Grzegorz Kaminski\textsuperscript{a,f} for ACCULINNA Collaboration

\textbf{STATUS OF THE NEW FRAGMENT SEPARATOR ACCULINNA-2 AND FIRST EXPERIMENTS}

\textbf{Outline}

- Light RI beam facility at FLNR (ACC&ACC-2)
- Status of the ACCULINNA-2 project & ACC-2 instrumentation
- First day experiments at ACCULINNA-2
- Experiments with OTPC at ACC
- Summary
Main areas of interest at FLNR, JINR

Elements 102 - 108 synthesized at FLNR

Elements 113 - 118 synthesized at FLNR

Elements:
113 Nihonium (2016)
114 Flerovium (2011)
115 Moscovium (2016)
116 Livermorium (2011)
117 Tennessine (2016)
118 Oganesson (2016) recently officially recognized IUPAC

Light & ‘Superlight’

‘Superheavy’

Grzegorz Kaminski, EMIS2018
Scope of activity with ACCULINNA-2

Grzegorz Kaminski, EMIS2018
Energy range and reaction selection

Intermediate energy reactions (20-70 MeV/nucleon)
- Transfer reactions
  - $^7$Li
  - $^6$He
- $^{10}$Be
- $^{12}$Be
- $^{13}$B
- $^{14}$Be

High energy reactions (>70-100 MeV/nucleon)
- Knockout reactions
- Population of highly aligned states in the intermediate energy transfer reactions
- Prospects for specific correlation studies

Complementary information from different reaction mechanism
- Lower reaction energy - easier to get higher energy resolution

Correlations and few-body dynamics studies

Correlations for aligned states populated in the direct reactions
- Few-body dynamics near the driplines
- Correlations in the three-body decays: two extra degrees of freedom
Layout of the ACCULINNA-2 separator

- RIB energy range 5 – 50 MeV/A
- $Z_{\text{RIB}} \sim 1 – 36$

<table>
<thead>
<tr>
<th></th>
<th>ACC</th>
<th>ACC-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \Omega$</td>
<td>msr</td>
<td>0.9</td>
</tr>
<tr>
<td>$\delta_P$</td>
<td>%</td>
<td>2.5</td>
</tr>
<tr>
<td>$P/\Delta P$</td>
<td>a.u.</td>
<td>1000</td>
</tr>
<tr>
<td>$B\rho_{\text{max}}$</td>
<td>Tm</td>
<td>3.2</td>
</tr>
<tr>
<td>Length</td>
<td>m</td>
<td>21</td>
</tr>
<tr>
<td>$E_{\text{min}}$</td>
<td>AMeV</td>
<td>10</td>
</tr>
<tr>
<td>$E_{\text{max}}$</td>
<td>AMeV</td>
<td>40</td>
</tr>
</tbody>
</table>

total length F0-F5 ~53m, 39 magnetic elements

2011: Contract signed with Sigma PHI
2016-17: Full commissioning + Beam

**2016-2017:** Zero-angle spectrometer
- **2017-2019:** RF kicker at F3
- **2017-2019:** New detectors

**2017-2019:** RF kicker at F3

**2018-2020:** Cryogenic target system & tritium target at F5

2019-20: Cyclotron upgrade
First radioactive ion beams at ACCULINA-2

\( ^{15}\text{N} \) (49.7 AMeV) + Be (2 mm)

\( I \sim 10^5 \) pps @ 100 pnA, \( \Delta p/p = 6\% \) (Be wedge 3 mm)

\( I = 100 \) pnA, \( \Delta p/p = \pm 2\% \) (Be wedge 1 mm)

<table>
<thead>
<tr>
<th>RIB</th>
<th>Energy, Amev</th>
<th>Intensity, 1/s</th>
<th>Purity, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{14}\text{B})</td>
<td>37.7</td>
<td>1.2 \times 10^4</td>
<td>65</td>
</tr>
<tr>
<td>(^{12}\text{Be})</td>
<td>39.4</td>
<td>1.5 \times 10^4</td>
<td>92</td>
</tr>
<tr>
<td>(^{11}\text{Li})</td>
<td>37</td>
<td>4 \times 10^2</td>
<td>67</td>
</tr>
<tr>
<td>(^{9}\text{Li})</td>
<td>33.1</td>
<td>1.1 \times 10^5</td>
<td>50</td>
</tr>
<tr>
<td>(^{8}\text{He})</td>
<td>35.8</td>
<td>2.5 \times 10^3</td>
<td>89</td>
</tr>
</tbody>
</table>

- Good agreement with calculations
- Intensity, Lise++
- Higher intensity compare to ACCULINNA in 15 times!

