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# LOOKING AT CLOSE NUCLEONS IN NUCLEI WITH HIGH–ENERGY PROBES

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Recently, we measured the reaction $^{12}$C(p,2p+n) and studied the correlation between the momenta of the struck target proton and the backward recoil neutron. We intend to continue this line of research and to measure the C(e,e'p+N) reaction at TJNAF (approved experiment E97-106). Two permanent magnetic spectrometers will be used to measure the (e,e'p) part of the reaction. We plan to add a third arm, consisting of a series of scintillation counters, to measure neutrons and protons in coincidence with the outgoing high momentum electron and proton. We choose kinematical conditions that will allow us to determine the fraction of (e,e'p) events which are associated with NN short-range correlations, as a function of the momentum of the proton in the nucleus. It will also allow us to compare between pn and pp correlated pairs in nuclei.

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## 1. Introduction

The importance of nucleon-nucleon correlations has been recognized for many years [1]. In recent years, much attention has been paid to the role that two-nucleon correlations play in nuclei. Large high-momentum tails in the nuclear spectral function were calculated with realistic potentials of two-and three-body interactions. A significant probability of NN correlations was predicted for light nuclei [2] for nuclear matter [3] and for an interpolation between them [4]. The field has been reviewed recently by Pandharipande et al. [5].

We will mention some experiments that addressed this issue. We will classify them by order of complexity, and by the kinematical parameters of the measurement. There are inclusive (e,e') experiments [6] at high-momentum transfers and $x > 1$. They obtained the momentum distribution of the nucleons in the nucleus in terms of the $y$-scaling variable. Relatively large high-momentum tails are observed. Theoretical models try to explain this by invoking short-range correlations (SRC) [7]. Others [8] explained the results in terms of final-state interactions (FSI).

There are (e,e') measurements in the "dip" region, between the quasi-elastic (QE) peak and the delta region, at $x \leq 1$ which show an anomalously large transverse cross section. This has been cited as evidence for NN correlations (Refs. 9 and 10, and references in Ref. 10).

In the next order of complexity, we mention the semi-exclusive (e,ep) experiments at small values of $Q^2$ and $x \leq 1$ [11]. One observes a depletion of spectroscopic strength which may be explained by nuclear correlations which push the nucleons to higher momentum states and high missing energies and are thus not visible at low momenta and low excitation energies [10]. The depletion can be as large as 35% [5]. Other (e,e'p) experiments [12], also at $x < 1$, show peaks at missing energies corresponding to the removal of two nucleons. There are two-nucleon knockout reactions (e,ed), (e,epp) and (e,epn) [13] and real photon absorption ($\gamma$,2N) [14]. In the above experiments, the knocked out proton was detected in the forward direction relative to the photon momentum.

There are measurements of backward scattered protons from a variety of projectiles [15] as well as (e,e'p) experiments at $x \leq 1$ [16] and deep inelastic ($\nu$,$\mu$p) [17] scattering where backward going protons were observed in coincidence with a forward going particle, electron and muon, respectively. Correlations were claimed between the transferred energy and the momenta of the backward going protons. There is also evidence from pion absorption experiments [18] which have to take place on (at least) a couple of nucleons.

Last but not least, we mention the reaction C(p,2p+n) that was measured by us at beam momenta of 5.9 and 7.5 (GeV/$c$)$^2$ [19]. We established the quasi-elastic character of the reaction in a kinematically complete measurement [20]. The neutron momentum was measured in triple coincidence with the two emerging high-energy protons. We found a correlation between the momenta of the neutron and the struck target proton. The events were associated with the high-momentum components of the nuclear wave function.

## 2. Proposed measurement at TJNAF

Based on our results from the (p,2p+n) reaction, we are encouraged to embark on a similar project with the electron probe. *Hopefully, with those measurements, together with the data we wish to collect at TJNAF, we will be able to establish a unified description of SRC in nuclei.*

