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SCALING VIOLATION AND SIZE OF THE NUCLEON IN NUCLEI FROM QUASIELASTIC ELECTRON SCATTERING*

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ABSTRACT

A y scaling analysis of the longitudinal and transverse response functions in the quasielastic region from electron scattering suggest that there is no meaningful scaling function one can extract from the inclusive cross section, unless one use a different parametrisation of the nucleon form factors in nuclei compared to their free ones.

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The quasielastic region in electron scattering has been viewed over the last decade as a suitable region to study nucleon-nucleon correlations,[1] meson exchange currents[2] and the nucleon momentum distribution in the nucleus.[3] During the past few years new motivations arose for investigating the quasielastic region. In particular, an increase of the nucleon size in the nuclear medium has been proposed to account for experimental data on deep-inelastic muon scattering on iron and deuterium (the so-called European Muon Collaboration (EMC) effect).[4,5]

It is believed that the EMC effect shows that quark wave functions are affected by the nuclear medium. However the EMC data are for high momentum transfers and high energy losses ($.1 < x < .8$, $Q^2 > 5$ $(\mathrm{GeV/c})^2$) where quark degrees of freedom are dominant. These data are not directly sensitive to modifications of intrinsic nucleon properties. The quasielastic region is known to be dominated by incoherent, quasifree electron scattering from individual nucleons in the nucleus. It is likely that if modification of the nucleon in the nuclear medium does occur it will show up in this region.

The new generation of electron scattering data where transverse and longitudinal response functions have been separated in the quasielastic region up to momentum transfers of $Q^2 = .3$ $(\mathrm{GeV/c})^2$ provide strong constraints on studying the aspect of nucleon properties in the nuclear medium.

In this letter we show, using a y-scaling approach, that a consistent picture of scattering processes in the quasielastic region has not yet been achieved. Any attempt to extract the nucleon momentum through a y-scaling analysis from the *total response function* (proportional to the inclusive electron scattering cross section) or to use the breakdown of the scaling properties of this latter to study the modification of nucleon properties is meaningless (especially for heavy nuclei), unless one resolves the observed inconsistency between transverse and longitudinal scaling functions.

The inclusive electron scattering cross section in the one photon exchange approximation is a function of two independants variables the four momentum transfer Q^2 and energy transfer ω:

$$\frac{d\sigma}{d\Omega d\omega} = \sigma_M \Big\{ \Big(\frac{Q}{|\vec{q}|}\Big)^4 R_L(Q^2,\omega) + \Big[-\frac{1}{2}\Big(\frac{Q}{|\vec{q}|}\Big)^2 + tg^2\frac{\theta}{2}\Big] R_T(Q^2,\omega) \Big\} \,, \tag{1}$$

$$Q^2 = \omega^2 - \vec{q}^{\,2} \,. \tag{2}$$

where $\vec{q}$ is the three momentum transfer carried by the virtual photon, σ_M is the Mott cross section, and R_L and R_T are the longitudinal (charge) and the transverse (convection and magnetization currents) response functions respectively.

The analysis of data at high momentum transfer,[6] $\{Q^2 \simeq 1\ (\mathrm{GeV/c})^2\}$ on ^{3}He assuming the dominance of the one nucleon knock-out process with the impulse approximation, has shown, that the experimental ratio

$$\frac{d\sigma(Q,\omega)}{d\Omega d\omega} \Big/ \Big\{ Z\ \frac{d\sigma(Q)}{d\Omega_p} + N\ \frac{d\sigma(Q)}{d\Omega_n} \Big\}\, d\omega = F(y)dy \tag{3}$$

becomes a function of the scaling variable y defined by the following kinematical equation:

$$\omega + M_A = (y^2 + 2yq + m^2 + Q^2)^{1/2} + (y^2 + M_{A-1})^{1/2} \tag{4}$$

$$\frac{dy}{d\omega} \simeq \frac{m}{q} \tag{5}$$

where m is the free nucleon mass, M_A and M_{A-1} respectively the mass of the target and the recoil nucleus. y should be interpreted as the minimum momentum of the struck nucleon before the reaction (y is parallel to $\vec{q}$), and $F(y)$ a function related to the probability to find nucleons with momentum component y in the nucleus. Several choices of the scaling variable y exist in the litterature, the differences between these variables lead to different shapes of the extracted scaling function $F(y)$. However for our study this is irrelevant since all these variables have the same value ($y = 0$) in the physical region of our main concern namely the *top of the quasielastic peak.*

