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Construction of the High Intensity Heavy-ion Accelerator Facility (HIAF)

XIAOHONG ZHOU
ON BEHALF OF THE HIAF PROJECT TEAM

ABSTRACT

As one of the Major National Science and Technology Infrastructure Facilities in China, the High Intensity Heavy-ion Accelerator Facility (HIAF) is now under construction and is scheduled to be commissioned in 2025. HIAF is composed of a superconducting Linac, a booster ring, a high-energy radioactive beam line, an experimental storage ring, and a few experiment setups. The major goals of 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 society. In this paper, the accelerator complex of HIAF is briefly introduced, and the associated physics research program and the experimental setups are presented.

Fig. 1: The groundbreaking ceremony for HIAF's construction.

INTRODUCTION

On December 23, 2018, we celebrated the groundbreaking construction of the High Intensity Heavy-ion Accelerator Facility (HIAF) in Huizhou, which is located in south China (see Fig. 1). The construction will take approximately seven years, and the facility commissioning is expected to begin in 2025. The Institute of Modern Physics, Chinese Academy of Sciences, is responsible for the design and construction of HIAF, and HIAF is sponsored by the National Development and Reform Commission of China. HIAF is composed of a superconducting Linac, a booster ring, a high-energy radioactive beam line, a storage ring, and several experiment setups. The total investment of HIAF is about 2.5 billion Chinese yuan (CNY), with 1.5 billion CNY provided by the central government for facility construction and 1.0 billion CNY provided by the local governments for infrastructure. The major scientific goals identified for HIAF are to explore the hitherto unknown territories in nuclear chart, to study exotic nuclear structure, to synthesize super-heavy nuclides and elements, to understand the origin of heavy elements in the Universe, and to develop new heavy-ion applications in space and material sciences.

ACCELERATOR COMPLEX

HIAF is a large-scale heavy-ion research facility. Fig. 2 shows the accelerator complex. The injector indicated as iLinac in Fig. 2 is a superconducting linear accelerator with a length of 180 meters, and it is equipped with a new-generation 45 GHz, 20 KW ECR ion source to deliver 1.0 emA current for all kind of ions. The iLinac can be operated in 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). The BRing, with a circumference of 569 meters and a maximum magnetic rigidity of 34 Tm, is used for beam accumulation and acceleration. Due to space charge and dynamic vacuum effects, stored ions are launched to high energy very quickly using the fast ramping rate operation. A radioactive beam line, called the High Energy Fragment Separator (HFRS), is coupled to the BRing. The HFRS can produce unstable ions using heavy-ion projectile fragmentations or in-fight fission of energetic heavy projectiles, and then the HFRS separates, identifies and transports the ions of interest for various experiments. With slow extraction of high-energy ions from the BRing, HFRS works as a standalone separator and spectrometer. While using fast extracted beams, HFRS injects unstable ions into the Spectrometer Ring (SRing) for storage-ring based experiments. Very intense heavy-ion beams will be available at HIAF; taking the ion of $^{238}U^{34+}$ as an example, over 1.0×10^{11} particles can be stored in BRing and the maximum energy of 800 MeV/u could be achieved. It is worth noting that higher beam energies could be available if needed, through a tradeoff of the beam intensities. In past years, an immense amount of effort has been devoted to the R&D of key accelerator techniques in order to achieve unprecedented beam intensities, and there is no technical barrier impeding the facility's construction.

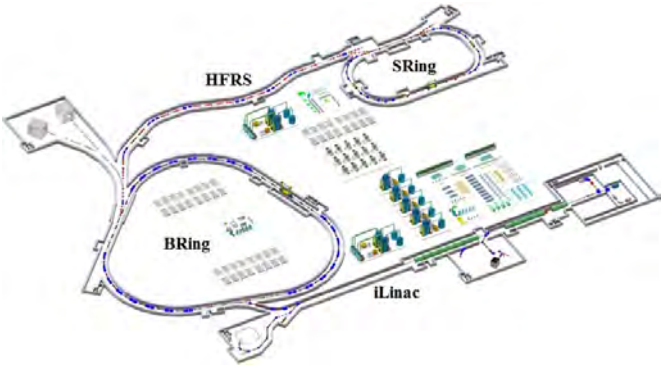

Fig. 2: Layout of HIAF. The major sub-systems and experimental caves are indicated.

