Bound-Nucleon Response Functions from the Reaction $^{40}Ca(e,e'p)^{39}K^*$ and Nuclear-Medium Effects

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Longitudinal and transverse structure functions for the quasielastic reaction $^{40}Ca(e,e'p)^{39}K^*$ have been obtained. Their q dependences appear like those for free nucleons. However, the ratio of the longitudinal to transverse structure functions is found reduced by 30% relative to theoretical calculations.

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The observation of a mass dependence in deep-inelastic muon scattering,[1] the European Muon Collaboration effect, has led to the conjecture that the properties of the nucleon in nuclear matter are modified relative to their free-space values.[2] This puts into question the interpretation of a large body of data based on the (e,e') inclusive quasielastic (QE) scattering reaction, where free-nucleon properties have been assumed. In inclusive scattering in the quasielastic region, where the one-nucleon knockout process dominates, transverse and longitudinal response functions have been obtained for nuclei ranging from ^3He to ^{238}U.[3-9] An important conclusion from these experiments is that the measured longitudinal responses appear to be quenched relative to theory for all nuclei except ^3He by an amount which reaches 40% for ^{40}Ca.[10] In order to explain both the European Muon Collaboration effect and the longitudinal quenching, it has been suggested that the electromagnetic form factors of nucleons imbedded in nuclear matter might differ from those in free space.[11-13].

The aim of the present work is to provide a direct measurement of the form factors of a proton imbedded in a ^{40}Ca nucleus. From the inclusive (e,e') electron-nuclear cross section, it is difficult to disentangle these forms factors from the reaction mechanism effects, since the electron-nucleon kinematic relationship is not directly observed. We therefore have turned our attention to the exclusive $(e,e'p)$ reaction which allows us to control independently the kinematic variables of the transferred virtual photon (energy and momentum transfer ω and $\mathbf{q}$) and the interacting detected nucleon (binding energy and momentum).[14] To be able to study the nucleon form factors in this manner, strictly speaking, is only true within the framework of the impulse approximation, and provided that final-state interactions can be handled.

For unpolarized electrons scattered from an unpolarized target, the coincidence cross section is expressed in first-order Born approximation as a sum of four structure functions[15]: T and L corresponding to transverse and longitudinal helicity states of the exchanged virtual photon, and TT and TL corresponding to transverse-transverse and transverse-longitudinal interfering helicity states. If one detects the outgoing proton momentum $\mathbf{p}'$ along $\mathbf{q}$, the TT and TL terms vanish. Such conditions are realized when the recoil momentum $\mathbf{p}_m$ is either parallel ($q=|\mathbf{q}|>p'=|\mathbf{p}'|$) or antiparallel ($q<p'$) to $\mathbf{q}$. The cross section can then be written as

$$\frac{d^6\sigma}{dE_{e'}d\Omega_{e'}dE_{p'}d\Omega_{p'}}=\Gamma[T+\epsilon L],$$

where

$$\Gamma=\frac{\alpha}{2\pi^2}\frac{E_{e'}}{E_e}\frac{q}{Q^2}\frac{1}{1-\epsilon}$$

is the flux of virtual photons with longitudinal polarization

$$\epsilon=[1+2(q^2/Q^2)\tan^2(\theta_{e'}/2)]^{-1}.$$

E_e and $E_{e'}$ are the incident- and scattered-electron energies; $E_{p'}$ is the outgoing proton energy. $\theta_{e'}$ is the electron scattering angle. $Q^2=q^2-\omega^2$. The L and T structure functions can then be obtained from a Rosenbluth-type separation.[16] In plane-wave impulse approximation, L and T are products of the elementary cross sections, L^P and T^P, respectively, which describe the scattering of the electron from a proton bound in the nucleus, and a "spectral function" $S(e_m,\mathbf{p}_m)$. The latter gives the probability of finding this proton in the nucleus with a separation energy e_m and momentum $\mathbf{p}=-\mathbf{p}_m$. This plane-wave impulse approximation model ignores final-state interactions (FSI). They are customarily accounted for by use of the distorted-wave impulse approximation, in which the outgoing nucleon wave is distorted by the medium. S is then replaced by "distorted" spectral functions, $S^D_{L(T)}(e_m, \mathbf{p}_m, \mathbf{p}')$, so that L (or T) $= L^P$ (or T^P) $\times S^D_{L(T)}$ [with $S^D_L \neq S^D_T \neq S$ (Boffi *et al.*)[17]]. The resulting distorted-wave cross sections in general include terms proportional to the elementary electron-neutron cross sections, since the optical potential which here mimics the medium has a nonzero charge-exchange component. Such exchange contributions amount to about 1% of the cross section in our case,[18] and we therefore neglect them. Obviously, accurate values of L^P and T^P can only be derived if S^D is known. Such is not the case, and we have sought a method that allows us to study L^P and T^P almost independently of knowledge of S^D. This has been achieved, as will be shown below, by the use of appropriate ratios of cross sections.

