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Inclusive electron scattering and pion degrees of freedom in light nuclei

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We demonstrate that realistic models of nuclear interactions and currents quantitatively reproduce the α-particle longitudinal and transverse responses as measured in inclusive electron scattering at intermediate energies. Pion degrees of freedom in both the nuclear interactions and currents play a crucial role in reproducing the experimental data. The charge-exchange character of the pion-exchange interaction leads to shifts of both longitudinal and transverse strength to higher excitation energies, thus producing a significant quenching of the response in the region of the quasielastic peak. However, in the transverse channel this mechanism is more than offset by the two-body pion-exchange currents required by gauge invariance, and hence the response is enhanced over the entire quasielastic spectrum. We relate these results to responses to idealized single-nucleon couplings and to quasielastic data from hadronic reactions on nuclei.

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Electron scattering experiments at moderate momentum transfers are sensitive to the role of virtual pions, and therefore provide direct tests of traditional nuclear models incorporating realistic nucleon-nucleon interactions and current operators. The importance of pion degrees of freedom in various contexts of nuclear physics has recently attracted much interest in the literature [1].

In this paper we present *ab initio* microscopic calculations of the α-particle longitudinal and transverse response functions measured in quasielastic (e,e') scattering. The calculated responses are found to be in excellent agreement with the experimental data [2,3]. These calculations incorporate a complete microscopic treatment of both final-state interactions (FSI) and two-body currents. The charge-exchange components of the nuclear interaction, specifically those associated with pion exchange, shift the longitudinal strength toward the high excitation-energy end of the spectrum, and consequently quench the response in the region of the quasielastic peak. A similar, but even larger, quenching is observed in the transverse channel. Here, though, this quenching is more than offset by the contribution of two-body currents associated with pion exchange. These currents, which are required by current conservation, play a crucial role over the entire spectrum, producing a large enhancement near the quasielastic peak as well as in the low excitation-energy regime, near threshold.

The resulting picture of inclusive scattering from light nuclei is markedly different from that obtained on the basis of naive independent particle models or plane-wave-impulse-approximation (PWIA) calculations. For example, the PWIA calculations predict far more strength than is experimentally observed in the peak region, particularly at low momentum transfers [4]. In the past few years progress beyond PWIA has been made by a number of different approaches, including continuum Faddeev [5] and real-time path integral Monte Carlo methods [6]. However, these calculations are based on very simplified interaction models in which pion exchange is not taken into account in either the FSI or the current operators. Hence it is impossible to assess its role within the scope of the previous calculations.

In a recent paper we developed an exact method to calculate response functions in imaginary time (Euclidean response functions), and applied it to the Euclidean proton response of the α particle [7]. Here we extend our calculations to incorporate "realistic" couplings to longitudinally and transversely polarized virtual photons, and compare them directly with experimental data on ^{4}He from Bates [2] and Saclay [3]. We also compute the Euclidean response to a variety of simple single-nucleon couplings in order to elucidate our understanding of nucleon propagation in the nuclear medium.

The response of a quantum many-body system to a weakly coupled external probe is characterized by a function $S(k,\omega)$ defined as

$$S(k,\omega) = \sum_n |\langle n|\rho(\mathbf{k})|0\rangle|^2 \, \delta(\omega + E_0 - E_n) \ ,$$

where E_0 and E_n are the energies of the initial and final states, respectively, and $\rho(\mathbf{k})$ is a suitably chosen coupling. The Euclidean response $E(k,\tau)$ is obtained by rotating the propagators to imaginary time and is related to $S(k,\omega)$ by a Laplace transform

$$\begin{aligned} E(k,\tau) &= \int_0^\infty \exp[-\tau(\omega-\omega_{\rm qe})] S(k,\omega) d\omega \\ &= \langle 0|\rho^\dagger(\mathbf{k}) \exp[-\tau(H-\omega_{\rm qe}-E_0)]\rho(\mathbf{k})|0\rangle \ , \qquad (1) \end{aligned}$$