HIAF will provide unprecedented heavy-ion beam intensities, and hence will give us great opportunities to explore the hitherto unknown territories in the nuclear chart. We have calculated the daily production yields of various isotopes using projectile fragmentation, in-flight fission, multi-nucleon transfer, and fusion reactions. The optimized yield for each isotope is presented in Fig. 3, in which the red lines are the boundaries of the known nuclides to date, and the gray lines are the proton and neutron drip-lines, 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. 3, prolific sources of nuclides will be provided at HIAF, and most importantly we should be able to 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, we anticipate that HIAF will be one of the most powerful facilities in the world to explore the nuclear chart.

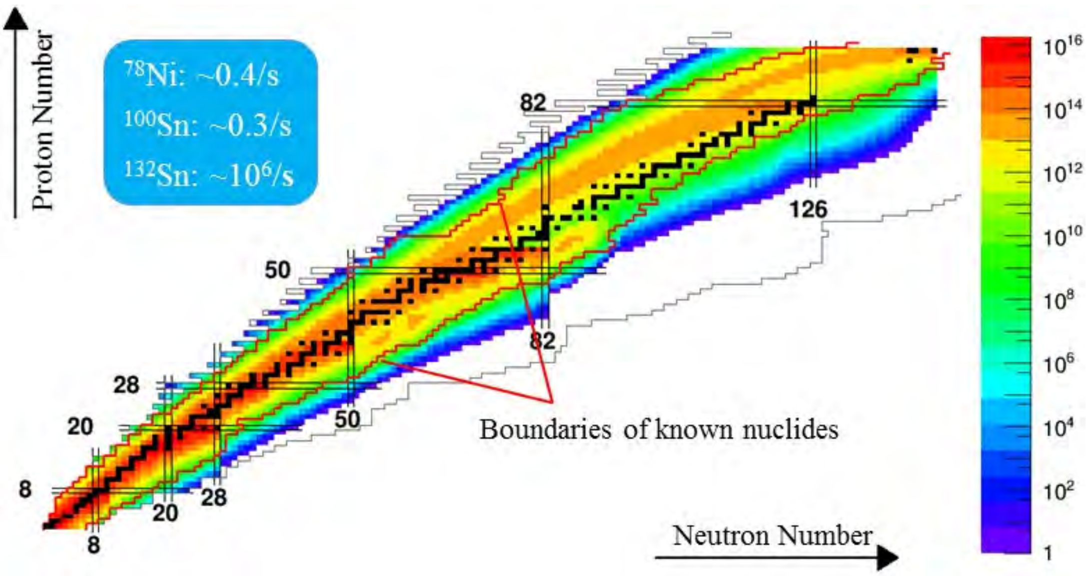

Fig. 3: The isotope production yields per day calculated using various reactions. The yields for the benchmark nuclides with double shell closures are given in the inset. The red and gray lines show the boundaries of known nuclides and the drip-lines, respectively. The different colors indicate the production yields in orders of magnitude.

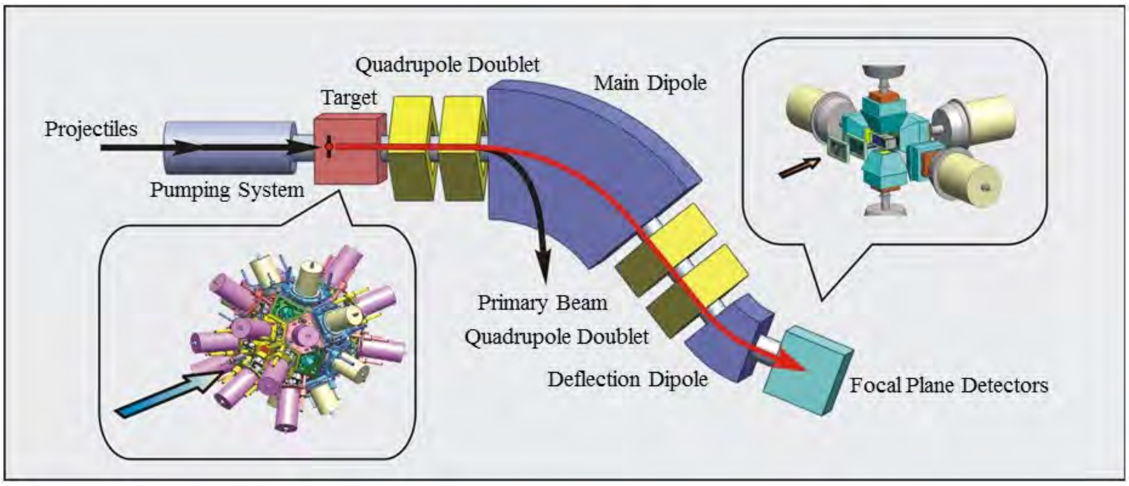

Fig. 4: The gas-filled recoil separator. The major components are indicated, and the detector arrays at the target position and focal plane are displayed in the insets.

