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The large momentum transfer reaction $^{12}C(p,2p+n)$ as a new method for measuring short range NN correlations in nuclei

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Abstract

The reaction $^{12}C(p,2p+n)$ was measured for momentum transfers of 4.8 and 6.2 $(GeV/c)^2$ at beam momenta of 5.9 and 7.5 GeV/c. We measured the quasi-elastic reaction $(p,2p)$ at $\theta_{cm} \simeq 90°$, in a kinematically complete measurement. The neutron momentum was measured in triple coincidence with the two emerging high momentum protons. We present the correlation between the momenta of the struck target proton and the neutron. The events are associated with the high momentum components of the nuclear wave function. We present sparse data which, combined with a quasi elastic description of the $(p,2p)$ reaction and kinematical arguments, point to a novel way for isolating two-nucleon short range correlations.

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The importance of nucleon-nucleon correlations has been recognized for many years [1]. In more recent years, specifically, the necessity for NN correlations has been emphasized by the observation of additional strength at large momenta and large excitation energies [2–4] and the relation between longitudinal and transverse response functions [2]. Some

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recent data on NN correlations (not necessarily short range) come from inclusive (e,e') scattering at $x > 1$ [5–8], the semi-exclusive (e,ep) measurements [9–12], real photon absorption $(\gamma,2N)$ measurements [13,14] and the two-nucleon knockout reactions (e,ed), (e,epp) and (e,epn) [15–18]. There is also evidence from hadronic interactions such as pion absorption [19,20], and backward scattered protons from a variety of projectiles [21], including neutrinos [22]. Thus, there is evidence for general two-nucleon correlations and evidence for short range correlations. The present work will try to combine these two aspects of nuclear correlations in one reaction. Since the early theoretical work of Jastrow [23], there is a continuing theoretical effort [24–29] to confront this connection with experimental data.

The short range correlations (SRC) between two nucleons in nuclei are a very elusive feature in nuclear physics. Their identification is very difficult because they are usually small compared to the single particle components. It is also difficult to separate SRC from effects such as meson exchange currents and Δ components in the nucleus and from the reaction dynamics. In this paper we describe a procedure we used to experimentally search for the existence of two-nucleon short range correlations (NN SRC), and we present data whose dramatic change in character at the Fermi sea level in carbon suggests that they have been identified in the quasi-elastic $^{12}C(p,2p+n)$ reaction at large momentum transfer.

What makes this reaction unique is that $d\sigma_{pp}/dt \sim 1/s^{10}$ at a fixed angle [30]. As a result the incoming proton will scatter preferentially from protons with large momentum in the beam direction, since that reduces the pp invariant energy s which, in turn, increases the scattering cross section [31,32]. In this way, the large mean field background of low nucleon momenta is suppressed. In the present work the transferred four-momentum $-t$ far exceeds the typical inverse inter-nucleon distances of $1/R_{\rm NN} \sim$ 300 MeV/c. This provides the desired resolution for the study of short range phenomena.

In a quasi-elastic (QE) scattering reaction with a high energy projectile, a single target nucleon with momentum p_m is removed from the nucleus leaving the residual nucleus at an excitation energy E_m. There are theoretical expectations as well as experimental indications that NN SRC become important at large p_m and E_m. Thus far the evidence for NN SRC is based on models that add SRC contributions to explain discrepancies with single particle interactions. However, it should be possible to obtain a more direct experimental signature for SRC by looking at the decay of the residual nucleus after the fast removal of one of its nucleons by the QE reaction [24]. If a high momentum target nucleon is correlated with a partner nucleon, the partner will recoil with a momentum $\boldsymbol{p}$ in the direction opposite to $\boldsymbol{p}_m$: $\boldsymbol{p} = -\boldsymbol{p}_m$, $p_m > k_F$, where k_F is the Fermi momentum surface. Since $k_F \simeq 220$ MeV/c (for ^{12}C), the signature will consist of two nucleons, each with high momentum (> 220 MeV/c).