In many aspects, the electron-nucleus interaction is better understood than the nucleon-nucleus interaction. The proposed experiment will be significantly more precise in determining the quasi-elastic nature of the reaction and will have much better statistics than the experiment at BNL. There are several excellent setups at the laboratory for measuring (e,e'p) scattering. For our main effort, we plan to add a third arm consisting of a series of counters to measure neutrons and protons in coincidence with the outgoing high-momentum electron and proton. Just as for the (p,2p+n) reaction, we will measure the full kinematics of the (e,e'p) reaction, but with much higher accuracy made possible by the TJNAF facilities. We can then extract the momentum of the struck proton. We will also measure the momentum and direction of an additional neutron or proton in coincidence with the outgoing e and p. *This will allow us to measure the fraction of* (e,e'p) *events in which NN correlated nucleons are observed, as a function of the initial momentum of the proton in the nucleus. It will also allow us to compare between* pn *and* pp *correlated pairs in nuclei.* We could not measure that ratio in the (p,2p+p) experiment because the targets were too thick and the low energy proton would loose a large amount of energy on its way out.

We will choose kinematical setups that select scattering from protons above the Fermi sea ($p_m > k_F$). We will use electron beams of 4 GeV (and above, if available), large momentum transfers in the region of $Q^2 = 2-3$ (GeV/$c$)$^2$ and missing energy in the region of $E_m = p_m^2/2m$. These conditions will minimize the contributions from FSI and meson exchange currents (MEC).

Why measure both neutrons and protons in the third arm? It is clear that one of the real exciting aspects of studying NN SRC is to understand it's isospin dependence. There are data on ($\gamma$,pp) and ($\gamma$,pn) [14] and the ratio between the two cross sections. However, the measurements with real photons measure only the transverse amplitudes, whereas with virtual photons one can study the longitudinal amplitude as well (depending on the electron scattering angle). Also, FSI may play a significant role in those data. *Thus, the ratio between the SRC* np *and* pp *pair contributions is not well known and is one of the expected outcomes of the proposed measurement.*

## 3. *Description of the* (e,ep+N) *reaction*

The cross section for the reaction when a proton is knocked out of the nucleus and a spectator nucleon in the final state is detected in coincidence with the scattered electron and proton, can be represented within the plane-wave impulse approximation, as follows:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}E'\mathrm{d}\Omega_e \mathrm{d}^3(p_f/E_f)(\mathrm{d}^3 p_s/Es)} = K_\mathrm{d}\sigma_{ep}(Q^2,\epsilon,E_m,p_m)\cdot D(E_m,\vec{p}_m,\vec{p}_s). \qquad (1)$$

The decay function $D$ represents the joint probability to find inside the nucleus a nucleon with missing momentum $p_m$ and missing energy $E_m$ and where the residual nuclear state contains the spectator nucleon with momentum $\vec{p}_s$. Any four-momentum $k$ can be represented as $k \equiv k(k_+, k_-, k_t)$ where $k_\pm = k_0 \pm k_z$, and the $z$ and $t$ components are defined along the direction and perpendicular to the direction of the transfered momentum (virtual photon momentum) $\vec{q}$, respectively.

Using the above definitions, we introduce the light-cone components of the missing momenta as $p_{m+} \equiv p_{f+} - q_+ = m - E_m + p_{mz}$ and $p_{m-} = p_{f-} - q_- = m - E_m - p_{mz}$. With the light-cone momenta $p_{m\pm}, p_{s\pm}$ representation, we write:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}E'\mathrm{d}\Omega_e \mathrm{d}^3(p_f/E_f)(\mathrm{d}^3 p_s/Es)} = K_\mathrm{d}\sigma_{ep}(Q^2, \epsilon, p_{m+}, p_{m-}) \cdot D(p_{m+}, p_{m-}, \vec{p}_{mt}, p_{s-}, \vec{p}_{st}). \tag{2}$$

where $K_d$ is the kinematic factor, $\epsilon = [1 + 2(q^2/Q^2)\tan^2(\theta_e/2)]^{-1}$ and $\sigma_{ep}$ describes the electron scattering on an off-shell proton.

The decay function is related to the spectral function of (e,e'p) reaction in the following way:

$$\int D(E_m, \vec{p}_m, \vec{p}_s)\mathrm{d}^3 p_s = S(E_m, \vec{p}_m) \tag{3}$$

or

$$\int D(p_{m+}, p_{m-}, \vec{p}_{mt}, p_{s-}, \vec{p}_{st})\mathrm{d}^2 p_{st}\mathrm{d}p_{s-} = S(p_{m+}, p_{m-}, \vec{p}_{mt}) \,. \tag{4}$$

The decay function defines the quantities which can be studied experimentally by a triple coincidence measurement.

