

Nov. 29, 2022

Dear officers of Philippine physics and nuclear physics society,

It is my great pleasure to let you know that your country was accepted to the Asia Nuclear Physics Association (ANPhA) formal member country. This decision was made after the voting among the board members in the ANPhA meeting dated Nov. 17, 2022, initiated by the application from Dr. Denny Sombillo on behalf of your country.

I would also like to let you know that, after voting for board members, Dr. Denny Sombillo was elected to be the board member of ANPhA from Jan. 1, 2023, on behalf of the Philippine nuclear physics community of your country.

Let me warmly congratulate the joining of your country to ANPhA family and I am expecting the future collaboration of nuclear physics research, application and exchange of Asia Pacific countries and regions with your country.

Best regards,

Meyoing din

Weiping Liu ANPhA chair



# Nuclear Physics News International

Nuclear Physics News

ISSN: 1061-9127 (Print) 1931-7336 (Online) Journal homepage: https://www.tandfonline.com/loi/gnpn20

### Ten Years of the Asian Nuclear Physics Association (ANPhA) and Major Accelerator Facilities for Nuclear Physics in the Asia Pacific Region

Anthony W. Thomas, Andrew E. Stuchbery, Weiping Liu, Guoqing Xiao, Yugang Ma, Jun Cao, Avinash C. Pandey, B. K. Nayak, Sumit Som, Kazuhiro Tanaka, Tohru Motobayashi, Hirokazu Tamura, Atsushi Hosaka & Byungsik Hong

**To cite this article:** Anthony W. Thomas, Andrew E. Stuchbery, Weiping Liu, Guoqing Xiao, Yugang Ma, Jun Cao, Avinash C. Pandey, B. K. Nayak, Sumit Som, Kazuhiro Tanaka, Tohru Motobayashi, Hirokazu Tamura, Atsushi Hosaka & Byungsik Hong (2020) Ten Years of the Asian Nuclear Physics Association (ANPhA) and Major Accelerator Facilities for Nuclear Physics in the Asia Pacific Region, Nuclear Physics News, 30:3, 3-45, DOI: <u>10.1080/10619127.2020.1790931</u>

To link to this article: https://doi.org/10.1080/10619127.2020.1790931

1	1	(	1
Г			

Published online: 14 Oct 2020.

Submit your article to this journal  $\square$ 

Article views: 114

View related articles



View Crossmark data 🗹

## Ten Years of the Asian Nuclear Physics Association (ANPhA) and Major Accelerator Facilities for Nuclear Physics in the Asia Pacific Region

**Nuclear Physics in the Asia Pacific Region** Anthony W. Thomas<sup>1,6</sup>, Andrew E. Stuchbery<sup>1,7</sup>, Weiping Liu<sup>2,8</sup>, Guoqing Xiao<sup>2,9</sup>, Yugang Ma<sup>2,10</sup>, Jun Cao<sup>2,11</sup>, Avinash C. Pandey<sup>3,12</sup>, B. K. Nayak<sup>3,13</sup>, Sumit Som<sup>3,14</sup>, Kazuhiro Tanaka<sup>4,15</sup>, Tohru Motobayashi<sup>4,16</sup>, Hirokazu Tamura<sup>4,17</sup>, Atsushi Hosaka<sup>4,18</sup> and Byungsik Hong<sup>5,19</sup> <sup>1</sup>ANPhA, Australia <sup>2</sup>ANPhA, China <sup>3</sup>ANPhA, India <sup>4</sup>ANPhA, Japan <sup>5</sup>ANPhA, Korea <sup>6</sup>University of Adelaide, ANPhA Vice Chair, Australia <sup>7</sup>Australian National University, Australia <sup>8</sup>CIAE, ANPhA Chair, China <sup>9</sup>IMP-CAS, ANPhA Board Member, China <sup>10</sup>Fudan University, ANPhA Board Member, China <sup>11</sup>IHEP, China <sup>12</sup>IUAC, ANPhA Board Member, India <sup>13</sup>BARC-TIFR, ANPhA Board Member, India <sup>14</sup>VECC, ANPhA Board Member, India <sup>15</sup>KEK, ANPhA Board Member, Japan <sup>16</sup>RIKEN, ANPhA Vice Chair, Japan <sup>17</sup>Tohoku University/JAEA, ANPhA Board Member, Japan <sup>18</sup>Osaka University/JAEA, ANPhA Board Member, Japan <sup>19</sup>Korea University, ANPhA Vice Chair, Korea

#### 1. Introduction

#### **Establishment of ANPhA**

On 18 July 2009, the Asian Nuclear Physics Association (ANPhA) [1] was officially launched in Beijing by representatives from China, Korea, Japan, and Vietnam.

The main objectives of ANPhA are clearly indicated in its bylaws:

- 1. to strengthen *collaboration* among the Asian communities in nuclear research through the promotion of basic nuclear physics and its applications,
- 2. to promote *education* in the Asian nuclear science communities through mutual exchange and coordination of resources,

- to encourage *coordination* among the Asian nuclear scientists for active utilization of existing research facilities, and
- 4. to *discuss future planning* of the nuclear science facilities and instrumentation among member countries.

According to the brief summary report prepared by Prof. Hideyuki Sakai, which appeared in *Nuclear Physics News* [2], entitled "Establishment of the Asian Nuclear Physics Association (ANPhA)," the story of the first days of ANPhA was as follows:

... Initially, the need of an organization like ANPhA was raised from time to time at the meetings of the Commission on Nuclear Physics (C12) of the International Union of Pure and Applied Physics (IUPAP) as well as at its Working Group (WG.9) on the International Cooperation in Nuclear Physics (ICNP). The first step was taken during the meetings of WG.9 and C12 in May 2008 held at CERN, where Shoji Nagamiya (KEK [High Energy Accelerator Research Organization]/J-PARC, Japan), Dong-Pil Min (Seoul National Univ., Korea), Hideyuki Sakai (Univ. Tokyo, Japan), and Wenqing Shen (National Natural Science Foundation of China) met together after the dinner of WG.9 and agreed to launch an initiative to form some organization in Asia similar to [the Nuclear Physics European Collaboration Committee] NuPECC in Europe. In Asia, the world class facilities, such as RIBF at RIKEN and J-PARC at Tokai in Japan, a new initiative on a heavy ion accelerator complex in Korea [which is now known as RISP/RAON], Heavy Ion Research Facility in Lanzhou (HIRFL) and BRIF(II) at CIAE, Beijing, in China, etc. were in operation or being planned.

It was widely recognized among the member countries that systematically organized usage of these facilities was still missing and a collaborative scheme was highly desirable to make the best use of them. Thus one of the major roles of ANPhA was to provide a common ground to discuss those issues in harmony. Another important role of ANPhA was to promote education in nuclear science among the Asian countries through various means.

The first preparation meeting was held in Tokyo, Japan in October 4, 2008 followed by the second one in Seoul, Korea in February 21, 2009.

On July 18, 2009 the Inauguration Ceremony took place in the Ying Jie Conference Center of Peking University in Beijing. First, the board members from China, Japan, Korea and Vietnam were officially confirmed. These board members gave their official approval to the Bylaws. These initial board members were Weiping Liu, Yugang Ma, Guoqing Xiao, and Yanlin Ye from China, Tohru Motobayashi, Shoji Nagamiya, Takaharu Otsuka and Hideyuki Sakai from Japan, Seung-Woo Hong, Wooyoung Kim, and Dong-Pil Min, from Korea, and Dao Tien Khoa from Vietnam. Second, for the first term Hideyuki Sakai was elected as the Chair of AN-PhA, Dong-Pil Min and Yanlin Ye were elected as Vice-Chairs, and Tohru Motobayashi was later appointed by the Chair as Scientific Secretary.

During the Inauguration Ceremony, congratulatory addresses were given by Wenqing Shen (Deputy Director of NSFC), Wenlong Zhan (Deputy Director of CAS), Huanqiao Zhang (Chair of NPSC), Jiaer Chen (Former President of Peking Univ.) and Guangda Zhao (Director of the Scientific Committee of the School of Physics of Peking Univ.), which were followed by speeches by the ANPhA board members representing the nuclear physics communities in their own countries. The ceremony was also witnessed by professors Boqiang Ma, Yuxin Liu and Furong Xu of Peking University. Finally, the commemorative photograph was taken [Figure 1].

After the ceremony, the first business meeting of AN-PhA took place. The main topics of the discussion were:

- 1. Invitation of new member countries and regions,
- 2. Preparation of documents for the existing research facilities and computing resources in member countries and regions,
- 3. ANPhA support for symposiums and schools,
- 4. Discussion on the long-range plan of ANPhA,
- 5. Decision on the second ANPhA meeting.

It is decided that the official ANPhA Office was located at the RIKEN Nishina Center in Japan. A very preliminary ANPhA home page was built at http://ribf.riken.jp/ ANPhA/. [It has moved to https://bisol.org/anpha/] Concluding the first ANPhA board meeting, it was proposed to organize the first ANPhA Symposium on "Asian Nuclear Physics Facilities" on January 14–15, 2010 at Tokai-mura, Japan. A visit to J-PARC, which was under construction there, for symposium participants was also planned, and the next ANPhA board meeting was scheduled on January 17 (Sunday), 2010 at Tokai-mura in conjunction with the First ANPhA Symposium.

#### **Present Status of ANPhA**

Ten years after its establishment, ANPhA is the central organization representing nuclear physics in Asia Pacific, consisting of 11 member countries and regions (i.e., Australia, China, Hong Kong, India, Japan, Kazakhstan, Korea, Mongolia, Myanmar, Taiwan, and Vietnam).

In 2015, ANPhA decided to play a role as the Division of Nuclear Physics (DNP) of the Association of Asia Pacific Physics Societies (AAPPS). The AAPPS approved our proposal in 2016, and AAPPS-DNP was established. Now the ANPhA chair is also the chair of AAPPS–DNP. In a nutshell, we can describe ANPhA (which is also known as AAPPS–DNP) as the sole organization to discuss and pursue issues in the Asian nuclear physics community at present.

Therefore, the ANPhA chair is a formal member of IU-PAP–WG.9 on the International Cooperation in Nuclear Physics, representing the Asia Pacific region.



**Figure 1.** Founding members of ANPhA gathered together in Beijing in 2009. Front row from left to right: Quanqiao Zhang; Wenqing Shen; Hideyuki Sakai; Shoji Nagamiya; Jiaer Chen; Seung-Woo Hong; Guangda Zhao. Second row from left to right: Yuxin Liu; Wooyoung Kim; Tohru Motobayashi; Weiping Liu; Dao Tien Khoa; Yanlin Ye; Wenlong Zhan; Takaharu Otsuka; Boqiang Ma; Hushan Xu; Yugang Ma; Furong Xu.

The participating countries or regions in ANPhA will appoint several (one to four) board members for ANPhA. The board members select one chairperson and several vice chairpersons by mutual election. The chairperson will also appoint a scientific secretary. However, they can be selected from outside the board members. The chairperson, vice chairperson, and scientific secretary constitute an executive officer team, and handle daily affairs of ANPhA. In Figure 2, you can see photos of current officers of ANPhA, whose term is 2020–2022.

The ANPhA board members meet once a year at some appropriate place in one of the ANPhA member countries or regions and exchange information concerning the status of nuclear physics in each country/region and have discussions on our future collaborations. This kind of meeting, the annual ANPhA board meeting, is organized in conjunction with the ANPhA symposium, with a subject related to the "Status of Nuclear Physics in Asia Pacific." The recent ANPhA board meetings were held in Halong City, Vietnam (the 12th) on 24 September 2017 with the International Symposium on Physics of Unstable Nuclei (ISPUN17), in Beijing, China (the 13th) on 14 September 2018 in conjugation with the ANPhA symposium on "Nuclear Physics Facilities in Asia," and on Jeju Island, Korea (the 14th) on 28 June 2019. The next board meeting will be held in Hong Kong in 2021. At the Jeju meeting, we organized a special ANPhA Symposium on the subject of "High-Energy Heavy Ion Studies in Asia/Pacific and World in Coming 10 Years," as a celebration event of the 10th anniversary of ANPhA (see Figure 3). This was the first trial to discuss the Asianwide policy for establishing the Long Range Plan of nuclear physics in Asia Pacific. We, ANPhA board members, discussed at the Jeju meeting how we should promote our activity concerning high-energy heavy-ion studies in Asia Pacific, where we have no high-energy heavy-ion accelerator and collider.

Immediately after the establishment of ANPhA in 2009, ANPhA and NuPECC agreed to exchange observers with each other, with the ANPhA chair invited to attend all Nu-PECC meetings (three times a year) as an observer. The NuPECC chair and a scientific secretary are also invited to attend the annual ANPhA board meeting. The ANPhA chair is also an invited member of Nuclear Physics Division of the European Physical Society (EPS–NPD) since the ANPhA chair is also the chair of the Division of Nuclear Physics of the Association of Asia Pacific Physics Societies (AAPPS–DNP).

As the chair of AAPPS–DNP, the ANPhA chair has to attend AAPPS extended council meetings. The most recent of the AAPPS extended council meetings was held in Kuching, Malaysia on 17 November 2019 in conjunction with the 14th Asia Pacific Physics Conference (APPC2019). Now there are only three divisions in AAPPS (Division of Plasma Physics, Division of Astrophysics, Cosmology and Gravitation, and DNP), so ANPhA (= AAPPS–DNP) activities are one of the major pillars of AAPPS.

ANPhA also supports various international meetings on physics in Asia Pacific by organizing a "Nuclear Physics Session" in symposiums, conferences, and workshops. Even at the APPC2019, preparation of the conference program, selection of speakers (including poster presentations), and finding the suitable reviewers for submitted papers for proceedings, and so on of the Nuclear Physics Session of the APPC2019 were provided by ANPhA with active discussions with the APPC2019 organizing committee. The International Conference on Physics, Mandalay 2018, held 25–27 November 2018 at Mandalay University, Myanmar, is another example of support of this kind by ANPhA. Another important activity of ANPhA is organizing AAPPS–DNP (= ANPhA) Awards for Young Scientists (AAYS) [3] for ANPhA-supported scientific meetings (symposiums, conferences, and schools). AAYS is a kind of poster session and/or presentation awards for young participants of the meeting. Several very good presentations are selected by an award nomination committee of the meeting organized in Asia Pacific, and AAYS certificates with a small amount of award money (just 100 USD for the first rank winner) is given to presenters. AAYS started in 2017 with financial support from AAPPS, which



**Figure 2.** Current officers of ANPhA (= AAPPS–DNP). From left to right: Weiping Liu (chair, CIAE, China); Tohru Motobayashi (vice chair, RIKEN, Japan); Anthony Thomas (vice chair, University of Adelaide, Australia); Byungsik Hong (vice chair, Korea University, Korea); Bing Guo (scientific cecretary, CIAE, China).



Figure 3. Photo of ANPhA board meeting held on Jeju Island, Korea in 2019.

Nuclear Physics News, Vol. 30, No. 3, 2020

served as the first source of the award money. Now, the award money of AAYS is covered by the annual fee of ANPhA member countries and regions. Fortunately, until now, we have had 17 occasions to present the AAYS. The latest one was given at the 9th International Symposium on Nuclear Symmetry Energy (NuSYM2019) held in Da Nang City, Vietnam, from 30 September–4 October 2019 (see Figure 4). In 2021, however, only two conferences were selected for AAYS—the Asia Pacific Few Body Conference, which will be held in Kanazawa, Japan and the Nuclei in Cosmos conference, which will be held in Chengdu, China. Many more applications to AAYS as well as ANPhA-supported meetings are always welcome!

