NUCLEAR PHYSICS

Knock-out interpretability

A detailed analysis of a nucleon-knockout experiment has put forward a methodological roadmap for overcoming ambiguities in the interpretation of the data — promising access to the nuclear wave functions in unstable nuclei.

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On Earth, there are nearly 300 stable nuclei, exhibiting a wide variety of nuclear properties. But because their stability means that the excess of the ratio of neutron to proton numbers is limited to about 60%, they can only offer incomplete answers to questions about the evolution of matter in the Universe. And although current nuclear theories are able to reproduce data for stable nuclei, they diverge dramatically when applied to nuclei with a large neutron-to-proton imbalance. Writing in *Nature Physics*[1], Maria Patsyuk and co-authors from the BM@N Collaboration showcase the potential of conducting nucleon-knockout experiments to extract reliable and detailed information about the wave functions in unstable nuclei.

The team studied proton–carbon collisions that result in the emission of at least one bound proton from the carbon nucleus, as illustrated in Fig. 1. The experiment was conducted in what is known as inverse kinematics in nuclear physics jargon: a mode in which an accelerated ion collides with a stationary proton. In this configuration, nucleon-knockout experiments are a powerful tool to study unstable nuclei[2,3].

By exploiting energy–momentum conservation in these experiments, one can infer the probability to find nucleons with certain quantum numbers and a fixed momentum, which provides access to the nucleonic wave functions in momentum space. But to connect the measured nucleon-knockout signals with qualitative information about the wave functions, challenges connected with the opaqueness of the nuclear medium need to be overcome.

On its way to and from the knockout point, the projectile proton (from the ion's point of view) interacts with the other nucleons in the ion. The effects of these initial- and final-state interactions need to be described — and the quality of the interpretation of the measured reaction probabilities often hinges on the availability of such models. Thus, the impact of the initial- and final-state interactions needs to be controlled by finding the optimum kinematics of the proton–ion collision.

In the experiments conducted at the Joint Institute for Nuclear Research, carbon-12 ions at about four times their rest mass are collided from a stationary liquid-hydrogen target. In particular, the team was interested in studying collisions involving two asymptotically free protons and a residual bound boron or beryllium fragment. This reconstruction method allowed them to extract complete information about the nature of the fragments, and consequently to infer the energy and momentum of the proton in carbon-12 that was bound before the collision.

This approach selects a subset of nuclear reactions, which should be relatively free from interpretational ambiguities and be suitable to extract reliable information about the nucleonic wave functions. Because the wave functions for nucleons with a well-defined quantum number in the stable carbon-12 nucleus are known, this method could be put to the test. And indeed, Patsyuk and colleagues demonstrated convincingly that the proton momentum evolution of the measured signals with a boron-11 fragment is fully compatible with the known wave functions of a bound proton in carbon-12.

Single-nucleon knockout experiments are well suited to probe the wave functions at momenta below the Fermi momentum, which is equal to about one-fourth of the nucleon's rest mass. To study their higher-momentum components, one needs to go one order higher in proton number to two-nucleon knockout processes. As evidence suggests, the majority of these components stem from nucleon pairs getting closer and closer to each other in a dense nuclear environment. In nuclear jargon, one refers to this phenomenon as 'short-range correlations'.

Patsyuk and colleagues not only established a methodology to probe the low-momentum parts of the nuclear wave functions but also studied processes with two knocked-out protons and a bound boron-10 or beryllium-10 fragment. With these selections, they identified

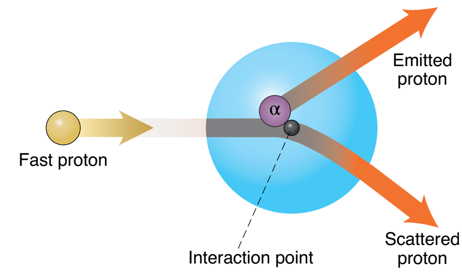

Fig. 1 | Single-nucleon knockout measurement. This schematic illustrates the interaction of an impinging proton with a bound nucleon in a target nucleus. Initial- and final-state interactions refer to the interactions before and after the actual knockout interaction point between the impinging and bound nucleon, which complicate the interpretation of the data. Therefore, the connection between the measured cross-sections and the wave functions of individual nucleons, such as nucleon-α or pairs of nucleons, is not straightforward.

collisions that give rise to the emission of short-range correlated nucleon pairs, pushing the limits of experimental feasibility further by studying rare events. Only 23 events with boron-10 and 2 events with beryllium-10 fragments were detected, which reflects the fact that nuclear high-momentum components have a relatively small probability to occur. Both the momentum dependence and the selectivity — the number of events with a beryllium-10 fragment versus those with a boron-10 fragment — of the signal provide information about the short-range behaviour of nucleon pairs in carbon-12 that illustrates the high potential of the developed methodology.

In nuclear physics, the synergy between theory and experiment is pivotal. To improve our understanding of compact objects such as neutron stars, we need to gain insight into the nuclear equation of state for neutron-to-proton ratios that are larger than those accessible with stable nuclei[4]. As the results of Patsyuk and colleagues[1] showcase, high-energetic proton–ion collisions allow the extraction of detailed information about the nuclear wave functions — provided the experiments adopt a very stringent selection of the fragments resulting from the collision. The proposed methodology can be used to probe unstable nuclei with a high neutron-to-proton imbalance at upcoming experimental facilities, such as the Facility for Rare Isotope Beams in the United States or the Facility for Antiproton and Ion Research in Germany, and help with the theoretical interpretation of the upcoming data. ❐

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Competing interests

The author declares no competing interests.