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Many-body soliton dynamics: Modification of nucleon properties in nuclei

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We propose a model of nuclear structure in which the degrees of freedom are quarks and mesonic fields. The quarks are organized into nucleons which interact via the exchange of mesons (σ,π,ρ,ω). The model is so structured as to reproduce the results of recently developed relativistic models of nuclear structure in which the degrees of freedom are nucleons and mesons. The model used to describe *nucleon* structure is taken from a previous work in which a fully covariant (soliton) model of the nucleon was developed. The model also allows one to consider the dynamics of solitons in the presence of the fields generated by other solitons. This feature enables us to investigate the modification of nucleon properties when the nucleon is inside a nucleus. Our central result is the prediction that nucleons will be bigger in the nucleus than in free space. Evidence for this modification of nucleon properties is discussed. We consider deep inelastic electron scattering from nuclei: We discuss the European-Muon-Collaboration effect and some recent (e,e′) experiments and relate the experimental results to our prediction of modified nucleon radii and form factors.

I. INTRODUCTION

In recent years there has been extensive discussion concerning the modification of standard nuclear models which is required to describe the quark presence in nuclei; however, no model has as yet found general acceptance as providing a satisfactory phenomenology. In this connection, the experimental results for nucleon structure functions in iron and other nuclei have received much attention.[1–4] The experiments show that the ratio of the cross sections (per nucleon) for scattering from a nucleus to that for scattering from a nucleon in deuterium is not unity. Many explanations of this effect have been put forth,[5] however, it is difficult to choose among the various models proposed. In our ongoing work on relativistic nuclear structure dynamics we have found a mechanism which provides some understanding of this effect and other features of nuclear dynamics. In this work we will describe our model in some detail since we believe it has some interesting features that allow for a unification of relativistic nuclear structure dynamics[6] and soliton models of nucleon structure.[7]

We begin in Sec. II with a review of the relativistic model of nuclear structure developed earlier in which the degrees of freedom are nucleons and mesons.[6] In Sec. III we describe a covariant soliton model of the nucleon which was first presented in Ref. 8. In Sec. IV we discuss a specific prescription for the calculation of soliton properties in the mean fields that one believes are present in nuclei. In the relativistic models in current use, these fields are intense (Lorentz) scalar and vector fields. The particular advantage of our formulation is that we can relate the known strengths of these fields to interactions which affect the properties of the nucleon. Finally, in Sec. V we show how various experiments may be interpreted as providing evidence that our model may be useful. Section VI contains some concluding comments.

II. RELATIVISTIC NUCLEAR STRUCTURE PHYSICS

In this section we review some recent work dealing with a relativistic model of nuclear structure based upon a Lagrangian where the degrees of freedom are nucleons and mesons, $\mathscr{L}(\psi_{\rm N},\sigma,\pi,\rho,\omega,\ldots)$. This model is highly successful in explaining a broad range of nuclear properties.[6,9]

There are two essential features characteristic of modern relativistic nuclear structure physics. The first is the recognition that a description of nucleon motion via the Dirac equation is appropriate. Second, the self-energy which appears in the Dirac equation contains quite intense scalar and vector fields. For example, let us consider the Dirac equation describing nucleon motion in nuclear matter. The spinor describing the motion of the nucleon may be obtained from the solution of the equation,[6]

$$[\vec{\gamma}\cdot\vec{\rm p}+m_{\rm N}+\Sigma(p,\{f\})]f(\vec{\rm p},s)=\gamma^0\epsilon(\vec{\rm p})f(\vec{\rm p},s)\ . \tag{2.1}$$

Here $\Sigma(p,\{f\})$ is the self-energy operator, a 4×4 Dirac matrix, which depends upon the spinors $f(\vec{\rm q},s)$ for $|\vec{\rm q}|<k_F$.

In order to understand this problem in the simplest approximation possible, we write

$$\Sigma=A+\gamma^0B\ , \tag{2.2}$$

where A and B are here taken to be constants.[10] Note therefore that the mass $m_{\rm N}$ is changed to $m_{\rm N}+A$ and the scale of the energy is shifted by the vector term, B. We can then write the energy of the positive-energy solutions of Eq. (2.1),

$$\epsilon(p)=B+[\vec{\rm p}^{\,2}+(m_{\rm N}+A)^2]^{1/2}\ , \tag{2.3}$$

$$\simeq B+A+\frac{\vec{\rm p}^{\,2}}{2(m_{\rm N}+A)}+\cdots \tag{2.4}$$

and

$$f(\vec{p},s)=\left[\frac{\tilde{E}+\tilde{m}}{2\tilde{m}}\right]^{1/2}\left[\begin{array}{c}|s\rangle\\ \dfrac{\vec{\sigma}\cdot\vec{p}}{\tilde{E}(\vec{p})+\tilde{m}}|s\rangle\end{array}\right], \quad (2.5)$$

where

$$\tilde{E}(p)=(\vec{p}^{\,2}+\tilde{m}^{\,2})^{1/2}$$

and $\tilde{m}=m_N+A$.[11]

Various phenomenological fits to nuclear data[12] using the Dirac equation yield values of $A\simeq-400$ MeV and $B\simeq+300$ MeV. Thus one can see that the relativistic character of the system can be said to be "hidden" since the dispersion relation, Eq. (2.3), appears to be that for a nonrelativistic particle.

