Structure study of light unbound nuclei near drip line*

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Abstract Some experimental techniques and theoretical analysis on unbound nuclei structure study are briefly introduced in this article. The unbound nuclei structure investigation can inspect the reliability of theoretical calculation, and is also important to extend the modern nuclear structure model to exotic nuclear regions. With the recent development of radioactive Ion Beam (RIB) facility and some new experimental methods, the structure of unbound nuclei near drip line can be studied in experiment.

Key words unbound nuclei, nuclear structure, resonant elastic scattering, isobaric analog state

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1 Introduction

In recent years, radioactive nuclear beam (RNB) physics have become one of the most interesting aspects of nuclear physics. From the exotic nuclei cross section and momentum distribution measurement at the beginning to exotic nuclear structure and spectroscopy study later, with updating and developing new RNB facilities as well, the investigation of spectroscopy of nuclei far from the beta stabile line, structure of halo nuclei and the key reaction rate of nuclear astrophysics et al., have become the hotspot in nuclear physics study. The unbound nuclei structure, decay character, and reaction kinematic investigation related with the astrophysics are important in these hotspots, so the study of high isospin and low binding energy light nuclei at extreme conditions is the benchmark to inspect the nuclei shell model. Some new experimental phenomena, for examples, halo nuclei, new shell model magic number, and ground state level intruder, double proton decay et al., have been observed in experiment, they increase the interesting to investigate structure characters of the unbound nuclei near drip line[1—4]. Some halo nuclei studies also need more core information, for instance, halo nuclei ^{11}Li needs some ^{10}Li nuclei low energy state parameters and wave functions. As we known, the even mass nuclei of helium isotopes are bound and the odd mass nuclei are unbound nuclei, the study shows that the helium isotopes have α cluster structure, ^{6}He is the α+2n system and ^{8}He is α+4n system, they are well known as halo nuclei, odd isotopes of ^{5,7}He are unbound nuclei, understanding of exotic nuclei structure need more precise experimental measurement about ^{5,7,9}He nuclei[5, 6].

For unbound nuclei near drip line, the direct measurement is very difficult; methods generally used are transfer reaction, projectile multi-fragment reaction and resonant elastic scattering. Indirect method, isobaric analogue state(IAS) of mirror nuclei is always used in measurement via the reaction $(A,Z)+(Z=1)\rightarrow(A+1,Z+1)$ (as shown in Fig. 1). Because the

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neutron rich nuclei have very big N/Z ratio, it IAS has large neutron decay rate than the proton decay, the compound nuclear isospin is $T_> = T_Z + 1/2$, and T_Z is the isospin of (A, Z) nuclei, considering the isospin is a good quantum number, the total wave function can be expressed as[7, 8]:

$$\psi(T_>) = \frac{1}{\sqrt{1+2T_z}} (\psi_{A,Z}\psi_p + \sqrt{2T_z}\, \psi_{A,Z+1}\psi_n).$$

If the reaction can be distributed to this IAS, the neutron decay to daughter nuclei wills prior to the proton decay, neutron decay possibility will be higher than proton decay. We can measure proton, neutron, and related gamma rays, or the coincidence measurements according to the emitted particle of exit channels.

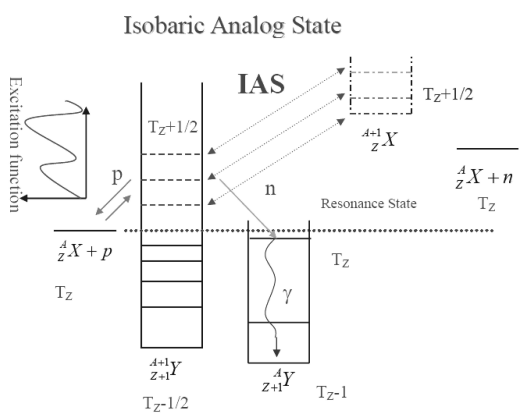

Fig. 1. The schematic views of IAS.

2 Experimental techniques

The classical methods in nuclear structure study are the direct reactions induced by light nuclei, for example the elastic scattering, inelastic scattering and few nucleons transfer reactions. But these methods are limited to stable beams, and for many isotopes with short life time, it is difficult to make as a target. With the appearance of RNB, project candidates are broadened in large scales. Because the RNB generally has very weak beam intensity, the inverse kinematics methods have also be used in experiment, i.e. bombarding the light target such as proton, deuteron, triton and helium. There are four dominating experimental measurement methods in the unbound nuclei structure study [9]:

1) Projectile multi-fragments, are adopted in many experiments, for instance in ^{11}Be→ n+^{10}Be, ^{14}Be→ n+^{13}Be, ^{14}B→p+^{13}Be reactions. High energy RNB bombards on heavy target or light target, proton, neutron, or other light ions from multi-fragments reaction can be measured, or coincident measurement of the decay particles from unbound nuclei, then the unbound nuclei structures can be studied from the relative energy spectrum of the measured particles[10].