EXPERIMENTAL SETUPS AND THE ASSOCIATED MAJOR PHYSICS

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

Low-energy experimental station

The Test Storage Ring (TSR) was built by the Max-Planck Institute for Nuclear Physics for studies of nuclear structure, reactions of astrophysical relevance, and atomic physics [1]. The transfer of TSR from Germany to China is under negotiation, and hopefully we will soon come to an agreement where the TSR is moved to HIAF. We plan to 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.

Heavy-ion beams are exacted at 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 the production of 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 [2-4]. The high angular acceptance and high transmission efficiency gas-filled recoil separator shown in Fig. 4 will be built, aiming mainly to synthesize new elements and neutron-deficient isotopes. In addition, if a gas cell, followed by an radio-frequency quadrupole (RFQ) cooler and buncher, is installed at the focal plane of the separator, pulsed high-quality, low-energy beams will be available for nuclear mass spectroscopy and collinear laser spectroscopy.

Multi-nucleon transfer reactions are characterized by large energy dissipation and nucleon exchange between the interacting nuclides. 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. Consequently, very neutron-rich heavy nuclides and even super-heavy nuclides are produced [5]. Presently, multi-nucleon transfer reactions employing a very heavy projectile and target 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 together with challenges. 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 effort 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. One of the most important areas to explore is the super-heavy region in the nuclear chart. 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. The multi-nucleon transfer reactions will offer us unprecedented opportunities for the synthesis of new neutron-rich super-heavy isotopes. If the reaction yields are enough, decay spectroscopy for these neutron-rich nuclides can be studied, and consequently the information of the single particle states can be 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.

High-energy experimental station

High-energy stable beams extracted slowly from the BRing are delivered to the high-energy experimental cave shown in Fig. 2. A 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 to a level similar to 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 ; hence hypernuclei is synthesized [6]. If the reaction energy is high enough (>3.75 GeV/u), hypernuclei with double strangeness can be also produced. One of the unique features of hypernuclear spectroscopy with projectile fragmentation is that, due to the 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. We hope that HIAF will become the world's best facility 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 [7]. It is of utmost importance to find how the nature of nuclear matter changes as we vary the temperature and baryon density. Lattice QCD calculations predicted that the transition from the quark-gluon plasma (QGP) to the hadronic phase is a smooth cross-over at the vanishing baryochemical potential, 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. The critical point would be a milestone

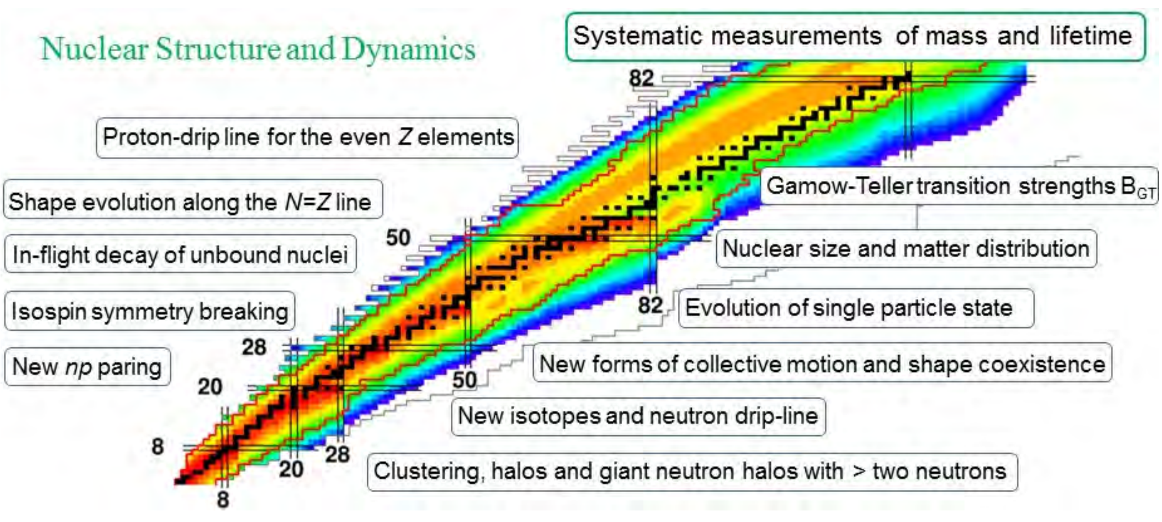

Fig. 5: The research subjects connected with nuclear structure and dynamics at HFRS.