We measured the high-momentum transfer quasi-elastic $C(p,2p)$ reaction at $\theta_{\rm cm} \simeq 90°$ on carbon for 5.9 and 7.5 GeV/c incident protons, in a kinematically complete coincidence experiment. The three-momentum components of both high p_t final state protons were measured, which determined the missing energy and momentum of the target proton in the nucleus. The QE nature of the $C(p,2p)$ reaction was verified by us in an earlier publication [4]. In that publication [4] we extracted also the missing momentum distribution of the target proton which was consistent with electron scattering data [7]. In the present paper we describe the measurement of the directions and momenta of neutrons in coincidence with these two protons. The experiment (E850) was performed at the AGS accelerator at Brookhaven National Laboratory with the EVA spectrometer [33–36], which was located in the secondary beam line C1. The beam passed through a sequence of two differential Cerenkov counters which identified the incident particles. A scintillator in the beam served as timing reference. The beams ranged in intensity from 1 to 2×10^7 particles over a one second spill, every 3 seconds. The spectrometer consisted of a super-conducting solenoidal magnet operated at 0.8 Tesla. The beam entered along the symmetry axis of the magnet (z). The scattered particles were tracked by straw tube drift chambers which provided the transverse momenta of the particles and their scattering angles. Details on EVA spectrometer are given in Refs. [33–36]. Two solid targets, CH_2 and C were placed on the z axis, separated by about 20 cm. They were 5.1×5.1 cm^2 and 6.6 cm long in the z

direction. Their positions were interchanged several times at regular intervals.

Quasi-elastic scattering events, with only two charged particles in the spectrometer, were selected. An excitation energy of the residual nucleus $|E_{miss}| < 500$ MeV was imposed in order to suppress events where additional particles could be produced without being detected in EVA. See Refs. [35,4] for details. The emerging neutrons were detected in (triple) coincidence with the two emerging high momentum protons. In Fig. 1 we present a schematic picture of this setup. Below the targets we placed a series of 16 scintillation bars covering an area of 0.8×1.0 m^2 and 0.25 m deep. They spanned a polar angular range of 102 to 125 degrees and an azimuthal range from −15 to +15 degrees. These counters measured the neutron momenta by time of flight (TOF) with a TOF resolution of $\sigma = 0.5$ nsec. This corresponds to a momentum resolution of $\sigma =$ 30 MeV/c at the highest momentum. A set of veto counters served to eliminate charged particles. Lead sheets with a thickness of 1.7 radiation lengths were placed in front of the veto counters in order to reduce the number of photons entering the TOF spectrum. A clearly identified peak at about 3 nsec per meter flight path, due to remaining photons from the targets, was used for calibration and to measure the timing resolution. We applied a cut off in the TOF spectrum at 6 nsec/m flight path, keeping neutrons below 600 MeV/c, in order to eliminate the photons. There is also a lower momentum cut off at 70 MeV/c due to the finite TDC range.

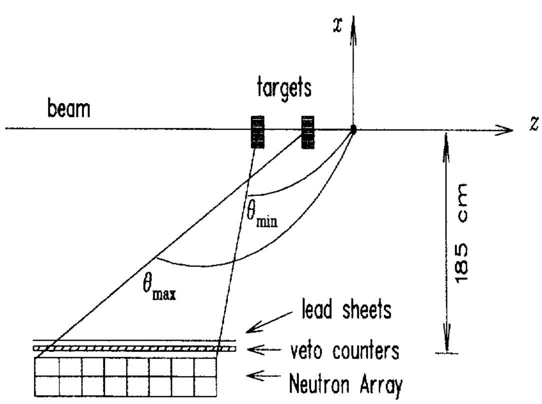

Fig. 1. The neutron counter set up. The z axis is the symmetry axis of the EVA spectrometer. The spectrometer itself is not shown. $\theta_{min} = 102°$ and $\theta_{max} = 125°$.