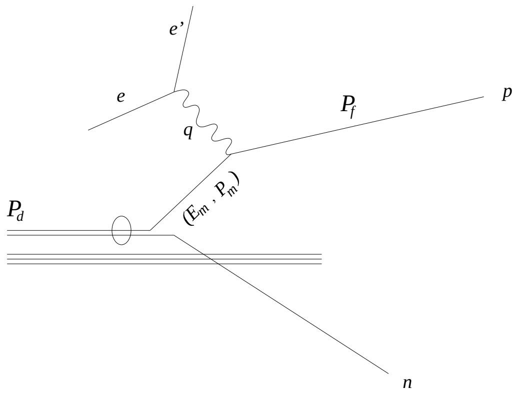


*Fig. 1. Diagram for the quasi-elastic breakup reaction of a pair at rest in the nucleus. The kinematical variables are defined in the text.*

Figure 1 shows the dominant process we wish to look for and defines the kinematical variables. We discuss the quasi-free break-up reaction of the pair at rest and we denote the pair, at rest in the nucleus, as d (deuteron):

$$\mathrm{e} + \mathrm{d} \rightarrow \mathrm{e'} + \mathrm{p} + \mathrm{n} \,. \tag{5}$$

The kinematical conditions of the quasi-elastic reaction sets:

$$(q + p_d - p_f)^2 = m^2 \,, \tag{6}$$

where $q = (q_0, \vec{q})$, $p_d = (m_d, \vec{0})$ and $p_f = (E_f, \vec{p}_f)$ are the four-momenta of the transfered momentum, the target pair and the detected final nucleon, respectively. From the (e,e') information, we determine the missing momentum as $\vec{p}_m = \vec{p}_f - \vec{q}$ and the missing energy as $E_m = q_0 - (E_f - m)$. From Eq. (6), we obtain the following relation between missing momentum and energy:

$$E_m = \sqrt{m^2 + p_m^2} + m - m_D \approx \frac{p_m^2}{2m} \,. \tag{7}$$

Thus in the breakup of a pair, there is a strong correlation between the measured missing momentum $p_m$ and the missing energy $E_m$.

In terms of the decay function, we concentrate on:

$$D(E_m = p_m^2/2m, p_m > k_F, \vec{p}_s = -\vec{p}_m) \,. \tag{8}$$

## 4. *Suppression of competing events*

The interpretation of existing low-energy electron-scattering data in terms of SRC has been plagued by contributions from meson exchange currents and final-state interactions whose importance depends on the transfered momentum and kinematical conditions. We choose the kinematics that minimize these effects. We discuss the relation of high-momentum transfer to FSI effects and the conditions for which the FSI are well understood. In addition, the use of light-cone kinematical variables will be introduced which facilitates the conservation of variables which are important for the extraction of the initial momentum of the correlated nucleon pair. In this section, we also discuss in detail the competing effects which can mask the SRC signal and how we intend to deal with them.

Final state interactions (FSI) can mimic NN SRC event. This can happen if one of the outgoing protons scatters elastically from a neutron in the same nucleus at an angle such that the recoil neutron enters the neutron counters. In this case, the actual momentum ($\tilde{p}_m$) that the proton had before scattering from the electron is not what we are measuring $\vec{p}_m = \vec{p}_f - \vec{q}$. As a result, one cannot be certain that the condition $p_m \geq k_F$, really probes the high-momentum components in the nuclear ground state wave function. It will also smear the correlation between the neutron and the target proton momenta.

An important feature of the kinematics we are considering (large $Q^2$, $p_f \geq 1$ GeV/$c$) is the applicability of the eikonal appoximation for the rescattering. It means that small-angle rescattering of GeV nucleons causes mainly transfer of momentum in the plane transverse to the direction of their high momentum (see Ref. 23). This allows us to control, to some extent, the amount of FSI by selecting the angle between the target proton momentum and the incident virtual photon $\vec{q}$.

The best geometry for the suppression of FSI would be the parallel kinematics (see Fig. 2c). The large $p_m$ and large $q$ combine to a very large $p_f$ which cannot be mimicked by FSI. Unfortunately, this geometry has some disadvantage. The large $p_m$ and large $q$ create a low $x$ which entails contamination from resonance production.

