# Modification of the Nucleon's Properties in Nuclear Matter

J. V. Noble
*Department of Physics, University of Virginia, Charlottesville, Virginia 22901*
(Received 29 September 1980)

The separated structure functions for large–momentum-transfer electron-nucleus scattering in the quasielastic region can be fitted by assuming that the effect of nuclear matter on nucleon structure is to increase the nucleon charge radius some 30%, and to quench the anomalous moments. These effects are consistent with a field-theoretic description of nucleon and nuclear structure.

PACS numbers: 21.65.+f, 12.40.Cc, 25.30.Cq

Nuclear physicists have long been interested in the question of whether nucleons in nuclei have the same properties as free nucleons.[1] In a nonrelativistic description of nuclear structure there is no option but to regard the nucleon's internal properties, including its mass, charge radius, and magnetic moment, as fixed and state independent. However, the recent movement toward a unified description of nuclear properties and of meson-nucleon interactions[2] has led to a class of theories in which the nucleon mass, e.g., is an interaction-dependent quantity. Such a situation can arise in models like the Gell-Mann–Levy[3] $\sigma$ model, in which the nucleon's mass would be zero were it not for the spontaneous breakdown of the symmetry of the vacuum, which leads to a nonzero average $\sigma$-meson field. The free nucleon mass is then given by

$$M = G\langle\sigma\rangle, \tag{1}$$

which is a form of the Goldberger-Treiman relation.[4] An important consequence of this kind of picture is that the average $\sigma$ field in nuclear matter is smaller than in vacuum, so that the nucleon's *physical mass* in a nucleus, $M^*$, will be smaller than that of a free nucleon.[2,5] By appending to the $\sigma$ model a neutral vector meson, the $\omega$, coupled to the (conserved) baryon current, one obtains a simple, renormalizable phenomenological quantum field theory which describes well the main features of low-energy $NN$, $\pi N$, and $\pi\pi$ physics, and which is known to give a good picture of nuclear one-body dynamics[6] and of nuclear structure.[2,7]

In a theory like the $\sigma+\omega$ model (described above) we expect the phenomenological nucleon current in nuclear matter to have the renormalized form

$$J_\mu^* = \bar{u}^*[F_1^*(q^2)\gamma_\mu + iF_2^*(q^2)(\kappa^*/2M^*)\sigma_{\mu\nu}q^\nu]\,u^*, \tag{2}$$

where the asterisks denote values of the parameters appropriate to nuclear matter (also note that nuclear matter provides a rest frame in which the total three-momentum of the filled positive-energy states vanishes). Thus the spinors satisfy ($V$ is proportional to the average $\omega$ field)

$$(\vec{\gamma}\cdot\vec{p} + M^*)u^*(\vec{p}) = \gamma^0(E-V)u^*(\vec{p}). \tag{3}$$

Recently I showed[8] that the anomalous moments appropriate to infinite nuclear matter, with $M^* = 520\ \mathrm{MeV}/c^2$ and $k_F = 260\ \mathrm{MeV}/c$, are

$$\kappa_p^* \simeq 0.91, \quad \kappa_n^* \simeq -1.34, \tag{4}$$

which leads to effective anomalous moments of 1.5 and $-2.2$ nm, respectively, for valence particles.

What of the nonstatic behavior of the nuclear-matter-modified form factors $F_1^*$ and $F_2^*$? One knows that $F_1^*(0) = F_2^*(0) = 1$, the first by charge conservation and the second by our choice of normalization. Lacking a complete theory of the structure of the nucleon, one is forced to guess at the modification of, say, the nucleon radius by its insertion into nuclear matter. In order that this radius not be a completely *ad hoc* parameter, I apply what little I know from either the bag model or from perturbation theory to constrain it: The former has a radius which scales inversely as the nucleon mass, whereas if one calculates the nucleon charge radius in the $\sigma+\omega$ model to $O(G^2)$, one finds a similar scaling. Since both models roughly agree, one should feel reasonably confident in guessing the nucleons in nuclei are somewhat more diffuse than free nucleons, with

$$r/r_{\text{free}} \simeq M/M^*. \tag{5}$$

(In what follows, *no* other prescriptions have been tried.)

The object of the present note is to point out that recent data on deep inelastic electron scattering from $^{56}$Fe can illuminate these questions. Altemus *et al.*[9] were able, for the first time, to separate the longitudinal from the transverse inelastic structure functions, at large, fixed three-momentum transfer $|\vec{q}|$. The longitudinal structure function $S_L(|\vec{q}|,\omega)$ derives most of its strength from one-body processes, since (as is well known[10]) the two-particle, two-hole (2p-2h) excitations, meson production, and virtual $\Delta$ excitation contribute primarily to the transverse structure function, $S_T(|\vec{q}|,\omega)$. Hence one-particle models such as the relativistic Fermi gas (RFG) should be applied first to the longitudinal structure function, which they should be adequate to describe.