Here, we concentrate on investigating the consistency of the function $F(y)$ since we can extract this function independently from the transverse and the longitudinal response functions. The electron scattering data[7–9] on ^{3}He, ^{12}C and ^{56}Fe in the quasielastic region are analyzed and the A dependence effect investigated. If we assume that the impulse approximation is valid and consider only the region near the top of the quasielastic peak where $y \simeq 0$ ($Q^2 \simeq 2M\omega$), then one can show that the transverse and longitudinal response functions are expressed in terms of the scaling function as follows:

$$R_L \simeq \left(1 + \frac{Q^2}{4m^2}\right) \widetilde{G}_E^2(Q^2).F_L(y).\frac{dy}{d\omega} \tag{6}$$

$$R_T \simeq \left(\frac{Q^2}{2m^2}\right) \widetilde{G}_M^2(Q^2).F_T(y).\frac{dy}{d\omega} \tag{7}$$

$$\widetilde{G}_E^2 = ZG_E^{p2} + NG_E^{n2} \tag{8}$$

$$\widetilde{G}_M^2 = ZG_M^{p2} + NG_M^{n2} \tag{9}$$

where $\widetilde{G}_E$, $\widetilde{G}_M$ are the effective electric and magnetic nucleon form factors and m is the free nucleon mass. F_L and F_T are the transverse and longitudinal scaling functions and y is the solution of Eq. (4).

The expressions (7), (6) are strictly valid in the limit $q \to \infty$ as dicussed in Ref. 10. However the available data don't satisfy the high momentum requirements, nevertheless they provide insights into use of the scaling approach to extract the right nucleon momentum distribution in the nucleus and also show the differences between light and heavy nuclei.

We have used these expressions to determine $F_L(y)$ and $F_T(y)$ separately from the transverse and the longitudinal response functions. This method provides a powerful test of the consistency of any analysis in terms of y scaling, because $F_L(y) = F_T(y) = F(y)$ should be a ***unique function*** independent of whether it is extracted from the transverse or the longitudinal response function, and provided that one nucleon knock out is the dominant reaction mechanism.

Of course, a more careful analysis should be made if one would concentrate on determining the right shape of the nucleon momentum distribution. However, we are interested in showing an unexpected behavior in a region where the formulae (7), (6) are valid in a model-independent way. Differences in the y scaling variable do not affect the result near $y \simeq 0$.

We have analysed the transverse and longitudinal data measured at Saclay on three nuclei ^{3}He, ^{12}C and ^{56}Fe shoosing fixed momentum transfers around 400 MeV/c and 550 MeV/c. The results in Fig. 1 clearly shows an expected result for ^{3}He nucleus. The transverse and longitudinal scaling functions agree from the low-y side to beyond the maximum of the quasielastic peak in ^{3}He. We should point out that ^{3}He data scale also with those of Ref. 6.

We emphasize, however, that this agreement was expected for every nucleus at least for the low energy side of the quasielastic peak where two body processes contributions through meson exchange currents are small.[2] Nevertheless the results for ^{12}C and ^{56}Fe show a *different behavior.* $F_L(y)$ and $F_T(y)$ scale independently, that is, they dont give a unique response function on the low side of the quasielastic peak. This feature has been observed on the ^{12}C data using a different scaling variable.[11]

Let us first concentrate on $F_T(y)$. Data from two different momentum transfers almost scale with y in the region of the quasielastic peak. The breaking of scaling in the high energy loss region is well known, indicating where the two body and pion production processes become important. The same feature has been observed using a scaling analysis of the total response function on ^{40}Ca.[12]

For $F_L(y)$ the scaling behavior is present from negative to positive values of y corresponding to the the entire range in energy loss covered by the experiment. This behavior suggests the known result that exchange current contributions are small in the longitudinal response function. We attempted to conclude at this stage that the quasielastic region is dominated by scattering from individual nucleons. Nevertheless, the inconsistency between transverse and longitudinal scaling functions, at least near the top of the quasielastic peak, is very intriguing and suggest strongly that our assumptions about the electromagnetic current of the nucleus or the reaction mechanism are wrong. The ratio F_T/F_L is about 1 for ^3He 65% in ^{12}C and 55% in ^{56}Fe reveals a density or mass number dependence.

It is important to recover the consistency between transverse and longitudinal scaling functions before any attempt to extract a momentum distribution as proposed in the early papers on y scaling or to use the y scaling appraoch to look at modifications of the nucleon size in the nuclear medium as described in Ref. 13. For that purpose two phenomenological approches can be attempted;

a) Modify the electromagnetic form factors of the nucleon in the nucleus keeping the free nucleon mass.

b) Use an effective mass for the nucleon ($m^\star$) in the definition of the electromagnetic current.