where $\omega_{\rm qe} = k^2/2m$. The Hamiltonian H is

$$H = \sum_i \frac{\mathbf{p}_i^2}{2m} + \sum_{i<j} v_{ij} + \sum_{i<j<k} V_{ijk} \ ,$$

where v_{ij} and V_{ijk} are the Argonne v_8 two-nucleon [8] and

Urbana model-VIII three-nucleon [9] interaction models, respectively. The v_8 model incorporates pion exchange at long distances, reproduces deuteron properties, and is phase equivalent to the full Argonne v_{14} [10] in the $^1S_0$, $^3S_1$-$^3D_1$, and all uncoupled P waves. When coupled with the three-nucleon interaction, this Hamiltonian overbinds the α particle by about 1 MeV in exact Green's function Monte Carlo (GFMC) ground-state calculations [11]. For a given k, $E(k,\tau=0)$ gives the total strength of the response, while the full $E(k,\tau)$ measures its energy distribution. Derivatives of the $E(k,\tau)$ at $\tau=0$ are trivially related to energy-weighted sums of the $S(k,\omega)$.

It is possible to calculate $E(k,\tau)$ straightforwardly in a path-integral representation, as presented summarily in Ref. [7]. In essence, one evaluates the imaginary-time propagator by splitting it up into many small steps $\exp(-\tau H) = \prod \exp(-\Delta\tau H)$, choosing an accurate approximation to the short-time propagator, and using stochastic techniques to sample the propagator over many steps. Methods suitable for the nuclear many-body problem, which allow the complicated spin-isospin structure of the two- and three-nucleon interactions to be treated in full, have been developed in Refs. [11,12]. Here we follow not only the propagation of the full ground-state wave function, but also various amplitudes associated with longitudinal or transverse photon couplings.

We assume that the nuclear charge (L) and current (T) operators consist of one- and two-body pieces,

$$\rho_\alpha(\mathbf{k}) = \rho_{\alpha,1}(\mathbf{k}) + \rho_{\alpha,2}(\mathbf{k}) , \quad \alpha = L,T .$$

A detailed discussion of these couplings can be found in Refs. [13,14]. Here we only note that the longitudinal one-body part contains the proton and neutron contribution as well as the Darwin-Foldy and spin-orbit relativistic corrections to the single-nucleon charge operator; the transverse one-body part is composed of the standard convection and spin-magnetization currents. The leading two-body contributions in both the longitudinal and transverse channels are associated with pion exchange. These operators have the momentum space structure

$$\rho_{L,\pi}(\mathbf{k}) = \sum_{i<j} \frac{3}{2m}\{[\tau_i\cdot\tau_j + \tau_{j,z}]v_\pi(k_j)(\sigma_i\cdot\mathbf{k})\,(\sigma_j\cdot\mathbf{k}_j) + i \rightleftharpoons j\},$$

$$\rho_{T,\pi}(\mathbf{k}) = \sum_{i<j} -3i(\tau_i\times\tau_j)_z \left\{ v_\pi(k_j)\sigma_i(\sigma_j\cdot\mathbf{k}_j) - v_\pi(k_i)\sigma_j(\sigma_i\cdot\mathbf{k}_i) - \frac{\mathbf{k}_i-\mathbf{k}_j}{k_i^2-k_j^2}[v_\pi(k_j)-v_\pi(k_i)](\sigma_i\cdot\mathbf{k}_i)\,(\sigma_j\cdot\mathbf{k}_j)\right\} ,$$

with $\mathbf{k}=\mathbf{k}_i+\mathbf{k}_j$. The longitudinal operator is a relativistic correction, while the transverse is required even in nonrelativistic order. In the actual simulations, the operators above are Fourier-transformed to r space. Shorter-range contributions arising from the exchange of heavier mesons as well as transverse corrections associated with virtual excitation of Δ resonances are also included. However, at the moderate momentum transfers considered here they are quantitatively much less important. It should be emphasized that these charge and current operators provide a very satisfactory description of the elastic form factors of the $A=3$ and 4 nuclei [9], and of the deuteron structure functions [15] in the momentum transfer range of interest here ($k \leq 600$ MeV/c). However, the present theory fails to reproduce the observed deuteron tensor polarization [16,17], but the associated large errors prevent, at the moment, a firm resolution of the issue [18].

