Outline of the progress in the study of radioactive nuclear physics and super-heavy nuclei *

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Abstract We briefly introduce the current status and progress in the field of radioactive ion beam physics and the study of super-heavy nuclei. Some important problems and research directions are outlined, such as the sub-barrier fusion reaction, the direct reaction at Fermi energy and high energies, the property of nuclei at drip-lines, new magic numbers and new collective motion modes for unstable nuclei and the synthesis and study of the super-heavy nuclei.

Key words radioactive nuclear physics, sub-barrier fusion, direct reaction, magic number, super-heavy nuclei

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1 Introduction

Since more than twenty years the availability of radioactive ion beam has allowed to study the exotic structure and special reaction mechanism of the nuclei far from the stability line. These nuclei have some special physical characters, such as low binding energy of valence nucleons, complex coupling including continuum states and strong isospin effects, which result in exotic structures such as halo, multi-cluster and changing of magic numbers. Due to these exotic structures, the reaction mechanism may also exhibit some special characteristics such as multi reaction channels coupling, enhanced multi-step processes, enhanced reaction cross section, and so on. All of these will challenge the traditional nuclear physics concepts and become the main trends of the current experimental as well as theoretical studies[1, 2]. At the beginning, subject to the relatively weak beam intensity and simple detection systems, the experiments were mostly concentrated on the measurement of some "macroscopic" observable quantity such as the total reaction (interaction) cross section and momentum distribution etc. Over last decade, along with the development of the beam intensity and quality and detection facilities, the experimental capability has largely been expanded, especially to apply various reaction tools, such as elastic and inelastic scattering, Coulomb excitation, nuclear breakup and knockout reactions, transfer reaction, and so on, in order to look into the specific internal structure of the exotic quantum many body system and to understand the related specific reaction processes[3—5]. In general these kinds of experiments require higher beam intensity and more complicate detection systems with large detection solid angle, high resolutions for energy, momentum and position measurement, multi-particle coincidence, etc. At the same time, the traditional decay spectrum detection is also very important for the study of the exotic structure.

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The β decay of nuclei far from the stability line releases generally large energy and easily populates the high excited states of the daughter nucleus. This gives a new way to study the high excited states of unstable nuclei. Another trend is to use multi-particle (γ, β, α, p, n, etc.) coincident detection to reconstruct the initial or intermediate states of the nucleus under study. In the mean time, correlated measurement of both decay (e.g. in-beam γ) and reaction processes play a role in discriminating the contribution from different reaction channels. Along with the development of experimental capability, nuclear theory also faces many new questions too. For instance，contribution of continuum spectrum, coupling of deformation and paring effects, etc. are very important for understanding the structure of weakly bound nuclei. The treatment of bound excited states as well as the resonant states are difficult too. Besides, the nuclear reaction theory is relatively getting behind the need of experiments, especially the treatment of many body and multi-reaction channel correlation effects. Due to these rich research opportunities several large scale facilities are being constructed in the world. The field of radioactive nuclear physics would have very strong vitality.

During the past fifteen years the Chinese scientists has built the Radioactive Ion Beam Line in Lanzhou (RIBLL) based on the existing Heavy Ion Research Facility in Lanzhou (HIRFL), and the Low Energy Radioactive Ion Beam Line (GIRAFFE) at Beijing National Tandem Accelerator Laboratory (HI13). At present, the Cooling Storage Ring (CSR), one of the National Big Science Projects, is commissioning in Lanzhou. Another National Big Science Projects, BRIF in Beijing, is also under construction and is planned to be completed in 2011. All of these will provide great opportunities for the radioactive nuclear physics research in China. Based on last program of Major State Basic Research Development Program (973), performed successfully from 2001 to 2005 and supported by Ministry of Science and Technology of China, a new 973 project: Radioactive Nuclear Physics and Nuclear Astrophysics, was approved in 2007. This project is divided as 5 sub-projects, namely: synthesis of new nuclide and seek for super heavy nuclide; structure of weekly bound exotic nuclei and strong coupling effects; stable and explosive astro-nuclear process; isospin dependence of nuclear matters and equation of state; spectroscopic study of weekly bound nuclei.

