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Probing Nuclei with High-Energy Hadronic Probes at Inverse Kinematics

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Abstract

Proton knockout reactions are a widely used tool to study nuclear ground-state distributions. While the interpretation of traditional experiments in direct kinematics has to account for initial and final state interactions, experiments in inverse kinematics can overcome such limitations. We discuss results of an experiment at the BM@N setup at JINR using a ^{12}C beam at 48 GeV/c to study quasi-elastic scattering reactions, single proton distributions, and short-range correlated nucleon-nucleon pairs. The inverse kinematics allows for the direct measurement of the nucleon-nucleon pair center-of-mass motion and provides first experimental evidence for scale separation of such pairs. Based on these results, we will in the future study neutron-rich nuclei in inverse kinematics in the context of short-range correlations and neutron stars.

Keywords

Nuclear Ground-State Distributions, High-Energy Hadronic Scattering, Inverse Kinematics, Short-Range Correlations, Neutron-Rich Nuclei, Neutron stars

1. Introduction

From superconductors to atomic nuclei, strongly-interacting many-body systems are ubiquitous in nature. Understanding the emergent macroscopic properties of such systems in terms of the underlying microscopic particle correlations is an outstanding challenge with wide ranging implications. In the case of nuclear systems, significant experimental and theoretical efforts are being devoted towards understanding the dynamics of protons and neutrons in both stable and radioactive nuclei, and its implications for the dynamics of dense matter in neutron stars, and astrophysical nucleosynthesis processes.

Measurements of high-energy scattering reactions are a time-honored method to study nucleons in nuclei. In such cases high-energy projectiles are shot at a stationary nucleus, the scattered projectile and knocked-out nucleons are detected, and the initial momentum of the struck nucleon in the nucleus is reconstructed. While such measurements are fundamental for mapping the structure of atomic nuclei, their interpretation is often complicated by Initial-State Interactions/Final-State Interactions (ISI/FSI) of the incoming and scattered particles. Such interactions reduce the scattered particle flux (attenuation) and distort their kinematics, complicating the relation between the measured reaction cross-sections and the inferred ground-state nuclear momentum distribution.

2. Experiment

Here we report on a recent study by the Baryonic Matter at Nuclotron (BM@N) collaboration at the Joint Institute for Nuclear Research (JINR) that overcame this fundamental limitation and extracted the distributions of nucleons and correlated nucleon pairs in nuclei. The experiment measured high-energy inverse-kinematics scattering, where a relativistic ion beam was scattered from a stationary proton target, see **Figure 1**. Large-angle quasi-elastic proton-proton scattering was measured in coincidence with a bound residual nuclear fragment. The detection of the residual nucleus was shown to choose the transparent part of the reaction, excluding the otherwise large kinematic distortions due to ISI/FSI that would also break the fragment apart.

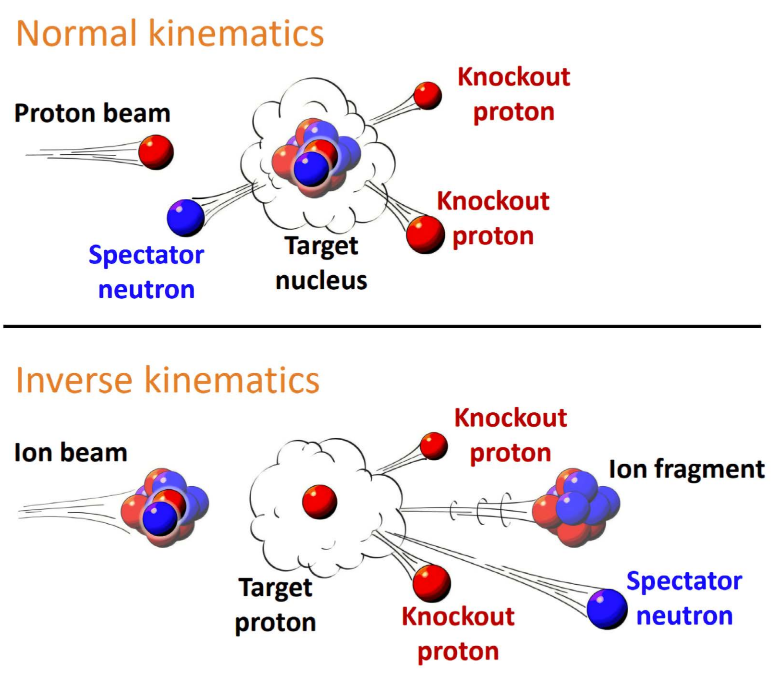

Figure 1. Study of SRC pair in nuclei by normal (above the line) and inverse (below the line) kinematics reactions. In this picture protons are shown in red, neutrons in blue.

