Change of Scale for Nucleons in Nuclei from Quasielastic Electron Scattering

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Quasielastic electron scattering ($0.1 \lesssim Q^2 \lesssim 1$ GeV^2) may be well suited to measure modifications of nucleons in nuclei. From an analysis of the longitudinal and transverse structure functions for inelastic electron scattering off ^{12}C in the region $0.1 \lesssim Q^2 \lesssim 0.25$ GeV^2, indications are found for increases of the charge radius and the magnetic moment of nucleons in ^{12}C. The mean square radius of the magnetic form factor shows virtually no increase.

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Experimental and theoretical work over the last twenty years has resulted in our present picture of nucleons composed of almost massless quarks. In QCD the quarks are confined in hadrons, where their wave functions typically have a spacelike extent of the order of 1 fm. It has been realized that if this picture is correct, the average energy density of a nucleus is not much smaller than that of a single nucleon. Therefore, one might expect strong effects of the quark degrees of freedom[1,2] or significant modifications of the properties of single nucleons in nuclei.[3,4] In the work of Aubert *et al.*[5] [the so-called European Muon Collaboration (EMC) effect], the deviation of the structure function F_2^{eA} in deep inelastic electron-nucleus scattering from the structure function F_2^{ed} in deep inelastic electron-deuteron scattering gave a strong impulse to more theoretical and experimental work on the problem of the quark structure in nuclei.

The EMC effect demonstrates that the quark wave functions are affected by the nuclear medium. It indicates a change of scale in nuclei.[6,7] For the momentum transfers involved ($Q^2 \gtrsim 5$ GeV^2) the quark-parton model is valid and the scattering can be described as an incoherent sum of scattering off quarks. Although the experiments are sensitive to changes in the quark wave functions, they cannot reveal what happens with nucleons or even whether nucleons do occur in the nucleus. That nucleons dominate the physics in the nucleus is shown in inelastic scattering of electrons off a nucleus at momentum transfers with $Q^2 \approx 0.1-1$ GeV^2. One clearly sees a quasielastic peak and a delta excitation peak. Therefore, *if modifications of properties of the nucleon in the nucleus do occur, this must show up specifically in the quasielastic region.*

In this Letter, I show that there is qualitative evidence for such modifications, and I try to estimate their magnitude. For this purpose I have analyzed the quasielastic ^{12}C(e,e') data, for which a longitudinal-transverse separation has been done.[8] The hadronic part of the inelastic electron scattering cross section,

$$W_{\mu\nu} = (2\pi)^{-1} \int d^4x \, \langle A | j_\mu(x) j_\nu(0) | A \rangle e^{iqx}, \qquad (1)$$

has the following structure for an unpolarized target:

$$W_{\mu\nu} = \left(\frac{q_\mu q_\nu}{q^2} - g_{\mu\nu}\right) W_1(\nu,Q^2) + \left(p_\mu - \frac{p\cdot q}{q^2} q_\mu\right)\left(p_\nu - \frac{p\cdot q}{q^2} q_\nu\right) \frac{W_2(\nu,Q^2)}{M^2}. \qquad (2)$$

The structure functions W_1 and W_2 depend only on the invariants in the scattering process, $Q^2 = -q^2$ and $\nu = p\cdot q/M$ (p is the target momentum, M the target mass), and they can be obtained from the cross sections. Instead of W_1 and W_2 we will use the longitudinal and transverse structure functions W_L and W_T. For elastic scattering of a nucleon, $W_{\mu\nu}$ becomes the product of nucleon currents. The structure functions then are

$$W_L(\nu,Q^2) = (1+\nu^2/Q^2) W_2 - W_1 = G_E^2(Q^2) \delta(\nu - Q^2/2M), \qquad (3)$$

$$W_T(\nu,Q^2) = W_1 = Q^2 [G_M^2(Q^2)/4M^2] \delta(\nu - Q^2/2M). \qquad (4)$$

The free-nucleon form factors approximately satisfy the relation

$$G_E^p(Q^2) \approx G_M^p(Q^2)/\mu_p \approx G_M^n(Q^2)/\mu_n \approx (1+Q^2/0.71)^{-2}, \qquad (5)$$

where $\mu_p = 2.79$ and $\mu_n = -1.91$; the parameter in the dipole form factor (0.71) is in square gigaelectronvolts; further, one has $G_E^n(Q^2) \approx 0$.

