Current Status of RAON & Nuclear Physics Experiments

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Overview of Rare Isotope Science Project

- **Goal**: To build a heavy-ion accelerator complex, RAON, in Korea for rare isotope science research
  - RAON: Rare isotope Accelerator complex for ON-line experiments

- **Budget**: KRW 1,432 billion (US$ 1.26 billion, U$ 1 ≈ KRW 1,200)
  - Accelerators and experimental apparatus: 460.2 billion KRW
  - Civil engineering & conventional facilities: 972 billion KRW (incl. 357 billion KRW for purchasing land)

- **Period**: Dec. 2011 ~ Dec. 2021

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**System Installation Project**

- Development, installation, and commissioning of the accelerator systems that provides high-energy (200 MeV/u) and high-power (400kW) heavy-ion beams

**Facility Construction Project**

- Construction of research and support facility to ensure stable operation of the accelerator and experiment systems and to establish a comfortable research environment (Accelerator & experiment buildings, supporting facility, administrative buildings, and guest house, etc.)

- Providing high intensity RIB by ISOL and IF
  - ISOL: direct fission of $^{238}$U by 70 MeV p
  - IF: PF of 200 MeV/u $^{238}$U at 8.3 pμA

- Providing high quality neutron-rich beams
  - e.g., $^{132}$Sn at 250 MeV/u
  - $\sim 10^8$ particles per second

- Providing more exotic RIBs by combining ISOL and IF
Geographical information

~160 km (~1 hour)
SCL1 has been postponed. SCL3 will play the role of SCL1 for IF in early stage operation.
Facility construction plan (Buildings)

- Campus Area: 952,066 m² (including the reservation area of 144,640 m²)
- Period: 2014~2021 (8 years)
- Cost: 972 billion won (incl. 357 billion won for land)
- Building Area: 76,259 m² (11 Bds)
- Total Bd. Area: 116,252 m²
- Constructor: POSCO Consortium (11 companies)
Some pictures of construction site

- High Energy Expts.
- ISOL
- SCL3 Tunnel
- Control Center
- Low Energy Expts.
- SCL3
- Bending Section

NUSYS 2019

12-17 August 2019
Milestones of RISP project

System Installation

- ECR-IS beam & ISOL beam (SI beam) (Dec 2015)
- SCL demo beam (Dec 2017)
- RFQ beam (Dec 2016)
- SCL Installation (May 2019)
- ISOL Commissioning (July 2020)
- D-1 Experiment (Jan 2021)
- SCL2 (Dec 2021)
- 18.5 MeV/u SI beam (Dec 2020)
- 18.5 MeV/u RI beam (Sep 2021)

Facility Construction

- Completion of basic design (Dec 2015)
- Completion of detail design (June 2017)
- Supply of utilities (Dec 2018)
- Completion of construction (Aug 2020)
- Completion of inspection of the radiation facility (Dec 2021)
- Building permit (April 2021)

Completion of detail design (June 2017)
Completion of construction (Sep 2017)
Supply of utilities (Dec 2018)
Completion of construction (Aug 2020)
Completion of inspection of the radiation facility (Dec 2021)
Building permit (April 2021)
Accelerator systems
Major achievements

- Superconducting RF test facility (2016.06)
- Low temperature test of quadrupole prototype magnets for IF: LTS (2016.01) & HTS (2017.01)
- QWR cryomodule test completed (2017.05)
- First Oxygen beam acceleration with QWR module, SCL Demo (2017.10)
- HWR cryomodule test completed (2018.03)
- First Oxygen beam acceleration with RFQ (2016.12)
- High purity Sn beam extraction using RILIS (2015.12)
Various high-intensity RIBs in wide energy range are expected from RAON.
RAON aims to provide an access to unexplored regions of nuclear chart.
Expected RIBs at RAON

J.W. Shin et al., NIMB349, 221 (2015)

□ Yield ratio: $^{132}\text{Sn}+^9\text{Be}/^{238}\text{U}+^9\text{Be}$
□ ISOL+IF is beneficial, for example, for n-rich isotopes for $45 \leq Z \leq 50$
Experimental systems

- Neutron Facility
- KOBRA
- MR-TOF (HPMMS)
- CLS
- BIS (Bio-medical facility)
- High Energy Expt. Bldg. (B)
- ISOL
- LAMPS

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The first part of stage 1 (stage1 part1) was contracted with foreign & domestic companies in April 2018. (Presently, the parts are being produced.)

