Inclusive Scattering of 500-MeV Protons and Pionic Enhancement of the Nuclear Sea-Quark Distribution

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We have measured a complete set of polarization-transfer observables in the inclusive scattering of 500-MeV protons from ^{2}H and Pb at $q = 1.75$ fm^{-1}. Axial longitudinal and transverse response functions derived from these data show no differences between Pb and ^{2}H. This implies no enhancement of the nuclear pion field in heavy nuclei and consequently that models of the low-x A dependence of certain nuclear structure functions requiring such an enhancement are unlikely to be correct.

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The recent discovery of significant differences[1] between the F_2 structure functions of ^{2}H and Fe has aroused much interest in both the nuclear- and particle-physics communities. This so-called European Muon Collaboration (EMC) effect[1] is strong evidence that some constituents of nuclear matter behave quite differently in a large nucleus compared with free (or almost free, as in deuterium) nucleons. The question of what specific quark or quark-cluster phenomena give rise to the enhancement in $F_2^{\mathrm{Fe}}/F_2^{\mathrm{D}}$ in the region of the scaling variable $x \leq 0.3$ has been the subject of numerous calculations.[2–10]

One possibility, closely connected to current issues in medium-energy physics, is that the enhancement in F_2^{Fe} at small x is due to the nuclear pion field.[2–5] For many years it has been conjectured that the pion field might be enhanced in a region of momentum transfer $q \sim 2$ fm^{-1}; extreme enhancements, currently out of favor, would lead to a low critical density for pion condensation. Scattering of a lepton by such an enhanced field naturally leads to increased scattering in the range $x \sim m_\pi/m_N$; thus pions seem an intuitively appealing candidate for understanding the low-x EMC effect.

The most direct probe of the nuclear pion field is the nucleon, which couples to other nucleons via pion exchange. Under suitable approximation (discussed below) the axial-longitudinal coupling of the nucleon to the pion field may be isolated from other couplings by measuring a complete set of polarization-transfer observables[11–13] and forming the longitudinal spin-flip probability, S_L.

We have measured a complete set of polarization-transfer observables for the inclusive excitation of the quasielastic continuum in ^{2}H and natural Pb with 500-MeV protons. At a momentum transfer of 1.75 fm^{-1} we find no enhancement of the longitudinal spin-flip probability for Pb compared with ^{2}H. We believe that this is strong evidence against any enhancement in the nuclear pion field in this range of momentum transfer; this in turn casts serious doubt on explanations of the EMC effect requiring excess pions.[2–5]

Beams of 500-MeV protons alternately polarized normal to the reaction plane ($\hat{N}$), longitudinally (along the beam, $\hat{L}$), and sideways ($\hat{S} = \hat{N} \times \hat{L}$) were provided by the Clinton P. Anderson Meson Physics Facility (LAMPF). Protons inelastically scattered at $\theta_{\mathrm{lab}} = 18.5°$ from natural Pb foils and a liquid deuterium target were momentum analyzed in the high-resolution spectrometer (HRS). Outgoing proton polarizations were determined by the HRS focal-plane polarimeter in a manner discussed in detail recently.[13,14] The beam polarization was continuously monitored with in-beam polarimeters and use of the quench-ratio method.[15]

The measurements for Pb consisted of five settings of the magnetic field of the HRS covering the broad quasielastic peak centered at an excitation energy $\omega = 66$ MeV. For the narrower quasielastic peak of ^{2}H, three HRS settings were required.

The five parity-allowed polarization-transfer observables, D_{NN}, D_{LL}, D_{SS}, D_{LS}, and D_{SL}, were derived for both targets for each excitation energy bin. The left (right) subscript denotes the initial (final) polarization direction, where the final polarization directions are referred to the outgoing proton momentum. The data for D_{NN}, D_{LL}, and D_{SS} are shown in Fig. 1.

