Fragment separator ACCULINNA-2 at U400M
Status and day-one experiments
Andrey Fomichev

January 21th 2016, Dubna PAC meeting
"In the beginning, there was Chaos" Creek Mythology – The Creation

Before 2011

Budker Institute of Nuclear Physics
Scientific Research Inst. of Electrophysical Apparatus
SIGMA PHI Magnets & Beam Transport
Mitsubishi Electric Corporation
Tokin Machinery Corporation
Sumitomo Heavy Industry

 ==> CONTRACT № 500/1535
Dated on 28.09.2011
Jan. 2015: installations of all magnets with high accuracy; power supply, cabling, cooling

- Leica laser tracker AT401
- Alignment accuracy within ± 0.1 mm
March 31, 2015
Vacuum test and first magnetic measurements
↓↓
Certificate of Acceptance
Dec. 2015: first beam test with $^{32}\text{S}$ at 51.5 MeV/nucl

Beam profile in F1 (LF diam. 80mm)

Beam profile in F2 (LF diam. 60mm)

~95% beam transmission between F0 and F2
Outlook for Acculinna-2 @ U-400M cyclotron

2016 – new cabin, first run and zero angle spectrometer

2017/18 – RF kicker at F3 and radiation shell at F1-F2

2019 – a new cryogenic gas-vacuum system at F5 (including liquid tritium target)

2020/22 – cyclotron upgrade:

\[ E_{HI} \sim 60\div80 \text{ AMeV}, \]
\[ 2 < Z_{HI} < 36, \]
\[ I \sim 1\div3 \text{ p\mu A} \]

Since 2020 – R&D works aimed on the storage rings physics

\( E_{\text{RIB}} \sim 10 \text{ AMeV}; \ E_e \sim 500 \text{ MeV} \)
### RF-kicker

«Radio Frequency Fragment Separator at NSCL»

**Purification ~ 50 - 100**

---

**factor ~ 20**

<table>
<thead>
<tr>
<th></th>
<th>ACC FLNR - JINR</th>
<th>ACC-2</th>
<th>LISE3 GANIL</th>
<th>$^{a}$A1900 MSU - NSCL</th>
<th>$^{a}$ARIS</th>
<th>RIPS RIKEN</th>
<th>$^{a}$BigRIPS</th>
<th>FRS GSI - FAIR</th>
<th>$^{a}$SuperFRS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \Omega$</td>
<td>msr</td>
<td>0.9</td>
<td>5.8</td>
<td>1.0</td>
<td>8.0</td>
<td>8.0</td>
<td>5.0</td>
<td>8.0</td>
<td>0.32</td>
</tr>
<tr>
<td>$\delta P$</td>
<td>%</td>
<td>2.5</td>
<td>6.0</td>
<td>5.0</td>
<td>5.5</td>
<td>5.5</td>
<td>6.0</td>
<td>6.0</td>
<td>2.0</td>
</tr>
<tr>
<td>$P/\Delta P$</td>
<td>1000</td>
<td>2000</td>
<td>2200</td>
<td>2915</td>
<td>4000</td>
<td>1500</td>
<td>3300</td>
<td>8600</td>
<td>3050</td>
</tr>
<tr>
<td>$B_{\rho \text{max}}$</td>
<td>Tm</td>
<td>3.2</td>
<td>3.9</td>
<td>3.2-4.3</td>
<td>6.0</td>
<td>8.0</td>
<td>5.76</td>
<td>9.0</td>
<td>18</td>
</tr>
<tr>
<td>Lengths</td>
<td>m</td>
<td>21</td>
<td>38</td>
<td>19(42)</td>
<td>55</td>
<td>70</td>
<td>21</td>
<td>77</td>
<td>74</td>
</tr>
<tr>
<td>$E_{\text{min}}$</td>
<td>10</td>
<td>5</td>
<td>40</td>
<td>90</td>
<td>100</td>
<td>50</td>
<td>100</td>
<td>220</td>
<td>300</td>
</tr>
<tr>
<td>$E_{\text{max}}$</td>
<td>40</td>
<td>50</td>
<td>80</td>
<td>160</td>
<td>300</td>
<td>90</td>
<td>350</td>
<td>1000</td>
<td>1500</td>
</tr>
</tbody>
</table>