The stage 1 will be installed in the low-energy Expt. hall (E1) by the end of June 2020.

The commissioning of Stage 1 will start in the beginning of 2021 with stable ion beams.

**PPAC**
- Two 10x10 cm$^2$, two 20x20 cm$^2$, and one 40x20 cm$^2$ active area PPACs were built.
- Four 10x10 cm$^2$ and one 40x20 cm$^2$ PPACs will be built in addition.

**SSD**
- Two 16 Channel detectors with 5x5 cm$^2$ active area and 50 μm thickness
- Energy resolution ~0.7% and S/N ~272 for 5.5 MeV $\alpha$ in vacuum

**Plastic scintillator detector**
- Two detectors read out both ends with 10x10 cm$^2$ active area and 100 μm thickness
- Time resolution < 42 ps for 5.5 MeV $\alpha$ in vacuum
LAMPS: Large-Acceptance Multipurpose Spectrometer

Beam energies up to 250 MeV/u for $^{132}$Sn ($\leq 10^8$ pps)
Brief history of LAMPS

12-17 August 2019
LAMPS will cover maximal area of beam species in the nuclear chart.
Physics goal: EoS and symmetry energy

- **General approach**
  - Investigate the energy per nucleon \( E/A = \varepsilon(\rho, \delta) \) as functions of baryon density \( \rho \) and isospin asymmetry \( \delta = (N - Z)/(N + Z) \):

\[
\varepsilon(\rho, \delta) = \varepsilon(\rho, \delta = 0) + E_{\text{sym}}(\rho)\delta^2 + \mathcal{O}(\delta^4) + \ldots
\]

with \( E_{\text{sym}}(\rho) \) the symmetry energy

- **Theoretical approach**
  - Calculate \( \varepsilon(\rho, \delta) \) by some density functionals or variational calculations

- **Experimental approach**
  - Constrain EoS and \( E_{\text{sym}}(\rho) \) using controlled laboratory experiments at specific \( \rho \)

![Graph showing energy per nucleon and symmetry energy as functions of baryon density and isospin asymmetry.](image)

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L.W. Chen et al., PRL 94, 032701 (2005)
Physics goal: Nuclear phase diagram

- Why are we doing heavy-ion collision experiment?
  → Only way to create dense (and hot) nuclear matter at laboratories
- Why are we using RI beams for heavy-ion collision?
  → Only way to control the isospin parameter (N/Z) of matter
Time Projection Chamber (TPC)

Original design

- 3-D tracking device for charged particles
- Large acceptance (~3π sr)
- Symmetric in azimuthal angle
- Triple GEM system for amplification
- Read readout at both endcaps
  (Total # of channels ~30k)

Simulate of a central Au+Au event at 250 AMeV (IQMD)
Prototype TPC with about half dimensions

- **Outer field cage**
- **Triple GEM**
- **Inner field cage**
- **Bottom Al frame for PAD & GEM**
- **Drift length: 570 mm**
- **150 mm**
- **490 mm**

**TPC: Prototype design**
TPC: Components

[Readout Pads]
Tested pads with the two different dimensions
3 × 10 mm²: 357 Ch/Sec
4 × 15 mm²: 175 Ch/Sec
Multi-layer PCB board

[Field Cage]
35 μm thick and 2 mm wide Cu strips
500 μm gap between adjacent strips
Mirror strips on the back
1 MΩ resistors with 0.1% variance
TPC body: G10 + Aramid honeycomb

[GEM Foil]
Trapezoidal shape
Thickness: 75 μm
Area: 166 × 118 mm²
Triple layers for each plane
Developed for CMS at LHC
TPC: Assembly