The derivation of axial-longitudinal and transverse form factors from polarization-transfer experiments has been discussed recently,[11–13] and hence only an outline of the method will be given here. We are dealing with inclusive quasifree nucleon-nucleon (N-N) scattering and will assume that relativistic N-N kinematics apply in the N-nucleus case with the effective interaction being identical to the free interaction. The free N-N scattering amplitude is commonly parametrized as

$$M(q)=A+B\sigma_{1n}\sigma_{2n}+C(\sigma_{1n}+\sigma_{2n})+E\sigma_{1q}\sigma_{2q}+F\sigma_{1p}\sigma_{2p}, \tag{1}$$

where the σ's are projections of the Pauli matrices along $\vec{n}=\vec{k}\times\vec{k}'$, $\vec{q}=\vec{k}'-\vec{k}$, and $\vec{p}=\vec{q}\times\vec{n}$; $\vec{k}$ ($\vec{k}'$) is the incident (outgoing) proton momentum direction. The combinations defining the axial-longitudinal, S_L, and transverse, S_T, spin-flip probabilities are

$$IS_L=\tfrac{1}{4}I[1-D_{NN}+(D_{SS}-D_{LL})\sec\theta_{\text{lab}}],$$
$$IS_T=\tfrac{1}{4}I[1-D_{NN}-(D_{SS}-D_{LL})\sec\theta_{\text{lab}}], \tag{2}$$

where I is the differential cross section. For N-N scattering one has $I^{N\text{-}N}S_L^{N\text{-}N}=E^2$, $I^{N\text{-}N}S_T^{N\text{-}N}=F^2$, and $I^{N\text{-}N}=A^2+B^2+2C^2+E^2+F^2$. For N-nucleus scattering one has

$$IS_L=I^{N\text{-}N}S_L^{N\text{-}N}R_L(q,\omega)N_e,$$
$$IS_T=I^{N\text{-}N}S_T^{N\text{-}N}R_T(q,\omega)N_e, \tag{3}$$
$$I=I^{N\text{-}N}R(q,\omega)N_e,$$

with the axial-longitudinal, transverse, and total response functions defined as

$$R_L(q,\omega)=|\langle q,\omega|\vec{\sigma}\cdot\vec{q}e^{i\vec{q}\cdot\vec{r}}|0\rangle|^2,$$
$$R_T(q,\omega)=|\langle q,\omega|\vec{\sigma}\times\vec{q}e^{i\vec{q}\cdot\vec{r}}|0\rangle|^2, \tag{4}$$
$$R(q,\omega)=\left(\frac{C^2+B^2+F^2}{I^{N\text{-}N}}\right)R_T+\left(\frac{E^2}{I^{N\text{-}N}}\right)R_L+\left(\frac{A^2+C^2}{I^{N\text{-}N}}\right)R_0,$$

where $R_0=|\langle q,\omega|e^{i\vec{q}\cdot\vec{r}}|0\rangle|^2$. N_e is the effective number of participating nucleons as defined by Bertsch and Scholten.[17] The approximations implied in Eq. (3) are well satisfied for forward-angle scattering of 500-MeV protons.[17–19]

Rather than calculate the N-N quantities from phase-shift solutions, we assume, as in the EMC experiment, that the ^{2}H data represent an average of the p-p and p-n observables. A small correction for the neutron excess of Pb can easily be made on the basis of the Arndt phase-shift solution.[16] From Eq. (3), one finds with $S^{\text{D}}=S^{N\text{-}N}$

$$S_L^{\text{Pb}}/S_L^{\text{D}}=R_L(q,\omega)/R(q,\omega),$$
$$S_T^{\text{Pb}}/S_T^{\text{D}}=R_T(q,\omega)/R(q,\omega), \tag{5}$$

and

$$\frac{S_L^{\text{Pb}}/S_L^{\text{D}}}{S_T^{\text{Pb}}/S_T^{\text{D}}}=R_L(q,\omega)/R_T(q,\omega). \tag{6}$$

