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ON MESON EXCHANGE CURRENTS AND NUCLEON POLARIZABILITY EFFECTS IN PROTON-PROTON BREMSSTRAHLUNG

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О мезонных обменных токах и поляризуемости нуклона в протон-протонном тормозном излучении

Обсуждается реакция протон-протонного тормозного излучения при энергии протонов ниже порога образования пионов. Рассмотрены поправки к амплитудам в потенциальной модели, которые включают обменные мезонные токи с учетом возбуждения Δ-изобары, радиационного перехода векторный мезон-пион, и новый член, определяющий зависящую от спина поляризуемость нуклона. На основе расчета поляризованных и неполяризованных сечений сделан вывод о том, что измерение коэффициентов спиновой корреляции протонов является наиболее чувствительным способом обнаружения вновь введенной поправки.

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On Meson Exchange Currents and Nucleon Polarizability Effects in Proton-Proton Bremsstrahlung

The proton-proton bremsstrahlung below the pion production threshold is considered. The corrections to leading potential model amplitudes include newly introduced, nucleon polarizability dependent term and the meson exchange currents with account for the Δ-isobar excitation and the vector meson-pion transition currents. Both unpolarized and polarized cross-sections are considered with conclusion that measurements of the proton spin-correlation coefficients are most promising to pin down the new, nucleon spin- and structure-dependent corrections.

The investigation has been performed at the Bogoliubov Laboratory of Theoretical Physics, JINR.

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Recently, much attention has been paid to nucleon–nucleon bremsstrahlung reactions as a potentially important source of new information about nucleon's interactions (e.g. [1] and references therein). The same reaction was suggested [2] to be a useful means to search for a certain subnuclear effects related to the possible virtual excitation and/or reclusterization of the initial nucleon constituents (mesons, quarks, etc.). The repeatedly emphasized need for more precise data can, hopefully, be provided by newly planned experiments at AGOR, CELSIUS, and COSY accelerators. Therefore, further elaboration and detalization of different approaches modelling the reaction mechanisms seems timely.

In this note, in addition to the standard potential model of the proton–proton bremsstrahlung reaction, we consider those parts of the full reaction amplitude which depend on the possible "deformability" of nucleon's internal structure and also on the more familiar corrections originating from the two–body (or the interaction/exchange) currents. As is well-known, the full nucleon-nucleon bremsstrahlung amplitude can be considered as a sum of two parts which represent the contributions from one-body and two-body currents. For *pp* scattering, one-body convection and magnetization currents dominate in the radiation process while contributions from one-body and two-body currents are approximately comparable for the hard photon emission in *pn* collisions. Below the pion production threshold the calculations of the one-body part of the total $pp\gamma$ amplitude are mostly carried out within the framework of potential models and the two-body contributions are neglected. In a potential approach, the off-shell nucleon-nucleon t-matrix, defined by a solution of the Lippmann-Schwinger equation with the realistic NN potential and the non-relativistic version of Green functions (the positive - frequency part of the nucleon propagators), are used. Also, the contributions from single and double (or rescattering) terms are taken into account and one or another kind of non-relativistic reduction is applied to the one-body current operator. This reduction may take the form of the Foldy-Wouthuysen transformation to obtain the one-body current with relativistic spin corrections or may have a form of the direct Pauli reduction. These approximations constitute the basis of most treatments of $pp\gamma$ reactions [3, 4, 5, 6, 7].

However, the potential model is definitely not a complete theory of the $NN\gamma$-reaction and its improvement implies generalization in many respects. The relevant generalization would be to use both the relativistic vertices and propagators, certainly containing the negative - frequency parts. Besides there are many possible mechanisms of the photon radiation neglected in the potential model which may give contributions to the $pp\gamma$ process. In particular, the investigations of the role of the meson exchange currents (MEC) in the *pp*-bremsstrahlung reaction have recently attracted a lot of attention [8, 9, 10]. The important MEC mechanisms of the $pp\gamma$ reaction are shown in Fig. 1a,b,c. In works [8], the contribution from Δ- isobar excitations were taken into account in a consistent way through a solution of the system of coupled channel equations which include nucleon and Δ - isobar degrees of freedom. But in such an approach it is difficult to take into account the internal radiative meson decays (graph on Fig. 1c). In [9, 10] the potential model was sup-

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plemented by the contributions from Δ -excitation and radiative meson decays. The corrections to the potential model have been done by calculating the corresponding relativistic Born amplitudes. The calculations have shown that the inclusion of the MEC contributions leads to improved agreement between the experimental data [12, 13] and theoretical predictions. However, discrepancy between theory and experiment is still left. This fact might indicate some new mechanisms not included in the calculations.

