High Intensity Heavy-ion Accelerator Facility
HIAF
Physics Opportunities

Zhou Xiaohong
Institute of Modern Physics
Social and economic developments in China are scheduled in a “five years plan”, and the twelfth “five years plan” started from the year of 2011.

In 2010, the National Development and Reform Commission (NDRC) decided to build a batch of large-scale research facilities in order to boost basic sciences in China, and appealed for project proposals nationwide. The Institute of Modern Physics (IMP) proposed the High Intensity Heavy-ion Accelerator Facility (HIAF).

In 2011, a high-rank committee charged by NDRC evaluated all of the proposals in various research fields, and then recommended 16 top priority projects to NDRC. The HIAF was selected to be one of them.

On December 31, 2015, HIAF was approved by the central government.

The identified key science drivers for HIAF: the exotic nuclear structure, origin of heavy elements in the Universe, and heavy-ion application in space and material science.

On December 26 of 2016, we expect that the HIAF project can go through the technical assessment, and we plan to start the construction in 2017.
The National Research Center at the Pearl River Delta will be built!
Location

HIAF Location
Huizhou city and Guangdong province will cover the expenses for buying land, preparing land, building roads, building electricity and water supply stations, …..
About 5.0 kilometers to the downtown area of Huizhou City.
Superconducting Linac:
Length: 180 m
Energy: 17 MeV/u (U^{34+})
CW and pulse modes

Booster Ring:
Circumference: 471 m
Rigidity: 34 Tm
Beam accumulation
Beam cooling
Beam acceleration

Spectrometer Ring:
Circumference: 188.7 m
Rigidity: 13 Tm
Electron cooling
Stochastic cooling
In-ring experiment

The approved budget is 1.5 billion CNY for “bare” machine construction

Layout of the Facility
Prolific sources of nuclides far away from the stability line will be provided using projectile fragmentation, in-flight fission, multi-nucleon transfer, and fusion reactions. The limits shown are the production rate of one nuclide per day, which enable the “discovery experiments”.
The iLinac can work in two modes:

- **Pulsed Mode**: to inject beams into the BRing, and to provide pulsed beams for the TSR.
- **CW Mode**: to deliver continuous heavy-ion beams.

### Typical beams from iLinac

<table>
<thead>
<tr>
<th>Ions</th>
<th>Intensity (emA)</th>
<th>Energy (MeV/u)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{238}$U$^{14+}$</td>
<td>1.0</td>
<td>17</td>
</tr>
<tr>
<td>$^{120}$Xe$^{27+}$</td>
<td>1.0</td>
<td>30</td>
</tr>
<tr>
<td>$^{78}$Kr$^{19+}$</td>
<td>1.0</td>
<td>30</td>
</tr>
<tr>
<td>$^{18}$O$^{8+}$</td>
<td>1.0</td>
<td>36</td>
</tr>
<tr>
<td>H$_2^+$</td>
<td>1.0</td>
<td>48</td>
</tr>
</tbody>
</table>

The TSR built by the Max-Planck Institute for Nuclear Physics might be moved to HIAF, to conduct investigations of nuclear structure, reactions of astrophysical relevance, and atomic physics, well documented in *Eur. Phys. J. Special Topics 207, 1-117 (2012).*
Main Concerns at HIAF-Linac

Multi Nucleon Transfer Reactions and Fusion Reactions

- Synthesize new isotopes
- Measure the g.s. properties
- Build the decay schemes
- Map out the drip lines
- Root the decay chains of the SHE
- Build a bridge to the island of SHN
- Simulate the $rp$ and $r$ processes
- Study the evolution of shell structure

The low-energy intense beams will enable producing very n-deficient nuclei by fusion reactions and particularly heavy and super-heavy n-rich nuclei by multi-nucleon transfer reactions.
MNT reactions would be the optimum method to populate and characterize neutron-rich super-heavy nuclei and isotopes around N~126 which are crucial for understanding both astrophysically relevant processes and the evolution of “magic” numbers far from stability.
Experimental Instruments

Separation and identification of products from MNT reactions

- Rotating target system
- Gas stopper
- RFQ cooler and buncher
- Mass separation
- Laser ionization

1\(^+\) Charge State

Isobar Selection

Ion trap
Collinear Laser Spectroscopy
Decay Spectroscopy
Post acceleration
Gas-filled Recoil Separator

Exploitation of low-energy fusion evaporation reactions

A fast and high-efficient separator for fusion products.

By coupling with a gas cell followed by a RFQ cooler and buncher, pulsed high-quality low-energy beams are available for ion trap and collinear laser spectrometer.
Is there a limit, in terms of proton and mass numbers, to the existence of nuclei?

Unprecedented opportunities for the synthesis of new isotopes and structure studies

- Produce new elements and isotopes
- Gain insight into the mechanisms of fusion
- Measure masses and lifetimes
- Perform chemistry with the heaviest elements
- Hunt for new K-isomers
- Obtain information on the single particle states
Properties of very n-rich isotopes around N=126

V. I. Zagrebaev and Walter Greiner
PRC 87, 034608 (2013).

Experiments:
- Measure masses and lifetimes
- Build the decay scheme
- Obtain the β-delayed n-emission probability
- Measure the energies of low-lying states

Modeling of the rapid neutron capture process.

