Sensitivity of pp-Bremsstrahlung to Meson-Exchange Currents

J. A. Eden and M. F. Gari

Institut für Theoretische Physik
Ruhr Universität Bochum, D-44780 Bochum, Germany
email: jamie@deuteron.tp2.ruhr-uni-bochum.de

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Abstract

We present pp-bremsstrahlung cross section calculations at the \( \pi \)-production threshold to search for kinematics that best differentiate model-dependent descriptions of the NN \( t \)-matrix and accentuate the contributions of isoscalar meson-exchange currents. Existing optimization procedures are shown to be completely unreliable due to the neglect of meson-exchange currents and phase space variations. We show that phase-space hides the most important differences in model \( t \)-matrices, but that improved data will be critical to further investigations of exchange currents.

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The dominant processes in pp-bremsstrahlung at energies near the $\pi$-production threshold are the nucleon-pole contributions shown in Fig. 1(a-b). It has long been thought [1] that this ‘nucleon-pole dominance’ would allow for the investigation of the off-shell behavior of various NN-interaction models, nearly all of which are fitted to the on-shell NN-scattering data. However, within the assumption of nucleon-pole dominance, gauge invariance and the soft-photon theorem [2,3] establish that the first two terms in the expansion of the bremsstrahlung amplitude in powers of the photon energy are completely specified by on-shell scattering [4,5].

To obtain new information from bremsstrahlung that is not already given by on-shell NN-scattering data, the kinematics of a recent experiment at TRIUMF [6] were optimized [7] to obtain large photon energies and highly off-shell nucleon-pole contributions. In earlier work [8] we compared this data from TRIUMF with relativistic meson-baryon model calculations that include only the processes of Fig. 1(a-c), but we obtained results that share the discrepancy with experiment reported elsewhere [9–15]. We have since repeated these calculations using wave functions obtained from the Paris [16], Nijmegen [17], Bonn B [18] and RuhrPot [19] NN-interactions, but we obtain results that are essentially all the same and continue to show a collective discrepancy with experiment. We realize that in all but the most forward scattering angle data, such discrepancies cannot be explained by any uncertainty in experimental absolute scale.

There are two important points here. The first is that, on the assumption of nucleon-pole dominance with maximum photon energies, the TRIUMF experiment was optimized to probe differences in model-dependent off-shell t-matrices, but the similarity of the model results indicates that it failed to do so. In the following we will show that this result could have been predicted from simple phase space considerations. The second point is that the collective discrepancy between the experiment and the impulse approximation calculations indicates that large contributions from meson-exchange currents may be present.

We attempt here a more rigorous procedure for selecting pp-bremsstrahlung kinematics that might differentiate the off-shell behavior of NN-interaction models. We also identify kinematics which enhance the contributions of the dominant isoscalar meson-exchange currents - a task which is clearly impossible within the universally accepted procedure of optimizing experiments according to nucleon-pole dominance.

Our procedure for calculating the impulse contributions of Figs 1(a-c) has been described in ref [8]. We add to this the perturbative $\rho\pi\gamma$, $\omega\pi\gamma$, $\rho\eta\gamma$, $\omega\eta\gamma$, and $N\Delta\gamma(\pi,\rho)$ exchange currents currents shown in Fig 1(d-e), all of which are easily calculated in the usual way [20–23] with,

\[
\mathcal{L}_{PV\gamma} = \frac{e_p g_{PV\gamma}}{2m} \epsilon^{\mu\nu\sigma\tau} F_{\mu\nu} \bar{\psi}_{\sigma} \gamma^\tau \psi_{\tau},
\]

\[
\mathcal{L}_{N\Delta\pi} = \frac{g_{N\Delta\pi}}{2m} \bar{\psi}_{\mu} \gamma^\nu \bar{\tau}_{N\Delta} \bar{\psi}_{\mu} \bar{\tau}_{N\Delta} + \text{h.c.}
\]

\[
\mathcal{L}_{N\Delta\rho} = -i \frac{g_{N\Delta\rho}}{2m} \bar{\psi}_{\mu} \gamma^5 \gamma^\nu \bar{\tau}_{N\Delta} \bar{\psi}_{\mu} + \text{h.c.}
\]

\[
\mathcal{L}_{N\Delta\gamma} = -i \frac{e_p g_{MN\Delta}}{2m} \bar{\psi}_{\mu} \gamma^5 \gamma^\nu \bar{\tau}_{N\Delta} F_{\mu\nu} + \text{h.c.}
\]

where $V=\rho, \omega$ and $P=\pi, \eta$. In the present work we neglect contributions involving negative-frequency particles. To fully specify the model, we fix the coupling constants and $\Delta$-decay width to their experimental [24] values of $g_{\rho\pi\gamma}=0.55$, $g_{\omega\pi\gamma}=2.03$, $g_{\rho\eta\gamma}=1.39$, $g_{\omega\eta\gamma}=0.31$.
\( g_{N\Delta\pi} = 28.85 \), and \( \Gamma_\Delta = 115 \text{ MeV} \). For the remaining experimentally unknown quantities, we adopt the familiar SU(6) results \( g_{N\Delta\rho} = g_{NN\rho}(1 + \kappa_{\rho})g_{N\Delta\pi}/g_{NN\pi}, \mu_{N\Delta} = \frac{1}{2}(1 + \kappa_{\rho})g_{N\Delta\pi}/g_{NN\pi}. \)

