**Study of Short Range Correlations with Hard inverse kinematic reactions**

**BM@N Project**

List of organizations and participants

Russia: Joint Institute for Nuclear Research – JINR (Dubna) the BM@N collaboration

Germany: TU Darmstadt and GSI

Israel: Tel Aviv University

USA: MIT

**Abstract**

We propose to study Short range Correlations (SRC) via hard inverse and complete kinematics measurements. With a 12C beam at 4 GeV/c per nucleon and the BM@N beam line we propose to knock out a proton from a two-nucleon correlation pair in the carbon nuclei and detect it in coincidence with the scattered proton. We are going to trigger on a large missing momentum, but also plan to detect the recoil partner from the correlation, and the A-2 spectator system. This is a pioneer measurement that can be done only at the Nuclotron in Dubna.

**Motivation**

The stability of the atomic nuclei is based on a delicate interplay between the long-range attraction that binds nucleons together and the short-range repulsion that prevents the system from collapse. In between, the dominant scalar part of the nucleon-nucleon (NN) force almost vanishes and the interaction is dominated by the tensor force, which depends on the spin orientations and the relative orbital angular momentum of the nucleons.

Recent high-momentum-transfer triple-coincidence 12C(e, e’pN) and 12C(p, 2pn) measurements [1-4] have shown that nucleons in the nuclear ground state form pairs with large relative momentum and small center-of-mass (CM) momentum, where large and small are relative to the Fermi momentum of the nucleus. We refer to these pairs as short-range correlated (SRC) pairs [5-7]. For the missing momentum of the knocked out proton (which is equal to the proton initial momentum in absence of interactions) in the range of 300-600 MeV/c, these pairs were found to dominate the nuclear wave functions, with neutron-proton (np) pairs nearly 20 times more prevalent than proton-proton (pp) pairs, and by inference neutron-neutron (nn) pairs (see Fig. 1). This is due to the strong dominance of the NN tensor interaction at the probed sub-fermi distances [8-10].

Measurements of Short Range Correlations (SRC) in nuclei probe the tensor part of the NN force and start approaching the repulsive core by studying the isospin decomposition of the SRC pairs. The experiment proposed here intends to verify these phenomenological findings using different reactions/kinematics. The use of nuclear beam and hard inverse kinematics is a breakthrough. In future it will allow to study SRC using unstable very asymmetric nuclei and also to gain information on the A-2 system left after the violent removal of the SRC pair from the mother nuclei.

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|  | Figure 1: The fractions of correlated pair combinations in carbon as obtained from the 12C(e, e’pp) and 12C(e, e’pn) reactions measured at JLab [1,2] as well as from previous, 12C(p, 2pn) data from BNL [3,4]. |

**Description of the proposed research**

We propose here a new experimental approach to SRC study via hard inverse and complete kinematics measurements. Inverse kinematics was used to study the equivalent of exclusive quasi-free proton knockout using 12C beam energy of less than 0.5 GeV/N [11]. Here using the BM@N beam line and equipment and the NeuLAND large acceptance neutron detector from GSI we extend the inverse kinematics measurement to higher energy, larger momentum transfer, large missing momentum, and add to it the detection of the recoil partner from the correlation.

We propose to measure simultaneously the following reactions:

1. 
2.  (np-SRC)
3.  (pp-SRC)
4.  (np-SRC)
5.  (pp-SRC).

These reactions should be measured with a large (p, 2p) missing momentum, which means they are dominated by 2N-SRC. The following ratios are to be extracted from the measured yields (after corrections for acceptance, efficiencies etc.):

 [Reactions (2) and (4), (3) and (5)]

 [Reactions (2) and (4), and (1)]

 [Reactions (3) and (5), and (1)]

The results are to be compared with the electron scattering, high energy proton induced study of SRC, and calculations.

**Objectives**

Identify 2N-SRC events in inverse kinematics.

**Experimental setup**

A schematic of the proposed experimental setup is shown in Fig. 3. It is based on the original BM@N layout with some important modifications accounting for the kinematics of the quasi-elastic scattering reaction 12C(p, 2p) A-2, p(n). The target ensemble, shown in Fig. 4, is placed inside the horizontal steering magnet SP-57. The beam will be focused using the quadruple lenses only, so that the steering magnets can be turned off. The space upstream the target will be used to monitor the beam direction using proportional chambers or several GEM stations. We plan to use the liquid hydrogen target and keep a CH2 target as a backup. The leading protons have a large opening angle with respect to each other. They pass through the trigger scintillator pairs (LS1 and LS2) and then are detected using the time-of-flight technique in two MRPC walls (TOF-400) located on both sides of the analyzing magnet SP-41.

The recoil nucleons have momentum of several GeV/c and are emitted forward symmetrically in phi with polar angles up to about 8 degrees. The trajectory before and after the analyzing magnet allows reconstructing the turning angle, which together with the time-of-flight information measured by TOF-700 helps to separate between 10B, 11B, and 10Be. The forward going recoil neutrons are measured beam right with the NeuLAND detector. ZDC is shifted beam left to detect the A-2 and a fraction of the recoil nucleons.

