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Study of Short-Range Correlations in Atomic Nuclei at JINR

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Abstract

The properties of atomic nuclei are determined by interactions between nucleons at low resolution and quarks and gluons at high resolution. Short-range two-nucleon correlations (SRC) bridge these approaches, representing a specific type of short-range fluctuations, when two nucleons are separated by distances comparable to their radii and have momenta higher than Fermi level. The results from electron scattering experiments have shown that the SRC effect is important for the behavior of multiparticle systems, nucleon-nucleon interaction, and the structure of nucleons. Modern SRC studies with ion beams and liquid hydrogen targets allow for the analysis of the properties of nuclear fragments after quasi-elastic knockout of nucleons or SRC from the beam ions thus ensuring new observables and ways to investigate the fine structure of nuclei. The first SRC experiment at BM@N in JINR (2018) demonstrated that the detection of the ^{11}B nucleus in the final state is a sign of scattering on a "transparent" carbon nucleus, and 25 observed events confirmed the SRC properties known from electron experiments. Currently, the analysis of the second SRC experiment at BM@N (2022) with an improved setup is ongoing, and the new SRC measurement with polarized deuteron beam in a new experimental area is being planned and prepared. This article discusses the historical insight in the problem of nuclear structure and the development of the SRC model, as well as the status and prospects of the SRC physics program at JINR (Dubna, Russia) within the current international SRC effort.

Introduction

In the 1950s and 1960s, there was a growing interest in reactions of the type $A + B \to C + X$, where A, B, and C are known particles, and X represents one or more unknown particles. These reactions are classified as inclusive reactions. As new particles such as pions, mesons, and hyperons were discovered and classified, the interest in these types of reactions significantly increased. During this period, Soviet scientists made substantial contribution to the understanding of processes occurring within atomic nuclei. One of the key contributions came from Dmitry Ivanovich Blochintsev, who proposed an idea of density fluctuations (fluctons) within nuclei in 1957 [1]. This theory was based on experiments involving the scattering of 675 MeV protons on light nuclei [2]. A flucton within the nucleus can be treated as an instantaneous scattering center with a size comparable to that of a nucleon and comprising two and more nucleons. In his work, D. I. Blochintsev provided the first estimate for the probability of finding two nucleons in the nucleus at a distance comparable to the size of a nucleon, as well as estimating the interaction cross-section of a proton with a two-nucleon pair.

In 1971, Alexander Mikhailovich Baldin described the cumulative effect arising during nuclear collisions [3]. A secondary particle is termed cumulative if it is formed with kinematical properties forbidden for scattering on a single nucleon being at rest. The degree of "cumulativeness" can be described by a special quantity $x = p/p_0$, where p is the momentum of the detected particle and p_0 is the momentum of the nucleon in the nucleus before the interaction. The cumulative effect, experimentally discovered and studied by Valentin Semenovich Stavinsky [4], indicates that as the energy of the colliding particles increases, there comes a point where the maximum fragmentation of the nucleus is reached, and the physical picture of the process remains unchanged under further increase of energy. This implies that increasing the collision energy is meaningful only in the search for new processes; for studying already known processes, energy at the threshold level is sufficient. Furthermore, the process of nuclear fragmentation was found to share many similarities with the processes of deep inelastic scattering of electrons on protons and protons on protons [5]. In 1972, under the guidance of Mikhail Grigorievich Meshcheryakov, an experiment commenced on the quasi-elastic knockout of nucleon pairs from light nuclei by high-energy protons. The experiment aimed to detect three-proton coincidences in the reaction $\mathrm{C(p,3p)}$, which corresponds to knocking out a proton-proton pair from the nucleus. Due to difficulties in separating true events from noise, the experiment took considerable time, but a paper detailing the results [6] was published in 1979. The reactions of quasi-free scattering of a 670 MeV proton beam on two-nucleon clusters within nuclear targets with knockout of deuterons $^{12}\mathrm{C}$ (p, pd) , $^{6/7}\mathrm{Li}$ (p, pd) and $^{6/7}\mathrm{Li}$ (p, nd) were studied at JINR using a dedicated two-arm spectrometer [7, 8, 9]. The study of the SRC properties of the deuteron and spin-singlet proton in the deuteron breakup reaction $\mathrm{pd} \to \mathrm{(pp)n}$ was performed at COSY [10] with participation of the JINR group and test of the short-range NN-interaction potentials on this basis was done in paper [11].

1 The Origin of The Theory of Short-Range Correlations in Atomic Nuclei

In the late 1970s, significant advancements were made in the understanding of nuclear structure by Mark Izrailevich Strikman and Leonid Lvovich Frankfurt, who began their research in Leningrad. In 1981, they proposed a novel interpretation for density fluctuations within the nucleus, considering specific two-nucleon configurations, where nucleons are separated by a distance comparable with the nucleon radius and having high and opposite momenta exceeding the Fermi level for the given nucleus. These configurations were termed short-range correlations (SRC) [12]. A distinctive feature of the SRC theory is that nuclear density fluctuations are attributed to correlations between nucleons rather than the formation of multi-quark configurations.