The NN-meson coupling constants and form factors are taken from the RuhrPot interaction to ensure that the meson-exchange currents, the strong interaction potential and the strong form factors \([25,26]\) are consistently defined. For the real photon, the Dirac and Pauli electromagnetic form factors obviously reduce to their normalization values, and since the present work is confined to low \( Q^2 \), we approximate \( F_{N\Delta\alpha} = F_{NN\alpha} \) for \( \alpha = \pi, \rho \). No form of soft photon approximation is adopted at any stage.

There are at least three fundamental differences between our exchange current calculations and the NN\( \rightarrow \)N\( \Delta \) t-matrix calculation reported elsewhere. First, like \([27]\), we include the \( \rho\pi\gamma, \omega\pi\gamma, \rho\eta\gamma \) and \( \omega\eta\gamma \) exchange currents that have been neglected in \([28]\). Although the \( \Delta \) contributions are certainly the largest of the exchange currents, the vector-meson decay contributions are non-negligible when interferences are correctly included. Second, our perturbative treatment of the N\( \Delta \gamma(\pi, \rho) \) exchange currents allows us to retain the meson recoil contributions that cannot be included in any t\( _{\Delta N} \)-matrix expansion. As is well known, the recoil and wave function re-orthonormalization contributions cancel in the static limit for NN\( \rightarrow \)NN interactions \([29]\), so that their combined contributions can reasonably be ignored to permit use of the ladder-approximation in calculating the corresponding t\text{-}matrix. However, no such cancellation occurs in the NN\( \rightarrow \)N\( \Delta \) interaction, so that the recoil and wave function re-orthonormalization terms are neglected without justification in refs \([27,28]\). Third, (and relevant to the second point) we have not fitted the isobar contributions to experimental data and no unphysical free parameters are required to avoid double-counting of N\( \Delta \) intermediate states. As such, the isobar mass, coupling constants and form factors we use are not effective fit parameters and can be unambiguously identified with the physical nucleon resonance \( \Delta(1232) \). In addition, we note that the impulse approximation rescatter amplitudes represent a correction of less than 15% to the dominant nucleon-pole contributions, and that this provides a crude measure of the accuracy of the perturbative exchange current amplitudes we include here. In view of the differences between the present approach and that reported in ref \([28]\) the numerical results of the two calculations are fairly similar, at least at the kinematics where comparison is possible.

For the kinematically complete bremsstrahlung reaction \( p_1 + p_2 \rightarrow p_3 + p_4 + k \), data is usually presented as a function of the photon emission angle \( \theta_\gamma \) for given proton scattering angles \( \theta_3 \) and \( \theta_4 \) and non-coplanarity \( \Phi = \frac{1}{2}(\pi + \phi_3 - \phi_4) \) \([30]\). All quantities are given in the Lab frame \((\vec{p}_2 = 0)\), and we denote \( \theta_3 \) (\( \theta_4 \)) as the scattering angle for the proton that is emitted on the same (opposite) side of the beam as the photon. Since we describe the hadronic wave functions non-perturbatively with NN t-matrices, we avoid the approximation of ignoring inelasticities by confining our present investigations to energies below the \( \pi^- \)-production threshold.

In the left-hand column of Fig 2, we present the ratio of pp-bremsstrahlung cross sections at \( E_{\text{lab}} = 280 \text{ MeV} \) including the nucleon-pole and rescatter contributions of Fig. 1(a-c), and using wave functions obtained from the RuhrPot \([19]\) and Bonn B \([18]\) potentials. In the middle column, we present similar cross section ratios at corresponding kinematics and use wave functions obtained from the RuhrPot model with the nucleon-pole and rescatter contributions of Fig.1(a-c), and which either retain (IA+Mexc) or neglect (IA) the meson-exchange currents of Fig.1(e-f). The phase space available to these reaction geometries is
shown in the right-hand column.

In Figs. 2a(1-3) we consider coplanar geometries with $\theta_3 = \theta_4$. Figs. 2a(1) shows the potential models have only weak and structureless differences at nearly all geometries, whereas Figs. 2a(2) shows that the isovector exchange currents are large near $\theta_3 = \theta_4 \sim 20^\circ$. We realize that recommendations [7,10] based nucleon-pole dominance with maximum photon energies call for increased emphasis on the extreme forward-angle geometries. Although these geometries succeed in maximizing the differences between the potential-model calculations, Figs. 2a(3) shows that only the regions of $\theta_\gamma \sim 0^\circ$ and $180^\circ$ have significant phase space, and here Figs. 2a(2) shows that such regions take non-negligible contributions from meson-exchange currents.