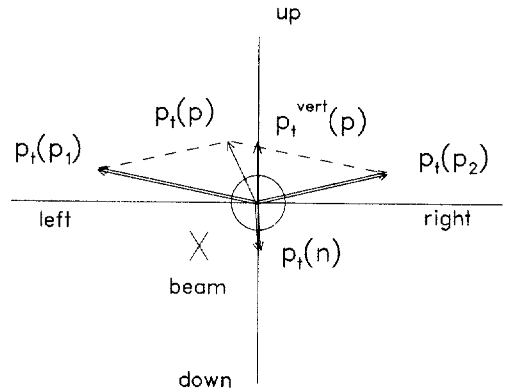

Fig. 2. A triple coincidence event measured at an incident momentum of 5.9 GeV/c. The vectors are projections on the plane normal to the incident beam. The axes are the vertical and horizontal directions in that plane. The $\boldsymbol{p}_t(p_1)$,$\boldsymbol{p}_t(p_2)$ are the transverse momenta of the outgoing protons, $\boldsymbol{p}_t(p)$ is the transverse momentum of the target proton before the interaction and $p_t^{vert}(p)$ is its vertical component. $\boldsymbol{p}_t(n)$ is the projection of the neutron momentum on the same plane. The circle indicates the scale for a momentum of 220 MeV/c.

An example of a triple coincidence event which displays a NN SRC, is shown in Fig. 2. We show the transverse components $\boldsymbol{p}_t(p_1)$ and $\boldsymbol{p}_t(p_2)$ of the two outgoing high momentum protons as they were reconstructed in the trajectory analysis. The transverse momentum component of the struck target proton $\boldsymbol{p}_t(p) = \boldsymbol{p}_t(p_1) + \boldsymbol{p}_t(p_2)$ and the component of the neutron on the plane perpendicular to the beam ($\boldsymbol{p}_t(n)$) are drawn as well. If the struck proton was correlated with a nearby neutron and the *pn* pair is at rest, the neutron will emerge in the direction opposite to that of the struck proton and with the same magnitude momentum $\boldsymbol{p}(n) = -\boldsymbol{p}(p)$. If the correlation is of a short range nature, we also expect both $p(n)$ and $p(p)$ to be above the Fermi sea level. Most of the events we measured do not have these ideal characteristics. The angular correlation is spread out due to limited experimental resolution, to center of mass motion of the *pn* pair in the nucleus and to final state interactions (FSI) of the outgoing protons. Notwithstanding the inevitable smearing of the angular correlation, we can extract information on the *np* correlation from our data by relaxing somewhat the stringent "back to back" requirement. All the neutrons are detected in the downward direction. Consequently, we concentrate on the vertical (up-down) component of the struck proton.

In Fig. 3 we present results from a Monte Carlo (MC) simulation which is based on the Impulse Approximation. The calculation factorizes the free pp elastic cross section from a target proton [32] with a decay function which describes the joint probability to remove a target proton with a certain missing momentum/energy while the residual nucleus decays by emitting a single backward neutron [24]. The nucleon momentum distribution consists of two components. Up to the Fermi sea level ($k_F = 220$ MeV/c) the distribution is calculated from a harmonic oscillator potential with parameters fitted to electron scattering data [37] and no correlation was assumed between the target proton and the ejected

