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# PROTON-PROTON BREMSSTRAHLUNG AND NARROW DIPROTON RESONANCES

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The possibility is suggested and discussed of using the bremsstrahlung reaction in proton-proton interactions as a new tool for searching and investigating the narrow diproton resonances.

The investigation has been performed at the Laboratory of Nuclear Problems, JINR.

## Протон-протонное тормозное излучение и узкие дипротонные резонансы

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Предлагается и обсуждается возможность использования реакции тормозного излучения в протон-протонном взаимодействии в качестве нового способа для поиска и исследования узких дипротонных резонансов.

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## 1. Introduction and Motivation

The discovery of the dibaryon (and, possibly, multibaryon) resonances would, undoubtedly, be of great importance for many parts of hadron physics including nuclear physics. Although the evidences for dibaryon resonances have repeatedly been reported in many experiments, the situation cannot be regarded as a well-determined. The current status of this problem [1,2,3] advances its unambiguous solution to the level of main tasks of the nucleon-nucleon interaction physics at intermediate energies.

Among the available dibaryon candidates, the group of narrow resonances with masses $M_B$ in the range $2m_p < M_B < 2m_p + m_\pi$ presents special interest. In this paper, we suggest discussing the novel means of searching and investigating the dibaryon resonances of that type. Our main purpose is to show the utility and expediency of the proton-proton bremsstrahlung to search for the narrow diproton resonances.

As the starting arguments in favour of this proposal the following remarks appear to be pertinent:

- The common feature of all dibaryon candidates is the small value of their coupling to the $NN$-channel. The direct confirmation of this salient feature is provided by the recent experiment on searching for narrow resonances in pp-scattering with a small step of the incident proton energy variation [4]. Therefore, the use of the inelastic $NN$-channels appears to be a more perspective way of inquiring into dibaryon resonances [5].
- The decay modes of resonances with masses $M_B < 2m_p + m_\pi$ are $pp$- and $pp\gamma$-channels. The experimental indications of radiative decay channels were obtained in reactions including atomic nuclei [5,6]. However, from the point of view of simplicity and reliability of data interpretation, the radiative processes in the «elementary» $NN$-interaction would have undoubted advantages. Among all inelastic $NN$-reactions the bremsstrahlung is the simplest one. The experience accumulated in the experimental and theoretical investigation of $NN \to NN\gamma$ reactions is very useful for estimation of the resonance-to-background ratio in indicated reactions.
- For some spatial or internal quantum numbers the decay $B \to pp$ may be forbidden or suppressed by the rigorous (Pauli principle) or approximate (isospin, etc.) selection rules. The radiative channel of the resonance production $pp \to \gamma B$ and subsequent decay $B \to \gamma pp$ will then be the unique or principal channel if the proton energy is below the pion production threshold. The use of the double bremsstrahlung reaction in the region of the assumed resonances (the coincidence measurement) allows favourable possibilities to determine the quantum numbers of the explored resonances at the advantageous signal to background conditions (i.e., background from the ordinary, bremsstrahlung mechanism is expected to be strongly reduced) and with the minimal free parameters to be determined experimentally.

## 2. The Model of «External» Radiation of Soft Photons Near the Resonance

Firstly, we consider the bremsstrahlung reaction near the resonance with quantum numbers allowing «elastic» decay channel $B \to pp$ when $\Gamma_{tot} \cong \Gamma(B \to pp)$. We refer to this case as the «external» bremsstrahlung because in this case the dominant radiation mechanism is described by the pole diagrams in Fig.1 (a—e) and is determined by the electromagnetic characteristics and resonant interaction amplitude of the colliding particles. As far as the quantum numbers of a resonance are regarded as unknown, it is impossible to calculate the radiative amplitude taking into account