2) Transfer reactions, are adopted in ^{9}Li(d,p)^{10}Li, ^{8}He(p,d)^{7}He, and ^{8}He(p,n)^{8}Li (0^+,T=1) reactions, in which the emitted particles are unbound nuclei, then they decay to some light stable particles, such as proton, deuteron, Triton and so on, coincident measurements of these secondary decay particle and their energy spectrum analysis can give the existence signal of the resonance state of the unbound nuclei.

3) Resonant elastic scattering, is used in ^{8}He(p,p)^{8}He reaction. According to different detectors used, there are two type of experiments, one of which use the Time Project Chamber (TPC) to measure the recoiled proton, record the total tracks and many angles, for example MAYA detector in GANIL[11, 12]. Another is multi-detector array measurement in zero degree (corresponding to C.M. 180°) in LAB system to measure the recoiled proton, in this kind measurement either gas target or solid target is used, main gas targets are CH_4, C^4H_{10}, or polyethylene solid target[13].

4) γ measurement by Doppler shift, this is a new techniques, used in ^{6}He+p→^{7}Li*→n+^{6}Li(0^+,T=1)→ n+^{6}Li(1^+,T=0) reaction in the first time, γ ray coming from the decay of ^{6}Li(0^+,T=0) to ^{6}Li(1^+,T=0), decay energy is 3.56 MeV. In inverse kinematic reactions, the velocity of excited daughter nuclei approximates to the velocity of projectile, and the γ decay time is less than the stopping time in measurement matter, so Doppler shift of the character γ ray strongly depends on the beam velocity in the interaction, which gives some total excitation function information[14].

3 Theoretical analysis

For the transfer reaction, for example, the ^{8}He(p,d)^{7}He→^{6}He+n reaction, The energy spectrum of coincident neutrons or light particles have been measured in experiment, then fit the spectrum via cross section equation with Breit-Wigner expression, obtain the decay energy, isospin, decay width of resonant state parameters. In many experiments, the R-matrix theory was adopted to analyze the resonant excitation function. In R-matrix theory, the elastic scattering amplitude can be decomposed in two components, resonant part and non-resonant part. Since the amplitude of non-resonant partial wave function is spin independent, and then the Breit-Wigner resonant terms can be simplified to following well known expression[9, 15]:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} \propto \left| \sum_{l=0}^{\infty} \left[(1-\mathrm{e}^{2\mathrm{i}\delta_l})(2l+1) + \mathrm{e}^{\mathrm{i}\delta_{lr}} \frac{\Gamma_{\mathrm{pl}}}{(E-E_{\mathrm{R}})+\mathrm{i}\Gamma_{\mathrm{T}}/2} \right] p_l(\theta) + f_{\mathrm{c}} \right|^2 ,$$

where $\delta_l = \delta_{l_r} + \delta_{l_i}$, is the complex optical model phase shift, Γ_{pl} is the elastic scattering width, Γ_{T} and E_{R} are the total width and the energy of the resonance respectively, f_{c} is the coulomb scattering amplitude, $p_l(\theta)$ is the Legendre polynomial. For an isospin analog state, $\Gamma_{\mathrm{T}} = \sum_{\mathrm{i}} \Gamma_{\mathrm{i}} + \Gamma'$, where Γ_{i} is the partial width for isospin allowed transitions, and Γ' the isospin forbidden width, it should be very small in light nuclei, hence the partial width for proton emission should be dominant. This equation demonstrates two important aspects:

1) The resonant amplitude will interfere with the non-resonant amplitude, a quantitative calculation of the non-resonant amplitude by optical model is straight forward.

2) The resonant amplitude for a given value of l is exactly zero for angles for which $p_l(\theta) = 0$, thus at least the attribution of l is without any ambiguity (if not too many resonance overlap), if excitation functions of the elastic scattering are measured for many angles.

4 Research outlook

Based on the recent radioactive beam line facility, and many new experimental methods, we can do some investigation on the unbound nuclei structures, such as ^{9}He, ^{9}C, ^{10,11,12}N, ^{14}F, ^{18}Na et al., to understand the exotic nuclear structure and decay characters from the stable line to the drip line neutron-rich nuclei. RIBLL (Radioactive Ion beam Line in Lanzhou) can produce light exotic nuclei beam, by degrading the radioactive ion energy, which can be used to induce resonance elastic scattering reactions, combined with a simple gas-filled chamber or the polyethylene target, as well as silicon detector arrays to measure the recoiled protons. Fig. 2 shows some exotic RIBs which can be produced by RIBLL (solid cycle), and the dash line marked the object of unbound nuclei can be studied.

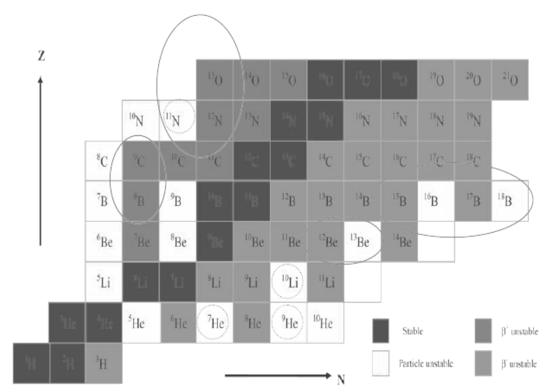

Fig. 2. some unbound nuclei can be studied in RIBLL recently.

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