#### **ANPhA White Paper**

Nuclear physics is a typical accelerator-based science. However, in contrast to elementary particle physics, which is another field of science based on accelerators, nuclear physics requires a variety of accelerators to tackle the various problems involved. In other words, one needs a distributed approach and effort; that is, different accelerator types and energies, in order to find answers to the nuclear physics problems existing in our universe, as shown in Figure 5. For example, we need accelerators with very high-intensity accelerators with relatively low beam energy (MeV-mA accelerators) for study of nuclear synthesis in the early universe, as well as fusion reactions that sustain the present solar energy. However, the study of quark gluon plasma requires very high-energy heavy-ion colliders (TeV energy). For the study of the high-density nuclear matter that should exist deep inside of the neutron stars, high-intensity, high-energy hadron accelerators (several tens GeV beam energy with several hundred kW beam power) and/or medium-energy highintensity heavy ion accelerators (several hundred MeV/u beam energy with several tens kW beam power). A wide variety of accelerators are needed!

We should be careful because the development of accelerator-based research facilities may involve big construction work. It is also expensive and requires a very large amount of money. Today, we can understand that it is very difficult to prepare all kinds of accelerators necessary for the nuclear physics research in one country or region. It is also becoming common to advance research through international collaboration; that is, international divisional cooperation of construction works.

Even in the Asia Pacific region, many advanced accelerator facilities have been constructed. Some of them are really world-class facilities. ANPhA is now preparing a list of accelerator facilities applicable for nuclear physics experiments existing in Asia Pacific. The list is known as the ANPhA White Paper [5]. This White Paper, the catalog of accelerators in Asia Pacific, is the most basic material for us to consider today's international collaboration within present accelerator facilities, and to establish the long range plan of the construction of accelerator facilities for our future activities of nuclear physics in Asia Pacific. At present, unfortunately, we have no formal Asian-wide long range plans for nuclear physics. We have just a long range plan in each country/region. However, by exchanging detailed information of present facilities and near-future construction plans of accelerator facilities in the whole Asia Pacific region, we can easily establish the construction plans of next-generation accelerator facilities in our own country/ region with less duplications.

Such an international co-operation scheme has been practiced globally. Thus, the ANPhA White Paper will provide useful information for our colleagues in Europe, and North America too.

It should be noted that accelerator facilities originally prepared for nuclear physics research have many applications of science, such as material science, life science, medicine, and especially education and training of young students. Therefore, the ANPhA White Paper can be a good guide for researchers in neighboring research fields to expand their research to accelerator-based science using nearby facilities.

Cancer treatments with accelerator beams are one very good example of the application of nuclear physics facilities. Now we know cancer treatments require approximately 250 MeV proton beam or 800 MeV/u heavy-ion (carbon) beam. These beams were originally developed for nuclear physics experiments and are now available as a part of hospital facilities from heavy-industry companies. In Japan, there are 24 accelerator-based hospital facilities of this kind (18 with proton beam and 6 with heavy-ion beam) [6]. However the first trial to use a several hundred MeV proton beam for cancer treatments started in 1983 at the KEK laboratory in Tsukuba, Japan by using a 500 MeV proton booster synchrotron [7], which was originally designed and used for the injector of a 12 GeV main proton synchrotron. The treatments were completed in 2000 at KEK, and a new accelerator facility dedicated for cancer treatments was constructed in a nearby hospital operated by the Medical School of the University of Tsukuba [7].

Cancer treatments using a heavy-ion beam started at the Heavy Ion Medical Accelerator in Chiba (HIMAC) [8], which is the first dedicated cancer therapy accelerator and can provide 800 MeV/u heavy ion beams. However,



Figure 4. Photo of the awarding ceremony of ANPhA Awards for Young Scientists at its 17th occasion at the 9th NuSYM, Danang City, Vietnam, 30 September–4 October 2019. From left to right, Prof. Dao Tien Khoa (symposium chair, Vietnam, former ANPhA board member), Dr. Sebastien Guillot (Institut de Recherche en Astrophysique & Planétologie, Centre National de la Recherche Scientifique, IRAP-CNRS), Dr. Vi Ho Phong (University of Science, Hanoi), Prof. Hirokazu Tamura (Tohoku University, Japan, ANPhA board member), and Prof. Byungsic Hong (Korea University, Korea, ANPhA board member).

the HIMAC was a kind of spinoff from the nuclear physics project NUMATRON [9].

The typical proton beam energy and intensity applicable for Boron Neutron Capture Therapy (BNCT) are 30 MeV and 1 mA (= 30 kW). The accelerated protons are converted to epi-thermal neutrons at the beam dump and neutrons thus generated are used for the irradiation for Boron compounds concentrated in tumor cells in the human body. The basic nuclear reaction of BNCT is n + <sup>10</sup>B ->  $\alpha$  + <sup>7</sup>Li, and the  $\alpha$ particle thus generated attacks the tumor cell. Traditionally, therefore, BNCT was carried out at the reactor facilities. However, recent development of compact high-intensity proton accelerators made BNCT possible in the accelerator facilities. Now, in 2020, there are approximately 10 accelerator facilities dedicated for BNCT in Asia Pacific.

There are 28 accelerator facilities for nuclear physics in Asia Pacific, which are listed in the ANPhA White Paper (see Table 1). Data will be updated frequently. The latest update was done in December 2017. Critical analysis of the present data is being done for future facility planning and for possible future international collaboration. The data are now temporarily available in the KEK Indico system [5].

#### **Major Accelerator Facilities in Asia Pacific**

Major accelerator facilities for nuclear physics in the Asia Pacific region are mainly located in China (HIRFL and Beijing Tandem Accelerator National Laboratory [BTANL]), India (Variable Energy Cyclotron Centre [VECC], Inter University Accelerator Centre [IUAC], and Bhabha Atomic Research Centre [BARC]), Korea (Rare Isotope Science Project [RISP]/Rare isotope Accelerator complex for ONline experiments [RAON]), and Japan (Radioactive Isotope Beam Factory [RIBF] at RIKEN, Japan Proton Accelerator Research Complex [J-PARC], Research Center for Nuclear Physics [RCNP], and Research Center for Electron Photon Science at Tohoku University [ELPH]/Laser Electron Photon beam-line at SPring-8 [LEPS]), as shown in Figure 6.

Most of them (HIRFL, BTANL, VECC, RISP/RAON, and RIBF) are medium-energy heavy-ion accelerator facilities for rare ion (RI) beam experiments and are competing with European and American facilities, such as SPIRAL2 (Systèm de Production d'Ions Radioactifs Accélérés en Ligne), HIE-ISOLDE (High-Intensity and Energy upgrade of Isotope mass Separator On-Line at CERN [DE was added by some Wagner fans in CERN in its early days]), SPES (Selective Production of Exotic Species), MYRRHA (Multi-purpose hYbrid Research Reactor for High-tech Application), ARIEL-II (Advanced Rare Isotope Laboratory-II), and FRIB (Facility for Rare Isotope Beams). In addition, future extension plans of these Asian facilities, such as the High Intensity heavy-ion Accelerator Facility (HIAF) in China, are really aiming far beyond the wave front of the research of this field of nuclear physics. In this meaning, Asian research facilities are keeping world-best positions in medium-energy heavy-ion physics. The hadron physics facility in Asia Pacific (J-PARC) is also world leading. The ring cyclotron of RCNP provides the world's best beams for high-resolution spectroscopic study. The ELPH/ LEPS facilities can provide world-competitive electron and photon beams for nuclear and hadron physics.

However, there are no high-energy heavy-ion accelerators and colliders (such as ALICE [A Large Ion Collider Experiment] in the Large Hadron Collider [LHC] at the European Laboratory for Particle Physics [CERN], the Relativistic Heavy Ion Collider [RHIC] at Brookhaven National Laboratory [BNL] in the United States, and the Nuclotron-based Ion Collider fAcility [NICA] at the Joint Institute for Nuclear Research in Dubna, Russia) in the Asia Pacific region. In other words, Asia Pacific facilities have concentrated their research resources to medium-energy heavy-ion physics and



**Figure 5.** From the viewgraph used at the official presentation of the NuPECC long range plan [4] given by permission of Angela Bracco at Brussels on 27 November 2017. The necessity of various type of accelerators in nuclear physics is clearly shown!

chosen to promote high-energy heavy-ion physics abroad (outside Asia). This approach seems successful at present.

However, should we keep on this way for the coming 10 years? Concentration on the medium-energy heavy-ion accelerator may be a subject to rethink. Should we be much more careful in our investment for our future activities in nuclear physics, which should have a much wider spectrum (?). One of the authors of this article is wondering that the same type of concentration is also seen in Europe and North America. This brief report, however, introduces only the present and future plans of some of our major accelerator facilities.

#### 2. Chinese Facilities

#### **Overview of Operational and Planned Facilities**

In China, major facilities are composed in the subfields of nuclear physics and high-energy physics. For concentration, this report mainly covered the local nuclear physics experimental part. Two centers of nuclear physics in Beijing and Lanzhou are included, which are affiliated with the China National Nuclear Corporation (CNNC) and Chinese Academy of Sciences (CAS), respectively, plus some more facilities. In Beijing, we start from the tandem accelerator, an Isotope Separator Online (ISOL) facility called the Beijing Rare Ion Facility (BRIF) has been developed, and the Beijing ISOL Neutron-Rich Beam Facility (BISOL) and the China Institute of Atomic Energy (CIAE) is under consideration. In Lanzhou, we start from the cyclotron, followed by the Cooling Storage Ring (CSR), then HIAF, which is under construction in Guangdong province, a truly large center of heavy ion (HI) study at the Institute of Modern Physics (IMP). Some other facilities are partially introduced. They are Jinping Underground Nuclear Astrophysics (JUNA) from CIAE, Shanghai Laser Electron Gamma Source (SLEGS) in the Shanghai Institute of Applied Physics (SINAP), Jiangmen Underground Neutrino Observatory (JUNO), and Daya Bay Reactor Neutrino Experiment (Daya Bay) at the Institute of High Energy Physics (IHEP). The operational costs of the aforementioned facilities are supported by the Ministry of Finance in China or the China Atomic Energy Agency (CAEA). The research programs are supported by the National Natural Science Founda-

#### Table 1. List of accelerators collected in ANPhA White Paper.

			1.1		
Town	Institute	Facility	Characteristics		
Canberra, Australia	Australian National University (ANU), Heavy Ion Accelerator Facility		15MV Tandem accelerator + superconducting Linear Accelerator		
Beijing, China	Beijing Tandem Accelerator Nuclear Physics National Laboratory	BTANL	15 MV tandem accelerator, 100 MeV 20 μA proton cyclotron, ISOL		
Shanghai, China	Shanghai Laser Electron Gamma Source	SLEGS	0.4-20 MeV BCS γ-ray source based on Synchrotro Radiation Facility		
Jinping, China	China Jinping underground Laboratory (CJPL), JINPING UNDERGROUND NUCLEAR ASTROPHYSICS EXPERIMENT (JUNA)	CJPL / JUNA	400 kV accelerator (lon species of Stable nuclei: H t He), Max. Energy: 400 kV*q, Beam Intensity: up to 2 emA		
Lanzhou, China	Heavy Ion Research Facility in Lanzhou	HIRFL	SSC cyclotron: K=450 and full ion acceleration CSRm booster synchrotron 12.2 Tm		
Huizhou, China	Heavy Ion Accelerator Facility, Institute of modern Physics	HIAF	Heavy-lon Linac, Booster-ring ~1GeV/u and Ring spectrometer (Phase 1). Compressor ring ~5GeV/u and Enrgy Recovery Linac.		
Huizhou, China	China Initiative ADS	CIADS	The 250 MeV and 10mA (maximum beam current) CW mode superconducting proton LINAC		
Munbai, India	Bhabha Atomic Research Centre - Tata Institute of Fundamental Research (BARC-TIFR)	BARC-TIFR	14MV heavy ion tandem + superconducting linac (PLF Pelletron LINAC Facility)		
New Delhi, India	Inter-University Accelerator Centre	IUAC	15MV heavy ion tandem + superconducting linac		
Kolkata, India	Variable Energy Cyclotron Centre	VECC	VECC K130 cyclotron (p,q), K500 Superconducting Cycrotron		
Chiba, Japan	Heavy Ion Medical Accelerator, National Institute of Radiological Sciences	НІМАС	High energy heavy ion beams, up to 800 MeV/u, supplied by linear accelerators and two synchrotron rings.		
Tokai, Ibaraki, Japan	J-PARC (Nuclear and Particle Physics Facility)	J-PARC	High Intensity Accelarators, 400MeV LINAC, 3GeV RCS, 50GeV MR		
Osaka, Japan	Research Center for Nuclear Physics, Osaka University	RCNP/LEPS	Cyclotron complex (K140 AVF + K400 Ring) Laser-electron back-scattered photon facility at SPring-8 site, 2.4 and 2.9 GeV.		
SPring-8 site, Hyogo, Japan	Laboratory of Advanced Science and Technology for Industry	NewSUBARU	Laser Compton Scattering Gamma-ray Beam Source (1 - 76 MeV)		
Wako, Saitama, Japan	RIKEN Nishina Center for Accelerator-Based Science, RI Beam Factory	RIBF	Heavy Ion Linac and several big Ring Cycrotrons (Ma K=2500MeV), Big Rips Projectile Isotope Separator		
Fukuoka, Japan	Kyushu University, Center for Accelerator and Beam Applied Science		FFAG synchrotron and tandem acceleror		
Tokai, Ibaraki, Japan	Japan Atomic Energy Agency (JAEA), Tandem Accelerator Facility		20MV tandem accelerator and superconducting linac booster.		
Tsukuba, Ibaraki, Japan	University of Tsukuba, Tandem Accelerator Complex	UTTAC	6 MV tandem accelerator / 1 MV Tandetron accelerato		
Sendai, Japan	Tohoku University, Cyclotron and Radioisotope Center	CYRIC	K110 and K12 cycrotrons		
Sendai, Japan	ai, Japan Research Center for Electron-Photon Science, Tohoku Univerisity		60 MeV High Intensity ELECTRON Linac, 1.3 GeV Booster Electron Synchrotron for GeV tagged photon beams		
Gyeongsangbu k-do, Korea	Korea Multi-purpose Accelerator Complex	KOMAC	100 MeV and 20 MeV Proton linac		
Seoul, Korea	Korea Institute of Science and Technology (KIST), The Accelerator Laboratory		2MeV and 6 MV tandetron accelerators		
Seoul, Korea	Korea Heavy Ion Medical Accelerator at Korea Institute of Radiological and Medical Sciences (KIRMAS)	KIRAMS	AVF cyclotron for 50MeV protons		
Jeollabuk-do, Korea	Advanced Radiation Technology Institute		15-30 MeV 500mA Proton Cycrotron		
Daejeon, Korea	Rare isotope Accelerator complex for ON-line experiments (RAON), Institute for Basic Science (IBS)	RAON	Superconducting Driver Linac (proton: 600MeV, 660 microA, HI: 200MeV/u), Superconducting Post Linac (HI: 18.5 Mev/u), Cyclotron: (proton 70 MeV, 1mA)		
Hsinchu, Taiwan	Graduate Institute of Nuclear Science (INS) National Tsing Hua University (NTHU)	INS / NTHU	3MV Van de Graaff (KN) Accelerator, 3MV Tandem accelerator (NEC 9SDH-2), open air 500kV accelerato		
Hanoi, Vietnam	Tandem machine at Hanoi University of Natural Science		1.7MV Tandem Pelletron,		
Hanoi, Vietnam	Military Central Hospital 108		30 MeV 300 microA proton cyclotron		



Figure 6. Location of major accelerator facilities in Asia Pacific.

tion of China (NSFC), Ministry of Science and Technology (MOST), CAS, and CAEA. The progress of the aforementioned centers is now introduced, one by one.