We will briefly introduce some key problems in the radioactive nuclear physics and super-heavy nuclei. Nuclear astrophysics will be described in another report and would not be dealt with here.

2 Study of the structure and reaction mechanism of light exotic nuclei

The research of weakly bound exotic nuclei began with the observation of abnormally large reaction (or interaction) cross sections. Followed was the measurement of the longitudinal momentum distributions of the core fragment. Halo nuclei were originally identified by the increase of the reaction cross sections and the decrease of the Longitudinal Momenta width. However, even the root mean square size of the halo turns out not to be an 'experimental observable', but is model dependent. At the same time, momentum distributions relies on the reaction progress[6]. So information of halo nuclei obtained from different experiments and different methods are quite different or even inconsistent with each other[7]. Besides, the life times of weakly bound nuclei are usually very short. They are also easy to breakup in reaction (coupling to the continuum). Hence study of structure of the exotic nuclei is closely related to that of the reaction mechanism, which resulted in many complicated processes and delicate phenomena[6].

2.1 Fusion reaction at around the Coulomb barrier

Fusion of weakly bound nuclei has new mechanisms and effects, such as sequential complete fusion(SCF, two steps process)[3]. Under some conditions, weakly bound nuclei may induce extremely large enhancement of the fusion cross section. For example, the fusion of ^{6}He with ^{206}Pb and ^{206}Bi at energies below the Coulomb barrier have a significant enhancement of the fusion cross section compared to ^{4}He. This effect was believed to be caused by two steps process[8]: as the first step, two valence neutrons of neutron-rich nuclei ^{6}He fuse with the target and release energy which accelerate the core ^{4}He. Then as the second step, ^{4}He fuses with the target at higher effective energy, so that the cross section will be largely enhanced. However, more delicate experiment for fusion of ^{6}He with ^{238}U found that the cross section of complete fusion (CF) do not enhance compared to that of stable nucleus[3]. Recently it was found that fusion cross section of neutron-rich Ni isotope at energies much below the Coulomb barrier is even decreased compared to that of the stable nucleus. Therefore, fusion of weakly bound nuclei depends on specific quantum process and needs careful analysis. Besides, the cross section of breakup of weakly bound nuclei is generally large, the impact of which on fusion reaction is also very important. So it is mandatory to realize the coupling between the breakup and fusion processes experimentally as well as theoretically. Due to the importance of fusion reaction in the fields such as synthesis of new element and super-heavy nuclei, a deep understanding of the enhancement of fusion cross section of weakly bound nuclei is necessary.

Related to the enhancement of the fusion cross section is the abnormally of the optical potential (OP) below the Coulomb barrier. Usually for the stable nuclei, the imaginary part of the optical potential goes to zero at very low energies, due to the very small fusion cross section below the Coulomb barrier. However, the fusion cross section of the weekly bound nuclei may have extremely large enhancement effects[3], the imaginary part of the OP may have abnormally large value. Since OP is a basic input for many other reaction channels, its abnormal phenomena may result in many other coupling effects. Up to now the experimental study of optical potential for weekly bound nuclei is still very scarce.

Scientists from China Institute of Atomic Energy (CIAE) has carried out much research work for fusion reaction and abnormally of OP for some weakly bound nuclei, such as ^{6}Li+^{208}Pb, ^{32}S+^{90,96}Zr systems, below the Coulomb barrier[9].

2.2 Direct nuclear reaction

Direct nuclear reaction mentioned here refers to elastic scattering, breakup and knockout reaction, and transfer reaction in the fermi energy region and high energy region.