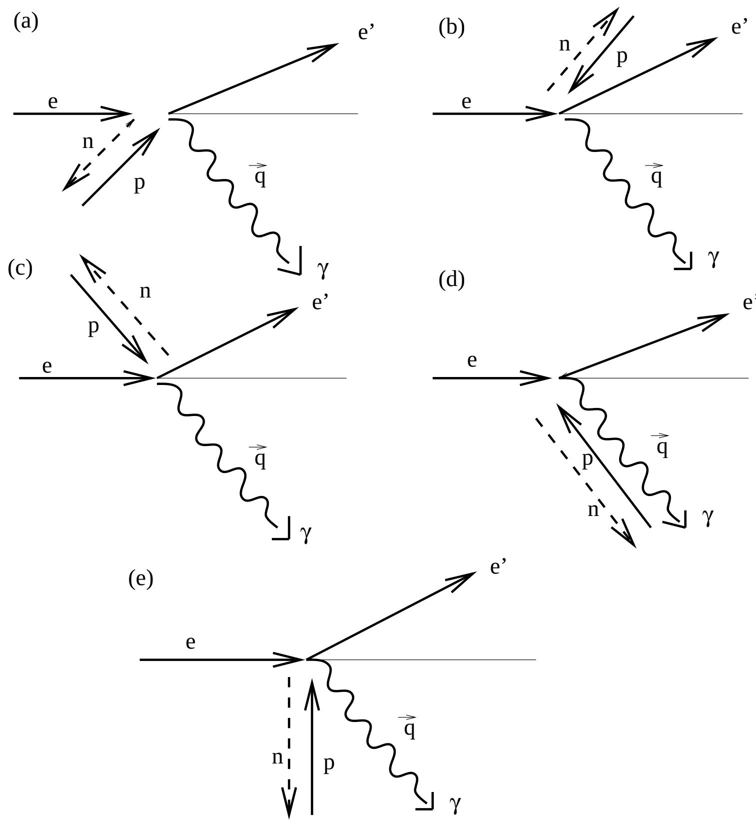


*Fig. 2 Relative geometry between the target proton momentum and the incident virtual photon momentum $\vec{q}$. a,b - perpendicular, c - parallel, d - antiparallel, e - 'almost anti-parallel'.*

In view of the above, we chose kinematics which we call 'almost anti-parallel' (see Fig. 2e) in which we look at high-momentum target protons (300-500 MeV/$c$) that are almost anti-parallel to the $\vec{q}$ direction ($x > 1$). If they are fully correlated with another spectator nucleon and the pair is at rest, the spectator will be ejected at about 90 deg to the beam. This specific kinematical setup is a good compromise between the singles rates in the neutron counters and the suppression of FSI.

For light nuclei, $A \leq 16$, calculations of FSI diagrams within the generalized eikonal approximation in Ref. 25 shows that in addition to $x > 1$, the condition:

$$|p_{mz} + \frac{q_0}{q} E_m| \geq k_F \qquad (9)$$

will confine the rescattering with another nucleon to within short range. As a result, the FSI will take place mainly with the nearby partner nucleon in the correlation. Thus, it will not spoil the SRC characteristics of the process.

In addition, we will use light-cone variables for the analysis of the data, because they are less sensitive to FSI effects, as follows. With the light-cone momenta $p_{m\pm}, p_{s\pm}$ the cross section of the reaction was given in Eq. (2). In our case, the specific decay function we wish to measure is:

$$D(p_{m-} \approx 2m - p_{s-}, p_{m+} \approx (m^2 + {p_{ts}}^2/(2m - p_{s-}), \vec{p}_{tm} \approx -\vec{p}_{ts}) . \qquad (10)$$

The advantage of describing high-energy transfer reactions ($q \geq 1$ GeV/$c$) with light-cone variables lies in the fact that, while $E_m$ and $\vec{p}_m$ change due to FSI, the combination of $p_m$ and $E_m$ in the form of the $p_{m-}$ (or $\alpha = p_{m-}/m$) survives the FSI [24,25]. The accuracy of the conservation of $p_{m-}$ is given by [26]:

$$\tilde{p}_{m-} - p_{m-} \approx \frac{Q^2}{2q^2} E_m, \qquad (11)$$

where the $\tilde{p}_{m-}$ is the corresponding momentum of the target nucleon before the interaction. It follows from this equation that the conservation of $p_{m-}$ improves with increasing energy.

