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STUDYING SHORT-RANGE DYNAMICS IN FEW-BODY SYSTEMS

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I present the case for studying the nature of short-range internucleon interactions with electron-scattering experiments on few-body nuclear targets. I first review what electron-scattering studies have unearthed about the nature of the interactions between nucleons in nuclei at small separation. Special consideration is given to a couple of recent experiments. The results essentially serve to construct a roadmap for future studies in this area. The related experimental program at Jefferson Lab is presented, along with suggestions for future theoretical work.

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1. Introduction

The most important length scale characterizing nuclei is roughly $\hbar/m_\pi c$ [1]. This is no accident, since exchange of pions is responsible for the most important part of the interaction between nucleons. There is another important length scale, but it is normally less apparent than the first. This scale is the nucleon radius, and it is important since nucleons are observed to repel each other strongly when their separation becomes less than 1 fm. It is not normally so apparent since the classical nuclear-physics literature is usually expressed in terms of the independent-particle model, which itself can be derived via Hartree-Fock type calculations using effective interactions. These interactions, however, have to be generated by a procedure which takes the strong short-range interaction into account. Thus in a real sense, those interactions are essentially responsible for the observed properties of nuclei.

The internucleon interaction at a length scale of $\hbar/m_\pi c$ is well understood in terms of the exchange of physical mesons. At shorter range, this interaction is phenomenological. This presumably reflects a breakdown of the meson-exchange picture at small separations, and our inability to carry out QCD calculations at low energies. It is interesting to measure this important component of the internucleon interaction, as we expect it will tell us something about how nuclear interactions evolve from mesonic to chromodynamic degrees of freedom.

2. The case for few-body systems

Intermediate-energy electron scattering is the tool most suited to mapping the properties of individual nucleons in a nuclear medium [2–5]. For heavier systems, theoretical calculations must use techniques which build the anticorrelation between nucleon locations, due to the short-range repulsion, into the strength of the interaction. The advantage of using a few-body system for the target is that the NN interaction is directly used for the computation of the wave functions. For $A = 3$ systems, Faddeev techniques allow a direct computation of the spectral function [6], and for heavier light nuclei, the technique of integral transforms [7] can be used to construct the spectral function. The spectral function $S(E_m, p_m)$ is closely related to the electron-scattering cross section and provides a probability distribution of nuclear protons versus their momentum p_m and binding energy E_m.

3. Results from inclusive electron scattering

At intermediate energies and quasifree kinematics, many inclusive (e,e') experiments have been performed. Plane-wave reasoning suggests that at large $Q^2 = -q^2$, the (e,e') cross section should become a function of only two factors. The first is the incoherent cross section to scatter electrons from all the nucleons in the nucleus, and the second is a partial integral over the proton spectral function [8]:

$$F(y) \equiv 2\pi \int_{E_m^0}^{\infty} \mathrm{d}E_m \int_{p_m^0(y,E)}^{\infty} S(E_m, p_m) p_m \mathrm{d}p_m$$

("partial integral" refers to the nonzero lower limit on the p_m integral). y is essentially the component of the struck proton's momentum along the (e,e') momentum transfer $\vec{q}$; it is also closely related to the deviation of $\omega = E_e - E_{e'}$ from the quasielastic value $\omega \approx |\vec{q}|^2/2m_{\mathrm{N}}$.

Figure 1 shows the most recent (e,e') data from Jefferson Lab [9]. $F(y)$ is constructed as

$$F(y) = \frac{\mathrm{d}^2\sigma}{\mathrm{d}\Omega \mathrm{d}\omega} [Z\sigma_{\mathrm{ep}} + N\sigma_{\mathrm{en}}]^{-1} \frac{q}{(M^2 + (y+q)^2)^{\frac{1}{2}}} \,. \quad (1)$$

For $y < 0$ (low ω relative to the quasielastic peak), data for different kinematics are in excellent agreement, indicating that the effects beyond PWIA are small.

In studying short-range phenomena, access to specific regions in $S(E_m, p_m)$ is desirable, so data on $F(y)$ are not sufficient. Coincidence data are required to access these regions. However, there is one further inclusive measurement of interest, namely that of the Coulomb Sum Rule. This sum rule relates the energy-integrated longitudinal response from (e,e') to the proton-proton correlation function [10]. However, analyses [11] have so far been inconclusive due to large theoretical corrections for reaction effects (e.g. meson-exchange currents (MEC)) and for incomplete ω coverage in the experiments [12].