In reality the scalar and vector potentials A and B are momentum dependent and the form of the self-energy is more complicated than that given in Eq. (2.2).[6] However, this simple model is used for introducing the basic ideas.

Values of A and B of the magnitude determined in phenomenological studies may be obtained from the study of the Lagrangian, $\mathscr{L}(\psi_N,\sigma,\pi,\rho,\omega)$. The coupling constants in this Lagrangian are taken from fits to nucleon-nucleon scattering using the one-boson-exchange model of nuclear forces.[13] To a first approximation the large scalar and vector fields arise from exchange of the σ and ω mesons. (Detailed calculations show that a significant part of the scalar field has its origin in *exchange* matrix elements associated with the exchange of ω mesons between nucleons, however, this feature is not particularly important for the general discussion given here.)

The point we wish to stress is that there is now very strong evidence that this relativistic model is correct in its main features. An explanation of a broad range of nuclear phenomena is given in Ref. 6, where we discuss the saturation density of nuclear matter, the density dependence and strength of the effective force in nuclei, the energy dependence and density dependence of the nuclear optical potential, etc. This successful description of nuclear dynamics, which does not involve the introduction of any free parameters other than those taken from fits to NN scattering, is supported by the recent, highly successful, application of a relativistic impulse approximation for the description of nucleon-nucleon scattering.[9] In this body of work it is seen that if the nucleon-nucleon scattering amplitude is written in terms of its Dirac matrix representation, the scalar and vector parts are quite large. (The scalar part is attractive and the vector part is repulsive.) Using the scattering amplitude in its Dirac matrix form and folding it with the density matrix of the target one obtains an optical potential to be used in the Dirac equation. The parameter-free fits to polarization data obtained in this manner are quite remarkable.[9]

We will not here undertake an extensive review of the successes of this relativistic model. However, we can conclude from the various studies made that nucleons experience intense scalar and vector fields in a nucleus. Now let us consider a model in which we address the fact that the nucleon is an *extended object.*[7,8] It appears to us to be essential to maintain the features of relativistic nuclear dynamics described above. The simplest extension of our model of nuclear dynamics is to consider a model for a nucleon of finite size for which the degrees of freedom are quarks and mesonic fields. Of course, there are many static models of nucleon structure available including the MIT bag model,[14] the chiral bag model,[15] the cloudy bag model,[16] and various soliton models of the type developed by Friedberg and Lee[7] and studied by Goldfram and Wilets.[17] Since our aim is to create a model of a nucleus, we consider these *static* models essentially useless for our purposes. Clearly, if one is constructing a model of *nuclear* structure, the constituents must be able to move about. With the goal of creating a viable model of nuclear structure we have constructed, in the preceding work, a covariant model of the nucleon. This model is based upon a Lagrangian containing quark and mesonic degrees of freedom, as well as an additional scalar field, $\chi(x)$, which serves to bind the system into a nucleon. As in the static soliton (or bag) models, our nucleon appears as a "bubble" in the vacuum. However, we have achieved a fully covariant description of this object.

III. SOLITONS IN NUCLEI

We have suggested that it may be profitable to consider a Lagrangian based upon quark and mesonic degrees of freedom in order to describe nucleon structure. In developing this suggestion we found it necessary to introduce a field, $\chi(x)$, which serves to bind the quarks in a finite region. This field is quite analogous to the field introduced by Friedberg and Lee. Its source is the quark scalar density and since the quarks are coupled to this field, a self-consistent solution to the field equations must be found. [We have not discussed the physical basis for the introduction of the χ field. An extended discussion may be found in Ref. 7 where an attempt is made to relate this field to quantum chromodynamics (QCD). There it may be seen that the χ field plays the role of an order parameter of the QCD vacuum. The discussion of Kuti[7] is particularly instructive.] In addition to the χ field we have included quark coupling to the σ, π, ρ, and ω fields with the aim of ultimately constructing a model of *nuclear* structure such as that discussed in the preceding sec-

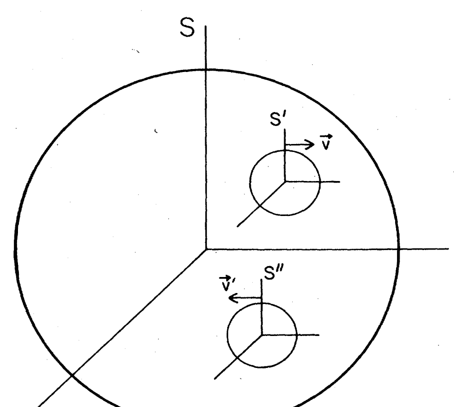

FIG. 1. Schematic representation of soliton motion in a nucleus. The nucleus rest frame is S and the soliton rest frames are S' and S''. (The solitons interact by exchange of mesonic fields in this model.)

tion. Thus we may write $\mathscr{L}(q,\chi,\sigma,\pi,\rho,\omega)$ as the Lagrangian of our model of *nucleon* structure. (Here q denotes the quark field.) The details of this model have been presented in the preceding paper.[8] The soliton may be characterized by its momentum $\vec{P}$ and its spin and isospin projections, s and t. The state vector of the soliton is $|\vec{P},s,t)$. Clearly the soliton has a rest frame where $\vec{P}=0$. We may indicate, in a schematic fashion, the soliton in a nucleus as in Fig. 1.

