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ELECTRODISINTEGRATION OF FEW BODY SYSTEMS AT SLAC AND THE Y SCALING APPROACH*

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It is proposed that extraction of the scaling function $F(y)$ from the transverse and longitudinal response functions in inclusive quasi-elastic electron scattering from ^3He and ^4He is a powerful method to either study the validity regime of the impulse approximation by allowing the access to the high nucleon momentum components in these nuclei, or the electromagnetic properties of bound nucleons.

INTRODUCTION

The prediction of possible scaling behaviour of the response function in quasi-elastic electron scattering from nuclei with respect to the longitudinal component of the nucleon momentum aroused great interest in the nuclear physics community. The idea, proposed by West [1] as a result of an analogy with atomic physics phenomena, provides a suitable approach in attempting to extract the momentum distribution of nucleons in nuclei, exploiting the scaling phenomenon as a signature of one-nucleon knock-out in the scattering process.

The reaction mechanism of electron scattering in the quasi-elastic region is usually described in the impulse approximation as a one-step process where the virtual photon knocks-out a single nucleon. Under this approximation, West formulated the expression

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of the scaling function $F(y)$ for the case of a non relativistic Fermi gas system. Since then, a great effort has been devoted not only to experimental testing of the original idea [2–4], but also to improve the definition of the scaling variable and to understand the relation between the scaling function $F(y)$ and the nucleon momentum distribution in realistic cases [5–8]. On one hand the theoretical progress achieved in clarifying the ambiguities of the early analysis of ^{3}He data in the quasi-elastic region has been significant, showing that higher momentum transfer data [in the range of $Q^2 = 5$ (GeV/c)^2] are needed to reach the perfect scaling regime. On the other hand the scaling behavior of the response in quasi-elastic electron scattering was proposed by Sick [9] also as a sensitive way to test the nucleon electromagnetic properties in nuclei since the European Muon Collaboration (EMC) effect [10,11] posed several questions about the size of nucleons in the nuclear medium.

In light of the new inclusive electron scattering data [12] on ^{4}He, which measured momentum transfers up to 2.5 (GeV/c)^2, we would like to propose a method of experimental analysis which we think would be a better test of the validity regime of the impulse approximation and also a powerful method to study the nucleon properties in the nuclear medium.

SCALING FUNCTION AND VARIABLE

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

$$\frac{d\sigma}{d\Omega d\omega} = \sigma_M \Big\{ \Big(\frac{Q}{|\vec{q}|}\Big)^4 R_L(Q^2,\omega) + \Big[-\frac{1}{2}\Big(\frac{Q}{|\vec{q}|}\Big)^2 + tg^2\frac{\theta}{2}\Big] R_T(Q^2,\omega) \Big\}, \tag{01}$$

$$Q^2 = \omega^2 - \vec{q}^{\,2}. \tag{02}$$

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.

A further step may be taken in the description of the electron-nucleus cross section in the quasi-elastic region, if, the Plane Wave Impulse Approximation is assumed. Under this approximation the relation between the spectral function S(k,ϵ) and the measured inclusive cross section is given by [5,7]:

$$\frac{d\sigma}{d\Omega d\omega} = \Big\{ Z\,\overline{\frac{d\sigma}{d\Omega_p}} + N\,\overline{\frac{d\sigma}{d\Omega_n}} \Big\} \Big| \overline{\frac{\partial\omega}{k\partial cos\alpha}} \Big|^{-1} \frac{1}{(2\pi)^2} \int_{\epsilon_-}^{\epsilon_+}, d\epsilon \int_{k_{min}(q,\omega,\epsilon)}^{k_{max}(q,\omega,\epsilon)} S(k,\epsilon) k dk \tag{03}$$

where $|\overline{d\sigma/d\Omega_{p(n)}}|$ is the electron proton (neutron) cross section evaluated at $k_{min}(q,\omega,\epsilon_{min})$, $\cos\alpha = \vec{q}\cdot\vec{k}/|q\cdot k|$ defines the angle between the struck nucleon momentum $\vec{k}$ and the incoming virtual photon momentum $\vec{q}$. k_{max} and k_{min} are defined by pure kinematical conditions. $S(k,\epsilon)$ is a probability of finding a nucleon in the nucleus with the momentum k and binding energy ϵ