In this work, in addition to the above-mentioned corrections we also consider new non-pole amplitudes $\sigma(\omega, \rho^0) + p \to \gamma + p$ which are the parts of the whole $p + p \to p + p + \gamma$ amplitude. It was stated [14] by analogy with the well - known case of the low energy Compton scattering, that these amplitudes can be parametrized, in the meson/photon low energy limit, through a few phenomenological constants that were called the electronuclear polarizabilities of nucleon. As in the pure electromagnetic case, these new "mixed" polarizabilities include coefficients of the "electric" $\alpha^{eln}_{\sigma,\omega,\rho}$ and "magnetic" $\beta^{eln}_{\sigma,\omega,\rho}$ type. Their physical meaning is that the (σ, ω, ρ) -meson exchange will either modify the already existing or give rise to new electromagnetic moments of nucleons which, in their turn are coupled with the final photon field. Formally, these new polarizabilities of the nucleon appear as coupling constants in the effective lagrangians which generate the contact vertices $\sigma\gamma NN$, etc. shown in Fig. 1c and give an additional contribution to the two-body currents. In the case of bremsstrahlung process, we rely on the known salient feature of the $pp\gamma$ - reaction mechanism, namely, on the dominant role of proton magnetic moments in the radiation of hard ($\omega_\gamma > 30$ MeV) photons. Therefore, in all calculations we retain only those electronuclear polarizability corrections which effectively interfere with the main terms of the whole amplitude due to photon radiation by magnetic moments. The effective lagrangian [14]

$$L_{eff} = \beta^{eln}_{\sigma} \overline{\psi} \sigma_{\mu\nu} \psi F_{\mu\nu} \phi_{\sigma}, \tag{1}$$

which includes the magnetic electronuclear polarizability generated by the σ - meson exchange, has the structure very similar to the usual one for interaction of the magnetic moment with the electromagnetic field and, probably, will be the most important. It should also be mentioned that we consider the σ - field as an effective representative of the 2π - meson exchange in the medium range of the NN - interaction and use the values following from the Bonn potential [11] for all meson couplings and masses. Concerning the numerical value of β^{eln}_σ, on this stage we prefer to proceed not from a given specific model but treat β^{eln}_σ as a phenomenological parameter which can be directly fixed from the approximate fit to the experimental data in the kinematic region most sensitive to this quantity. In the "Harvard" geometry it is the data with the minimal angles of the coplanar final protons where the emitted photon has a higher energy. In such a way we can obtain the maximum scale estimation of effects from nucleon polarizability and investigate its influence on various bremsstrahlung observables including spin-dependent ones at different kinematic conditions.

Below we list the main ingredients of the calculations giving the results presented in Fig. 2-4. Dominant contributions came from the potential model. They include the half-off-shell nucleon-nucleon t-matrix, the positive - frequency part of the nucleon propagator and the one-body electromagnetic-transition operator. The NN t-matrix was obtained [2] from a solution of the Lippmann-Schwinger equation with the one-boson exchange Bonn potential (OBEPQ) [11]. The equation was solved in the momentum space and partial waves with total momentum $J \leq 6$ were considered. For calculations of the matrix elements of the one-body current operator a direct Pauli reduction was used [4]. The contributions from the one-body rescattering (or double scattering) were taken into account. This model gave us a background (potential) amplitude. All corrections were treated at the level of Born diagrams and added coherently to the main potential amplitude. The Born diagrams were calculated up to terms of an order of $O(M_N^{-1})$ and include:

- all Born diagrams, Fig. 1a, with the $\pi, \rho, \omega, \sigma$- exchange and with the negative - frequency part of the nucleon propagator;
- the virtual excitation of the Δ-resonance in the diagrams, Fig. 1b, with the π- and ρ- meson exchange;
- the radiative $\omega\pi^0\gamma$ and $\rho\pi^0\gamma$ meson decay diagrams, Fig. 1c;
- a new contribution due to the magnetic electronuclear polarizability of the nucleon, represented by the diagram in Fig. 1e.