- Inner field cage installed
- Outer field cage installed
- Prototype TPC completed

Prototype TPC: back

Prototype GET
TPC: Beam test at ELPH

- ELPH: Research Center for Electron Photon Science at Tohoku University, Japan
- Dates: November 2016
- Beams: $e^+$ beams at 500 MeV
- Gas: Ar(90%)+CH$_4$(10%) (P10)  
  Ar(90%)+CO$_2$(10%) (ArCO$_2$)
- Purpose: To study the detailed characteristics, such as $v_{drift}$, diffusion and $\sigma_x$, of LAMPS TPC
TPC: Position resolution

- **4×15 mm² pad**
  - 175 Ch.
  - Resolution $\sigma = 513 \, \mu m$

- **3×10 mm² pad**
  - 357 Ch.
  - Resolution $\sigma = 228 \, \mu m$
TPC: Drift velocity

- **ELPH beam test**
  - Beam height: 20.24, 35.24 & 50.24 cm
  - Electric field:
    115~155 V/cm for Ar-CH\(_4\)(90:10)
    170 V/cm for Ar-CO\(_2\)(90:10)

- **Cosmic-ray muon test**
  - Trigger counter: 4 cm & 20 cm
  - Electric field:
    155~175 V/cm for Ar-CH\(_4\)(90:10)
    155~205 V/cm for Ar-CH\(_4\)(80:20)

- \( v_{drift} \lesssim 5.3 \text{ cm/\( \mu \)s} \) for P10 from the beam test:
  Maximum distance: 512 timing bins \( \times 0.04 \text{ \( \mu \)s/bin} \times 5 \text{ cm/\( \mu \)s} \lesssim 100 \text{ cm}

- P20 with cosmic muons: \( v_{drift} > 6 \text{ cm/\( \mu \)s} \) that is suitable for LAMPS TPC if we want to read out signals only from the upstream endcap.
TPC: Final design

- Final design of readout, gas vessel, and field cage is in progress.
  - Readout will be only at the upstream endcap.
  - P20 with $v_{drift} > 6$ cm/µs covers entire readout time of GET over full drift length
  - Inner radius: 150 →100 mm, Outer radius: 500 →535 mm
  - Maximize the active region for R = 105~503.5 mm

- Test of the real-size GEM foil is underway.
  - If gain is too small, the quadruple GEM configuration will be tested.

- LAMPS TPC will be constructed in 2019-2020 and tested by 2021.

• Pad dim.: ~ $3 \times 10$ mm$^2$
• # of Ch.: 2,618/sector $\times$ 8 sectors = 20,944
• FEE: 11 AsAD/sector $\times$ 8 sectors = 88 AsAD
Neutron detector array

PMT (Hamamatsu H7195)  BC408 (Polyvinyltoliene)  Light guide (Acryl)

Veto wall

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10 x 10 cm²  2 m
Neutron detector: Beam test at RCNP

- E479 approved in B-PAC in March 2016
- Date: May 2016
- Beam specifications
  - Protons on Li production target ($p + ^7\text{Li} \rightarrow n + ^7\text{Be}$)
  - Neutron energies: 65 and 392 MeV in N0 beamline
  - 10 nA flux $\times$ 1/9 chopping
  - Background neutron above 3 MeV is less than 1% [NIMA629, 43 (2011)]
Neutron detector: Beam test at RCNP

- Distance from target to the detector: 15 m
- Gap between stations: 60 cm
- Dim. of each S1 detector: $10 \times 10 \times 100$ cm$^3$
- Dim. of each S2 detector: $10 \times 10 \times 200$ cm$^3$
- Beam size at S1: $25 \times 30$ cm$^2$
Large energy loss in Li target at 65 MeV
Low-energy background dominated by the 3-body decays $^7\text{Li}(p, n \, ^3\text{He}) \, ^4\text{He}$
Energy resolution (FWHM):
- $3.1\% \, @ \, 392 \, \text{MeV}$
- $3.4\% \, \text{without background subtraction}$
- $1.3\% \, @ \, 65 \, \text{MeV}$
Neutron detector: Position resolution