Here S denotes the rest frame of the nucleus and S' is the rest frame of the soliton which moves in the nucleus with some velocity $\vec{v}$, etc. These solitons interact by exchanging mesonic fields (σ,π,ρ,ω) in our model. *We suggest, but do not prove,* that the Lagrangian $\mathscr{L}(\psi_N, \sigma,\pi,\rho,\omega)$ is an effective Lagrangian that adequately describes the interaction of these objects. Let us recall the form of this Lagrangian, leaving out the ρ and π fields for simplicity,

$$\mathscr{L}(x)=\bar{\psi}_N(x)[i\gamma^\mu\partial_\mu-m_N-G_{\sigma NN}\sigma(x)-G^V_{\omega NN}\gamma^\mu\omega_\mu(x)]\psi_N(x)+\tfrac{1}{2}[\partial^\mu\sigma(x)\partial_\mu\sigma(x)-m_\sigma^2\sigma^2(x)]$$
$$-\tfrac{1}{4}F^\omega_{\mu\nu}(x)F^{\mu\nu}_\omega(x)+\tfrac{1}{2}m_\omega^2\omega_\mu(x)\omega^\mu(x)\ . \tag{3.1}$$

We have not written a tensor coupling for the ω field since the phenomenological value of this quantity, $G^T_{\omega NN}$, is zero. We also note that when this Lagrangian is used to describe nucleon-nucleon scattering vertex cutoffs are introduced. A typical cutoff might be of the form $\Lambda^2/(-q^2+\Lambda^2)$ with Λ about 1–2 GeV.[18] (One evaluates the NN scattering amplitude using a ladder approximation. If other prescriptions were used in developing the NN scattering amplitude, the coupling constants would be modified. Therefore, these constants are clearly model dependent. One reason for writing Eq. (3.1) here is to note that this model Lagrangian contains the parameter m_N and is therefore so arranged as to give the correct mass for the nucleons when they are widely separated, that is, when the interaction terms are negligible. We will return to this point at a later stage.

We have suggested that the Lagrangian of Eq. (3.1) is an effective Lagrangian that adequately describes the interaction of our relativistic solitons. What we have *not* shown is that one can pass from $\mathscr{L}(q,\chi,\sigma,\pi,\rho,\omega)$ to $\mathscr{L}(\psi_N,\sigma,\pi,\rho,\omega)$ by "integrating out" the quark degrees of freedom. Nor have we discussed how quarks and gluons organize themselves into nucleons and mesons. These are clearly very difficult problems.

It is clear, however, that we can reproduce the relativistic model of nuclear structure described in Sec. II given our assumption that the χ field does not participate in soliton-soliton scattering.[8] For example, the calculation of the soliton self-energy is shown in Fig. 2 to be equivalent (by construction) to the corresponding calculation for nucleons. (It should be clear that we are attempting to be quite conservative in introducing many-body soliton dynamics. Basically, we are interested in preserving all the successes of the relativistic description of nuclear structure based upon the use of nucleon and meson degrees of freedom. Therefore, except for the modification of properties of the soliton in the medium, relatively little else is changed in our description of relativistic nuclear dynamics.)

Our model suggests that $f(\vec{p},s)\chi_t$ describes the motion of the soliton in nuclear matter. That is, we can start from a soliton at rest, $|\vec{0},s,t)$ and "boost" it to momentum $\vec{p}$. If we also include the interaction with the medium we have an object whose motion is described by $f(\vec{p},s)\chi_t$ in nuclear matter. [A more general four-component spinor would be used in the case where the soliton is in a finite system. The modifications of Eq. (2.1) to describe motion in a finite system are straightforward.]

We have presented this rather extensive introduction since we now wish to argue that *the intense fields that the soliton feels in the nuclear medium modify its properties.*[19] Let us again consider the equation that determines the properties of the soliton which is depicted in Fig. 3. The quark moves in the field generated by the nucleon itself, however, in nuclear matter, there are additional fields present due to the other nucleons. In this figure the second term on the right-hand side denotes the effect of the mean field of the medium in modifying the equation for the quark wave function. The magnitude of this field may be calculated as indicated in Fig. 3(b). Here the source of the mean field is shown to be the quarks in other nucleons. In the next section we discuss how the strength of this field may be calculated. There we consider nuclear matter, for simplicity. Therefore, we may limit our considerations to uniform fields.

