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Physics Opportunities at the New Facility HIAF

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Abstract: The Institute of Modern Physics, Chinese Academy of Sciences, proposed the Major National Science and Technology Infrastructure Facility named as High Intensity Heavy-ion Accelerator Facility (HIAF) in 2010. After a series of assessments charged by the National Development and Reform Commission of China, HIAF was officially approved by China government in December, 2015. HIAF will be constructed in Huizhou, Guangdong Province, and the groundbreaking ceremony of construction is scheduled around the end in the year of 2018. HIAF is composed of a superconducting Linac, a booster ring, a high-energy radioactive beam line, a storage ring, and a number of experiment setups. The total investment of HIAF is about 2.5 billion Chinese Yuan. The major goals for HIAF are to explore the hitherto unknown territories in nuclear chart, to approach the experimental limits, to open new domains of physics researches in experiments, and to develop new ideas and heavy-ion applications beneficial to the societies. In this paper, the accelerator complex of HIAF is briefly introduced, and the experimental setups and associated physics research program are presented.

Key words: heavy ion; accelerator facility; nuclear physics

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1 Introduction

In the year of 2010, China government decided to build a batch of Major National Science and Technology Infrastructure Facilities in order to boost fundamental sciences and called for proposals nationwide. The Institute of Modern Physics, Chinese Academy of Sciences, proposed the project entitled as High Intensity Heavy-ion Accelerator Facility (HIAF). A high-rank committee evaluated all of the proposals in various research fields, and then recommended 16 top priority projects to the National Development and Reform Commission of China in 2011. Fortunately, the HIAF was selected to be one of them. In December of 2015, HIAF was approved by the National Development and Reform Commission of China and the construction site was fixed in Huizhou city in south China. The HIAF project went through the technical assessment in April of 2017. The groundbreaking ceremony of construction is scheduled in 2018 and the commissioning is planned in 2024. HIAF is composed of a superconducting Linac, a booster ring, a high-energy radioactive beam line, a storage ring, and a number of experiment setups. The total investment of HIAF is about 2.5 billion Chinese Yuan, including about 1.5 billion Yuan from the central government for facility construction and 1.0 billion Yuan from the local governments for infrastructure. The major scientific goals identified for HIAF are to explore the hitherto unknown territories in nuclear chart, study exotic nuclear structure, synthesize super-heavy nuclides and elements, understand origin of heavy elements in the Universe, and develop new heavy-ion applications in space and material sciences[1]. This paper describes briefly the accelerator complex, planned experimental setups, and physics motivations of HIAF.

2 The accelerator complex

HIAF is a next-generation storage-ring based heavy-ion facility. Fig. 1 shows the accelerator complex. The injector iLinac is a superconducting linear accelerator with a length of 180 m, which is equipped with a new-generation 45 GHz, 20 kW ECR ion source to deliver ion current of 1.0 emA. The iLinac can be operated with either continuous wave mode or pulse mode, providing intense heavy-ion beams for low-energy experiments or injecting highly charged ions into the Booster Ring (BRing), respectively. The BRing is used for beam accumulation and acceleration

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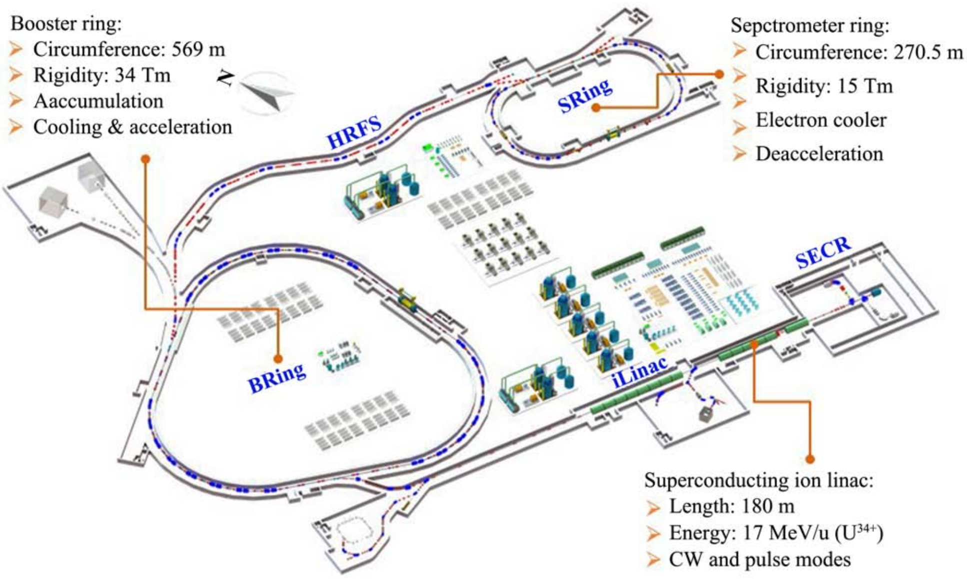

Fig. 1 (color online) The layout of HIAF. The major parameters and performance of the sub-systems are presented.

with a circumference of 569 m and a maximum magnetic rigidity of 34 Tm. Two-plane painting injection scheme is adopted to store huge ion number in the ring. Due to space charge and dynamic vacuum effects, ions stored is launched to high energy very quickly using the fast ramping rate operation. A radioactive beam line, named as High Energy Fragment Separator (HFRS), is coupled to the BRing. The HFRS is able to produce unstable ions using heavy-ion projectile fragmentations or in-fight fissions of energetic heavy projectiles, and then separates, identifies and transports the ions of interest for various experiments. With slow extraction of high-energy ions from the BRing, the HFRS is used as a separator and spectrometer. While using fast extracted beams from the BRing, the HFRS injects unstable ions into the Spectrometer Ring (SRing) for storage-ring based experiments. Typical beam parameters from the BRing are presented in Table 1. We can see that very intense heavy-ion beams will be available at HIAF; taking the ion of $^{238}U^{34+}$ as an example, over 10×10^{11} particles can be stored and the maximum energy of 800 MeV/u could be achieved. It is worth noting that higher beam energies could be available if needed on a tradeoff of the beam intensities.