For ^{12}C the structure functions W_L and W_T have been measured separately in the region $Q^2 \lesssim 0.25$ GeV^2.[8] The data show the quasielastic peak that corresponds to scattering off nucleons. We assume that for nucleons in nuclei the form factor can differ from the free form factors, $G_E \to G_E^*$, $G_M \to G_M^*$, $\mu_N \to \mu_N^*$, but that the relation between proton and neutron is unchanged. It is not possible, however, to obtain these from the data in a completely model-independent way, although for $Q^2 \gtrsim 0.1$ GeV^2 the results are not expected to be very sensitive to the choice of model. I have used a simple Fermi-gas model, which is expected to be valid for $Q \gtrsim p_F$, where p_F is the Fermi momentum. Following Ref. 9 one obtains (for simplicity $Z = N = \frac{1}{2}A$)

$$(W_{\mu\nu}^{eA})_{\rm LAB} = \frac{3A(1-\delta)}{16\pi p_F^3} \int d^3p\, \theta(p_F - |\mathbf{p}|)\theta(|\mathbf{p}+\mathbf{q}| - p_F)\, W_{\mu\nu}^{eN}(p,q). \tag{6}$$

The first θ function ensures that the initial state nucleon has a momentum smaller than p_F, while the second θ function ensures the Pauli exclusion principle. The factor $1-\delta$ allows for other degrees of freedom than single nucleons, e.g., ^{12}C (elastic peak), α particles, deuterons, and six-quark clusters, which are assumed to give incoherent contributions. For the Fermi momentum the value $p_F = 0.22$ GeV has been used.[10] The tensor $W_{\mu\nu}^{eN}$ is given by the expression in Eq. (2) with the following modifications. The form factors are those for nucleons in nuclei, and the delta function appearing in the structure functions in Eqs. (3) and (4), which expresses energy conservation, is replaced by

$$\delta(\nu - [(\mathbf{p}+\mathbf{q})^2 + M_N^2]^{1/2} + (\mathbf{p}^2 + M_N^2)^{1/2} - \epsilon_0), \tag{7}$$

where $\epsilon_0 = B/A + \frac{3}{5}p_F^2/2M_N$ (B is the nuclear binding energy) is the average potential energy of a nucleon in the nucleus. I have not introduced an effective mass for the nucleon. The modified form factors and magnetic moment can be determined by comparison of the experimental data for W_L and W_T for fixed Q^2 with the Fermi-gas calculation. For that purpose I have determined the reduction factor with which a Fermi-gas calculation for pointlike nucleons ($G_E^p = 1$, $G_E^n = 0$, $G_M = \mu_N$) has to be multiplied to reproduce the data in the quasielastic peak. This reduction factor to the power $-\frac{1}{4}$ has been plotted in Fig. 1 (open circles and triangles). For a dipolelike form factor the points should fall on a straight line. In first order G_E^* follows from the longitudinal points (circles) and G_M^* follows from the transverse points. For $Q^2 \lesssim 0.15$ GeV^2 the points start to deviate from a straight line. Deviations also show up between the theoretical and experimental positions of the maximum of the quasielastic peak. Both deviations become smaller if we allow for a momentum dependence of the energy shift ϵ_0 in Eq. (7). Such an energy dependence is quite natural if one recalls the energy dependence of the nucleon-nucleus interaction.[11] Therefore, I have used $\epsilon_{\mathbf{p}+\mathbf{q}}$ instead of ϵ_0, where $\epsilon_{\mathbf{p}} = \epsilon_0[1 - \exp(-p^2/p_0^2)]$ with $p_0 = 0.3$ GeV. Such a shift improves for $Q^2 \approx 0.1$–0.2 GeV^2 the agreement between the theoretical and experimental positions of the maximum of the quasielastic peak. The reduction factor that is found in this case is indicated by the filled circles and triangles in Fig. 1.

For the longitudinal data an excellent straight-line fit is obtained for the (solid) points in Fig. 1. From this we find $\delta = 0.21$ and

$$G_E^*(Q^2) = (1 + Q^2/0.54)^{-2}.$$

We conclude from the value of δ that there is a relatively small[12] probability of $\sim 20\%$ for other degrees of freedom. It must be clear, however, from Fig. 1 that this number strongly depends on nuclear structure effects which are of the order of the difference between the open and solid points. The mass parameter of 0.54 GeV^2 in G_E^* indicates *an enhancement of the nucleon charge radius r_E of 15%*. From Fig. 1 one sees that the error in this parameter is not very large ($\sim 5\%$).