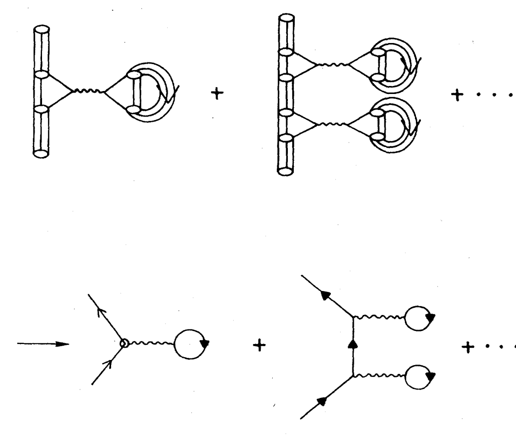

FIG. 2. Schematic representation of the calculation of the soliton self-energy due to the presence of other solitons. Here downward arrows on a triplet of lines indicate a soliton in an occupied state. There we show a ladder of mesonic exchanges and, on the right-hand side, the corresponding (Goldstone) diagrams appropriate to the one-boson exchange (OBE) model (Ref. 6).

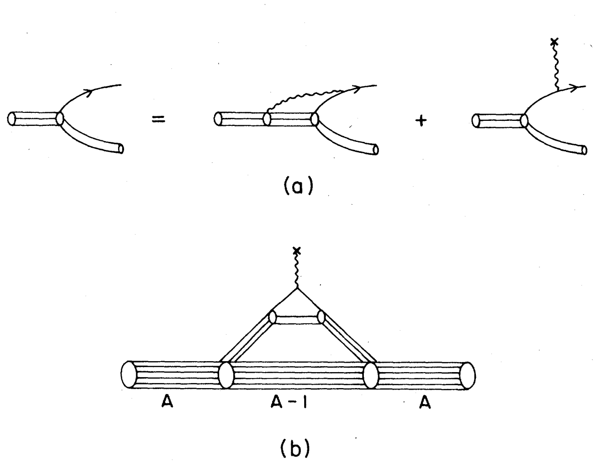

FIG. 3. Pictorial representation of the equation determining the structure of the soliton. (See Ref. 8 for a detailed discussion of this equation.) (a) In addition to motion in fields which have their source in the nucleon, the quark moves in external fields which have their source on other nucleons. (b) Schematic representation of the mean field in a nucleus. (The mean field depends upon the hadronic form factors of the nucleon and the meson-nucleon coupling constants.)

IV. MODIFICATION OF SOLITON PROPERTIES IN NUCLEAR MATTER

We begin this section with a calculation of the modification of the quark self-energy due to the presence of nuclear matter. We write

$$\delta\Sigma_q = a + \gamma^0 b \tag{4.1}$$

and calculate values for a and b. The main effect in our equations governing quark dynamics will be the replacement of the constituent quark mass, m_q, by $\tilde{m}_q = m_q + a$. In the infinite medium the term $\gamma^0 b$ will only give rise to a shift of the energy scale.

The particular advantage of the formulation given here is that a and b are not free parameters but may be calculated as follows:

$$a = g_{\sigma qq}\sigma(x) = -g_{\sigma qq}\left[\frac{G_{\sigma NN}\rho_S^{NM}}{m_\sigma^2}\right], \tag{4.2}$$

$$b = g_{\omega qq}\omega^0(x) = g_{\omega qq}\left[\frac{G_{\omega NN}\rho_B^{NM}}{m_\omega^2}\right]. \tag{4.3}$$

Here ρ_S^{NM} and ρ_B^{NM} are the scalar and baryon densities of nuclear matter and $\sigma(x)$ and $\omega^0(x)$ are the average values of the scalar and vector fields. We take $\rho_B^{NM} = 0.17$ $(\mathrm{fm})^{-3}$ and $\rho_S^{NM} = 0.16\ \mathrm{fm}^{-3}$. From the boson-exchange potential of Holinde, Erkelenz, and Alzetta[18] (HEA) we find $G_{\sigma NN}^2/4\pi = 4.63$, or $G_{\sigma NN} = 7.62$, and $m_\sigma = 500$ MeV. Furthermore, $G_{\omega NN}^2/4\pi = 14$; however, the incorporation of additional propagator modifications[18] for the vector mesons in the potential HEA leads to $(G_{\omega NN}^2/4\pi)_{\mathrm{eff}} = 8.5$ and $(G_{\omega NN})_{\mathrm{eff}} = 10.3$. Linear relations between $g_{\sigma qq}$ and $G_{\sigma NN}$ and between $g_{\omega qq}$ and $G_{\omega NN}$ follow from a simple mapping of quark meson into meson-nucleon dynamics. (This is discussed in some detail in Ref. 8.) The relations are

$$g_{\sigma qq} = \frac{G_{\sigma NN}}{\rho_S(0)} \tag{4.4}$$

and

$$g_{\omega qq} = \frac{(G_{\omega NN})_{\mathrm{eff}}}{3}. \tag{4.5}$$

In Eq. (4.4) $\rho_S(0)$ is the value for $q^2 = 0$ of the scalar form factor of the soliton defined in Ref. 8. Our calculations of soliton structure reported in Ref. 8 yield a value of $\rho_S(0) = 1.94$. Noting that $m_\omega = 782.3$ MeV for the potential HEA, we finally obtain

$$\delta\Sigma_q = (-147 + 90\gamma^0)\ \mathrm{MeV}, \tag{4.6}$$

for nuclear matter. Using a local density approximation we may write

$$\delta\Sigma_q = \left[-147\left[\frac{\rho_S}{\rho_S^{NM}}\right] + 90\gamma^0\left[\frac{\rho_B}{\rho_B^{NM}}\right]\right]\ \mathrm{MeV}, \tag{4.7}$$

where ρ_S and ρ_B are the *local* values of the scalar and baryon densities.

