nuclei for collecting information on the structure and dynamics of $d_1^*(1956)$ which can shed light on its nature.

Узкий дибарионный резонанс с массой $\sim$ 1956 МэВ и сильным подавлением его константы связи с $NN$-состояниями был обнаружен в 2000 г. коллаборацией ДИБ2$\gamma$ на основе измерения энергетического спектра двух фотонов, образованных в реакции $pp \to pp2\gamma$ при 216 МэВ. Наиболее вероятные квантовые числа резонанса $J^P = 1^+$ препятствуют его распаду на два протона в силу принципа Паули, а распады с испусканием пиона невозможны из-за закона сохранения энергии. Обсуждается роль этого резонанса в интерпретации ряда других эксклюзивных и инклюзивных реакций, связанных с образованием фотонов в нуклон-нуклонных и ядерных реакциях при различных энергиях. Подчеркивается важность ведущихся в настоящее время и планируемых экспериментов по изучению упругого и неупругого комптоновского рассеяния на легчайших ядрах для получения информации о структуре и динамике $d_1^*(1956)$-резонанса, которая может пролить свет на его природу.

PACS: 13.75.Cs; 12.39.Mk; 13.60.Fz; 25.10.+s

## INTRODUCTION

Multiquark systems involve more complicated color subsystems which cannot be studied in the simplest meson and baryon systems. Therefore, multi-$q$'s are principally important for a full study of the low-energy typical hadronic-scale behavior of QCD and the structure of strongly interacting matter. The theory of strong interaction, QCD, is still unable to predict the properties of the multiquark systems such as nuclei or other possible bound states of hadron clusters. Even in the simplified case of $SU(2)$ gauge symmetry, the lattice calculation of the four-quark systems (e.g., [1] and references therein) is still in the initial phase though the results already obtained show the principally important effects of mutual screening of gluon flux-tubes connecting the quarks. There are also arguments telling us that explicit gluon degrees of freedom may be involved in the description of all such multiquark states [2]. Therefore, the reliable experimental identification of even one multiquark state, e.g., the long-sought for six-quark dibaryon, would play the role of the necessary prompting for theory. Among different possibilities, the nonstrange $NN$-decoupled dibaryons with small widths look to be most promising and easy for experimental searches.

## 1. THE REACTION $pp \to pp2\gamma$ IN DUBNA AND ELSEWHERE: THE RESONANCE AND NONRESONANCE INTERPRETATION

The new experimental method using the two-photon mechanism of the production and subsequent decay of the $NN$-decoupled ($6q$)-resonance(s) in proton–proton collisions was proposed to facilitate the identification and further study of the exotic nature of these resonances [3]. This method is free of inherent difficulties of many earlier used reactions connected with the participation or production of multihadron states in the initial or final states. The specific experimental signature of the production and decay of nonstrange dibaryon, having mass below the pionic decay modes, was indicated and discussed [4]. On the basis of this method, the DIB2$\gamma$ Collaboration (JINR) observed the specific structure in the spectrum of final photons which was interpreted as the production and decay of the narrow dibaryon with the mass $\simeq 1950-1960$ MeV [5]. The diagram in Fig. 1 with the double line representing an intermediate resonance may serve as an illustration to different processes touched upon in the subsequent sections. With the solid lines in Fig. 1, representing free nucleons, it describes the double-photon production in the nucleon–nucleon collisions (Sec. 1); if all nucleons are bound inside nuclei, it may be considered as the photon scattering on the correlated pair of nucleons in a nucleus, or just as the Compton scattering on the deuteron (Sec. 2); and if the initial photon line is replaced by any meson line this diagram can be referred to as the photon production in a meson capture by a correlated nucleon pair accompanied by the resonance excitation or just as a part of the resonance excitation process induced via the strong initial nucleon–nucleus interaction.

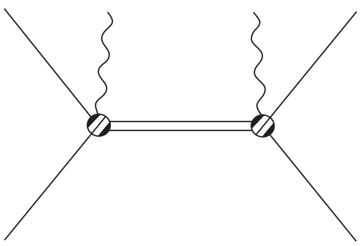

Fig. 1

The energy spectrum for coincident high-energy photons ($\omega_\gamma > 10$ MeV) emitted from the process $pp \to \gamma\gamma X$ at an energy of 216 MeV, measured by the DIB2$\gamma$ Collaboration, consists of a narrow peak at a photon energy of about 24 MeV and a relatively broad peak at an energy around 65 MeV with the statistical significance $5.3\sigma$ and $3.5\sigma$, respectively [5].

