Transverse Response Functions in Deep-Inelastic Electron Scattering for ^{40}Ca, ^{48}Ca, and ^{56}Fe

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Deep-inelastic inclusive electron-scattering cross sections from ^{40}Ca, ^{48}Ca, and ^{56}Fe have been measured at 60°, 90°, and 140° and at energy transfers including the $\Delta(3,3)$ region. The transverse response function in the momentum interval 300 MeV/c < $|\mathbf{q}|$ < 600 MeV/c was extracted by the Rosenbluth prescription. Different theoretical approaches to the quasielastic region are compared to the data. A mass-number scaling is observed.

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At energies above giant resonances, the inelastic electron-scattering cross section can be divided into three regions. First, there is the quasielastic region which appears as a broad peak, in which the dominant process is direct ejection of one bound nucleon from the nucleus through elastic scattering. Second, as the energy transfer becomes larger than the pion mass, it becomes possible to produce real pions and the $\Delta(3,3)$ resonance gives rise to a second large and broad peak. Finally, between these two peaks there is a dip, which is dominated by direct ejection of two nucleons from the nucleus via the two-body currents. It should be pointed out that such divisions are somewhat arbitrary in that these processes may tend to overlap over a large range of energy transfer.

New theoretical interest in deep-inelastic electron scattering on nuclei arises from the ability to separate experimentally the total response function into its transverse and longitudinal parts. If the one-photon exchange process is assumed, the inclusive differential cross section takes the following form:

$$\frac{d\sigma}{d\Omega\, d\omega} = \sigma_M \left\{ \left(\frac{q_\mu}{|\mathbf{q}|} \right)^4 R_L(\mathbf{q},\omega) + \left[\frac{1}{2} \left(\frac{q_\mu}{|\mathbf{q}|} \right)^2 + \tan^2\frac{\theta}{2} \right] R_T(\mathbf{q},\omega) \right\}, \quad \sigma_M = \left(\frac{\hbar c \alpha \cos\theta/2}{2E_i \sin^2\theta/2} \right)^2, \quad q_\mu^2 = \omega^2 - \mathbf{q}^2,$$

where R_L and R_T are the longitudinal and transverse response functions, q_μ is the four-momentum transfer, ω the energy transfer, $\mathbf{q}$ the three-momentum transfer, E_i the incident energy, θ the laboratory scattering angle, and α the fine-structure constant.

It is known[1,2] that nuclear structure and dynamic effects, such as meson exchange currents and the $\Delta(3,3)$ resonance, contribute differently in the two response functions and thus a selective study of these processes can be made after their separation from the total response function. A strong constraint on the different theoretical approaches has been provided by recent experimental results.[3–6] However, data at large momentum transfers were needed for a more consistent and complete interpretation of these processes.

In this Letter we present results from deep-inelastic (e,e') measurements on ^{40}Ca, ^{48}Ca, and ^{56}Fe performed at the Saclay linear accelerator. In order to separate the transverse response function according to the Rosenbluth prescription, data were collected at incident energies ranging from 120 to 695 MeV and at three scattering angles: 60°, 90°, and 140°. The experimental procedure has been described in detail elsewhere.[5,7,8]

Although the maximum energy available at the linac (700 MeV) allowed us to cover the $\Delta(3,3)$ peak when measuring the total response function, the separation only goes slightly beyond the dip region. The reason is that the minimum scattered energy accessible at backward angle is limited to 100 MeV by experimental constraints (detector efficiency, electron-pair–produced correction). Nevertheless, the dominance of the transverse character in the $\Delta(3,3)$ resonance region is well known from previous studies on the nucleon,[9] and the same feature was observed in the ^{12}C experiment.[5] This led us to study the $\Delta(3,3)$ resonance in the total response function, where data are available at incident energies from 560 to 700 MeV and at 60° scattering angle.

