Meson-exchange currents in pp-Bremsstrahlung

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The long-standing discrepancy between pp-bremsstrahlung data and calculations based on the relativistic impulse approximation current is substantially reduced by the inclusion of the PV_γ and intermediate-state Δ-resonance isoscalar meson-exchange currents. The success of the standard procedures adopted here shows that pp-bremsstrahlung provides a powerful tool for the further study of $T = 1$ isoscalar exchange currents. The need for additional high-precision data is stressed. © *1996 American Institute of Physics.* [S1063-7761(96)00210-7]

In earlier work[1] we calculated a number of pp-bremsstrahlung observables within a relativistic meson-baryon model. We included initial- and final-state interactions, as well as the numerically cumbersome rescatter contributions, as shown in Fig. 1a–c. We placed special emphasis on a consistent approach to both the 1- and 2-body problems, i.e., the strong interaction potential[2,3] and the form factors it contains[3,4] were both microscopically calculated from a consistently parameterized meson field-theoretic Lagrangian. However, we considered the electromagnetic interaction only in the relativistic impulse approximation and our results shared the discrepancy with experiment[5] reported elsewhere.[6–12].

In Fig. 2 we present results of these calculations, now extended to provide the first fully consistent comparison of the Paris[13], Nijmegen[14], Bonn[15] and RuhrPot[2] interactions. The selected geometries essentially correspond to best- and worse-case comparison with experiment. It may be observed that, when the data is not dominated by uninteresting phase space variations, the difference among the results from these models is smaller than their collective discrepancy with experiment. We conclude that the failure of all recent attempts to describe the pp-bremsstrahlung data has little to do with the model-dependent choice of the half-off-shell t-matrices, but indicates a sensitivity to the $T = 1$ isoscalar meson-exchange currents.

Indeed, some 16 years ago Taitor *et al.*[16] showed that the pp-bremsstrahlung observables at photon energies as low as 80 MeV may take large contributions from meson-exchange currents involving an intermediate-state Δ-resonance. Such results must be taken as indicative, rather than conclusive, because the off-shell direct amplitudes shown in Fig. 1a–c were included as the measured elastic scattering cross section data. This not only implies that the direct amplitudes are taken in the notoriously unreliable soft-photon approximation, it also means that all interferences between the meson-exchange and direct amplitudes are necessarily neglected. Even the relative sign of these contributions cannot be properly defined and must simply be chosen to optimize the correspondence with experiment. Nonetheless, the calculations by Taitor *et al.* are useful and interesting because they predicted a large contribution from the intermediate-state Δ-resonance exchange currents, and this motivates us to examine such processes in a more systematic fashion.

In the present work we extend our earlier calculations to include the dominant meson-exchange currents contributing to the pp-bremsstrahlung observables. The exchange currents are calculated in the standard field-theoretic formalism[17–19] and include not only the intermediate-state Δ-resonance excitation via π- and ρ-meson exchange, as shown in Fig. 1d, but also the $\rho\pi\gamma$, $\omega\pi\gamma$, $\rho\eta\gamma$, $\omega\eta\gamma$ interactions, as shown in Fig. 1e. We adopt the RuhrPot[2] interaction in order to obtain consistency between the meson-exchange currents and the wave functions. This immediately fixes all NN-meson coupling constants and form factors. For the exchange currents involving intermediate-state Δ resonance excitation we use

$$\mathscr{L}_{N\Delta\pi}=-\frac{g_{N\Delta\pi}}{2m}\bar{\psi}^{\mu}\boldsymbol{\tau}_{N\Delta}\psi\partial_{\mu}\boldsymbol{\pi}+\text{h.c.},$$

