Recent Advancements in Knockout Reactions.

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The nuclear shell model assumes that nucleons move in an average field created by the remaining nucleons. In addition to this average field, Hartree-Fock calculations account for the residual nucleon-nucleon (N-N) interactions, which consist of both long-range and short-range components. The long-range residual interactions lead to the clustering of nucleons into d, t, ^{3}He or α-particles within nuclei. Conversely, the short-range residual interactions between similar nucleons result in pairing. These residual interactions populate different shell model single-particle states to varying extents. The occupation numbers of these single-particle states are referred to as the spectroscopic factors.

The spectroscopic factors and momentum distributions provide detailed information about the bound wave function. Proton knockout reactions from nuclear ground states, using proton beams, are considered ideal tools to probe the wave function in terms of momentum distributions and spectroscopic factors. Theoretical analysis of these (p,2p) reactions is performed using the Distorted Wave Impulse Approximation (DWIA), where the basic reaction is considered to be a p-p scattering. Detailed DWIA analysis of various (p,2p) reactions on low and medium mass nuclei at medium energies of around 100-300 MeV has had limited success[1]. This is due to various approximations made in the DWIA mechanism. Some of these include the Zero Range (ZR) approximation for the p-p t-matrix, neglect of off-shell (binding of the proton in the target nucleus) effects, and the choice and problems of distorted potentials for the protons because of their spins and uncertainties of the bound proton wave function. All these uncertainties cast doubt on the accuracy of the predictions.

To address the uncertainties in DWIA analyses, we have started investigation on both theoretical and experimental fronts. On the theoretical side, efforts are being made to derive more realistic finite-range t-matrix effective interactions incorporating off-shell effects and realistic p-p interactions, and to perform the complex and lengthy finite-range calculations for the transition matrix element for knockout reactions[2]. Experimentally, high-energy heavy ions on hydrogen targets in reverse kinematics are used to perform proton or neutron knockout reactions. The advantage of GeV/u heavy projectiles is the ability to use secondary radioactive beams of sufficient intensity to study halo nuclei and nuclei of astrophysical importance. However, high energies bring their own problems, such as the use of the eikonal approximation and the Glauber Model to describe the scattering state for the reaction[3, 4]. Additionally, the kinematics are not always favorable for the magnetic spectrometers, affecting the choice of recoil momenta and the determination of ℓ-values and other bound state parameters. Different models, such as the no-core shell model or ab-initio Monte Carlo wave functions, used to extract effective bound state wave functions or overlap integrals, provide nearly a factor of two difference. Naturally, approximations built into these models come with their own uncertainties[5].

Beyond the single-particle structure properties observed in (p,2p) knockout reactions, examining the pairing or clustering aspects reveals interesting results in α-cluster knockout or even heavier cluster knockout reactions, such as $^{24}\mathrm{Mg(C, 2C)C}$ or $^{24}\mathrm{Mg(O, 2O)}^{8}\mathrm{Be}$ reactions[6, 7]. While (p, pα) reactions provided reasonable estimates of alpha clustering probabilities, (α, 2α) knockout reactions exhibited anomalies in the spectroscopic factors, dependent on changes in incident energies[8]. This was resolved by understanding the α-α t-matrix effective interaction[9]. The α-α interaction changes due to the strong binding of nucleons in the α-particles. When two α-particles attempt to overlap, antisymmetrization prevents this overlap below a certain relative energy, which depends on the nucleon's separation energy from the α-particle. It was concluded that this effectively corresponds to a repulsive core interaction below a lab α energy of approximately 170 MeV for the α-α interaction, resolving the uncertainty in (α, 2α) reactions.

Coming to even heavier cluster knockout one can compare results from ^{16}O(α, 2α)^{12}C reactions with the $^{16}\mathrm{O}(^{12}\mathrm{C}, 2^{12}\mathrm{C})\alpha$ reactions and find them providing similar spectroscopic factors and momentum distributions from the α-^{12}C clustering to form ^{16}O. This should have been expected and was found. However, similar to the (α, 2α) reactions the $(^{12}\mathrm{C}, 2^{12}\mathrm{C})$ reactions FR-DWIA analysis required ^{12}C-^{12}C interactions vertex also to have repulsive core besides attraction at larger distances. Another point to emphasize here is that these α-α interactions are obtained from normal attractive Woods-Saxon type of potentials which fit the phase shifts for different partial waves, hence these α-α optical potentials used to derive the knockout t-matrix effective interaction are ℓ-dependent. The same has been found to be case for ^{12}C-^{12}C optical potentials to be ℓ-dependent repulsive core. A bye-product of these ℓ-dependent repulsive core may be found in describing the ^{12}C-^{12}C high lying high ℓ-resonances found in ^{24}Mg*[10].

The high excitation energy ℓ-resonances found in ^{24}Mg* have led to a revival of the Heavy Cluster structure model in the ground and excited states of heavier nuclei[11]. According to the Harvey prescription, predictions of α cluster structure suggest the presence of various heavy clusters, such as ^{12}C-^{12}C, in the ground state of ^{24}Mg. However, a heavy cluster knockout experiment on the $^{24}\mathrm{Mg}(^{12}\mathrm{C}, 2^{12}\mathrm{C})^{12}\mathrm{C}$ reaction at approximately 100 MeV disproved this, showing no ^{12}C-^{12}C structure in $^{24}\mathrm{Mg}_{(g.s.)}$[6]. Conversely, recent experiments around 120 MeV involving the ^{16}O knockout from $^{24}\mathrm{Mg}_{(g.s.)}$ revealed significant $^{8}\mathrm{Be}_{(g.s.)}$ and $^{16}\mathrm{O}_{(g.s.)}$ clustering[12]. With similar kinematics, ^{24}Mg* resonance may decay into $^{16}\mathrm{O}_{(g.s.)}$ and $^{8}\mathrm{Be}_{(g.s.)}$. An event mixing technique using the Monte Carlo method has been developed to distinguish between direct knockout and resonance contributions in the Dalitz plot[12, 13].

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