Table 1 Typical beam parameters from the BRing. The beam intensities are given in the unit of particles per pulse (ppp).

Ion species	Energy/(GeV/u)	Intensity/ppp
P	9.30	2.0×10^{12}
$^{18}O^{6+}$	2.60	6.0×10^{11}
$^{78}Kr^{19+}$	1.70	3.0×10^{11}
$^{209}Bi^{31+}$	0.85	1.2×10^{11}
$^{238}U^{34+}$	0.80	1.0×10^{11}

In the past years, great efforts have been devoted to the R&D on the key accelerator techniques in order to achieve the unprecedented beam intensities. For the very heavy beams, such as Bi and U, the existing highly charged ion sources cannot meet the requirements of HIAF. We have designed a next-generation 45 GHz superconducting ECR ion source with a novel structure, and the simulation shows that very intense highly charged ions of 1.0 emA can be produced by the ion source. We will adopt the superconducting quarter-wave cavities with β value of 0.052 and working frequency of 81.25 MHz for the low-energy section of the iLinac, and superconducting half-wave cavities with β values of 0.1 and 1.15 and frequency of 162.2 MHz for the high-energy section. Prototypes of the cavities were manufactured and tested successfully in laboratory. Due to fast ramping rate operation of the booster, thin walled vacuum chambers are needed for all magnets in order to keep eddy currents at a tolerable level. A 0.3 mm thick vacuum chamber prototype was made of stainless steel, which has an elliptical aperture and rib supporters in parallel with the magnetic fields. The prototype was installed at the Heavy Ion Research Facility in Lanzhou (HIRFL)[2], and it works very well. In a storage ring, stored ion might collide with the residual gas in the beam pipelines. This might result in change of the charge state of the ion, and consequently the ion hits the pipeline and produces huge number electrons. If the electrons are captured by beam ions, a cascade of ion loss phenomenon might happen, and eventually cause beam collapse suddenly. This phenomenon limits the ion number stored. Therefore, we have to install dynamic vacuum collimators at specific positions at the booster. A dedicated dynamic vacuum simulation software has been developed in collaboration with GSI for the optimization of the collimator design, and a collimator prototype was built and near 100% collimation efficiency could be realized according to simulation. In order to obtain high quality radioactive beams for precision measurements, we will install Stochastic cooling device and electron cooler at the SRing. A prototype of Stochastic cooling device with a novel 2.76 m long slotted pick-up was fabricated and installed at the Cooler Storage Ring(CSR)[1], and the beam test results show that this cooling device is suitable for the SRing. We have designed electron cooler which can provide hollow electron beams for cooling down ion beams. The hollow electron beam can solve the problem of space charge effect and reduce the recombination between the ions and electrons, and consequently high-quality ion beams would be produced. With the tremendous endeavours, we come to the stage to start the facility construction.

HIAF is characterized by the unprecedented heavy-ion beam intensities, and hence gives us great opportunities to explore the hitherto unknown territories in nuclear chart. We have calculated the daily production yields for isotopes using projectile fragmentation, in-flight fission, multi-nucleon transfer, and fusion reactions. The optimized yield for each isotope is presented in Fig. 2, in which the red lines are the boundaries of the known nuclides to date, and the gray lines are the proton and neutron drip-line, respectively. The limits shown are the production rate of one nuclide per day, which enables the “discovery experiments”, *i.e.* the production and identification of new nuclides. As shown in Fig. 2, prolific sources of nuclides will be provided at HIAF, and most importantly we could access the proton drip-line nuclides up to uranium and the neutron-rich nuclides far away from the stability line in medium and heavy mass regions. Therefore, HIAF is one of the most powerful facilities in the world to explore the nuclear chart.

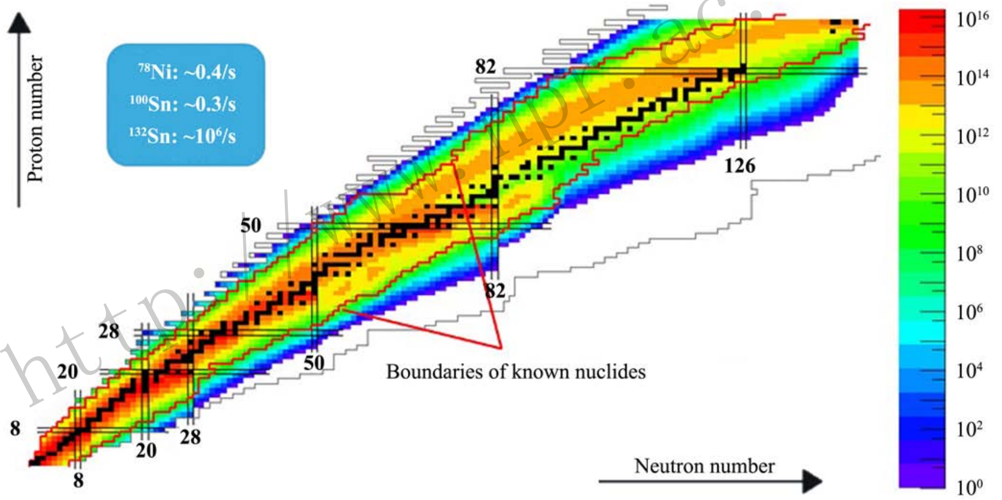

Fig. 2 (color online) The isotope production yield per day calculated using various reactions. The yields for the benchmark nuclides with double shell closures are given in the inset. The red and gray lines show the boundaries of known nuclides and the drip-lines, respectively. The different colors indicate the production yields in orders of magnitude.

3 The experimental setups and the associated major physics

In order to exploit the very intense various stable and radioactive beams with energies from MeV/u to GeV/u provided by HIAF, we will build a number of experimental setups coupled to the iLinac, BRing, and SRing. The experimental apparatuses and related major physics will be described below.