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

$$\mathscr{L}_{N\Delta\gamma}=-i\frac{e_p\mu_{N\Delta}}{2m}\bar{\psi}^{\mu}\gamma^{5}\gamma^{\nu}\tau^{3}_{N\Delta}\psi F_{\mu\nu}+\text{h.c.} \tag{1}$$

and take $g_{N\Delta\pi} = 28.85$ to be consistent with the observed width $\Gamma_\Delta = 115$ MeV (this value is also consistent with both Chew–Low theory[20] and the Strong Coupling Model[21]). We also adopt the familiar SU(6) result

$$g_{N\Delta\rho}=g_{NN\rho}(1+\kappa_\rho)g_{N\Delta\pi}/g_{NN\pi},$$

so that vector dominance implies

$$\mu_{N\Delta}=\frac{1}{2}(1+\kappa^{iv})\frac{g_{N\Delta\pi}}{g_{NN\pi}}.$$

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 the strong form factors as $F_{N\Delta\alpha}=F_{NN\alpha}$ for $\alpha=\pi,\rho$. For the electromagnetic coupling to the vector-pseudovector meson currents we have

$$\mathscr{L}_{PV\gamma}=-\frac{e_p g_{PV\gamma}}{2m_V}\epsilon^{\mu\nu\sigma\tau}F_{\mu\nu}\phi^{V}_{\sigma}\partial_{\tau}\phi^{P}, \tag{2}$$

with $V=\rho,\omega$ and $P=\pi,\eta$, and we fix the coupling constants to their experimental[22] values of $g_{\rho\pi\gamma}=0.55$, $g_{\omega\pi\gamma}=2.03$, $g_{\rho\eta\gamma}=1.39$ and $g_{\omega\eta\gamma}=0.31$. We emphasize that this de-

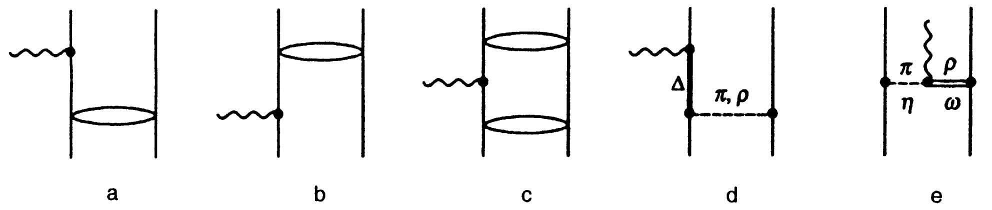

FIG. 1. Dominant contributions to pp-bremsstrahlung observables: a—initial-state, b—final-state, c—rescatter impulse contributions, d—intermediate-state Δ-resonance, e—$\rho\pi\gamma$, $\omega\pi\gamma$, $\rho\eta\gamma$ and $\omega\eta\gamma$ meson-exchange currents. All such contributions are included in the present work.

scription of the meson-exchange currents introduces no free parameters and is fully consistent with both the strong-interactions and the form factors it contains. Since we retain our microscopic description of the NN-interaction, all interferences are included. No form of soft photon approximation is adopted at any stage.

There are important differences between the present work and other recent calculations which incorporate $N\Delta\gamma(\pi,\rho)$, $\rho\pi\gamma$, $\omega\pi\gamma$, $\rho\eta\gamma$, and $\omega\eta\gamma$ currents into pp-bremsstrahlung. First, like Ref. 23, we retain the dominant $VP\gamma$ exchange currents that are neglected in Ref. 24. These currents are certainly smaller than the $N\Delta\gamma(\pi)$ exchange currents but, in particular, the $\omega\pi\gamma$ contribution has a magnitude which is similar to that of the $N\Delta\gamma(\rho)$. Second, we require no unphysical free parameters to avoid double-counting of $N\Delta$ intermediate states and our approach guarantees a consistent description of coupling constants, form factors and particle masses in both the exchange currents and the wave functions. Finally, although the $t_{\Delta N}$-matrix expansion carries the advantage of providing a non-perturbative description of the Δ degrees of freedom in the wave function, it also creates the necessity to compute wave function reorthonormalizaiton contributions. We realize that the well known cancellation of wave function reorthonormalization and meson-recoil amplitudes in the $NN\rightarrow NN$ transition[25] fails for $NN\rightarrow\Delta N$ transitions, even in the static limit. Therefore, the neglect of both meson-recoil and wave function reorthonormalizaton contributions in Ref. 23 and 24 introduces an approximation whose importance is difficult to assess in the presence of a free parameter.