The $(e,e'p)$ measurements were carried out at the linear accelerator of Saclay with the two-spectrometer setup of the HE1 end station.[19] A maximum current of 15 μA was used with a 209-mg/cm^2 ^{40}Ca target suitably oriented to optimize the resolution in e_m and p_m. The overall efficiency of our apparatus was checked at the 1% level (i) by repeatedly measuring elastic cross sections in both spectrometers, and (ii) by tracking each possible source of error in the observed rate of coincidence events (e.g., dead-time and software inefficiency losses). Cross sections were corrected for radiation effects,[20] and Coulomb distortion effects were taken into account by means of a distorted-wave calculation[21,22] which differs by about 5% from the so-called effective-q approximation.

In order to separate the transverse and longitudinal components, measurements were performed at forward and backward electron angles (i.e., at two values of ϵ) for fixed q, p', p_m, and e_m. Four values of p_m were explored (Table I). At $p_m = 115$ MeV/c, the q dependence of the cross section was studied for q between 330 MeV/c and $q_{\max} = 825$ MeV/c. This was achieved by going from antiparallel to parallel kinematics and by varying the proton kinetic energy $E^{\text{kin}}_{p'}$. A missing energy interval from 0 to 60 MeV was covered. In order to indicate where, relative to the quasielastic condition at $\omega_{\text{QE}} = Q^2/2M_p$, the reaction kinematics of a given measurement was situated, the mean value of $\Delta\omega = \omega - \omega_{\text{QE}}$ is also listed in Table I. Parallel kinematics tends to have a negative $\Delta\omega$, whereas for antiparallel kinematics, $\Delta\omega$ is positive. For the latter case, the kinematics approach that corresponding to the region of the so-called dip seen in the transverse responses of the inclusive (e,e') reaction. It is recognized that in this region two-nucleon process begin to show up.

TABLE I. The kinematics used for the longitudinal transverse separation. Note that except for the last point, two angles $\theta_{e'}$ were measured for each $E^{\text{kin}}_{p'}$, p_m, and q.

$E^{\text{kin}}_{p'}$ (MeV)	p_m (MeV/c)	q (MeV/c)	$\Delta\omega$ (MeV)	$\theta_{e'}$ (deg)	ϵ
100	−115	329.6	92.6	35, 97	0.80, 0.24
158	−115	451.4	110.3	45, 96	0.70, 0.25
100	+40	484.6	25.3	18, 111	0.70, 0.18
100	+80	524.6	3.8	53, 113	0.65, 0.17
100	+115	559.6	−16.4	57, 114	0.61, 0.16
100	+140	584.6	−31.6	60, 115	0.59, 0.16
152	+115	669.6	−27.2	73, 111	0.45, 0.18
238	+115	824.6	−80.5	107	0.20

From the data taken at constant p_m, 115 MeV/c (Table I), we obtained the q dependence of the separated electron-proton cross sections, L^P and T^P. To achieve this, it was necessary to correct the $(e,e'p)$ cross sections for the change in FSI due to the variation of p' (or of the relative orientation of $\mathbf{p}_m$ and $\mathbf{q}$) as we varied q. To this end we have used optical-potential predictions for both S^D_L and S^D_T (Ref. 17). For the range of $E^{\text{kin}}_{p'}$ explored (100 to 238 MeV) in which the cross sections vary by approximately 2 orders of magnitude, S^D varies by at most 30%. The $q_{\max}$ point was obtained from a single backward-angle measurement at $\theta_{e'} = 106.8$, where an L/T separation was not possible. Since the longitudinal component at this angle contributes less than 10% to the cross section, we removed it by using the L^P/T^P ratios measured at smaller q. We thus obtained the variation of T^P in the range $q = 330$ MeV/c to $q_{\max} = 825$ MeV/c and the variation of L^P in the range 330 MeV/c to 670 MeV/c.