3.1 The low-energy experimental stations

The iLinac works in two modes; the one is pulse mode either to inject beam into the BRing or to provide pulsed beam for the Test Storage Ring (TSR), and the other one is continuous wave mode to deliver intense low-energy heavy-ion beam for experiments. The TSR was built by the Max-Planck Institute for Nuclear Physics for studies of nuclear structure, reactions of astrophysical relevance, and atomic physics[3]. The transfer of TSR from Germany to China is under negotiation, and hopefully we will soon come to an agreement that the TSR is moved to HIRFL for several years of operation and then to HIAF. We will build a radioactive beam line to connect the TSR to the end of the iLinac, and high-precision experiments will be conducted by the existing TSR collaboration.

As shown in Fig. 1, heavy-ion beams are exacted around the middle point of the iLinac, and the beam energies can be adjusted finely around the Coulomb barriers of nuclear reactions. The low-energy intense beams will enable producing very neutron-deficient nuclei using fusion reactions and particularly heavy and even super-heavy neutron-rich nuclei using multi-nucleon transfer reactions. The gas-filled recoil separator is an ideal tool to separate and study the nuclides produced in complete fusion reactions[4–6]. The high angular acceptance and high transmission efficiency gas-filled recoil separator shown in Fig. 3 will be built, mainly aiming to synthesize new elements and neutron-deficient isotopes. In addition, if a gas cell followed by an RFQ cooler and buncher is installed at the focal plane of the separator, pulsed high-quality, low-energy beams are available for nuclear mass spectroscopy and collinear laser spectroscopy.

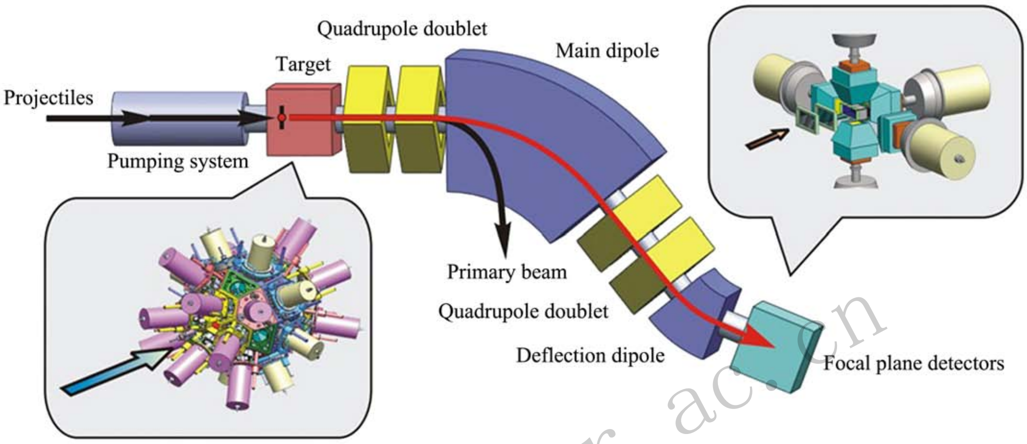

Fig. 3　(color online) The gas-filled recoil separator. The major components are indicated, and the detector arrays at the target position and focal plane are displayed in the insets.

Multi-nucleon transfer reactions are characterized by a large amount of energy dissipation, a large flow of nucleons between the interacting nuclides, and a noticeable time delay in the reaction. For an appropriate reaction system with beam energy around the Coulomb barrier, such as ^{238}U+^{248}Cm, the projectile evolves to the doubly magic nuclide ^{208}Pb and transfers nucleons to the target, and consequently very neutron-rich heavy nuclides and even super-heavy nuclides are produced[7]. Presently, multi-nucleon transfer reactions employing very heavy projectile and target isotopes would be the optimal method to produce neutron-rich heavy nuclides and practically the only way to assess neutron-rich super-heavy nuclides. However, opportunities always come with challenges together. The reaction products of multi-nucleon transfer reaction have very broad distributions in recoil energy, emitting angle, and charge state. It is a great challenge experimentally to separate efficiently the products of interest from the huge background. With tremendous efforts, we have figured out conceptually a separator for separation and identification of multi-nucleon transfer reaction products, which consists of a rotating target system, gas stopper, sextupole ion beam guide, RFQ cooler and buncher, isobaric analyzer, laser ionization device, and isotopic analyzer. The separator can provide pulsed low-energy, high-quality neutron-rich beams with mass and atomic numbers well identified, and then distribute the beams to a multi-reflection time-of-flight mass spectrometer, ion trap, decay spectrometer, and collinear laser spectrometer for various measurements.

At the low-energy station equipped with the two separators, we aim to synthesize new elements and isotopes, hunt for K-isomers, study nuclear decay properties, measure nuclear masses and lifetimes, and determine nuclear charge radii and moments. Of the most importance is to explore the super-heavy region in the nuclear chart, as shown in Fig. 4. New super-heavy elements might be synthesized using the actinide targets, for instance, using the ^{54}Cr, ^{55}Mn and ^{58}Fe+^{243}Am reactions to produce the 119, 120, and 121 elements, respectively. Reactions of various projectiles bombarding thorium and uranium targets are employed to synthesize new super-heavy isotopes bridging the decay chains observed in ^{48}Ca induced reactions at Dubna to the known nuclides. The multi-nucleon transfer reactions will offer us unprecedented opportunities for the synthesis of new neutron-rich super-heavy isotopes, and the isotopes indicated by the filled circles in the lower right corner of Fig. 4 would be identified experimentally. If the reaction yields are sufficient, decay