The next step requires inserting $\delta\Sigma_q$ of Eq. (4.7) into our dynamical equation that determines the structure of the soliton. We refer to Ref. 8 for the details of the dynamical equation of our covariant soliton model.

In Table I we present the values of various nucleon properties calculated in vacuum and for different values of the parameter a. (We maintain the relation $\rho_S = 0.95\rho_B$ for definiteness.) The quantities in the table labeled $\langle r_p^2\rangle_E^{1/2}$, $\langle r_p^2\rangle_M^{1/2}$, and $\langle r_n^2\rangle_M^{1/2}$ are the electric and magnetic radii of the proton and neutron determined from the slope of the form factor. For example,

$$\langle r_p^2\rangle_E = -6\left[\frac{dG_E^p(q^2)}{dq^2}\right]_{q^2=0}. \tag{4.8}$$

The quantities denoted as the rms radii of the baryon and scalar densities are calculated by forming the expectation values of r^2 using quark wave functions constructed in the nucleon rest frame. These quantities may be thought of as giving some idea of the "physical" size of the object as opposed to the electromagnetic size. The latter, of course, has a precise definition in terms of the slope of the appropriate form factor. In addition, we present the values of the proton and neutron magnetic moments in the table and the value of g_A.

In general, we see that the values for the observables of the nucleon in vacuum are quite well reproduced. The charge radius of the proton is calculated to be 0.86 fm and the moments, in nuclear magnetons, are found to be $\mu_p = 2.90$ and $\mu_n = -1.90$. (Note that the ratio $\mu_p/\mu_n = -1.50$ is always obtained when using our model.) The value of g_A, which is found to be 1.09, is a bit small compared to the experimental value of 1.25. We note, however, that in the calculations reported in Ref. 8 we have good values for *all* the observables except for the nucleon mass which was about 23% too large when compared to the SU(6) value: $(m_\Delta + m_N)/2 = 1087$ MeV. In

TABLE I. Calculated properties of the nucleon as a function of the quark self-energy parameter, a. (The constituent quark mass is $\tilde{m}_q = m_q + a$ with $m_q = 600$ MeV.) We have the approximate identification [See Eq. (4.7)]: (i) $a=0$: vacuum; (ii) $a=-50$ MeV: $\rho = \frac{1}{3}\rho^{\rm NM}$; (iii) $a=-100$ MeV: $\rho=\frac{2}{3}\rho^{\rm NM}$; (iv) $a=-150$ MeV: $\rho=\rho^{\rm NM}$. Here the coupling constants and meson masses are the same as that in the preceding paper (Ref. 8), except that $g_\chi = 7.5$.

a (MeV)	0	-50	-100	-150
$\langle r_{\rm p}^2\rangle_E^{1/2}$	0.86 fm	0.92 fm	1.00 fm	1.10 fm
$\langle r_{\rm p}^2\rangle_M^{1/2}$	0.77 fm	0.83 fm	0.91 fm	1.01 fm
$\langle r_{\rm n}^2\rangle_M^{1/2}$	0.77 fm	0.83 fm	0.91 fm	1.01 fm
$-\left[\frac{dG_E^{\rm n}(q^2)}{dq^2}\right]_{q^2=0}$	3.93×10^{-2} fm^{+2}	4.15×10^{-2} fm^2	4.38×10^{-2} fm^2	4.63×10^{-2} fm^2
$\mu_{\rm p}$	2.90	3.04	3.22	3.45
$\mu_{\rm n}$	-1.90	-2.00	-2.12	-2.28
g_A	1.09	1.12	1.16	1.21
Baryon density rms radius	0.63 fm	0.69 fm	0.77 fm	0.90 fm
Scalar density rms radius	0.44 fm	0.49 fm	0.57 fm	0.70 fm

the fit reported in Table I the nucleon mass is 1100 MeV, which reproduces the value expected in an SU(6) model quite nicely. It is possible that further parameter manipulation could yield a simultaneous fit to all the nucleon observables; however, we have not attempted an extensive parameter search.