- Robustness of the 126 shell gap?
- Shape co-existence?
- Evolution of nuclear collectivity?
The HIAF facility will be “next generation” type.

One of the two storage-ring based facilities (FAIR and HIAF). Complementary to other future facilities (FAIR and FRIB).

Although IMP will take the responsibility for the facility construction, the Society of Nuclear Physics of China is expected to play a key role in defining the physical program and building the detector systems. It is a great chance to foster and grow up experimental strength in universities in China.

HIAF must be a domestic user facility and should be an international user facility. International collaboration and theories in assistance are very needed!
Acknowledgment


Beihang University: I.Tanihata, B.H.Sun, S.Terashima, …

Beijing Normal University: F.S.Zhang and K.Zhao

Peking University: Y.L.Ye, F.R.Xu, …

CIAE: C.J.Lin, …

CNS: S.Kubono

GSI: Y. Litvinov, T. Saito and C.Scheidenberger

Thank you for your attention!
Nuclear Physics:
- What are the limits to nuclear existence?
- What are new forms of nuclear matter far from stability?
- How about the quantum levels far from stability?
- What are new forms of collective motion far from stability?
- What dynamical symmetries appear in exotic nuclei?

Nuclear Astrophysics:
- How were the elements from carbon to uranium created?
- How is energy generated in stars and stellar explosions?
- What is the behavior of stars and supernovae?

Heavy-ion Applications
历程与进展

“十二五”大装置项目申报

2009年：提出概念，方案设计
2010年：科学院论证、发改委领域评审，开始选址
2011年1月11日：HIAF和CIADS列入国家规划
2012年：方案论证、研讨
2013年3月23日：国务院发布规划
2014年：方案研讨、论证，签订落户广东惠州协议
2015年1月15日：提交建议书到中科院

5月19日：项建书专家预算评审
5月21日：向中咨上报调整后估算表

3月11-12日：中咨领导惠州现场调研
3月18日：HIAF及CIADS项建书专家咨询
3月25-26日：HIAF及CIADS项建书专家评审
4月1-30日：形成专家评审意见回复
4月1-30日：准备简版材料

6月4日：中咨同CAS沟通协调会
8月17日：中咨正式向发改委递交咨询报告
12月1日：向发改委递交院配套补充请示文
12月31日：项目建议书批复

9月24日：正式向院提交调整后项建书
Experimentally deduced cross sections for the production of the N=126 isotones as a function of the atomic number. The filled circles are from the present work and the filled stars are from the fragmentation of 208Pb (1 GeV/nucleon) + Be. The solid and dashed lines are to guide the eye.
Layout of the Facility

Energy Recovery Linac:
Pulsed electron beam
Energy: 100 MeV

Compression Ring:
Circumference: 804 m
Rigidity: 43 Tm
Barrier bucket Stacking
Beam compression
Beam acceleration
In-ring experiment

Booster Ring:
Circumference: 402 m
Rigidity: 34 Tm
Beam accumulation
Beam cooling
Beam acceleration

Spectrometer Ring:
Circumference: 188.7 m
Rigidity: 15 Tm
Electron cooling
Stochastic cooling
In-ring experiment

Superconducting Linac:
Length: 180 m
Energy: 25 MeV/u (U^{34+})
CW and pulse modes

The expected cost is around 2.5 billion RMB ( ~400 million US$)
The government sets the limitation not exceeding 1.5 billion RMB
Main Concerns at HIAF

Complementarities between the different experimental stations

Uncultivated: Heavy and super heavy regions
- In flight fission of heavy projectiles
- Multi nucleon transfer reactions
- Projectile fragmentations
- Fusion reactions
The pion exchange interactions may contribute about 80% of attraction in light nuclei, and hence are essential to bind nucleons together.

The tensor force leads to a strong correlation between a np pair and high-momentum nucleons in nuclei.

The tensor force can be clarified by observing high momentum nucleon and correlated nucleons in nuclei.

While the high-momentum nucleon is picked up by a particle, the correlated nucleon may be emitted and measured using (p,pd), (p,nd), and (d,pt) reactions.

A comparison of correlations between pn pairs and pp (or nn) pairs provides a means to isolate the effect of tensor forces.

Proposed by I.Tanihata and S.Terashima
In order to understand the properties of nuclides far away from the stability, it is crucial to precisely locate the position of single particle states near the Fermi surface, and to investigate the degree to which their wave functions reflect pure single-particle motion.

The momentum distributions of fragments following one- or two-nucleon removal is the spectroscopic method well established, that gives knowledge on the wave function of the initial nucleons. Using very low intensity beam (~10 /s)!