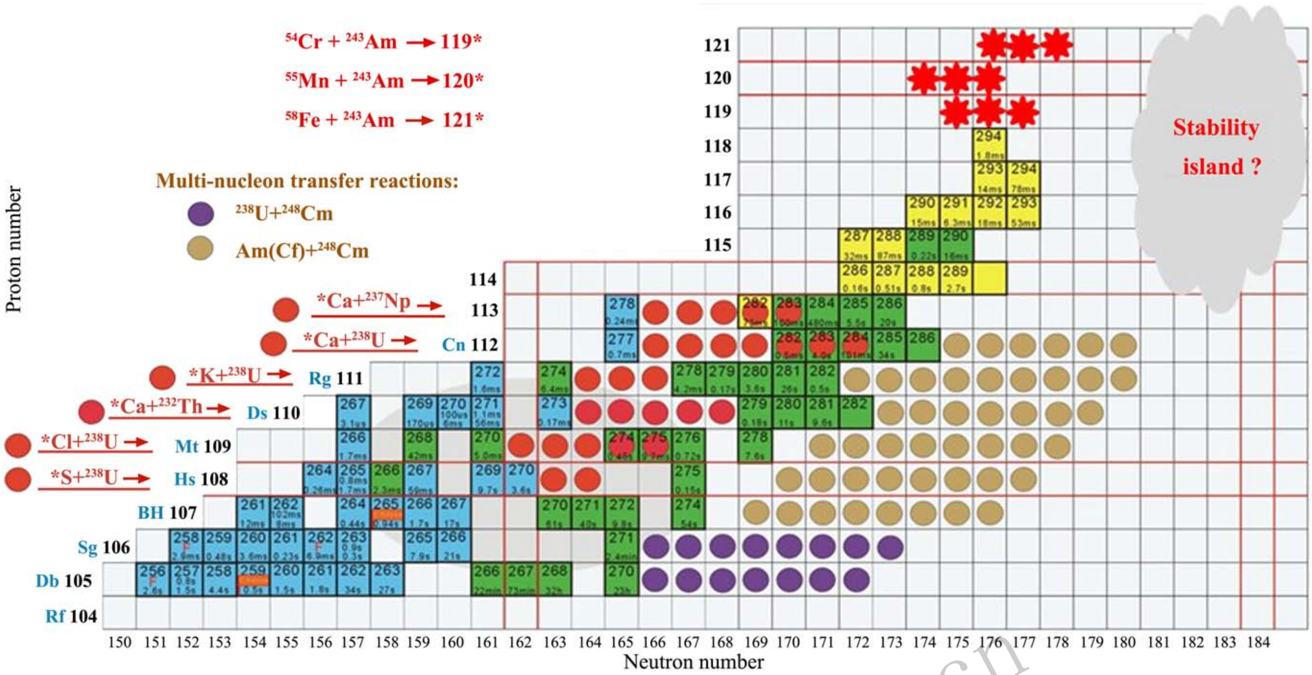

Fig. 4　(color online) The physics goals in the super-heavy region. The shaded area shows schematically the island of the super-heavy stability predicted theoretically long time ago. The red stars are the new elements with atomic numbers of 119, 120 and 121, which could be produced using the reactions given in the top right corner. The filled circles with different colors indicate the nuclides produced by the corresponding reactions.

spectroscopy for these neutron-rich nuclides can be studied, and thus the information of the single particle states is obtained, which is essential to localize the center of the super-heavy stability island theoretically predicted. The neutron-rich isotopes are expected to be longer-lived, and they are ideal samples for study of chemical properties of the super-heavy elements.

3.2　The high-energy experimental station

High-energy stable beams extracted slowly from the BRing are delivered to the high-energy experimental cave shown in Fig. 1. The 9.3 GeV proton beam and A/Z=2 primary beams up to 4.25 GeV/u energy will be available. We have defined the hypernuclear physics and properties of nuclear matter as our high priority research program at the high-energy station.

It has been proven that hyperons can be produced in peripheral nuclear collisions at incident energies of 1.0~2.0 GeV/u, and the hyperons may coalesce with the projectile fragments and hence hypernuclei are synthesized[8]. If the reaction energy is high enough (>3.75 GeV/u), hypernuclei with double strangeness are also produced. One of the unique features of hypernuclear spectroscopy with projectile fragmentation is that, due to a large Lorentz factor of the produced hypernuclei, the decay is observed in flight behind the production target. The half-life of an observed hypernucleus can be determined from the distribution of the flight length before it decays. In collaboration with GSI and RIKEN, we designed the experimental setup for hypernuclear physics research, which is located in the high-energy cave of HIAF. We hope that HIAF would be the world best place for such studies, and a dramatic expansion of the hypernuclear chart is expected.

The properties of nuclear matter, described by the theory of the Quantum Chromodynamics (QCD), can be summarized in a phase diagram just like any other form of matter[9]. It is of utmost importance to find how the nature of nuclear matter changes as we vary the temperature and baryon density. Lattice QCD calculation predicted that the transition from the quark-gluon plasma (QGP) to the hadronic phase is a smooth cross-over at the vanishing baryochemical potential of $\mu_{\rm B}\sim0$ while at the finite chemical potential the phase transition is of the first-order. Thermodynamically, hence, there must exist a critical point, *i.e.* the end point of the first-order phase transition line, see Fig. 5[9]. The critical point would be a milestone in the QCD phase diagram and is the Holy Grail for the field of the heavy-ion collisions at relativistic energies[10–11]. During 2010—2017, a beam energy scan was carried out in order to search for the critical point. Interesting non-monotonic behaviors as a function of collision energy have been observed in the net-proton fluctuation and net-baryon first order collectivity, implying the expected criticality and softening of the equation of state, respectively[9]. Both of