In the overall center-of-mass system the energy of the photon $\omega^F$ associated with the resonance production (formation) is determined by the mass $M_R$ of the resonance and the energy of colliding nucleons $W = \sqrt{s}$ as

$$\omega^F = \frac{W^2 - M_R^2}{2W}. \tag{1}$$

It is clear that owing to narrowness of the considered dibaryon resonance the energy distribution of these photons should also be very narrow. The energy of the photon $\omega^D$ arising from the three-particle decay of the resonance $d_1^*$ in its rest frame is given by

$$\omega^D = \frac{M_R^2 - M_{NN}^2}{2M_R}, \tag{2}$$

where $M_{NN}$ is the invariant mass of the final $NN$ state which is determined by the relative momentum of the nucleons in this state. Since the momentum distribution of $M_{NN}$ is closely connected with interaction between these nucleons, the energy distribution of photons from the resonance decay will be strongly sensitive to $NN$ final state interactions (FSI).

The KVI Group (Groningen) accumulated a large sample of the $2\gamma$ events at lower energy of the incident proton beam 190 MeV. In their published work [6], they prefer to interpret the similar structure of the photon spectral distribution as due to a nonresonance mechanism of the double bremsstrahlung. In principle, the initial kinetic energy of proton $T_p = 190$ MeV is sufficient to produce the $d_1^*(1956)$-resonance together with the photon energy $\omega^F \simeq 12$ MeV which is two times lower than the photon energy in the JINR experiment. However, due to lower energy of the initial proton in the KVI experiment, the cross section of the resonance excitation is markedly ($\sim 2^3 = 8$) lower than in the Dubna experiment and the nonresonance mechanism, i.e., ordinary double bremsstrahlung of photons, appears to become comparable with the resonance mechanism and interferes with it preventing the reliable separation of two mechanisms.

Taking for granted the resonance mass $M(d_1^*) = 1956$ MeV, one gets the maximal value $M_{\gamma\gamma} \simeq 63$ MeV coming as a result of the resonance excitation at $T_p = 190$ MeV, while the experimental distribution in the KVI experiment shown in Fig. 2, *b* [6] extends for significantly higher values testifying to significant nonresonance two-photon production. The resolution of the question about the relative contributions of the resonance and nonresonance mechanisms would consist in the long ago suggested way of checking the sign of the resonance presence, namely, in the repetition of the experiment at several initial proton energies below the $\pi^0$ threshold to observe the quantitatively calculable shift of the narrow peak.

Two more exclusive experiments should be mentioned which deal with the photon production in the proton–proton reactions at higher energies. First, the CELSIUS–WASA Collaboration [7] analyzing its *pp*-bremsstrahlung data collected at 200 and 310 MeV claimed