2.2.1 Elastic scattering of weakly bound nuclei

Elastic scattering of weakly bound nuclei brings information related to the dispersed nuclei surface, and is strongly correlated to the continuum (breakup) states. The optical potential obtained from the elastic scattering has an essential position because it reflects the total average interaction between the two colliding nuclei, and in addition is often the required input parameter for other reaction channels. An typical example is the scattering of ^{6}He at 38.3 MeV/nucleon on a ^{12}C target carried out at Grand Accélérateur National d'Ions Lourds (GANIL)[10]. They found the sensitive coupling of breakup channel to the elastic scattering. Such coupling may be simulated by the so-called dynamic polarization potential(DPP) that should be added to the microscopic optical potential, or more completely treated by the continuum-discretized coupled channel (CDCC) method.

Scientists from Peking University (PKU) measured the elastic scattering of halo nucleus ^{6}He at 25 MeV/nucleon on ^{9}Be target at The Institute of Physical and Chemical Research(RIKEN), Japan, and has obtained the corresponding optical potential[11].

2.2.2 Breakup and knockout of weakly bound nuclei

Breakup and knockout of weakly bound nuclei have cross sections as large as for elastic scattering, and can be measured with good statistics even at low beam intensity. Breakup and knockout often cause sequential process, which means firstly break up of the projectile with its fragment at excited resonance state and the latter decays subsequently. This is called sequential breakup or resonant breakup[12]. For the simplicity of the theoretical treatment breakup and knockout experiments are normally carried out at energies above 50 MeV per nucleon.

In the breakup reaction the interaction is relatively weak and the products are focused at forward angles. It is in favor of probing the cluster structure of the projectile at both ground or excited states. When applying light target (e.g. C target) the interaction is basically nuclear one, corresponding to the nuclear diffraction breakup. When applying heavy target(e.g. Pb target), the interaction is dominantly Coulomb interaction, corresponding to the Coulomb (electromagnetism) breakup. Ashwood et al. did a typical nuclear diffraction breakup experiment with $^{10-12,14}$Be projectile[13]and measured cross section for various cluster composition. Palit et al. did a typical Coulomb breakup experiment with ^{11}Be projectile and measured the decay products accurately which allowed to reconstruct the resonance states[14]. The ground state structure of ^{11}Be could then be obtained by comparing the accurate calculation of the electromagnetic excitation to the experimentally reconstructed spectrum.

In the knockout reaction, one part of the projectile (e.g. the valence nucleons) collide strongly with target (usually light nucleus with simple structure, e.g. proton or ^{12}C) and was absorbed by the target (stripping) or scattered to large angles. The residual part flys out to forward angles with little disturbing. The knockout reaction is a good tool to probe the special quantum states of valence nucleons. For instance Aumann et al. has used a knockout reaction to determine the ground state structure of ^{11}Be[15] and has determined the probability of the halo structure with the valence nucleon at the $2S_{1/2}$ state and the probability of the core excitation. Recently, another knockout reaction experiment was carried out at GANIL to look into the valence neutron states of ^{12}Be, and has provided evidence for the collapse of neutron magic number 8.

The knockout reaction at high energies has many advantages, such as directly obtaining the ground state information of the projectile, and being described by relatively simple theoretical model. By detecting the recoil target nucleus in coincidence with the projectile fragment, it is possible to distinguish the knocked out fragment or knocked out valence nucleons. Then it is possible to choose the undisturbed spectator to analyze its original state in the projectile. This selectivity is more important for multi-cluster nucleus (e.g. ^{8}He)[16] since it is a way to avoid the contamination of some unexpected component.

In breakup and knockout reaction it is required to measure the energy and momentum of all charged fragments and valence nucleons in an accurate way. Besides in the case of sequential decay it is also important to accurately measure the angle between the decay particles in order to assure the accuracy of the re-constructed excitation spectrum. Some detailed simulation calculation is necessary before the experiment to optimize the detection setup. The magnetic spectrometer or high precision charged particle telescope is needed to detect the charged particles, and silicon strip detector or multi-wire proportional chamber should be applied to determine the position or angle of the decay particles. Usually the Time of Flight (TOF) method is used to detect neutron energy. However it has always been an difficult task to distinguish two or more neutrons in a small zone at the same time.

