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# Towards the drip lines of the nuclide landscape

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In the paper we review the recent progress of studies in unstable nuclei, mainly affiliated with the facilities of radioactive ion beams in China, including both experimental and theoretical aspects of researches. Many experiments for reactions, decays and structures have been performed targeting better understandings of properties of unstable nuclei. Special experimental measurements related to nuclear astrophysics have been done to seek insights into the processes of syntheses of elements in the universe. Theoretical calculations have provided many useful predictions on the behaviors of unstable nuclei, with model developments. Studies covered many mass regions from light to superheavy nuclei, giving plenty of information about the structures of unstable nuclei, towards the limits of existence of atomic nuclei.

**unstable nuclei, radioactive ion beams, nuclear astrophysics, experiment, theory**

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In the universe the number of stable nuclei is less than 300. But theories predicted that there would exist more than 7000 bound nuclides (see e.g. the recent theoretical paper [1]). Today, about 3000 nuclides have been known experimentally (see e.g. [2]) with the heaviest element of $Z = 118$ synthesized in the laboratory [3].

Usually, nucleons inside an atomic nucleus are bound tightly due to strong nucleon-nucleon force. With increasing the number of neutrons or protons, however, outer neutrons or protons become less and less bound, with separation energy approaching zero. The nuclei with zero separation energy of the outermost nucleon(s) form the so-called drip lines (proton or neutron drip line) of the nuclide landscape, indicating the limits of existence of atomic nuclei. Most of nuclei belong to the category of unstable nuclei. Thanks to the advance of modern experimental techniques with radioactive ion beams (RIB), experimental studies have reached the limits in light mass regions up to $Z \approx 30$ in the proton-rich side and $Z \approx 10$ in the neutron-rich side. The unstable nuclei are motivating our researches in both experiments and theories.

In neutron-rich mass regions, for example, some exciting phenomena have been observed, such as neutron halo [4], neutron skin, giant dipole resonance and pygmy dipole resonance (see e.g. [5]). Also, new shell closures have been found. For instance, both experiments and theories have pointed out that the neutron numbers of $N = 14$ and 16 are new magic shells in neutron-rich oxygen isotopes [6–11]. The new findings are challenging current nuclear models. More experimental and theoretical studies are demanded for RIB physics. For this, experimental colleagues in China with RIB facilities mostly in Lanzhou and Beijing have achieved plenty of experimental studies on unstable nuclei [12]. At the same time, many theoretical works have provided useful information for experimental studies [13]. This paper outlines some of recent experimental and theoretical works done within a ”973 Program” of China.

## 1 Experimental and theoretical studies of unstable nuclei

Using RIB facilities in Lanzhou and also in RIKEN, Ye et al. performed several experiments investigating the reaction mechanisms and structures of light unstable nuclei, involving the different types of reactions including scattering, breakup and knockout [14–16]. Particularly, they have succeeded an

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experiment on the knockout reaction for the unbound $^8$He nucleus [17], performed at RIKEN with an intense $^8$He beam at 82.3 MeV/u supplied by the RIPS beam line. The authors reported for the first time the discrimination of the core fragment knockout and valence nucleon knockout reaction mechanisms at medium energy range, by the use of the recoil proton tagging technique [17]. An earlier reaction experiment for the halo $^6$He nucleus was done at RIKEN [18]. The quasielastic scattering of $^6$He on a $^{12}$C target was measured at 82.3 MeV/u. The measured differential cross-sections show a large enhancement at small angles relative to the Rutherford cross-section, similar to those observed at lower energies for the scattering of halo nuclei [18]. The knockout reaction mechanism for the $^6$He projectile was studied as well [19]. Their experiments provide useful experimental data for further understandings of unstable helium isotopes and also give some general information about the mechanism of reactions involving unstable nuclei. These may be used to extract the cluster structure information of unstable nuclei as well.

Heavy ion reaction around the Coulomb barrier is another interesting topic in nuclear physics. Zhang et al. have made systematical experimental investigations to get insight into the mechanisms of reactions near Coulomb barriers in different mass regions [20–22]. The experiments were performed at the HI-13 tandem accelerator of the China Institute of Atomic Energy (CIAE) Beijing. Fusion excitation functions have been measured for the $^{32}$S+$^{90}$Zr and $^{32}$S+$^{96}$Zr reactions near and below the Coulomb barriers [21]. Their experiment gave that the sub-barrier cross sections for $^{32}$S+$^{96}$Zr are much larger than for $^{32}$S+$^{90}$Zr, which was well explained by their coupled-channel calculations with considering inelastic excitations [21]. In the experiment for the $^{32}$S+$^{184}$W reaction, the angular distributions of fission fragments at center-of-mass energies of 118.8, 123.1, 127.3, 131.5, 135.8, 141.1 and 144.4 MeV were measured [22]. The experimental fission excitation function was obtained. Calculations by the dinuclear system model (DNS) were performed and reproduce well the data [22]. Their experimental and theoretical investigations have provided better understandings of mechanisms of reactions near the Coulomb barrier.

Liu and his colleagues at CIAE and also from the Chinese nuclear community are pushing two important RIB-facility projects moving on in China [23]. As the key facility, the Beijing rare ion beam facility (BRIF) is under construction at CIAE. As a longer term project, the China advanced RIB facility (CARIF) has been proposed. The ISOL type facility BRIF is composed of a 100 MeV 300 μA proton cyclotron, an ISOL with mass resolution of 2000, and a superconducting LINAC of 2 MeV/q. The CARIF facility is planned to use both ISOL and PF techniques, which will be based on the China advanced research reactor CARR, with an ISOL separation of fission fragment, post acceleration to 150 MeV/u, and the fragmentation of neutron-rich fission fragment beam. We can expect that these two RIB facilities will play important roles for the studies of unstable nuclei. The details of the two facility projects can been found in [23].