We show in Fig. 1 the differential cross sections of the three nuclei ^{40}Ca, ^{48}Ca, and ^{56}Fe at 695-MeV incident energy and 60° scattering angle. It can be seen that the position of the experimental resonance peak is at higher energy loss than the free-nucleon resonance. The same behavior was observed in the same region of momentum transfer ($|\mathbf{q}| \sim 1.3\ \mathrm{fm}^{-1}$) in the ^{12}C experiment of Ref. 5. This effect is well understood[1] if

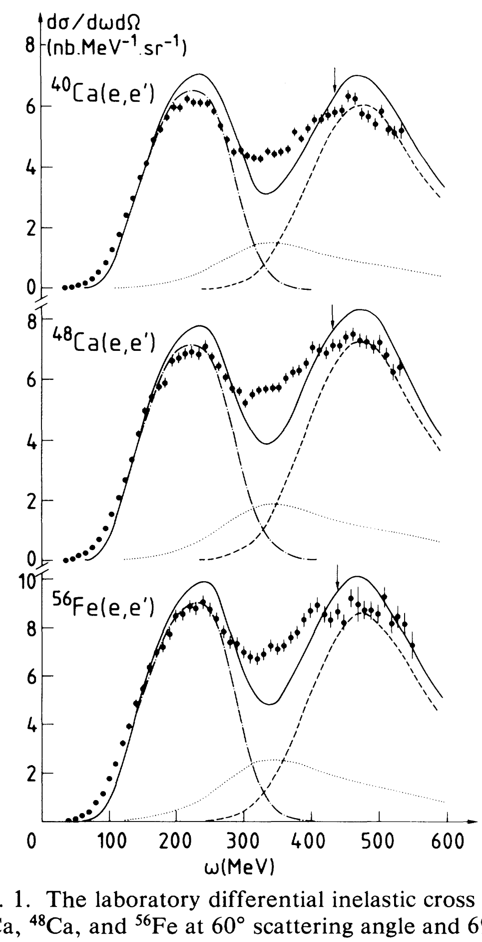

FIG. 1. The laboratory differential inelastic cross sections for ^{40}Ca, ^{48}Ca, and ^{56}Fe at 60° scattering angle and 695-MeV incident energy. The curves represent the calculations by Laget (Refs. 1 and 2). The dot-dashed line is the quasielastic contribution. The dotted line is the exchange-current contribution, while the dashed line is the pion electroproduction one. The arrows indicate the position of the free Δ.

we consider that we spend more energy to create a resonance on a bound nucleon. However, at lower momentum transfer ($|\mathbf{q}| \sim 0.6\ \mathrm{fm}^{-1}$) on ^{12}C the opposite behavior was seen. The effect of the nuclear medium on the position and the width of the experimental resonance region is very sensitive to different dynamic processes which do not create a real resonance. To have a better understanding of the different known contributions, these data are compared with calculations by Laget.[1] The first peak (dot-dashed line) is interpreted in the impulse-approximation frame with use of a nonrelativistic reduction of the electromagnetic current of the nucleon. The nuclear ground state is described by a shell model which reasonably reproduces the momentum distributions derived from $(e,e'p)$ experiments.[10] The distortion effect of the knockout nucleon is accounted for by use of the real part of an optical potential.[11] The pion electroproduction peak (dashed line) arises from two contributions: One is the nonresonant terms (Born terms) in pion electroproduction evaluated with the pseudovector coupling, and the second is the resonant term where the pion production occurs via the $\Delta(3,3)$ resonance decay.[2] As before, the impulse approximation, nonrelativistic operators, and a shell-model ground state are the ingredients of this calculation. The meson-exchange currents (dotted line) were evaluated with a new version of the quasideuteron model.[1] The energy dependence of the Levinger factor which renormalizes the deutron wave function in the nucleus was the same as in the ^{12}C calculation,[1] where this dependence was extracted from photodisintegration experiments.[12] When comparing the total contribution to the experimental data we observe the same kind of agreement as in ^{12}C.[5] An improvement is observed in the deep region where *s*-wave pion production and exchange currents account for most of the strength; however, a significant part is still missing. Coherent charged- and neutral-pion electroproduction in this region give a negligible contribution as a result of the rapid decrease of the nuclear form factor.[13]

Figures 2(a) and 2(b) show the transverse response functions for ^{40}Ca, ^{48}Ca, and ^{56}Fe at $|\mathbf{q}| = 410$ MeV/c and $|\mathbf{q}| = 550$ MeV/c. The quasielastic and part of the dip regions can be seen. We have compared the data to different theoretical interpretations.

