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Quark effects in nuclear longitudinal response functions

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We calculate the longitudinal response function for (e, e′) reactions on ^{40}Ca and ^{56}Fe at $|\mathbf{q}|=550$ MeV/c and show that a large discrepancy between theory and experiment found in the impulse approximation can be resolved by using the medium-modified nucleon electromagnetic form factors we have calculated in an earlier work.

Recently, there has been much interest in the possible modification of nucleon properties in nuclei.[1,2] Most work has been concerned with inclusive (e, e′) reactions at quite high momentum transfer in relation to the so-called "EMC effect."[3] One explanation of this effect follows from an assumed increase in the volume of quark confinement in nuclei.[4–6] In a recent work we have calculated the modification of nucleon properties in nuclei[2] and provided an explanation[7] of the EMC effect through an increase of the size of the nucleon itself. Associated with an increase in nucleon size, one (unavoidably) finds modified nucleon electromagnetic form factors.[2] Therefore, it is natural to ask for experimental evidence for medium-modified nucleon form factors by studying those aspects of traditional nuclear physics that involve the nucleon form factors in their analysis.

In a recent work[8] we have shown that the use of our medium-modified form factors leads to an improved agreement between theory and experiment for the charge distribution in ^{208}Pb. In particular, our calculation of the charge distribution results in a marked reduction of the oscillations of this quantity found in the standard analysis which is made with unmodified form factors. The nucleon electromagnetic form factor also plays an essential role in the theoretical study of inclusive (e, e′) reactions near the nucleon quasielastic peak[9,10] and we study that process in this work. We use the formalism developed in Ref. 11; however, we no longer advocate the model developed there for quenching the longitudinal response. In Ref. 11 we argued that it was possible that longitudinal transition strength was shifted to higher energies than those investigated in the experiments in question. However, the size of the quenching of the longitudinal response (a reduction of about a factor of 2 from impulse-approximation values) makes this explanation unlikely. In particular, at the higher momentum transfers considered here, $|\mathbf{q}|=550$ MeV/c, the effective nucleon-nucleon interaction is quite weak. Recent calculations of collective modes of nuclear matter using realistic nuclear forces and the Tamm-Dancoff approximation show no collective response at such large values of the momentum transfer.[12] That is, the calculated response of the interacting system was essentially the same as that of the noninteracting system.

We now report on calculations made using the medium-modified form factors given in Ref. 2. Here we used a local-density approximation and replaced the free-space form factors of the nucleon, $F_1(q^2)$ and $F_2(q^2)$, by $F_1(q^2,\rho_M(r))$ and $F_2(q^2,\rho_M(r))$, where $\rho_M(r)$ is the local density of nuclear matter. Tables of medium-modified form factors may be found in Ref. 2. [These tables actually contain the ratios $G_E(q^2,\rho_M)/G_E(q^2)$ and $G_M(q^2,\rho_M)/G_M(q^2)$, from which one can construct $F_1(q^2,\rho_M)$ and $F_2(q^2,\rho_M)$ for both protons and neutrons.]

We will concentrate on the data[10] at $|\mathbf{q}|=550$ MeV/c, since one expects final-state interaction effects to be least important at the higher momentum transfers. (In our calculations the continuum nucleon is represented by a plane wave and improved calculations, particularly at lower momentum transfers, would require that we orthogonalize the outgoing wave to the bound orbitals. These effects are expected to be quite unimportant for analysis of the data at $|\mathbf{q}|=550$ MeV/c.) The results of our calculations are presented in Figs. 1–4. In Fig. 1 we show the data of Mezi-

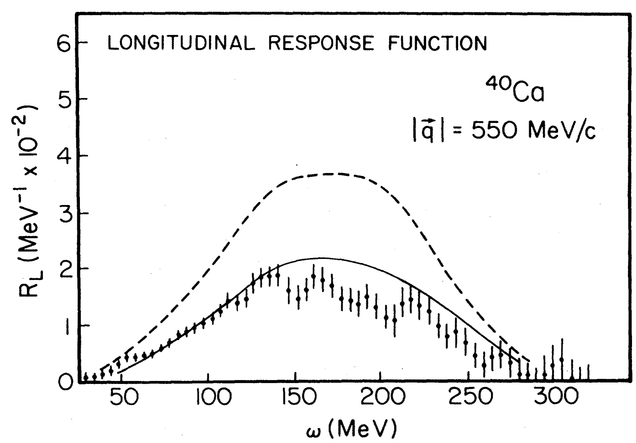

FIG. 1. The experimental data for the longitudinal response for ^{40}Ca (Ref. 10) are compared with calculations using unmodified (dashed line) and medium-modified (solid line) nucleon electromagnetic form factors. [We use the relativistic formalism developed in Ref. 11. Note that a factor of 4 should be inserted in the right-hand side of Eqs. (2.27) and (2.28) in Ref. 11.]

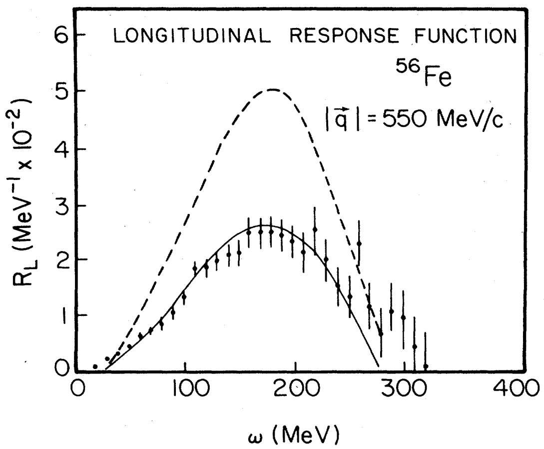

FIG. 2. Comparison of theory and experiment for the longitudinal response for ^{56}Fe. (See caption of Fig. 1.)

