Radiative processes of nucleon interactions and possible existence of exotic dibaryons
S.B.Gerasimov
Bogoliubov Laboratory of Theoretical Physics, JINR,Dubna

Abstract

The cross section of the reaction \( pp \rightarrow pp\gamma\gamma \) is estimated and the exploration possibilities of this reaction to probe for a possible excitation of subnuclear degrees of freedom in two-nucleon systems, in particular, the production and decay of the NN-decoupled dibaryon resonances, are briefly discussed. Some arguments for and implications of the intermediate dibaryon resonance excitation are inferred from preliminary data on the two-photon yield and energy distribution observed by the DIBAR2\( \gamma \) - Collaboration at the kinetic energy of the initial proton \( T_{lab} \approx 200\text{MeV} \).

1 Introduction

In this report, we are addressing still unexplored reaction of two-photon production in nucleon-nucleon interactions. Our immediate motivation to start the discussion of this reaction is the experiment in progress at JINR aimed at observing 2\( \gamma \)-emission in \( pp \)-interaction below the pion threshold and thereby to probe a possible existence of exotic dibaryon resonances in the corresponding mass-range. We believe, however, that these reactions merit dedicated studies on their own right. In particular, they could contribute to our understanding of dynamics of two-current processes with few-nucleon systems, like the Compton scattering on nuclei, and to serve as a source of information on the role of subnucleonic degrees of freedom in different kinematic conditions. The double (in general, multiple) bremsstrahlung of photons by nucleons may be relevant to determine the space-time extension of the emittance region, arising during nucleus-nucleus collisions, via the study of the intensity (or the Hanbury-Brown and Twiss) correlations of photons, registered in coincidence. Evidently, the observation of the two-photon emission is interesting but very difficult experimentally, the main difficulties being the low production cross section and requirements of good resolution and an effective discrimination of the background. A few examples illustrating this statement can be listed. For two-photon emission in electron-atom collisions, the considerable efforts and time were needed after the first claims \(^\text{1}\) of observation of this process, to bring subsequent measurements \(^2\) into a qualitative agreement with existing calculations \(^3\). In the area of low energy nuclear and particle physics, two-photon decays of some levels in heavy \(^{131}Xe,^{137}Ba\) \(^4\) nuclei are known in the case of competition with the one-photon \( M4 \)-transitions, the observed branching ratios being of the order \( O(10^{-3}) \). In \( 2\gamma \)-decay of the \( 0^+(3.35\text{MeV}) \)-excited state in \( ^{40}Ca \) \(^5\), where one-photon transitions are forbidden, and in the two-photon \( \pi^- \)-absorption in nuclei \(^6\) the relative probability of \( 2\gamma \)-emission is of the order \( O(10^{-4}) \). Taking these branching ratios as a typical order-of-magnitude estimation for the two-photon emission one can expect a very favorable background situation while looking for resonance enhancement effects in the reaction \( pp \rightarrow pp\gamma\gamma \) with even a weak resonance signal. The explicit estimation of both the non-resonance and resonance mechanism contribution to cross sections will be given in Section 3.

\(^1\) This work was supported by the RFBR, grants No. 96-02-197147 and 96-15-96423
2 Experimental Study Motivations and Data

In this section some results are reproduced of the first study of the reaction $pp \rightarrow pp\gamma\gamma$ at the proton energy $\sim 200\text{MeV}$ [7].

We believe that in addition to the ordinary bremsstrahlung, $pp \rightarrow pp\gamma$, the two-photon production process also deserves a special investigation as a source, maybe, of a unique information on some important aspects of hadrodynamics, underlying the NN-interaction. In particular, the primary goal in this study was to probe possible existence of exotic narrow dibaryon resonances that could escape distinct observation in other reactions used earlier for the same aim.

Existence of narrow states with a baryon number $B = 2$ was considered in several QCD-inspired models [8, 9, 10] and in alternative standard models of the NN-interaction [11]. However, all available predictions for their masses and widths are model-dependent and, therefore, cannot be treated as reliable yet. The experimental situation has been somewhat confused. Although a number of claims were made for the observation of narrow structures [12, 13, 14, 15], some of them were not confirmed in later experiments [16]. Most of the dedicated experiments performed so far were aimed at looking for NN-coupled dibaryon resonances. Meanwhile, one might consider some processes leading to formation of dibaryons with quantum numbers for which the direct decay $2B \rightarrow NN$ is either forbidden by the Pauli principle, or strongly suppressed by the isospin selection rule (NN-decoupled dibaryons). In this respect the process $pp \rightarrow \gamma^2B \rightarrow pp\gamma\gamma$ has unique possibilities of searching for and investigating narrow NN-decoupled dibaryon resonances with masses below the pion production threshold [18, 19].