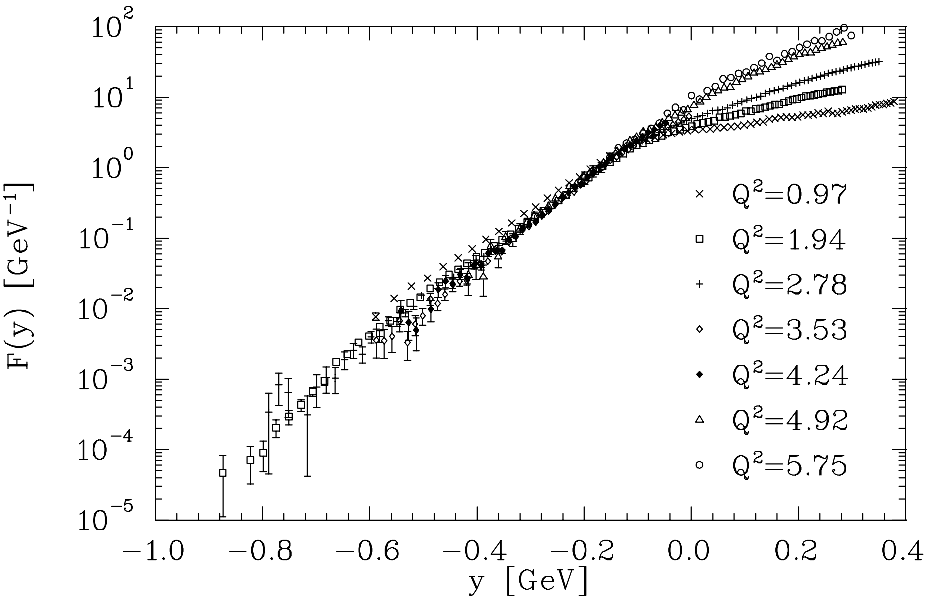

Fig. 1. Scaling function derived from Jefferson Lab (e,e') *data.*

4. Coincidence (e,e'p) *experiments*

Coincidence (e,e'p) experiments can in principle more directly probe the spectral function $S(E_m, p_m)$. In plane wave, the cross section is

$$\frac{\mathrm{d}^6\sigma}{\mathrm{d}\Omega_{e'}\mathrm{d}E_{e'}\mathrm{d}\Omega_p\mathrm{d}E_p} = |\vec{p}_p| E_p \sigma_{ep} S(E_m, p_m) \qquad (2)$$

and an extraction of the spectral function is unambiguous. The variables E_m and p_m are computed by using the measured four-momenta of the incident electrons, scattered electrons and knocked-out protons to reconstruct the four-momentum of the residual $(A-1)$ system $R = (E_R, \vec{p}_R)$. $p_m = |\vec{p}_R|$ and $E_m = \sqrt{R^2} + m_p - M_A$. However, additional reaction-mechanism effects can break the direct link between the cross section and spectral function.

Figure 2 shows data measured at NIKHEF [13] for the reaction $^4\mathrm{He}(\mathrm{e},\mathrm{e}'\mathrm{p})^3\mathrm{H}$. The dotted curve is the plane-wave prediction, and the sharp minimum is a feature of the spectral function which has been directly linked to the short-range part of the NN interaction [14]. The data do not exhibit this minimum, and the calculation attributes this discrepancy to *p–t* final-state interactions (FSI) and to MEC.

Another example of reaction effects thwarting access to interesting information comes from the large-E_m data from the same experiment. Simple arguments lead to the prediction [15–17] of a "ridge" in the spectral function, due to short-range

NN interactions, along the locus $E_m \sim 2S_\mathrm{N} + (p_m)^2/2m_\mathrm{N}$ where S_N is the single-nucleon separation energy. Computations of the spectral function have supported

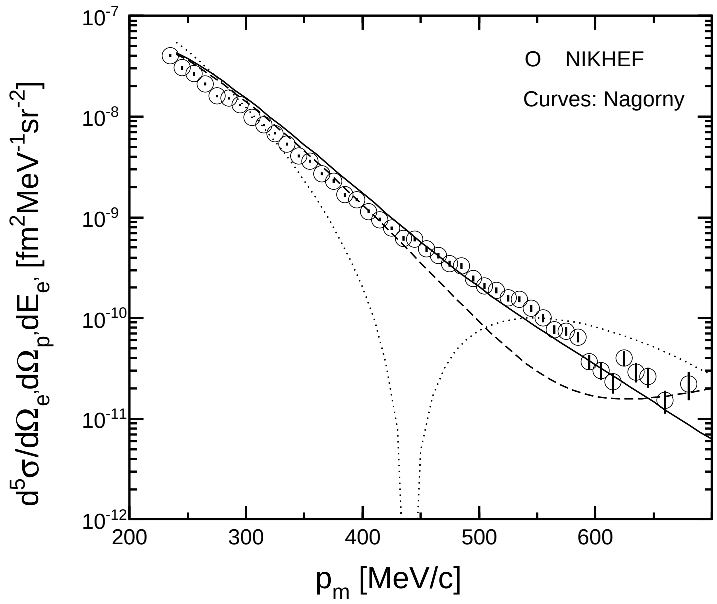

Fig. 2. $^4\mathrm{He(e,e'p)}^3\mathrm{H}$ *cross section measured at NIKHEF. The dotted curve is a PWIA calculation, and the other two curves include various classes of additional reaction effects.*

