Symmetry Breaking, Quark Deconfinement, and Deep-Inelastic Electron Scattering

L. S. Celenza, A. Rosenthal, and C. M. Shakin
Department of Physics and Institute for Nuclear Theory, Brooklyn College of the City University of New York, Brooklyn, New York 11210
(Received 4 June 1984)

It has recently been shown that deep-inelastic electron scattering from nuclei at large momentum transfer can be explained if quarks move in a larger effective volume in nuclei than in free nucleons. We argue that this "partial deconfinement" may be understood as arising from the modification of symmetry-breaking dynamics as one passes from vacuum to nuclear matter.

PACS numbers: 12.35.Cr, 11.30.Qc, 13.60.Hb, 21.10.−k

It has been shown experimentally that deep-inelastic electron scattering from nuclei cannot be understood as the incoherent scattering from a collection of nucleons with characteristics unmodified from those in vacuum. [This phenomenon has become known as the EMC effect.] Recently, Jaffe, Close, Roberts, and Ross[1–3] have argued persuasively that the EMC effect[4] may be understood if quarks occupy a larger volume in nuclei than in nucleons in vacuum. These authors are also able to give an account of the A dependence of the effect; however, the precise mechanism leading to this partial deconfinement is not fully understood. Here we argue that the effect may be understood as arising from the increase of the size of the nucleon in nuclear matter. (As we will see, the parameters of our model are fixed when fitting the properties of the nucleon in *vacuum* and our discussion of the modification of nucleon properties in *nuclei* is parameter free. In our calculation the increase in nucleon size is about 15% in iron and about 27% in nuclear matter.[5])

In two recent works[5,6] we developed a covariant nontopological soliton model of the nucleon and achieved a remarkably good fit to the electric and magnetic radii, g_A, the magnetic moments, and the nucleon form factors. This was accomplished by making a fully covariant analysis of the nontopological model of Friedberg and Lee.[7] In this model the quarks are coupled to a scalar field, χ, which plays the role of an order parameter of the QCD vacuum. [In addition, we also included quark coupling to the σ, $+\pi$, ρ, and ω fields which appear in the one-boson exchange (OBE) model[8] of the nuclear force, for example.] The field χ measures the deviation of the order parameter from its vacuum value and is thus nonzero only in the vicinity of the soliton. The ρ, π, and ω fields play an important role in the description of the nuclear force; however, they are relatively unimportant for our considerations here and therefore we do not write their contributions to the Lagrangian density of the model in this work.

We have, therefore,

$$\mathscr{L}(x)=\bar{q}(x)[i\gamma^\mu\partial_\mu-m_q-g_\chi\chi(x)-g_\sigma\sigma(x)]q(x)+\tfrac{1}{2}\partial_\mu\chi(x)\partial^\mu\chi(x)-\tfrac{1}{2}m_\chi^2\chi^2(x)$$
$$+\tfrac{1}{2}\partial_\mu\sigma(x)\partial^\mu\sigma(x)-\tfrac{1}{2}m_\sigma^2\sigma^2(x). \qquad (1)$$

We make closer contact with the Friedberg-Lee model by introducing a scalar field $\phi(x)$ such that $\phi(x)=\phi_{\rm vac}+\chi(x)$ and $m_q\equiv g_\chi\phi_{\rm vac}$. Thus we have

$$\mathscr{L}(x)=\bar{q}(x)[i\gamma^\mu\partial_\mu-g_\chi\phi(x)-g_\sigma\sigma(x)]q(x)+\tfrac{1}{2}\partial^\mu\phi(x)\partial_\mu\phi(x)-\tfrac{1}{2}m_\chi^2[\phi(x)-\phi_{\rm vac}]^2$$
$$+\tfrac{1}{2}\partial^\mu\sigma(x)\partial_\mu\sigma(x)-\tfrac{1}{2}m_\sigma^2\sigma^2(x). \qquad (2)$$

[We are here using a simplified version of the potential $U(\phi)$ of Ref. 7.]

In the development of our model we found[6] $g_\chi = 6.3$, $m_q=600$ MeV, so that $\phi_{\rm vac}=95$ MeV. We also put $m_\chi=500$ MeV and used the empirical (OBE) value[9] of $m_\sigma=500$ MeV. The *σ-quark* coupling, g_σ, was fixed so that the *σ-nucleon* coupling, $G_{\sigma NN}$, was given correctly. We found $g_\sigma=3.93$ in our analysis,[6] which made use of the OBE value[9] of $G_{\sigma NN}^2/4\pi=4.63$.