The calculated values for the Euclidean longitudinal and transverse responses at k=300 and 400 MeV/c are shown in Figs. 1 and 2, where they are compared with the corresponding experimental data, obtained from the measured response functions $S_\alpha(k,\omega)$, $\alpha = L,T$ [2,3] (circles and squares with error bars). These are available only to a maximum energy $\omega=\omega_{\rm max}$. In the longitudinal channel it is possible to estimate the unobserved strength at $\omega > \omega_{\rm max}$ by means of sum-rule techniques [19,20]. The effect of including this high-energy strength in $E_L(k,\tau)$ is shown by the curve labeled "extrapolated" (short-dashed line). It decreases rapidly with τ because of the exponential damping factor $\exp(-\tau\omega)$, and is negligible for $\tau \geq 0.015$ MeV^{-1}. In the transverse channel we simply show the experimental results corresponding to the truncated $S_T(k,\omega)$. Since the Saclay measurements extend to higher ω, they naturally lead to an increased $E_T(k,\tau)$ near τ=0. Again,

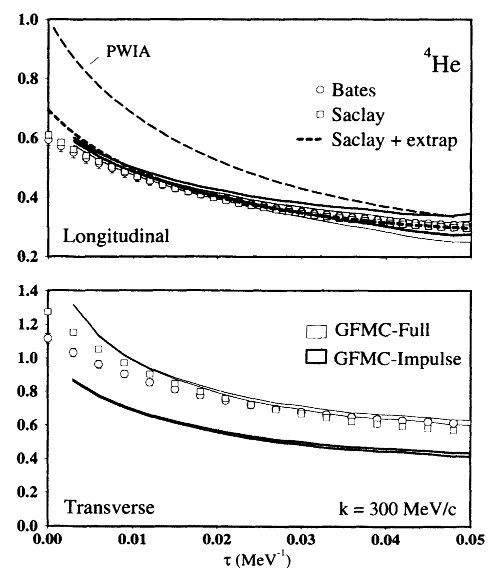

FIG. 1. ^{4}He Euclidean longitudinal and transverse responses at k = 300 MeV/c. The GFMC calculations with (GFMC-full) and without (GFMC-impulse) two-body corrections to the electromagnetic couplings are compared with the Bates and Saclay data. The PWIA results are shown for the longitudinal response only.

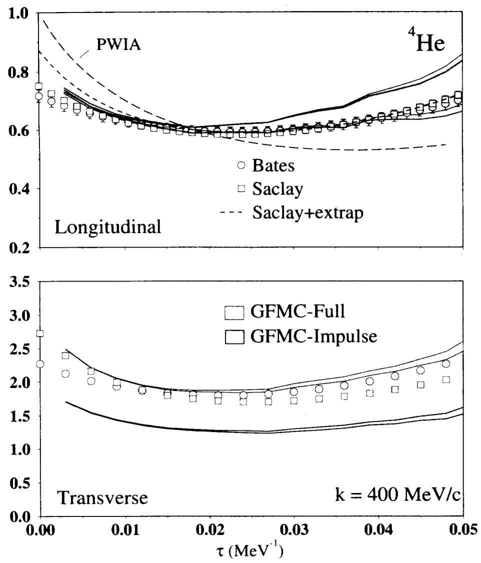

FIG. 2. ^{4}He Euclidean longitudinal and transverse responses at k = 400 MeV/c (as in Fig. 1).

though, the effects of this high-energy strength (mostly due to the Δ resonance) are rapidly suppressed at finite τ, so that the Bates and Saclay measurements are nearly identical by $\tau \sim 0.02$ MeV^{-1}. The difference between their $E_T(k = 400\ \mathrm{MeV}/c, \tau)$ at large τ is associated with a $\sim$ 5 MeV relative shift in the corresponding $S_T(k = 400\ \mathrm{MeV}/c, \omega)$.