The continuous line is a calculation by Alberico, Ericson, and Molinari[14] in the random-phase approximation (RPA) framework, where the nucleus is considered as an interacting Fermi gas. The particle-hole (p-h) force is transmitted through a coherent superposition of 1p-1h excitations and leads to a collective feature of the response function. Both 1p-1h and 2p-2h excitations induced by the isovector piece of the electromagnetic current of the nucleons $[\mathbf{J}^{\mathrm{em}} = \mu(\boldsymbol{\sigma} \times \mathbf{q})\tau_3/2]$ are considered. The p-h force used in the

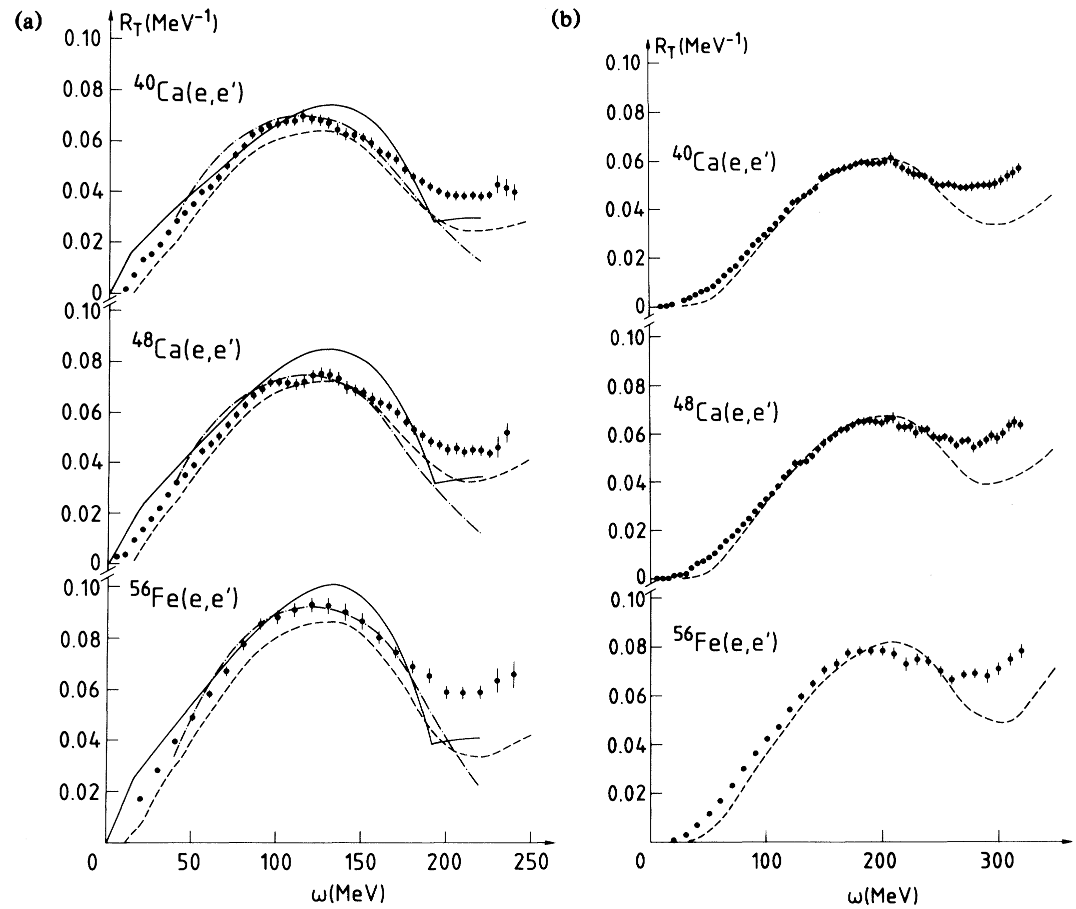

FIG. 2. The transverse response functions for ^{40}Ca, ^{48}Ca, and ^{56}Fe at (a) $|\mathbf{q}|=410$ MeV/c and (b) $|\mathbf{q}|=550$ MeV/c. The dashed line is the total contribution from calculation by Laget. The dot-dashed line is the Do Dang and Van Giai (Ref. 16) calculation containing only the quasielastic process. The solid line is the RPA calculation with 1p-1h and 2p-2h excitations by Alberico, Ericson, and Molinari (Ref. 14).