#### **BRIF/JUNA/BISOL**

The HI-13 tandem accelerator can generate ion beams from H to U, with  $^{238}$ U the heaviest nuclide being so far accelerated. The steel cylinder is 25 meters long with the maximum central diameter of 5.5 meters. The maximum voltage of the accelerator can reach 15 MV, but the operating voltage is controlled below 13 MV for stable operation. The tandem accelerator maintains a stable operation of 4,000 hours user time per year. Its key components, such as the ladder and the divider resistor system, are laboratory made, consequently saving large amounts of operation and maintenance costs.

BRIF is composed of a 100 MeV, 200  $\mu$ A proton cyclotron and an ISOL with a mass resolution of 20,000 as a RI beam source or driver and the HI-13 tandem accelerator as post accelerator, to set up as an ISOL facility. Thus, it fills

the gap as a moderate-energy, high-intensity proton, high-resolution isotope separator and tandem quality RI ISOL facility in China [10] (see Figure 7).

In October 2019, an experiment with a post-accelerating RI beam was successfully carried out. The <sup>22</sup>Na beam intensity on the target is  $2 \times 10^5$  particle per second (pps), for scattering and transfer experiments, with preliminary research results delivered.

The exotic  $\beta - \gamma - \alpha$  decay of <sup>20</sup>Na has been studied as the day-one experiment at BRIF. The intense <sup>20</sup>Na source was produced by using a 100 MeV proton beam bombarding a stack of microporous MgO thick target, and delivered as a mass separated beam after online ionization. A highefficiency simultaneous measurement of  $\beta$ ,  $\gamma$ , and  $\alpha$  enables the  $\beta$ -delayed  $\gamma - \gamma$  and  $\gamma - \alpha$  coincidence spectroscopy. Three  $\beta - \gamma - \alpha$  exotic decay sequences in <sup>20</sup>Na have been directly observed by the  $\gamma - \alpha$  coincidence, which determine the direct  $\beta$ -feedings and logft values to the 5,621 keV 3<sup>-</sup> and 5,788 keV 1<sup>-</sup> states in <sup>20</sup>Ne associated with the recently observed low-energy  $\alpha$  groups below 1 MeV. Moreover, a



Figure 7. BRIF layout and physics.

 $\beta - \alpha - \gamma$  decay sequence through the 11,327 keV 2<sup>+</sup> state in <sup>20</sup>Ne to the 6,130 keV 3<sup>-</sup> state of <sup>16</sup>O is established. The experimentally deduced B(GT) values are compared to the Shell-Model calculations in the sd and psd-shell model.

The  ${}^{12}C(\alpha,\gamma){}^{16}O$  reaction is one of the most crucial reactions in nuclear astrophysics. The E2 external capture to the <sup>16</sup>O ground state (GS) has not been emphasized in previous analyses but may make a significant contribution to the  ${}^{12}C(\alpha,\gamma){}^{16}O$  cross-section, depending on the value of the GS asymptotic normalization coefficient (ANC). In the present work, we determine this ANC to be  $337 \pm 45 \text{ fm}^{-1/2}$ through the<sup>12</sup>C(<sup>11</sup>B,<sup>7</sup>Li)<sup>16</sup>O reaction using a high-precision magnetic spectrograph Q3D in the HI-13 tandem. This sheds light on the existing large discrepancy of more than two orders of magnitude between the previously reported ANC values. Based on the new ANC, we experimentally constrain the GS external capture and show that, through interference with the high-energy tail of the 2<sup>+</sup> subthreshold state, a substantial enhancement in the GS SE2(300) factor can be obtained  $(70\pm7 \text{ keV b})$  compared to that of a recent review (45 keV b), resulting in an increase of the total S-factor from 140 keV b to 162 keV b, which is now in good agreement with the value obtained by reproducing supernova nucleosynthesis calculations with the solar-system abundances (see Figure 8). This work emphasizes that the external capture contribution for the ground state transition cannot be neglected in future analyses of this reaction [11]. This work was based on the HI-13 tandem in CIAE/BRIF.

The long-lived  $^{60}\text{Fe}$  is a very interesting tracer isotope for the nucleosynthesis in our galaxy and supernovae near our solar system. The  $^{59}\text{Fe}(n,\gamma)^{60}\text{Fe}$  reaction is considered to be



**Figure 8.** New S-factor for the GS E2 component of the  ${}^{12}C(\alpha,\gamma){}^{16}O$  reaction.

the key reaction to produce <sup>60</sup>Fe in massive stars. To determine the neutron capture cross-section experimentally, we carried out the <sup>58</sup>Fe(<sup>18</sup>O, <sup>16</sup>O)<sup>60</sup>Fe<sup>\*</sup> and <sup>56</sup>Fe(<sup>18</sup>O, <sup>16</sup>O)<sup>58</sup>Fe<sup>\*</sup> reactions and obtained the  $\gamma$ -decay probability ratios of <sup>60</sup>Fe<sup>\*</sup> and <sup>58</sup>Fe<sup>\*</sup> to determine the cross-section of the <sup>59</sup>Fe(n,  $\gamma$ )<sup>60</sup>Fe reaction with the surrogate ratio method. The Maxwellianaveraged cross-section was derived to be 27.5±3.5 mb at kT = 30 keV and 13.4±1.7 mb at kT = 90 keV. This work was done by the CIAE group with the tandem accelerator at JAEA (Japan Atomic Energy Agency).

The experimental terminal in BRIF is composed of a full spectrum of instruments, like a versatile magnet spectrometer, gamma array, decay measurement, and large area and microbeam radiation stations. A 1.2 meter multipurpose reaction chamber was commissioned with the capacities of a time-of-flight (TOF) measurement. A 40X high-purity germanium (HPGe) gamma array (see Figure 9) was jointly developed by CIAE and IMP.

More traditional and contemporary research is carried out, namely nuclear structure, reaction, astrophysics, start from stable beams, and gradually to RI beams. A 23–34% overestimation of nuclear astrophysical <sup>12</sup>C( $\alpha$ ,  $\gamma$ )<sup>16</sup>O and <sup>13</sup>C( $\alpha$ , n)<sup>16</sup>O reaction cross-sections was discovered by using a nuclear astrophysics reaction with a GS spectroscopic factor. With the RIBLL (Radioactive Ion Beam Line in Lanzhou) beam-line at IMP, a precise mass of <sup>27</sup>P was measured by using the isobaric multiplet mass equation (IMME) method, resulting in a much lower value of <sup>26</sup>S(p,  $\gamma$ ) <sup>27</sup>P reaction rates (see the details below).

The BRIFII project (mainly the radio frequency quadrupole [RFQ]–drift tube linear accelerator [DTL]–superconducting [SC] linear accelerator [LINAC] and experimental facilities) is under construction. In 2022 they will provide stable and unstable beams up to 12 MeV/u or 35 MeV/q with a mass number of 25–240.

JUNA is based on the China Jinping underground physics laboratory, which is 2,400 meters deep. Managed by CIAE,





Figure 9. Target chamber and gamma array.

JUNA will try to carry out the measurements of key  $(\alpha, \gamma)$  and  $(\alpha, n)$  reactions in the helium burning of a star, as well as the measurements of key (p,  $\gamma$ ) and (p,  $\alpha$ ) reactions in hydrogen burning. One can provide critical nuclear physics inputs for understanding the stellar evolution and element origin. Joint support for JUNA comes from NSFC, CNNC, and CAS. So far, development of a high-intensity ion source and high-intensity accelerator has been completed, and the proton beam reaches 10mA and helium beam 2mA. After being put into operation, it will become the highest beam-intensity accelerator at an underground laboratory in the world. Before going underground, the integrated verification of ground experiments for the JUNA accelerator and detector system will be completed in 2020, and research is expected to be carried out in the underground laboratory at the end of 2021 [12]. The layout and physics of JUNA are found in Figure 10.

In CIAE, the future plan for BISOL is proposed. It will be driven by the dual source of the China Advanced Research Reactor and accelerator, generating a high-intensity neutron-rich nuclear beam and high-intensity fast neutron beam by using the ISOL technique and projectile fragmentation (PF) method. Thanks to the unique idea of being driven by the reactor, the BISOL can generate extremely neutron-rich nuclear beams at several key mass regions that are 1 to 2 orders of magnitude stronger than the existing facilities throughout China, thus pushing nuclear science research to the extremely neutron-rich area not yet reached. In addition, the high-intensity deuterium ion accelerator of the BISOL facility cannot only generate neutron-rich beams as a complementary fission drive source; it also can independently operate to generate high-intensity fast neutron beams for the urgently needed fast neutron irradiation assessment and other application research of nuclear energy materials. In August 2014, the project was included in the Roadmap of China's Large-Scale Scientific Facility at the 502nd Xiangshan Science Forum. In December 2016, the project was included into the Major Scientific and Technological Infrastructure Projects for further determination in the 13th Five-Year Plan of China. In June 2018, the research and development (R&D) of Beijing ISOL was funded by the CNNC [13]. The BISOL layout and physics are shown in Figure 11. BISOL R&D is in progress, with an offline inreactor ion source and some key prototype components for super-conduction LINAC and RI beam diagnostics.

#### **CSR/HIAF**

HIRFL/CSR at IMP is an HI center in Lanzhou affiliated with CAS. Its highlights are mass measurement in CSR and super heavy element (SHE) study. Significant results and achievements at HIRFL are achieved (see Figure 12).



Figure 10. JUNA layout and physics.



Figure 11. BISOL layout and physics.

Nuclear Physics News, Vol. 30, No. 3, 2020

China's First Self-Developed Carbon-Ion Cancer Therapy System Gets Approval for Registration and Market Access

In September 2019, China's carbon-ion therapy system, self-developed by IMP and its holding company Lanzhou Kejin Taiji Corporation, obtained the approval of the national drug regulator for the Class-III Medical Device Product registration. Installed in Wuwei Cancer Hospital in Gansu province, the system is the first time that the National Medical Products Administration has approved a domestically produced carbon-ion therapy system. Since 1993, through the R&D of advanced accelerator technology and nuclear detection technology, basic biological research related to heavy ion beam therapy and the accumulation of preclinical research conducted in cooperation with relevant medical institutions, IMP has cultivated a high-level team of heavy ion therapy technical personnel and mastered relevant core technologies.

#### New Isotope <sup>220</sup>Np: Probing the Robustness of the N=126Shell Closure in Neptunium

The examination for the persistence of shell effects for nuclei far from stability is an intriguing topic in contemporary nuclear physics. While the onset of deformations together with the weakening of the magic shell effect in most proton-rich isotones with neutron number N=126 was expected, the extension of nuclei in this region of the nuclear chart is undoubtedly interesting for checking the nuclear shell model. A research team from IMP, led by Prof. Zaiguo Gan, reported the discovery of a new nucleus <sup>220</sup>Np with proton number Z=93 and neutron number N=127. The

experiment was carried out on the gas-filled recoil separator Spectrometer for Heavy Atoms and Nuclear Structure (SHANS) at HIRFL in Lanzhou. Eight correlated alpha-decay chains from <sup>220</sup> Np were identified significantly. Their decay-energy spectra and decay-time distributions for each chain member are shown in Figure 13. The measured alphadecay properties of the new neptunium isotope, as well as the recently reported <sup>219, 223</sup>Np, around the N=126 closed shell and 11 protons above the well-known doubly magic center <sup>208</sup>Pb (Z=82, N=126), allowed us for the first time



**Figure 13.** Left: Energy spectra of the correlated decay events from <sup>220</sup>Np, with decay-time distributions for each chain member. Right: Decay-time distributions for each chain member.



Figure 12. General layout of the CSR.

to test the stability of the N=126 shell effect in Np isotopes. In addition, the new results indicated that, in the region of nuclei with  $Z \ge 83$ , the proton drip-line has been reached for all odd-Z isotopes up to Np. Prior to this work, the last identification of the proton drip-line in this mass region was for Z=91 protactinium in 1995, more than 20 years ago.

#### Progress on $\beta$ -Decay Protons Spectroscopy Research

 $\beta$ -decay spectroscopy provides valuable nuclear physics input for accurate modeling of nova and X-ray burst observables and a stringent test for shell-model theories far from the stability line. The decay scheme of <sup>27</sup>S is complicated and far from being understood due to a lack of experimental data prior to this work. Researchers from the CIAE, IMP, and others made the latest progress in

β-delayed proton spectroscopy research. The researchers measured the β-delayed γ-ray spectrum of  $^{27}$ S and β-delayed proton spectrum with the highest statistical precision so far by using a self-designed and developed detection system composed of several Double Sided Silicon strip Detectors (DSSDs) and Quadrant silicon detectors, constructed the relatively complete decay scheme of  $^{27}$ S, and gave the  $^{27}$ P quality measurement value with the highest accuracy compared with the result of theoretical shell-model calculations (see Figure 14). Based on the new experimental results, it was found that the calculated thermonuclear  $^{26}$ Si(p, γ)  $^{27}$ P reaction rates were far lower than that recommended in the JINA Reaclib Database for nuclear reaction rates to be used in astrophysical model calculations (see Figure 14).



**Figure 14.** Decay scheme of <sup>27</sup>S. All the energies, mass excesses, and intensities labeled in the scheme are deduced from the present work, except for the mass excess of <sup>26</sup>Si, with<sup>27</sup> P levels populated in<sup>27</sup>S  $\beta$  decay obtained from a Universal sd shell-model calculation.

Nuclear Physics News, Vol. 30, No. 3, 2020

16

Positive-Parity Linear-Chain Molecular Band in 16C

An inelastic excitation and cluster-decay experiment  $^{2}$ H( $^{16}$ C,  $^{4}$ He +  $^{12}$ Be or  $^{6}$ He +  $^{10}$ Be)  $^{2}$ H was carried out to investigate the linear-chain clustering structure in neutronrich 16C. For the first time, decay-paths from the 16C resonances to various states of the final nuclei were determined, thanks to the well-resolved Q-value spectra obtained from the threefold coincident measurement. The close-threshold resonance at 16.5 MeV is assigned as the  $J\pi = 0+$  band head of the predicted positive-parity linear-chain molecular band with  $(3/2-\pi) 2 (1/2-\sigma) 2$  configuration, according to the associated angular correlation and decay analysis. Other members of this band were found at 17.3, 19.4, and 21.6 MeV based on their selective decay properties, being consistent with the theoretical predictions. Another intriguing high-lying state was observed at 27.2 MeV, which decays almost exclusively to 6He + 10Be(~6MeV) final channel, corresponding well to another predicted linearchain structure with the pure  $\sigma$ -bond configuration [14] (see Figure 15).