The results of our Monte Carlo calculations are displayed as error bands representing plus or minus one standard deviation. Results obtained with full one- plus two-body charge and current operators are indicated by the shaded error band, while those obtained with the one-body terms only are enclosed between solid lines. All the Monte Carlo results include a complete treatment of FSI.

The contributions due to two-body couplings in the longitudinal channel are found to be extremely small except at very low τ (high ω). In the transverse channel, however, they account for more than 20% of the total $E_T(k,\tau)$ over the entire τ spectrum. For $\tau \geq 0.02$ MeV^{-1} the strength in the quasielastic peak region of $S_T(k,\omega)$ is being probed, thus indicating that two-body currents, specifically the components due to pion exchange, produce a large enhancement in this ω region.

The theoretical framework employed here does not include pion production nor a dynamic treatment of the Δ resonance, and hence cannot explain the response in the Δ-peak region, corresponding to $\tau \leq 0.02$ MeV^{-1}. However, for larger values of τ a static parametrization of the currents associated with virtual Δ production, such as the one used in the present work, should be adequate, since the product $\tau\Delta E \gg 1$, where ΔE is a typical $\Delta - N$ energy excitation.

We note that for both the longitudinal and transverse responses there is excellent agreement between the full calculations and the data for $\tau \geq$ 0.015–0.02 MeV^{-1}. It should be emphasized that these calculations include FSI effects exactly. Their contribution is large as indicated by the difference between the GFMC and PWIA results (here shown only for the longitudinal channel), and drastically change the τ dependence of the E_L(PWIA). At low τ E_L(GFMC) $<$ E_L(PWIA) as expected from sum rule considerations. However, at high τ (low ω), the trend is reversed, implying that FSI substantially enhance the response on the low ω side of the quasielastic peak. At the largest values of τ considered here we are sensitive to the low-ω tail of the response; the response at the peak is suppressed by a factor of $\exp(-\tau k^2/2m)$, or roughly 0.015 for k=400 MeV/c at $\tau = 0.05$ fm^{-1}.

To further our understanding of the dynamical mechanisms involved in quasielastic scattering, in particular of the role of the charge exchange and tensor components of the nuclear interaction, we have also studied the α-particle Euclidean responses to a variety of single-nucleon couplings. The nucleon, proton, isovector, spin-longitudinal, and spin-transverse couplings are defined, respectively, as

$$\rho_N(\mathbf{k}) = \sum_i e^{i\mathbf{k}\cdot\mathbf{r}_i} \ ,$$

$$\rho_p(\mathbf{k}) = \sum_i e^{i\mathbf{k}\cdot\mathbf{r}_i} \frac{1+\tau_z(i)}{2} \ ,$$

$$\rho_\tau(\mathbf{k}) = \sum_i e^{i\mathbf{k}\cdot\mathbf{r}_i} \tau_+(i) \ ,$$

$$\rho_{\sigma\tau L}(\mathbf{k}) = \sum_i e^{i\mathbf{k}\cdot\mathbf{r}_i} (\sigma_i \cdot \hat{\mathbf{k}})\tau_+(i) \ ,$$

$$\rho_{\sigma\tau T}(\mathbf{k}) = \sum_i e^{i\mathbf{k}\cdot\mathbf{r}_i} (\sigma_i \times \hat{\mathbf{k}})\tau_+(i) \ .$$