In Fig. 1, I plot the data of Altemus *et al.*[9] for $S_L(|\vec{q}|,\omega)$ at $|\vec{q}|=410$ MeV/$c$, together with RFG calculations for several different values of the effective mass, $M^*$, and Fermi momentum, $k_F$. [The point of view adopted here is that the so-called average binding correction, $\Delta\omega$, frequently used to adjust the peak position in the quasielastic spectrum, is completely unphysical, since it violates charge conservation.[11] In any event, its use does not improve the agreement.[9]] The shape of the spectrum, especially the position of the quasielastic peak, and of its high-energy cutoff, demand values of $M^*$ and $k_F$ near 700 MeV/$c^2$ and 220 MeV/$c$, respectively, as can be seen in Fig. 1. However, as the dotted curve in Fig. 2(a) makes clear, if one allows the form factors, $F_1^*$ and $F_2^*$, and the anomalous moments, $\kappa_p^*$ and $\kappa_n^*$, to retain their free-nucleon values, then the theoretical values are far too large! There are strong reasons to believe that neither short-range correlations[12] nor final-state interaction effects[13] can reduce significantly the theoretical spectrum. Fortunately, there is a simple, if radical, resolution of the difficulty: If one replaces the usual dipole fit to the free-nucleon form factors,

$$F_1(q^2)=F_2(q^2)=(1-q^2/\mu^2)^{-2}, \tag{6}$$

by a version scaled according to Eq. (5),

$$F_1^*(q^2)=F_2^*(q^2)=(1-q^2M^2/\mu^2M^{*2})^{-2} \tag{7}$$

then an excellent fit is achieved, essentially over the entire range of the data. The three curves (dashed, solid, and dash dotted) in Fig. 2(a) differ only by the prescriptions taken for the anomalous moments. We see in Fig. 2(b) an equivalently good fit to the $|\vec{q}|=370$ MeV/$c$ data. Here

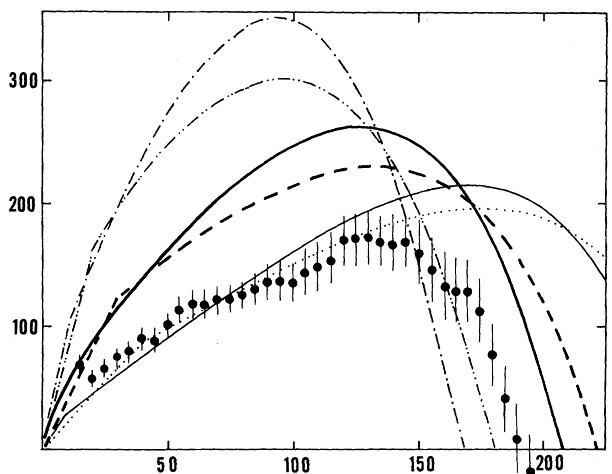


FIG. 1. Relativistic Fermi-gas calculations of the longitudinal structure factor for $^{56}$Fe, at $|\vec{q}|$ = 410 MeV/$c$. Solid circles represent the data of Ref. 9. The heavy solid line has $M^*$ = 700 MeV/$c^2$ and $k_F$ = 220 MeV/$c$. The heavy broken line has $M^*$ = 700 MeV/$c^2$ and $k_F$ = 260 MeV/$c$. The thin solid line has $M^*$ = 520 MeV/$c^2$ and $k_F$ = 220 MeV/$c$; the dotted line has $M^*$ = 520 MeV/$c^2$ and $k_F$ = 260 MeV/$c$. The dash-dotted line has $M^*$ = 940 MeV/$c^2$ and $k_F$ = 220 MeV/$c$, and the dash–double-dotted line has $M^*$ = 940 MeV/$c^2$ and $k_F$ = 260 MeV/$c$. All curves are obtained in impulse approximation, with free-nucleon form factors and moments.