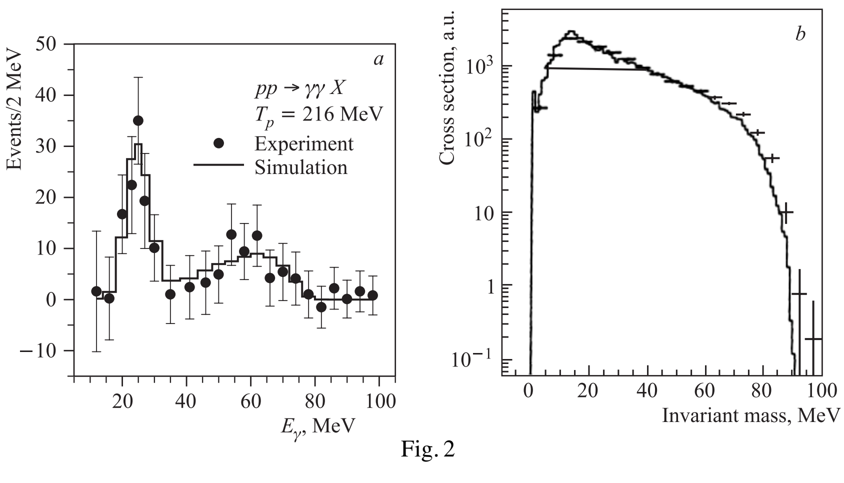


Fig. 2

that it did not find the signal of narrow dibaryon in the mass range from 1900 to 1960 MeV. Further, rather recently, the same CELSIUS–WASA Collaboration reported on a study of the exclusive reaction $pp \to pp\gamma\gamma$ at energies of 1.36 and 1.2 GeV [8] which resulted in the measurements of the invariant mass spectra of photon pairs emitted from this reaction. These measurements enable one to construct the invariant mass spectrum ($M_{\gamma\gamma}$) of its photon pairs. The surprising feature of the measured spectra is that they both contain pronounced resonant structures located at about 290 MeV. The conservative estimates of the statistical significance amount to $4.5\sigma$ for the spectrum measured at $T_p = 1.36$ GeV and to $3.2\sigma$ — at $T_p = 1.2$ GeV. We made a simple model-dependent analysis showing that it is the dibaryon mechanism of the two-photon production in $pp$ collisions $pp \to \gamma d_1^* \to pp\gamma\gamma$ that bears the responsibility for these structures at higher energies [9] and why the same mechanism and the adopted experimental cuts did not discover the signal of $d_1^*(1956)$ in the $pp$-bremsstrahlung data accumulated in measurements at 310 MeV which are most full and reliable.

Briefly, the model assumptions are illustrated by a sequence of transitions in the matrix element of the process

$$\begin{gathered}
M(p_1p_2 \to \gamma_1\gamma_2 p_1' p_2') = M_F M_I M_D, \\
M_F = M_F(p_1p_2 \to \gamma(k_1,\ \epsilon_1)_{M1}, \Delta_1(1231)_{\rm virt}\ p_2), \\
M_I = M_I(\Delta_1(1231)_{\rm virt}\ p_2 \to d_1^*(1956) \to \Delta_1'(1231)_{\rm virt}\ p_2'), \\
M_D = M_D(\Delta_1'(1231)_{\rm virt} \to p_1'\gamma(k_2,\ \epsilon_2)_{M1}).
\end{gathered} \tag{3}$$

The ingredients of the quantum-mechanical (i.e., noncovariant) calculation have been the spin-angular and radial parts of the total $\Delta(1231)N$ wave function, the usual structure of the dominating magnetic-dipole ($M1$), spin-dependent $\Delta \to N\gamma$ radiative transition vertex, and the initial and final antisymmetric $pp$-continuum wave functions. The fitting parameters of the quasi-bound $\Delta N$ wave function resulted in the ratio $\sqrt{\langle r^2\rangle_d/\langle r^2\rangle_{d_1^*}} \simeq 3.6$, which means that the average distance between the baryon constituents in $d_1^*(1956)$ is markedly less than in the deuteron and that a significant overlap of internal quark structures of the virtual $\Delta$ and nucleon inside the $d_1^*$-resonance has to take place. In turn, this hint can be of importance in construction of more detailed QCD-based dynamical models of the $d_1^*(1956)$-resonance.

Leaving the absolute normalization of the cross section arbitrary, i.e., normalized to experiment, we present only the calculated distribution of $M_{\gamma\gamma}$ in comparison with that measured at the proton energy 1.36 GeV [8], Fig. 3, *a*, and at the proton energy 0.31 GeV [7] in comparison with the distribution from the $\pi^0$ decays. Being very close to each other as seen in Fig. 3, *b*, both kinds of last events were dropped of registration because both were considered as the background. Hence, the conclusion about absence of the $d_1^*$-excitation traces can follow.