We should note at this point that it is possible to carry forward this analysis with only a single scalar field rather than the two used above. This would require that the scalar field be coupled to the quarks in the nucleon by a somewhat different coupling constant when calculating the structure of the nucleon itself than when constructing the potential for nucleon-nucleon scattering using the OBE model. One may argue that the dynamics of soliton-soliton scattering is not well understood and various effects such as vacuum polarization and distortion of quark wave functions would lead to a different *effective* coupling constant for the scattering problem and for the *nucleon* structure problem. In our analysis we have avoided this problem by using two scalar fields, $\sigma(x)$ and $\chi(x)$, and making the *ad hoc* assumption that the χ field does not participate in the description of soliton-soliton scattering. (Indeed, one may argue that there are two order parameters in QCD, one describing the phase transition associated with confinement and the other describing the breaking of chiral symmetry. Thus the use of two scalar fields may not be unreasonable.) We can see, however, that the results we describe here are independent of whether one uses one or two scalar fields to describe the structure of the nucleon and nucleon-nucleon scattering. Since we have used the model with two scalar fields in our recent work we will continue our analysis using that model. The reader can readily transcribe our results for a model with a single scalar field.

The field equations for a nucleon in *vacuum* are

$$[i\gamma^\mu\partial_\mu - g_\chi\phi(x) - g_\sigma\sigma(x)]q(x) = 0, \quad (3)$$

$$(\Box + m_\chi^2)(\phi(x) - \phi_{\text{vac}}) = -g_\chi\hat{\rho}_s(x), \quad (4)$$

$$(\Box + m_\sigma^2)\sigma(x) = -g_\sigma\hat{\rho}_s(x). \quad (5)$$

Here $\hat{\rho}_s(x)$ is the scalar density of the *nucleon.* We will develop these equations in the static limit, for simplicity, and refer to our fully covariant analysis for various numerical results.[5,6]

We now consider our soliton to be in nuclear matter. We find that the right-hand side of Eq. (5) has a new source term, $-G_{\sigma NN}\rho_s^{\text{NM}}$ where ρ_s^{NM} is the value of the scalar density in nuclear matter, $\rho_s^{\text{NM}} \simeq 0.16\ \text{fm}^{-3}$. In accord with our assumption that the ϕ field does not participate in nucleon-nucleon scattering, we do not modify the right-hand side of Eq. (4).

It is now useful to introduce a shifted field, $\sigma'(x)$:

$$\sigma(x) = \sigma'(x) - \frac{G_{\sigma NN}\rho_s^{\text{NM}}}{m_\sigma^2} = \sigma'(x) + \sigma^{\text{ext}}. \quad (6)$$

Thus we have

$$[i\gamma^\mu\partial_\mu - g_\chi\phi(x) - g_\sigma\sigma^{\text{ext}} - g_\sigma\sigma'(x)]q(x) = 0, \quad (7)$$

$$(\Box + m_\chi^2)[\phi(x) - \phi_{\text{vac}}] = -g_\chi\hat{\rho}_s(x), \quad (8)$$

$$(\Box + m_\sigma^2)\sigma'(x) = -g_\sigma\hat{\rho}_s(x). \quad (9)$$

It is clear that these equations are the same as Eqs. (3)–(5) with a density-dependent shift in the quark mass: $m_q \to \tilde{m}_q = m_q + g_\sigma\sigma^{\text{ext}}$. Here $g_\sigma\sigma^{\text{ext}} \simeq -150$ MeV in nuclear matter so that we can put $\tilde{m}_q = m_q - 150(\rho_s/\rho_s^{\text{NM}})$ for arbitrary $\rho_s \leq \rho_s^{\text{NM}}$.

From a *formal* point of view these equations are equivalent to those obtained from Eq. (2) after the replacement of ϕ_{vac} by $\bar{\phi}_{\text{vac}} = \phi_{\text{vac}} + g_\sigma\sigma^{\text{ext}}/g_\chi$. If one then makes an expansion about the new minimum of the ϕ-field potential, i.e., $\phi(x) = \bar{\phi}_{\text{vac}} + \chi(x)$, the equations of motion would read

$$[i\gamma^\mu\partial_\mu - \tilde{m}_q - g_\chi\chi(x) - g_\sigma\sigma'(x)]q(x) = 0, \quad (10)$$

$$(\Box + m_\chi^2)\chi(x) = -g_\chi\hat{\rho}_s(x), \quad (11)$$

$$(\Box + m_\sigma^2)\sigma'(x) = -g_s\hat{\rho}_s(x). \quad (12)$$

Thus we see that the replacement of m_q by $\tilde{m}_q$ can be interpreted as a shift: $\phi_{\text{vac}} \to \bar{\phi}_{\text{vac}}$. In other words, there is a density-dependent shift in the parameter which measures the degree of broken symmetry.