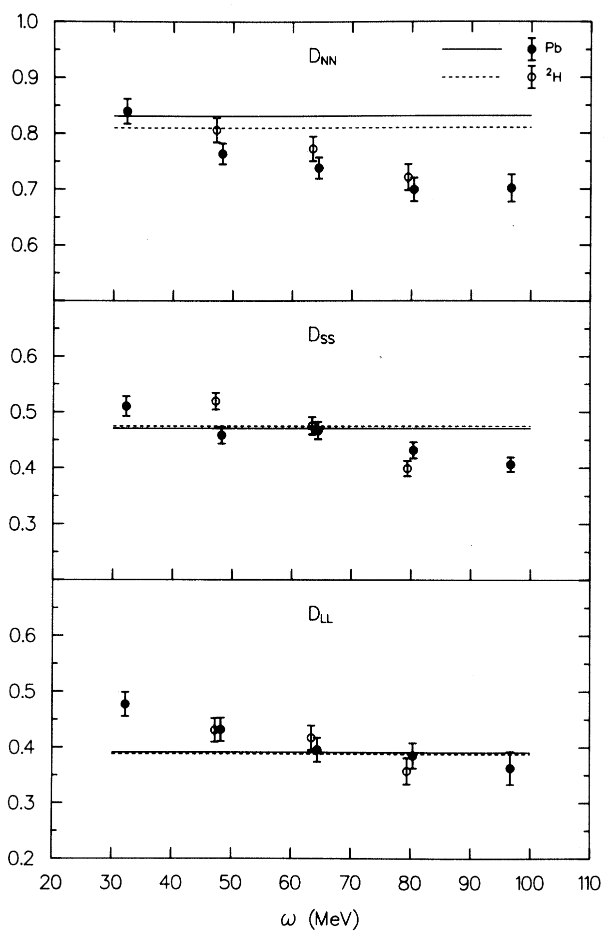

FIG. 1. Polarization-transfer observables from inclusive scattering of 500-MeV protons. The lines are isospin-averaged values for N-N scattering at 500 MeV from Ref. 16.

It is clear from Fig. 1 that the spin-flip probabilities derived from the polarization-transfer observables will show no significant differences between Pb and ^{2}H. The ratios $S_{L,T}^{\text{Pb}}/S_{L,T}^{\text{D}}$ of Eq. (5) are, in fact, consistent with unity. One knows from inclusive (e,e') continuum measurements[20] that R_T

at this momentum transfer is not far from the single-particle response. Our result is consistent with this if we assume that R is also near the single-particle value (a reasonable expectation since this is far from the region of scalar giant resonances in both q and ω). To compare with theory, we present the data of Fig. 2 in terms of the ratio R_L/R_T [values of $S^{\mathrm{D}}_{L,T}$ integrated over ω were used in Eq. (6)]. This has the advantage of eliminating much of the theoretical uncertainty[3] associated with the Fermi-gas (FG) treatment of continuum-spin response functions; our conclusions would be altered in no way by using $R_{L,T}/R$ of Eq. (5) instead. It is clear that the data show no evidence of an enhancement in the nuclear pion field. We will now examine the implications of this result in the understanding of the EMC effect.

High-energy lepton-nucleon scattering with low x is dominated by the quark-antiquark sea. If we assume that the sea can be represented as pions, the value $(F_2^{\mathrm{Fe}} - F_2^{\mathrm{D}})/F_2^{\mathrm{D}}$ extrapolated to $x=0$ is roughly the fractional pion excess per nucleon in Fe[2]; the EMC value is $\sim 15\%$. The nuclear physics which provides the surplus pions in the models of Refs. 2–5 is an enhancement in R_L in the momentum range $(2\text{–}3)m_\pi$. Both nucleon-hole and delta isobar-hole configurations are crucial in producing this collective behavior.