Diproton emission is an exotic decay mode which happens in proton-rich nuclei. Though only a few cases have been observed, the new decay mode is motivating many aspects in both experiment and theory. Ma et al. at SIAP and Lin et al. at CIAE have performed experiments to study the possibility of diproton decays in mass region close to the proton drip line [24–27]. In the experiment [24] with an earlier experiment which focused on the structure the proton-rich Al isotopes [28], the authors measured two-proton relative momentum distributions from the break-up channels $^{23}$Al→p+p+$^{21}$Na and $^{22}$Mg→p+p+$^{20}$Ne at the energy of 60 − 70 A MeV, giving the evidence of diproton emissions from exited $^{23}$Al and $^{22}$Mg [24]. In the experiments [25–27], the authors obtained the relative momentum, opening angle, and relative energy of two protons, as well as the invariant mass of the final system with complete-kinematics measurements for proton-rich $^{28}$P, $^{28,29}$S and $^{17,18}$Ne. Two-proton emissions were observed from the excited states of the proton-rich P, S and Ne isotopes [25–27]. These experiments enriched the new phenomenon of diproton decays. The neutron halo structure of an excited state in $^{13}$C is addressed experimentally [29].

Nuclei near drip lines play important roles in the processes of syntheses of elements in the universe. Experiments related to nuclear astrophysics have been carried out at HIRFL in Lanzhou [30] and at the HI-13 tandem accelerator in Beijing [31]. Excited states in $^{18}$Ne, which could affect significantly the reaction rate of the key stellar $^{14}$O($\alpha$,p)$^{17}$F reaction, have been studied via the proton elastic scattering of $^{17}$F+p. Clear proton resonances in $^{18}$Ne were seen [30]. Lithium isotopes play special roles in the process of nucleosyntheses. Reaction experiments involving lithium were performed to investigate the role of lithium isotopes in nucleosyntheses including the primordial lithium abundance [31]. The data obtained in these experiments have given some better understandings of problems related to astrophysics [30–37].

The $\gamma$ spectroscopy of nuclei is a powerful tool in both experiment and theory to probe the structures of nuclei. Many successful spectroscopic experiments have been done by Chinese colleagues in the recent years [38–40]. High-spin states in $^{161}$Er have been studied experimentally with three rotational bands built on different configurations extended to higher spins, and signature inversions were discussed [38]. The high-spin states in neutron-rich $^{103}$Nb, $^{107,109}$Tc have been investigated by prompt $\gamma$-$\gamma$-$\gamma$ coincident measurement [39,41], observing one- and two-phonon $\gamma$-vibrational bands. Particularly, it was the first time to observe two-phonon bands in odd-Z nuclei [39, 41]. A new rotational band was identified in $^{188}$Au for the first time with an assignment of the $\pi h_{9/2} \otimes \nu i_{13/2}$ configuration [40]. Various possible shapes in $^{188}$Au were discussed [40]. Many other experiments for the $\gamma$ spectroscopy of nuclei in different mass regions gave new experimental results which lead to new insights into the structures of nuclei investigated [42–52].

The $\beta$ decay has become an important experimental method to study the properties of unstable nuclei. Due to large decay energies ($Q$ values) in neutron-rich nuclei, daughter nuclei can be populated to highly excited states, which provides a good ground to study the structures of neutron-rich nuclei by measuring the $\gamma$ spectroscopy or particle emissions. Using the PKU neutron sphere and wall, the experiments which studied the $\beta$ decays of neutron-rich $^{18,21}$N were performed at HIRFL in Lanzhou [53–56]. The first spectroscopic data for the $\beta$ decay of $^{21}$N was obtained with $\beta$-n, $\beta$-$\gamma$, and $\beta$-n-$\gamma$ coincidence measurements. Thirteen new $\beta$-delayed neutron groups are observed. The half-life for the $\beta$ decay of $^{21}$N is determined to be 82.9±7.5 ms which gave an accurate measured value so far [54].

Theoretical studies cover many different topics including cluster structures and decays [57–62], resonances in unstable nuclei [63–65], heavy and superheavy nuclei [66–70] (see [71] for the experimental synthesis of $^{271}$Ds), rotational states [72–80], shape transitions [81–83], mean-field models [84–87], nuclear symmetry energy [88–93] and some other topics [94, 95]. The theoretical works have motivated model developments, and also provided many useful theoretical predictions and explanations for the experiments.

## 2 Summary

In the past few years, great progress in the studies of unstable nuclei has been made using the current RIB facilities in China. Experimental reaction studies which involved unstable nuclei gave interesting results about the structures of weakly-bound or unbound neutron-rich nuclei. Heavy ion reaction experiments led to the further understanding of mechanisms of reactions around the Coulomb barrier. Several diproton decays were observed challenging current experimental techniques and theoretical models. Nuclear astrophysics experiments provided new experimental results on the reaction rates of some key stellar reactions. The studies of nuclear $\gamma$-spectroscopy have been always active. Many spectroscopic experiments have been performed providing new insights into the structures of nuclei investigated. For unstable nuclei, $\beta$ decay is a common decay mode. The $\beta$-decay experiments adopting the neutron sphere and wall have showed advantage using $\beta$-decay channels to study the structures of unstable nuclei. To reach a higher goal of experimental researches, the RIB facility called the Beijing rare ion beam facility (BRIF) is under construction at CIAE. As a longer term project, the China advanced RIB facility (CARIF) has been proposed. Theoretical studies are productive, which involve almost all aspects of nuclear structures, reactions and astrophysics.

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