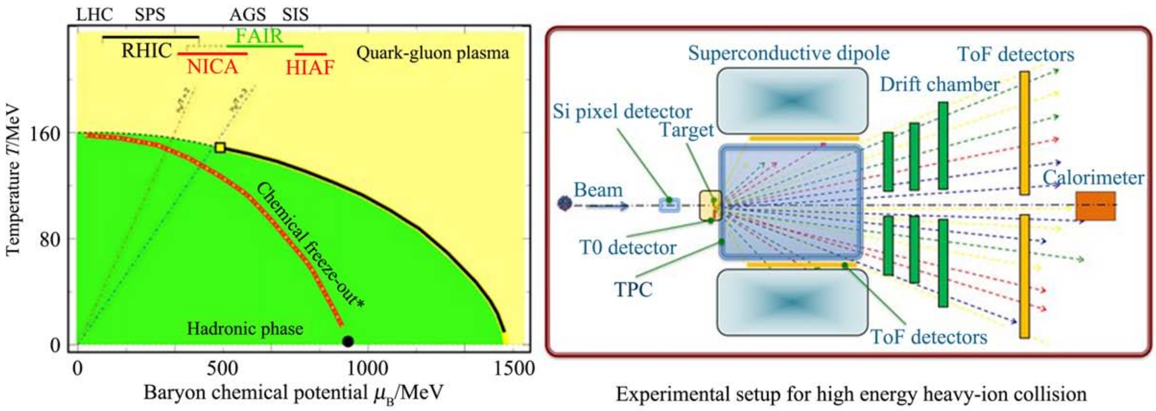

Fig. 5 (color online) Shown in the left is the schematic of the QCD phase diagram in temperature T as a function of the baryochemical potential μ_B. At LHC/RHIC high energy region, a smooth cross-over at $\mu_B \sim 0$ is expected. At the lower energy region, the phase transition occurs by passing the first-order phase boundary. The QCD critical point, if exists, should be within this region. The left figure presents the experimental setup for study of heavy-ion collisions at relativistic energies at HIAF, and the major detectors are indicated.

the observations occur at the low energy end of the beam energy scan at RHIC. HIAF extends the coverage of the baryochemical potential to lower energy. The beam energy scan program would be incomplete without the results from the energy region at HIAF. In heavy ion collisions at relativistic energies at HIAF, the peak nucleon density can reach 2∼3 times of the saturation density, where is an ideal place for studying symmetry energy in order to constrain the equation of state of asymmetric nuclear matter at high density. We will build a detector system dedicated to study the QCD phase structure and symmetry energy using various physical observables, as shown in the right of Fig. 5.

3.3 The radioactive beam facility

The next-generation radioactive beam line is a crucial facility to perform a large variety of modern nuclear physics experiments with outstanding potential for scientific discoveries[10−11]. The relevant researches include mainly production and identification of new isotopes located far away from the stability line, measurements of nuclear charge and matter distribution and radii, search for new exotic radioactivity modes and collective motions, recognizing the importance of tensor forces and high-momentum nucleons in nuclei, study of in-flight decays and continuum spectroscopy by nucleon and cluster emissions of drip-line nuclei, investigation on weak-interaction governed processes via nuclear charge-exchange reaction, study on the evolution of the single particle states and the magic numbers, and constraining the equation-of-state of cold asymmetric nuclear matter. We have surveyed the optimum experimental conditions for a batch of typical physics cases, such as the appropriate reactions to produce the exotic nuclides of interest and the required performance of the radioactive beam line including the angular acceptance, momentum acceptance, and momentum resolution. Based on the requirements from the physics program, we have designed the high-energy radioactive beam line HFRS. In order to exploit the very intense primary beams, the HFRS is composed of a pre-separator and a main-separator. The major functional modes for the main-separator are presented in Fig. 6.

The exotic nuclides are produced via high-energy projectile fragmentation, in-flight fission of energetic heavy projectile, and two-step reactions. The nuclides of interest will be separated in flight within several hundred nanoseconds and delivered to the detector systems. The HFRS is characterized with a long flight path of 180 m, maximum magnetic rigidity of 25 Tm,

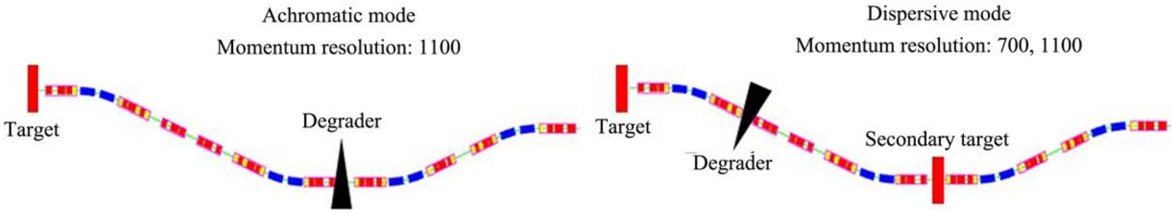

Fig. 6 (color online) The major functional modes of the main-separator. In the beam line, the sections in red and blue colors indicate the dipole and quadrupole magnet groups, respectively.

angular acceptance of ±30 mrad (x) and ±15 mrad (y), longitudinal momentum acceptance of ±2.0%, and momentum resolution of 700∼1100. These challenging performance parameters are achieved with a multistage magnetic system, comprising intermediate degrader stations. Best-performance detectors are placed at the different focal and dispersive planes of the HFRS. Assuming reasonable detector performance of 20 ps time resolution, 0.2 mm position resolution, and 1.0% energy resolution, the HFRS is able to achieve unambiguous event-by-event particle identification for all nuclear reaction products at high counting rates. The HFRS is the world-unique facility as compared to any yet existing or planned next-generation facility. Its peculiarities are manifested by the maximum magnetic rigidity of up to 25 Tm and thus high-energy secondary beams available with energies over 2.0 GeV/u, high primary-beam suppression power, high separation power of radioactive nuclides, providing fully stripped ions of all elements from hydrogen through uranium, and versatile spectrometer modes using different combinations of the separator sections.