Systematic study along isotopic and/or isotonic chains:
- Evolution of single particle states?
- Robustness of the 28, 50, 126 shells?
- Appearing new magic numbers?
- Evolution of nuclear shapes?
- Proton-neutron pairing?
- Coupling to the continuum?
- Giant and deformed halos?
- ……
Measurements of nuclear matter and/or charge radii provide the most original evidences for neutron and proton halos, neutron skins, and new magic numbers.

**Nucleon distributions or radii**
- Total interaction cross sections.
- Elastic proton scattering.

**Proton distributions or radii**
- Isotope shifts.
- Electron scattering.
- \( \mu \) atom.
- Charge changing cross section.

**Neutron distributions or radii**
- Halos in heavier nuclides.
- Giant neutron halos with > two neutrons.
- Deformed halos.
- Coupling of continuum and discrete states.

**Skin**

The equation of state (EOS) for cold asymmetric nuclear matter:

\[
E(\rho, \delta) = E(\rho, 0) + \delta E_{\text{sym}}(\rho) + O(\delta^4) \quad \delta = (\rho_n - \rho_p) / (\rho_n + \rho_p)
\]

A systematic change of neutron skin thicknesses is a sensitive tool to study the EOS which is of upmost importance for understanding neutron stars and supernovae.
A new approach for determining nuclear charge radii

Charge Changing Cross Section (CCCS) Measurement at relativistic energies + Glauber model

Angeli, Marinova, ADNDT 99, 69 (2013)

Experimental uncertainty (fm)

Charge radii:
- electron scattering.
- μ Atom.
- K X-ray isotope shifts.
- optical isotope shift.

CCCS at high energies:
- Weak energy dependence.
- Clean reaction mechanism.
- Statistic, \( N_{in} > 10^5 \).

At high energies, CCCS, reflecting interaction probability between the valence protons and the target nuclide, is sensitive to the proton distribution in the projectile nuclide. Analogous to the total cross section measurement, nuclear charge radii can be deduced from the CCCS.

\[
N_{out} = N_{in} e^{-\sigma_{cct}}
\]

Proposed by B.H. Sun and I. Tanihata
Properties of Un-bound Nuclear System

Nuclei beyond the drip-lines show interesting phenomena, and their surviving time are determined by the centrifugal and Coulomb barriers as well as nucleon correlations.

Nucleon and cluster emissions from the ground and excited states of nuclides.

- Directly determine the drip lines.
- Study the $pp$ and $nn$ correlations.
- Understand the decay mechanism.
- Study the $n-n$ and $p-p$ interactions.
- Reveal the properties of neutron matters.

Employing secondary reactions from a nearby unstable beam.
(relatively large cross section, simple identification, and low background)

Invariant-mass and missing-mass methods, and in-flight decay technique coupling to inclusive measurements covering half-life ranges from ~1ps to 1ns.
By coupling with a gas stopper, the follow-up RFQ cooler and buncher could provide pulsed high-quality low-energy beams, which enable the use of ion trap, collinear laser spectrometer and chemistry device.
**Gas-filled Recoil Separator**

**HIAF Fragment Separator (HFRS)**

- **Max. magnetic rigidity**: 15 Tm
- **Angular acceptance**: ±30 mrad (x), ±15 mrad (y)
- **Momentum acceptance**: ±2.0%
- **Momentum resolution**: 1500 (ε=30π mmmrad)
- **Total length**: 152 m

**Case 1**: Pre-Separator → Main-Separator → Spectrometer Ring

**Case 2**: Pre-Separator → Main-Separator → Possible extension to dipole magnet

In collaboration with Beihang University.
Gas-filled Recoil Separator

Exploitation of low-energy fusion evaporation reactions

- Collective motions
- Shape coexistences
- Single particle excitations
- Search for isomers
- Decay studies
- Synthesis of new isotopes

By coupling with a gas cell followed by a RFQ cooler and buncher, pulsed high-quality low-energy beams are available for ion trap and collinear laser spectrometer.
CUSTIPEN (China-U.S. Theory Institute for Physics with Exotic Nuclei) was established in May, 2013. The purpose of the CUSTIPEN is to enhance collaborations between U.S. and Chinese scientists in pursuit of a basic understanding of exotic nuclei and of their functions in astrophysics and other areas. Physicists from other countries are welcomed to join the collaborations.

The CUSTIPEN-IMP-PKU workshop keeps the spirits of the CUSTIPEN.

Organizing Committee of the CUSTIPEN-IMP-PKU Workshop on Physics of Exotic Nuclei
Pawel Danielewicz (Michigan State University)
Bao-An Li (Co-Chair, Texas A&M University-Commerce)
Guoqing Xiao (Institute of Modern Physics, Chinese Academy of Science)
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Yanlin Ye (Peking University)
Xiaohong Zhou (Co-Chair, Institute of Modern Physics, CAS)
Yuhu Zhang (Institute of Modern Physics, Chinese Academy of Science)
Fengshou Zhang (Beijing Normal University)
Remarks

Scientific Secretaries:
Guangshun Li from IMP and Junchen Pei from PKU.

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