The data were analyzed level by level in the residual ^{39}K, and averaged over two bins of missing energy: a low-e_m bin (0–20 MeV), almost entirely below the two-nucleon emission threshold, where narrow levels are observed, and a high-e_m bin (20–60 MeV) above this threshold where broader levels are observed. The ratios of L^P and T^P to the transverse cross section $T^P(q_0)$ were formed, where the reference momentum transfer $q_0 = 559$ MeV/c is such that the kinematics is close to the QE condition. To emphasize the sensitivity of the data relative to the theory, we display in Fig. 1 the double ratios

$$\mathcal{L} = [L^P(q)/T^P(q_0)]/[L^{\text{CC1}}(q)/T^{\text{CC1}}(q_0)]$$

and

$$\mathcal{T} = [T^P(q)/T^P(q_0)]/[T^{\text{CC1}}(q)/T^{\text{CC1}}(q_0)].$$

CC1 refers to cross sections calculated by de Forest[24] which include the effects of nucleon binding and retain the free-proton form factors.[25] $L^{\text{CC1}} = (4\pi^2 \alpha p' E_{p'} Q^2/q^3) W_C$ and $T^{\text{CC1}} = (2\pi^2 \alpha p' E_{p'}/q) W_T$, where W_C and W_T are defined in the formula (17) of Ref. 24. Almost identical features for both the low- (solid circles) and the high- (open circles) e_m data are obtained.

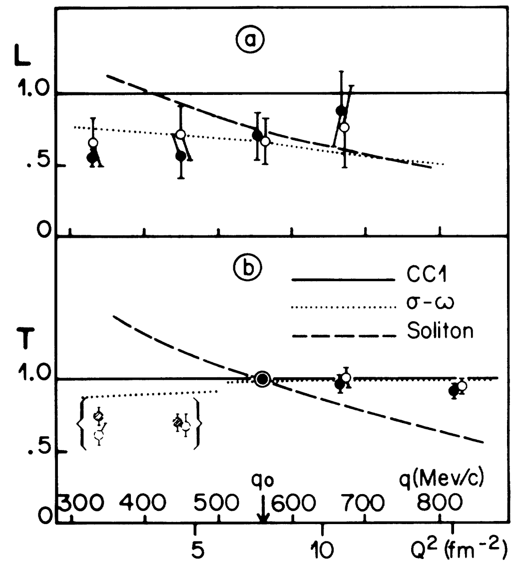

FIG. 1. The q dependence of (a) the longitudinal and (b) the transverse cross section for a proton bound in ^{40}Ca expressed respectively as double ratios: $L=[L^P(q)/T^P(q_0)]/[L^{\mathrm{CC1}}(q)/T^{\mathrm{CC1}}(q_0)]$ and $T=[T^P(q)/T^P(q_0)]/[T^{\mathrm{CC1}}(q)/T^{\mathrm{CC1}}(q_0)]$, where CC1 denotes theoretical reference cross sections (see text). Solid circles denote cross sections for missing energies below the two-nucleon emission threshold. Open circles denote points above this threshold. The bracketed points in (b) correspond to the dip region of the transverse response. The dotted curve indicates the σ-ω prediction (Ref. 23). The dashed curve denotes predictions of a soliton model (Ref. 12) having a mean density $\frac{2}{3}$ that of nuclear matter and nucleon form factors modified from those of free space.

For T^P the values corresponding to the two lowest-momentum-transfer points are 30% less than those at higher momenta. These two points are in the dip region ($\Delta\omega=100$ MeV), where from inclusive experiments we know that exchange currents cannot be neglected.[6] Hence these points are not appropriate for the study of one-nucleon interactions; consequently they have been excluded from our final analysis. On the other hand, for the three points remaining located near or below the QE kinematics ($\Delta\omega\leq 0$), the contribution of exchange currents is expected to be small. For these points we find a q dependence for T^P strikingly close to the CC1 prediction.