The method of searching for these narrow dibaryon resonances is based on the measurement of the photon energy distribution in the $pp \rightarrow pp\gamma\gamma$ reaction by detecting both photons in coincidence. The narrow dibaryons, if they exist, should be seen as sharp $\gamma$-lines against a smooth background due to the photons from the radiative resonance decays ($2B \rightarrow \gamma pp$) and double pp-bremsstrahlung with an anticipated good signal-to-background ratio. The position of this line depends on the energy of the incident proton and the resonance mass $M_B$. Its width is determined by the total width of resonance $\Gamma_{tot}$ and energy resolutions of the experimental setup. In Ref. [17] the first results were reported of searching for the narrow NN-decoupled dibaryons in the process $pp \rightarrow \gamma^2B \rightarrow pp\gamma\gamma$ at the proton energy $\sim 200\text{MeV}$. Measurements of the $\gamma$-ray energy spectra of this reaction showed a well noticeable peak at the energy $E_\gamma \sim 47\text{MeV}$, which was interpreted as evidence for the narrow dibaryon resonance with a mass $\sim 1917\text{MeV}$.

Unfortunately, the statistics of that experiment was insufficient to draw any firm conclusion on existence of the narrow dibaryon.

In what follows some results are reproduced from Ref. [18] on new measurements of the photon energy spectra for the process:

$$pp \rightarrow \gamma^2B \rightarrow \gamma\gamma pp$$

(1)

The experiment was performed with a proton beam from the JINR phasotron with the proton energy 198 MeV and the energy spread about 1.5%. The experimental setup includes a liquid hydrogen target and two detectors of $\gamma$-quanta placed on either side of the beam to detect backward emitted photons at angles of $111^0$ and $240^0$, respectively. The solid angles covered by photon detectors were 35 msr and 70 msr, respectively. The energy spectra of $\gamma$-rays were measured in the energy range from 10 to 100 MeV. In the spectrum obtained as a result of subtraction of the empty target contribution a structure at energy near 42 MeV is clearly seen.
fit to a Gaussian gave the energy of the observed peak $42.0 \pm 4.5$ MeV with width (FWHM) $26.3 \pm 4.0$ MeV. If one assumes that a narrow dibaryon resonance is responsible for this peak, then one can reconstruct the corresponding dibaryon mass distribution. This distribution has a maximum at $M_B \sim 1923$ MeV. When fitted with a Gaussian, the distribution gave a fitted mass $1923.5 \pm 4.5$ MeV and a width FWHM $31.3 \pm 5.0$ MeV.

To conclude this section, the γ-ray energy spectrum for the $pp \rightarrow pp\gamma\gamma$ reaction at the proton energy 198 MeV has been measured in Ref.[7]. A distinct enhancement at the photon energy about 42 MeV was observed in measured energy spectrum. It can be interpreted as a signal due to the narrow exotic dibaryon $^2B$ formation and decay in the $pp \rightarrow \gamma^2B \rightarrow pp\gamma\gamma$ processes. Distribution of the dibaryon mass obtained under this assumption shows a narrow peak with mass $M_B = 1923.5 \pm 4.5$ MeV and width FWHM = $31.3 \pm 5.0$ MeV. The statistical significance of this peak exceeds $8\sigma$. The results presented in Ref.[7] are in agreement with the previous ones [1].

### 3 A Model Estimation of Effect and Background.

In two decades after the first attempts of theoretical description of the six-quark (or dibaryon) states[20] the whole situation in theory remains obscure. The lattice QCD approaches to the multiquark, e.g. the $q^2q^2$ states[21] were instrumental to-date only in the denying of some simple pairwise forms of the $qq$-interaction, which were guessed and used in the potential and cluster models of multiquark (mainly, six-quark) states. Therefore we adopt the explicitly phenomenological approach in our estimations. Having in mind the completeness of colourless hadron states, we shall estimate the probability of the radiative transition $d_1(IJ^P = 1^+) \rightarrow \gamma pp$ or the inverse reaction $pp \rightarrow \gamma d_1$ as a two-step process, where the presumably lowest pp-decoupled state with the $J^P = 1^+$, tentatively called $d_1$, is coupled with the initial or final hadron states through the intermediate $N\Delta$-state with the same quantum numbers. The "Δ" symbol may be referred also to the virtual $\pi N$-complex with quantum numbers of the $\Delta (1232)$-resonance but a different invariant mass. The $d_1\Delta N$-vertex is described by a simple form of the quasi-two-body wave function, for which the Hulthen-type radial dependence was chosen by analogy with the deuteron radial wave function:

$$R(r) = N\frac{1}{r} \exp(-\alpha r)(1 - \exp(-\beta(r - r_c)))$$  \hspace{1cm} (2)

where $N$ is the normalization constant, $\alpha = \sqrt{2M_{\text{red}} \varepsilon}$, $\varepsilon = M + M_\Delta - M_{d_1}$, $M_{\text{red}}^{-1} = M^{-1} + M_\Delta^{-1}$, $\beta = 5.4 fm^{-1}$, $r_c = 0.5 fm$ and $R(r) = 0$ for $r \leq r_c$ is understood. The second factor in Eq.(2), representing the behavior of wave function in the "interior" region outside the hard core with the radius of $r_c = 0.5 fm$ is taken quite similar to the deuteron case. Taking $M_{d_1} \approx 1920 MeV$ for granted, the transition magnetic moment $\mu(p\Delta^+) = 2\sqrt{2}/3\mu(p)$ according to the $SU(6)$-symmetry and plane waves for initial protons, we get an estimation

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{c.m.}} \simeq \frac{\alpha(W - M_{d_1})^3(\mu(p)I(q))^2}{9Mq} \simeq 40 \text{ nb sr}$$  \hspace{1cm} (3)

$$I(q) = \int_{r_c}^{\infty} dr r^2 R(r) \frac{\sin(qr)}{qr}$$
where $\alpha = 1/137, \mu(p) = 2.79, q \simeq \sqrt{MT_{lab}/2}, M$ is the mass of the proton. It turns out justified to neglect the retardation corrections, i.e. we are using the long-wave approximation for the matrix element of magnetic-dipole transition. Further, the result does not depend strongly on variation of the "effective" mass $M_\Delta$ from $M + m_\pi$ to $M_\Delta = 1232 MeV$. With the integrated luminosity $L = 10^{37} cm^{-2}$, the data gave about 130 events after integration over energies of both photons in the interval $10 \leq \omega_i \leq 100 MeV$. Assuming the spherical-symmetric distribution of photons, we obtain an estimate of the cross section for one of photons to be registered in the element of solid angle

$$\frac{d\sigma}{d\Omega_\gamma} \simeq 4\pi \frac{d\sigma}{d\Omega_\gamma_1 d\Omega_\gamma_2}_{exp} \simeq 65 nb/sr$$

By definition, this is the quantity which should be confronted with Eq.(3) and we estimate the result of this comparison as a reasonable one.

We turn now to the usual non-resonance double-bremsstrahlung reaction. The most reliable would be the calculation based on the NN-potential models taking into account off-shell effects in nucleon-nucleon interactions explicitly. This is, however, an extremely complex task requiring much of numerical computations. To perform the exploratory calculation, we make use of the following simplification. In the "suspected" resonance region all photons have energy $\sim 40 MeV$ at which, in one-photon bremsstrahlung reaction, the radiation by magnetic moments of interacting protons becomes to dominate over the non-spin-dependent convection current contributions. We adopt this magnetic transition dominance also for the two-photon emission in our specific energy region. Therefore two photon lines are attached in all possible ways to the external proton lines of the corresponding Feynman graphs. A set of such diagrams represents the amplitude of the reaction considered. The most drastic approximation is the use of a model construction $T_{av}$ instead of the complicated off-shell $T$-matrix of NN-scattering entering into the Feynman diagrams. The $T_{av}$ is assumed to be the spin- and angle-averaged quantity, defined through the total pp-cross section:

$$\sigma_{c.m.}^{pp}(q) = \frac{1}{2} \int d\Omega_q \frac{d\sigma_{el}^{pp}}{d\Omega_q} = \frac{(WT_{av}(q))^2}{32\pi}$$

(5)

where we keep only the energy dependence of cross sections according to the following prescription. If both photons are radiated by the initial (or final) protons, then the total cross section is taken at the invariant energy $W_f = \sqrt{s_f} = \sqrt{(p_1 + p_2 - k_1 - k_2)^2}$ or $W_i = \sqrt{s_i} = \sqrt{(p_1 + p_2)^2}$, $p_j(k_j)$ are the 4-momenta of corresponding protons(photons), $j = 1, 2$. If one of photons is radiated by initial protons and another by final ones, we propose to use the average value $\bar{W} = 1/2(W_1 + W_2)$, where $W_j = \sqrt{(p_1 + p_2 - k_j)^2}, j = 1, 2$. In calculation, we are using the pp-cross sections from available compilation thereof, except at very low energies, where the effective range parametrization with account of the Coulomb interaction is taken. We refrain from writing down all standard phase space and normalization factors and cite only the result obtained after integration over energies of photons in the interval $10 \leq \omega_j \leq 100 MeV$, the angle between photon directions being $\vartheta = 130^0$:}

