A relativistic meson-baryon description of $pp$-Bremsstrahlung

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Abstract. We describe a relativistic approach to the calculation of nucleon-nucleon Bremsstrahlung, where all meson-baryon and meson-baryon-photon interactions can be calculated consistently and microscopically. In this first relativistic approach to the problem, we present numerical results including both single-scatter and rescatter contributions with a relativistic current density, within a model where the explicit photon coupling to meson-exchange currents are small. The need for high precision $(p, p\gamma)$ measurements is stressed.

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The consistent microscopic prediction of $(p, p\gamma)$ observables requires the calculation of the photon coupling to an interacting meson-baryon system. For processes where the photon couples to a free nucleon before or after strong-interactions, one can express the $(p, p\gamma)$ invariant amplitude in the two-potential formalism of Gell-Mann and Goldberger [1], consisting of a one-body nuclear current density and an off-shell NN $T$-matrix. The essential advantage of this approach is that the NN $T$-matrix is defined to all orders in the strong-interaction coupling constant. All recent $(p, p\gamma)$ calculations use this two-potential formalism, and obtain the NN $T$-matrices from the Lippmann-Schwinger [2-4] or Blankenbecler-Sugar [5, 6] equations for a non-relativistic boson-exchange potential such as Bonn [7] or Paris [8], or from inverse-scattering methods [9], and therefore include only the positive frequency components of the two-nucleon wavefunctions. Under this restriction, only the positive frequency processes that are shown in Fig. 1 are included.

In all existing $(p, p\gamma)$ calculations, where the non-relativistic strong-interaction models neglect the negative-frequency components of the off-shell nucleons, it is necessary to apply some kind of non-relativistic reduction to the current operator. This may take the form [2, 4] of a Foldy Wouthuysen transformation to obtain a non-relativistic current with 'relativistic' spin corrections, which are retained to some approximate order, according to where the infinite $p/m$-expansion is truncated. In a more approximate scheme, it may take the form [6] of a direct Pauli reduction. These two approaches lead to differences of order 7% in the $(p, p\gamma)$ cross section at 280 MeV [10], and differ from the results that are obtained with a completely non-relativistic current density [3, 5] by as much as 15% [2, 6]. The corresponding differences in the spin-observables are generally even larger.

This suggests the need for relativistic wave functions in $(p, p\gamma)$ calculations, so that the relativistic current density can be calculated without recourse to any $(p/m)$-expansion, and the off-shell two-nucleon state can be properly described as including both its the positive and negative frequency contributions, as shown in Fig. 1. In the Feynman-Stückelberg interpretation, the negative frequency contributions represent $NN$ creation and annihilation processes, and in any truly relativistic calculation [11, 12] they must be regarded as the natural partners to the positive frequency contributions.

![Fig. 1. Some of the processes occurring in the $(p, p\gamma)$ reaction, a initial-state correlation, b final-state correlation and c rescatter contributions. The $(\pm)$ and $(-\pm)$ labels indicate the positive and negative frequency components of the off-shell proton. The ovals indicate meson-exchange processes taken to all orders by the $NN T$-matrix, and solid blobs indicate the electromagnetic form factors](image-url)
By now it is widely recognized that the rescat tern, shown in Fig. 1c, represents an important correction to the dominant single-scatter processes, shown in Fig. 1a–b, and it’s positive frequency components have been included non-relativistically in most of the recent \((N, N\gamma)\) calculations. However, there are additional processes which might be of similar importance but have been entirely neglected. For example, in addition to the negative frequency components of the relativistic states, there are intermediate-states involving nucleon resonances. The essential point here is that a complete calculation of the \((p, p\gamma)\) observables cannot be confined to a one-body current density and a non-relativistic off-shell \(NN\) \(T\)-matrix, but must include a consistent and microscopic description of the photon coupling to an interacting meson-baryon system.