this prediction, and evidence for this ridge structure has been observed in few-body systems [18].

Figure 3 shows data for $^4\mathrm{He(e,e'p)}$ at large E_m [19] along with theoretical predictions. The peak in the cross section (for both the data and the curves) follows the ridge relation noted above. However, the theory indicates that only about half of the observed cross section is due to direct knockout (dashed line). The rest is due to MEC. Also, for the lowest-p_m data (the top panel), the calculation severely underpredicts the data at large E_m.

5. The few-body program at Jefferson Lab

The preceding discussion makes clear that accessing the spectral function in regions of (E_m, p_m) relevant to short-range nuclear dynamics is difficult. The problem is that the spectral function is relatively much smaller in these regions than at lower momenta and energies. This leads to the possibility that other reaction processes, even if weak, can substantially contaminate the data.

Many ideas have been formulated about how to suppress these contaminant processes in experiments. These ideas were difficult to implement in experiments at labs such as NIKHEF and Mainz, mainly because their beam energies were too low to provide the necessary kinematic flexibility. I now discuss some of these ideas and how they are being implemented at Jefferson Lab.

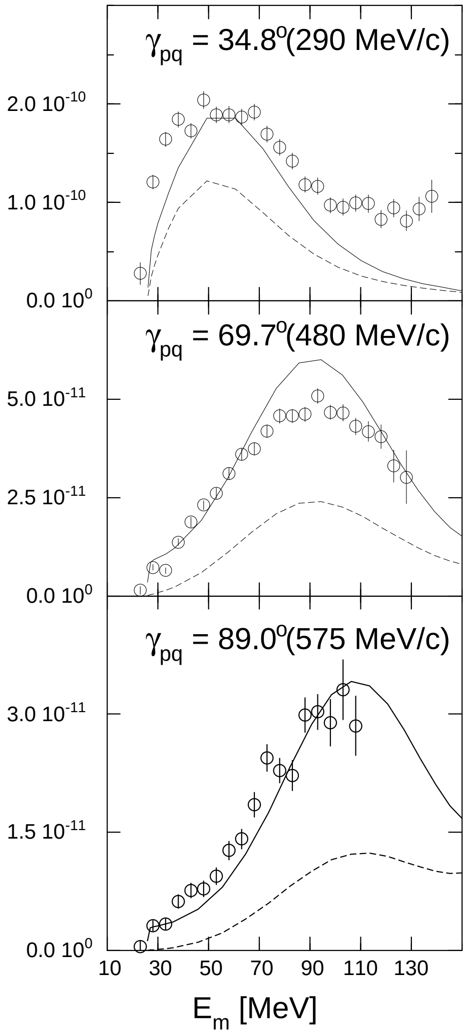

Fig. 3. Large-E_m data for ^{4}He(e,e'p) *from NIKHEF. The mean p_m for each panel is indicated.*

5.1. Parallel kinematics

Figure 4 depicts how measurements (including those of Refs. 13 and 19) of cross sections at large p_m were previously made. The simultaneous constraints on ω, q, and p_m made it impossible to reach large p_m values unless the knocked-out protons were detected at large angles with respect to $\vec{q}$. Elastic FSI can seriously distort measurements in this type of measurement, since at the same electron kinematics, reactions such as that at left in Fig. 4 are also possible. The associated spectral function is several orders of magnitude larger due to the lower p_m involved. Such low-p_m protons can rescatter through large angles and contribute to (and perhaps even dominate) the large-p_m cross section. This qualitative argument is supported by calculations [20] which show that for experiments in the kinematic domain appropriate at Jefferson Lab, FSI contributions are at a minimum in parallel kinematics.