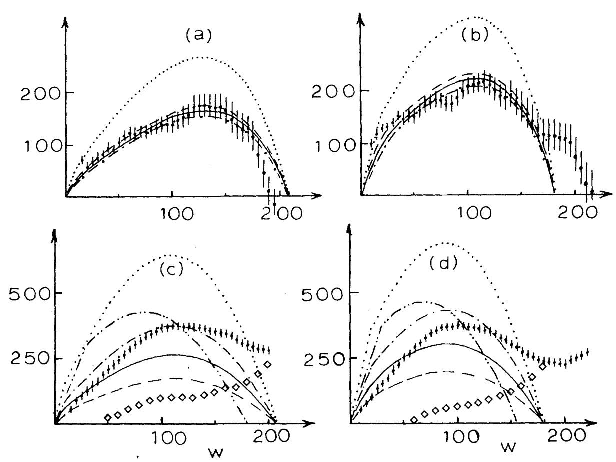


FIG. 2. (a) Longitudinal form factors for $|\vec{q}|$ = 410 MeV/$c$, $M^*$ = 700 MeV/$c^2$, and $k_F$ = 220 MeV/$c$. The dotted line is the impulse approximation. The other three curves have the same (scaled) rms nucleon radius $\langle r^2\rangle^{1/2} = \langle r^2\rangle_{\rm Free}{}^{1/2}M/M^*$. The dash-dotted curve has $\kappa_p^*$ = 1.79 and $\kappa_n^*$ = −1.91; the solid curve has $\kappa_p^*$ = 1.35 and $\kappa_n^*$ = −1.63; the dashed (upper) curve has $\kappa_p^*$ = 0.91 and $\kappa_n^*$ = −1.34. (b) Same as 2(a), except for $|\vec{q}|$ = 370 MeV/$c$. (c) Same as 2(a), except that the structure functions are transverse; the dash–double-dotted curve represents the impulse approximation (all free-nucleon parameters). The open diamonds are the data minus the solid theoretical curve. (See text.) (d) Same as 2(c), except for $|\vec{q}|$ = 370 MeV/$c$.

also the data do not permit the discrimination of one set of anomalous moments from another.

The success of the simple scaling prescription (for the nucleon form factors) in describing the longitudinal structure function encouraged me to apply these ideas to the transverse structure function. Since I expect a substantial contribution from 2p-2h excitations, the one-body contribution should fall well short of the data. From Figs. 2(c) and 2(d) we see that neither for the pure impulse approximation ($M^*=M$, all form factors and moments unscaled) shown in the dash–double-dotted curves, nor for the effective-mass prescription with free-nucleon form factors and moments ($M^*=700$ MeV/$c^2$, dotted curves) is this constraint satisfied. More to the point, perhaps, is the fact that even with the scaled form factors, Eq. (7), the free-nucleon anomalous-magnetic-moment values, 1.79 and $-1.91$ {which could not be discriminated from the values [Figs. 2(a) and 2(b)] in the fits to longitudinal structure functions}, are definitely ruled out by the transverse structure functions. The diamonds appearing in Figs. 2(c) and 2(d) represent the differences between the data and the solid curves (which represent my best estimates of the single-particle contribution to $S_T$). These difference curves closely resemble van Orden's calculations[14] of 2p-2h *cum* meson-production contributions, had the latter not been carried out when an absurdly high threshold of ~ 70 MeV is assumed, predicated on twice including the one-body binding correction $\Delta\omega$. (Recall that these binding corrections seemed necessary because the standard impulse approximation to the one-body part of the transverse structure function is already too large, and peaked in the wrong place.) In fact, if one were to combine the present calculation of the one-body contribution to $S_T$ with van Orden's calculation of 2p-2h and pion production, with the threshold behavior of the latter effects adjusted to reflect the prejudices expressed above, one would almost certainly explain the infamous "dip" which has hitherto proven so hard to fill in.[10]

In this paper, I have shown that a reasonable, internally consistent picture of both longitudinal and transverse inelastic structure functions may be based on two ideas: a relativistic Fermi-gas model of the single-particle dynamics, together with a simple prescription for the effect of nuclear matter on the internal structure of the nucleon. The results also agree with the longitudinal sum rule,[9,12] which had hitherto seemed to disagree with theory.[9] There does not seem to be any important disagreement between these ideas and what we currently know about the structure of large nuclei; for example, the scaling of the charge radius of the nucleon would alter the nuclear size parameter $r_0$, as measured in elastic electron scattering, by a mere 0.02 fm or so. If there is any mystery in these fits, it is why they prefer $M^*\simeq 700$ MeV/$c^2$, rather than 500–600 MeV/$c^2$ as we might have expected from various relativistic Thomas-Fermi or Hartree-Fock calculations.[1,6] Finally, one should recall that although the present prescription eliminates the "binding correction" parameter, it introduces a scaling parameter for the nucleon size. The difference, in my opinion, is that whereas the old prescription violated gauge invariance, the new one does not; moreover, the new prescription accords better with the modern, field-theoretic, picture of nuclear dynamics.

I am grateful to R. Altemus for providing me with her separated data, and to J. S. McCarthy and R. R. Whitney for helpful discussions. This work has been supported in part by the National Science Foundation.

[1] S. D. Drell and J. D. Walecka, Phys. Rev. 120, 1069 (1960); M. Chemtob and M. Rho, Nucl. Phys. A163, 1 (1971); Y. Nogami, Rev. Bras. Fis. 7, 19 (1978); J. O. Eeg, M. Martinis, and H. Pilkuhn, Phys. Lett. 92B, 271 (1980).