#### HIAF

 $(3/2^{-})^{2}(1/$ 

2.251.0

HIAF is a complete upscale of CSR, in Huizhou, Guangdong province. HIAF has been approved as one of the large-scale national science and technology infrastructural facilities in the 12th Five-Year Plan and has been under construction since December 2018, with a seven-year

27.2 (0

21.6 (6

19.4 (4

17.3 (2

16.5 0

positive-parity linear-chain

configuration of <sup>16</sup>C

.171 S

J#=0

<sup>12</sup>Be

 $(2^{-}_{\sigma})^{2}(1/2^{+}_{\sigma})^{2}$ 

πσ 6.263 2

πσ 5.960 1

 $\pi^2 \alpha \alpha$ 

5 958 2

3.368 2

<sup>0</sup>Be /#=0

**Figure 15.** Schematic drawing of the selective decay pattern for the presently observed resonance in 16C. The width of each arrow from the four lowest 16C resonances represents the decay strength relative for the 12Be(g.s.) final state, while that from the 27.2 MeV state of 16C is marked in magenta-dashed. The valence neutron configuration, symbolized by  $\pi$ - or  $\sigma$ -bond, is depicted for each chain-like structure. construction period and total budget of 1.67 billion CNY, approved by the National Development and Reform Commission, China. The HIAF project is organized by CAS and implemented by IMP.

The HIAF facility is a new generation, world-leading, high-intensity heavy-ion accelerator complex (see overall layout, Figure 16). The facility is able to produce radioactive nuclides extremely far away from the line of beta stability (see Figure 16 and Ref. [14]). It can provide lowenergy heavy ion beams with the highest peak current in the world. It will be a state-of-the-art nuclear mass spectrometer that can provide pulsed heavy ion beams with a maximum energy of 4.25 GeV/u. The facility can provide a world-leading research platform to identify new nuclides, study weakly bound nuclear structures and reaction mechanisms, and especially measure the accurate masses of shortlived nuclei mass. The HIAF project mainly consists of the accelerator complex, the experimental terminals, auxiliary devices, and civil constructions. The accelerator complex is designed based on a combination of one superconducting LINAC and two synchrotrons. A series of new technologies are used in order to provide high-intensity, high-energy, and high-quality heavy ion beams, and to produce radioactive nuclides far away from the stable line. The experimental terminals are constructed around the HIAF beam-lines to provide excellent research conditions for nuclear physics, atomic physics, nuclear astrophysics, and applications in materials and biology.

#### HIAF CONSTRUCTION PROGRESS

Since the start of construction at the end of 2018, all the key technologies and their prototypes have been made a significant breakthrough, which means the most critical technical problems of the HIAF construction have



Figure 16. HIAF layout and physics.

Vol. 30, No. 3, 2020, Nuclear Physics News

been solved. All prototypes are completed in the middle of 2020. The magnetic core and the coils of the BRing fast ramping dipole prototype, as well as a high-precision single copper wire with a large rectangular cross-section, have been produced successfully. Two high-voltage modulates and one low-voltage modulate were tested for the full-energy storage fast-cycle pulse power source prototype. In addition, a magnetron sputtering gold-plated film on zirconia ceramic has been developed to solve the problem of beam impedance. A half aperture Canted-Cosine-Theta superconducting magnet prototype combined with quadrupole and sextupole has been fabricated. The key technologies related to coil former machining, coil winding, and vacuum impregnation have been investigated.

The total civil construction and auxiliary system budget of both HIAF and the Chinese initiative of Accelerator Driven System (CiADS) projects is 2.35 billion CNY. In 2019, about 6.6 million cubic meters (about 85%) of earthwork construction had been completed and the total earthwork construction will be accomplished in September 2020 (see Figure 17). The water supply construction was started in December 2019 and will be finished in October 2020. The power grid construction is scheduled to be completed in September 2020. The East Road has been completed in June 2020.

It should be noted that the HIAF facility will be constructed next to CiADS. By combining the very strong proton driver prepared for CiADS, unstable nuclear beams separated from the ISOL target, as well as the subcritical Accelerate Driven System (ADS) reactor of China initiative Accelerator Driven System (CiADS), will be able to be used as the starting beams instead of "stable" nuclear beams in the future (see Figure 18).

#### More Selected Facilities in China

SLEGS

SLEGS is one of 16 beam-line stations under construction for the second phase of the Shanghai Light Source (also known as Shanghai Synchrotron Radiation Facility [SSRF]) at SINAP. It will be installed by the end of 2020,



Figure 17. Overview of the HIAF campus in December 2019.



**Figure 18.** *HIAF is constructed next to CiADS. The powerful CiADS proton driver will be used as the ISOL driver for HIAF, and fission products from the CiADS subcritical reactor will be injected to the HIAF accelerator complex in the future.* 

and open to users in 2022. The layout is shown in Figure 19. Using the 3.5GeV electron beam in the storage ring to scatter the photons from the externally introduced  $CO_2$  laser in the wavelength of 100W/10.64um (CW mode), the MeV gamma ray is generated by the Inverse Compton backscattering effect.

The scientific objectives of the SLEGS [15] beam-line station are: (1) basic research on photonuclear reactions, nuclear astrophysics, polarization physics, and so on. It especially could help to solve problems of great scientific value in nuclear physics and nuclear astrophysics, such as nuclear structural parameters, nuclear collective excitation mode, mechanism of heavy element generation of cosmological evolution, and so on; (2) basic application research on strategic needs, such as nuclear energy production, calibration of space gamma detector, key photonuclear cross-sections, and gamma transmutation research on nuclear waste, and so on. Therefore, the SLEGS is going to become a multifunctional experimental platform for the combination of basic nuclear physics and basic application research in the second phase beam-line station of SSRF (see Figure 19).

#### Daya Bay/JUNO/TAO

The Daya Bay experiment aims to measure the neutrino mixing angle  $\theta_{13}$  with reactor neutrinos emitted from the Daya Bay nuclear power plant. The experiment was proposed in 2003, started operation at the end of 2011, discovered an unexpectedly large oscillation driven by  $\theta_{13}$  in 2012, and plans to operate to the end of 2020. The Daya Bay experiment is located in the campus of the power plant. It consists of eight antineutrino detectors, each has 20-ton gadolinium-doped liquid scintillator as the anti-

Nuclear Physics News, Vol. 30, No. 3, 2020

neutrino target. The eight detectors are installed in three underground experimental halls, located from 360 m to 1,910 m from the reactors. Daya Bay will measure the neutrino oscillation parameter  $sin^2 2\theta_{13}$  to a precision better than 3%. Furthermore, Daya Bay accumulated the largest reactor neutrino sample in the world, and revealed that neither the conversion method based on  $\beta$ -spectrum, nor the summation method based on nuclear database, could predict the reactor antineutrino production correctly. The data show a significant deficit in total flux and a prominent bump around 5 MeV when comparing both models. These deviations inspired a lot of interest in a more precise nuclear database. JUNO [16] aims to determine the neutrino mass ordering and precisely measure three neutrino oscillation parameters with reactor neutrinos, following the measurement of the large  $\theta_{13}$  by Daya Bay (see Figure 20). With its huge mass, JUNO will also perform leading research in astrophysics, like supernova neutrino, solar neutrino, geoneutrino, and so on. The detector is located at equal baseline of 53 km to the Yangjiang and Taishan nuclear power plants. It is a 20,000-ton liquid scintillator detector submerged in a water pool filled with 40,000 tons of pure water, 700 meters underground. JUNO was approved in 2013 and plans to take data in 2022. Taishan Antineutrino Observatory (TAO) is a ton-level liquid scintillator detector at about 30 meters from a reactor core of the Taishan nuclear power plant. Given the inaccurate information of the fine structure of the reactor neutrino spectrum currently, TAO will provide a reference spectrum for JUNO with high precision and unprecedented high-energy resolution. It will also provide a benchmark measurement to test nuclear databases, provide increased reliability in measured isotopic IBD yields due to a larger sampled range of fission fractions, and provide an opportunity to improve nuclear physics knowledge of neutron-rich isotopes [17]. The detector consists of a 2.6 ton gadolinium-doped liquid scintillator and about 10 m<sup>2</sup> SiPM of higher than 50% photon detection efficiency. The detector will operate at -50°C to lower the dark noise of the SiPM to an acceptable level. The experiment is under design and plans to take data in 2022 (see Figure 20).

#### **Summary for Chinese Facilities**

Both research in nuclear physics and construction of big facilities are growing very well in China. Unstable nuclear physics and nuclear astrophysics are both focused on long range plans, which are organized by NSFC. A roadmap for large-scale facilities was discussed in the Xiangshan forum (a top-class scientific forum in China), with HIAF and BISOL to be the future focus (see Figure 21 and Ref. [18]). The level and scale of facilities and support for young workers are impressive. But to achieve the full performance of those many facilities and relevant research culture, as well as government understanding of openness, operational



Figure 20. JUNO layout.



Figure 19. SLEGS layout and physics.

Vol. 30, No. 3, 2020, Nuclear Physics News



Figure 21. Nuclear physics facility roadmap in China.

cost, and long-term stable support to nuclear physics basic research, the challenge is very large. We need to have continuous input to the government about top-level research achievements. The international collaboration is expected to be a good way to achieve this. We also need to add the China plan to the Asia and world roadmap of nuclear physics facilities to have collaborative and complementary efforts to resolve profound questions of nuclear physics, nuclear astrophysics, and related application.

#### 3. Korean Facilities

#### **RAON Rare Isotope Beam Accelerator**

The construction of the new rare isotope accelerator was approved by the Korean government in 2009. As a body that has the responsibility to complete the construction project, RISP was launched in December 2011. The goal of RISP is to build the cutting-edge rare isotope beam accelerator facility RAON by the end of 2021 in the then newly established Institute for Basic Science (IBS). After a couple of revisions, the master plan for the new facility was finalized in 2015, including the detailed implementation strategy. Presently, RISP is aggressively carrying forward to timely completion of RAON in Daejeon, Korea [19].

The construction of RAON is very challenging, as RAON employs the five different types of superconducting resonators; those are, Quarter Wave Resonator (QWR), two types of Half Wave Resonator, and two types of Single Spoke Resonator (SSR). Especially, RAON is the first machine to employ SSR for accelerating rare isotope beams. In collaboration with the Tri-University Meson Facility in Canada, Fermi National Accelerator Laboratory in the United States, RIKEN in Japan, and IMP and IHEP in China, as well as domestic industry, the development and production of the accelerator components are in progress with top speed. Figure 22 shows the schematic layout of the RAON facility with the various experimental setups. Note that the construction of SCL1 was recently postponed to the later stage and that SCL3 would play the role of SCL1 in the early phase of the operation. Figure 23 shows a picture of the construction site taken in early 2020.

RAON consists of ISOL and In-flight Fragmentation (IF) systems together. ISOL and IF at RAON can be operated independently but will be eventually combined to provide rare isotope beams existing closer to the neutron drip-line, which cannot be generated by the other accelerators. In the combined operation mode, the rare isotope beams produced by ISOL will be accelerated by the post-accelerator SCL3 and, subsequently, SCL2 and impinge on the IF production target to generate more exotic rare isotope beam species.

In ISOL, light ions are accelerated and bombard the heavy target system. Then, the rare isotope beams are ex-



**Figure 22.** Schematic diagram of RAON. The green and purple boxes represent the accelerator components and the experimental detector setups, respectively. The construction of SCL1 was recently postponed to the second stage and electron cyclotron resonance (ECR) in the beginning part of SCL3 will be initially used as the ion source for stable beams.



**Figure 23.** *Picture of the RAON construction site taken in early 2020.* 

tracted from the fragmentations of the UC<sub>X</sub> target disks. ISOL is advantageous, as it generates a large abundance of rare isotopes with high purity, but requires a post-accelerator. The ISOL system of RAON is going to use proton beams from the high-power (70kW) cyclotron. Then, the rare isotope beams will be produced by the direct fission process of <sup>238</sup>U and accelerated by SCL3 up to, for example, 17.5 MeV/u.

For ISOL there are four experimental setups being prepared. Colinear laser spectroscopy and the high-precision mass measurement system (MMS) employing multi-reflection TOF will be available in the ultra-low-energy experimental hall right after the ISOL target system. In addition, the KOrea Broad-acceptance Recoil spectrometer and Apparatus (KOBRA) and the Nuclear Data Production System (NDPS) will be installed in the low-energy experimental hall.

Among them, the most important experimental facility for nuclear physics would be KOBRA [20]. Figure 24 displays the design of KOBRA, consisting of a series of bending and focusing magnets with Wien filter. The emphasis in design is to obtain high mass resolution with large momentum and angular acceptances for the maximum magnetic rigidity up to 3 Tm. Several detector elements, such as the clover-type HPGe gamma detectors, parallel-plate avalanche chamber, Si strip detectors, and scintillation counters are in preparation. The commissioning run of KOBRA is planned in 2021 with stable light nuclear beams. After that, the KOBRA system is expected to record the experimental data for interesting processes in nuclear structure and astrophysics.

MMS is expected to measure the mass of the shortlived rare isotopes with the resolution of  $6.67 \times 10^{-7}$ . The



Figure 24. Schematic design of KOBRA.

system, developed in collaboration with RIKEN, was assembled and successfully tested. In addition, NDPS plans to measure the various neutron-induced reaction data for nuclear science, and the installation will start in 2021.

In December 2019, the Center for Exotic Nuclear Studies (CENS) was established at IBS as one of its research centers [21]. CENS will conduct various experiments on the basic properties of short-lived nuclei, the identification of the origin of cosmic elements, and the discovery of new isotopes, using rare isotope beams supplied by RAON. It is expected that the research activity in the low-energy nuclear physics at RAON will be strongly supported by CENS in the future.

In the 120-m-long IF system, the heavy-ion beam from the ECR source is accelerated by SCL1 and SCL2 and bombards the light element target like Be. (Note that SCL3 will replace SCL1 in the beginning phase because the construction of SCL1 was postponed to the later time.) Then, the rare isotopes of interest are extracted from numerous kinds of fast fragments via rapid separation using a series of strong dipole magnets. The beam power of RAON's IF system will be 200kW in the initial stage, but eventually increased to 400kW. The beam energy of, for example, <sup>132</sup>Sn isotopes will be about 250 MeV per nucleon with an intensity being up to about 10<sup>9</sup> pps.

For the high-energy experiments, the three experimental setups will be available at RAON when completed. The Bio-Medical Irradiation System and muon spin relaxation/ rotation/resonance will be built at the end of SCL2 before the IF production target. In the end of the IF system, the Large Acceptance Multi-Purpose Spectrometer (LAMPS) will be constructed and perform the various high-energy experiments for nuclear physics. Figure 25 shows the schematic design of the starting version of the LAMPS setup that has been optimized for measuring the various observables for studying the nuclear equation of state (EoS) and symmetry energy [22, 23].