By describing the exchange currents perturbatively, we automatically include the meson-recoil contributions and we formally have no need of wave function reorthonormalization terms.[25] In addition, the precision of this perturbative approach can be crudely estimated by noting that the impulse approximation rescatter amplitudes of Fig. 1c represent a correction of less than 15% of the dominant nucleon-pole contributions shown in Fig. 1a,b. For the geometries where comparison is possible, the numerical results of our exchange current calculations are actually fairly simi-

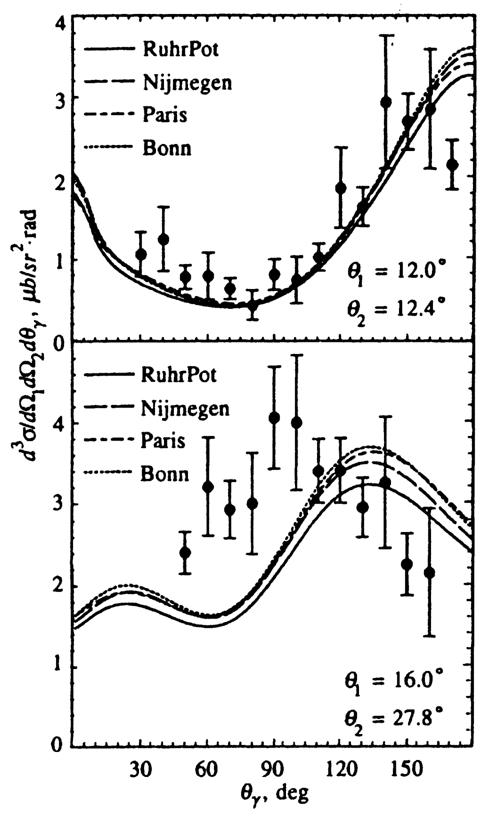

FIG. 2. Comparison of coplanar pp-bremsstrahlung data[5] at $E_{\rm lab}$ = 280 MeV with calculations using wave functions obtained from various NN-interaction models but current densities confined to the relativistic impulse-approximation. Initial-, final- and rescatter-correlations are included with partial waves summed to $J_{\rm max}$ = 8. All models give essentially equivalent results which differ from experiment when phase space variations are not extreme.

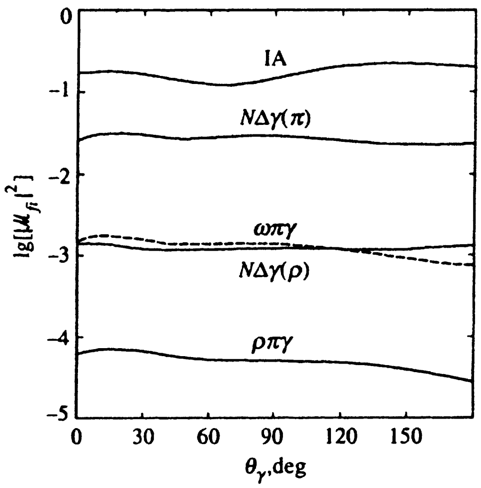

FIG. 3. Square of the pp-bremsstrahlung invariant amplitude as a function of the photon emission angle at $E_{\rm lab}$ = 280 MeV for proton coplanar scattering angles of 16.0° and 27.8°. The impulse approximation (IA) corresponds to Fig. 1a–c. The π- and ρ-exchange contributions to the $N\Delta\gamma$ exchange currents of Fig. 1d are shown separately. The $\rho\pi\gamma$ and $\omega\pi\gamma$ contributions correspond to Fig. 1e. The negligible amplitudes resulting from the $\rho\eta\gamma$ and $\omega\eta\gamma$ contributions are not shown.