For the transverse data the same procedure as above may be questionable because of pionic effects.[13] These do not play any significant role in the longitudinal structure function. From the increase in the nucleon radius we also expect an increase of the magnetic moment, since for massless quarks in the nucleon the magnetic moment is proportional to the size of the quark wave function.[14] The intercept of the fit to the

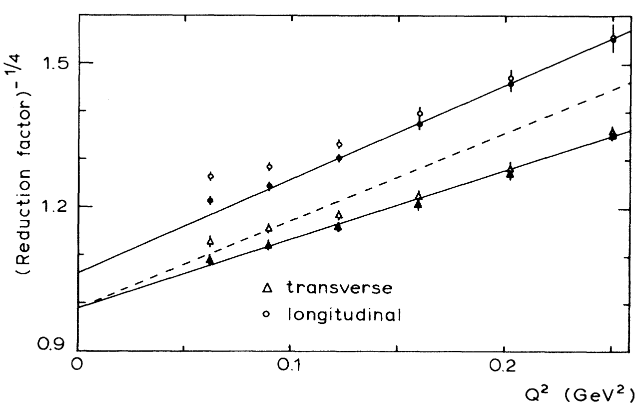

FIG. 1. Reduction factor (see text) as a function of Q^2 for the longitudinal and transverse structure functions. The open (solid) fixed points are for a constant (momentum dependent) energy shift ϵ in the Fermi-gas calculation. The solid lines are fits to the filled data points. The dashed line indicates the reduction if r_M is taken to be equal to the fitted value of r_E.

transverse data in Fig. 1, indeed, shows that there is an increase for the magnetic moment. This increase is also of the order of 15% ($\pm 5\%$). The parameters obtained from the solid line in Fig. 1 are $\mu_N^* = 1.15\mu_N$ and

$$G_M^*(Q^2)/G_M^*(0) = (1 + Q^2/0.69)^{-2}.$$

This indicates that the *magnetic moment of nucleons in nuclei is increased.* In ^{12}C we find roughly the same increase as for r_E. *The mean square radius of the magnetic form factor r_M, however, is almost unchanged.* In Fig. 1 also the result has been shown for the case that r_M^* would be equal to the fitted value of r_E^* (dashed line). This gives too strong a reduction.

Before discussing the results I want to show the quality of the fit to the data. The comparison between the calculations with G_E^*, G_M^*, μ_N^*, and δ and the experimental data is shown in Fig. 2 for $Q^2 = 0.25$ GeV^2. The agreement over the whole quasielastic peak is very good. For the longitudinal structure function W_L there are no substantial deviations, except for very low energy transfers. For the transverse structure function W_T the same is true up to the threshold for pion production on single nucleons. The same good agreement is obtained for other $Q^2 \gtrsim 0.1$ GeV^2.

The results for the longitudinal structure function show that the charge radius of nucleons in ^{12}C is increased by 15%. Although the extrapolation to $Q^2 = 0$ induces a large error it seems that there is some probability that the scattering does not occur from single nucleons. There indeed is a small excess at energy transfers $\lesssim 50$ MeV due to photon absorption on nuclear multinucleon clusters (^{12}C, d, α). Also at higher energy transfers effects can be expected. There is a considerable probability that nucleons do overlap, in which case they may be better described in terms of six-quark clusters. The energy that plays a role for such objects is typically on the order of $M_N + M_\Delta$. Therefore, effects should show up in the region between the quasielastic N and Δ peaks in *both* W_L and W_T. More precise separated data in this region would be needed.

The increase in the magnetic moment is similar to the increase in the charge radius r_E. The magnetic moment and r_E are also the best quantities from which to deduce the size of the quark wave functions in nuclei. They appear respectively in the terms $\sim q$ and $\sim q^2$ in the Fourier transform of the nucleon currents, while r_M appears in the term $\sim q^3$. The thus obtained increase in the size of the quark wave functions is in agreement with typical numbers obtained from other sources. An analysis of the EMC effect[7] yields an increase of the average confinement scale of (10–15)%. The increase of 15% in ^{12}C does not seem unreasonable if we compare it with increases of 7% and 11% that would be needed in ^{3}H and ^{3}He, respectively, in order to explain the nuclear magnetic moments. Such an explanation gives a result similar to the explanation involving six-quark clusters[15]; quasielastic scattering data may be able to distinguish between these explanations.