The main detector elements of LAMPS are the forward neutron detector array and Time-Projection Chamber (TPC) in a superconducting solenoid magnet. The construction of the neutron detector array for LAMPS, consisting of four stations with a total of 160 scintillator bars and a veto wall, was already finished in early 2019. Figure 26 shows the pictures of the assembled detector and the employed electronics. Using cosmic muons, the timing and position resolutions of the whole system are determined to be about 300 ps and 4.8 cm, respectively, in full-width at half maximum, which are so far the best results for the detector systems with a similar configuration [24]. The prototype TPC was also constructed and tested with cosmic muons and positron beams at ELPH. With these tests the mixture rate of the gas components, which gives large enough drift velocity of the avalanched electrons to cover the whole active volume, and the size of each pad were determined for the final design. Even though the main physics goal of LAMPS is to investigate EoS and  $E_{svm}$ , the detector setup can be also powerful for studying the nuclear structure if the postponed dipole



**Figure 25.** Schematic design of the starting version of the LAMPS setup at RAON. Both endcaps of the superconducting solenoid magnet are open in the final design to minimize the material budget for neutrons.



**Figure 26.** (*Left*) *Picture of the neutron detector array for LAMPS. Three out of four stations are stacked up for the cosmic muon tests.* (*Right*) *Flash analog-to digital converter readout and trigger electronics with high-voltage power supply module.* 

spectrometer section between TPC and the neutron detector array is supplemented, as it detects the fragments of the projectiles [22].

On the other hand, the Center for Extreme Nuclear Matters (CENuM), which is one of the Science Research Centers supported by the National Research Foundation of Korea, is developing the various detector components for the low-energy experiments at RAON. Presently, CENuM is developing the LaBr<sub>3</sub>(Ce) gamma detector system, Active-Target TPC (AT-TPC) and Si-CsI telescope. Figure 27 shows the superconducting solenoid magnet for AT-TPC, designed and manufactured by CENuM and the local industry. The diameter and length of central opening are 60 cm each, and the maximum strength of the magnetic field is 1.5 Tesla, which will greatly enlarge the territory of the research subjects. For the Si-CsI telescope CENuM recently joined the Four Pi A and Z Identification Array (FAZIA) Collaboration in Europe. As a part of the Collaboration, the members of CENuM are participating in the upgrade project of the FAZIA detector system and plan to build the FAZIA-like Si-CsI telescope system for LAMPS at RAON in the future.

#### **KOMAC** Proton Accelerator

KOMAC (KOrea Multi-purpose Accelerator Complex) in Gyeongju operates a 100 MeV high-power proton accelerator, which is mostly used for research on nanotechnology, biology, medical application, radiation effect, space



**Figure 27.** Superconducting solenoid magnet designed and manufactured by CENuM for the low-energy experiments at RAON.

technology, and detector development [25]. The KOMAC facility consists of an ion source, RFQ, DTL, beam-lines, and target systems. The proton beams are extracted from hydrogen atoms in the ion source and then focused and accelerated by quadrupole magnets in RFQ. The beams are further accelerated in DTL installed in a cylindrical metal tank. Figure 28 shows the schematic layout of the KOMAC



Figure 28. Schematic layout of the KOMAC accelerator facility.

accelerator facility with the various experimental sites. Figure 29 shows the RFQ and DLT.

KOMAC started to offer users the beams from 2013 with the maximum beam current of 10 mA, which is the third in the world after the Spallation Neutron Source in the United States and J-PARC in Japan. KOMAC is constantly developing sophisticated accelerator technologies and devices to control the beam energy and current, implanting, for example, uniform irradiation over a broad area, spread-out Bragg peak, and dose measurement. Currently, the available beam energy ranges from 3 to 100 MeV over a large area up to about 30 cm in diameter. In addition to the proton beams, the low-energy (about 30–200 keV) ion beams are also available for the ion implantation.

#### **Other Facilities**

#### KIST Accelerator Laboratory

The accelerator laboratory at the Korea Institute of Science and Technology (KIST) in Seoul operates three lowenergy ion accelerators [26]. First, the 6MV Tandetron, commissioned in 2013, supplies various ion beam species from <sup>10</sup>Be to <sup>129</sup>I for accelerator mass spectrometry (AMS), ion beam application, and ion beam material modification. In addition, a 2MV Pelletron and 400kV ion implanter, commissioned in 1995 and 2013, respectively, are also available for users. With them, the experiments on Rutherford backscattering spectrometry (RBS), elastic recoil detection, medium-energy ion scattering, and particle-induced X-ray emission are possible. The low-energy accelerators at KIST are also useful for developing the detectors for nuclear physics, as well as industrial applications.

#### MC50 Cyclotron at KIRAMS

The Korea Institute of Radiological And Medical Sciences (KIRAMS) in Seoul operates the MC50 cyclotron,



**Figure 29.** *Picture of the KOMAC proton accelerator. The two focusing quadrupole magnets and a cylindrical DTL tank are shown from right to the left.* 

which was built in 1986. The proton beams are accelerated by MC50 up to 51 MeV with a current of 60  $\mu$ A [27]. It can also provide deuteron and alpha beams up to 25 and 45 MeV, respectively, with somewhat lower currents. The main objective of MC50 is to produce various radio isotopes for medical treatment. In fact, KIRAMS is the first institute in Korea to have succeeded in developing 20 types of accelerator radioisotopes and radiopharmaceuticals, such as <sup>67</sup>Ga, <sup>123</sup>I, <sup>201</sup>T1, and <sup>111</sup>In. In addition, MC50 has been also useful for the development of radiation detectors, low-energy nuclear reactions, low-dose proton implantation, nondestructive evaluation methods, BNCT, and neutron radiography [28].

#### RFT30 Cyclotron at ARTI

The Advanced Radiation Technology Institute (ARTI) in Jeongeup operates the RFT30 cyclotron that provides the proton beams at  $15 \sim 30$  MeV with a current up to 300  $\mu$ A [29]. It is mainly used for the development of

the novel isotope labeled compounds and radiopharmaceuticals, but ARTI also welcomes proposals for basic nuclear physics research and applications. For example, users can use this machine for the cross-section measurement of the various nuclear reactions, radiation hardness of semiconductor devices, and characterization of metals and semiconductors.

#### 4. Japanese Facilities

#### Overview

There are several large-scale accelerators in Japan, as shown in Figure 30. Among them, the following two research complexes and their future plans were endorsed by the Japanese Nuclear Physics Executive Committee in 2018 as the most important (Rank S) facilities and future plans of nuclear physics, which should be realized in Japan for the coming ~5 years. These are:

- 1. J-PARC (KEK) for hadron/nuclear physics with hadron beams, and some for particle physics with muons. It has a future project of the Hadron Experimental Facility (Hd) Extension to install several new secondary beam-lines for further hypernuclear and hadron physics experiments.
- 2. RIBF (RIKEN) for nuclear structure and nuclear reaction studies using the world's highest-intensity RI beams, which has as its future project to increase RI beam intensity for expanding research opportunities to cover more neutron- and proton-rich isotopes and the trans-uranium region, including nuclei of superheavy Z=119-120 elements and beyond.

In addition, the following three research projects were selected as important ones (Rank A or B) for Japanese nuclear physics. However, some of them will have to be implemented at U.S. and European facilities.



Figure 30. Large-scale accelerator complexes located in Japan.

Vol. 30, No. 3, 2020, Nuclear Physics News

- High-energy heavy-ion collision experiments (LHC, RHIC, and J-PARC-HI) to study Quark Gluon Plazma (QGP) properties, Quantum Chrono Dynamics (QCD) phase diagram, and high-density nuclear matter. They have future projects of an ALICE upgrade, STAR upgrade, and s-PHENIX construction. J-PARC-HI is an addition of a heavy-ion injector to J-PARC (Rank A).
- 2. High-energy heavy-ion and electron collisions at electron Ion Collider (eIC) at BNL (Rank B).
- 3. The nuclear physics part of the project of the nuclear transmutation system for long-lived fission fragments produced in nuclear fuel (Rank A).

In Japan, several other facilities are also playing important roles in nuclear physics. The Separated Sector Cyclotron at RCNP, Osaka University, provides high-quality light ion beams for high-resolution spectroscopy. ELPH and LEPS (operated by RCNP at the SPring-8) provide GeV energy electron and photon beams for hadron physics experiments. Recently, the activity and the facility in RCNP, including LEPS, were reported in *Nuclear Physics News* [30] and research activities in ELPH are briefly introduced in the *AAPPS Bulletin* [31], together with describing respective accelerator systems. Please see these references for details. HIMAC [32] is the first dedicated cancer therapy accelerator, which can provide 800 MeV/u heavy ion beams for nuclear physics experiments for nontherapy hours weekends and midnights.

#### RIBF

The RIKEN RIBF or RI Beam Factory has had the world's top capability of access to nuclei far from the stability for more than 10 years [33]. As illustrated in Figure 31, the facility consists of a cyclotron-based accelerator complex and various experimental apparatuses [34]. Standard operation uses the four separate-sector (ring) cyclotrons, Riken Ring Cyclotron, fixed-frequency Ring Cyclotron (fRC), Intermediate-stage Ring Cyclotron, and Superconducting Ring Cyclotron (shown in Figure 32), connected in cascade with three options of the injector for different mass ranges of accelerated ions. The part "old facility" has been in operation since 1986, and the RIBF "new facility" started its service in 2007. Beams of ions over the entire atomic-mass range can be accelerated typically up to 345 MeV/nucleon.

The accelerated ions are delivered to the target of the fragment separator BigRIPS [35] ("e" in Figure 31), which produces various fast RI beams or beams of unstable nuclei

produced by the in-flight fission of uranium ions, which has an advantage of efficient production of neutron-rich, medium-mass nuclei, or by the projectile fragmentation. Big-RIPS accepts about half of the fission products. For the projectile fragmentation, having small angular and momentum spreads, the acceptance is essentially 100%. The energy range of the RI beams is typically 200–250 MeV/nucleon. Thanks to the high primary-beam intensity and the large acceptance of BigRIPS, RIBF is the world's top RI beam facility, with the highest intensity for most unstable nuclei.

Another important operation scheme is direct use of the intense beams from the LINAC injector RIKEN linear accelerator (RILAC) ("B") or RILAC2 ("C"). The energy range of these accelerators matches the optimum condition, typically 5 MeV/nucleon, of heavy-ion fusion reactions for superheavy element search. The gas-filled recoil separator GARIS ("a") or GARIS II ("b") is employed to selectively transfer fusion products, which decay by spontaneous fission or characteristic  $\alpha$ -particle emissions. The latter identifies decay chains from a superheavy nucleus. Three events for nuclei with Z=113, created by the <sup>209</sup>Bi(<sup>70</sup>Zn,n)<sup>278</sup>113 fusion reaction, were observed during the 9-year period of 2004-2012 [36], and the element "Nihonium (Nh)" was named in 2016. Recently, a new LINAC booster based on superconducting cavities has been added to RILAC for synthesis of new elements Z > 118 [37].

For RI beam-based experiments, several devices are in operation or under construction. The spectrometer, called ZeroDegree [34] ("f"), is connected to BigRIPS, and analyzes the reaction products emitted from a secondary reaction with a target set at a focus of BigRIPS. Forward-going radioactive ions with magnetic rigidities matched to a setting of ZeroDegree can be detected with particle identification made by measuring the rigidities, TOF, and energy losses by various detectors. This combination, BigRIPS



Figure 31. Layout of RIKEN RIBF [34].

Nuclear Physics News, Vol. 30, No. 3, 2020

and ZeroDegree, is extensively used in "in-beam" studies of unstable nuclei in the final channel of direct reactions like inelastic scattering and nucleon removal. The nucleus in the final state is identified with ZeroDegree, and hence the reaction channel is specified. The energy of the level populated by the reaction can be determined by measuring de-excitation  $\gamma$ -rays. An example of the experimental setup is shown in Figure 33. This new type of in-beam  $\gamma$ -ray spectroscopy has been extensively employed to study, for example, the evolution of nuclear-shell structure for nuclei with neutron- or proton-imbalance. Recent highlights in-



Figure 32. Superconducting Ring Cyclotron.

clude observation of a large shell gap at N=34, which is not expected in less neutron-rich nuclei, for <sup>54</sup>Ca [37], and confirmation of the "doubly magic" character in <sup>78</sup>Ni with Z=28 and N=50 [38].

For studying unbound states, their particle decay inflight should be measured. For that purpose, RI beams from BigRIPS are delivered to the Superconducting Analyzer for Multi-particles from RadioIsotope beams (SAMURAI, "g") [39], a magnetic spectrometer composed of a largegap superconducting dipole magnet and various counters for neutron and charged particles. High-efficiency measurements of neutrons or protons in coincidence with heavy reaction products are possible. For example, light neutronrich nuclei beyond the neutron drip-line with very large N/Zratios as  ${}^{26}O$  [40] and  ${}^{28}O$  can be studied.

The combination of BigRIPS and ZeroDegree can serve as a long spectrometer without the reaction target. A straightforward use is to identify new isotopes [41]. Thanks to the excellent particle-identification capability and intense RI beams, most of the more than 100 isotopes found in the last 10 years are from RIBF [42]. Another application is "decay studies" for neutron- or proton-rich nuclei. RI beams are stopped at the final focus of ZeroDegree, and delayed emission of  $\beta$  rays and/or  $\gamma$  rays are measured. One of the milestones of such  $\beta$ - $\gamma$  spectroscopy is lifetime measurements, which for the first time reached nuclei involved in the r-process nucleosynthesis [43]. Precision data for more than 200 neutron-rich nuclei have been obtained,



Figure 33. Experimental setup for the in-beam spectroscopy at RIBF.

Vol. 30, No. 3, 2020, Nuclear Physics News

including many new half-lives, and they will strongly constrain network calculations of the r-process.

RI beams also can be transported to the Spectroscopy with High-Resolution Analyzer of RadioActive Quantum Beams (SHRAQ, "h"), which is designed for high momentum-resolution experiments in normal kinematics, where RI beams serve as probe particles [44]. One of the recent highlights is the observation of events indicating tetra neutron states populated by the double-charge-exchange reaction <sup>4</sup>He(<sup>8</sup>He,<sup>8</sup>Be)4n [45]. Two  $\alpha$  particles forming the ground state resonance of <sup>8</sup>Be are detected by the SHRAQ spectrometer to extract the missing mass or the energy of the four-neutron system.

The Self Confined RI Target (SCRIT) provides a unique way to enable electron-RI scattering experiments. It utilizes the attractive force acting between positively charged RI ions and electrons in the stored intense beam to realize a reasonably high luminosity [46]. The system SR2 (SCRITequipped Riken Storage Ring, "j") is under construction as a stand-alone device independent of the RI beams.

Another unique piece of equipment under construction is the Rare RI Ring ("i"), which stores a single RI ion in an isochronous condition to measure the mass of the ion [47]. It can access short-lived nuclei for which other methods of mass determination can hardly be applied.

To exploit the rich potential of the facility, many experimental programs have been conducted in collaboration with worldwide researchers. Some of them involve sophisticated detection devices developed in their home laboratories.

The Euroball-RIKEN cluster array (EURICA) collaboration [48] is based on Ge Cluster detectors from the Euroball, which have been used in a variety of decay studies from 2013 to 2016, including the aforementioned lifetime measurements. Following EURICA, a new program, Betadelayed neutrons at RIKEN (BRIKEN) [49], started in 2017. Delayed neutrons are measured with a large-volume array of <sup>3</sup>He proportional counters assembled from several laboratories in the world.

Part of the NeuLAND detector [50] being constructed for the Society for Heavy Ion Research Facility for Antiproton and Ion Research has been delivered to RIBF. It was used from 2015 to 2017, together with the existing detectors. The multi-neutron detection efficiency for SAMURAI experiments was greatly enhanced to enable, for example, four-neutron coincidence measurements necessary for the study of the unbound nucleus <sup>28</sup>O mentioned previously.