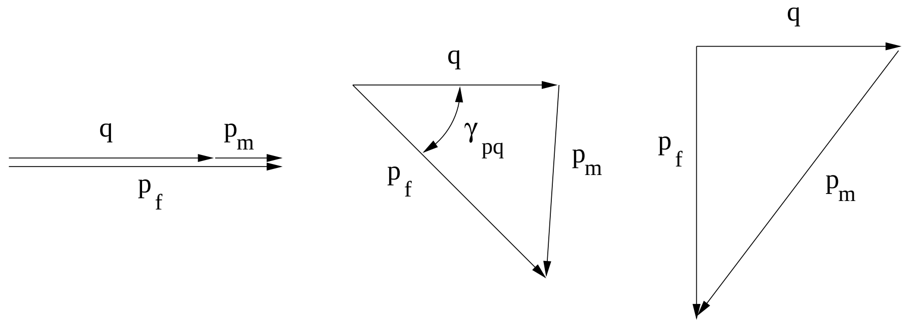

Fig. 4. Various values of p_m for fixed $(\omega, \vec{q})$.

The large beam energies available at Jefferson Lab make it possible to perform large-p_m experiments at parallel kinematics, and several proposals utilizing this principle [21–23] are already in the books.

5.2. Variation of Q^2

Experiments at lower-energy labs were not able to make substantial variations in Q^2 for a given (E_m, p_m) region. Q^2 variations are useful in two respects: to help discriminate between one- and two-body currents contributing to the cross section; and to suppress the contaminant (two-body) currents. The one-body direct-knockout process of interest only depends on Q^2 through the electron-proton cross section, while MEC and IC contributions are expected to have a very different Q^2 behaviour. There is no general agreement about whether larger or smaller Q^2 experiments are better for suppressing the two-body currents. All of the experiments studying short-range dynamics at Jefferson Lab plan to make measurements at multiple values of Q^2.

5.3. Large negative y values

In Fig. 1, the data clearly violate the scaling hypothesis for $y > 0$. This is generally accepted to result from contributions outside the one-body impulse-approximation framework. At negative values of y, the data scale well. In addition, theoretical studies [20] have indicated that FSI are best suppressed when the ejected proton's longitudinal (along $\vec{q}$) component is large and negative; this condition also yields a large, negative y value. I should mention that these studies indicate that FSI are also suppressed when the longitudinal momentum is large and positive, but it is unclear how this condition constrains two-body currents. Two experiments in Hall A at Jefferson Lab [22,23] plan to make measurements at large negative y kinematics.

5.4. *Suppression of multistep FSI*

Ingo Sick has pointed out [21] an additional mechanism which contaminates (e,e'p) measurements at large E_m. Multistep FSI, or p − N scattering within the nucleus, change both the energy and direction of knocked-out protons. This causes the proton to be detected with (E_m, p_m) values much different than those at the (e,e'p) reaction vertex. If these FSI "move" events from a region where the spectral function is large to a region where it is low, these "moved" events can generate cross sections larger than the "native" protons at this (E_m, p_m) which did not undergo multistep FSI.

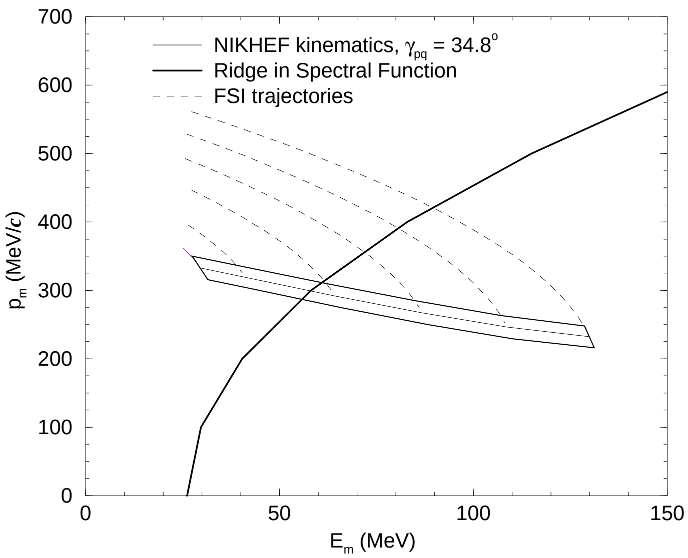

Fig. 5. FSI trajectories for NIKHEF large-E_m data.

Figure 5 shows the kinematics in the (E_m, p_m) plane for the upper panel of Fig. 3. The dark line shows the "ridge" in the spectral function where the greatest strength is expected. The dashed lines show how multistep FSI move events in the (E_m, p_m) plane; reactions with vertex (E_m, p_m) values all along the dashed lines can contribute, by undergoing a (p,p'N) reaction, to the experimental measurement (the box is the experimental acceptance, and the thin solid line gives the central kinematics for which these calculations were performed.) It is clear that for missing energies greater than about 65 MeV, one may expect increasing contributions from multistep FSI to the data. This is a plausible explanation for the calculation's underprediction of the data for $E_m > 90$ MeV.