Experimentally, we are interested in extracting the so called scaling function $F(y)$ expressed as the following ratio:

$$F(y) = \frac{d\sigma}{d\Omega d\omega} \Bigg/ \left\{ Z \overline{\frac{d\sigma}{d\Omega_p}} + N \overline{\frac{d\sigma}{d\Omega_n}} \right\} \left| \overline{\frac{\partial \omega}{k \partial cos\alpha}} \right|^{-1} \frac{1}{(2\pi)^2}$$

$$= \int_{\epsilon_-}^{\epsilon_+} d\epsilon \int_{k_{min}(q,\omega,\epsilon)}^{k_{max}(q,\omega,\epsilon)} S(k,\epsilon) k dk \qquad (04)$$

where y is the momentum solution of the total energy conservation equation evaluated at $\epsilon = \epsilon_{min}$ and $\cos\alpha = -1$. In other words y is the minimal momentum of the struck nucleon verifying the energy conservation of the process as follow;

$$\omega + M_A = (M^2 + q^2 + y^2 + 2yq)^{1/2} + (M_{A-1}^2 + k^2)^{1/2} \qquad (05)$$

where M_A and M_{A-1} are respectively the total mass of the initial and the recoil nucleus, k and q are the magnitudes of the nucleon and the virtual photon momenta, respectively.

It is important to notice that the phase space factor defined as $d\omega/dy$ in the early scaling analysis of ^{3}He is incorrect unless one uses West's definition of the scaling variable. The correct phase space factor needed, independently of the definition of the scaling variable used, is $|\overline{\partial\omega/k\partial\cos\alpha}|_{k=k_{min}}$. This factor arises naturally from the angular integration performed using the full energy conservation δ function.

The ^{3}He data in the quasi-elastic region have been reanalyzed in Refs. [6,7] showing almost the same scaling behavior of the data with a different shape of the scaling function compared to the early analysis due to the different phase space factor used. We want in this case to concentrate on the ^{4}He data obtained SLAC's new Nuclear Physics Facility. Inelastic cross sections have been measured at two energies and three angles covering a range of momentum transfer from 0.5 (GeV)^2 to 2.5 (GeV)^2. We have analyzed these new preliminary data combined with the previous data from Ref. [13] allowing to cover a range of longitudinal momentum y from 0.0 GeV/c to -0.8 (GeV/c). Fig. 1 shows the experimental results compared with a theoretical scaling function obtained using the following relation:

$$F(y) = \int_y^{\infty} n(k) k dk \qquad (06)$$

where $n(k)$ is a momentum distribution given in Ref. [14] generated by solving the Shrœdinger equation using the ATMS method.

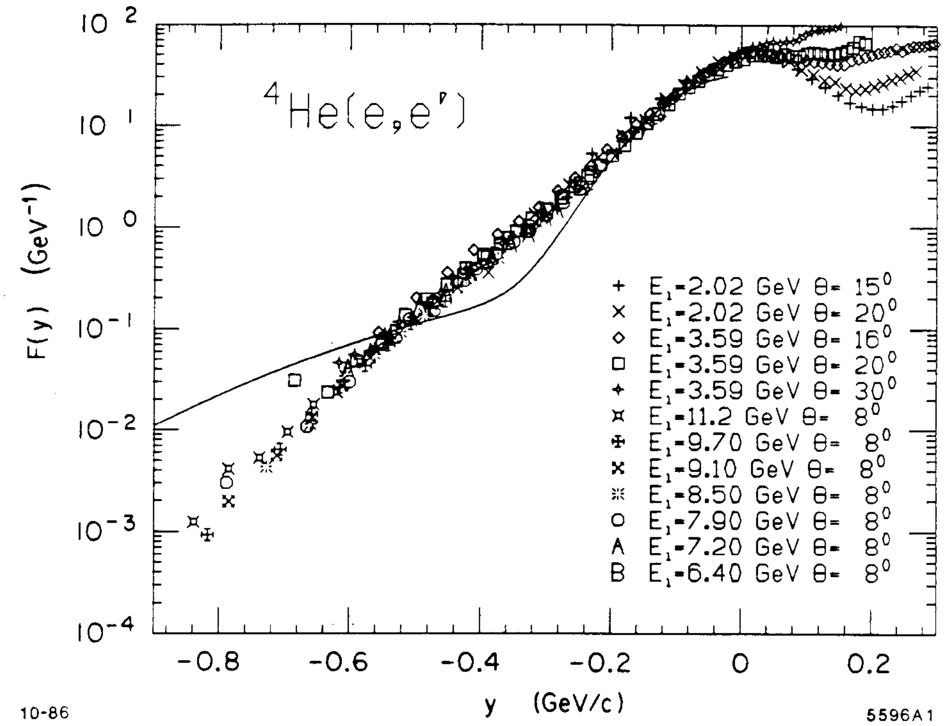

Fig. 1. Scaling function of ^{4}He obtained using (04) with data of Refs. [12,13] compared to theoretical scaling function obtained using (06).