For all baryon-meson coupling constants we used the same values as in the Bonn potential (OBEPQ) [11]. Coupling constants for the γ-decay of Δ were used from fitting to the $M1^+$ and $E1^+$ multipole data on the photoproduction of pions from nucleons [15]. Coupling constants for radiative meson decays in the vector-pseudovector meson currents $\omega(\rho)\pi\gamma$ were fixed to experimental values [16].

In Fig. 2 the theoretical calculations of exclusive cross sections and analyzing power are compared with the bremsstrahlung experimental data for proton-proton collisions at 280 MeV [12, 13], where the scattered protons were detected at smallest measured angles. It is a most favorable kinematic situation for investigation of effects of nucleon polarizability in a given experiment. The dotted line shows the results of potential model calculations and the dashed line additionally includes the contributions from all the meson exchange currents. It follows from Fig. 2 that at a given kinematic condition the included corrections are rather small and cannot satisfactorily describe experimental data. The solid line shows the calculations where we additionally take into account a photon emission induced by a nucleon nuclear polarizability as described above. The value of polarizability was fixed empirically ($\beta^{eln}_\sigma = 0.6\ fm^2$) to obtain a reasonable description of experimental data. We see that this contribution improves agreement with an experiment for both the cross section (Fig. 2a) and for analyzing power (Fig. 2b) data. The obtained value of β^{eln}_σ qualitatively agrees with old one [14] and probably is the upper limit of an estimation for nucleon nuclear polarizability since all our ambiguities and model approximations are included implicitly in that value. With increasing angles of detected protons the influence of nuclear polarizability becomes smaller. In Fig.3, the theoretical calculations are compared with the experimental cross sections measured at the largest proton angles ($\theta_{P1} = 27.8^0$ and $\theta_{P2} = 28^0$). The dotted line gives the results of potential model calculations. The dashed-dotted, dashed and solid lines additionally include corrections from Δ - isobar excitations, all meson exchange currents and nucleon nuclear polarizability, respectively. We see that at this kinematic condition the meson exchange currents give a significant correction (dashed line) to the results from the potential model. It is interesting to clarify the role of different parts of meson exchange current played in the reaction mechanism. At first, the "pair" current (diagrams 1a) is rather small for the NN interaction we used. The Δ - isobar contributions (dashed- dotted line) give sizeable corrections to the potential model. We also observe, in agreement with other calculations [9, 10], that considerable mutual compensation takes place between the Δ - isobar and radiative meson decay (diagram 1c) currents. The total effect (dashed line) from all meson exchange currents is roughly two times less comparing to the separate contribution from the Δ - isobar. The inclusion of polarizability current (solid line) with a strength fixed earlier makes only modest changes to other corrections. The calculations cannot reproduce experimental cross sections.

It is interesting to investigate the influence of polarizability on different spin observables. Fig. 4 shows the calculations of the diagonal spin correlation coefficients which provide a measure of sensitivity of the NNγ reaction to the mutual spin orientation of projectile and target nucleons. The dashed, dotted and solid lines represent the calculations for the potential model, including additional meson exchange currents and nuclear polarizability, respectively. It is seen that spin correlation coefficients reveal a stronger sensitivity to different corrections than cross section data. Concerning the nuclear polarizability, it has diverse effects on different spin correlation observables. For the C_{zz} coefficient its contribution interferes constructively with the meson exchange currents (Fig. 4a), for C_{yy} the interference is destructive (Fig. 4b) and has a mixed character for C_{xx} (Fig. 4c). Therefore, the study of spin correlation coefficients seems to be a much better means for detection and further investigation of these newly introduced corrections.

We remind now that we referred some part of the remaining discrepancy between the calculations and unrenormalized TRIUMF data as due exclusively to the earlier neglected polarizability contribution. However, the treatment of the nucleon as an elementary particle, while using the negative-frequency parts of the propagators in the calculation of ω- and σ- and especially the ρ- and π- exchange induced two-body currents, may also be subjected to revision. This may happen despite some justifying arguments given earlier [17] for approximate numerical closeness of the elementary and composite picture of the nucleon for the case of isoscalar meson exchanges. Nevertheless, concerning the relative importance of the new polarizability,