The next picture, Fig. 4, refers to somewhat «artificial» situation of the reaction $p(T = 2\ \text{GeV}) + p \to \gamma + d_1^*(1956) \to 2\gamma + 2p$, with the two-photon opening angle $28+26\,^\circ$, each item is counted off the initial beam direction, and the final proton phase space is integrated over. The calculated $M_{\gamma\gamma}$ distribution normalized to unity can nevertheless be compared with the invariant $2\gamma$-mass distribution measured in the inclusive nuclear reaction $d(2\ A\text{GeV}) + {}^{12}\text{C} \to 2\gamma + X$ [10], where a resonance structure was observed with $\Gamma_{\rm tot} = (63.7 \pm 17.8)$ MeV at $M_{\gamma\gamma} = (360 \pm 7 \pm 9)$ MeV on the basis of collected statistics $(2339 \pm 340)$ events,

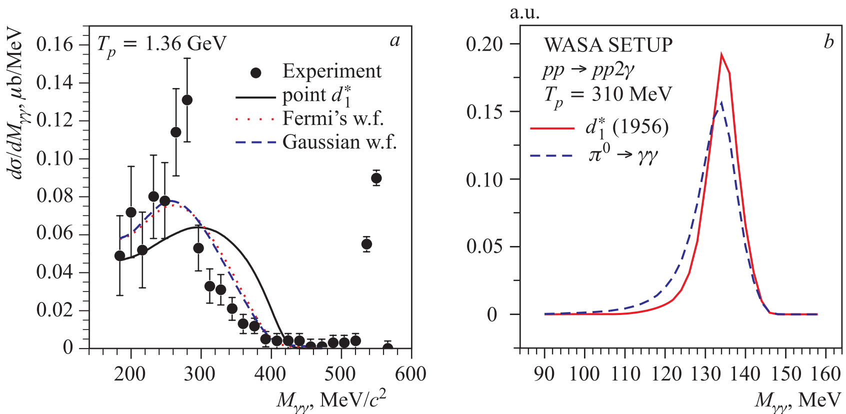


Fig. 3

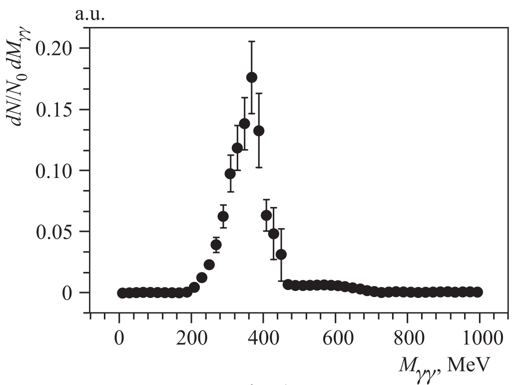


Fig. 4

obtained with the setup including the above-mentioned photon's opening angle. Close coincidence of maxima of the $M_{\gamma\gamma}$-mass distributions at $\simeq$ 360 MeV gives, in our opinion, a viable interpretation of the resonance structure observed in the nuclear reaction as due to $d_1^*(1956)$-dibaryon radiative production with subsequent radiative decay.

## 2. SEARCH FOR EVIDENCE OF EXOTICS IN REACTIONS $pd \to \gamma X,\ \gamma d \to \gamma d(\gamma np)$ OR ALIKE

The last example refers to the inclusive reactions $pd \to \gamma X$ and $p\mathrm{C} \to \gamma X$ below the $\pi^0$ threshold, where the inclusion of the $d_1^*(1956)$-excitation and its radiative decay in addition to an ordinary mechanism of single-photon bremsstrahlung helps to describe the measured photon energy distribution [11]. Note that $\mathrm{BR}(d_1^* \to \gamma pn) \simeq 1$, which means that the allowed, in principle, resonance excitation in the *strong* $pd$ interaction turns out to be of the order of $NN$-bremsstrahlung cross section which is the lowest order *electromagnetic* process (i.e., of the order $\mathcal{O}(\alpha_{\mathrm{em}})$).

The experimental data and theoretical curve (the dashed line) are taken from [12] and [13] in Fig. 5, *a*, and from [14] in Fig. 5, *b*.

| Reaction | $\alpha_{p[n]}$ | $\beta_{p[n]}$ |
|---|---|---|
| $\gamma p \to \gamma p$ | 12.1(.3) | 1.6(.4) |
| $n + \mathrm{Pb} \to n + \mathrm{Pb}$ | [12.0(1.5)] | — |
| $\gamma d \to \gamma d$ | [8.8(2.4)] | [6.5(2.4)] |
| $\gamma d \to \gamma np$ | [12.5(1.8)] | [2.7(1.8)] |