- Hit position difference between $D1$ and $D2$ for neutrons with simultaneous hits: $\Delta x_{S1} \equiv x_{D1} - x_{D2}$ for 10 MeV threshold and $\delta t < 3$ ns
- Relative position resolution for neutrons for one bar: $\sigma_n = \frac{\sigma(\Delta x_{S1})}{\sqrt{2}} = 4.5$ cm: $R_x(n) = 7.5$ cm (FWHM)
- Position difference between the projected and hit positions for cosmic muons: $\Delta x_4 \equiv x_{D4,proj} - x_{D4,\text{hit}}$
- Relative position resolution for cosmics for one bar: $\sigma_x = \frac{\sigma(\Delta x_4)}{1.87} = 2.0$ cm: $R_x(\mu) = 4.8$ cm (FWHM)

- Single-bar detection efficiency: Experimental data agree with the simulation results.
Characteristics of prototype LAMPS neutron detectors

<table>
<thead>
<tr>
<th>Data</th>
<th>Cosmic muons</th>
<th>Neutron beams at 65 MeV</th>
<th>Neutron beams at 392 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time resolution (ps)</td>
<td>309</td>
<td>7.6</td>
<td>7.5</td>
</tr>
<tr>
<td>Position resolution (cm)</td>
<td>4.8</td>
<td>1.3</td>
<td>3.1</td>
</tr>
<tr>
<td>Energy resolution (%)</td>
<td></td>
<td>9.0 ± 1.6</td>
<td>6.3 ± 1.0</td>
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<tr>
<td>Efficiency (%)</td>
<td></td>
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Comparison of performance for similar kind of neutron detectors

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<tr>
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<tbody>
<tr>
<td>Dimensions (cm³)</td>
<td>10 × 10 × 200</td>
<td>10 × 10 × 200</td>
<td>12 × 12 × 180</td>
</tr>
<tr>
<td>Time resolution (ps)</td>
<td>309</td>
<td>423</td>
<td>376</td>
</tr>
<tr>
<td>Position resolution (cm)</td>
<td>4.8</td>
<td>5.2</td>
<td>6.1</td>
</tr>
</tbody>
</table>


H.H. Shim et al., NIMA 927, 280 (2019)
Neutron detector: Frame

Array frame

Light-tight PMT clamps

Module fixture
Detector modules, sorted by PMT gains, are waiting for final assembly on the frame.
Installation of all modules (160 detectors + 20 vetos) in the frame was completed at the Sejong campus Lab. of Korea University in Dec. 28, 2018.

Cosmic muon test just started.

Detector operation can be remotely done in Seoul.
### Status of the LAMPS Collaboration

**RISP/IBS**: **Young Jin Kim**, Hyo Sang Lee, Min Sang Ryu

**Korea University**: Jung Keun Ahn, **Byungsik Hong**, Young Seub Jang, Jiseok Kim, Minho Kim, Jong-won Lee, Jaehwan Lee, Jung Woo Lee, Kyong Sei Lee, Byul Moon, Benard Mulilo, Seon Ho Nam, Jaebeom Park, Jeonghyeok Park, Hyunha Shim

**Chonbuk Nat. University**: **Eun-Joo Kim**

**Chonnam Nat. University**: **Dong Ho Moon**, SeongHak Lee

**Inha University**: **Min Jung Kweon**, Hyungjun Lee

**Sejong University**: **Yongsun Kim**, Hyebin Song

**Jeju Nat. University**: **Jong-Kwan Woo**

**KRISS**: **Sanghoon Hwang**

- 6 Korean Universities and 2 Institutes
- 27 Collaborators including 7 Profs., 7 research staffs and 13 students
- Globalization is needed!
- Contact me at bhong@korea.ac.kr if you’re interested in the project.