For each coupling ρ_α there is an associated response E_α, as shown in Fig. 3. These are normalized such that $E_\alpha(k \to \infty, \tau = 0) = 1$. Note that the spin response functions $E_{\sigma\tau L}$ and $E_{\sigma\tau T}$ defined here are purely isovector, and that by neglecting isospin-breaking interactions one may replace τ_+ by τ_z when calculating $E(k,\tau)$ for an isoscalar target. The spin-independent isovector response E_τ is simply a weighted average of $E_{\sigma\tau L}$ and $E_{\sigma\tau T}$, and is not displayed in Fig. 3. In the limit $\tau \to \infty$ the only contribution to $E_{N,p}$ is due to elastic scattering, and therefore $E_N(k,\tau) = E_p(k,\tau)/2$, given our normalization above. The elastic scattering contribution vanishes in the

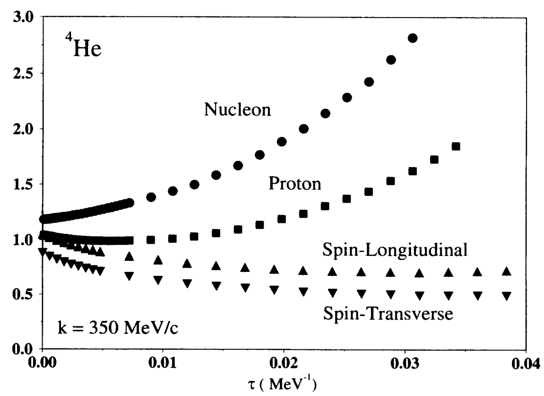

FIG. 3. The ^{4}He Euclidean responses at k = 350 MeV/c for the single-nucleon couplings given in the text. Each response has been normalized such that $E_\alpha(k \to \infty, \tau = 0) = 1$.

isovector $E_{\tau,\sigma\tau L,\sigma\tau T}$. The rapid increase (decrease) of $E_{N,p}$ ($E_{\tau,\sigma\tau L,\sigma\tau T}$) at large (small) τ indicates that there is substantial response at $\omega < \omega_{\rm qe}$ ($\omega > \omega_{\rm qe}$).

The strong isospin dependence displayed in Fig. 3 arises naturally in any interaction model incorporating charge exchange, as is the case for all realistic interactions. For example, the proton response $E_p(k,\tau)$ measures the propagation of charge in imaginary time in a nucleus, and can be written as

$$E_p(k,\tau) = \sum_{ij} \int d\mathbf{r}_{ij}\; j_0(kr_{ij})\; E_p(\mathbf{r}_{ij},\tau) \;,$$

where $\mathbf{r}_{ij}$ is the distance between the initial position of proton i at time 0 and final position of proton j at time τ, $\mathbf{r}_{ij} \equiv \mathbf{r}_i - \mathbf{r}'_j$. In the limit $\tau \to 0$, the propagator $\langle \mathbf{R}|e^{-\tau H}|\mathbf{R}'\rangle \to \delta(\mathbf{R}-\mathbf{R}')$. As τ increases the nucleons move, the imaginary-time free particle propagator is proportional to $\exp[-(m/2\tau)(\mathbf{R}-\mathbf{R}')^2]$. In addition, the charge-exchange terms in the interaction shift the charge from one nucleon to another, substantially reducing the contribution of the incoherent ($i = j$) terms to the response. The difference between the nucleon and proton response indicates the importance of the charge-exchange mechanism in quasielastic scattering. Similar conclusions had been reached previously on the basis of sum rule calculations for the $S_{N,p}(k,\omega)$ [21]. However, sum rules provide only the moments of the response, which are insensitive to details of the energy distribution, particularly at low ω. They can also be very sensitive to short-range cutoffs in exchange currents, much more so than calculations at finite τ.