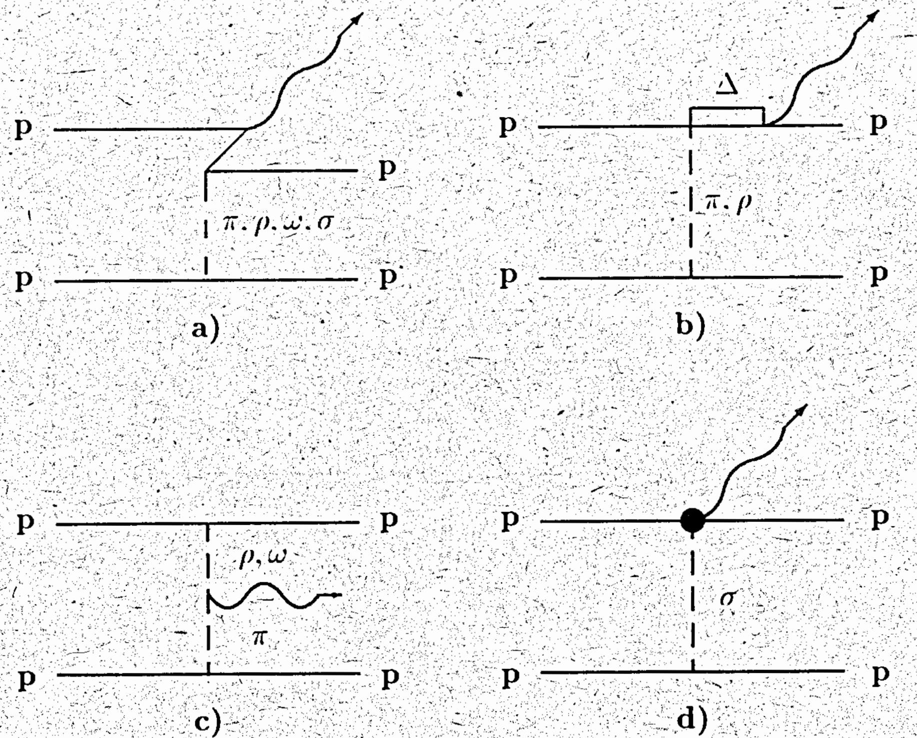

Fig. 1 Diagrams of meson exchange currents included in the description of the pp-bremsstrahlung: (a) $\pi, \rho, \omega, \sigma$- exchange with the negative - frequency part of the nucleon propagator; (b) the virtual excitation of Δ-resonance; (c) $\rho\pi\gamma$ and $\omega\pi\gamma$ radiative meson exchange currents; (d) electronuclear polarizability.

