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Review

Breakup reactions of light and medium mass neutron drip line nuclei

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ABSTRACT

The formal theories of breakup reactions are reviewed. The direct breakup mechanism that is formulated within the framework of the post-form distorted-wave Born approximation, is discussed in detail. In this theory, which requires the information about only the ground state wave function of the projectile, the fragment–target interactions are included to all orders while fragment–fragment interaction is treated only in the first order. We put special emphasis on the breakup reactions of the near neutron drip line nuclei on heavy nuclear targets, which are dominated by the pure Coulomb breakup mechanism. The applicability of this theory to describe such reactions involving both spherical as well as deformed projectiles, is demonstrated by comparing the calculations with breakup data for total, energy and angle integrated cross sections and momentum distributions of fragments emitted in such reactions. Roles played by the pure Coulomb, pure nuclear and the Coulomb–nuclear interference terms in describing the breakup observables are discussed. Postacceleration effects in the Coulomb breakup of neutron halo nuclei are elaborated. The function of the pure Coulomb breakup mechanism in the one-neutron removal reactions of the type $A(a, b\gamma)X$ on heavy target nuclei is underlined. The relationship between the parallel momentum distribution of the fragments and the break down of the magic numbers as the neutron drip line is approached, is highlighted.

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1. Introduction

Of the 7000 particle stable nuclear species predicted theoretically only about 300 stable isotopes are found in the nature. Major part of our current understanding of nuclei, the strongly interacting finite quantum many-body systems, has emerged from the studies made with the beams of these stable isotopes and a few long-lives radioactive ones that can be used as beams. There are a large number of nuclei having very short half-lives and very small one- or two-nucleon separation energies. During eighties and nineties it became possible to perform experiments with the beams of short-lived radioactive nuclei due to advances made in the technology of accelerators, ion sources and mass separators that enabled to produce, separate and accelerate the radioactive ions [1–7]. This led to the revelation of new features in the structures of such nuclei (see, e.g. Refs. [1,2,8–31]).

These nuclei lie very close to drip lines (the limit of neutron or proton binding). Nuclei at extremes of binding can exhibit behaviors which are quite different from those of the stable isotopes. We still lack a fully microscopic understanding of the stability of these unique many body systems. These nuclei are important also in studies related to nuclear astrophysics [32–35]. Nuclear processes are responsible for the energy generation in all the stellar systems. Since radioactive nuclei are involved in many astrophysical sites, knowledge of their properties are crucial for the understanding of the underlying astronomical processes. The rapid neutron capture (the r-process) together with the slow neutron capture (the s-process), which are the dominant mechanisms for the nucleosynthesis of heavy elements above the iron isotope, pass mostly through the neutron rich region [36–39]. The properties of these nuclei are important inputs to theoretical calculations on stellar burning, which otherwise are often forced to rely on global assumptions about nuclear masses, decays and level structures extracted from the stable nuclei.

The first generation measurements involving neutron rich nuclei [1,40–47] have confirmed the existence of a novel structure in these systems where a low density tail of loosely bound neutrons extends too far out in the coordinate space as compared to the stable core (also known as the neutron halo—a term introduced in Ref. [48], in the context of the bulk of the neutron density extending further out in space than the proton density). The quantum mechanical tunneling of very loosely bound valence neutrons leads to the formation of such a structure (see, e.g. Ref. [49]). The existence of neutron halo has been confirmed in ^{11}Be [42,43,45],^{14}B [50,51],^{19}C [44,50,52] (one-neutron halo), and ^{6}He and ^{11}Li [1,53],^{14}Be [54,55], and ^{17}B [55] (two-neutron halo). Some proton halo nuclei have also been identified, they include ^{8}B [56–58],^{17}Ne [59],^{20}Mg [60], and ^{26,27,28}P [61]. More details of the experimental situation can be found in Refs. [18,62–64]. Recent reviews of the experimental work on halo nuclei are presented in Refs. [65,66].

New generation of RNB facilities with drastically enhanced performance and capability of producing beams of radioactive nuclei in the medium mass region have been planned at several places around the world (see, e.g., [67]). These include RIBF at RIKEN in Japan, which is already operational [68], FAIR at GSI in Germany [69], FRIB in Michigan State University in USA [70], SPIRAL2 at GANIL in France, [71], and ISOLDE in CERN Geneva [72].

First series of experiments performed at the RIBF at RIKEN have already added a new dimension to the study of the unstable neutron rich nuclei. It is now possible not only to produce medium mass neutron rich nuclei in the vicinity of the neutron drip line but also employ them as beams to initiate their reactions on nuclear targets [73]. These developments provide an excellent opportunity to perform quantitative study of the single particle structure and the shell evolution in this region which could fall in the island of inversion [74]. Breakup reactions performed at RIBF with beams of ^{31}Ne and ^{37}Mg isotopes on a Pb target at beam energies around 240 MeV/nucleon have already revealed that these nuclei have one-neutron ($1n$) halo structure [75,76]. Both these nuclei lie in the island of inversion and observation of the halo phenomena in such nuclei, signals major changes in the shell evolution in these systems as compared to that seen in the spherical ones [77–79]. At the same time, compared to the light $1n$-halo nuclei, which have predominant s-wave neutron plus core configurations [20,45,80–82], the properties of halo components in heavier nuclei could be very different due to more complex mixing of the configurations.

Halo nuclei, in most cases, have only one bound state (the ground state) and a broad featureless continuum. Thus, methods of conventional nuclear structure studies, namely, measurements of energies and spin-parities of excited states are not applicable in these cases. However, due to their small binding energies, they can be easily excited above their particle

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