The physics research program based on the HFRS emerges from the experiments performed at the existing radioactive beam facilities worldwide. It will exploit the HFRS as flexible, high-resolution ion-optical device. A rich physics program is defined and shown in Fig. 7. The major goals are to pin down the limits to nuclear existence particularly in the neutron rich regions, search for new forms of nuclear matter to appear far from the stability line, determine the ordering of quantum levels in nuclei far from the stability line, study the evolution of nuclear shapes along isotope chains, find new forms of collective motion in very neutron-rich nuclides, study dynamical symmetries in exotic nuclei particularly along the $N=Z$ line, *etc.*[10–11]. Due to the large variety of research subjects shown in Fig. 7, it is inappropriate to introduce the experimental method and physics importance for each subject in detail. Below, two examples are given just for demonstration.

Determination of neutron skin thicknesses of exotic nuclides: The thickness of neutron skins is one of the sensitive ways to constrain the equation of state of asymmetric nuclear matter, which is of utmost importance for understanding the neutron stars and their dynamic changes. On the other hand, the thickness of neutron skins gives the most direct evidence for the discovery of giant neutron halos including more than two neutrons predicted in extremely neutron-rich nuclides. Such exotic structures could reveal a new quest on the coupling of continuum and discrete states, and consequently prompt nuclear theories to understand bound and unbound objects from first principles. Neutron skin thicknesses can be determined by combining the matter radii extracted from the interaction cross sections and the charge radii mostly measured by laser spectroscopy methods. In case of nuclides for which charge radii are difficult to be measured by laser spectroscopy, a nuclear charge changing cross section provides a mean to determine the charge radius[12–13]. A particular advantage of this method is that it can be applied for very short-lived nuclides using weak beam intensities, and thus has the possibility to reach the most neutron-rich isotopes. The HFRS is an ideal instrument in the world to perform measurements of the interaction cross sections and charge changing cross sections due to its high mass resolution and transmis-

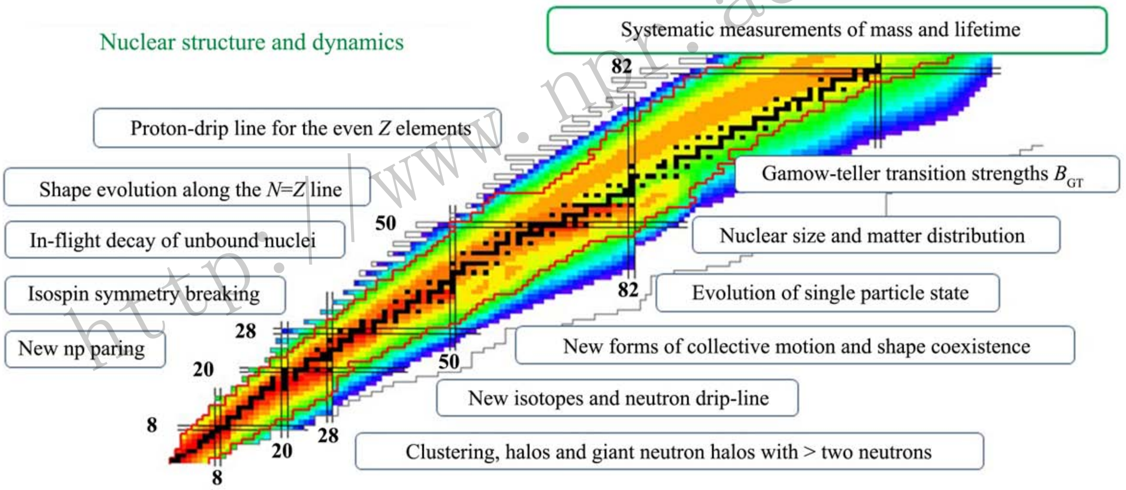

Fig. 7 (color online) The research subjects connected with nuclear structure and dynamics at the HFRS. For each subject, the detailed experimental method and physical importance are well documented in the literatures and references therein[10–11].

sion.

Measurement of the momentum distribution of fragments. The momentum distributions of fragments following one- or two-nucleon removal were proven to be spectroscopic methods that give knowledge on the wave function of the nucleons in the initial nucleus[14]. It is of great importance to extend these studies into higher-mass regions far away from the stability in order to probe whether the 50, 82, and 128 magic numbers still persist and whether new magic numbers will appear. The advantage of the method is that a very low intensity beam (~10/s) can be used for detailed spectroscopy. The experiments will benefit from the high-resolution momentum measurements by employing the dispersion-matching mode of the HFRS.

Last but not least, the HFRS has the highest magnetic rigidity up to 25 Tm as compared with any existing or planned radioactive beam facilities in the envisaged future. This feature reinforces the HFRS with a large discovery potential, and unique experiments are in consideration, which were never possible in the past and will not be possible by other lower-energy facilities. The research program exploring fully the high magnetic rigidity includes synthesis of very neutron rich hypernuclei, nucleon excitations inside unstable nuclei along isotope chains, new giant resonance of neutron rich nuclei, and spectroscopy of exotic meson-nucleus bound system[15]. For these experiments, dedicated detector setups are built and coupled to the specific focal planes of the HFRS.

3.4 The spectrometer ring

The HFRS couples the SRing to the BRing. Using fast extracted projectiles from the BRing, the HFRS produces, separates and injects the nuclides of interest into the SRing, which is in essence a storage ring equipped with electron cooler, stochastic cooling device, and deacceleration cavity. Based on the SRing, we will build the Dielectronic Recombination Spectrometer, Isochronous Mass Spectrometer, Schottky Spectrometer, and Setup for In-ring Nuclear Reactions, as schematically shown in Fig. 8.

