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Reply to "Comment on 'Quasielastic Lepton Scattering and b=Back-to-Back Nucleons in the Short-Time Approximation' "

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Reply to "Comment on 'Quasielastic lepton scattering and back-to-back nucleons in the short-time approximation' "

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We briefly review the concept of scaling and how it occurs in quasielastic electron and neutrino scattering from nuclei, and then the particular approach to scaling in the short-time approximation. We show that, whereas two-nucleon currents do significantly enhance the transverse electromagnetic response, they do not spoil scaling, but, in fact, enhance it. We provide scaling results obtained in the short-time approximation that verify this claim. The enhanced scaling, although obtained empirically, is not "accidental"—as claimed in [O. Benhar, Phys. Rev. C **105**, 049801 (2022)]—but rather reflects quasielastic kinematics and the dominant role played by pion-exchange interactions and currents in the quasielastic regime.

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I. QUASIELASTIC SCATTERING AND SCALING IN NUCLEAR PHYSICS

The concept of scaling originated from the idea of treating the response functions as arising from the incoherent sum of scattering from single nucleons (Ref. [1]). Ignoring final-state interactions of the struck particle with the rest of the nucleus yields final states that are products of free single-particle states with the momenta of the original nucleon plus the transferred momentum and of the final states of the remaining interacting nucleons. Ignoring final-state-interaction effects in the final system altogether or including the removal energy of the struck nucleon results in the plane-wave impulse approximation (PWIA) [2,3] or the spectral function approach [4–7]. The latter is an improvement as it contains additional information on the energy to remove a nucleon from the nucleus. Scaling has been a very useful concept in a wide variety of contexts including neutron scattering, response in cold atoms, etc.

Whereas these approximations are useful to get an initial picture of quasielastic scattering, they are incomplete. They predict, for example, that the longitudinal and transverse scaling functions obtained from the corresponding response functions would be the same, which is not observed experimentally. For example, Fig. 30 of the review article by Benhar *et al.* [8] shows that the scaling functions extracted from longitudinal and transverse data on ^{12}C differ in magnitude by approximately 40% for momentum transfers in the range $q = 400$–600 MeV/c across the entire quasielastic region. Calculations in subsequent (as well as previous) years [9–12] have demonstrated that this dramatic difference arises largely due to the interference between processes involving single-nucleon currents with an accompanying correlated nucleon and processes involving two-nucleon currents. Such interference might be considered beyond the scope of the traditional scaling approach, however, we demonstrate that it can be accommodated within an empirical scaling picture. We note that scaling of the individual longitudinal and transverse response functions with energy and momenta provides a much better description of the data than using a single scaling function for both.

II. THE SHORT-TIME APPROXIMATION AND SCALING

As discussed in our paper [11], quasielastic scaling is dominated by relatively high momentum and energy scales, larger than the typical Fermi momentum and Fermi energy. In such a regime, the electroweak response is dominated by nearly local quantities that can be calculated in terms of the one- and two-body off diagonal density matrix and single- and two-nucleon currents. Whereas the incoherent scattering from individual nucleons is dominant, two-nucleon processes provide substantial corrections. This is natural in the path-integral picture since high energies correspond to short propagation times and, hence, short distances.

The short-time approximation is based on this path-integral picture, and scaling will naturally occur, both the y scaling associated with the response at different momentum transfer and the superscaling associated with the response of different nuclei. The latter is a consequence of the locality of inclusive scattering. The short-time approximation reduces to the plane-wave impulse approximation if we ignore: (i) coherent scattering terms where two different nucleons are struck, (ii) two-nucleon currents, and (iii) isospin-violating interactions in the two-nucleon propagator. In this simplification the calculation reduces to calculating the one-body off diagonal density matrix or the momentum distribution.

Whereas the standard PWIA or spectral function might superficially appear to be independent of two-nucleon dynamics, they certainly depend on the momentum distribution in the ground state. As demonstrated both theoretically [13,14] and experimentally [15,16], the momentum distribution in the range of $k \approx 2\ \mathrm{fm}^{-1}$ is dominated by the two-nucleon pion-exchange interaction. So from this perspective it can be argued that PWIA, whereas it uses single-nucleon kinematics for the final state, includes initial-state correlations arising from two-nucleon dynamics. The two-nucleon currents act similarly, yielding significant interference with initial-state components with two correlated nucleons.