<table>
<thead>
<tr>
<th>System</th>
<th>2018</th>
<th>2019</th>
<th>2020</th>
<th>2021</th>
<th>2022</th>
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<tbody>
<tr>
<td></td>
<td>3Q</td>
<td>4Q</td>
<td>1Q</td>
<td>2Q</td>
<td>3Q</td>
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<td></td>
<td>4Q</td>
<td>1Q</td>
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<td>1Q</td>
<td>2Q</td>
<td>3Q</td>
<td>4Q</td>
<td>1Q</td>
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<tr>
<td><strong>Solenoid magnet</strong></td>
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<tr>
<td></td>
<td>manufacturing design</td>
<td>production</td>
<td>performance test</td>
<td>LAMPS building construction finished</td>
<td>production completed</td>
</tr>
<tr>
<td><strong>IF-LAMPS beam line magnet</strong></td>
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<tr>
<td></td>
<td>technical design</td>
<td>production</td>
<td>performance test</td>
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<tr>
<td><strong>TPC system</strong></td>
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<td></td>
<td>TPC GEM, gas vessel, field cage production</td>
<td>TPC assembly</td>
<td>performance test</td>
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<td><strong>Neutron Detector Array</strong></td>
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<td></td>
<td>cosmic test</td>
<td>experimental test (e.g. in KOBRA)</td>
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<tr>
<td><strong>Beam line/beam diagnostic detector</strong></td>
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<tr>
<td></td>
<td>simulation, R&amp;D</td>
<td>design</td>
<td>production</td>
<td>performance test</td>
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<tr>
<td><strong>Target system</strong></td>
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<tr>
<td></td>
<td>simulation, R&amp;D</td>
<td>design</td>
<td>production</td>
<td>performance test</td>
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<td><strong>ToF/Trigger detector</strong></td>
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<tr>
<td></td>
<td>simulation, R&amp;D</td>
<td>design</td>
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<td>performance test</td>
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<td><strong>DAQ</strong></td>
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<td>individual DAQ R&amp;D</td>
<td>optimization</td>
<td>integration</td>
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Revival on low-energy Expts. by LAMPS

Center for Extreme Nuclear Matters (Director: B. Hong)
Supported by the National Research Foundation of Korea (NRF) via the “Science Research Center for Excellency” program from 2018 (Total 7 years and possible extension after evaluation)

▪ Three groups
  □ Group 1: High-energy heavy-ion collisions
  □ Group 2: Hadron physics
  □ Group 3: Radioactive ion beam physics

▪ Members
  □ 9 professors, >15 postdocs & research staffs, >30 students

▪ Research center is independent of RISP/IBS, but …
  □ Experimental professors in CENuM are very much interested in the low-energy experiments at RAON in early operational phase.
  □ Therefore, CENuM started to develop some essential detector components for the low-energy nuclear experiments at RAON:
    – LaBr$_3$(Ce) gamma detector system
    – AT-TPC & Superconducting solenoid magnet
    – FAZIA type Si-CsI detector system
Revival on low-energy Expts. by LAMPS

- **LaBr$_3$(Ce) gamma detector system**
  - Fast timing PMTs ($R_t < 200$ ps, $R_E < 3.5\%$, $\varepsilon \sim 6.8\%$ at 664 keV)
  - Total 24 modules (Plan to build 12 modules by 2020 and additional 12 by 2021)

- **AT-TPC & Superconducting solenoid magnet**
  - Superconducting solenoid magnet: 1.5 T, inner radius & length = 60 cm each
  - Magnet construction in 2019
  - AT-TPC construction by 2021

- **FAZIA Si-CsI detector**
  - Excellent isotope separated PID up to $Z \approx 25$
  - Very useful for low-energy experiments at RAON

Figure borrowed from R. Bougault’s presentation at IWND
□ Rare Isotope Science Project (RISP) at IBS is the first large-scale nuclear physics project in Korea.

□ The civil engineering, accelerator development, and detector construction for RAON have been aggressively progressed.

□ LAMPS is a dedicated spectrometer for nuclear EoS and symmetry energy at RAON.

□ Various components for LAMPS, including TPC, neutron detector array, magnet, are making a very good progress.

□ Expect to finish the detector construction in about 2-3 years for nuclear experiments at early stage.