The charge-exchange mechanism becomes even more important in the purely isovector channel. Since ^{4}He is an isoscalar target, up to Coulomb effects $E_p = (E_N + E_\tau)/2$, implying a much more substantial shift of strength from the quasielastic peak towards higher energies in S_τ than in S_N. Indeed, this effect has recently been observed in comparisons of quasielastic spectra for (p,p') and (p,n) reactions measured for a variety of nuclear targets [21], see Fig. 4. As these hadronic probes do not couple weakly to the nucleus, care should be taken in interpreting the experimental results. Nevertheless, it is clear that the basic difference between the (p,p') and (p,n) reactions lies in the different isospin nature of the couplings, to which ρ_N and ρ_τ are only a rough approximation. Therefore, the essential feature of the empirical spectra, namely the significantly stronger shift of strength for isovector couplings, has a simple dynamical interpretation: it is a manifestation of the charge-exchange character of the underlying nucleon-nucleon force. It should be noted that these same experiments have also measured spin polarization observables in an attempt to separate $S_{\sigma\tau,L}$ and $S_{\sigma\tau,T}$ [22].

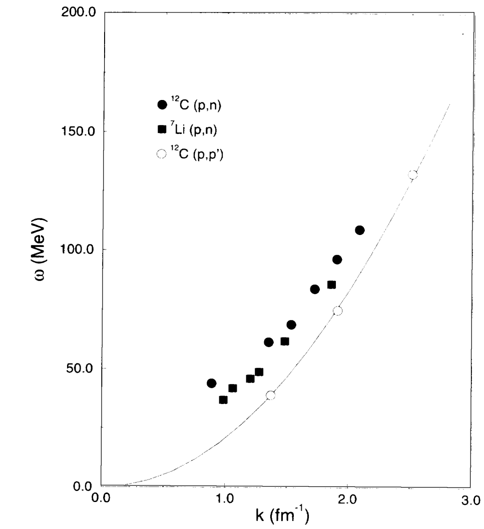

FIG. 4. Centroids of (p,p') and (p,n) quasielastic response functions. The solid line corresponds to the free particle energy $k^2/2m$.

In contrast to a naive interpretation of the experimental results, we do find excess strength in the longitudinal channel. However, the calculated enhancement $E_{\sigma\tau,L}/E_{\sigma\tau,T}$ is much smaller than that obtained in traditional random-phase-approximation calculations. These questions are addressed thoroughly in Ref. [23].

To conclude, we have shown that an *ab initio* microscopic calculation based on realistic interactions and currents leads to a quantitatively satisfactory understanding of inclusive electron scattering from light nuclei in the quasielastic regime. The essential role played by virtual pion exchange should be emphasized, in contrast with recent claims in the literature concerning hadronic probes [1]. A variety of important physics issues remain in inclusive scattering experiments. They include microscopic calculations of response functions in heavier nuclei, description of the pion and delta electroproduction region, effects of FSI and two-body currents on polarization observables, and response to other probes, including the weak interaction couplings probed in parity-violating electron scattering. Inclusive scattering remains an important area for studying nuclear dynamics, and a rich field for both theory and experiment.

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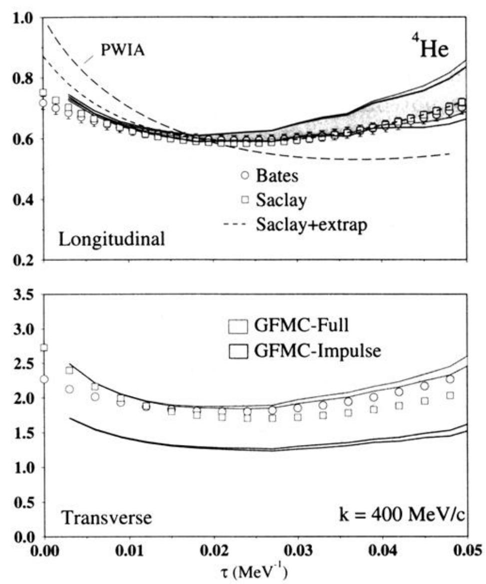

FIG. 2. ^{4}He Euclidean longitudinal and transverse responses at $k = 400$ MeV/c (as in Fig. 1).