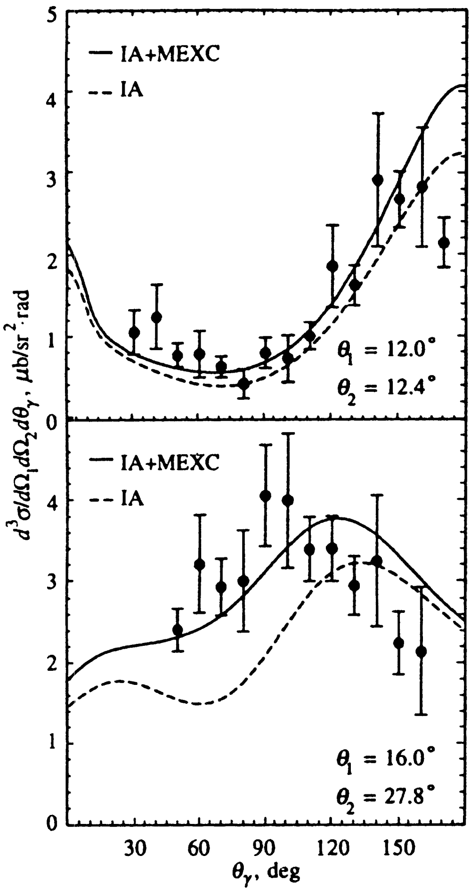

FIG. 4. Comparison of coplanar pp-bremsstrahlung data[5] at $E_{\text{lab}} = 280$ MeV with calculations using wave functions obtained form the RuhrPot NN-interaction and current densities that include (IA+MEXC or neglect (IA) the $N\Delta\gamma$, $\rho\pi\gamma$, $\omega\pi\gamma$, $\rho\eta\gamma$ and $\omega\eta\gamma$ exchange currents. The long-standing discrepancy with experiment is substantially reduced for these and other geometries.

lar to the $t_{\Delta N}$-matrix calculations reported in Ref. 23 and 24, although we realize this conclusion depends on the free parameter adopted in those works.

In Fig. 3 we compare the individual contributions of the impulse approximation current, the perturbative intermediate-state Δ-resonance excitation via π- and ρ-exchange, and $\rho\pi\gamma$, $\omega\pi\gamma$, $\rho\eta\gamma$ and $\omega\eta\gamma$ exchange currents. We fix the coplanar kinematics for this analysis at $E_{\text{lab}} = 280$ MeV with $\theta_1 = 16.0°$ and $\theta_2 = 27.8°$ since the existing data at this geometry exhibits significant variation from phase space and is typical of other data that are poorly described by recent calculations. We observe that the $\omega\pi\gamma$ contribution is clearly larger than those of the $\rho\pi\gamma$, $\rho\eta\gamma$ and $\omega\eta\gamma$, the last two being essentially negligible. Clearly the most important exchange current contribution involves intermediate-state Δ-resonance excitation via π-exchange.

In Fig. 4 we compare pp-bremsstrahlung observables with calculations that include or neglect intermediate-state Δ-resonance excitation and $\rho\pi\gamma$, $\omega\pi\gamma$, $\rho\eta\gamma$ and $\omega\eta\gamma$ interactions. Clearly the inclusion of the exchange currents substantially reduces the long-standing discrepancy with experiment. We checked all other geometries reported in Ref. 5 and found essentially the same result. (The data are presented here without the arbitrary 2/3 scaling that has sometimes been introduced to improve the correspondence to the impulse approximation results.) The magnitude of the exchange current contributions shows, contrary to the expectations of earlier publications, that pp-bremsstrahlung cannot be simply calculated in the impulse approximation to test the accuracy of various off-shell NNt-matrices. The obvious consequence of this is that the process can only be meaningfully investigated within a microscopic theory where consistency between the strong form factors, the NN-interaction and the exchange currents can be explicitly guaranteed.

We stress that both the sensitivity and selectivity of the pp-bremsstrahlung data to the $T = 1$ isoscalar meson-exchange currents provide a unique opportunity for the study of a range of more subtle effects of current interest. These include not only resonance width effects, but also relativistic corrections to the exchange current operators. To that end, we appeal to the experimental community to provide higher precision data, particularly under the kinematical conditions where the impulse approximation calculations fail.

In conclusion, we find that a consistent and microscopic inclusion of the dominant meson-exchange current contributions in pp-bremsstrahlung shows that the applications of standard calculation procedures substantially reduces the long-standing discrepancy with experiment. No free parameters enter the present calculation. Consistency between the wave functions and exchange currents is guaranteed since the NN-interaction, the strong form factors and all meson-exchange currents are all calculated form a consistently parametrized effective Lagrangian. All interferences have been calculated without approximation and no form of the soft photon approximation is used at any stage. Additional high-precision data will be critical to the further study of resonance width and relativistic effects, provided the emphasis is placed on the kinematically complete geometries where the impulse approximation results are at variance with experiment.

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