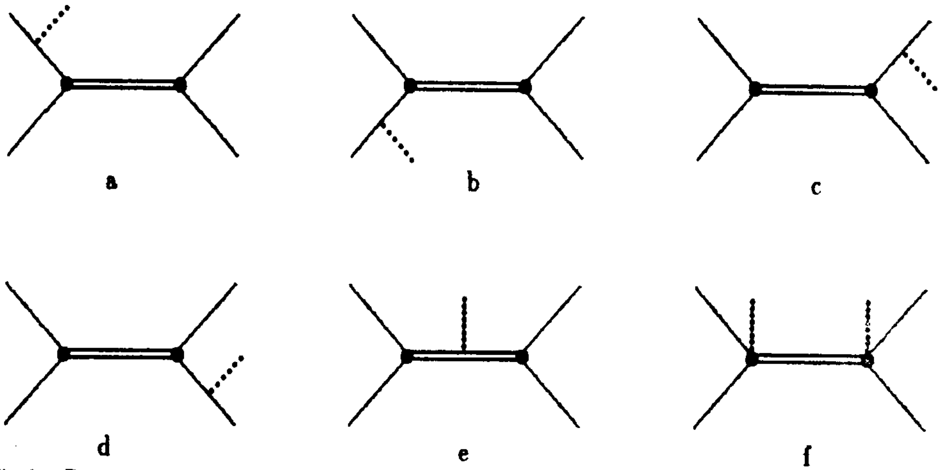

Fig.1. Diagrams of the bremsstrahlung reaction. The solid line corresponds to nucleons; the double line, to dinucleon resonance; the doted line, to photon

consistently all spin dependent characteristics of particles (magnetic moment, etc.) and the interaction, and therefore, we have to confine ourselves to retaining only the «charge» (convection) part of the corresponding electromagnetic currents. However, as it has been shown for the case of the ordinary, nonresonant bremsstrahlung [8], the neglect of the magnetic moments is justified at relatively low photon energies. The inclusion of only the convection current results in obtaining the lower bound of the considered cross section. The presence of the narrow resonance will, obviously, produce the characteristic, narrow $\gamma$-line in the emitted photon spectrum. The position and shape of this line are mainly determined by kinematics of the initial stage of the quasi-two-particle reaction $pp \to \gamma B \to \gamma X$ through the resonance mass $M_B$ and width $\Gamma_{tot}$. Our approximation (allowing for charge/convection current only) and dominance of the contribution to the cross section from the initial particle radiation permit us to give the general expression for the inclusive photon distribution in an arbitrary reaction $a + b \to \gamma + R \to \gamma + X$ near the resonance $R$ with mass $M_R$, spin $J_R$ and partial width $\Gamma_{ab} \equiv \Gamma(R \to ab)$ for any charge $Z_{a(b)}$ (in units of $e$) and masses $M_{a(b)}$ of the colliding particles:

$$\frac{d^2\sigma}{d\omega d\Omega_k}(ab \to \gamma R \to \gamma X) = \frac{\alpha}{4\pi^2}\,\frac{1}{\omega}\,F_{ab}(p, \theta)\,\frac{p'W'}{pW}\,\sigma^{BW}(s'), \qquad (1)$$