We observe mainly the same features shown in the analysis of ^{3}He data from Ref.[7], namely that the theoretical calculation using no interaction in the final state overestimates the data $|y| > 0.25$ GeV/c, and we also notice a pronounced change of slope at that y value. On the contrary experimental data behave more like a straight line. From a detailed calculation by Laget [15] on ^{3}He we expect that final state interactions of the residual nucleus and the ejected nucleon to have both significant contribution. It is thus, very important not to draw quik conclusions about our understanding of the high nucleon momentum components. The reaction mechanism in a nucleus such as ^{4}He is complicated. One has to wait for a more complete four body calculations, in which the continuum solutions of the Bethe-Salpeter equation are provided to understand the region beyond $|y| >= 0.25$ GeV/c. However it is clear that in the region where the data and the theoretical curve give a unique answer, the dominant process is one-nucleon knockout ($|y| < 0.25$ GeV/c). In this region the PWIA works quite well and the momentum distribution can be extracted safely from the data. It is then a matter of preference performing exclusive $(e, e'p)$ or inclusive (e, e') experiments to access the momentum distribution in nuclei. Exclusive experiments are a powerful tool in these studies. However reaching the high component of the momentum distribution requires electron beam machines with high duty cycle factors.

TRANSVERSE AND LONGITUDINAL SCALING FUNCTIONS

One further step can be advanced in inclusive experiments, in studying either the momentum distribution or the electromagnetic properties of the nucleon in the nucleus, by expressing the equation (03) in such a way that the electric and magnetic contributions of the electron nucleon cross section are explicitely separated. If the electric and the magnetic parts of the resulting separated equation are compared with equation (1.1) we can obtain expressions of the scaling function F(y) in terms of the transverse and longitudinal response functions:

$$R_T(y) = \left|\frac{\partial\omega}{k\partial\cos\alpha}\right|^{-1} \frac{-q_n^2}{2E_kE_{k'}}\, \tilde{G}_M^2\, F_T(y) \tag{07}$$

$$\begin{aligned} R_L(Q,\omega) = &\left|\frac{\partial\omega}{k\partial\cos\alpha}\right|^{-1} \tilde{G}_E^2\, \frac{(E_k+E_{k'})}{4E_kE_{k'}(1+\tau)}\, F_L(y) \\ &- \frac{1}{2E_kE_{k'}}\left(q^2 - \frac{(E_k+E_{k'})^2}{2(1+\tau)}\right) \tilde{G}_M^2\, F_L(y) \end{aligned} \tag{08}$$

$$\tau = \left(1 + \frac{Q^2}{4M^2}\right)$$

where (E_k, k) and ($E_{k'}$, k') are respectively the energy-momentum of the struck and outgoing nucleons. $\tilde{G}_E^2$ and $\tilde{G}_M^2$ are the effective electric and magnetic form factors of the nucleus;

$$\begin{aligned} \tilde{G}_E^2 &= ZG_E^{p2} + NG_E^{n2} \\ \tilde{G}_M^2 &= ZG_M^{p2} + NG_M^{n2} \end{aligned} \tag{09}$$

and

$$q_n^2 = (E_K - E_{K'})^2 - (K - K')^2 \ .$$

We want to emphasize that besides the PWIA no further approximations are needed to obtain the relations (07),(08). This consequently imposes the following relation:

$$F_L(y) = F_T(y) = F(y)$$

This relation can be checked experimentally if one has data of the transverse and longitudinal response functions obtained by the Rosenbluth technique. These separated response functions are not available in the region of high momentum transfer. However, if one restricts the range of momentum transfers from .2 (GeV/c)^2 to .5 (GeV)^2 the results of the existing data analyzed following (07) (08) show an interesting behavior. Fig. 2 shows the extracted longitudinal F_L(y) and transverse $F_T(y)$ scaling functions from the data of ^3He according to Ref. [17] It is suprising to see that these two functions are different but tend to converge to the same value at q=0.5 (GeV/c). These results show that the impulse approximation is not valid for this nucleus at transfers lower than about 0.5 (GeV/c). As an example, a heavier nucleus [18] (^{12}C) has been analyzed