While much more complex than traditional "normal-kinematics" measurements, such "inverse-kinematics" measurements also allow us to study radioactive nuclei with large neutron excess that are too short-lived to be used as a fixed target in the laboratory, cf. **Figure 1**. Understanding the structure and properties of radioactive nuclei is fundamental for our understanding of nucleosynthesis processes in astrophysics.

The experiment took place at the JINR using a 48 GeV/c ^{12}C ion beam from the Nuclotron accelerator, a stationary liquid hydrogen target, and a modified BM@N experimental setup as shown in **Figure 2**. A two-arm spectrometer was placed downstream of the target to detect the two protons from the quasi-elastic (QE) (p,2p) scattering at ~90˚ in the pp center-of-mass (c.m.). The residual nuclear fragments (^{11}B, ^{10}B, or ^{10}Be) were identified in coincidence, and their momenta were determined, based on their energy deposition in two thin scintillators and their measured trajectories as they passed through a large-acceptance dipole magnet. The data was first published in [1], here we wish to show the results in the context of previous data obtained by different measurement methods.

3. Results and Discussion

The suppression of ISI/FSI was demonstrated by comparing the reconstructed knocked-out proton initial momentum distribution for QE ^{12}C(p,2p) events with and without the coincidence detection of a bound ^{11}B fragment. The results are shown in **Figure 3** (adapted from [1]) compared with Plane-Wave Impulse Approximation (PWIA) calculations for knockout of p-shell protons from the ^{12}C that assumes no distortion due to ISI/FSI. As can be seen, the ^{11}B fragment detection significantly suppresses ISI/FSI effects, especially above the nuclear Fermi momentum (k_F ~ 250 MeV/c), where the kinematical distortion of the scattered nucleons due to secondary processes becomes significant.

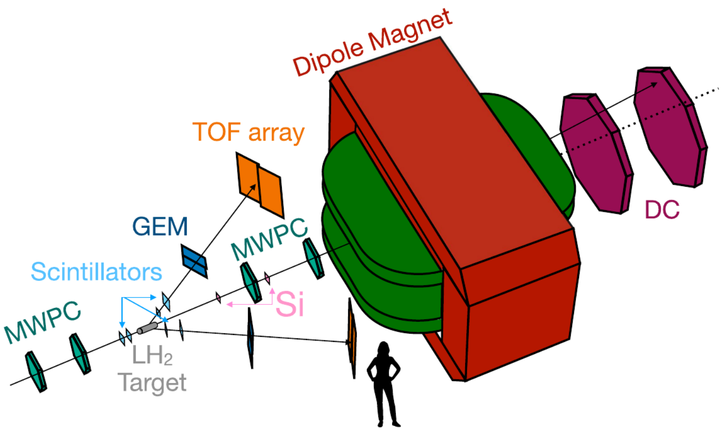

Figure 2. Illustration of the SRC@BMN experimental setup at the JINR in Dubna, Russia. A 48 GeV/c ^{12}C beam is incident from the left on a liquid hydrogen target. The (p,2p) reaction is measured using a non-magnetic time-of-flight spectrometer. The residual nuclear fragment is measured using a magnetic spectrometer downstream the target.

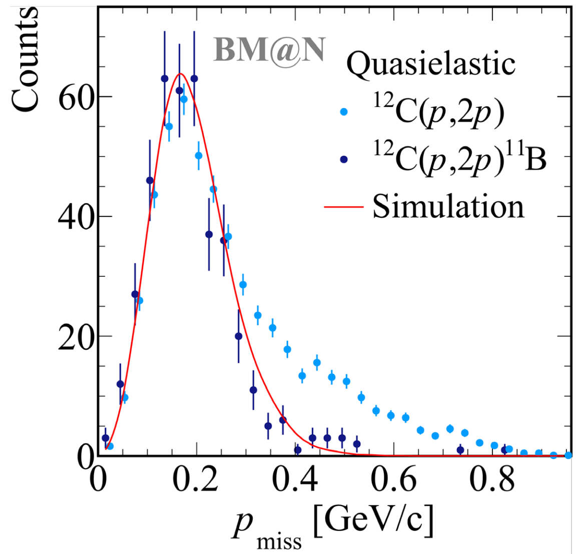

Figure 3. Measured missing-momentum distribution in the ^{12}C rest-frame for the quasi-elastic inclusive ^{12}C(p,2p) and exclusive ^{12}C(p,2p)^{11}B reactions. The data are compared with a PWIA-based simulation of proton knockout from the ^{12}C p-shell. The ^{11}B tagging clearly suppresses ISI/FSI distortions at high momenta. Figure adapted from [1].