where

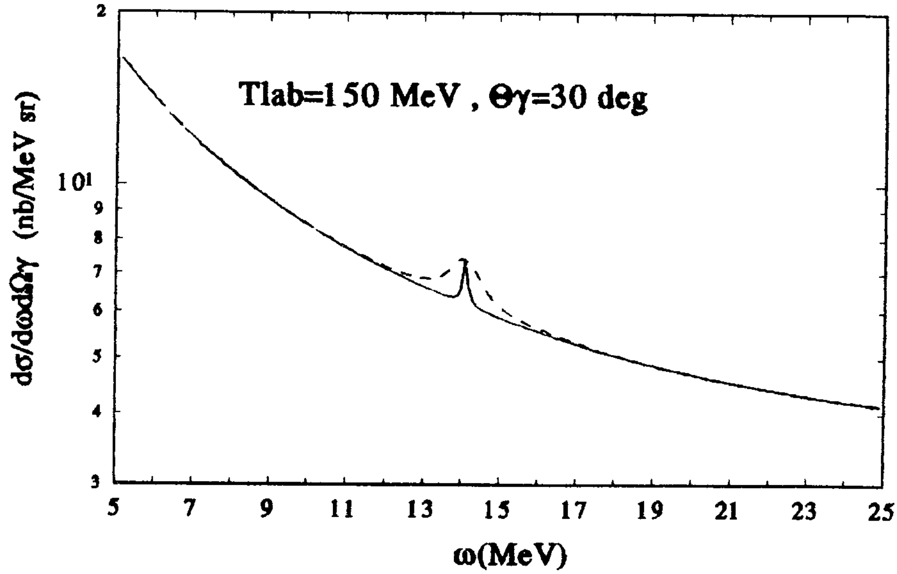


Fig.2. Differential cross section for $pp \to \gamma X$ reaction («external» radiation). The solid curve corresponds to $\Gamma_{tot} = 0{,}150$ MeV; the dashed curve, to $\Gamma_{tot} = 1.0$ MeV

$$F_{ab}(p, \theta) = \frac{[Z_a\beta_a - Z_b\beta_b + (Z_a + Z_b)\beta_a\beta_b \cos\theta\,]^2 \sin^2\theta}{(1 - \beta_a \cos\theta)^2\,(1 + \beta_b \cos\theta)^2}, \tag{2}$$

$$\sigma^{BW}(s') = \frac{4\pi}{p'^2}\,\frac{2J_R + 1}{(2J_a + 1)\,(2J_b + 1)}\,\frac{M_R^2\Gamma_{ab}\Gamma_{tot}}{(s' - M_R^2)^2 + M_R^2\Gamma_{tot}^2}, \tag{3}$$

$$p = \frac{(s - (M_a + M_b)^2)^{1/2}\,(s - (M_a - M_b)^2)^{1/2}}{4s^{1/2}}, \tag{4}$$

$$\beta_{a(b)} = \frac{p}{E_{a(b)}} = \frac{2ps^{1/2}}{s + M_{a(b)}^2 - M_{b(a)}^2}, \tag{5}$$

$s \equiv W^2 = (p_a + p_b)^2$, $s' \equiv W'^2 = (p_a + p_b - k)^2 = s - 2\omega\sqrt{s}$, $p \leftrightarrow p'(s \leftrightarrow s')$, $\cos\theta \equiv \hat{\mathbf{p}}_a \hat{\mathbf{k}}$, $J_{a(b)}$ — spin of the particle $a(b)$, $\alpha = 1/137$, $\omega$ — photon energy in c.m.s. For $a \to N$ and $b \to N$ in various charge states, we obtain from Eq.(2) in the leading nonrelativistic appraximation:

$$F_{NN}(p,\theta) = \begin{cases} 4\frac{p^4}{m^4}\sin^2\theta\cos^2\theta & (a \leftrightarrow p,\ b \leftrightarrow p) \\ \frac{p^2}{m^2}\sin^2\theta & (a \leftrightarrow p,\ b \leftrightarrow n), \\ 4\frac{p^2}{m^2}\sin^2\theta & (a \leftrightarrow p,\ b \leftrightarrow \bar{p}) \end{cases} \qquad (6)$$

where $m$ is a nucleon mass. For the illustrative purposes, and to estimate the possible signal-to-background ratio the $pp \to \gamma X$ reaction cross section is presented in Fig.2 at some fixed values of the initial proton kinetic energy $T_{lab}$, and photon angle $\theta_\gamma$. Rather arbitrary, we take $\Gamma_{tot} \cong \Gamma(B \to pp) = 0.15 \div 1$ MeV, $J_B = 0$ and $M_B = 1936$ MeV for the assumed resonance parameters. It should be noted that for $J_B \neq 0$ the height of the resonant peak must be increased $(2J_B + 1)$ times.