However, recent theoretical developments in \((p, p\gamma)\) calculations appear to have neglected the need for such processes. Indeed all recently published \((p, p\gamma)\) calculations acknowledge only the positive-frequency processes shown in Fig. 1, and emphasis has been placed on improving a number of approximations used to calculate these contributions alone. For example, in some calculations the relativistic spin corrections \([2, 4]\) have been retained, and in others \([3, 5]\) the rescat tern contributions (Fig. 1c) have been calculated without recourse to the soft-photon approximation. From a complete comparison \([3]\) with the experimental data from TRIUMF \([13]\), it is clear that the differential cross section data is not well predicted except at forward proton scattering angles, where the variation of the cross section with the photon emission angle can be heavily influenced by phase space. Unfortunately, there are doubts about the accuracy of the absolute scale of the measured differential cross sections, but it is clear that no rescaling of the data could account for the discrepancies with recent calculations. The measured spin-observables are, of course, independent of phase space and the absolute scale of the cross section data, but they are not well predicted except at larger proton scattering angles, where the photon energy becomes smaller and the \(NN\) scattering kinematics approaches it’s on-shell limit. In the only recently published calculation \([6]\) which includes both relativistic spin corrections and rescat tern processes, only minimal differences to earlier results are observed, and the familiar and persistent discrepancies with experiment are seen to remain.

The mixed success of recent \((p, p\gamma)\) calculations appear to have been interpreted purely in terms of the off-shell behaviour of the non-relativistic \(NN\) \(T\)-matrix, with some authors \([3]\) calling for an analysis of the on- and off-shell tensor contributions in each partial wave, and others \([6]\) reporting that, if the normalization of the TRIUMF data is correct, then the \((p, p\gamma)\) reaction cannot be described with modern non-relativistic potentials.

We wish to look at the problem quite differently. It seems clear by now that the \((p, p\gamma)\) observables are not described by the positive frequency processes shown in Fig. 1 alone. We stress that an off-shell two-nucleon state is described by the linear superposition of both positive and negative frequency components, so that a proper description of the off-shell two-nucleon \(T\)-matrices required in \((N, N\gamma)\) calculations can only be obtained from a relativistic potential. Since all existing calculations ignore these negative frequency components, it may be unwise to rush to conclusions over the merits of various strong-interaction models.

We wish to pursue a consistent approach to the calculation of \((p, p\gamma)\) observables so that all meson-baryon-photon interactions can be calculated on an equal footing. This requires a consistent microscopic description of the strong interaction potential and the form factors it contains, as well as the meson-baryon electromagnetic form factors needed to describe the complete current density. We adopt a two-phase description of the strong-interaction, where low \(Q^2\) meson-baryon interactions are calculated in a fully consistent meson field theory, and high \(Q^2\) interactions are described with a phenomenological parameterization which is consistent with perturbative QCD.

Such a two-phase model has already been applied to the description of the strong- and electromagnetic nucleon form factors. At low \(Q^2\), vector-meson dominance describes the photon coupling to the nucleon via an intermediate \(\omega\)- or \(\rho\)-meson, so that the well-known dipole form of the nucleon electromagnetic form factors is described by a monopole strong form factor and a meson propagator. At very high \(Q^2\), perturbative QCD calculations show that the form factors have a stronger \(Q^2\) power suppression. The QCD-VMD model \([14]\) connects these low- and high \(Q^2\) descriptions of the electromagnetic form factors by describing the strong form factors in a two-scale parameterization. At low \(Q^2\), where the strong form factors are well approximated by a monopole representation, the meson scales have been calculated to all orders in a self-consistent one-loop ladder approximation \([15, 16]\), and the results are consistent with a recent analysis of experiment \([17]\). At high \(Q^2\), the form factors are parameterized to fulfill the counter rules of perturbative QCD, and the relevant scale is determined by comparison with the experimental data \([17]\).

The same approach has been adopted in the construction of the strong-interaction potential \([15]\). The low \(Q^2\) interactions are dominated by meson-exchange processes, but extending the description to high \(Q^2\), the potential gains an additional ‘contact interaction’, which has a slower \(Q^2\) suppression than the meson-exchange terms, as is required to describe direct quark-exchange processes. At high \(Q^2\), where the meson exchange processes are suppressed, the potential is dominated by contact interactions which involve strong form factors that satisfy perturbative QCD requirements. We illustrate the relationship between the electromagnetic form factors and the strong-interaction potential in Fig. 2.

Below the \(\pi\)-production threshold, the total relativistic wave function can be written as \([18]\),

\[
\Psi = (1 + F) \frac{1}{\sqrt{1 + F^+ F}} (\chi^{(+)\perp} + \chi^{(-)\perp})
\]