A further comment on the nucleon mass is in order. The Lagrangian $\mathscr{L}(\psi_{\rm N},\sigma,\pi,\rho,\omega)$ contains the nucleon (vacuum) mass, $m_{\rm N}$, as a parameter and this Lagrangian is so arranged as to describe a collection of free nucleons, with the correct mass, when the nucleons are widely separated. Our soliton also has a good value for its mass when isolated, as noted above. When the soliton is in nuclear matter its mass increases. (The increase is about 20% for $\rho=\rho^{\rm NM}$.) Thus we see that a mapping of the model described by the Lagrangian $\mathscr{L}(q,\chi,\sigma,\pi,\rho,\omega)$ into the model described by the Lagrangian $\mathscr{L}(\psi_{\rm N},\sigma,\pi,\rho,\omega)$ is complicated by the necessity of determining exactly how the field energy is distributed in the two models. This is a difficult problem which we hope to investigate at some future time.

We now return to a further description of the modification of the properties of the soliton in a nuclear environment. In Fig. 4 we present values for $\langle r_{\rm p}^2\rangle_E^{1/2}$ and for the rms radius of the baryon density as a function of the magnitude of the external (Lorentz scalar) field, $a=g_{\sigma qq}\sigma(x)$—see Eq. (4.2). The value of $a\simeq-150$ MeV would be appropriate for nuclear matter, while a nucleus such as ^{56}Fe would have, *on the average,* a value of $a\simeq-100$ MeV.

We may introduce the notation $G_E^{\rm p}(q^2,\rho/\rho^{\rm NM})$, $G_M^{\rm p}(q^2,\rho/\rho^{\rm NM})$, and $G_M^{\rm n}(q^2,\rho/\rho^{\rm NM})$ to denote form factors calculated for nucleons in a nuclear medium of varying density. Thus $G_E^{\rm p}(q^2,0)=G_E^{\rm p}(q^2)$ is the value for the form factor for a nucleon in vacuum. In Figs. 5—7 we present values for $G_E^{\rm p}(q^2,\rho/\rho^{\rm NM})$, $G_M^{\rm p}(q^2,\rho/\rho^{\rm NM})$, and $G_M^{\rm n}(q^2,\rho/\rho^{\rm NM})$ for $\rho=0$ and $\rho=\rho^{\rm NM}$.

Finally, in Tables II—IV we present some numerical values for these form factors and ratios such as

$$G_E^{\rm p}(q^2,\rho/\rho^{\rm NM})/G_E^{\rm p}(q^2,0)\ ,$$

etc., for three values of $\rho/\rho^{\rm NM}$.

As may be seen from the tables and the figures, there is a significant modification of the radius of our soliton in nuclear matter as well as significant changes in the form factors. One can understand this effect from several points of view. First, we can say that the reduction of the constituent quark mass creates an additional "Fermi pressure" which leads to the expansion of the soliton. (Alternatively, other authors have related an increase in nucleon size to a reduction of the vacuum pressure.[20]) Further-

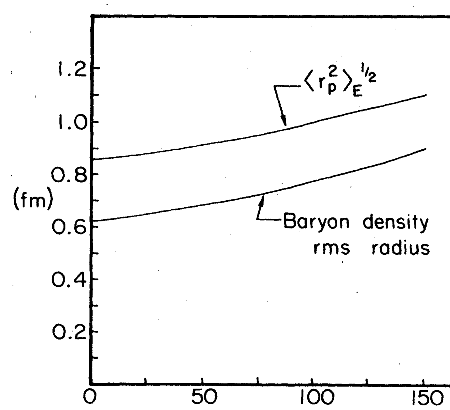

FIG. 4. Radius of the soliton in a (Lorentz scalar) external field. (a) The electromagnetic radius,

$$\langle r_{\rm p}^2\rangle_E^{1/2}=\left[-6\frac{dG_E^{\rm p}(q^2)}{dq^2}\right]_{q^2=0}^{1/2},$$

is shown. (b) The square root of the expectation value of r^2 calculated for the baryon matter density in the soliton rest frame is shown. Nuclear matter density would correspond to a mean field of about -150 MeV. [See Eq. (4.6).]

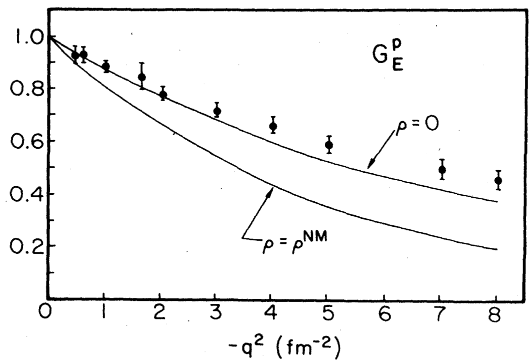

FIG. 5. Calculated values of $G_E^p(q^2,\rho/\rho^{NM})$ as a function of $-q^2$ for, (a) $\rho/\rho^{NM}=0$ (nucleon in vacuum); (b) $\rho/\rho^{NM}=1$ (nucleon in nuclear matter).

more, one can discuss this phenomenon by considering the modification of the symmetry breaking mechanism which generates the quark mass, as one moves from vacuum to the interior of a nucleus.[21] In the next section we discuss experimental evidence which supports the picture of modified nucleon properties developed here.