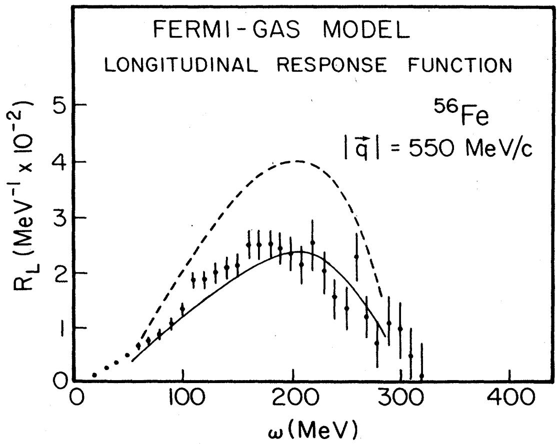

FIG. 4. Comparison of theory and experiment for the longitudinal response in ^{56}Fe using a Fermi-gas model. (See caption to Fig. 3.)

ani *et al.*[10] and a calculation of the longitudinal response using unmodified nucleon form factors (dashed line). A discrepancy between theory and experiment of a factor of 2 is immediately apparent. The solid line is the result of our calculations using our medium-modified form factors. (The theoretical curves have been shifted downward in energy by 20 MeV, a shift we ascribe to mean-field effects.) It can be seen that the solid line provides a rather good fit to the data. A similar calculation was made for the longitudinal response in ^{56}Fe and is presented in Fig. 2. (There the theoretical curves have been also shifted downward by 20 MeV.)

One should, of course, be concerned with the model dependence of our results. Usually one attempts to fit (e, e′) inclusive data using a Fermi-gas model, for simplicity.[9] Such a model has the advantage that it is an easy matter to incorporate the effects of the Pauli principle and it is not particularly difficult to insure the gauge invariance of the calculation. On the other hand, the limitations of such a calculation in describing the detailed shape of the response function for a finite nucleus are obvious. In order to provide some test of the model dependence of our results, we have carried out a Fermi-gas calculation[13] with and without medium modifications of the form factors. (In these Fermi-gas calculations the modified form factors used were those appropriate to the *mean density* of ^{56}Fe or of ^{40}Ca.) The results are presented in Figs. 3 and 4. Again, the dashed curve represents the result obtained using the impulse approximation and the solid curve is the result obtained when one uses medium-modified electromagnetic form factors.[2] It is clear that the essential features of our previous analysis also appear in the analysis based on the Fermi-gas model.

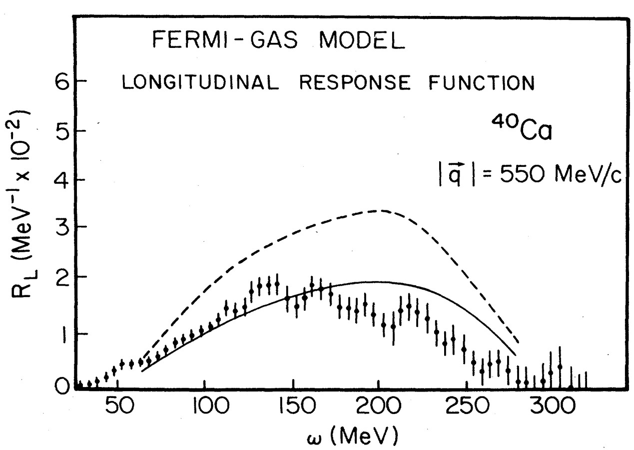

FIG. 3. Comparison of theory and experiment for the longitudinal response in ^{40}Ca. Here, we use a Fermi-gas model for the theoretical calculations. The dashed line represents the impulse approximation and the solid curve is the result obtained using medium-modified form factors. (See text.) The theoretical curves have been shifted upward by 35 MeV.

One may wonder why a calculation made in the impulse approximation (with medium-modified form factors) represents a satisfactory model if nucleon properties are modified significantly in nuclei. There are two points which can be made in response to such concerns.

Even considering increased nucleon size, the system is still fairly dilute. In our model of nucleon structure we found that the volume of a nucleon in vacuum is about 1 fm^3 (Ref. 2). The volume per nucleon in nuclear matter is about 6 fm^3. Thus, even if the nucleon doubles in volume in nuclear matter, the system is still reasonably dilute. It may also be argued that nucleons are rather close to being on mass shell in nuclei. In a relativistic model of nuclear structure, nucleons experience large (Lorentz) scalar and vector fields, however, when calculating the energy of the nucleon these fields largely cancel. Thus the use of standard characterizations of kinematic parameters (associated with estimates of nuclear binding effects) is not expected to lead to significant errors. More precise statements could be made if we were to develop a theory of interacting *extended* objects (nucleons); however, such a model is not available at this time.

In conclusion, we note that our explanation of the EMC effect based upon an increase of nucleon size in the nucleus[7] finds support in the analysis of inclusive (e, e′) reactions at very much lower momentum transfer.[14] We hope to continue and refine these studies to support our picture of medium-modified nucleon properties. The modified properties can be interpreted as a direct manifestation of the quark presence in nuclei,[2] since it is the modification of the quark wave functions that leads to the modification of the electromagnetic form factors of the nucleon in a nucleus.

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