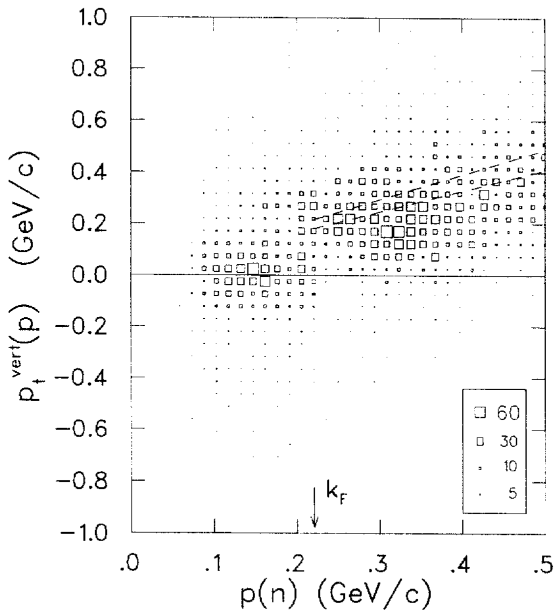

Fig. 3. Results of the MC simulation. The vertical component of the target nucleon momentum vs. the total neutron momentum. The positive vertical axis is the upward direction. The simulated events shown are for triple coincidences of the neutron with the two high energy protons emerging from the QE $C(p,2p)$ reaction at a beam momentum of 6 GeV/c. The dashed curves represent the region of the correlation. If the CM motion of the pair and the ISI/FSI would not play a role, all the correlated events would lie between the dashed lines. The sizes of the boxes are proportional to the number of counts. (See the lower right hand corner for some examples).

neutron. The direction of the neutron was chosen randomly. Above the Fermi sea level, we assumed that the neutron and the target proton formed a correlated pair in the nucleus. The rough transition at the Fermi sea level is justified, considering the limited statistics of our data and by the lack of exact theoretical knowledge for that region and beyond. We used a two-nucleon SRC model based on references [24] and [38]. This combination successfully reproduces the spectral functions calculated in the large removal energy region [38] and provides a fairly good description of inclusive (e,e') data at $x > 1$ [39]. For the center of mass motion of the pair we chose a Gaussian distribution with a standard deviation of 140 MeV/c. Thus, the back to back emission of the knocked out proton and the correlated neutron is smeared by the center of mass motion. The initial and final state interactions (ISI/FSI) for the protons are estimated with a simple model [40]. We assume that the fast protons are scattered, with known cross sections, by nucleons in the nuclei which have a momentum distribution as discussed above. The rescattering can cause artificial correlations and can alter the determination of the momentum of the struck nucleons, as well. The MC simulation also includes the EVA spectrometer and the neutron counter acceptances. We plotted the vertical (up-down) component with respect to the *total momentum* of the neutron for a beam momentum of 6 GeV/c. The reason for choosing the total momentum was that the neutron momentum is well measured and clearly represents the nucleon momentum distribution. Each simulated data point represents a single event.

We will explain the expected signal for two-nucleon SRC with the aid of Fig. 3. The location of the neutron counter array below the targets insures that the downward components of the neutron momenta are nearly as large ($\sim 90\%$) as the total momenta. In order for neutrons to reach the counters below the targets they need downward component p_n^{vert}, in a range between some minimal and maximal limits which increases with the total neutron momentum. If the neutron is correlated with a proton, that proton will need an upward component which is equal in size to p_n^{vert}. The slanted dashed lines in the figure represents this transverse momentum balance. All "correlated points" would lie between these lines if there was no motion of the *pn* pair, no ISI/FSI and no deviations due to experimental resolution. *The paucity of downward pointing proton momenta at high neutron momenta in the simulation is a signature for the dominance of two-nucleon correlations for large nucleon momenta in the nucleus.* The MC simulation shows that the effects of ISI/FSI and the center of mass motion of the pair are not sufficiently large to prevent us from determining whether the momentum of the target proton pointed upwards or downwards.

In Fig. 4 we plot our actual data in the same way as the simulated points in Fig. 3, for both the 5.9 and 7.5 GeV/c beam momenta. The resolution of the vertical momentum component depends on the azimuthal angle of the pp scattering plane. The resolution is best if that plane is horizontal and worst if it is vertical. The different sizes of the error bars in Fig. 4 reflect this variation in the resolution. The data follow the signature for 2N SRC that we discussed for the MC simulation. It is what one expects for correlated nucleon pairs. The large neutron momenta are associated with upward going protons while below the Fermi level, where the momenta can originate from the mean field, there is no preference.