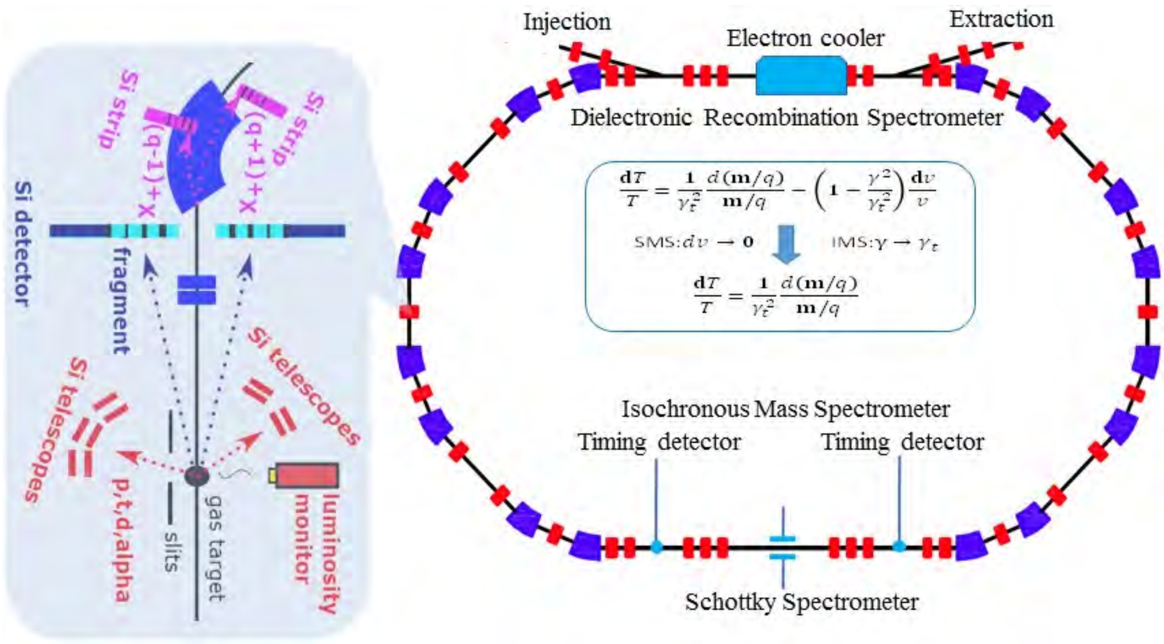

Fig. 6: Diagrammatic sketches of the Dielectronic Recombination Spectrometer, Isochronous Mass Spectrometer, Schottky Spectrometer, and Setup for In-ring Nuclear Reactions. The formulas shown in the inset in the right figure are the principle for nuclear mass measurements.

in the QCD phase diagram and is the Holy Grail for the field of the heavy-ion collisions at relativistic energies [8-9]. 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 were observed in the net-proton fluctuation and net-baryon first order collectivity, implying the expected criticality and softening of the equation of state, respectively [7]. Both the observations occured 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, which 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.

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 [8-9]. We have surveyed the optimum experimental conditions for a batch of 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, HFRS is composed of a pre-separator and a main-separator.

The exotic nuclides are produced via high-energy projectile fragmentations, in-flight fission of energetic heavy projectiles, and two-step reactions. The nuclides of interest will be separated in flight within several hundred nanoseconds and delivered to the detector systems. HFRS is characterized with a long flight path of 180 m, maximum magnetic rigidity of 25 Tm, 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 multi-stage magnetic system, comprising intermediate degrader stations. Best-performance detectors are placed at the focal and dispersive planes. 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 are 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 HFRS emerges from the experiments performed at existing radioactive beam facilities around the world. It will exploit HFRS as a flexible, high-resolution ion-optical device. A rich physics program is defined and shown in Fig. 5. 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, and to study dynamical symmetries in exotic nuclei particularly along the N=Z line, *etc.* [8-9].

Last but not least, HFRS will have 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 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 will be exploring fully high magnetic rigidity, which 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 [10]. For these experiments, dedicated detector setups will be built and coupled to the specific focal planes of HFRS.