2.2.3 Transfer reaction

Thanks to the two body characteristics in both incoming and outgoing channels, transfer reaction could be theoretically described in a strict way. Therefore transfer reaction is a convenient tool to study the correlation amount various quantum states, and to realize the manipulation of the quantum states. However, the cross section of transfer reaction is usually very small. For example, single nucleon transfer cross section is only about 1—10 mb/sr, and two nucleon transfer cross section is even smaller by one or two order of magnitude. So a typical transfer reaction experiment requires a beam intensity higher than 10^5 pps. The transfer reaction of weakly bound nuclei have new characteristics, such as strong coupling of multi-quantum states(including continuum states), easy to go through multi-step processes etc.. These require more complicate theoretical description and more difficult calculation, but also brings more rich research objects. Transfer reaction usually takes place at the energies around 10—30 MeV/u, which is equivalent to the Fermi energy of surface nucleons of a stable nucleus[17]. However, due to the weakly bound property the surface nucleons may move much slower for an exotic nucleus than for a stable one. Therefore the favorable energy of transfer reaction should be lower for unstable nuclei. At present, transfer reaction data of light halo nucleus ^{6}He have been measured for a few targets. Combined with theoretical analysis, it is proved that the two valence neutrons are strongly correlated to become the so called di-neutron with about 80% probability[17]. Recently, K.Hagino et al. showed that the forming of di-neutron pair is favored at an environment of nuclear matter density which is about 0.4 times that of the nuclear center[18]. They also point out that these features is very important since it corresponds to a change from the BCS-like pair to an BEC-like particle. This kind research is extremely interesting for light weakly bound nuclei.

Since last few years, scientists from Institute of Modern Physics, Chinese Academy of Sciences(IMP), Shanghai Institute of Applied Physics, Chinese Academy of Sciences(SINAP), CIAE and PKU have carried out many nuclear reaction experiments at the Fermi energy region and contributed to the understanding of the structure of exotic nuclei, such as ^{27}P, ^{12}B, ^{13}C, ^{6}Li, ^{6}He, ^{8}He[19].

3 Drip line nuclei, new magic number and new collective motion

3.1 Drip line nuclei

Since the predictions of the structure for nuclei very near the drip line by various theoretical models are very different to each other, the experimental measurement of the properties of drip line nuclei is especially important to test these models. Besides, there exists many resonant states for nuclei near drip line, which may play an appropriate role to study the correlation between the bound states and the continuum states[20].

At present, the neutron drip line has been determined up to Oxygen isotopes, and in the mean time, very neutron-rich nuclei, such as ^{31}F, ^{34}Ne, ^{37}Na, ^{38}Mg, have been observed, and ^{16}Be has been found to be unstable. In future, the strong intensity beam facility (at about hundreds of MeV/nucleon) will allow to extend the production of neutron-rich drip line nuclei to the Nickel isotope region.

Breakup reaction and decay experiment are usually performed to study the properties of the drip line nuclei. For example, in the study of ^{11}Li structure[21], resonant states can be reconstructed from coincident measurement of the charged core fragment and the decay neutrons. Then theoretical calculations can be carried out to relate the resonant state to the ground state configuration of valence neutrons. Further experiments of this kind are planned for two neutron decay of ^{26}O, ^{33}F, ^{36}Ne, ^{39}Na, and ^{40}Mg nuclei.

Another very important method is the β-delayed neutron and γ decay experiment. Here very neutron-rich nuclei go through β decay firstly, and due to the high decay energy, the daughter nucleus will be populated mostly to excited states including particle unstable states which will decay via particle emission. In a real experiment, parent nucleus beam (neutron rich as for example) is injected into the decay target, which is also served as β detector and surrounded by neutron detector. Time of Flight(TOF) method has been widely used to get the neutron energy spectrum. This way, we can study the ground state structure of the parent nucleus and the excited states of the daughter nucleus. Scientists from MSU, GANIL, RIKEN are working on this kind decay experiment. PKU group has also built a neutron detect array and has studied the very neutron-rich Nitrogen isotopes in recent years[22].