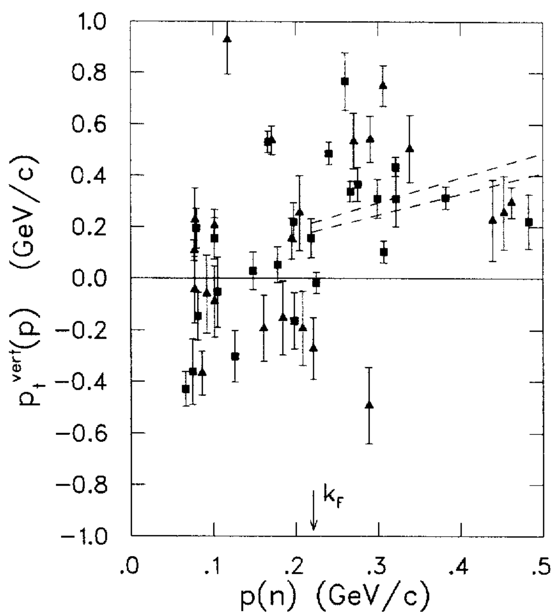

Fig. 4. The measured vertical component of the target nucleon momentum vs. the total neutron momentum. The positive vertical axis is the upward direction. The events shown are for triple coincidences of the neutron with the two high energy protons emerging from the QE $C(p,2p)$ reaction. The squares are for the 5.9 GeV/c incident beam and the triangles are for 7.5 GeV/c. The dashed and dotted lines are the same as in Fig. 3. We associate the events in the upper right corner with NN SRC.

We performed a series of tests to ascertain that the up/down asymmetry in Fig. 4 is not an experimental artifact of the spectrometer or of analysis procedures. We will mention just three of them. 1) We looked for asymmetries in the double coincidence $(p,2p)$ quasi-elastic scattering data, and restricted them to target proton momenta in the direction of the neutron counters and opposite. Out of 900 events 53 % point upwards. 2) Next we checked the triple coincidence data, where the third coincidence was taken from the photon peak in the neutron counter. Out of 600 events 64 % point upward. 3) As a further test we changed the E_{miss} region to 1.2 $< E_{miss} <$ 2 GeV. In this case, 52% out of 73 events pointed upward. In all these tests the average p_p^{vert} was always less than 0.1 GeV/c. Thus, there were no asymmetries in any one, or combinations, of these tests that could be responsible for the observed asymmetry of our data in Fig. 4. A χ^2 test shows that the probability that the data above the Fermi sea level can be consistent with a symmetric distribution is less than 0.01 %.

Final state interactions could, in principle, mimic this asymmetry. 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. The momentum transferred to the proton cannot be distinguished from the original momentum of the struck proton before the hard interaction. Since the neutron detectors are positioned at a backward angle (about 114 ± 12 deg), the probability for such a recoil neutron to enter the counters is very small. We estimated the FSI contribution to the events shown in Fig. 4 under the same assumptions as the above described MC simulation and determined the number of neutrons and their momenta that could contribute to Fig. 4, for all the $(p,2p)$ quasi-elastic events accepted by the spectrometer. The contribution of ISI/FSI to the events in Fig. 4 is about 3 above 220 MeV/c and about 2 below 220 MeV/c.

In summary, we point out that it is difficult to separate two-nucleon short range correlations from other physical effects. Also, our MC simulation contains only a very simple 2N SRC model and the ISI/FSI are treated in a very elementary fashion. Nevertheless, on the basis of the strong similarity between the MC simulation (Fig. 3) and the real data (Fig. 4) we conclude that, even with the sparse data, we have found a method which relies mostly on kinematical arguments that can isolate the combination of *two-nucleon* and *short range correlations*. These data and forthcoming data with better statistics as well as high energy (e,epN) measurements [41] should encourage further theoretical work to describe the detailed nature of the NN interaction in the nucleus.

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