\( \Phi \sim 17 \) mm
The zero degree spectrometer

- Weight ~ 20 t
- Max. 1.38 Tm
- Thin (330 mm) open-frame design
- Mounted on guide rails. Precision in different positions ±0,2 mm. Repeatability ~ 0,1 mm
- Min. distance from phys. target ~ 700 mm

<table>
<thead>
<tr>
<th>Maximum field</th>
<th>$B_{\text{max}}$</th>
<th>T</th>
<th>1.44</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum field</td>
<td>$B_{\text{min}}$</td>
<td>T</td>
<td>0.4</td>
</tr>
<tr>
<td>Effective length for $B = 1.2$ T</td>
<td>$L$</td>
<td>mm</td>
<td>524</td>
</tr>
<tr>
<td>Gap</td>
<td></td>
<td>mm</td>
<td>180</td>
</tr>
<tr>
<td>Good field region dimensions</td>
<td>$H/V$</td>
<td>±mm</td>
<td>250/75</td>
</tr>
<tr>
<td>Field homogeneity for $B = 1.2$ T</td>
<td>$dB/B$</td>
<td></td>
<td>0.003</td>
</tr>
</tbody>
</table>

Neutrons
(stilbene array)

Distance to target > 2 m
TOF accuracy < 1%

Protons, deuterons, tritons
$B_\rho = 0.4 ~ 1.0$ Tm
Cone 0 ~ 14°

$B_\rho = 1.0$
$B_\rho = 0.4$
$B_\rho = 1.1$
$B_\rho = 1.7$

Heavy decay products
$B_\rho = 1.1 ~ 1.7$ Tm
Cone 0 ~ 6°

Particle tracking system
(2017-2018 – designing, construction)
RF-kicker phase correction from pickup in primary beam or cyclotron RF signal

**Improvement of RIB purity - RF-kicker**

- **Frequency range (MHz)**: 15 – 22
- **Peak voltage (KV)**: 120
- **Gap (mm)**: 70
- **Width of electrode (mm)**: 120 min
- **Length of electrodes (mm)**: 700
- **Cylinder diameter (mm)**: 1200 max
- **Stem diameter (mm)**: 120 max
- **Length of coaxial line (mm)**: 1830
- **Distance from A-2 primary target (m)**: 25

**Delivery in first quarter of 2019**

**ADJUSTMENT OF RF FREQUENCY – AUTOMATIC REGULATION**

**RF AMPLIFIER**

**RF GENERATOR**

**RF KICKER**

- Frequency selection
- RF fine tuning
- RF measuring loop
- RF coupling loop

**SOFTWARE**

Control and monitoring

**C&C - Automatic**
Improvement of RIB purity - RF-kicker

Main application of RF kicker: improvement of RIB purity at neutron-deficient nuclei
First experiments with $^6\text{He}$ and $^9\text{Li}$ on $\text{CD}_2$ target were carried out at ACC-2 in spring:

- elastic and inelastic scattering of $^6\text{He}$;
- $d(^6\text{He},^3\text{He})^5\text{H}$ reaction;
- $d(^9\text{Li},p)^{10}\text{Li} \rightarrow n+^9\text{Li}$ run.
Elastic and inelastic scattering of $^6\text{He}$ (26 AMeV) on $^2\text{H}$:

Beam parameters:
- 78% of $^6\text{He}$
- Energy 26 AMeV
- Intensity $10^5$ pps

Experimental data for B. Zalewski
Ph.D Thesis (HIL, UW, Warsaw)
Preliminary results of elastic and inelastic scattering of $^6$He (26 AMeV) on $^2$H: $d\sigma/d\Omega$ in a wide angular range (3 runs, $\theta_{CM} \sim 30\div110^o$) with a good statistics.
Radiation shell around F1-F2 area is completed.
Radiation shell will let to operate at full beam intensity.
Modernized U-400M cyclotron will provide highly intended beams (~ 3 \( \mu \text{A} \) on the target in case of \( ^{15}\text{N} \)).
Moving ahead to the flagship experiment $^7\text{H}$ - primary target

- Water cooled beryllium target mounted on magnetic liquid feedthrough with rotation speed up to 1500 rpm
- Heating power up to 2 kW
- Vacuum chamber for fast opening and service
- Integrated system of water cooled diaphragms
- Special port for beam profile monitor (BPM)
First day flagship experiment $d(^8\text{He},^3\text{He})^7\text{H}$