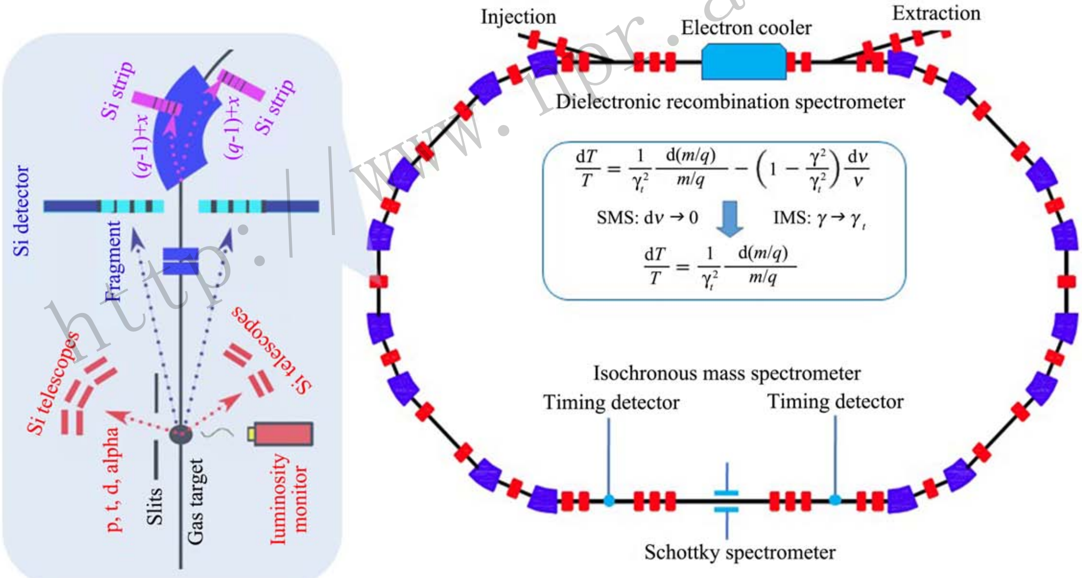

Fig. 8 (color online) Diagrammatic sketches of the Dielectronic Recombination Spectrometer, Isochronous Mass Spectrometer, Schottky Spectrometer, and Setup for In-ring Nuclear Reactions. The formulas shown in the inset in the right figure are the principle for nuclear mass measurements.

3.4.1 Dielectronic Recombination Spectrometer

In the electron cooler, the ion beam stored is merged with the electron beam. If the ion A^{q+} captures a free electron with well-defined energy provided by the electron cooler and a bound electron is excited simultaneously, the so-called dielectronic recombination phenomenon occurs. This is a resonance process. The electron beam usually has a longitudinal temperature of less than 1.0 meV. Interacting with the cooling electrons results in a very narrow momentum spread for the ion beam of the order of 10^{-5}. If detuning the electron energy from the cooling point, the resonance energies can be measured by recording recombination rate as a function of the electron energy. In the experiment, recombined ions are separated from the primary beam in the dipole magnet located downstream with respect to the interaction zone, and then detected by the particle detectors installed in the outer side of the ring. We can deduce the nuclear charge radius of the stored ion from the resonance spectrum. This technique is well established at the storage rings at GSI and IMP[16–17]. We will design and build the Dielectronic Recombination Spectrometer at the SRing, and measure systematically the nuclear charge radii for unstable nuclei after their survival for the electron cooling process.

3.4.2 Setup for In-ring Nuclear Reactions

Storage-ring based nuclear reactions open new opportunities to measure cross sections of specific reaction channels and to study the resonance properties of excited states in nuclides[18–20], which could not be addressed or are difficult to be addressed by conventional methods. The experiments of in-ring nuclear reactions benefit from the unique conditions of extremely low background in high vacuum, high luminosity using efficiently circulating ions, and high-resolution measurement associated with very thin target materials. A position-sensitive Si detector array will be constructed, which is coupled to a gas-jet target system, as shown in Fig. 8. The primary physics goal is to measure the cross sections of various nuclear reactions, for instance, the (p, γ), (α, p), (α, n), (α, γ), *etc.* The measured data is indispensable as inputs to simulate the nucleosynthesis processes in stellar environments. In addition, experiments of proton scattering or light particles scattering with low-momentum transfer in inverse kinematics will be carried out in order to measure the nucleon density distribution in neutron-rich nuclides, study the isospin dependence of the saturation density of nuclear matter, and provide unique information on the incompressibility of the incident nuclide.

3.4.3 Isochronous Mass Spectrometer

A heavy-ion storage ring coupled to an in-flight separator has been proven to be a powerful tool for direct mass measurements of short-lived nuclides[21–24]. The Isochronous Mass Spectrometry (IMS) has been well developed at GSI and IMP[25–26]. The masses of the ions stored are determined from their revolution times measured using a timing detector in the IMS, and typical relative mass accuracy of 10^{-6} to 10^{-7} is achieved[21–24]. Since a storage ring is a large-acceptance machine, it allows to store ions in a broad range of m/q values. This feature is essential for the IMS to measure masses of a few nuclides simultaneously. In the isochronous working mode of a storage ring, the revolution times of the stored ions should be independent of their velocity spread. However, the isochronous condition is fulfilled only in first order and in a small range of revolution times. We shall develop the advanced IMS with double timing detectors, by which the velocity of stored ion is measured to correct for the effect of the non-isochronicity. In order to measure the velocity of each ion stored, two timing detectors will be installed in the straight section of the SRing. This technique was already verified in principle at HIRFL[27]. We will focus on mass measurements of short-lived nuclides in medium and heavy neutron-rich regions using the IMS with double timing detectors.

3.4.4 Schottky Spectrometer

Conventional Schottky spectrometry is an ideal method to measure precisely nuclear masses and observe exotic decay modes of highly charged ions. The stored ions have to be cooled down using electron cooler before the measurements, and the cooling process takes several seconds. Therefore, the Schottky spectrometry could not be applied to nuclides with lifetime shorter than second, which is the lifetime for most nuclides with unknown mass yet. We will develop novel Schottky spectrometry, *i.e.* single-ion sensitive Schottky resonator working in the isochronous mode of a storage ring. The present method takes the merits of the conventional Isochronous Mass Spectrometry and Schottky spectrometry; the ions can survive for long time in the storage ring due to the usage of non-interceptive Schottky resonator and the measurement can be started immediately after injection in isochronous mode. The new Schottky spectrometry is applicable to nuclides with broad lifetimes, and importantly nuclear mass and lifetime can be measured simultaneously.