$$\left(\frac{d\sigma_{el}^{2\gamma}}{d\Omega_{\gamma_1} d\Omega_{\gamma_2}}\right)_{nonres} \simeq \frac{\alpha^2 \mu_p^4}{128\pi^5 M^2} \int d\omega_1 d\omega_2 \omega_1 \omega_2 (T_{av}(s_f) + T_{av}(s_i))^2 R(\omega_1; \vartheta) P(\omega_1; \vartheta) \simeq 1.3 \frac{nb}{sr^2}$$

(6)
\[
R(\omega_{1,2}; \vartheta) = 5a + 3b + (a - b) \cos^2 \vartheta
\]

\[
a = (1 - 2T_{av}(\bar{s})/(T_{av}(s_f) + T_{av}(s_i)))^2, \quad b = ((\omega_2 - \omega_1)/(\omega_2 + \omega_1))^2
\]

\[
P(\omega_{1,2}; \vartheta) = \sqrt{1 - \frac{2(\omega_1 + \omega_2)}{T_{lab}} - \frac{\omega_1^2 + \omega_2^2 + 2\omega_1\omega_2 \cos \vartheta}{2MT_{lab}}}
\]

\[
\frac{d\sigma_{\text{nonres}}}{d\sigma_{\text{exp}}^2} < O(10^{-3})
\]

The estimation obtained as a level of the expected physical background is seen to be much lower than the effect recorded, and this finding reinforces the probability of its interpretation as due to the NN-decoupled dibaryon resonance excitation with a subsequent dominant radiative decay. We notice that the transition into the final state where two protons form the singlet \( ^1S_0(0^+, T = 1) \) - state plays very significant role in the \( pp2\gamma \)-reaction. It is worth to make a few qualitative remarks about role of this "singlet level" in other bremsstrahlung reactions. It is easy to see that the static \( E1 \)- and \( M1 \)-transitions into the \( ^1S_0(pp) \) - state are absent in the \( pp\gamma \)-reaction, while the \( E2 \)-transition is small \( \sim O((p/m_N)^4) \). Such the suppressing factors are absent for the \( np\gamma \)-reaction. Therefore in the \( np\gamma \)-reaction and especially in the \( np2\gamma \)-reaction the transition to the \( ^1S_0(np) \) - state should be much more important and accessible for investigation. One can expect also a significant role of the meson exchange currents (MEC) in the radiative \( np \)-reactions. In particular, the study of the \( np2\gamma \)-reaction seems to be especially interesting as the check of the MEC in different kinematic conditions: the \( 0^+ - 0^+ \)-transition is possible in this case which is most sensitive to the short-range nucleon interaction. Furthermore, the knowledge of this reaction is necessary for correct interpretation of the H-B-T-type experiments dealing with the \( 2\gamma \)-interferometry in the nucleus-nucleus reactions \( AA \rightarrow 2\gamma X \) at energies below the pion threshold.

### 4 Concluding Remarks

We conclude with a few remarks.

1. Among theoretical models predicting dibaryon resonances with different masses there is one giving the state with the \( IJ^P = 11^+ \) and the mass value \( \sim 1940\,\text{MeV} \) surprisingly close to the value \( \sim 1920\,\text{MeV} \) extracted from the observed maximum of the \( pp \rightarrow pp2\gamma \)-reaction. This is the chiral soliton model applied to the sector with the baryon number \( B = 2 \). The theoretical uncertainty at the level of \( \pm 30\,\text{MeV} \) 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 cited radiative width of the order \( \sim O(e\,\text{V}) \) looks much too low.

2. Continuation of experiment in different kinematic conditions and, hopefully, with an improved photon energy resolution is of undoubted importance because the reliable discovery of even a single exotic multiquark state would be immensely important and would lead to far reaching consequences for the development of low-energy QCD in the domain both of hadron and nuclear physics.

3. Closely related processes such as the (double) radiative pion-capture or radiative muon-capture in deuterium mesoatoms would be very helpful not only as different area of checking
the very existence of exotic dibaryons, but also as a means to discriminate between possible values of their isospin. In particular, one can anticipate the spectacular anomalous high branching ratio for the radiative muon-capture in deuterium $\mu$-mesoatoms due to excitation in the intermediate state of the sufficiently low-lying $NN$-decoupled isovector dibaryon(s), like one shown up in the $2\gamma$-production, Ref.[7], but excited this time by the charged weak current. In heavier nuclei this effect may be absent due to a more probable radiationless decay of virtual dibaryon resonances in the nuclear field of nearby nucleons. These possibilities deserve more detailed elaboration and exposition that will be done elsewhere.