Presently, much of the information on the fundamental properties of the neutron has to be extracted from the processes including atomic nuclei. In particular, this refers to the coefficients of electric and magnetic polarizabilities of the neutron. Naturally, data on the elastic and quasi-elastic Compton scattering on the deuteron are the most accurate and easily interpretable by the theory. The amplitude $T_{\gamma\gamma}(s,t)$ of the Compton scattering

$$T = (\varepsilon' \cdot \varepsilon) A_1(s,t) + \ldots$$

depends, in the low-energy limit, on static properties of a given target particle and its coefficients of the electric $(\alpha)$ and magnetic $(\beta)$ polarizabilities. Omitting the spin-dependent terms and higher polynomials in $\omega$, we have

$$A = -\frac{(eQ_N)^2}{m_N} + 4\pi(\alpha_N + \beta_N \cos\theta)\omega^2. \tag{4}$$

The data that have been accumulated for many years from different processes and gradually improving with the time are reproduced in the Table (the units are $10^{-4}$ fm$^3$) [15].

Encoded into the effective Lagrangian

$$\mathcal{L} = -\frac{1}{m^2}(\alpha+\beta)\partial_\mu(\bar\psi)(\partial_\nu\psi)F_{\mu\lambda}F_{\nu\lambda} + \frac{1}{2}\beta F_{\mu\nu}F_{\mu\nu}\bar\psi\psi,$$

the «meson» polarizabilities of nucleons can be used in different low-energy reactions, such as the Compton effect on heavier nuclei, etc. The study of $\gamma d \to \gamma d$ enables one to extract the «isoscalar(vector)» polarizabilities of the nucleon $\alpha^{s,v} = (1/2)(\alpha_p \pm \alpha_n)$ and $\beta^{s,v}$. The

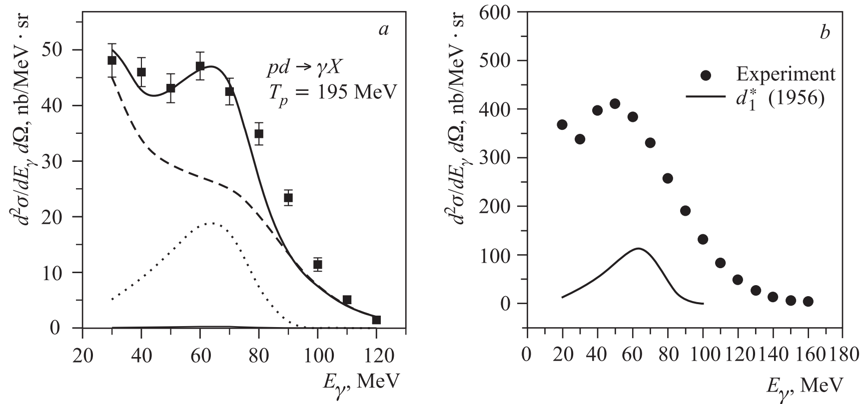


Fig. 5

lower-energy extractions from experiments at $\omega = 49$ and 69 MeV (Urbana Univ.) and at 55 and 69 MeV (Lund, MAXLab) are consistent with small isovectorial polarizabilities [15]. The treatment of the higher energy $\omega = 94$ MeV experiment (SAL, Saskatoon) with the earlier theoretical calculations [16] gives

$$(\alpha^s - \beta^s) = 2.6 \pm 1.8$$

instead of expected value $\simeq 9.0$ (in units of $10^{-4}$ fm$^3$). More recent and corrected calculation of the same authors, presented as the contributed paper at EMIN-2009, essentially removed this discrepancy.

In view of available data and planned experiments on the $\gamma d \to \gamma d$ reaction we stress its utility to inquire on new information and/or constraints on characteristics of $d_1^*(1956)$, in this «formation-type» resonance excitation process. The contributions of possible $NN$-decoupled dibaryon resonances to the photon–deuteron processes like $\gamma d \to \gamma d$ or $\gamma d \to \pi^- pp$ have earlier been considered in [17]. The emphasis was made there on the isoscalar resonances with quantum numbers $I = 0, J^P = 0^{\pm}, 1^-$. Continuing our earlier line of discussion [18], we focus here on the $d_1^*(I = 1, J^P = 1^+)$-resonance and present some additional comments aiming to attract more attention to the specifics of the explication of this resonance in the energy range pertinent to the forthcoming new data on the Compton scattering from deuteron and $^3$He. We have in view the ongoing investigation of the $\gamma d$ reaction in MAXLab, where the tagged-photon facility will be used to measure the scattered photon angular distribution between 60 and $150^\circ$ over the photon energy range $60-115$ MeV in 5 MeV steps [19].