The Shell evolution and search or two-plus energies at RIBF (SEASTAR) campaign program was organized from 2014 to 2017 for a systematic survey of low-lying states in neutron-rich nuclei. The MagIc numbers off stability

(MINOS) liquid hydrogen target developed at Saclay [51] was set around the secondary target, together with the extensively used  $\gamma$ -ray detector array DALI2 (indicated in Figure 33) [52]. The MINOS can track the recoiling protons created in (p,2p)-type knockout reactions with RI beams for better Doppler shift correction in  $\gamma$ -ray measurements.

It should be noted that only limited examples of the experimental studies at RIBF and related equipment are presented here. More extensive and detailed descriptions can be found elsewhere [53, 54].

Over the years since the new facility of RIBF started its operation, continuous efforts have been made to increase the beam intensity. Today (in 2020) the goal primarily set (e.g., 1 p $\mu$ A for light ions as 48Ca and 100 pnA for uranium) is almost reached. A plan toward higher primary-beam and RI-beam intensities is being considered. It includes the introduction of a new charge-stripping method (see Figure 34), and modification of fRC and the fragment separator BigRIPS for RI-beam production, some of which already started. These upgrades will greatly enhance research opportunities by extending the accessible range of unstable nuclei.

#### J-PARC

J-PARC is the most advanced accelerator facility in Japan. It started operation 10 years ago. J-PARC consists of three accelerators: the 400 MeV LINAC, the 3 GeV Rapid Cycle Synchrotron (RCS), and the 50 GeV-PS (Main Ring, MR). A bird's-eye view of J-PARC is shown in Figure 35. The most important characteristics of J-PARC is



**Figure 34.** Present (upper panel) and proposed (lower panel) accelerator chains for the uranium beam at RIBF. The stripping efficiency is expected to be increased from 5% to about 50% by introducing two charge stripper rings (CSR1 and CSR2) [34].

its high design beam power, which is 1MW for RCS and 0.75MW for MR. RCS provides intense proton beams to a neutron spallation source (n) and a pulsed muon source ( $\mu$ ) prepared in the Materials and Life Science Facility (MLF). Some fraction of the beam extracted from RCS is injected to MR, accelerated up to 30 GeV, and extracted through two extraction lines. One is the fast extraction for

the Neutrino Beam Facility (v) for a long baseline neutrino oscillation experiment, T2K (see Figure 36), and the other is the slow extraction for counter experiments in the Hd. The four experimental facilities (n,  $\mu$ , v, and Hd) provide characteristic intense secondary beams for experimental users.



**Figure 35.** *J-PARC site at Tokai campus of JAEA. "Hadron Hall" means the Hd for the fixed target experiments with slow extraction. "v to SK" indicates the Neutrino Experimental Facility with fast extraction. "MLF" is where the spallation neutron and pulsed muon sources are operated by using an intense 3 GeV proton beam provided from RCS [55].* 



Figure 36. T2K experiment shoots neutrinos to Super-Kamiokande, which is located 295 km away from J-PARC [56].

Vol. 30, No. 3, 2020, Nuclear Physics News



Figure 37. Schematic layout of beam-lines and experimental subjects for Hadron Experimental Facility (Hd). Strangeness nuclear physics experiments such as hypernuclear spectroscopy and studies of kaonic nuclei are the main subjects in Hd [57].

The highest proton beam energy of MR is now only 30 GeV instead of its design energy of 50 GeV. It is mainly because of the budget problem for preparing power supplies of the MR magnets.

Most nuclear physics experiments are performed in the Hd with a slow extraction beam. Figure 37 shows a schematic layout of the beam-lines in Hd with illustrations of experiments performed at each beam-line. The 30 GeV proton beam extracted from J-PARC MR is introduced to Hd and irradiated to a main production target, T1. Four secondary beam-lines, K1.8, K1.8BR, K1.1, and KL, are connected to T1. The K1.8 beam-line has double-stage electrostatic separators and can provide a clean charged kaon beam with the  $K/\pi$  ratio better than unity for hypernuclear spectroscopy. The number 1.8 means the approximate maximum beam momentum and K1.8 can provide beams up to ~2 GeV/c. At present, the main theme of the research at K1.8 is the study of S=-2 hypernuclei. The K1.8BR beam-line is a branch of K1.8. Since K1.8BR can use just a single-stage electrostatic separation, high-intensity but somewhat pion-contaminated  $(K/\pi \text{ ratio} < 1)$  kaon beams are available there. Study of kaonic nuclei is the main theme of physics at K1.8BR. At present, the maximum momentum of K1.8BR is 1.2 GeV/c because of the limit from bending power of the downstream dipole magnets. KL is the neutral kaon beam-line prepared for the CP-violating rare decay experiments. K1.1 is the double-stage electrostatically separated beam-line up to 1.1 GeV/c. Unfortunately, the K1.1 beam-line is now shut down for construction of the High-p beam-line. The main physics theme of K1.1 is S = -1 hypernuclear spectroscopy.

Figure 38 shows the 300-ton Superconducting Kaon Spectrometer (SKS) temporarily installed at the K1.8 area. It was prepared for S = -1 hypernuclear spectroscopy. You can see the size of experimental apparatus at J-PARC Hd by comparing the size of SKS and experimenters. For S=-2 hypernuclear spectroscopy, several new spectrometers are available. Among them, the S-2S spectrometer prepared by Kyoto University is ready to be installed.

The K1.8 and K1.8BR lines have produced several exciting results for strangeness nuclear physics. By employing a newly developed germanium detector array and the K1.8 beam-line together with the SKS spectrometer, the E13 group observed  $\gamma$  rays from  ${}^{4}_{\Lambda}$ He and  ${}^{19}_{\Lambda}$ F hypernuclei and revealed their level schemes [59, 60]. As shown in Figure 39, the energy of the  ${}^{4}_{\Lambda}$ He(1<sup>+</sup> $\rightarrow$ 0<sup>+</sup>) transition was found to be largely different from that of the corresponding transition in the mirror hypernucleus of  ${}^{4}{}_{\Lambda}H(1^{+}\rightarrow 0^{+})$ . This result clearly confirmed the existence of a large charge symmetry breaking (CSB) effect in the A=4  $\Lambda$  hypernuclei, which was suggested by old emulsion experiments. This large CSB effect cannot be theoretically explained yet, sending a challenge to our understanding of hadron interactions.

At the K1.8 beam-line, doubly strange hypernuclei have been also studied with nuclear emulsion technique combined with the ordinary counter technique to tag  $\Xi^{-}$  production via the  $(K^-, K^+)$  reaction and its injection to the emulsion plates [61]. More than 30 double strange nuclear



Figure 38. SKS, a yellow sector magnet, and its beam analyzer (a green magnet) prepare at the K1.8 experimental area of Hd. This is a typical size of strangeness nuclear physics experiments performed in Hd [58].

events have been observed. Among them, a new  $\Lambda\Lambda$  hypernucleus of  ${}^{11}_{\Lambda\Lambda}$ Be was observed and the  $\Lambda-\Lambda$  interaction energy was quantitatively derived [62]. In addition, a new event of the  $\Xi^{-14}N$  deeply bound state has been observed, providing a precise value of the binding energy of the  $\Xi^-$ <sup>14</sup>N hypernucleus [63]. Further studies of doubly strange systems,  $\Xi$  hypernuclear spectroscopy experiments via the  $(K^{-},K^{+})$  reaction with the S2S spectrometer as well as an H dibaryon search via the H-> $\Lambda\Lambda$  decay, are also planned at the K1.8 beam-line.

On the other hand, the E15 group studied a possible K<sup>-</sup>nuclear bound state via the  $K^{-3}He \rightarrow \Lambda p$  n reaction with a 1.0 GeV/c kaon beam at the K1.8BR beam-line. In the Ap invariant mass spectrum measured with a cylindrical spectrometer around the target, a distinct peak was observed at a mass below the K-pp threshold by ~47 MeV with a width of ~115 MeV, as shown in Figure 40 [64]. It is kinematically well separated from the quasi-free  $\overline{K}N$  scattering followed by the  $\overline{K}NN \rightarrow \Lambda N$  absorption. The observed peak is naturally interpreted as a K<sup>-</sup>pp bound state, since the  $\Lambda(1405)$ is regarded as a K<sup>-</sup>p bound state with a binding energy of ~25 MeV. This result provides valuable information of the  $\overline{K}N$  interaction and opens a new possibility of meson-nucleon bound systems with strangeness.

In the J-PARC Hd, other types of hadron physics experiments are planned at the High-p beam-line. The construction of the High-p beam-line has been just finished. The High-p beam-line is a branch from the existing primary proton beam-

350 < q < 650 MeV/c

acceptance

corrected



*do/dM* [nb/(MeV/c<sup>2</sup>)] 50 data 40 K<sup>-</sup>pp  $QF_{\bar{K}A}$ 30 BG 20 all 10 0L 2.0 <sup>2.4</sup> *M*[GeV/*c*<sup>2</sup>] 2.2 2.8 3.0

**Figure 39.** Level schemes of the mirror hypernuclei,  ${}^{4}_{A}He$ and  ${}^{4}_{\Lambda}H$ . The  $\gamma$ -transition of  ${}^{4}_{\Lambda}He(1^{+}\rightarrow 0^{+})$  measured in the J-PARC E13 has confirmed the existence of a large charge symmetry breaking effect [59].

**Figure 40.** Ap invariant mass spectrum in the  $K^{-3}He \rightarrow \Lambda p$ n reaction measured in the J-PARC E15 experiment. A distinct peak observed below the K<sup>-</sup>pp threshold is interpreted as a  $K^{-}pp$  bound state [64].

Vol. 30, No. 3, 2020, Nuclear Physics News

80

70

60



**Figure 41.** *High-p and COMET beam-lines at J-PARC Hd. All the heavy construction has already been completed. These two lines are branches from the new primary proton beam-line (i.e., B-line), and B-line is a branch from the present primary proton beam-line (i.e., A-line). Beam tuning has been started in 2020.* 

line in the Switch Yard located between the Main Ring and Hd, and in Hd, the beam-line is split again for the  $\mu$ -e conversion search experiment called Conversion of Muon to Elec-Tron (COMET) (see Figure 41). We can use 30 GeV primary protons directly for experiments at the High-p experimental area. The first experiment at the High-p beam-line is a study of vector meson mass inside nuclear matter, where the vector meson mass is expected to be reduced because of the partial restoration of chiral symmetry. For this experiment, a big dipole magnet was set at the High-p experimental area to measure the momenta of the paired leptons. From the momenta of paired leptons, we can reconstruct the mass of vector mesons. When a  $\varphi$  meson is produced in a large mass-number target nucleus, it decays inside the nucleus if the velocity of the  $\varphi$  is slow while it mostly decays out of the nucleus if the velocity is fast. Thus, we expect to detect a mass shift of the  $\phi$  meson in nuclear matter. You can see the lepton pair spectrometer in Figure 42.

The Hd extension project is one of the top two major upgrading projects for nuclear physics in Japan. The present size of Hd,  $60 \text{ m} \times 55 \text{ m}$ , is too small to accommodate various experimental setups as well as new beam-lines for them. We are planning to extend Hd approximately three times longer for the beam direction and to newly install two production targets and four secondary beam-lines, as shown in Figure 43.

#### Supercomputers

Two national supercomputer projects, K (since 2011) and Fugaku (from 2021), are supporting the activities in



**Figure 42.** A large magnetic spectrometer prepared for a lepton pair spectroscopy experiment at the High-p beam-line. The magnet of the spectrometer came from the FM Cyclotron, which was constructed in 1958 and played an important role in the history of nuclear physics in Japan.

theoretical nuclear physics and related fields as one of the important fundamental sciences (Figure 44). The name K (京) is after the decimal unit of  $10^{16}$  that is 10 peta. Fugaku (富岳) is a nickname of Mt. Fuji, expressing the high peak and wide tail covering a wide research area. These supercomputers are developed and operated by RIKEN [66].

## Hadron Hall Extension



Figure 43. Hd extension project [65].



Figure 44. The K and Fugaku supercomputers.

The K supercomputer, whose system is constructed in Kobe, started its public service in 2012 with 10 peta-flops performance. Before it started public service, the K was ranked as the top by the TOP500 of 2011. The next generation Fugaku will achieve performance of about one hundred times more than the K. One of the feature projects of Fugaku is to combat COVID-19. It is expected to advise us on how we can resolve the pandemic.

The research fields that can be studied by these supercomputers cover medical sciences, disaster prevention, environment problems, drug discovery, energies, manufacturing, economy, and fundamental sciences. The fundamental science includes nuclear, particle, and astrophysics, where the important subjects are in nuclear structure, lattice QCD for hadrons, and galaxy formation and its dynamics. In all these subjects nuclear physics plays the central role. In addition to the K and Fugaku supercomputers, there are other supercomputer systems operated by several universities. All of them form the High Performance Computer Infra in Japan [67]. In the particle nuclear physics community, we also have a unique system of data storage network that is called the Japan Lattice Data Grid (JLDG) [68]. It works as a regional grid of the International Lattice Data Grid and is shown in Figure 45. The JLDG is the gfarm file system that enables users to access large data storages that are physically located at seven national universities by connecting them by the 10 GB network and by the account-sharing system. Much of the data are occupied by the so-called lattice gauge configurations that enable the first principle calculations of strong interaction physics.

Here we pick up the two main physics outputs that have been achieved by these supercomputers. One is the first principle derivation of the baryon force by the lattice QCD. The method is now referred to as the HALQCD [69]. It is proposed to compute the Nambu-Bethe-Salpeter function by the lattice QCD, from which the nuclear potential is derived as an inverse problem. It turns out that the method is more powerful for the systems where actual experiments are difficult, such as those of hyperons with strange quarks. The method solved the long-standing problem of the so-called Hdibaryon [70] and also predicted the most strange dibaryon, called di-Omega [71]. Another example of achievement is in the nuclear structure, where a new concept of revolution of the shell structure of nuclei was proposed [72]. Unlike the conventional concept of the well-fixed ones, it has been shown that the magic numbers are dynamically generated and may change depending on the numbers of protons and neutrons forming nuclei. This has been shown explicitly for neutron rich nuclei and is expected to play important roles for the understanding of the problems in nuclear synthesis.

#### 5. Australian Facilities

Research in nuclear physics in Australia has three major components: the new underground laboratory in Stawell, accelerator facilities at the Australian National University (ANU), and theory. The Australian Nuclear Science and



Sharing lattice QCD data over a widely distributed file system [@CHEP2015, J. Phys.: Conf. Ser. 664 042058]

Figure 45. An illustration of the Japan Lattice Data Grid.

Nuclear Physics News, Vol. 30, No. 3, 2020

Technology Organisation (ANSTO) in Sydney operates a reactor for research in applied science, from condensed matter to biology, as well as a number of accelerators used in applied programs. It plays a major role in isotope production but is not involved in fundamental research in the physics of nuclei.