Next we studied short-range correlated (SRC) nucleon pairs by measuring two-nucleon knockout ^{12}C(p,2p^{10}B)n and ^{12}C(p,2p^{10}Be)p reactions. SRCs are fluctuations of strongly interacting nucleon pairs at short distances [2] [3] [4]. Their formation and properties are sensitive to the many-body dynamics of nuclear systems, properties of the short-distance nucleon-nucleon interaction, nucleon structure, and properties of cold dense nuclear matter such as in the outer core of neutron stars [5] [6].

In SRC breakup reactions, ^{10}B and ^{10}Be nuclei are produced when a proton-neutron (pn) or proton-proton (pp) pair in the projectile interacts with a proton in the target. We measured 23 ^{12}C(p,2p^{10}B)n and two ^{12}C(p,2p^{10}Be)p events. The other isospin-symmetric nn pairs are not accessible here because neutron knockout was not measured. The large ^{10}B to ^{10}Be event-yield ratio is consistent with the previously observed dominance of pn- over pp-SRC pairs [7] [8] [9], and fully agrees with predictions based on ab-initio many-body calculations. Contributions from inelastic reactions and from reactions due to mean-field QE scattering followed by FSI are negligible.

Beyond the suppression of ISI/FSI, the fragment momentum distribution is equal to the SRC pair c.m. momentum distribution. This distribution is consistent with that of a Gaussian.

In **Figure 4** we compare the Gaussian width measured directly by BM@N with previous indirect extractions from electron scattering measurements at the Thomas Jefferson National Accelerator Facility (JLab) done in "normal kinematics" and with several theoretical predictions [10]. All measurements agree with each other and with the theoretical calculations, showcasing the probe-independence of SRC measurements and the success of its theoretical description.

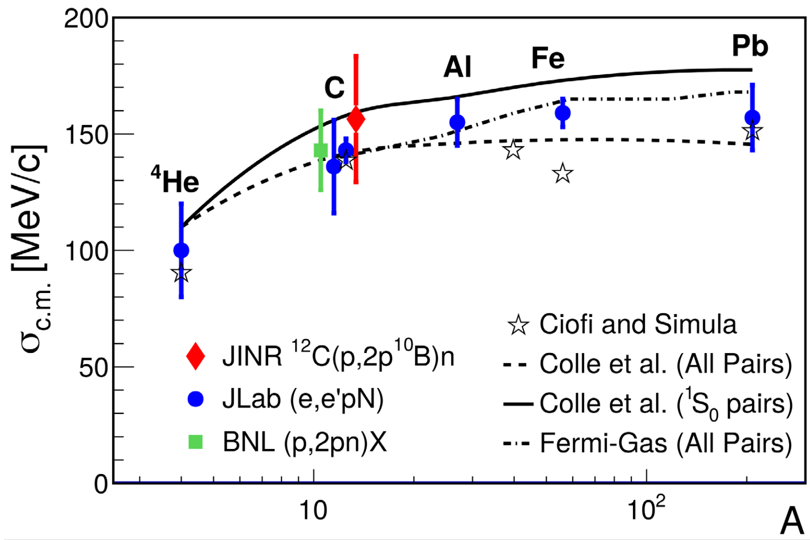

Figure 4. The width of the SRC pair c.m. momentum distributions extracted from the direct fragment detection in inverse kinematics and from normal-kinematics electron and proton scattering measurements, cf. [10].