In their subsequent works [13], M.I. Strikman and L.L. Frankfurt demonstrated that the backward scattering of protons and pions, observed in numerous experiments, can be linked to the breakup of SRC pairs in nuclei caused by the probe. Initially it was assumed that the internal quark-gluon structure of nucleons remained unaffected by the nuclear medium, as quark interactions occur at small distances and at higher energy scales than typical nuclear interactions. However, measurements from deep inelastic scattering (DIS) experiments indicated that the momentum distribution of quarks within nucleons is altered when nucleons are bound in atomic nuclei, thereby blurring the distinction between nucleon structure and nuclear structure. This was first identified in DIS measurements by the European Muon Collaboration (EMC) at CERN and became known as the EMC effect. In 1985, M.I. Strikman and L.L. Frankfurt published a paper [13] asserting that SRC could account for the EMC effect, describing it as a short-range yet significant alteration of the structure of individual SRC nucleons within the nucleus. A more recent review of the interpretation of the EMC effect using SRC nucleons and a phenomenological relation between the SRC and EMC effects is given in [14]. Based on a comparison of cross-sections for inclusive deep inelastic scattering processes of electrons on various nuclei measured in different experiments throughout the 1980s, the universality of SRC was established [15, 16, 17, 18, 19, 20, 21].

Up until the early 2000s, experiments specifically designed to search for SRC pairs were lacking. It was not until 2003 that at the Thomas Jefferson Laboratory (JLab) they conducted experiments on inclusive electron scattering on various atomic nuclei [22, 23, 24, 25, 26, 27, 28]: $\mathrm{A(e, e'\ N)}$ and $\mathrm{A(e, e'pN)}$, where N stands for proton or neutron and $\mathrm{A = 4H/C/Al/Fe/Pb}$. Since then, the physics program of Thomas Jefferson Laboratory (JLab) includes SRC experiments on a regular basis. Several SRC experiments were also done at Brookhaven National Laboratory [29, 30]. The results suggested that the high-momentum part of the nucleon momentum distribution is dominated by SRC pairs [31], the probability of detecting an SRC pair in a carbon nucleus is approximately 20%. Notably, the number of two-nucleon SRC pairs significantly exceeds that of multi-nucleon formations, and the likelihood of forming a proton-neutron SRC pair is about 20 times greater than that of a proton-proton pair. The presence of SRC in nuclei results in the fact, that the average kinetic energy of protons in the neutron-rich nucleus exceeds that of neutrons, leading to a new understanding of atomic nucleus structure and potentially contributing to unraveling the mysteries surrounding neutron stars in future research endeavors. These findings align well with theoretical predictions, even considering the limited statistical data, and provide strong motivation for further investigation. A detailed review of the state-of-the art SRC studies can be found in [32].

2 Search for SRC Pairs at the NICA Accelerator Complex

The exploration of short-range correlated (SRC) pairs has recently progressed through measurements conducted at the Joint Institute for Nuclear Research (JINR) at the BM@N spectrometer. The first and second measurements focused on the properties of SRC pairs in inverse kinematics, utilizing a carbon beam with momenta of 48 GeV/c and 44.4 GeV/c, derived from the Nuclotron circular accelerator.

This type of measurements, when the beam ions interact with a proton target, allows for detailed studies of residual nuclear fragments passing through the detection system, opposed to the electron scattering experiments where the residual nuclear system rests inside the target after interaction. The two measurements were performed in 2018 and 2022, respectively, with the focus on hard quasi-free scattering ^{12}C(p, 2p)X (where X is ^{11}B, ^{10}B, ^{10}Be or a few lighter fragments) off a liquid hydrogen target. The BM@N setup was modified through the incorporation of a dedicated two-arm spectrometer (see Figure 1), enabling the detection of the scattered and knocked-out protons at an angle of approximately 30° relative to the beam direction.

This configuration corresponded to elastic pp-scattering at 90° in the center-of-mass system. The probability of interactions with high-momentum nucleons (protons) is enhanced in this case because of a strong dependency of the pp-elastic cross-section on Mandelstam s predicted by auto-model behavior [33]. The detailed outcomes of the initial pilot measurement conducted in 2018 are discussed in [34]. These results were analyzed recently within a theoretical model [35] based on the fractional parentage coefficients of the translationally-invariant shell model (TISM). The successful proof-of-principle measurement confirmed the theoretical framework and facilitated the investigation of the ground state properties of ^{12}C in the quasi-free single-step knockout reaction ^{12}C(p,2p)^{11}B, establishing a solid foundation for the follow-up measurement in 2022. The second experiment focused on increasing the statistics, determining absolute cross-sections, quenching and attenuation at high momentum transfer within the context of quasi-elastic knockout of a single proton. The key objectives of the SRC research also included reconstructing multiple fragments to investigate fragmentation and the mechanism of SRC pair formation.