#### SUPL

The most recent development is the creation of the Stawell Underground Physics Laboratory (SUPL). This is currently under construction a little over 1 km underground (about 3 km water equivalent) in a Victorian gold mine not quite half way between Melbourne and Adelaide. It will initially have two experimental laboratories, one to be used by ANSTO and the other for dark matter experiments. In parallel with the establishment of SUPL, the Australian Research Council has funded a new Centre of Excellence for Dark Matter Particle Physics (CDMPP), involving a consortium of six Australian universities (Melbourne, Adelaide, ANU, Swinburne, Sydney, and Western Australia), plus ANSTO, along with a number of overseas institutes, at A\$35M over seven years, from mid-2020. CDMPP will support a program of experiments searching for dark matter, starting with sodiumiodide with active background rejection, an updated version of dark matter experiment/large sodium iodide bulk for rare processes with much improved background rejection, which will run in SUPL and simultaneously at Gran Sasso.

#### HIAF

At ANU, the research conducted at HIAF (see Figure 46) can be grouped into three broad themes: (1) Quantum Physics of Nuclei, (2) *Nuclei in the Cosmos*, and (3) *Nuclei for Society*. The three main research groups focus on Reaction Dynamics, Nuclear Structure, and AMS.

#### Quantum Physics of Nuclei

This theme represents much of the work of the Reaction Dynamics and Nuclear Structure groups. It encompasses studies on the foundations of the nuclear force, the nuclear many-body problem in nuclear reactions and nuclear structure, and the quantum mechanics of nuclear dynamics, excitations, correlations, and decay. There are strong links between the experimental and theoretical research activities. ANU nuclear theorists develop nuclear few and many-body approaches to support and guide experimental programs.

#### Nuclei in the Cosmos

Examples of nuclear astrophysics are use of AMS to search for supernova remnants (e.g., <sup>60</sup>Fe) on Earth [73]

and extensive studies to improve the measurement of the radiative width of the Hoyle state in <sup>12</sup>C. Dark matter–related research is a newer activity that will grow as SUPL comes online.

#### Nuclei for Society

Nuclear physics for medicine includes established research to both compute and measure the emission of Auger electrons from medical radioisotopes, as well as research to support hadron therapy and radiobiology. The Department of Nuclear Physics hosts the internal conversion coefficient website (bricc.anu.edu.au), which has around 8,000 unique visitors per year. The AMS program has supported extensive research into environmental science for several decades. The initial emphasis was on <sup>36</sup>Cl measurements (e.g., to date groundwater), but recent work has focused more on landscape evolution studies. Recently, HIAF has been used for Australian space research activities and a dedicated beam-line is under consideration to meet increased demand.

Instrumentation for nuclear spectroscopy includes the Compton suppressed array of 11 Compton suppressed  $\gamma$ -ray detectors; the Super-e, a superconducting electron spectrometer designed to measure conversion electrons and electron–positron pairs; and the Hyperfine Spectrometer used to measure nuclear moments. SolenoGam is an array of electron and  $\gamma$ -ray detectors that can be placed around the focal plane of the 8-Tesla solenoidal separator (see Figure 46), to measure the spectroscopy of long-lived weakly populated states.

Nuclear structure research themes include studies of shape-coexistence and characterization of metastable states in heavy nuclei. Recent work has focused on the emergence of collectivity near doubly magic <sup>132</sup>Sn, pair spectroscopy to study E0 transitions, and experiments to eliminate alternative explanations of recent evidence of isomer depletion due to nuclear excitation by electron capture (NEEC) [74].

Instrumentation for studies of reaction dynamics includes the CUBE, a wide-acceptance fission spectrometer consisting of large-area position-sensitive multiwire proportional counters; two superconducting solenoidal separators (one 6.5 T, one 8 T, on separate beam-lines), and Break-up Array for LIght Nuclei (BALIN), an array of position-sensitive double-sided silicon strip detectors with large angular coverage and high granularity. Solienoidal Exotic Rare Isotope Separator (SOLEROO) is a low-mass radioactive ion beam capability that has been developed using the 6.5-Tesla solenoid as the separator element.



**Figure 46.** Overview of Australia's HIAF and beam-line instrumentation. The facility comprises the 14UD Pelletron accelerator and a superconducting booster LINAC housed in and operated by the Department of Nuclear Physics in the Research School of Physics at ANU.

The CUBE can be configured to suit a wide range of experiments to study nuclear fusion and fission, particularly by measuring the mass angular distributions of fission fragments and cross-sections. BALIN and SOLEROO are being used to measure breakup mechanisms of weakly bound nuclei and the roles of breakup versus cluster transfer in fusion reactions.

#### THEORY

There is a strong nuclear theory program at the Centre for the Subatomic Structure of Matter (CSSM) in Adelaide, ranging from studies of hadron structure and confinement using lattice QCD to nuclear astrophysics and nuclear structure. The latter two programs are built on the observation that the change in hadron structure generated by the strong mean scalar field in-medium should play a significant role in nuclear structure. Many of the experimental projects at HIAF benefit from support and guidance of local nuclear theorists as well as those at CSSM. Nuclear theory projects at ANU range from investigations of the origin of the nuclear force (in collaboration with University of Adelaide), reactions in few-body systems, many-body dynamics, and predictions of nuclear form factors for the interaction of dark matter particles with nuclei.

#### 6. Indian Facilities

As is very well known, there are three major accelerator centers in India. These are:

- *Kolkata*. VECC: K=130 Room Temperature Cyclotron, K=500 SC Cyclotron (now operational), and Cyclone-30 Medical Cyclotron and Saha Institute of Nuclear Physics: Facility for Research in Experimental Nuclear Astrophysics.
- *Delhi*. IUAC: Representing all the university users, 15 MV Pelletron coupled to SC LINAC.
- Mumbai. BARC and the Tata Institute of Fundamental Research (TIFR), 14 MV Pelletron coupled to SC LINAC (Pelletron LINAC facility [PLF])

The thrust areas of these facilities are:

- Low- and high-energy nuclear physics using accelerator and reactor.
- Nuclear data.
- Indigenous development of accelerators, detector, and instrumentation.
- Use of national facilities, international facilities like Legnaro National Laboratory, Grand Accélérateur National d'Ions Lourds, CERN, BNL, and the Facility for Antiproton and Ion Research (FAIR), among others.

#### VECC

Of these three major accelerator centers in India, only VECC operates three cyclotrons, but the other two are facilities based on the Pelletron electrostatic accelerator. The oldest cyclotron in VECC is the famous K130 room temperature cyclotron, which became operational in 1977 (see Figure 47). Recently, both the two new cyclotron facilities of VECC became fully operational for their respective applications. One is the K500 Superconducting Cyclotron (see Figure 48) for nuclear physics and the other is the CYCLONE30 Medical Cyclotron (see Figure 49). The K500 Superconducting Cyclotron is the sixth one of this kind in the world. Accelerator tuning is now underway. The CYCLON30 cyclotron was constructed by Ion Beam Applications S.A. in Belgium and used for the production of medical isotopes, such as F-18, In-111, Ga-67, Tl-201, I-123, and others.

VECC plans to construct the next generation facility, called the Advanced National facility for Unstable and Rare Isotope Beams (ANURIB). ANURIB is envisaged as a combined ISOL and fragmentation facility with beam energy from 1.5 keV/A to 100 MeV/A. As a pilot project of ANURIB, the Rare Ion Beam (RIB) accelerator project is now underway at VECC.

Figure 50 shows the plan view of the RIB facility in VECC. At present, the RIB accelerator at VECC is completed up to LINAC #3 to give 415keV/u (see Figure 51). It is aimed to





Figure 47. Variable energy K130 AVF cyclotron in VECC.

Figure 48. K500 Superconducting Cyclotron at VECC.



Figure 49. 30 MeV Medical Cyclotron at VECC.



Figure 50. RIB facility plan view in VECC.



Figure 51. The photograph of RIB facility at present.

give 1 MeV/u after LINAC #5 in 2018 and up to 2 MeV/u with QWRs. At present, the facility can be used for material science experiments with energy in the range 10 keV/u to 415 keV/u.

Recently, the present status of accelerators in VECC has been briefly introduced in the *AAPPS Bulletin* [75] together with describing other related facilities for continuing the associated research program. Please see the reference for more details.

#### IUAC

The IUAC [76] heavy ion accelerator facility (Figure 52), currently operational, consists of a 15UD/16 MV Pelletron

tandem accelerator and a superconducting booster linear accelerator (SC-LINAC). The tandem accelerator has a multicathode source of negative ion by cesium sputtering source that can produce ion beams ranging from proton to lead. Stable operation is currently limited to a maximum potential of 13 MV. DC and pulsed beams (with chosen repetition rate, especially for 12C and above) can be delivered to various experimental areas. The superconducting linear accelerator is based on solid niobium quarter wave resonators housed in three cryostat modules, each having eight resonators. Presently, the booster LINAC accelerator is used to boost ion beams ranging from C to Ag. The beam energies are variable and can be changed within a short tuning period. These accelerators form the heart of the core facilities for doing the majority of the acceleratorbased research by university users in India. There is an ongoing development to commission a High Current Injector (HCI) consisting of a superconducting (based on high Tc superconducting coil) ECR ion source, RFQ, six Drift Tube LINAC (DTL) modules, and beam transfer line composed of three momentum achromat sections to inject the beam into the SC-LINAC. The intensities of beams are expected to increase by a couple of orders of magnitude. Thus, the potential of the Beam Hall II experimental facilities for nuclear physics research can be fully exploited using highenergy, high-intensity beams from the HCI+SC-LINAC combination (Figure 53).

State-of-the-art experimental facilities provide important infrastructure for research in basic experimental nu-



**Figure 52.** Accelerator schematic at IUAC at Delhi (i.e., 15 MV Pelletron coupled to SC LINAC) and inset plot shows beam energy deliverable by these accelerators.

clear physics, accelerator mass spectrometry, and ion-beam modification and analysis of materials. Experimental facilities are attached to dedicated beam-lines installed in two halls, Beam Hall I and Beam Hall II. Beam Hall I facilities use beams accelerated from the Pelletron tandem accelerator only. The main objective of the Centre is to provide facilities for internationally competitive research and opportunities for growth of trained humanpower conversant with the technologies related to the focused area of acceleratorbased research in the Indian universities.

Nuclear physics research accounts for a large portion of beam time provided in these large accelerators. The major nuclear physics-related facilities (Figure 54) are (1) the recoil mass spectrometer with ED-MD-ED ion-optical configuration (the first in Asia), namely, the Heavy Ion Reaction Analyzer (HIRA); (2) the gamma detector array, initially consisting of 12 high-purity germanium detectors; (3) the general purpose scattering chamber, with an internal diameter 1.5 m in Beam Hall I; (4) the dual stage, dual mode recoil separator/spectrometer, HYbrid Recoil mass Analyzer (HYRA), which can operate in gas-filled as well as in vacuum mode; (5) the Indian National Gamma Array (INGA) with pooled germanium clover detectors (up to 24) from the Delhi, Mumbai, and Kolkata research centers; and (6) the National Array of Neutron Detectors (NAND), consisting of one hundred  $5" \times 5"$  liquid scintillators positioned in a dome-shaped array of 1.75 m radius, in Beam Hall II. Several other smaller, but crucial, ancillary detectors augment the major facilities. Some of these

facilities are coupled together, as a whole or in parts, for exclusive measurements. HIRA has also been used to produce low-intensity, highly pure 7Be RIB (first RIB used for experiments in India), produced in inverse kinematics and separated using the in-flight technique. HIRA, HYRA, and NAND are unique facilities at IUAC, as they are the only facilities of their kind in India.

The fields of research being pursued include (1) fusion and transfer around and below the Coulomb barrier; (2) channel coupling effects and barrier distributions; (3) compound nuclear decay, fission hindrance, and nuclear viscosity effects; (4) shell closure, deformation, and entrance channel dependence; (5) elastic scattering and quasi-elastic back-scattering; (6) incomplete fusion reactions; (7) fission angular and mass distributions and/or neutron multiplicities; (8) fusion-fission dynamics and effect of quasi-fission; (9) angular momentum distributions in fusion evaporation reactions; (10) Giant Dipole Resonance (GDR) decay; (11) high spin spectroscopy; (12) shape changes with spin; (13) chirality; (14) magnetic and antimagnetic rotations; (15) lifetime measurements using the Doppler-shift attenuation method and recoil decay method; (16) microsecond isomer decay; (17) Coulomb excitation; (18) nuclear g-factor and quadrupole moment measurements; and so on.

A 1.7 MV Pelletron accelerator has been installed at IUAC, equipped with a radio frequency ion source for initially producing negatively charged He ions. The overall facility has a 1.7 MV Pelletron accelerator, a RBS chamber, and a four-axis goniometer with a surface barrier de-



**Figure 53.** Schematic layout of the High Current Injector (HCI) (upper drawing) under commissioning, and its photograph (lower part) seen from the downstream. The beam from HCI will be injected into the SC-LINAC directly through new transfer line. By combining HCI and SC-LINAC, intensities of heavy-ion beam will be twice or more at the experimental area.

Nuclear Physics News, Vol. 30, No. 3, 2020



Heavy Ion Reaction Analyzer (HIRA)



Gamma Detector Array (GDA)



General Purpose Scattering Chamber (GPSC)



HYbrid Recoil mass Analyzer (HYRA)

Indian National Gamma Array (INGA)

National Array of Neutron Detectors

(NAND)

Figure 54. Major facilities for nuclear physics research (reaction dynamics and nuclear structure) at IUAC, Delhi.

tector to measure the number and energy of ions backscattered after colliding with atoms of the sample, enabling the determination of atomic mass and elemental concentration versus depth below the surface. Two low-energy ion beam facilities have also been developed and are operational at IUAC. A positive ion beam facility has been set up using an ECR ion source mounted on a high-voltage deck. The positive ion accelerator (or ion implanter) provides multiple charged positive ion beams with a wide range of relatively lower, tunable energy (~50 keV to about 3 MeV) for experiments in atomic, molecular, and materials sciences. The negative ion accelerator (or implanter) facility provides negative ion beams up to 200 keV and uses an ion source based on sputtering by cesium ions. This facility is extensively used for ion implantation studies, which have wide applications in pursuit of materials science basic research.

A 500kV accelerator mass spectrometry (AMS) facility for radiocarbon dating has been established at IUAC for dating or time-stamping of geological and prehistoric samples. The facility uses a 500 kV Pelletron accelerator and automated graphitization equipment. AMS is an ultra-sensitive technique that can be applied for the detection of long-lived radionuclides in many branches of science (e.g., geology, archaeology, hydrology, environmental science, biomedicine). This facility has capabilities to perform 10Be and 26Al measurements as well.

IUAC also intends to participate under a Coordinated Research Project for facilitating access to "guests" from all International Atomic Energy Agency member states. Besides, IUAC is in the process of identifying a "Joint University-IUAC Ion Beam Centre" among upcoming facilities, namely a focused ion beam facility with a 1.7 MV high-current tandem accelerator at IIT-Kanpur; 200 KV ion beam facility at Kurukshetra University, Kurukshetra; high-fluence ion beam facility at the University of Allahabad, Prayagraj; and National Centre for Accelerator-Based Research at Guru Ghasidas Vishwavidyalaya, Bilaspur and the Mumbai University Accelerator Centre.

