Can one learn anything from proton-proton bremsstrahlung? Comment on H. W. Fearing preprint [nucl-th/9710061].

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Recently, Fearing [nucl-th/9710061] has argued that, as a matter of principle, proton-proton bremsstrahlung can yield no more information about the off-shell properties of the nucleon-nucleon interaction than can already be deduced from the on-shell properties. In this note we challenge Fearing’s conclusion.

In his paper [1], Fearing gives plausible but inconclusive arguments that proton-proton bremsstrahlung can yield no more information about the off-shell properties of the nucleon-nucleon interaction than can already be deduced from the on-shell properties, and supports his conclusions with a detailed calculation for $\pi^+ + \pi^0 \rightarrow \pi^+ + \pi^0 + \gamma$, using a simple model Lagrangian involving only the pion and photon fields. We have no quarrel with his analysis of this latter process, but question the validity of drawing general conclusions from that very simple special case. We also question the generality of Fearing’s discussion of off-shell effects in the nucleon-nucleon case. Fearing’s arguments are of two kinds. Firstly, he gives a general argument that contributions to proton-proton bremsstrahlung arising from the nucleon-nucleon interaction are inextricably mixed with contributions from “contact terms” which are in principle uncomputable within a potential model of the NN interaction, thus leading to an unresolvable ambiguity. From this he concludes that calculations of proton-proton bremsstrahlung using only a potential model are incomplete and intrinsically unreliable. Secondly, some off-shell contributions to the bremsstrahlung amplitude are necessary consequences of the on-shell NN interaction. Fearing argues that field transformations which leave the $S$-matrix unaltered affect any additional off-shell contributions, different from those which are necessary consequences of the on-shell NN interaction, in an arbitrary manner, allowing them to be eliminated entirely. Consequently he argues that proton-proton bremsstrahlung can yield no information about off-shell properties of the nucleon-nucleon interaction beyond those already implied by the on-shell properties. We respond to these arguments in turn.

Fearing envisages computing the NN scattering amplitude both on-shell and off-shell from some model (such as a potential model) of the NN interaction, and using it (represented by shaded areas) in bremsstrahlung graphs such as Fig. 1(a)–(c). However there must also be contact terms represented by Fig. 1(d) which cannot be correctly computed using only a potential model for the NN interaction. Figure 2(a) shows an example of an irreducible contact term. Furthermore, off-shell contributions to the nucleon propagator in internal lines in diagrams Fig. 1(a)–(c) effectively collapse the line, leading to a contribution similar to a contact term. Fearing therefore asserts that off-shell contributions to the amplitude are inextricably intermixed with irreducible contact terms which are intrinsically impossible to compute in a potential model of the NN interaction. In response, we argue that there is a significant difference between a (computable) contact term arising from off-shell contributions to the internal proton propagators in Figs. 1(a)–(c), modified so that the NN$\gamma$ vertex is fully renormalized, and irreducible contact terms such as those illustrated by Fig. 2(a). In a meson exchange theory of the nonrelativistic nucleon-nucleon interaction, it is well known [2] that crossed diagrams such as Fig. 2(a) are less important than box diagrams, such as Fig. 2(b), of the same order. The contributions to the bremsstrahlung amplitude differ from the contributions to elastic scattering from the corresponding diagrams only by an additional propagator and an additional vertex. Therefore we expect to find a similar result for bremsstrahlung provided at least the final state protons are nonrelativistic. The singularity structure associated with diagrams Fig. 2(a) and Fig. 2(b), examined using approximations similar to those described by Gross [2], confirms this expectation. A distorted wave approach is appropriate for low energy nucleons. Therefore for the kinematical region in which the protons are nonrelativistic we expect that irreducible point contributions to the $pp \rightarrow pp\gamma$ amplitude will be suppressed and that a distorted wave Born approximation (DWBA) should provide the dominant contribution. Recent work [3] shows that such a kinematical region is of real interest.