To go beyond this simplified picture, the short-time approximation (STA) includes interactions in the two-nucleon propagator. The two-nucleon propagation is no longer a function only of the distance between the initial and the propagated nucleon, it also depends strongly on the spin and isospin of the nucleons and the time separation in the two-point correlations function. Indeed, the response can be quite different depending on the nature of the single-nucleon coupling and responses obtained with a number of different such couplings are compared in Ref. [17]. For example, in the longitudinal channel charge can propagate through the exchange of charged pions in addition to the momentum of the struck proton. This additional mechanism again defies the notion of longitudinal scattering as being driven only by single-nucleon dynamics. It turns out that such a mechanism gives a significant contribution to the energy-weighted sum rule, as the vertex and the Hamiltonian do not commute and produces a redistribution of strength and, in particular, a larger tail in the response at energies above the quasielastic peak. The noncommuting nature of the coupling operator and the evolution operator is important in electroweak responses and does not occur in many applications of scaling in other fields.

We demonstrate the scaling properties of the STA response functions in Fig. 1 for the transverse channel in ^{4}He. The dashed lines show the scaling function at various momentum transfers using only single-nucleon current operators. The scaling is reasonable but not perfect as additional mechanisms (incoherent scattering, final-state interactions, etc.) come into play. In the lower panel we plot the ratio of the scaling function at various momentum transfers to the average scaling function obtained at higher average q. Note that the one-body response approaches the average scaling from below, substantially increasing with q near the quasielastic peak.

The full curves show the scaling function including two-nucleon currents [10]. The most important two-nucleon currents in this regime are those due to pion exchange [10]. The scaling function is enhanced compared to that obtained with single-nucleon currents only due to the interference

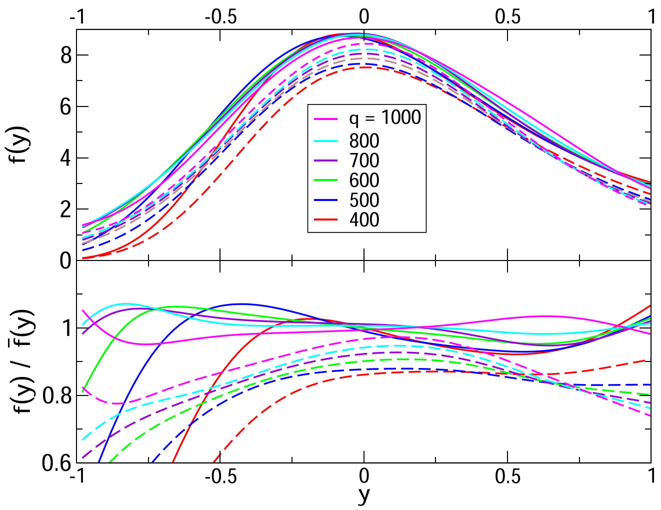

FIG. 1. Transverse scaling functions for ^{4}He with one-body and one plus two-body currents. The upper panel shows the scaling functions with dashed lines for one-body incoherent scattering and full lines for the complete response. The lower panel shows the ratio of the scaling functions for various momentum transfers (in units of MeV/c) divided by the average scaling function used in the analysis. Results from Barrow *et al.* [18].

described in our paper. More importantly, the scaling with momentum transfer is, in fact, substantially better with the inclusion of two-nucleon currents. This result is an empirical observation based on full calculations rather than an analytic approach, it is not surprising since both currents and correlations yield high-momentum nucleons immediately after the vertex. For most momentum transfers considered, the scaling violations are only a few percent in the critical regime near the quasielastic peak at $y = 0$.

As we describe in our paper [11], the momentum structure of the pion exchange in the strong interaction arises in exactly the same way as the momentum structure in the pion-exchange two-nucleon currents. Hence, the scaling is no less apparent in the full calculation as in the calculation with single-nucleon currents only. In our view, calling this scaling “accidental” [1] is akin to calling the relation between two-nucleon currents and two-nucleon interactions accidental when, in fact, it is governed by the same underlying dynamics of pion-exchange mechanisms, an essential feature in describing quasielastic scattering.

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