transverse channel is essentially due to ρ-meson exchange. No average binding energy is introduced to adjust the maximum as in the calculation by Van Orden and Donnelly.[15] The shift of the peak relative to a free Fermi-gas calculation is caused essentially by the strength suppression in the low energy transfer as a result of 1p-1h interaction. The dashed line is the calculation by Laget described before, containing the quasielastic process, exchange currents, and pion electroproduction. The dash-dotted line is the contribution of the quasielastic scattering, evaluated by Do Dang and Van Giai[16] at 410 MeV/c only. This calculation has the advantage of reproducing the longitudinal part of the response function at this momentum transfer.[8] Do Dang and Van Giai's approach is to treat the nucleon in nuclear matter using the Dirac equation with scalar and vector Lorentz potentials.[17] The consequence is a renormalization of the wave function and of the current operators, which has a different effect on the transverse and the longitudinal part of the total response function. The ground state of the nucleus is described by the shell model with harmonic-oscillator wave functions.

Most of the relevant properties of the nuclear matter are contained in the response function $\Pi(\mathbf{q},\omega)$.[18] This function is generally called the polarization propagator and its imaginary part is related to the transverse part of the inelastic cross section following the relation[14]

$$\mathrm{Im}\Pi(\mathbf{q},\omega) = -\frac{k_F^2}{6\pi}\frac{2m^2}{\mathbf{q}^2}\frac{R_T(\mathbf{q},\omega)}{[ZG_M^p(q_\mu^2)+NG_M^n(q_\mu^2)]},$$

$$\frac{G_M^p}{2.78} = \frac{G_M^n}{-1.91}\left[1-\left(\frac{q_\mu}{855\ \mathrm{MeV}/c}\right)^2\right]^{-2},$$

where $G_M^{p,n}(q_\mu^2)$ are the magnetic proton and neutron form factors and k_F is the Fermi momentum of nuclear matter (260 MeV/$c \equiv 1.32$ fm^{-1}). In practice we have removed from the transverse response function

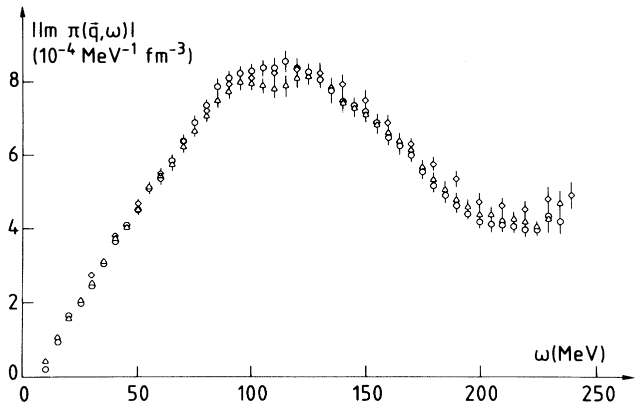

FIG. 3. The polarization propagator extracted from data in the framework of Ref. 14, at momentum transfer $|\mathbf{q}|=410$ MeV/c. The circles represent ^{40}Ca, the triangles represent ^{48}Ca, and the rhombs represent ^{56}Fe. The Fermi momentum used is $k_F = 1.32$ fm^{-1}.

of the nucleus the magnetic scattering of Z protons and N neutrons and the effect of nuclear matter density. Figure 3 shows $\mathrm{Im}\Pi(\mathbf{q},\omega)$ extracted from the data of the three nuclei. It is interesting to see that all experimental points for ^{40}Ca, ^{48}Ca, and ^{56}Fe fall on the same line up to a high energy-loss region where meson-exchange currents are dominant. The same behavior is observed at $|\mathbf{q}|=550$ MeV/c. This leads us to conclude that we are studying the bulk properties of nuclear matter.

In summary, we have measured ^{40}Ca, ^{48}Ca, and ^{56}Fe cross sections up to the $\Delta(3,3)$ resonance and separated the transverse part R_T of the total response up to a momentum transfer $|\mathbf{q}|=550$ MeV/c. The position and the magnitude of the $\Delta(3,3)$ resonance is rather well reproduced. In the quasielastic region the transverse scattering is reasonably reproduced by different models. In contrast to the longitudinal scattering[8] the transverse is less sensitive to the different models. A universal character of the response in magnetic scattering from nuclear matter is observed. The fit in the dip region is improved by the introduction of meson-exchange currents through the quasideuteron model or the RPA. Nevertheless, other mechanisms must probably be considered.

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