We know that for a free nucleon the dipole parametrisation is a good approximation to the measured data up to momentum transfers Q^2 of 1.0 $(\text{GeV/c})^2$, also that the following relation

$$G_E^p = \frac{G_M^p}{2.78} = -\frac{G_M^n}{1.91} = f_D(Q^2) \tag{10}$$

where $f_D(Q^2)$ is the well known dipole parametrisation. The prescription a) has been applied to the data following reference.[14] The free nucleon electric form factor G_E^p has been modified allowing an increase of the charge radius and the static magnetic moment μ_N. The mean square radius of the nucleon magnetic form factor G_M^p has been kept almost unchanged.

By examining the relation between Sachs (measured experimentally) and Pauli-Dirac form factors;

$$G_E^{p,n} = F_1^{p,n} + \frac{Q^2}{4m^2} F_2^{p,n} \tag{11}$$

$$G_M^{p,n} = F_1^{p,n} + F_2^{p,n} \tag{12}$$

one can better understand the prescription b), where new Sachs form factors are generated in Eqs. (11), (12) by using an effective mass $m^\star$ without modifying the Pauli-Dirac form factors. The net result is as previously to change the electric keeping the magnetic form factor as for the free nucleon. We followed the procedure of Ref. 11 without using an effective mass in the definition of the scaling variable y. The modification of the nucleon mass in the kinematics as tested in Ref. 11 do not restore the consistency that we look for.

In Fig. 2 we present the results for the ^{12}C and ^{56}Fe. It is clear that one can recover consistency in the interpretation of the transverse and longitudinal scaling functions. The quality of the scaling is obviously poor in the low energy loss region of the peak, however the high momentum transfer limit is not reached and also final state interactions are not negligible in this region. We don't aim to extract a momentum distribution through the y scaling analysis, but to show that if one wants to do so in heavy nuclei (as soon as data at higher momentum transfer will be available) one should be careful to first assure a consistent interpretation between transverse and longitudinal response functions. The attempt to recover the consistency by modifying the electromagnetic properties of the free nucleon seems to be a suitable way to explain the data and to make a connection with one of the various interpretations of the EMC effect. For ^{3}He the analysis performed in Ref. 6 is valid because we have seen a consistent behavior of the separated response functions .

Any y scaling analysis needs high momentum transfers data. However in this region of transfers the transverse response function dominate the inclusive cross section. As we have seen previously, the mean square radius of the magnetic form factor remains unchanged. Then, one should not expect any breakdown of the scaling behavior on the inclusive cross section (total response function). Consequently, any test of nucleon intrinsic properties modifications without performing separation of the two response functions is difficult.

In conclusion, In spite of other complications due to several choices of the y variable, we emphasize that the first step in a y scaling analysis is to understand how one can recover the consistency between transverse and longitudinal scaling functions. Otherwise one must use only the *longitudinal response function* to extract momentum distributions or study the eletromagnetic properties of the nucleon. The transverse processes (exchange currents, pion production through the Δ resonance decay) dominate the total response function at these transfers which make the dominance of the one nucleon knock-out process assumption wrong and the resulting scaling function meaningless.

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FIGURE CAPTIONS

1. Transverse $F_T(y)$ (A) and longitudinal $F_L(y)$ (B) scaling functions for ^{3}He, ^{12}C and ^{56}Fe extracted from data at fixed three-momentum transfers of 410 MeV/c (respectively $\square, \diamond$) and 550 MeV/c (respectively $+, \circ$).

2. Transverse $F_T(y)$ and longitudinal $F_L(y)$ scaling functions for ^{12}C and ^{56}Fe using modified electric form factor and static magnetic moment. No increase for the magnetic radius was needed. The symbols are the same as in Fig. 1.