## 3. The Case for «Internal» Bremsstrahlung Near the Resonance

For the radiative processes, like the nuclear photodisintegration or meson photoproduction [9] or considered here bremsstrahlung reaction, the case when the dinucleon resonance decay into the $NN$-channel is either forbidden or hindered presents special interest. It is easily seen that the Pauli principle forbids the parity-odd (even) spin-singlet and parity-even (odd) triplet $NN$-states with the isospin $I = 1$ $(I = 0)$. For any of the possible spin values of the $NN$-system the following combinations of the total angular momentum $J$ and parity $P$ are forbidden:

$$J^P = \begin{cases} 1^+, 3^+, 5^+ \ldots, & \text{if } I = 1 \quad (7a) \\ 0^\pm, 2^-, 4^- \ldots, & \text{if } I = 0 \quad (7b) \end{cases}$$

For the $pp$-state the validity of the selection rule (7a) takes place regardless requirements of the isospin symmetry. Thus, if the diproton resonance has $J^P$ from the set values (7a), then $\Gamma_{tot} \cong \Gamma(B \to pp\gamma)$ for $M_B < 2m_p + m_\pi$. Therefore, because of $\Gamma(B \to pp) \cong 0$, the photon emission processes entering into the resonance excitation and decay vertices will, in place of the pole diagrams in Fig.1(a-e), be described by the diagrams as is shown in Fig.1(f). This «internal» radiation mechanism must be accompanied by essential change of the intrinsic motion of constituents composing the resonating hadronic system. We shall describe such radiative transition with the help of the effective Lagrangian $\mathcal{L}_{eff} = \mathcal{L}(F_{\mu\nu}, P_{\rho\sigma...}, \overline{\Psi}, \Psi_c)$ involving the electromagnetic field tensor $F_{\mu\nu}$ and the fields $B_{\rho\sigma...}, \overline{\Psi}, \Psi_c$ representing the dibaryon resonance and initial or final nucleons ($\Psi_c$ being the charge-conjugated field operator that is introduced for the baryon number conservation in appropriate vertices). To write down even the simplest form of the Lagrangian we need to know the quantum numbers (spins and parities) of the dinucleon resonance and the nucleon pair in the continuum. Taking into account the relative proximity of $M_B$ and invariant mass of nucleons to the threshold value $W_{thr} = 2m_p$, we take, in accordance with Eq.(7a), the simplest assignment $J^P = 1^+$ for the $B$-resonance and $J^P = 0^+$ for the $pp$-pair in the continuum. Electromagnetic vertices entering into the diagram in Fig.1(f) have then the conventional form of the magnetic dipole transition, and we obtain for the cross section of the resonance reaction $pp \to \gamma B \to \gamma\gamma pp$, expressed through two free parameters ($M_B$ and width $\Gamma_{tot} = \Gamma(B \to pp\gamma)$ and reduced to the non-relativistic limit, the following form:

$$\frac{d\sigma(pp \to \gamma B \to \gamma\gamma pp)}{d\omega_1 d\Omega_{k_1} d\omega_2 d\Omega_{k_2}} = \frac{9}{64\pi} \frac{\sqrt{m(\Delta w - \omega_1 - \omega_2)}}{|\mathbf{p}|} F_2 |D^{BW}|^2$$

$$F_2 = (1 + \cos^2(\hat{\mathbf{k}}_1 \hat{\mathbf{k}}_2)) \frac{\omega_1^3 \omega_2^3 M_B^2 \Gamma_{tot}^2}{m\Delta_B^9 C^2} \tag{8}$$

$$|D^{BW}|^2 = |D_1|^2 + |D_2|^2 + 2\mathrm{Re}(D_1^* D_2)$$

$$D_j = (W^2 - 2\omega_j W - M_B^2 + i M_B \Gamma_{tot})^{-1}, \quad j = 1, 2,$$

where $\Delta_W = W - 2m$, $\Delta_B = M_B - 2m$, $\Gamma_{rad} = \Gamma_{tot} = \Gamma(B \to \gamma pp)$, the numerical constant $C \cong 0.1016$ being determined after the integration over the final state phase volume in the decay $B \to pp\gamma$, while we express unknown coupling constant in the effective Lagrangian through also unknown but measurable $\Gamma_{rad}$.