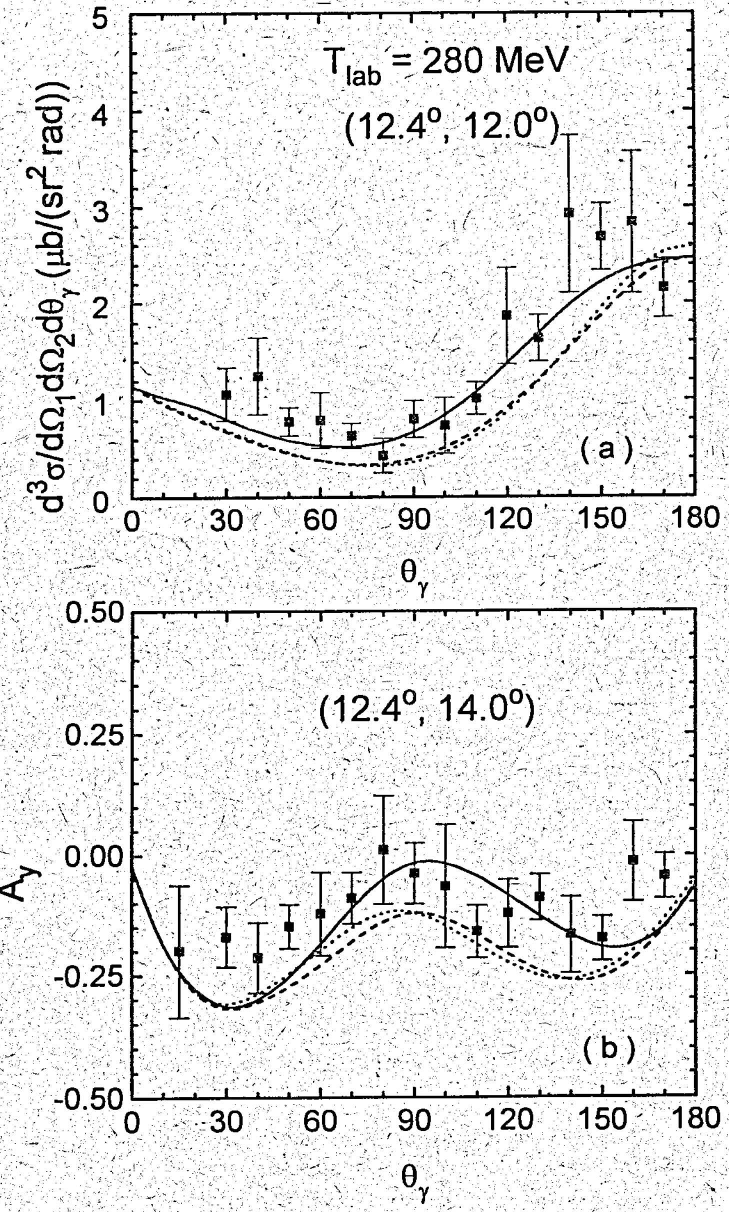

Fig. 2 Comparison of coplanar *pp*-bremsstrahlung data at T_{lab}=280 MeV [12, 13] with theoretical calculations of a) exclusive cross sections and b) analyzing power. The dotted curve corresponds to the potential model, the dashed curve includes additionally meson-exchange currents and the solid curve includes the electronuclear polarizability additionally to the previous contributions . The experimental cross section data have no arbitrary factor of 2/3.

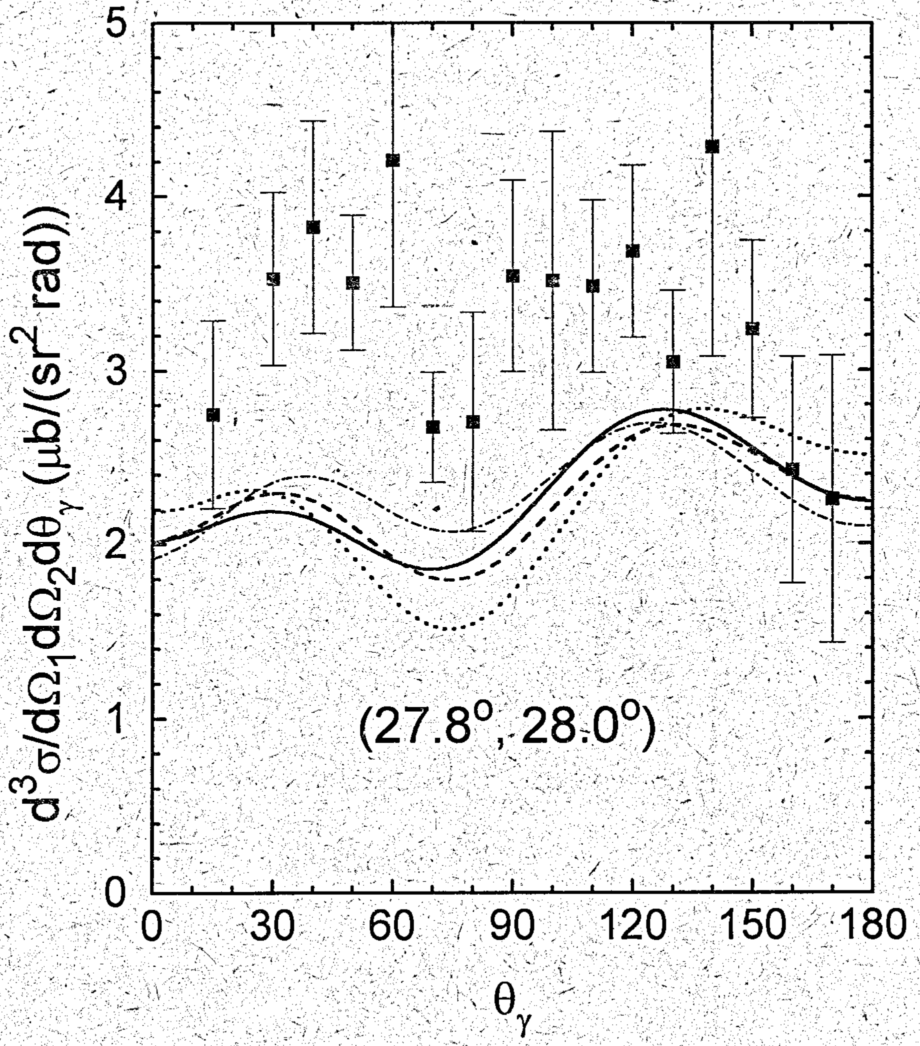

Fig. 3 Comparison of coplanar *pp*-bremsstrahlung data at T_{lab}=280 MeV [12, 13] with theoretical calculations of exclusive cross sections for proton scattering angles of 27.8° and 28°. Labelling of the dotted, dashed and solid curves is as in Fig. 2. The dot-dashed curve includes the contribution from Δ-isobar excitations additionally to the potential model . The experimental cross section data have no arbitrary factor of 2/3.