Below we give the estimation of the contribution of the photoexcitation of $d_1^*$ into the averaged differential $\gamma d$-scattering cross section and to the real part of the dynamic magnetic polarizability of the deuteron which should, in principle, be added to the meson polarizabilities of bound nucleons as an additional structure-dependent effect that might influence the observables of the $\gamma d$-elastic scattering, around the photon energies close to $\omega_{\rm lab}^{\rm res} \simeq 82$ MeV, the resonance photoexcitation energy of $d_1^*(1956)$. The second mentioned estimation can be done with the help of the known dispersion sum rule

$$\mathrm{Re}\ \delta\beta(\omega) = \frac{1}{2\pi^2} P \int d\omega' \frac{\sigma^{\rm BW}{}_{M1}(\omega')}{\omega'^2 - \omega^2}, \tag{5}$$

where the cross section of the magnetic-dipole radiative transition $\gamma d \to d_1^* \to X$ is taken in the standard Breit–Wigner form, in which one should define $\Gamma_{\rm tot}(d_1^*)$ and $\mathrm{BR}(d_1^* \to \gamma d) \leqslant 1$. The data of the SAL Collaboration [20] on $\gamma d$ scattering at $\omega_{\rm lab} \simeq 94$ MeV have the scale of 12–18 nb/sr, with variations of approximately 2 nb/sr in energy bins of $\Delta W \simeq 3$ MeV. The distance of their energy from the presumed $\omega_{\rm lab}^{\rm res} \simeq 82$ MeV is much larger than $\Gamma_{\rm tot}(d_1^*)$ and this enables one to get an upper bound of $\Gamma(d_1^* \to \gamma d) \leqslant 5$ keV which is rather weak one. Much stronger bounds will follow from the forthcoming data of MAXLab measurements in the resonance region $\omega_{\rm res} \pm 2 \simeq (82 \pm 2)$ MeV. For instance, if we take maximally large $\mathrm{BR}(d_1^* \to \gamma d) = 1$, then the resonance enhancement of the cross section, averaged over $\Delta W \simeq 3$ MeV, by amount, say, of $5 \cdot \delta\langle d\sigma/d\Omega\rangle = 10$ nb/sr will result in the total width estimate of $\Gamma_{\rm tot}(d_1^*) \simeq 1$ eV. Hence, either $\Gamma_{\rm tot}(d_1^*)$ acquires the values of the order of $\mathcal{O}$(eV), as estimated within the soliton model of the narrow $NN$-decoupled dibaryons [23], or $\mathrm{BR}(d_1^* \to \gamma d) \ll 1$, which would still need proper dynamic justification. The evaluated $\mathrm{Re}\ \delta\beta(\omega)$ reveals the crossover at $\omega = \omega_{\rm res} \simeq 82$ MeV, but as it is proportional to the value of $\Gamma_{\rm tot}(d_1^*)$, the maximal difference of its values before the crossing zero and after the crossing is of percent order as compared to typical experimental uncertainty of $\beta_{p[n]}$ itself, that is negligibly small.

Returning to the discussed $pp \to pp2\gamma$-processes exhibiting the positive signs of the $d_1^*(1956)$-excitation and decay, it is natural to expect that the effective strength in the vertex $\mathcal{V}((pp)_{J^P,I=1};\, \gamma;\, d_1^*)$ may be quite different (in fact, higher) as compared to effective coupling in the vertex $\mathcal{V}(d_{J^P=1^+,I=0};\, \gamma; d_1^*)$. This will result in a quantitatively different effect of the resonance explication in the Compton scattering on $^3$He or on $^4$He comparatively to the Compton scattering on deuteron target. This means, therefore, that the resonance effect should be estimated and properly taken into account in the extraction of the neutron polarizabilities from the planned studies of the elastic $\gamma^3$He scattering, either in the spin/polarization-independent experimental setup (e.g., [21]), or in experiments aiming to measure the spin-dependent electromagnetic polarizabilities which are under preparation at TUNL (USA) [22].