- **$^3\text{He}$:**
  - $\text{Si} - 22 \mu$
  - $\text{Si} - 1000 \mu$

- **$^8\text{He}$:**
  - $\sim 50 \text{ kps}$
  - $E \sim 25 \text{ AMeV}$/

- **$^3\text{H}$:**
  - $X_Y_D E$
  - $\text{Si} - 1000 \mu$
  - $32 \times 32 \text{ strips}$

- **$D_2$-target**
  - $3 \times 10^{20} \text{ at/cm}^2$

- **Neutrons, Cone 0 ~ 14°**

- **CsI array GADAST**
  - 64 units

- **Energy & position:**
  - decay tritons & RIB
  - $B_\rho = 0.4 \sim 1.0 \text{ Tm}$
  - Cone 0 ~ 14°

- **Stilbene array**
  - 40 units

- **$\sim 5 \ ^7\text{H per day (two telescopes)} @ 5 \times 10^4 \ ^8\text{He}/s \rightarrow \sim 140 \ ^7\text{H during 4 weeks}$**
Optical Time Projection Chamber (OTPC) - A new type of modern ionization chamber with an optical readout. Invented at the University of Warsaw by W. Dominik

Miernik et al., NIM A581 (2007) 194

Identified ion (typically by TOF&dE)

Spectroscopy of $\beta$-delayed charged particle emission

OTPC - chamber

OTPC installed at ACCULINNA

Experimantal group

Grzegorz Kaminski, EMIS2018
Plans for 2019: $\beta$-delayed charged particle emission from $^{27}\text{S}$ and $^{26}\text{P}$

$^{32}\text{S} @ 50 \text{ MeV/u} + ^{9}\text{Be} \rightarrow \text{ACC} \rightarrow ^{27}\text{S}, ^{26}\text{P}$

We have too low statistic to get the limit for observation of $\beta3p$


Thomas et al., EPJ A21 (2004) 419

Canchel et al., EPJ A12 (2001) 377

P $\beta3p < 0.08\%$
In 2019 new measurements of $\beta$-delayed particle emission from $^{27}\text{S}$ at ACCULINNA-2 are planned. Much better statistic of two orders of magnitude is expected (we plan to purify the beam with RF-kicker). Observation of $\beta 3p$ channel is still an open question.

$^{32}\text{S} @ 50\text{ MeV/u} + ^9\text{Be} \rightarrow \text{ACC} \rightarrow ^{27}\text{S}, ^{26}\text{P}$

We have too low statistic to get the limit for observation of $\beta 3p$.

$L.\ Janiak, N.\ Sokolowska\ et\ al.,\ PRC\ 95\ (2017)\ 034315,\ N.\ Sokolowska,\ Master\ Thesis,\ AGH,\ Krakow\ 2016$
ACCULINNA-2 fragment separator commissioned in 2017 is now ready for first-day experiments.

The intensities obtained in the fragmentation reaction $^{15}\text{N} (49.7 \text{ AMeV}) + ^{9}\text{Be}$ for the RIBs of $^{14}\text{B}$, $^{12}\text{Be}$, $^{9,11}\text{Li}$, $^{6,8}\text{He}$ were on average 15 - 20 times higher in comparison with the values for the old facility.

In 2018 experimental program with RIBs has been focused on $\beta$-delayed exotic decays of $^{11}\text{Be}$, $^{6}\text{He}+\text{d}$ scattering and $\text{d}(^{6}\text{He},^{3}\text{He})^{5}\text{H}$ reaction study.

Method to study low-lying states of $^{10}\text{Li}$ populated in the reaction $\text{d}(^{9}\text{Li},\text{p})^{10}\text{Li} \rightarrow \text{n}+^{9}\text{Li}$ was tested too (registration of protons, emitted backward in laboratory system, in coincidence with neutrons moving in forward direction).

The study of the $^{7}\text{H}$ and its 4n-decay in the reaction $\text{d}(^{8}\text{He},^{3}\text{He})^{7}\text{H}$ is proposed for the fall 2018.

Further plans: search for $\beta$-delayed 3p emission from $^{27}\text{S}$ is considered by means of the OTPC (with RF-kicker), experiments (with RF-kicker and zero angle spectrometer) will be aimed on $^{26}\text{S}$ observation in $(\text{p},\text{t})$ reaction with $^{28}\text{S}$.

We are open for collaboration

Thank you for attention