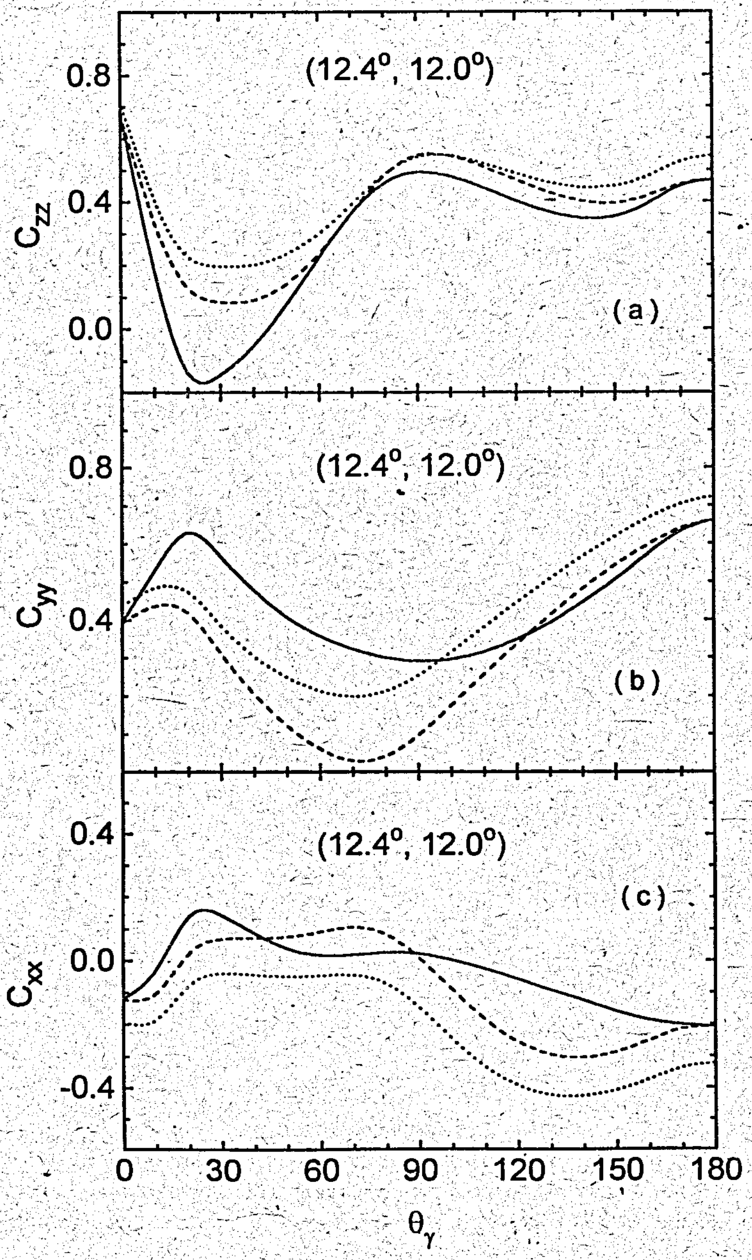

Fig. 4 Spin correlation coefficients for *pp*-bremsstrahlung at T_{lab}=280 MeV and for proton scattering angles of 12.4° and 12.0°. Labelling of the curves is as in Fig. 2.

our opinion is that it should be taken into account when the limits of applicability of the standard potential model results are questioned. Furthermore, its study is important as a potential source of new information about the nature of the σ-meson and hence about further implications of the chiral symmetry and its breaking in different processes.

In conclusion, we believe that improvement of the accuracy, extension of the kinematic domain explored, and future studies of the bremsstrahlung reactions with a polarized proton beam and target, can yield important information on parameters characterizing "deformability" (or polarizability) of the interacting nucleons during the bremsstrahlung process.

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