Upon the recommendations of nucleon-pole dominance, an experiment was recently reported [31] at $E_{\text{lab}} \sim 294$ MeV and $\theta_3 = \theta_4 = 6.0^\circ \pm 1.2^\circ$. However, the data suffers from very large phase space variations over the detector acceptance angles and simply reflects the peculiarities of various experimental efficiencies. As such, a meaningfully comparison with theory is impossible. The fact that this region is of limited interest has only recently been appreciated in a phenomenological analysis [32], although this lead to some conclusions that we cannot corroborate. Similar difficulties in future experiments can be avoided by adopting an analysis like that that shown in Fig 2.

In Figs. 2b(1-3) and Figs. 2c(1-3) we consider coplanar scattering with $\theta_3 \neq \theta_4$. Again we observe large contributions from the isovector exchange currents, but structured differences in the potential-model calculations occur only in regions suppressed by phase space.

Finally, Figs. 2d differ from Figs. 2a in that we fix $\theta_3 = \theta_4 = 20$ and scan the kinematically permissible non-coplanar geometries. From the outset, such geometries are undesirable since the dynamic range of $\theta_\gamma$ is suppressed by momentum conservation and enormous phase space variations will dominate any data which includes events near the kinematic limit of non-coplanarity (for example, the data of ref [31]). In addition, we realize that a dramatic improvement in the data will be required before non-coplanar analyzing powers [15] will be of interest. This shows that increasing the non-coplanarity offers no immediate gains to off-set some inherent disadvantages, at least at $\theta_3 \sim \theta_4 \sim 20$.

Fig 2 establishes that the exchange currents are manifest in pp-bremsstrahlung in regions where phase space is large and smooth. We recommend an increased experimental emphasis on coplanar reaction geometries involving larger proton scattering angles. To compare our results with others [27,28], in Fig 3, we provide a conventional representation of the exchange current effects and observe a qualitative similarity amongst all of the recent exchange current calculation results.

We conclude that pp-bremsstrahlung data at energies near the $\pi$-production threshold is unlikely to distinguish the differences between potential models because phase space suppresses the cross section in precisely the regions where the off-shell $t$-matrix elements are most different. This has not been recognized in the past analyses, all of which are essentially based on nucleon-pole dominance and, as such, neglect the critical roles of phase space and meson-exchange currents. However, a modest reduction in the experimental uncertainty of the coplanar data near $0 \leq \theta_3 \leq 25$ and $\theta_4 \sim 20$ would provide extremely useful information for the further investigation of relativistic- and resonance width-effects in $T=1$ isoscalar exchange currents. The current emphasis on highly non-coplanar geometries should probably be reconsidered.
ACKNOWLEDGMENTS

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FIGURES

FIG. 1. Dominant contributions to pp-bremstrahlung observables: (a-b) nucleon-pole and (c) rescatter contributions to the impulse approximation (IA) current, and (d) \(N\Delta\gamma(\pi, \rho)\) and (e) \(\rho\pi\gamma, \omega\pi\gamma, \rho\eta\gamma\) and \(\omega\eta\gamma\) meson-exchange currents (Mexc). All such contributions are included in the exchange-current calculations of the present work.

FIG. 2. pp-bremstrahlung calculation results at \(E_{lab}=280\) MeV for proton scattering angles of \(\theta_3\) and \(\theta_4\), photon emission angle \(0 \leq \theta_\gamma \leq 180^\circ\) and non-coplanarity \(\Phi\). In Fig 2(a-d)(1) we explore model dependence by plotting cross sections ratios for the RuhrPot and Bonn models including the processes of Fig. 1(a-c). In Fig 2(a-d)(2) we explore exchange currents by plotting cross sections ratios for the RuhrPot model including the processes (IA) of Fig 1(a-c) and (IA+Mexc) of Fig 1(a-e). In Fig 2(a-d)(3) we show the phase space for the reaction geometry. The spikes in Fig d(3) simply reflect the plot grid points in the region of the square-root singularity at the kinematic limit of non-coplanarity [30]. Phase space is either small or structured where the models are most different, but is smooth and large where the exchange currents are important.

FIG. 3. Coplanar pp-bremstrahlung calculation results at \(E_{lab}=280\) MeV. We find the \(\rho\pi\gamma, \omega\pi\gamma, \rho\eta\gamma, \omega\eta\gamma\) and \(N\Delta\gamma(\pi, \rho)\) exchange currents enhance the cross section for \(\theta_3=28.0\) and \(\theta_4=27.8\) near \(\theta_\gamma=75\%\) by about 50\%. Given that the \(\rho\pi\gamma, \omega\pi\gamma, \rho\eta\gamma\) and \(\omega\eta\gamma\) exchange currents are ignored in [28], we realize that results are qualitatively similar - the corresponding enhancement there being \(\sim 45\%\). This geometry is a good candidate for better measurement since the cross section is large, phase space is smooth, and the contributions of the exchange currents are clearly visible.
This figure "fig2-1.png" is available in "png" format from:

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