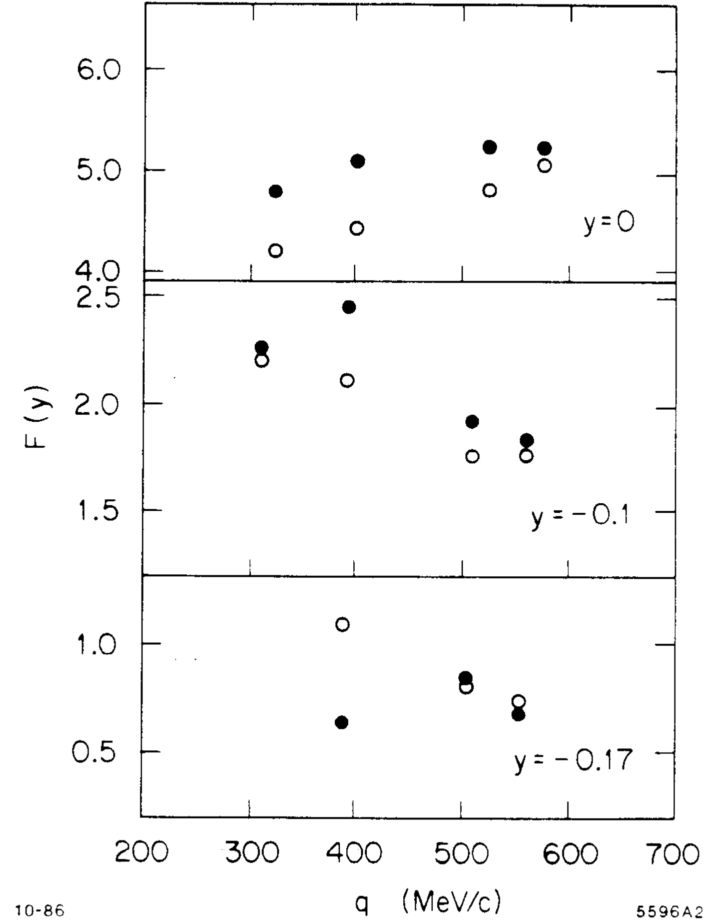

Fig. 2. Separated transverse $F_T(q,y)$ (triangles) and longitudinal $F_L(q,y)$ (circles) extracted from ^3He data of Ref. [16] using formulae (7,8).

the same way and the result are shown in Fig. 3. The situation in this case is more critical, since the scaling regime seems to be reached around 0.5 (GeV/c) in momentum transfer; however, no convergence of the two scaling functions is observed.

At this stage it is important to notice that if one assumes that the free nucleon form factors that we have used in the analysis are correct, then this result is an obvious breakdown of the impulse approximation. However the separate scaling behavior of each function is disturbing and can lead to the following question: Could a modification of the nucleon electromagnetic form factors lead to a convergence of these functions and maintain their scaling behavior? The answer to this question is yes. As suggested by Mulders for ^{12}C in Ref. [19] if one modifies the electric nd magnetic form factors as follow:

$$G_E^\star = \left(1. + \frac{Q^2}{0.54(GeV/c)^2}\right)^{-2}$$

$$G_M^\star = \mu^\star_{p,(n)}\left(1. + \frac{Q^2}{0.69(GeV/c)^2}\right)^{-2} \qquad (010)$$

$$\mu^\star_{p,(n)} = 1.12\ \mu_{p,(n)}$$

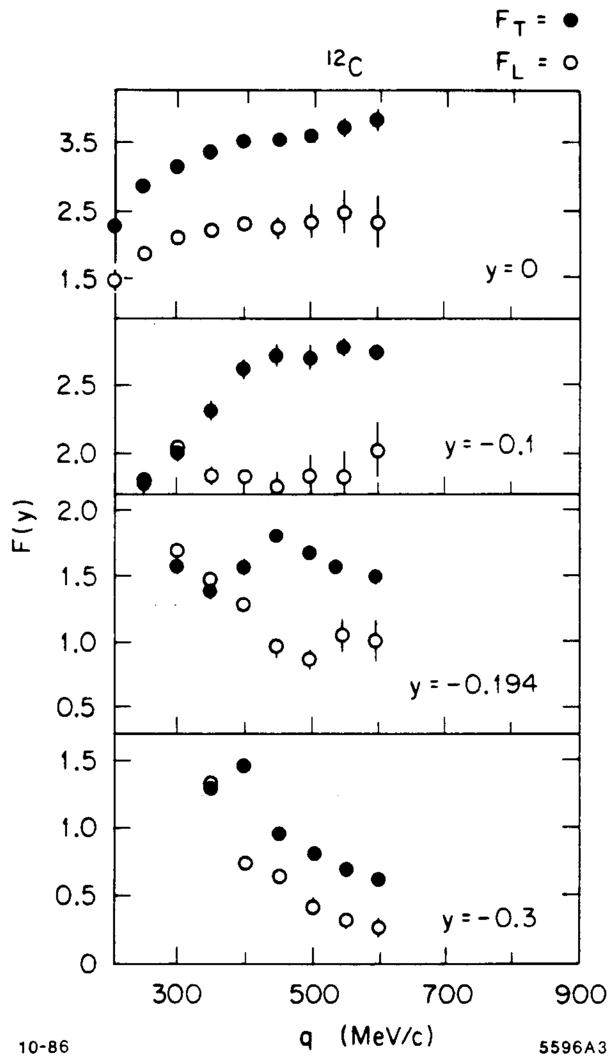

Fig. 3. Same as Fig. 2, but for ^{12}C data from Ref. [18].