Numerical results for the modification of nucleon properties in nuclear matter are given in Ref. 5. We reproduce here (Fig. 1) the dependence of the electromagnetic radius of the proton on the value of

$$\tilde{m}_q - m_q = a = g_\sigma\sigma^{\text{ext}} = -g_\sigma G_{\sigma NN}\rho_s^{\text{NM}}/m_\sigma^2.$$

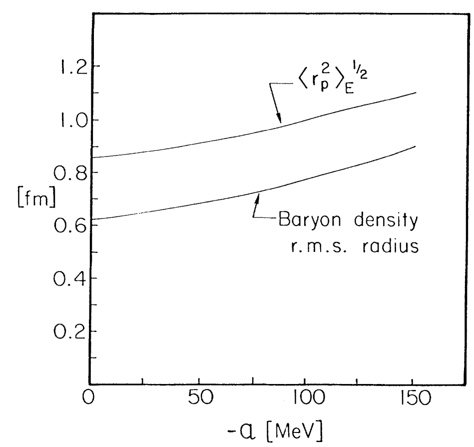

FIG. 1. Radius of the soliton in a (Lorentz) scalar external field. The electromagnetic radius,

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

is shown as well as the rms radius calculated for the baryon matter density in the soliton rest frame. The value of a is about -150 MeV in nuclear matter and is estimated to have an average of about -100 MeV in iron, for example.

TABLE I. The radius of the nucleon in nuclei relative to the radius in free space (Ref. 5). The *average* of the baryon density is given for various nuclei and is used to convert the nuclear-matter results of Ref. 5 to corresponding results for finite nuclei. The values in the last column are based upon the geometrical-overlap model of Ref. 1 and represent the increase in the *effective* radius of quark confinement in nuclei relative to that in vacuum.

	ρ_{av} (fm^{-3})	ρ_{av}/ρ^{NM}	R/R_0 (Ref. 5)	R/R_0 (Ref. 1)
^{12}C	0.089	0.52	1.11	1.104 → 1.124
^{27}Al	0.106	0.62	1.14	1.14 → 1.165
^{56}Fe	0.117	0.69	1.15	1.153 → 1.18
^{107}Ag	0.126	0.74	1.17	1.168 → 1.198
^{197}Au	0.147	0.86	1.20	1.195 → 1.229
Nuclear matter	0.17	1.00	1.27	

The quantity $\langle r_p^2 \rangle_E^{1/2}$ is obtained from the slope of the electromagnetic form factor, while the curve labelled "Baryon density rms radius" is obtained by calculating the expectation value of r^2 using quark wave functions evaluated in the soliton rest frame.[5] We note that the increase in radius is about 15% in ^{56}Fe if we use the fact that ^{56}Fe is about 0.69 of the density of nuclear matter on the average. The values obtained here for the increased volume of quark confinement in nuclei are quite in accordance with the values used in Refs. 1–3 for the explanation of the EMC effect. In Table I we present the values given in Ref. 1 for the ratio of the *radius* of the quark confinement volume in the nucleus to that in free space, R/R_0. These values are compared to values obtained by use of the model described here and the calculations of Ref. 5—see Fig. 1. The values taken from Ref. 5 are subject to some uncertainty since we have to use average values of the baryon density to convert our calculations for solitons in nuclear matter of varying densities to values for R/R_0 for finite nuclei. Given these reservations we see that our calculations reproduce the values of R/R_0 needed to explain the EMC effect quite well. Since, in Ref. 5, we have also presented predictions for modified electromagnetic form factors for nucleons in nuclei, we should ultimately be able to distinguish between the various models that predict increased values for the quark confinement volume in nuclei.[1-3,5]

This work was supported in part by the National Science Foundation and the PSC-BHE Faculty Award Program of the City University of New York.

[1]R. Jaffe, F. E. Close, R. G. Roberts, and G. G. Ross, Phys. Lett. **134B**, 449 (1984), and Rutherford Appleton Laboratory Report No. RAL-84-028, 1984 (to be published).

[2]F. E. Close, R. G. Roberts and G. G. Ross, Rutherford Appleton Laboratory Report No. RAL-84-029, 1984 (to be published), and Phys. Lett. **129B**, 346 (1983).

[3]F. E. Close, Rutherford Appleton Laboratory Report No. RAL-84-038, 1984 (to be published).

[4]J. J. Aubert *et al.* (EMC collaboration), Phys. Lett. **123B**, 275 (1983); see also A. Bodek *et al.,* Phys. Rev. Lett. **50**, 1431 (1983), and **51**, 534 (1984).

[5]L. S. Celenza, A. Rosenthal, and C. M. Shakin, Brooklyn College Report No. BCINT 84/041/123 (to be published).

[6]L. S. Celenza, A. Rosenthal and C. M. Shakin, Brooklyn College Report No. BCINT 84/031/122 (to be published).

[7]R. Friedberg and T. D. Lee, Phys. D **15**, 1694 (1977), and **16**, 1096 (1977), and **18**, 2623 (1978). See also T. D. Lee, Phys. Rev. D **19**, 1802 (1979).

[8]See, for example, K. Erkelenz, Phys. Rep. **13C**, 191 (1974).

[9]K. Holende, K. Erkenlenz, and R. Alzetta, Nucl. Phys. **A198**, 598 (1972).