In contrast, the L^P cross section exhibits a smooth behavior for all points. We expect no anomalous behavior here because longitudinal photons have a small coupling to exchange currents for all values of $\Delta\omega$. Within the error bars, the q dependence of L^P is again parallel to the CC1 prediction within the errors bars, but the experimental accuracy is less than that for T^P. We point out the existence of a significant 30% reduction for the longitudinal structure function relative to the transverse. This can be due to either anomalously small longitudinal or anomalously large transverse contribution or both.

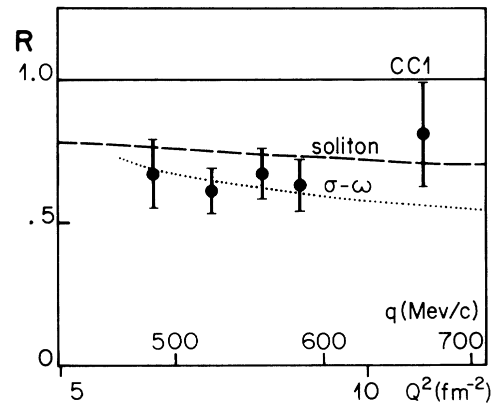

FIG. 2. The ratio of the longitudinal to transverse cross sections for a bound proton expressed as $R=(L^P/T^P)/(L^{\mathrm{CC1}}/T^{\mathrm{CC1}})$, where CC1 denotes theoretical reference cross sections (see text). Theory curves are as in Fig. 1.

In order to confirm this last feature, we formed the longitudinal-to-transverse cross-section ratio, L^P/T^P for all p_m values: 40, 80, 115, and 140 MeV/c. We display in Fig. 2 the double ratio $R=(L^P/T^P)/(L^{\mathrm{CC1}}/T^{\mathrm{CC1}})$ for all the points of Table I except those in the dip region. As we do not observe any significant difference between the low- and high-missing-energy bin, for these points, we have averaged the ratios over e_m. The reduction already observed in Fig. 1 for $p_m=115$ MeV/c evidently applies to all four p_m values. Averaging the ratios of all the points shown leads to the value $R=0.65\pm0.04$. This reduction is reminiscent of and consistent with what is observed in the inclusive data. The results of the inclusive and exclusive experiments can be related by use of a nuclear model. If done with a Fermi-gas model, the inclusive ^{40}Ca data yield $R=0.69$, in striking agreement with the exclusive result (in the inclusive experiment the reduction of R is due to an anomalously low longitudinal cross section[10]). A similar but somewhat smaller effect has also been observed in the reaction $^{12}\mathrm{C}(e,e'p)^{11}\mathrm{B}^*$.[26]

Several attempts have been made to account for the L/T anomaly observed in the inclusive experiments and now confirmed in our exclusive experiment. For example, the role of correlations has been investigated in the nonrelativistic framework[27] but does not account for the discrepancy. Attempts to go beyond the traditional approaches have led to suggestions that modifications of the nucleon current within the nucleus may account for the anomalous behavior.[11–13] Within this context, a simplified version of a mean-field model, the σ-ω model, has been proposed.[28] A calculation based upon a crude version of this model (without FSI and correlations) was made by de Forest.[23] Another approach, as mentioned initially, involved a "swelling" of the nucleon, i.e., a modification of its form factors. Such an approach with a soliton model has been realized by Celenza *et al.*[12] but only up to $Q^2=8\ \mathrm{fm}^{-2}$. We compare this model to our data by extrapolating its results to $Q^2=15\ \mathrm{fm}^{-2}$ by use of a dipole-type form factor. As seen in Fig. 2, both the σ-ω and the soliton model reproduce the observed quenching of the longitudinal response. However, with regard to the q dependence (Fig. 1), we see (omitting the dip-region results for T^P) that the q dependence of both T^P and L^P for the soliton model is steeper than for the data. We also find that the q dependence of L^P in the σ-ω model agrees poorly with the data although its agreement is excellent for T^P.

In conclusion, we have individually determined the transverse and longitudinal structure functions for the reaction $^{40}\mathrm{Ca}(e,e'p)^{39}\mathrm{K}^*$. The interpretation of these functions in the framework of the distorted-wave impulse approximation does not suggest a significant modification within ^{40}Ca of the q dependence of the nucleon electromagnetic form factors. However, the ratio of the proton structure functions, L^P/T^P, is reduced significantly from its theoretical value, and is consistent with the quenching of the longitudinal response observed in the inclusive experiments. Relativistic calculations including correlations and FSI might help to understand this anomaly.

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