the overlap of the two scaling functions can be obtained. One cannot make the same statement about ^{3}He since the effect seems to be density dependent, it must be small in this nucleus. However it is important to know this that behavior is pronounced in ^{4}He compared to ^{3}He since the former is strongly bound. These issues can be studied as soon as separated response functions data become availaible for ^{4}He at high momentum transfers.

We do not recommend to study this problem as suggested in Ref. [9] using the scaling behavior of the total response function without performing the separation, the main reason being that at high momentum transfer the total response function is dominated by its transverse part. By examining the suggested modification of the nucleon form factors for ^{12}C (equation 010) one can clearly see that no change in the momentum dependence of the magnetic form factor is needed to explain the observed difference between the transverse and longitudinal scaling functions. In this case the total response function at high momentum transfer will always display scaling behavior. We illustrate this statement in Fig. 4 by showing the scaling function obtained using modified electromagnetic form factors following relation (010). It is evident that no change is

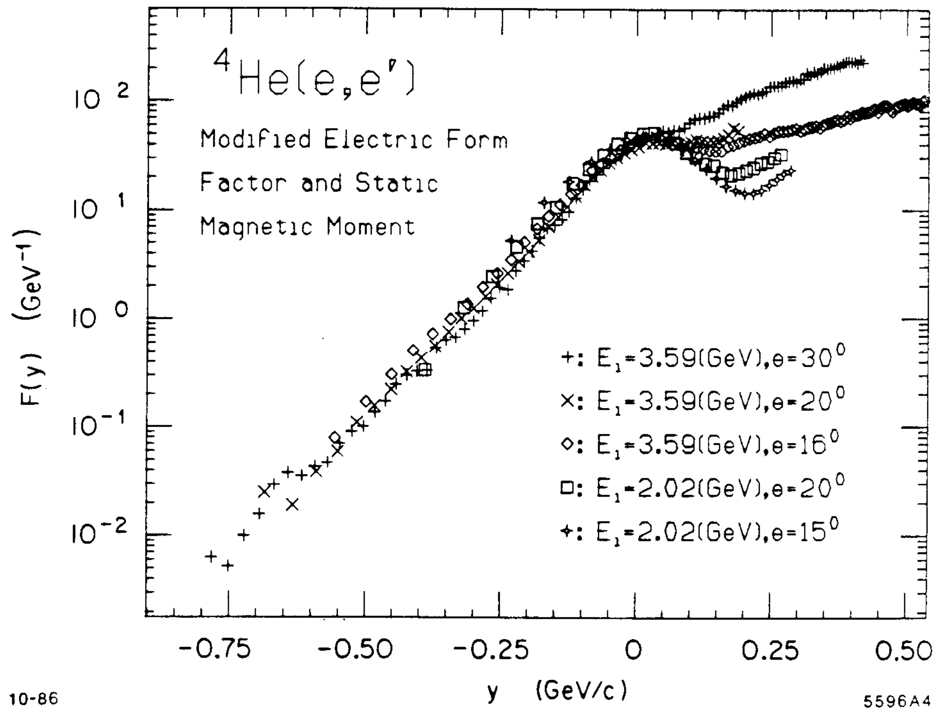

Fig. 4. Scaling function of ^{4}He obtained using the suggested modified nucleon electromagnetic form factors. The data are preliminary data of Ref. [12]. This scaling function is to be compared to the one of Fig. 1.

observed in the quality of the scaling if one compare this result to Fig. 1 where the free electromagnetic form factors hve been used. It is thus very important to understand that the best way to study the modification of the electromagnetic form factors is by performing first the separation of the electric and magnetic components in the total cross section then analysing the data using relations (07),(08).

A new experiment (NE-9) is planned at the Nuclear Physics Injector at SLAC to perform the separations of the two response functions R_L and R_T for ^{3}He,^{4}He and ^{56}Fe around $Q^2 = 1$ (GeV/c)^2. Our aim for this experiment is to have a comparative study between few body (calculable) and many body systems in order to examine in a powerfull way the different issues discussed.

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