An approved experiment [21] in Hall C will make measurements on both sides of the "ridge" and in several different types of kinematics, to test whether this effect is indeed important. If the argument is correct, the data on the high-p_m side of the ridge will access the correlated part of the spectral function free from contamination by this multistep effect.

6. *Representative expected results at Jefferson Lab*

Figure 6 shows an example of what we hope to achieve at Jefferson Lab. This figure is a calculation for $^4\mathrm{He(e, e'p)}^3\mathrm{H}$ at a beam energy of 4 GeV. Experiment [23] in Hall A proposes to measure this reaction in an attempt to observe the spectral-function minimum discussed in relation to Fig. 2. The dashed lines in Fig. 6 are plane-wave calculations; the solid curves include FSI in the framework of the generalized eikonal approximation [20]. The upper curve corresponds to $y \approx 100$ MeV/c, and the bottom curve corresponds to $y \approx 400$ MeV/c. The bottom curve is also computed for parallel kinematics. The calculations display the expected reduction in FSI due to parallel kinematics and large $-y$ values. Unfortunately, these calculations do not yet include two-body current contributions.

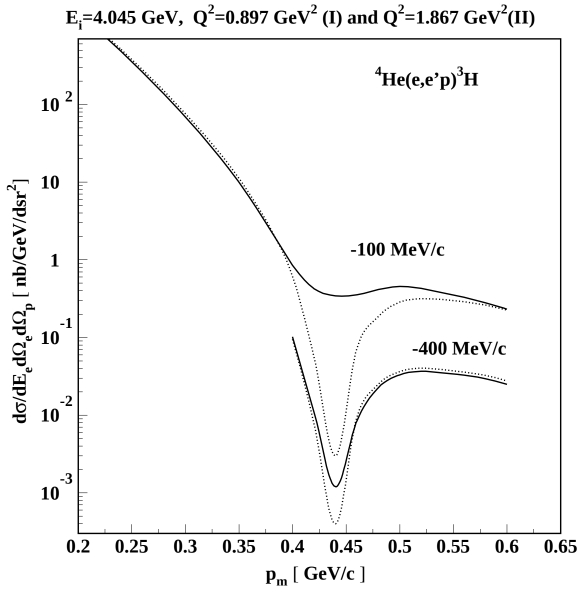

Fig. 6. Expected results for experiment 97-111 in Hall A.

7. *Outlook*

A broad program exists to study (e,e'p) reactions, with an emphasis on few-body nuclei, at Jefferson Lab. The experiments comprising this program have a new set of tools, courtesy of the large JLab beam energy, with which to (attempt to) force nature to give us clean information about the nuclear spectral function in regions relevant to short-range nuclear dynamics. Parallel kinematics will be an important feature of almost all these experiments. Furthermore, data will be taken at a variety of Q^2 and y settings in an attempt to suppress two-body current contributions to a manageable level.

I have not mentioned two other powerful techniques which will be exploited at Jefferson Lab and elsewhere: response-function separations and multi-nucleon knockout experiments. Both techniques are in principle more selective for accessing the large-momentum one-body current of interest. However, both are experimentally more demanding, thus the program outlined above provides a better starting point for testing our understanding of the (e,e'p) reaction mechanism at high energies. The results can be used to design more effective response-function separation or multinucleon-knockout experiments.

On the theoretical side, there are many nice frameworks, models and techniques in circulation for computing spectral functions exactly, treating two-body currents, computing FSI at large proton momenta, and so on. However, no one group seems to have all "nice" ingredients. Figure 6 provides a good example; it uses a state-of-the-art spectral function from the Argonne group, and a modern FSI computation, but no two-body currents are included. It is highly unlikely that the program outlined above will suppress reaction effects to the point that PWIA is valid; interpretation of these results will require close collaboration with our theoretical colleagues.

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PROUČAVANJE KRATKODOSEŽNE DINAMIKE U MALOČESTIČNIM SUSTAVIMA

Izlaže se važnost proučavanja kratkodosežnih međunukleonskih sila mjerenjem elektronskog raspršenja u maločestičnim jezgrama. Prvo se raspravlja što su otkrila mjerenja elektronskog raspršenja o prirodi sila među nukleonima u jezgrama na malim udaljenostima. Posebna se pažnja daje dvama nedavnim mjerenjima. Rezultati služe kao putokaz budućim proučavanjima. Opisuje se odgovarajući program u Jeffersonovom laboratoriju i predlaže budući teorijski rad.