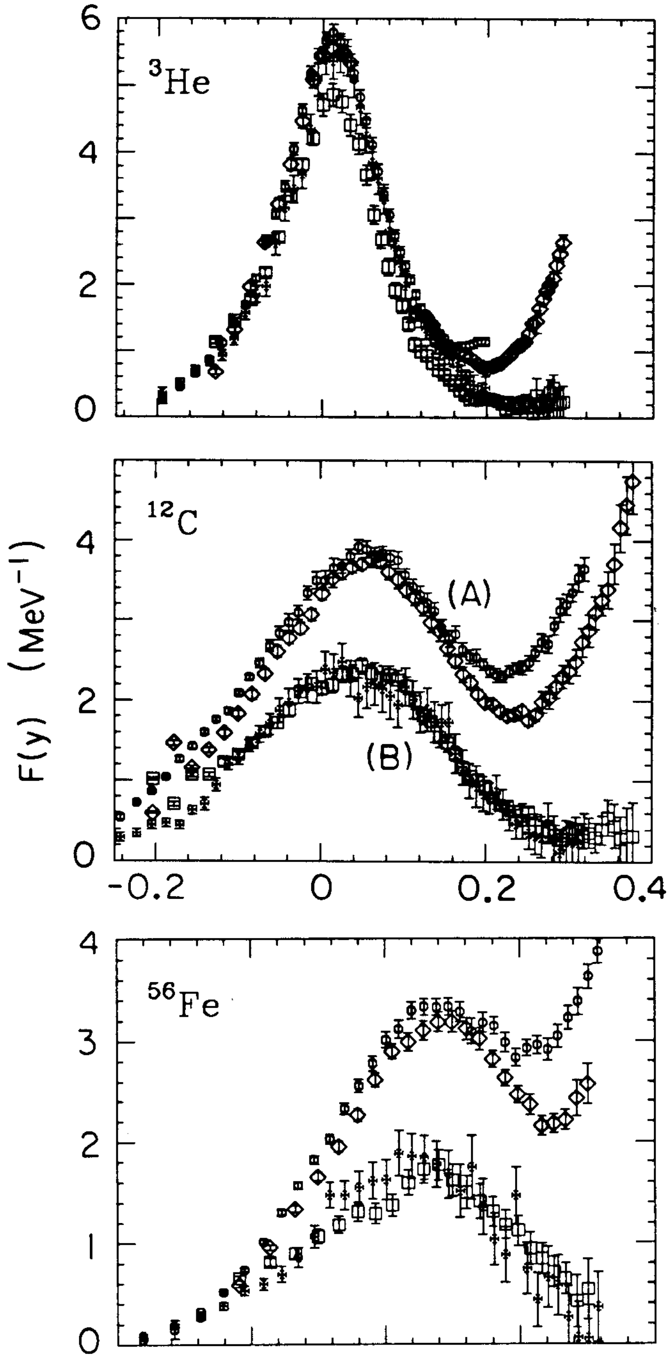

Fig. 1

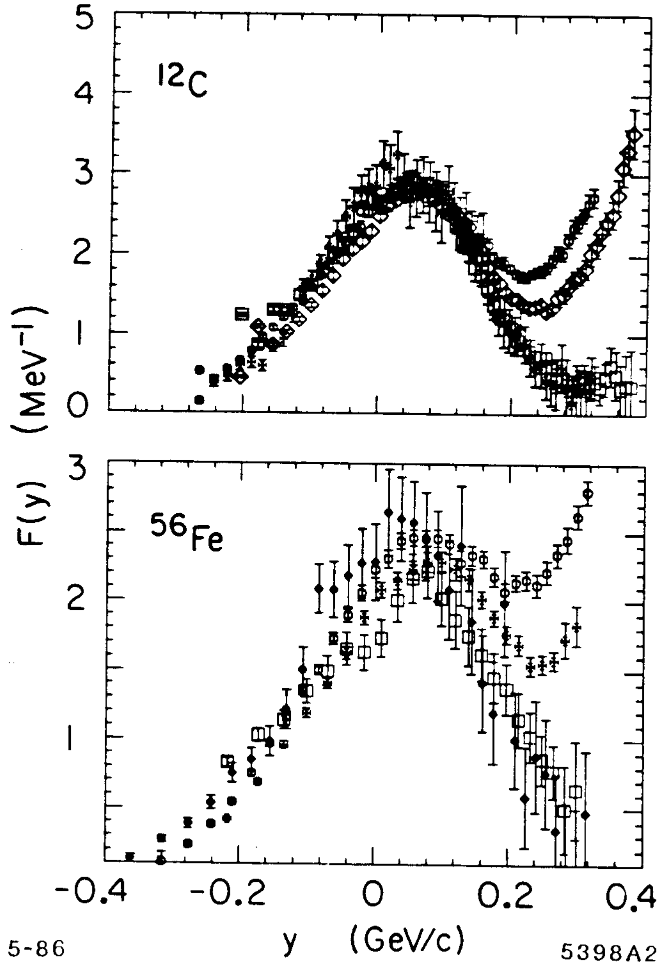

Fig. 2