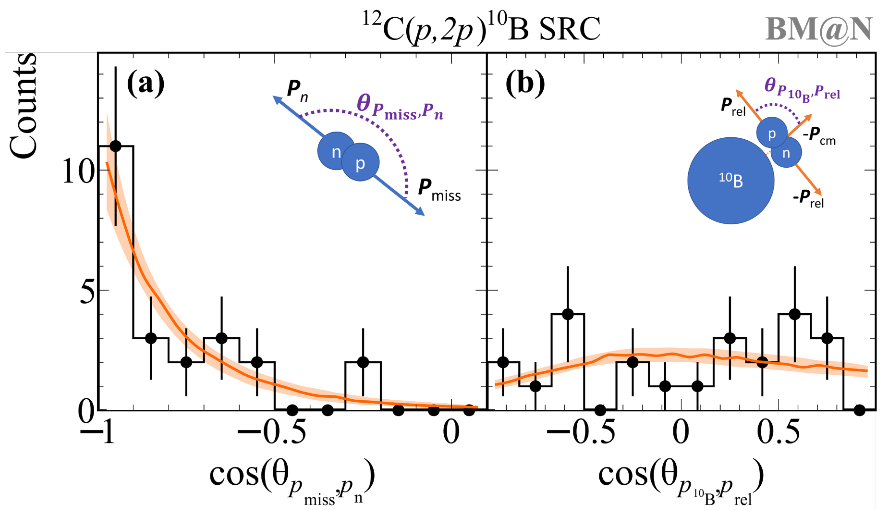

Figure 5. Angular correlation between the two nucleons in the SRC pair (a) and between the SRC pair c.m. and relative momenta (b). Data are compared with theoretical calculations using the nuclear Generalized Contact Formalism (GCF), assuming full factorization of SRC wave function from the residual nuclear system. Figure adapted from [1].

Lastly, detecting the residual nucleus allows, also for the first time, measuring the interaction between the SRC pair and the residual nuclear system. From a theoretical standpoint, the strong two-body interaction between the nucleons in SRC pairs is expected to be significantly stronger than the average mean-field nuclear interaction [11] [12]. Therefore, the pair interaction should be scale separated from that of the residual nuclear system, allowing us to model the distributions of SRC pairs by independent functions of the pair c.m. and relative momenta that do not depend on the angle between the two.

This is shown in **Figure 5** (adapted from [1]). A clear back-to-back correlation between the momenta of the nucleons in the SRC pair is observed, as expected for strongly-correlated nucleons. The width of the distribution is driven by the pair c.m. motion and agrees with the Generalized Contact Formalism (GCF) simulation [11] [12]. In contrast, no correlation is observed between the angles of SRC c.m. momentum (*i.e.* ^{10}B) and the relative momentum between the nucleons in the pair, providing the first direct experimental evidence for the factorization of SRC pairs from the many-body nuclear medium.

4. Summary

To conclude, we demonstrated the feasibility of directly accessing properties of single nucleons and SRC nucleon pairs in nuclei using a 48 GeV/c ion beam from the JINR Nuclotron accelerator and a stationary liquid hydrogen target to measure high-energy inverse kinematics scattering. We identified SRC pairs and performed the first direct measurement of their c.m. momentum distribution. We used this to experimentally verify the SRC factorization assumption which leads to a universal description of the high-momentum tail in all nuclei. This measurement opens the way for SRC studies in radioactive nuclei at the forthcoming FAIR and FRIB facilities, focusing on the dynamics of high-density nucleon-pair fluctuations in very neutron-rich systems. These studies will be pivotal for developing a microscopic understanding of the structure and properties of nuclei far from stability and the formation of visible matter in the universe.

5. Outreach

The study of the structure of radioactive nuclei and its relation to nucleon correlations is a growing frontier of nuclear physics, motivated by the importance of neutron-rich nuclei for modeling astrophysical processes. Measurements have shown that nuclear shell occupations (magic numbers) evolve with nuclear asymmetry where for neutron-rich nuclei "known" shells disappear and new shells appear. This evolution of shells has dramatic astrophysical implications as "magic number nuclei" serve as a waiting point for element formation in the r-process. Extending the study to radioactive nuclei using the new experimental approach reported here, based on measurements of hard nucleon-knockout reactions in inverse kinematics, is paramount for a ground-breaking experimental and theoretical program to understand very asymmetric cold dense nuclear systems from unstable nuclei to neutron stars.

From an ab-initio theory perspective, understanding the manner by which two-body correlations impact the emergence of collective phenomena such as shell closure in neutron-rich nuclei is a significant challenge, undertaken by nuclear EFT calculations using many-body numerical techniques such as lattice, coupled-cluster, and Quantum Monte-Carlo calculations. Measuring the ground-state distributions of particles and particle-pairs in such exotic systems is crucial to improving our understanding of such correlation effects in other strongly interacting many-body systems.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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