V. EXPERIMENTAL EVIDENCE FOR MODIFIED NUCLEON PROPERTIES

A. The EMC effect

As remarked upon earlier, deep-inelastic lepton scattering from nuclei indicates that quark-parton distributions are significantly modified from their values for the nucleon in vacuum. (We refer to the reviews of Vary[5] and Jaffe[22] for a fairly complete set of references to the various theoretical interpretations put forth.) In trying to understand this phenomenon, one may study the role of meson-exchange currents, delta isobars, six-quark clusters, etc. However, we are most interested in the general observation that the enhanced scattering for $x<0.3$ and the suppressed scattering for $x>0.3$ is suggestive of a larger volume of quark confinement in a nucleus.[23,24] This suggestion is probably most clearly stated in Ref. 23, where it is concluded that reasonable agreement with experiment is obtained if the *confinement size in iron is* 10—20 % *greater than that in a free nucleon.* These authors suggest that the structure function in a heavy nucleus, $F_2'(x,Q^2)$, is related to that for a free nucleon by a simple scaling,

$$F_2'(x,Q^2)=F_2(x,\xi Q^2) .$$

(An expression for ξ is given in Ref. 23.) Furthermore, they show that if one puts $\xi=\frac{1}{2}$ and plots

$$F_2^{\rm iron}(x,Q^2/2)/F_2^{\rm deut}(x,Q^2)$$

vs x, rather than

$$F_2^{\rm iron}(x,Q^2)/F_2^{\rm deut}(x,Q^2) ,$$

a large part of the "EMC effect" disappears. (The structure functions are here normalized "per nucleon.") Thus, we see that the first of these ratios is much closer to unity than the second when considered as a function of x.

Now inspection of Table I shows that $\langle r_p^2\rangle_E^{1/2}$ increased

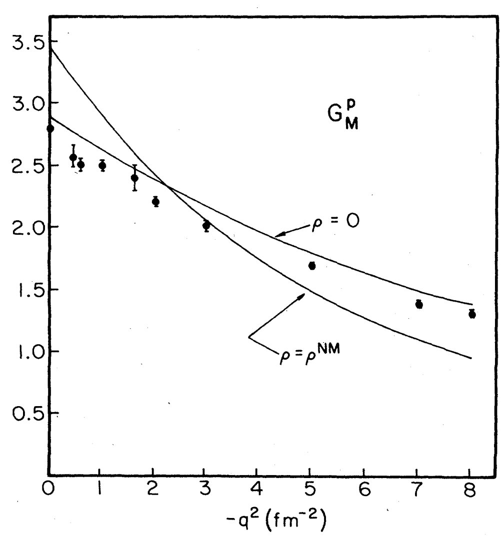

FIG. 6. Calculated values of $G_M^p(q^2,\rho/\rho^{NM})$ as a function of $-q^2$ for, (a) $\rho/\rho^{NM}=0$ (nucleon in vacuum); (b) $\rho/\rho^{NM}=1$ (nucleon in nuclear matter).

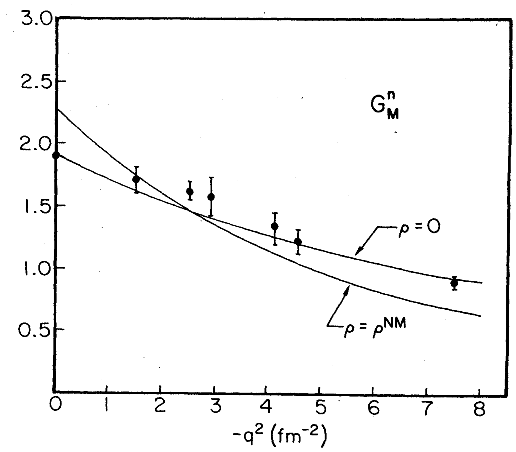

FIG. 7. Calculated values of $G_M^n(q^2,\rho/\rho^{NM})$ as a function of $-q^2$ for, (a) $\rho/\rho^{NM}=0$ (nucleon in vacuum); (b) $\rho/\rho^{NM}=1$ (nucleon in nuclear matter).

TABLE II. The values of $G_E^p(q^2,0)$ and the ratios $G_E^p(q^2,\rho/\rho^{NM})/G_E^p(q^2,0)$.

$-q^2$ (fm^{-2})	$G_E^p(q^2,0)$	$\frac{G_E^p(q^2,\frac{1}{3})}{G_E^p(q^2,0)}$	$\frac{G_E^p(q^2,\frac{2}{3})}{G_E^p(q^2,0)}$	$\frac{G_E^p(q^2,1)}{G_E^p(q^2,0)}$
0	1.00	1.00	1.00	1.00
1	0.88	0.98	0.96	0.92
2	0.78	0.97	0.92	0.85
3	0.68	0.95	0.88	0.78
4	0.61	0.93	0.84	0.72
5	0.53	0.92	0.81	0.67
6	0.48	0.90	0.78	0.62
7	0.42	0.89	0.75	0.58
8	0.37	0.87	0.73	0.55

TABLE III. The values of $G_M^p(q^2,0)$ and the ratio $G_M^p(q^2,\rho/\rho^{NM})/G_M^p(q^2,0)$.