#### **BARC-TIFR**

PLF (see Figure 55), set up as a collaborative project between BARC and TIFR, has been a major center for the heavy ion accelerator-based research in India. The Pelletron accelerator was formally inaugurated on 30 December 1988, and marked an important milestone in nuclear physics research in India. The Pelletron accelerator has been



Figure 55. A schematic layout of 14MV Pelletron accelerator and LINAC.

running round-the-clock since then, with consistently high uptime, delivering more than 45 different ion species from proton to iodine. The accelerator is mainly used for basic research in the fields of nuclear, atomic, and condensed matter physics, as well as material science. The application areas include AMS, production of track-etch membranes, radioisotopes production, radiation damage studies, secondary neutron production for cross-section measurement, and so on.

It should be noted that the PLF of BARC-TIFR has already been reported on in *Nuclear Physics News* [77].

#### 7. Summary

At present, ANPhA is collecting data for accelerator facilities applicable for nuclear physics in the Asia Pacific region. At present, data from 28 facilities have been accumulated. The collection includes future plans of facilities as well as their present status. Among the 28 facilities, major "world-class" accelerator facilities for nuclear physics in Asia Pacific have been briefly reviewed in this article. In this summary section, we would like to perform some critical analysis of the present facility data. However, the analysis may be made from very personal view points of authors.

Please see Table 2, which is a kind of summary table of our White Paper, and is the comparison of Asian accelerator facilities for nuclear physics with European and North American facilities.

Glancing at the table, we can understand that we have some of the world's top-level accelerator facilities in Asia Pacific. However, we have to be very careful of the fact that we have already so many "top-class" facilities in a specific field of nuclear physics—medium-energy heavy-ion (RI beam) physics. This is the reason why we need a long range plan of accelerator construction in Asia Pacific for our future opportunities of nuclear physics experiments, which should have as wide a spectrum as possible and should not to be very similar to each other.

More generally, we can say the following things about our facilities in Asia Pacific:

- Major accelerator facilities in the Asia Pacific region are mainly located in China and Japan.
- Most of them are, however, medium-energy heavy-ion accelerator facilities for RI beam physics, and they are competing with European and North American facilities.
- Furthermore, our future plans, such as RISP/RAON in Korea and HIAF in China, are standing at the wave-front of RI beam physics.
- In recent years, RIBF in Japan is one of the world's leading nuclear physics facilities in RI beam intensity and scientific outputs.
- Therefore, we can say that Asian research facilities are keeping world's-best positions in medium-energy heavy-ion physics (i.e. RI beam physics).
- On the other hand, we do not have any high-energy heavy-ion accelerators and colliders in Asia Pacific, and we have chosen to promote high-energy heavy-ion physics abroad (i.e.,) outside Asia.
- The hadron physics facility in Asia Pacific (J-PARC) is also a world-leading facility.

- We have only one facility for electromagnetic probes (ELPH/LEPS) for hadron physics in Asia Pacific.
- RCNP provided unique probes for nuclear physics for long time (i.e., medium-energy light ion beams for high-resolution nuclear spectroscopy).
- Now RI beam facilities are changing and expanding from a PF facility to the target ion source (ISOL) facility.
- Employing fission fragments generated in the atomic reactor as the starting projectile for PF facility can be the short cut to realize the new generation experiments using very high intensity radioactive ion (RI) beams, which will be available at the future Super ISOL facilities such as the 'next-generation' European ISOL (EURISOL) radioactive ion beam (RIB) facility.
- At present, we can say that we have concentrated our research resources on RI beam physics. This approach seems successful at present.
- However, for the coming 10 years, we should be a bit careful in order to have a wider spectrum of nuclear physics research in Asia Pacific.
- For example, how about baryon-rich nuclear matter physics in Asia Pacific; that is, heavy ion accelera-



**Figure 56.** A viewgraph used at the official presentation of the NuPECC long range plan given by Angela Bracco at Brussels on 27 November 2017. Importance of nuclear physics study with both RI beams and Hadron beams at the same time is dramatically shown in connection with the latest most spectacular event in the Universe, neutron star mergers.

Vol. 30, No. 3, 2020, Nuclear Physics News

**Table 2.** Comparison of Asian accelerators with European and North American accelerators for nuclear physics.

Accelerators for Nuclear Physics in the World								
	Beams	Asia	Europe	America	Comments			
Hot QCD	A+A		LHC(ALICE) FAIR(SIS300) NICA	RHIC	Missing Asian? J-PARC-HI or HIAF for dense matter?			
Cold QCD	hadron	J-PARC+Hdex HIRFL+HIAF	FAIR(SIS100)		Missing American?			
	γ, e <sup>-</sup>	Spring8 (LEPS) ELPH	мамі	JLAB-12GeV	1+many			
	collider	BES-III Belle-II	NICA LHCb	elC	Good competitions? Missing Asian?			
Many body Problem (Rl Beam)	PF	RIBF+upgrade HIRFL HIAF	GSI/FAIR	FRIB				
	Both	RISP(RAON)			Good competitions!!			
	ISOL	BRIF-II RIB-ANURIB HIAF+CIADS	SPIRAL2 SPES HIE-ISOLDE MYRRHA	ARIEL-II				
	Super ISOL	Beijing-ISOL	EURISOL		FRIB upgrade for US?			
(High Resolution)	Pol proton	RCNP RC	к∨і	Texas A&M	iThemba (South Africa)			

tion at J-PARC (J-PARC-HI), and/or an energy upgrade program for HIAF (HIAF phase II)? Should we build both? Or is it just one of them? In any case, this could be the first high-energy heavy-ion facility in the Asia Pacific region. In addition, we should pay sufficient attention to whether it can compete with FAIR in Germany and NICA in Dubna when it is completed.

Finally, we would like to make another summary of this report and conclude it.

- It becomes clear that the entire knowledge of nuclear physics is necessary to understand what is going on inside the most spectacular event in our Universe (i.e., neutron star mergers; see Figure 56).
- We need more precise knowledge of beta decays (mass of nuclei!) around the neutron drip-line.
- EoS of merging neutron stars must be the EoS of hypernuclear matter, since the 3r<sub>0</sub> world naturally contains strangeness.
- Nuclear physics is now stepping into the new horizon of the unification. There is no distinct border between hypernuclear physics, hadron physics, and RI beam physics.

• Therefore, the preparation plan of nuclear physics facilities in Asia Pacific should cover the wider range of nuclear physics.

At the closing of this review report, we would like to add the last sentence as the final summary: The completion of a facility does not mean the success of physics. Also, we believe that collaborative works of worldwide nuclear physicists at worldwide facilities are key for the future fruitful outputs of good physics.

#### References

- 1. ANPhA, https://bisol.org/anpha/
- 2. H. Sakai, Nucl. Phys. News 19(4) (2009) 3.
- 3. K. Tanaka, AAPPS Bull. 28(1) (2018) 43.
- 4. NuPECC Long Range Plan, http://www.nupecc.org/pub/ lrp17/lrp2017.pdf
- 5. ANPhA White Paper, https://kds.kek.jp/indico/category/1706/. Note for KEK Indico users: please find the username and password at the first page you opened (most users) or "click for the password" on the page that you can find after closing the popup window to login (Google Chrome users).
- 6. Accelerators for Hadron Therapy in Japan, http://www.antm. or.jp/05\_treatment/04.html (Japanese only).
- 7. https://www.pmrc.tsukuba.ac.jp/en/index.html

- 8. http://www.nirs.qst.go.jp/ENG/core/hospital/index.html,
- 9. Y. Hirao, IEEE Trans. Nucl. Sci. NS-26 (1979) 3736.
- 10. W. P. Liu et al., *Sci. China* A 54 (2011) s14.
- 11. Y. P. Shen et al., *Phys. Rev. Lett.* 124 (2020) 162701.
- 12. W. P. Liu et al., Sci. China Phys. Mech. Astro. 59 (2016) 642001.
- 13. BISOL design paper 2014, https://bisol.org
- 14. Y. Liu et al., *Phys. Rev. Lett.* 124 (2020) 192501.
- H. Wang, G. Fan, L. Liu, et al., *Nuclear Physics Review*, 37(1) 2020. (In Chinese)..
- 16. Z. Djurcic et al. (JUNO Collaboration), arXiv:1508.07166 (2015).
- 17. CSR/HIAF progress report 2019. http://hiaf.impcas.ac.cn/
- 18. Xiangshan roadmap report 2014, internal, in Chinese.
- 19. https://www.risp.re.kr/
- 20. J. Y. Moon et al., JPS Conf. Proc. 6 (2015) 030121.
- 21. https://www.ibs.re.kr/eng/sub02\_03\_10.do
- 22. B. Hong et al., *Eur. Phys. J.* A 50 (2014) 49.
- 23. B. Hong et al., Nucl. Sci. Tech. 29 (2018) 171.
- 24. H. Shim et al., Nucl. Instr. Meth. Phys. Res. A 927 (2019) 280.
- 25. https://komac.kaeri.re.kr:448/komaceng/main.do
- 26. https://aac.kist.re.kr/accelerator (in Korean).
- 27. https://www.kirams.re.kr/eng/hospital/equipments4.jsp
- 28. C. Kim et al., Nucl. Instr. Meth. Phys. Res. A 609 (2009) 276.
- 29. https://www.kaeri.re.kr/artie/board?menuId=MENU00873
- 30. T. Nakano et al., Nucl. Phys. News 29 (2019), 4.
- 31. H. Hama, AAPPS Bull. 30 (2020) 41.
- http://www.nirs.qst.go.jp/publication/pamphlets/pdf/himaceng201709.pdf
- 33. Y. Yano, Nucl. Instrum. Meth. B 261 (2007) 1009; T. Motobayashi and Y. Yano, Nucl. Phys. News 17 (2007) 5; H. En'yo, Nucl. Phys. News 25 (2015) 5.
- O. Kamigaito et al., Proc. 22nd Int. Conf. Cyclotrons and Their Applications, Cape Town, MOB01 (2019). Cape Town, South Africa, Sep. 2019, pp. 12–16. doi:10.18429/JACoW-Cyclotrons2019-MOB01.
- 35. T. Kubo et al., Prog. Theor. Exp. Phys. 2012 (2012) 03C003.
- K. Morita et al., J. Phys. Soc. Jpn. 73 (2004) 2593; 76 (2007) 045001; 81 (2012) 103201.
- N. Sakamoto et al., Proc. 19th Int. Conf. RF Superconductivity, Dresden, Germany, WETWB1 (2019); D. Steppenbeck et al., Nature 502 (2013) 207.
- 38. R. Taniuchi et al., Nature, 569 (2019) 53.
- 39. T. Kobayashi et al., Nucl. Instrum. Meth. B 317 (2013) 294.
- 40. Y. Kondo et al., Phys. Rev. Lett. 116 (2016) 102503.
- T. Ohnishi et al., J. Phys. Soc. Jpn. 77 (2008) 083201; T. Ohnishi et al., J. Phys. Soc. Jpn. 79 (2010) 07320; H. Suzuki et al., Phys. Rev. C 96 (2017) 034604; O. B. Tarasov et al., Phys. Rev. Lett. 121 (2018) 022501.
- 42. M. Thoennessen, Rep. Prog. Phys. 76 (2013) 056301.
- S. Nishimura et al., *Phys. Rev. Lett.* 106 (2011) 052502; G. Lorusso et al., *Phys. Rev. Lett.* 114 (2015) 192501; J. Wu et al., *Phys. Rev. Lett.* 118 (2017) 072701.
- 44. T. Uesaka et al., Prog. Theor. Exp. Phys. 2012 (2013) 03C007.

- 45. K. Kisamori et al., Phys. Rev. Lett. 116 (2016) 052501.
- 46. M. Wakasugi et al., *Eur. Phys. J.* A 42 (2009) 453; T. Suda et al., *Prog. Theor. Exp. Phys.* 2012 (2012) 03C008.
- A. Ozawa, T. Uesaka, and M. Wakasugi, *Prog. Theor. Exp. Phys.* 2012 (2012) 03C009.
- 48. P.A. Soderstrom et al., Nucl. Instrum. Meth. B 317 (2013) 649.
- 49. J. L. Tain et al., Acta Phys. Pol. B 49 (2018) 417.
- 50. K. Boretzky et al., GSI Sci. Rep. 2016 (2017) 207.
- 51. A. Obertelli et al., Eur. Phys. J. A 50 (2014) 8.
- 52. S. Takeuchi et al., Nucl. Instrum. Meth. A 763 (2014) 596.
- T. Motobayashi and H. Sakurai, Prog. Theor. Exp. Phys. 2012 (2012) 03C001.
- 54. H. Sakurai, Front. Phys. 13 (2018) 132111.
- 55. J-PARC Homepage. http://j-parc.jp/index-e.html
- 56. T2K Homepage. http://t2k-experiment.org/
- https://j-parc.jp/Hadron/en/index.html; K. Agari et al., Prog. Theor. Exper. Phys. 2012 (2012) 02B008; K. Agari et al., Prog. Theor. Exper. Phys. 2012 (2012) 02B009; T. Takahashi et al., Prog. Theor. Exper. Phys. 2012 (2012) 02B010; K. Agari et al., Prog. Theor. Exper. Phys. 2012 (2012) 02B011.
- 58. https://www.kek.jp/en/Facility/IPNS/K18BeamLine/
- 59. T. O. Yamamoto et al., Phys. Rev. Lett. 115 (2015) 222501.
- 60. S. B. Yang et al., Phys. Rev. Lett. 120 (2018) 132505.
- 61. J. Yoshida et al., JPS Conf. Proc. 26 (2019) 023006.
- 62. H. Ekawa et al., Prog. Theor. Exp. Phys. 2019 (2019) 021D02.
- 63. K. Nakazawa et al., Prog. Theor. Exp. Phys. 2015 (2015) 033D02.
- S. Ajimura et al., *Phys. Lett.* B 789 (2019) 620. https://doi. org/10.1016/j.physletb.2018.12.058
- 65. https://arxiv.org/pdf/1706.07916.pdf
- 66. https://www.r-ccs.riken.jp/en/postk/project
- 67. https://www.hpci-office.jp/folders/english
- 68. https://www.jldg.org
- N. Ishii, S. Aoki, and T. Hatsuda, *Phys. Rev. Lett.* 99 (2007) 022001, e-Print: nucl-th/0611096 [nucl-th]; S. Aoki, T. Natsuda, and N. Ishii, *Prog. Theor. Phys.* 123 (2010) 89, e-Print: 0909.5585 [hep-lat].
- HAL QCD Collaboration, Takashi Inoue (Nihon U., Fujisawa) et al., *Phys. Rev. Lett.* 106 (2011) 162002, e-Print: 1012.5928 [hep-lat]
- S. Gongyo et al., *Phys. Rev. Lett.* 120 (2018) 21, 212001, e-Print: 1709.00654 [hep-lat].
- 72. T. Otsuka et al., *Rev. Mod. Phys.* 92 (2020) 1, 015002, e-Print: 1805.06501 [nucl-th].
- 73. J. Wallner et al., Nature 532 (2016) 69-72.
- 74. C. J. Chiara et al., Nature 554 (2018) 216.
- 75. https://www.vecc.gov.in/; T. Samanta, *AAPPS Bull.* 30 (2020) 46.
- IUAC Home page. http://www.iuac.res.in/index.html; https:// youtu.be/69QvdUssk0s
- https://www.tifr.res.in/~pell/pelletron/index.php; https:// youtu.be/69QvdUssk0s V. Nanal and B. K. Nayak, *Nucl. Phys. News* 28 (2018) 4.