At the first stage of investigation of this reaction one could confine oneself in searching for the narrow $\gamma$-line at $\omega = \omega_{res} = (W^2 - M_B^2)/2W$, which would give evidence for very existence of the resonance with mass $M_B$. In Fig.3, the dependence is shown of the cross section $\frac{d^2\sigma}{d\omega d\Omega_k}(pp \to \gamma X)$ on the energy of a detected photon. This is obtained by integration of the reso-

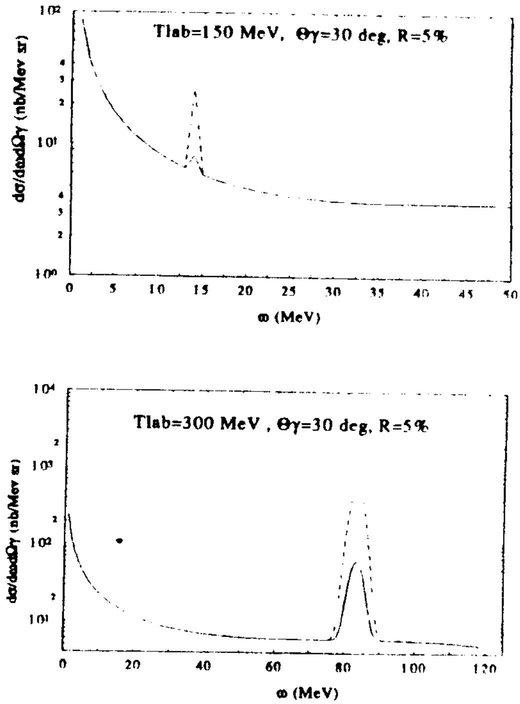


Fig.3. Differential cross section for $pp \to \gamma X$ reaction («internal» radiation). The solid curve corresponds to $\Gamma_{tot} = 0.1$ keV; the dashed curve, to $\Gamma_{tot} = 1.0$ keV.

nance cross section, Eq.8, over variables of one photon. Numerical values around the resonance peak correspond to $M_B$=1936 MeV, $\Gamma_{rad}$ = 01÷1 keV and the Gaussian function of the experimental energy resolution with $R_\gamma = \Delta\omega/\omega = 5\%$. The smooth, «background» curve corresponds to the calculation of the *pp*-bremsstrahlung from Ref. [8].

## 4. Conclusion

Our estimates reveal utility of the bremsstrahlung reaction as a means of finding out and especially of further investigation of the narrow diproton resonance. We treat them as very promising and opening good perspectives. The model calculations of the radiative widths of the diproton resonances give rather crude estimations in the range 0.1÷1 keV [10,11] for the case when $\Gamma_{tot} \cong \Gamma(B \to pp\gamma)$. We believe that with a fairly simple experimental set-up one could find a more stringent upper bound limit on $\Gamma(B \to pp\gamma)$ as compared with the model estimates. If unambiguous confirmation of the narrow diproton resonances is gained, the *pp*-bremsstrahlung opens new and, seemingly, unique possibilities of their further study, e.g. the determination of the quantum numbers by using the polarized beams (targets), measuring the photon-angle-correlations in the double bremsstrahlung near resonance, supplement studying of the final particle distributions in the bremsstrahlung reactions (this aspect of the problem is discussed, within more general context, in Ref. [12]), etc.

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