Spectrometer ring

Using fast, extracted projectiles from the BRing, HFRS produces, separates and injects the nuclides of interest into the SRing, which is in essence a storage ring equipped with an electron cooler, a stochastic cooling device, and a 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. 6. We shall develop advanced Isochronous Mass Spectrometry with double timing detectors, by which the velocity of the stored ion is measured to correct for the effect of the non-isochronicity. Two timing detectors will be installed in the straight section of the SRing. This technique was already verified in principle at the existing facility [11]. We will develop single-ion sensitive Schottky spectrometry in the isochronous mode of a storage ring, which 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 SRing, we mainly measure nuclear masses, half-lives, reaction cross sections, and exotic decay modes of highly charged ions. One particularly 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 some of the most fundamental questions in low-energy nuclear physics are closely related to nuclear masses; for example, in the drip lines, the prediction of the decay models of drip-line nuclides, in the recognition of the disappearance of spherical magic numbers and the appearance of new magic numbers, and in the identification of the onset of deformation along isotope chain and shape coexistence, *etc.* [8-9]. 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. 7 presents an example to demonstrate the importance of nuclear mass measurements. Theories predicted that there might exist about 80 Sn isotopes, roughly about half of what their masses were measured experimentally. In general, the various mass models reproduce the experimental data well, but the predictions deviate significantly in the regions far from the stability [12-13]. The predicted two-neutron drip-line points, *i.e.* the nuclides with two-neutron separation energy equal to zero, differ by over 20 neutrons, which are shown by the gray area in Fig. 7. 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, we anticipate that our understanding of the origin of the heavy elements in the Universe and our understanding of the dynamics of the explosive astrophysical events will deepen.

SUMMARY

The primary aim of nuclear physics is striving to understand the origin, structure, evolution, and phases of strongly interacting matter, which constitute nearly 100% of the visible matter in the Universe. Despite the great achievements made in the past decades, there still exists overarching questions that animate nuclear physics today. To answer these immensely important and challenging questions, the construction of various advanced research facilities is necessary, of which intense heavy-ion accelerator facilities play a key role internationally. HIAF will be 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 in promoting the most vigorous and fascinating fields in nuclear physics, which include areas such as exploring the limits of the existence of nuclei in terms of proton and mass numbers, finding exotic nuclear structure and studying the physics behind those structures, understanding the origin of the heavy elements in the Universe, and depicting the QCD phase diagram of nuclear matter. We eagerly await HIAF's scheduled completion.

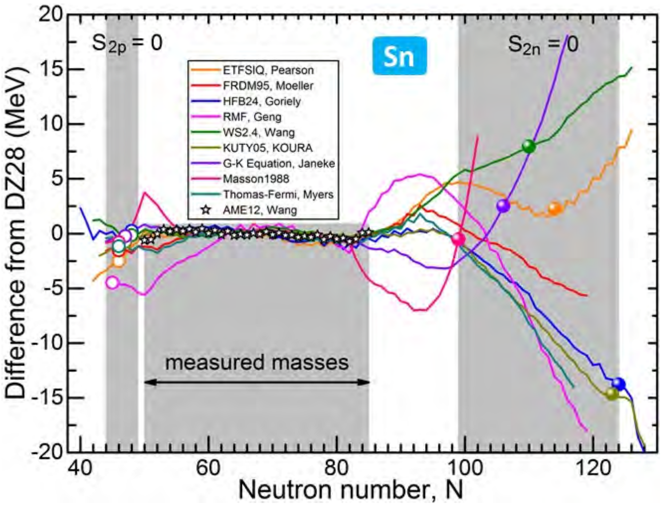

Fig. 7: Comparison of experimental masses of Sn nuclides with the calculated results of various mass models, displayed relative to the calculated values of the DZ28 model. The black stars are experimental data, and the colored lines represent the predictions from the mass models indicated in the inset [12-13]. The open and filled circles show the nuclides predicted theoretically to be unbound with respect to two-proton and two-neutron emission, respectively.

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Xiaohong Zhou is a senior researcher at the Institute of Modern Physics, Chinese Academy of Sciences. Since receiving a PhD from the Chinese Academy of Sciences in 1995, he has been working on nuclear structure and synthesis of new isotopes in the heavy mass region. Presently, he serves as the deputy director of the High Intensity Heavy-ion Accelerator Facility (HIAF) project and is responsible for the design and construction of the experimental detector systems of HIAF.