The proton drip line has been set up to Z=28 isotopes and part of isotopes between Z=29 and Z=82. Due to the Coulomb barrier there are many unbound excited states outside the proton drip line, of which the life time is far longer than the time needed for particle to travel through the target nucleus (in the order of 100 ns). Single and double-proton emission, including β-delayed proton emission, are good ways for studing the proton drip line nuclei. At present, double-proton emission were observed for only very limited number of nucleus such as ^{45}Fe, ^{48}Ni, ^{54}Zn, of which the beam intensities range from 0.1 to 10 pps. Single proton emission have been studied quite extensively, especially in the region between Z=51 and Z=83. The observed double-proton emission nuclei are ^{45}Fe, ^{48}Ni and ^{54}Zn, and those predicted include ^{64}Se, ^{67}Kr, and ^{71}Sr.

Scientists from IMP has synthesized many proton drip nuclei in Lanthanon region,and has contributed a lot to the drip line nuclear physics[23].

3.2 New magic number

Shell structure and related magic numbers are not merely details but are fundamental to our understanding of one of the most basic features of nuclei– independent particle motion. However, robust shell structure, or at least the familiar magic numbers, may prove to be a property only for nuclei near the valley of stability. Theory suggests that some of the known shell gaps close significantly as nuclei become very neutron rich and/or extended in radius. For example in the neutron rich region, the magic number N=20 may move to N=16 or 14. The magic number N=28 may move to N=32. All of these are correlated with the in medium proton-neutron interaction, or isospin dependent nucleon-nucleon interaction[24].

The mass measurement of nuclei firstly give the evidence for changing of magic number[25]. Single neutron separation energy show some up and down big changes at around the magic number. For stable nuclei, these changes occur at around the traditional magic numbers, such as N=8, 20, 28 etc. However, with increasing of isospin, this phenomenon vanish at N=8 and the magic number N=20 seems moved to

N=16.

Another important method to study the magic number is to look at the transition from 0^+ to 2^+ state of even-even nuclei[24]. At the vicinity of Magic nuclei it appears a high energy for the first excited state with a small transition probability $B(\mathrm{E2}: 0^+ \to 2^+)$ compared to neighboring stable nuclei. The observation of this transition near the β-stability line is almost completed, but that for nuclei far from the β-stability line is very scarce. Many experimental tools, such as β decay, γ decay, inelastic scattering of proton and Coulomb excitation etc., could be used to observe the transition from 0^+ to 2^+ state. Recently B.Bastin et al. at GANIL have measured the energies of excited states in ^{42}Si and the ^{41,43}P nuclei through in-beam γ spectroscopy[26], and has found the gradual disappearance of the magic neutron number 28.

3.3 New collective motion

Some new collective motion modes have been found in unstable nuclei, such as pygmy dipole resonance[27], which is described as a collective oscillation of the valence neutrons versus the core nucleons. It is a good candidate to study the effective nucleon interaction as a function of isospin and the properties of isospin dependent nuclear matter. In the region far from the stability line, the deformation, collective motion and symmetry breaking etc. also provide much new information. But this kind of study often requires radioactive beams of heavy nuclei which is hard to produce nowadays. Therefore the research in this region is only at its very beginning[20].