5 Acknowledgements

The author is much indebted to A.S.Khrykin for collaboration on different parts of this report. This work was supported in part by the Russian Foundation for Fundamental Researches, grants No. 96-15-96423 and 96-02-19147.

References

[1] J.C.Altman and C.A.Quarles, Phys.Rev. A31 (1985) 2744.

[2] J.Liu and C.A.Quarles, Phys.Rev. A47 (1993) R3479.
R.Hippler, Phys.Rev.Lett. 68 (1992) 1690.

[3] A.I.Smirnov, Yad.Fiz. 25 (1977) 1030.
M.Dondera, et al., Phys.Rev. A53 (1996) 1492.

[4] T.Alv"ager and H.Ryde, Phys.Rev.Lett. 4 (1960) 363.
W.Beusch, Helv.Phys.Acta, 38 (1960) 362.

[5] E.Beardworth, et al., Phys.Rev. C8 (1973) 216.

[6] J.Deutsch, et al., Phys.Lett. 80B (1979) 347.
E.Mazzucato, et al., Phys.Lett. 96B (1980) 43.

[7] The DIB2$\gamma$ Collaboration, V.M.Abazov, Yu.K.Akimov, V.F.Boreiko, S.N.Ershov, S.B.Gerasimov, N.V.Khomutov, A.S.Khrykin, N.A.Kutchinsky, A.B.Lazarev, A.G.Molokanov, S.N.Shilov, Yu.G.Sobolev, V.P.Zorin., JINR E1-96-104, Dubna,1996;
A.S.Khrykin, in Proc. of Int.Conf. PANIC-96, May 22-28,1996,Williamsburg, USA, (to be publ.)

[8] P.J.G. Mulders et al. Phys. Rev. D19, 2635 (1979), D21, 2653 (1980); H.J.Lipkin, Phys. Lett. 117B, 457 (1982); S.Fredrikson and M. J"adel, Phys. Rev. Lett. 48, 14 (1982); M.Imachi et al., Prog. Theor. Phys. 55, 551 (1976).

[9] L.A.Kondratyuk, B.V.Martemyanov and M.G.Shepkin, Yad. Fiz. 45, 1252 (1987)

[10] V.B.Kopeliovich, Yad. Fiz. 58 (1995),1317
[11] Yu.E.Pokrovsky, ZhETF 94, 55 (1988)

[12] C.Besliu et al., in: Relativistic Nuclear Physics and Quantum Chromodynamics (Proc. of the Xth Int. Seminar on High Energy Physics Problems, Dubna, Russia, 1990) Eds. A.M. Baldin, V.V. Burov and L.P.Kaptari, World Scientific, Singapore, p.189

[13] V.V.Glagolev et al., Preprint JINR, E1-89-246, Dubna, 1989
Ya.A.Troyan et.al, Preprint JINR, P1-90-78, Dubna, 1990

[14] B.Bock et al., Nucl. Phys. A459, 573 (1986); V.P.Andreev et al., Z. Phys. A327, 363 (1987); V.V.Avdeichikov et al., Yad. Fiz. 54, 111 (1991); Ya.A.Troyan et al., Yad. Fiz. 54, 1301 (1991)

[15] B.Tatischeff et al., Phys.Rev. C45, 2005 (1992); Z. Phys. A328, 147 (1987)

[16] N.P.Aleshin et al. Preprint LNPI, 1753, 1991; B.M.Abramov et al., Yad. Fiz. 57, 850 (1994)

[17] A.S.Khrykin, in πN Newsletter, No.10, ed. by D.Drechsel, G.Höhler, W.Kluge and B.M.K.Nefkens, October, 1995, p.67

[18] S.B.Gerasimov and A.S. Khrykin, Mod. Phys. Lett. A8, (1993)2457.

[19] S.N.Ershov, S.B. Gerasimov and A.S. Khrykin, Yad. Fiz. 58 (1995)911.

[20] V.A.Matveev and P.Sorba, Nuovo Cim.Lett. 20 (1977) 443.
R.L.Jaffe, Phys.Rev.Lett. 38 (1977) 195.

[21] A.M.Green, C.Michael and J.E.Paton, Nucl.Phys. A554 (1993) 701.

[22] R.J.Slobodrian, Phys.Rev.Lett. 21 (1968) 438.