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More important are Fearing’s arguments using field transformations. We are interested with off-shell properties of the NN interaction which are not automatic consequences of the on-shell interaction. These must be “EOM” terms, i.e. terms which vanish in consequence of the equations of motion of an assumed underlying field theory. One could in principle enumerate all possible EOM contributions to the effective Lagrangian of the underlying field theory, consistent with all necessary symmetries, and include them with arbitrary coefficients analogous to the β’s of Fearing’s pion model. Now it is precisely EOM terms which are modified as a result of field transformations. We next consider the most general field transformation consistent with all of the symmetries of the theory. This will also depend on a number of parameters, analogous to the α’s of Fearing’s pion model. These field transformations will merely replace the EOM terms in the Lagrangian by the same terms (since the most general terms were already included) but with modified coefficients β = β’(α, β). In the simple π+π0 bremstrahlung model treated in detail by Fearing, given any β1 and β2 it was possible to find α1 and α2 such that β12 = 0. However the most that can be concluded from the general theory is that EOM terms in the Lagrangian representing differing off-shell properties of the NN interaction can affect observable processes only through a set of functions γ(β) which are invariant under the group of field transformations. It is necessary to show that the set {γ} of such functions is empty, and Fearing has not shown this for the NN bremstrahlung case.

Can we understand why the set {γ} need not be empty for proton-proton bremstrahlung even though {γ} = ∅ for the simple pion model treated by Fearing? We suggest that Fearing’s result is a consequence of the “Cancellation theorem,” stated on p. 384 of Ref. [2]. However this theorem does not hold for nucleons interacting through the exchange of pions, because both nucleons and pions carry isospin (see pp. 387–388 of Ref. [2]).

Even if the set {γ} could be shown to be empty for a particular field theory underlying the NN interaction, Fearing’s argument fails if the assumed underlying field theory is changed. The effective field theory underlying the OBE potentials, based on nucleons and mesons, cannot be changed by field transformations into a theory incorporating quarks in the “broken chiral symmetry” phase, gluons, and Goldstone bosons. While there does not yet exist any NN potential rigorously derived from a quark-gluon-Goldstone boson field theory, this approach inspired the development of the “Moscow potential” [5], which has been successfully adapted to fit nucleon-nucleon properties. This model assumes that the short range NN interaction is dominated by a 6-quark configuration with orbital structure s4p2, which implies that the s-wave NN wave function has a node at short distances. Recent work by Stancu et al. [3], using a quark-Goldstone boson model which has shown success in describing the hadron spectrum [4] also requires the dominant 6-quark orbital structure to be s4p2, although the permutation symmetry properties are different from those of Ref. [3]. One should expect observable differences, due to differing off-shell properties of the NN interaction, in the predictions for proton-proton bremstrahlung in treatments based on a nucleon-meson field theory or a quark-gluon-Goldstone boson field theory, whether the calculation is performed using field theoretical methods or potential models. Indeed, recent distorted wave calculations [6] of the pp → ppγ cross section, comparing the predictions of the Paris, Hamada-Johnston, and Moscow potentials, show dramatic differences in the cross section for incident (laboratory frame) energies of 350 MeV and 450 MeV in kinematic regions which correspond to the emission of hard photons. Although an ambiguity in Ref. [6] arises from the difference in the center of mass reference frames of the initial state and final state protons, this is not as great as the difference between the predictions of the Moscow and the other two potentials, and will be resolved by work in progress [6].

In summary, we believe that Fearing has failed to demonstrate his thesis that proton-proton bremstrahlung can yield no information concerning the off-shell properties of the nucleon-nucleon interaction. We argue that the ambiguity in the contribution of contact terms noted by Fearing can be minimized in a potential model by using distorted waves for the nucleons and by suitably choosing the kinematical region. We also claim that Fearing has not fully proved his formal results based on field transformation in the case of proton-proton bremstrahlung. Even if correct, however, his argument cannot apply to potential models based on effective field theories which use interpolating fields with different symmetry properties, such as quarks versus nucleons.

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[1] Harold W. Fearing, “Off-shell effects in nucleon-nucleon bremsstrahlung,” nucl-th/9710001, TRIUMF preprint TRI-PP-97-31 (1997).
[2] See Franz Gross, Relativistic Quantum Mechanics and Field Theory, §§12.1–12.2 (John Wiley & Sons, Inc., 1993).
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**FIG. 1.** Diagrammatic representation of contributions to proton-proton bremsstrahlung. Off-shell effects contribute to the internal line propagators in (a)–(c). Figure 1(d) represents contact terms.

**FIG. 2.** (a) A typical irreducible “contact term” diagram. (b) Box diagram for bremsstrahlung.