4 Synthesis of super-heavy nuclide

Synthesize of new super-heavy element has been one of the Human's most important research aim in the last several decades[28]. From 1969 to 1974, several isotopes of the elements with Z=104, 105, and 106 were produced by heavy-ion induced hot-fusion reaction at Berkeley Laboratory in USA and Dubna Laboratory in Russia. At GSI- Darmstadt in Germany it was a big success to synthesize new elements with cold-fusion method. In 1975, they have constructed heavy ion linear accelerator with very strong beam intensity, developed heavy residue separator and the single nucleus identification technique. Based on this they were able to separate evaporation residues with life time of only a few microseconds and to measure their decay properties. Starting from 1981, a series of isotopes of 6 new elements with Z=107—112 were synthesized at GSI group by using strong intensity beam of ^{54}Cr, ^{58}Fe, ^{62}Ni, and ^{60}Zn ions impinging on ^{208}Pb and ^{209}Bi targets. For cold-fusion reaction the production cross sections decreases exponentially along with the increase of the atomic numbers. So it was the utmost limit of the cold fusion technique to synthesize the element up to Z=112. In 2004 RIKEN group has synthesized the element 113 by applying extremely strong intensity beam of ^{60}Zn ions on a ^{209}Bi taret. In recent years, Dubna group has chosen another way of using a strong beam of the double magic nucleus ^{48}Ca impinging on neutron rich actinide targets. With this so called “warm fusion” method, they have been successful to approach the predicted super-heavy island. Since 1998, they has produced and identified many events of new elements with Z=114, 115, 116, and 118, based on the coincident decay measurement for every super-heavy nucleus. But since it is still not evident to combine these decay chains with the known nuclei, more confirmation experiments are required in order to finally decide the discovering of these new elements.

At present, all the synthesized super-heavy nuclei are still not at the so called super-heavy island. Besides the very small production cross section, there are at least two other key difficulties. Firstly neither “cold fusion” nor “hot fusion” could produce stable (at the island) super-heavy nuclei with necessary number of neutrons as predicted by the theory, although the required number of protons could be generated with the fusion of two existing nuclei. To reach the island it is necessary to use more neutron rich projectile or target, and to use the new knowledge of radioactive nuclear physics. Secondly, The lifetime of the super heavy element at the stability island may become very long, and they may not necessarily decay to other detectable particles. Therefore it is necessary to develop new separation and identification techniques. Aiming at these difficulties extensive investigation are being under taken. In the mean time study of the chemical properties of the super-heavy elements are also progressed. In recent years, nuclear chemists have achieved to determine the position of elements Z=106—108 in the periodic table, which is a big breakthrough in the field of studying super-heavy element.

Scientists from IMP have worked at the synthesis of the superheavy nuclei for many years, and has synthesized new elements 259Db (Z=105) and ^{265}Bh (Z=107) successively[29]. The next step is to get into the region of $Z \geqslant 110$ and to become one of the main research group in the super-heavy community[30].

5 Summary

Radioactive ion beam physics is an explore of new and broad unknown region of nuclear territory, where the traditional knowledge of atomic nucleus has to be changed a lot. Subject to the ability of producing RIB, the research is initially concentrated at the region of light nuclei and part of middle heavy nuclei. Along with the development of the second and third generations of RIB facilities, the research region as well as the new observation will be extended. At the same time, the knowledge of the structure and reaction of unstable nuclei is a necessary basis for the synthesis and identification of the super-heavy nuclei, for the study of nuclear-astrophysics and large scale nuclear matter, and for many new applications including possibly new nuclear materials, new energy systems, new nuclear data and so on.

We limit ourselves in this article basically to the experimental part of the RIB physics. In fact, the theory of nuclear structure and reaction for nuclei far from the stability line has rapidly advanced[31]. The effect field theory (EFT) which is based on the QCD and the ab initio model based on the first principle calculation could now applied to nuclei with some 12 nucleons[32]. Shell model, mean field theory, few-body theory, deformation theory, and symmetry theory etc., are also progressed[20, 31]. The theory of nuclear reaction is deficient presently and should be advanced in the coming years. The Chinese scientists are relatively strong in the field of theoretical nuclear structure, especially the shell model and mean field theory, and has carried out many important works[33], which we could not mention in this short report.

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