We have found that the increase in r_M is much smaller than for r_E. Assuming that r_M^* is equal to the fitted value of r_E^* (dashed curve in Fig. 2) and attributing the difference to meson-exchange currents seems not very plausible since this difference peaks at the same place as the quasielastic peak; there is no reason that exchange currents should show such a behavior. Actually, a reduction of meson effects is expected in nuclei when the nucleon radius has grown. Nucleons thus may be closer to pure quark bags; in the MIT bag model one has $r_E^2 = 0.53R^2$ and $r_M^2 = 0.39R^2$, and hence $r_M < r_E$. The observed ratio even numerically approaches the bag-model ratio. In order for this argu-

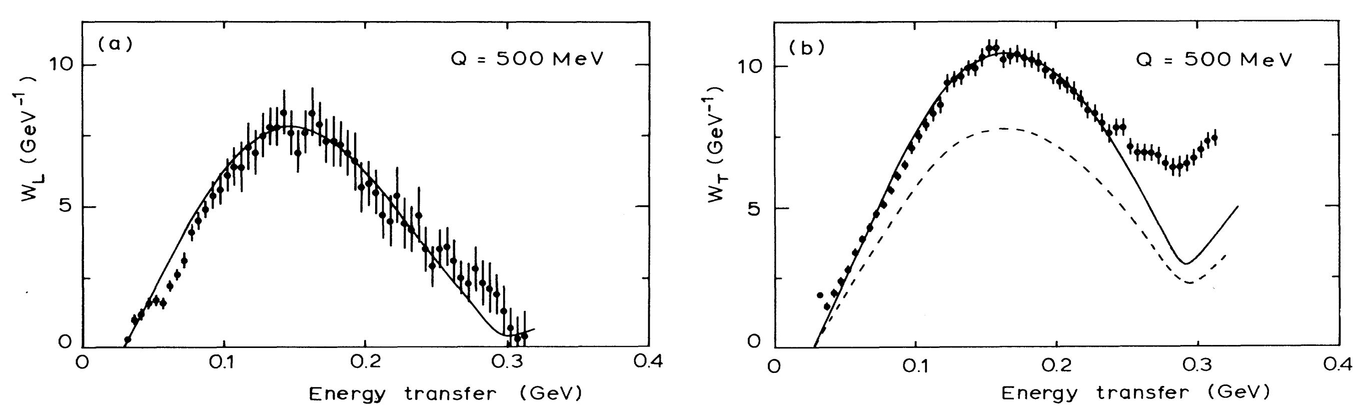

FIG. 2. Comparison between calculation with modified nucleon form factors (see text) and experimental data for $Q^2 = 0.25$ GeV^2 in ^{12}C: (a) longitudinal structure function, (b) transverse structure function (dashed curve corresponds to dashed curve in Fig. 1).

ment to work it should be checked whether the pion cloud in the free nucleon is responsible for $r_E \approx r_M$, but the difficulty of separating pionic and center-of-mass effects[16] makes a reliable estimate impossible.

The next point I want to discuss is the quasifree treatment of nucleons. This treatment is justified if the mass of the nucleons in nuclei is about the same as the free-nucleon mass. An increase of the radius means a reduction of the mass, since $M \sim 1/R$ (this scaling law, e.g., was used in Ref. 3). This is only valid, however, for the quark contribution to the mass. If we include pion corrections, the bare (three-quark) mass is about 200 MeV larger,[17] i.e., $M_N^{(0)} \approx 1140$ MeV. A reduction proportional to the increase of R gives $M_N^{(0)*} \approx 990$ MeV in nuclei. Since the pionic effects are also substantially reduced one may indeed have $M_N^* \approx M_N$.

Finally, there is the crucial question of how the single-nucleon modifications change the conventional nuclear structure. At low momentum transfers, $Q^2 \lesssim 0.05$ GeV, the effect of the change in r_E leads to a change in the nucleon form factors of less than 5%, whereas at higher momentum transfer elastic form factors of nuclei become dominated by the size of the nucleus. Also—and this is important at low Q^2—there are effects because of other degrees of freedom in the nuclear wave function. These can no longer be added incoherently, however, which makes the problem more complicated.

A more detailed analysis of different nuclei is of course needed to learn more about the systematics of modifications of nucleons in nuclei. I have also analyzed the ^{56}Fe(e,e') data.[18] Although the analysis is less precise, since the data only extend up to $Q^2 \approx 0.18$ GeV^2, similar increases are observed, $\sim 24\%$ for the magnetic moment, $\sim 16\%$ for r_E, and no increase for r_M.

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