[2] L. D. Miller, Ann. Phys. (N.Y.) 91, 40 (1975); J. D. Walecka, Ann. Phys. (N.Y.) 83, 491 (1974); R. Brockmann, Phys. Rev. C 18, 1510 (1978); B. D. Serot, Phys. Lett. 86B, 146 (1979); B. D. Serot and J. D. Walecka, Phys. Lett. 87B, 172 (1979); J. V. Noble, Phys. Rev. C 20, 225 (1979).

[3] M. Gell-Mann and M. Levy, Nuovo Cimento 16, 705 (1960).

[4] M. Goldberger and S. B. Treiman, Phys. Rev. 110, 1178 (1958).

[5] T. D. Lee, Rev. Mod. Phys. 47, 267 (1975).

[6] J. V. Noble, Nucl. Phys. A329, 354 (1979).

[7] J. Boguta and J. Rafelski, Phys. Lett. 71B, 22 (1977); F. E. Serr and J. D. Walecka, Phys. Lett. 79B, 10 (1978); L. D. Miller, Phys. Rev. C 14, 706 (1976).

[8] J. V. Noble, "How Do the Nucleon Anomalous Magnetic Moments Behave in Nuclear Matter" (to be published).

[9] R. Altemus, A. Cafolla, D. Day, J. S. McCarthy, R. R. Whitney, and J. R. Wise, Phys. Rev. Lett. 44, 965 (1980).

[10] T. W. Donnelly, J. W. van Orden, T. de Forest, and W. C. Hermans, Phys. Lett. 76B, 393 (1978).

[11] That is, it implies a different Hamiltonian for the

initial states than for the final states. See, e.g., J. V. Noble, Phys. Rev. C 17, 2151 (1978).

[12]R. D. Viollier and J. D. Walecka, Acta Phys. Pol. B 8, 25 (1977).

[13]Y. Horikawa, F. Lenz, and N. C. Mukhopadhyay, to be published.

[14]J. W. van Orden, Ph.D. thesis, Stanford University, 1978 (unpublished).

# Anomalous Behavior of High-Spin States in $^{248}$Cm

R. B. Piercey
*Physics Department, Vanderbilt University, Nashville, Tennessee 37235, and Gesellschaft für Schwerionenforschung, D-6100 Darmstadt, Germany*

and

J. H. Hamilton and A. V. Ramayya
*Physics Department, Vanderbilt University, Nashville, Tennessee 37235, and Institut für Theoretische Physik, Universität Frankfurt, D-6000 Frankfurt, Germany*

and

H. Emling, P. Fuchs, E. Grosse, D. Schwalm, and H. J. Wollersheim
*Gesellschaft für Schwerionenforschung, D-6100 Darmstadt, Germany*

and

N. Trautmann
*Institut für Kernchemie, Universität Mainz, D-6500 Mainz, Germany*

and

Amand Faessler
*Institut für Theoretische Physik, Universität Tübingen, D-7400 Tübingen, Germany*

and

M. Ploszajczak
*Institut für Theoretische Physik, Universität Tübingen, D-7400 Tübingen, Germany, and Institute of Nuclear Physics, PL-31-342 Cracow, Poland*

(Received 24 November 1980)

The ground-state band of $^{248}$Cm has been studied up to spin $28^+$ and tentatively to $30^+$ by observing $\gamma$ rays following multiple Coulomb excitation with use of $^{208}$Pb ions at 5.3 MeV/u. A smooth, gradual increase in the effective moment of inertia is seen at lower spin with an anomalous forward bend above spin $22^+$. Calculations are presented which indicate that this behavior including the forward bend can be understood in terms of the alignment of single-particle angular momenta along the rotation axis.

PACS numbers: 25.70.Kk, 21.10.Re, 27.90.+b

Anomalies in the energy level spacings of yrast states in well-deformed rare-earth and transition-metal nuclei have generated much theoretical and experimental activity.[1-3] The anomalous yrast spectra of rare-earth nuclei at spins around 12–16 are understood in terms of a superband built on two-quasiparticle rotation-aligned states which crosses the ground rotational band. Now additional crossings of rotation-aligned bands have been discovered at even higher spin.[4] The question of what happens to the collective-rotation and single-particle configurations as the nuclear angular velocity increases further is of much current interest.[1-3] Important to the extension of our understanding is to observe the behavior of more purely rotationallike states to higher angular momenta and of rotation-aligned configurations in very-high-$J$ orbitals like $\nu j_{15/2}$ and $\pi i_{13/2}$ as can occur in actinide nuclei.

With one of the lowest first excited $2^+$ energies and largest collectivity, $^{248}$Cm should offer one of the best opportunities to study a rotational

 