$-q^2$ (fm^{-2})	$G_M^p(q^2,0)$	$\frac{G_M^p(q^2,\frac{1}{3})}{G_M^p(q^2,0)}$	$\frac{G_M^p(q^2,\frac{2}{3})}{G_M^p(q^2,0)}$	$\frac{G_M^p(q^2,1)}{G_M^p(q^2,0)}$
0	2.90	1.05	1.11	1.19
1	2.62	1.03	1.07	1.10
2	2.39	1.02	1.03	1.02
3	2.16	1.00	0.99	0.95
4	1.97	0.99	0.95	0.88
5	1.79	0.97	0.92	0.82
6	1.64	0.96	0.89	0.78
7	1.50	0.95	0.87	0.74
8	1.38	0.94	0.84	0.71

TABLE IV. The values of $G_M^n(q^2,0)$ and the ratios $G_M^n(q^2,\rho/\rho^{NM})/G_M^n(q^2,0)$.

$-q^2$ (fm^{-2})	$G_M^n(q^2,0)$	$\frac{G_M^n(q^2,\frac{1}{3})}{G_M^n(q^2,0)}$	$\frac{G_M^n(q^2,\frac{2}{3})}{G_M^n(q^2,0)}$	$\frac{G_M^n(q^2,1)}{G_M^n(q^2,0)}$
0	−1.90	1.05	1.12	1.20
1	−1.72	1.03	1.07	1.11
2	−1.56	1.02	1.03	1.03
3	−1.41	1.00	0.99	0.95
4	−1.29	0.99	0.96	0.89
5	−1.17	0.97	0.92	0.83
6	−1.07	0.96	0.89	0.77
7	−0.98	0.95	0.87	0.74
8	−0.90	0.94	0.85	0.71

over the vacuum value by 7% at $\rho=\frac{1}{3}\rho^{NM}$, by 16% at $\rho=\frac{2}{3}\rho^{NM}$, and by 28% at $\rho=\rho^{NM}$. This is clearly in the range required to explain the European Muon Collaboration (EMC) effect since, even in a large nucleus, a significant number of nucleons are in the nuclear surface, a region of relatively low density. Indeed, the EMC effect becomes more pronounced with increasing mass number, A, of the target,[4] reflecting the smaller percentage of surface nucleons as one considers larger values of A. Quite recently, the A dependence of the EMC effect has been studied by Jaffe, Close, Roberts, and Ross.[25–27] They obtain an effective radius of quark confinement in various nuclei by considering a geometric-overlap model for nucleons of *fixed size.* However, as we have shown in Ref. 21, our calculation of the increase of nucleon size (see Fig. 4) as a function of average nuclear density reproduces the values required to fit the mass-number dependence of the EMC effect[25–27] to a remarkable degree. We refer the reader to Refs. 21 and 25–27 for a more detailed discussion of this matter.

B. The (e,e′) reaction at the quasielastic peak

In the previous discussion we have shown how we are able to explain the EMC effect by predicting an increase in the size of the nucleon within the context of a model that combines aspects of our relativistic theory of nuclear structure and our approach to (covariant) soliton dynamics. We remind the reader that the increased nucleon size also modified the *elastic form factors* of the nucleon, and specific predictions for these modifications were presented in the figures and tables. The experimental support for the suggestion of modified form factors is not as clear as the evidence for modified structure functions; however, it has been argued that modification of nucleon form factors in nuclei provides a natural explanation of data for (e,e′) reactions on nuclei at lower momentum transfer.[19] We may consider the data for deep-inelastic electron scattering on ^{56}Fe *near the quasielastic peak.*[28] In Ref. 28 longitudinal and transverse response functions were separated experimentally. Calculations of the longitudinal response function made in the impulse approximation yield results that are systematically about 35% too high at the quasielastic peak.[19,29] If we assume that configuration mixing effects do not lead to a *major* broadening of the peak or a *major* shift in strength to higher energies, there is a significant problem in relating theory and experiment. While more work is required to fully understand these data, it is clear that a reduction of the value of the nucleon elastic form factors, such as demonstrated in our model, can go a long way toward explaining these data. (See Figs. 5–7 and Tables II–IV.) In a future work we discuss the data of Ref. 28 in some detail and show that the model presented here provides a natural explanation of the experimental results.

VI. SUMMARY AND CONCLUSIONS

By bringing together a relativistic model of *nuclear* structure and a relativistic model of *nucleon* structure, we are able to make parameter-free predictions of the modification of nucleon properties in nuclei. These modifications are approximately linearly dependent upon the density of the nuclear medium. Thus we suggest that the nucleon expands in size as it moves from the outer regions of the nuclear surface to the nuclear interior. The nucleons which are in the last filled shells would be least modified as they have a large probability for being in the nuclear surface. On the other hand, deeply bound nucleons could exhibit a major size modification, possibly as large as a 25% increase in radius.

As we have seen, the predicted modifications of nuclear size can explain the EMC effect[21] and may be important for understanding (e,e′) reactions near the quasielastic peak.[30] Major modification of the cross sections for coincidence experiments [for example, (e,e′p)] would also follow from the modified elastic form factors predicted in this work.

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