It is difficult to isolate the effects due to nucleons at close proximity from those caused by NN effects such as meson exchange currents, isobaric currents and other long-range correlations. Also, final-state interactions can mimic large nucleon momenta and the signature for SRC. High $Q^2$ is the best way to select the SRC. The sensitivity to short ranges increases as the virtuality of the photon increases. Competing two-body effects diminish as $1/Q^2$ and are also reduced for $x > 1$ (see Ref. 26). The FSI become less important at high $Q^2$ and become easier to deal with by using light-cone variables. For quasi-elastic scattering the knocked out proton moves in the forward direction with high energy and the eikonal approximation can be used in the calculations. Also, the high energy of that proton makes it easy to distinguish it from the spectator correlated hadron.

Both the $x < 1$ (parallel geometry) and $x > 1$ (anti-parallel geometry) regions provide large values for the initial momentum of the interacting nucleon. In order to achieve some large target nucleon momentum, a larger $Q^2$ is needed for the $x > 1$ region. This was the reason why low-energy experiments mainly explored the $x < 1$ region. However, all experiments in the region of $x < 1$ have the disadvantage of being near the inelastic threshold for pion production. This situation becomes more acute with increasing energy transfer. For example, for nuclei with $A \geq 12-16$, the broad Fermi distribution causes the inelastic contribution to be as high as 40% of the (e,e') cross section at $Q^2 = 2$ (GeV/$c$)$^2$, even at $x \approx 1$ [7,27]. The good missing energy resolution and the exclusiveness,i.e. the measurement of the momentum of the recoil nucleon in triple coincidence will allow, in the proposed experiment, to avoid backgrounds such as pion production above and below threshold, which could contribute to double coincidence (e,ep) measurements. All this leads to an exclusive measurement of three particles in coincidence in a region of high energy, high $Q^2$

and $x > 1$. We choose to pay the price of the small cross section at $x > 1$ in order to decrease contributions from resonance effects. We propose to do the measurement at $Q^2 = 2$ (GeV$/c)^2$ with enough statistics for exploring the tail up to 600 MeV$/c$. We also plan to make a measurement at $Q^2 = 2.7$ (GeV$/c)^2$ to check the scaling and make sure that we really have the assumed QE behavior. This check at a second $Q^2$ value is important since it is required to ensure the 'FSI and MEC free situation'. This way can we check the quasi-elastic nature of the reaction by verifying that the cross sections scale as the known free cross sections.

## 5. *Conclusions*

This paper presents an exploratory measurement proposed to TJNAF to probe the short-range structure of nuclei using high-energy electron beams and the triple coincidence large-momentum transfer (e,epN) reaction. The kinematics, high $x$ and $Q^2$, were carefully chosen to minimize contributions of FSI and MEC. Measuring simultaniously the knocked out nucleon and the correlated recoil one is a new step that will allow to suppress and understand the background contributions as well as focus on the relevant events. Within the optimized kinematical conditions, we think that we will be able to determine the fraction of (e,ep) events which are associated with NN short range correlations, as a function of the momentum of the proton in the nucleus. It will also allow us to study and compare the short-range np and pp pairs in nuclei. This together with new data obtained at BNL will establish a unified description of short-range two-nucleon correlation in nuclei.

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## PROMATRANJE BLIZIH NUKLEONA U JEZGRAMA VISOKOENERGIJSKIM PROBAMA

Nedavno smo mjerili reakciju $^{12}$C(p,2p+n) i proučavali korelacije među impulsima udarenog protona u meti i unatrag odbijenog neutrona. Ta ćemo istraživanja nastaviti mjerenjima reakcije C(e,e'p+N) u TJNAF (odobreno mjerenje E97-106). Rabit će se dva spektrometra s trajnim magnetima za mjerenje dijela reakcije (e,e'p). Predviđa se treća mjerna grana s nizom scintilacijskih detektora radi sudesnog mjerenja neutrona i protona s izlaznim elektronom i protonom velikih impulsa. Odabiru se kinematički uvjeti koji dozvoljavaju određivanje udjela (e,e'p) događaja u svezi s kratkodosežnim NN korelacijama u jezgri u ovisnosti o impulsu protona u jezgri. To će omogućiti i usporedbu koreliranih parova pn i pp u jezgrama.