At the SRing, we mainly measure nuclear masses, half-lives, reaction cross sections, and exotic decay modes of highly charged ions. Of the most high-priority research program is to measure systematically nuclear masses in broad regions. The mass represents a basic characteristic of the nuclear system. The difference between the mass of a nucleus and the sum of the masses of its constituent free nucleons, *i.e.* the binding energy, provides direct information about the complex interactions that are responsible for the nuclear binding. There are many reasons for measuring the masses of nuclides in their ground or isomeric states. Perhaps the most fundamental questions in low-energy nuclear physics are closely related to nuclear masses, such as to locate the drip lines, predict the decay models of drip-line nuclides, recognize the disappearance of spherical magic numbers and appearance of new magic numbers, identify the onset of deformation along isotope chain and shape coexistence, *etc.*[10–11]. The development of nuclear models crucially depends on nuclear masses as experimental input, and such data are particularly valuable if obtained for long chains of isotopes or isotones. Fig. 9 presents an example to demonstrate the importance of nuclear mass measurements. Theories predicted that there might exist about 80 Sn isotopes,

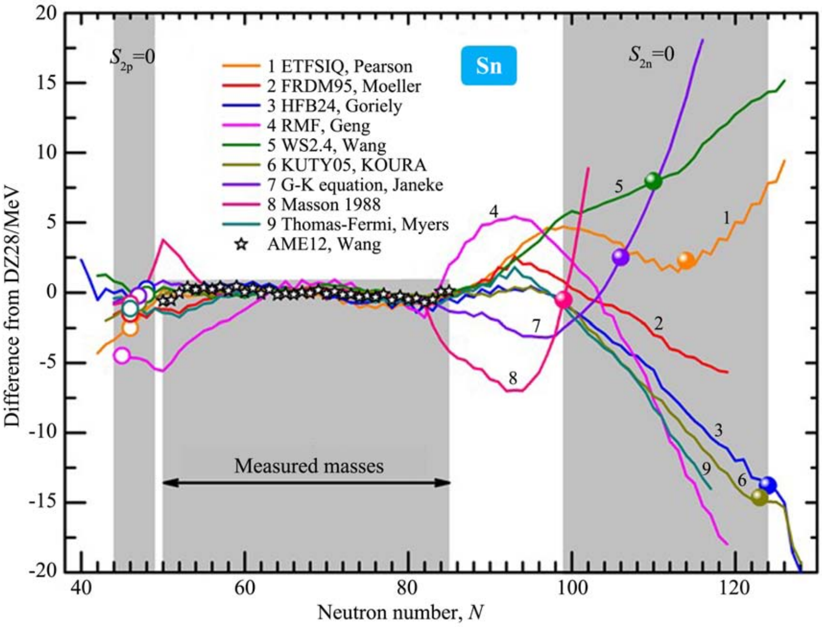

Fig. 9 (color online) Comparison of experimental masses of Sn nuclides with the calculated results of various mass models, displayed relative to the calculated values of the DZ28 model[28–29]. The black stars are experimental data, and the colored lines represent the predictions from the mass models indicated in the inset[28–29]. The open and filled circles show the nuclides predicted theoretically to be unbound with respect to two-proton and two-neutron emission, respectively.

roughly for half of which their masses were measured experimentally. The various mass models reproduce well in general the experimental data, but the predictions deviate significantly in the regions far from the stability[28–29]. The predicted two-neutron drip-line points, *i.e.* the nuclides with two-neutron separation energy equal to zero, differ by over 20 neutrons shown by the gray area in Fig. 9. It is therefore indispensable to measure the unknown masses to constrain and develop nuclear mass models. In addition, precision nuclear masses are of utmost importance to simulate various nuclear processes in staller environments, and in studies of fundamental symmetries and interactions. Taking the nuclear masses, half-lives, and reaction rates of astrophysical relevance as inputs, we will simulate the rapid neutron capture process and reproduce the observed element abundance distribution in the Universe. By connecting the simulated results to the core-collapse supernovae and two neutron star mergers, it would deepen our understanding of the origin of the heavy elements in the Universe and the dynamics of the explosive astrophysical events.

4 Conclusion

The primary aim of nuclear physics is striving to understand the origin, structure, evolution, and phases of strongly interacting matter, which constitutes nearly 100% of the visible matter in the Universe. Despite the great achievements in the past decades, there still exists overarching questions that animate nuclear physics today. It requires various advanced research facilities to study these immensely important and challenging questions, of which intense heavy-ion accelerator facilities play a key role worldwide. HIAF is a next-generation heavy-ion research facility for nuclear physics, complementary to other future heavy-ion accelerator facilities in the world. It will bring us to the forefront of promoting the most vigorous and fascinating fields in nuclear physics, such as to explore the limit to the existence of nuclei in terms of proton and mass numbers, to find exotic nuclear structure and study the physics behind, to understand the origin of the heavy elements in the Universe, to depict the QCD phase diagram of nuclear matter, *etc.* We eagerly await HIAF to come to the stage as scheduled.

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基于HIAF的物理研究

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摘要： 在2010年，中国科学院近代物理研究所向国家发展和改革委员会建议了重大科技基础设施——强流重离子加速器装置(High Intensity Heavy-ion Accelerator Facility，简称HIAF)。经过一系列评估和论证，HIAF于2015年12月被国家发展改革委立项。HIAF建设地址位于广东省惠州市，计划于2018年年底正式开工建造。HIAF由超导直线加速器、同步增强器、高能放射性束流线、储存环谱仪以及若干实验测量装置构成，总投资约为25亿人民币。依托HIAF，我们将拓展核素存在版图，研发先进实验技术和方法，开展前沿物理研究；同时，开展重离子束应用研究，服务国家经济社会发展。简要介绍拟建的加速器系统、实验测量装置以及相关的物理研究计划。

关键词： 重离子；加速器；核物理

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