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|  | Figure 3: schematic of the experimental layout based on the BM@N setup. |

The NeuLAND is a new high precision large acceptance neutron detector, which will be transported to Dubna from GSI (Darmstadt). The sensitive area of the detector is 2.5 m x 2.5 m. The expected efficiency for the neutrons with momentum of 4-6 GeV/c is about 40%. The timing resolution is 150 ps, and the spacial resolution is about 1.5 cm in x, y, and z directions for the distance between the target and the detector of 15 m. The NeuLAND will allow precise reconstruction of the neutron momentum based on the time of flight, which gives access to the initial momentum of the projectile proton participated in the interaction.

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|  | Figure 4: Target ensemble including a target and the trigger detectors: T0, two scintillator pairs for the leading protons (LS1 and LS2), and a Cherenkov counter providing a signal ~Z2 for the identification of the A-2 system. The trigger is provided by the coincidence of T0 \* LS1 \* LS2 \* C. |

**Beam time request**

We plan to use a carbon beam with momentum of 4 GeV/c per nucleon and intensity of 106 ions/spill and momentum spread of 1% for net two weeks in the next period of operation (November – December 2017). The duty cycle is about 12-20% with 2 s slow extraction and 10-15 s of the total beam cycle. We expect to have a week for preparation of the experiment followed by two weeks of beam time. The NeuLAND detector can be positioned in the BM@N hall only before the start of the autumn period of operation. It should be placed in the final position using a crane through the roof. The support frame should be manufactured by the JINR in advance.

**Event selection and expected rates**

To study 2N-SRC we are looking for events with missing momentum above kFermi in the 12C rest frame. Kinematical distributions for the two trigger protons, the recoil nucleon, and the A-2 system assuming a hard process (i.e. >2 (GeV/c)2) are shown in Fig. 5.

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|  | **Figure 5**: The distributions of momentum and polar angle for the final state particles of the reaction 12C + p 🡪 2p + A-2 + p(n). The red rectangle marks the acceptance for detecting the triggered proton pair. All figures except the top left assume two trigger protons end up in the red box. |

For the events within the acceptance and with a cut on the reconstructed t and u fulfilling [GeV/c]2 , the expected resolution for the missing momentum and recoil momentum is about 40 MeV/c. The A-2 momentum in the transverse (longitudinal) direction can be reconstructed with a resolution of 20-40 (150) MeV/c.

There are two criteria chosen for SRC event selection. The first criterion selects events with the A-2 system detected additionally to the both leading protons (reactions 1, 2, 3). To ensure events with Pmiss above the Fermi level we need to cut on the reconstructed Pmiss of at least 0.4 GeV/c. Assuming all the 2N-SRC removal have a spectator A-2 nuclei that survives the hard scattering, we expect 1100 events from reaction (2) and 100 events from reaction (3) during two weeks of beam time. The second criterion selects 2N-SRC events with two protons, the A-2 nuclei, and the recoil nucleon in the final state. Assuming all recoil particles produce a signal in the detection system and all the A-2 spectators do not break up, we expect about 250 4-fold coincidence of reaction (3) and about 120 events coming from reaction (5). The random trigger coincidental rate was estimated both in calculations and simulation using QGSM generator to be less than 1% of the signal rate.

**Estimation of the additional resources**

In terms of manpower we provide two PostDocs full time present at JINR as well as several PhD/undergrad students for part-time participation in the project. Two experts (on electronics and DAQ) are coming accompanying the NeuLAND. The estimated cost of the design and manufacturing of the necessary support structures for the detectors (performed by JINR) is about 75 kUSD.

**Refrences**

[1] R. Shneor et al., Phys. Rev. Lett. 99, 072501 (2007).

[2] R. Subedi et al., Science 320, 1476 (2008).

[3] A. Tang et al., Phys. Rev. Lett. 90, 042301 (2003).

[4] E. Piasetzky, M. Sargsian, L. Frankfurt, M. Strikman and J. W. Watson, Phys. Rev. Lett. 97, 162504 (2006).

[5] L. L. Frankfurt and M. I. Strikman, Phys. Rep. 76, 215 (1981).

[6] L. L. Frankfurt and M .I. Strikman, Phys. Rep. 160, 235 (1988).

[7] J. Arrington, D. W. Higinbotham, G. Rosner, and M. Sargsian, Prog. Part. Nucl. Phys. 67, 898 (2012).

[8] R. Schiavilla, R. B. Wiringa, S. C. Pieper, and J. Carlson, Phys. Rev. Lett. 98, 132501 (2007).

[9] R. B. Wiringa, R. Schiavilla, S. C. Pieper and J. Carlson, Phys. Rev. C 78, 021001 (2008).

[10] R. B. Wiringa, R. Schiavilla, S. Steven, C. Pieper, and J. Carlson, Phys. Rev. C 89, 024305 (2014).

[11] V. Panin et al., Phys. Lett. B 753 (2016) 204-210.