The experimental setup for the 2022 SRC experiment at BM@N was substantially enhanced compared to the configuration used in 2018. A scheme of the upgraded setup is shown in Figure 1. Two new scintillator counters were designed and manufactured to measure the start time and charge of the incoming beam ions, along with three scintillator beam detectors for determining the charge of the fragments (labeled "Sci" in Figure 1). Each scintillator detector was equipped with two photomultiplier tubes (PMTs), and the light signal was transmitted from the scintillator to the PMT using plexiglass fish-tail light guides, marking a departure from 2018 when each detector had a single PMT and air light guide. Additionally, a new compact and robust cryogenic liquid hydrogen target [36] was developed and manufactured at JINR.

The two-arm spectrometer was further augmented with new detectors compared

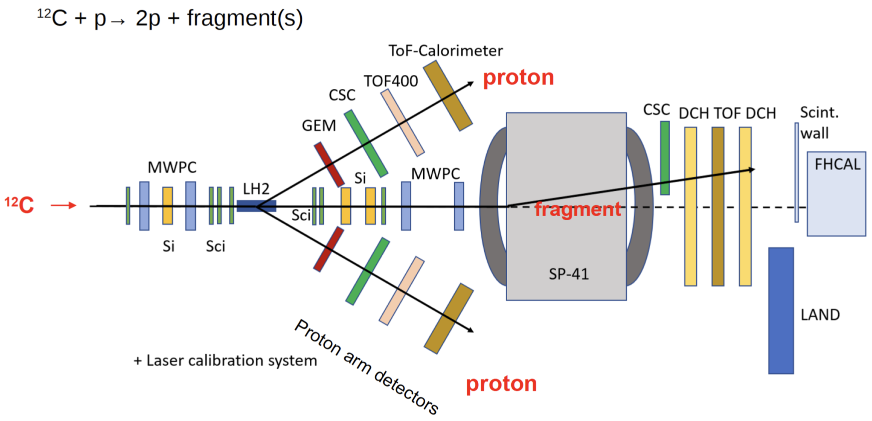

Figure 1: Scheme of the experimental setup. Not to scale.

to 2018 configuration. Each arm now included a Gas Electron Multiplier (GEM) [37] coordinate detector plane, a Cathode Strip Chamber (CSC), and a TOF400 time-of-flight detector based on Multi-gap Resistive Plate Chamber (MRPC) technology. A new large TOF-calorimeter with the dimensions of 1.5 m in width and 2 m in height, was installed in each arm, consisting of a scintillator layer for timing information and three layers of LAND modules [38] that provided statistical separation of protons and pions. The nuclear fragments in the final state were measured along the beam with two pairs of double-sided silicon detectors. Another CSC was added downstream the SP-41 analyzing magnet to track light fragments at large angles, while the scintillation wall at the end of the experimental hall offered information on the charge of practically each fragment in the final state. Additionally, a new laser calibration system with optical fibers connected to all scintillation detectors was implemented for time calibration without the need for a beam. The main physics trigger was generated based on signals from the beam scintillation counters and the TOF scintillator layer in both arms.

3 Prospects for Studying SRC at JINR

Currently, data analysis from the 2022 experiment is underway, and the findings from this analysis will be instrumental in refining the physics program for forthcoming measurements of SRC at JINR. The upcoming measurements are planned to take place at the HyperNIS experimental area. Concurrently, engineering efforts have been commenced to establish a new modern experimental complex dedicated to the study of SRC in a newly designated experimental zone. The SRC physics program at JINR has several pivotal aspects: the availability of unique high-energy ion beams generated by the NICA accelerator complex, coupled with the capability to conduct complete exclusive measurements in inverse kinematics at both the BM@N and HyperNIS setups. Special emphasis is placed on utilizing polarized deuteron beams with high energies, reaching up to 6 GeV/nucleon, and exhibiting high intensity. The dominant fraction of SRC pairs are the neutron-proton pairs with quantum numbers of a deuteron, so that the measurements of quasi-elastic proton knockout p(d, 2p)n at high energies and large momentum transfers, and the ability to detect the leading particle and the spectator partner, presents opportunities to explore previously uncharted or less studied facets of SRC. These include investigating the mechanisms of SRC pair formation and their spin structure, identifying three-nucleon correlations, refining nucleon-nucleon potential at high resolution scales, establishing relationships between SRC properties and their dependencies on nuclear density and asymmetry.

4 Summary

As a many-body system, SRC can serve as a laboratory for studying cold dense nuclear matter across various scales, including resolution, density, and asymmetry. JINR's unique high-energy ion beams facilitate exclusive measurements in inverse kinematics that are essential for SRC research. The SRC project at JINR has successfully commenced with two measurements at the BM@N experimental area in 2018 and 2022, and continues to evolve. The physics program for future SRC experiments is being developed based on insights gained from previous studies, along with contemporary advancements in both experimental and theoretical physics related to SRC. The state-of-the-art international SRC effort includes experiments with different probes: electron, proton, ion, and photon [39], as SRC is a feature of nuclear matter, and usage of different reaction mechanisms helps to focus on the properties of the nucleus eliminating the reaction effects. The SRC project at JINR harmoniously complements the international SRC effort, thereby contributing to the global understanding of nuclear structure and the fundamental interactions governing nucleon behavior. As the project progresses, it is expected to yield significant insights that will enhance the collective knowledge in the field of nuclear physics.

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