The calculations of R_L and R_T by Alberico, Ericson, and Molinari (AEM)[21] closely parallel those described by Ericson and Thomas in their analysis of the EMC effect. The ratio of integrated responses calculated by AEM is compared to this experiment in Fig. 2(a); there is clearly a substantial discrepancy. In order to make a quantitative statement about the disagreement, one needs to account for the fact that 500-MeV protons are somewhat surface localized ($1/\rho\sigma = 1.7$ fm). To accomplish this we performed extensive intranuclear cascade (INC) calculations[22] to assess contributions of real nuclear densities. Based on the most recent N-N data, the calculations reproduce both the shape and absolute magnitude of measured 500- and 800-MeV $p+\mathrm{Pb}$ quasielastic-excitation cross sections with no adjustable parameters. They directly provide a radial distribution for the probability of interaction. While peaked near the Pb half-density radius, the distribution has a significant width with half of all interactions at $\theta_{\mathrm{lab}} = 18.5°$ occurring inside this radius and 12% occurring inside the 90%-density radius. This distribution was then numerically folded with AEM-type calculations of $R_{L,T}$ also made as a function of density to produce the dashed line in Fig. 2(a). A similar result would be obtained from the density dependence of the pion excess given by Friman *et al.*[6] If we assume now that the AEM calculation, reduced by surface effects, would yield a pion excess of $\sim 15\%$ (conservative since we are comparing to Pb, not Fe), our experimental result is consistent with a maximum pion excess of only 2%.

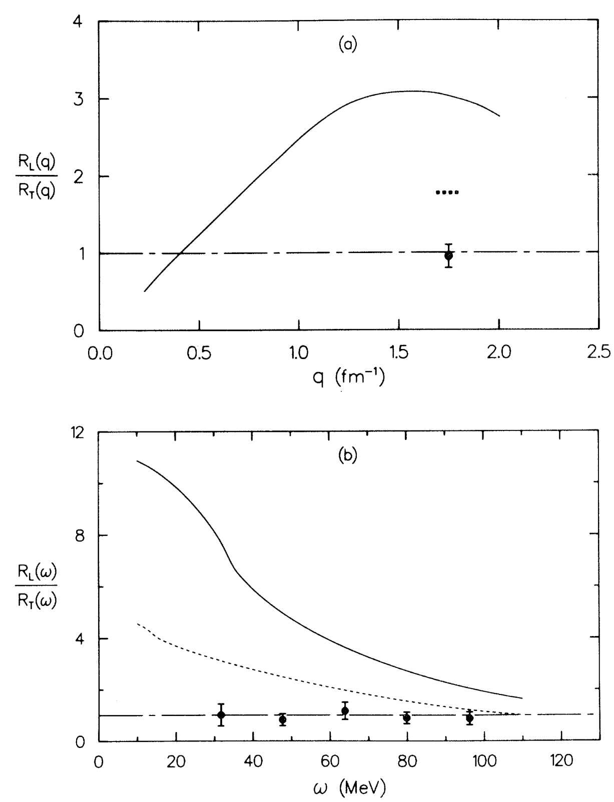

FIG. 2. Ratio of the response functions for Pb at 1.75 fm^{-1} with use of Eq. (6). (a) ω-integrated values have been used to form the ratio. The solid curve is the calculation of Ref. 21. The short dashed curve is a reduction of the theoretical prediction due to surface effects. (b) The calculations were performed with the model of Ref. 21. The solid curve is at full nuclear density; the dashed curve at half nuclear density.

It is also clear in the ω-dependent ratio that no spin-collective effects are present. Figure 2(b) shows that the data for $R_L(\omega)/R_T(\omega)$ are consistent with unity, whereas calculations which we have performed using the model of AEM show a large contrast between the responses at low ω.

One final word of caution is that the proton is not a perfect probe of the spin-isospin densities because of its mixed isoscalar-isovector interaction. Using the Arndt phase-shift solutions[16], at $q = 1.75$ fm^{-1}, we find that the longitudinal coupling is dominantly isovector, $E^2_{T=1}/E^2_{T=0} = 3.6$. The transverse ratio is about unity. Thus, barring unusual cancellation, it is unlikely that isoscalar contributions can explain the lack of enhancement.

In summary, we have made very precise measurements of a complete set of polarization-transfer observables for inclusive scattering of 500-MeV protons from ^{2}H and Pb at $q = 1.75\ \mathrm{fm}^{-1}$. The data, as well as axial-longitudinal and transverse spin-flip probabilities derived from them, show no differences between Pb and ^{2}H. This implies that there is no enhancement of the nuclear pion field in this range of momentum transfer and consequently that models of the EMC effect requiring such enhancements are unlikely to be correct.

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