## 3. CONCLUDING REMARKS

We briefly discuss here the question of probable $d_1^*(1950{-}1960)$ quantum numbers.

• Among theoretical models predicting dibaryon resonances with different masses there is one giving the state with $IJ^P = 11^+$ and the mass value ($\sim 1940$ MeV) surprisingly close to the value ($\simeq 1956$ MeV) extracted from the observed maximum of the $pp \to pp2\gamma$ reaction. This is the chiral soliton model [23] applied to the sector with the baryon number $B = 2$. The theoretical uncertainty at the level of $\pm 30$ MeV might be taken here because the model gives this numerical (unrealistic) value for the mass difference of the deuteron and the singlet level. However, the estimated radiative width of the order $\sim \mathcal{O}$(eV) may seem to be too low.

• There is also a kind of the hadron-constituent oriented models, e.g., the relativistic dynamic $\pi NN$-interaction model based on the Faddeev-type equations with the specifically chosen ansatz for the off-mass-shell pion–nucleon interaction amplitude [24]. Specific feature of the last-mentioned approach is the statement about the relative orbital moment $l = 1$ and isospin $I = 2$ for the most strongly bound cluster configuration $P_{33}(\pi N) + N$ of the considered three-body $\pi NN$ system. Yet the estimated resonance mass is different from the value suggested by experiment.

• In the composite models, the cluster decomposition $(6q) = (3q) \times (3q)$ or $(6q) = (qq) \times (qq) \times (qq)$, or $(6q) = (qq) \times (qqqq)$ can be assumed. The fractional-parentage expansions of colour-singlet 6-quark states in a cluster model were considered in several works (e.g., [25]).

For qualitative estimations one can choose the $N\Delta$ model with possible values of spin ($S$) and isospin ($I$) $S(I) = 1$ or 2. In fact, this model was used in our calculations of the $2\gamma$-invariant mass distribution to be compared with data of the CELSIUS–WASA Collaboration. The quantum numbers of relevant dibaryons within the 3-diquark model, which are consistent with the Bose nature of diquarks and $L = 0$ for total orbital moment, require two axial-vector ($J^P = 1^+$) diquarks with isospin $I = 1$ and one (iso)scalar diquark ($J^P = 0^+$). This model gives the following combinations of the total spin and isospin for the lowest mass dibaryons: ($I = 1, J = 0$, i.e., the quantum numbers of the «virtual» $NN$ state), ($I = 0, J = 1$, i.e., the quantum numbers of the deuteron), ($I = 2, J = 1$ — the exotic, $NN$-decoupled quantum numbers for narrow dibaryon) ($I = 1, J = 2$ coinciding with the quantum numbers of known ${}^1D_2$ (2.17)-resonance, lying close to the $N\Delta$ threshold). The overlap of possible $NN$-decoupled quantum numbers with $L = 0$ following from either $N\Delta$ or diquark model selects as more probable isospin and spin values $I = 2, J = 1$ for our low-lying $d_1^*$-resonance. However, one can escape a potentially problematic situation with the long-lived isotensor ($I = 2$) dibaryon if one unites, following [26, 27], one axial-vector diquark ($A_2$) and one scalar diquark ($S_2$) into a single four-quark cluster ($A_4 = S_2 \otimes A_2$) which should be the color-triplet isovector ($I = 1$) and spin-parity $J^P = 1^+$. Hence, as most perspective we would suggest for $d_1^*(1956)$ the following configuration structure:

$$|d_1^*(1956)\rangle = c_0|N, \Delta\rangle + c_{\bar{3}_c 3_c}|S_2(\bar{3}_c, 0^+), A_4(3_c, 1^+)\rangle.$$

The presence of the color-octet $3q$-baryons is associated in the decomposition of [25] with the antisymmetric radial wave function, hence with the negative parity and, therefore, we drop it. Needless to say in conclusion that deciphering and testing of such a complex structure would require further development of the theory and new experimental data.

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