---

$\sim 10$ via primary beam energy increase
Estimated parameters of several radioactive beams depending on a primary beam energy for Acculinna-2 @ U400M

<table>
<thead>
<tr>
<th>Primary beam</th>
<th>Energy MeV/nucl</th>
<th>RIB</th>
<th>Intensity 1/s</th>
<th>Energy MeV/nucl</th>
<th>Purity %</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{11}$B</td>
<td>34</td>
<td>$^8$He</td>
<td>$3 \times 10^5$</td>
<td>25</td>
<td>99</td>
</tr>
<tr>
<td>$^{11}$B</td>
<td>56</td>
<td>$^8$He</td>
<td>$5 \times 10^6$</td>
<td>35</td>
<td>99</td>
</tr>
<tr>
<td>$^{15}$N</td>
<td>47</td>
<td>$^{11}$Li</td>
<td>$8 \times 10^4$</td>
<td>35</td>
<td>40</td>
</tr>
<tr>
<td>$^{15}$N</td>
<td>67</td>
<td>$^{11}$Li</td>
<td>$1 \times 10^6$</td>
<td>49</td>
<td>90</td>
</tr>
<tr>
<td>$^{18}$O</td>
<td>33</td>
<td>$^{14}$Be</td>
<td>$6 \times 10^3$</td>
<td>28</td>
<td>30</td>
</tr>
<tr>
<td>$^{18}$O</td>
<td>50</td>
<td>$^{14}$Be</td>
<td>$1 \times 10^5$</td>
<td>35</td>
<td>70</td>
</tr>
<tr>
<td>$^{36}$S</td>
<td>33</td>
<td>$^{24}$O</td>
<td>20</td>
<td>20</td>
<td>0.1</td>
</tr>
<tr>
<td>$^{36}$S</td>
<td>64</td>
<td>$^{24}$O</td>
<td>300</td>
<td>43</td>
<td>1</td>
</tr>
<tr>
<td>$^{16}$O</td>
<td>42</td>
<td>$^{13}$O</td>
<td>$7 \times 10^5$</td>
<td>25</td>
<td>2</td>
</tr>
<tr>
<td>$^{16}$O</td>
<td>62</td>
<td>$^{13}$O</td>
<td>$7 \times 10^6$</td>
<td>37</td>
<td>10</td>
</tr>
</tbody>
</table>
Where we are? What we could propose?

Advantages: tritium target, intermediate RIB energies (10-50 AMeV), sufficient beam time; 1n, 2n transfer and charge-exchange reactions.

Status of researches for the light exotic nuclei near drip-lines. The following properties are foreseen to be studied for the isotopes: halo structure (green), 2p and 2n emitters (red), 4p and 4n emitters (blue). (here closed shells for neutrons or protons are shown by dotted lines)
## Acculina-2 ‘shopping list’

<table>
<thead>
<tr>
<th>Product name</th>
<th>Product name</th>
<th>Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>$^{23}\text{Si}$</strong> : $P(\beta^3\text{He})$ – yes/no/limit</td>
<td>$T_{\text{min}}$ U400M</td>
<td>Prim. beam, E, I</td>
</tr>
<tr>
<td>$^{26}\text{S}$ : observation, states</td>
<td>One week</td>
<td>$^{32}\text{S}$, 52 AMeV, 0.2 – 0.5 pμA</td>
</tr>
<tr>
<td>$^{17}\text{Ne}$ : 2p decay for $3/2^-$ state</td>
<td>Two weeks</td>
<td>$^{20}\text{Ne}$, 54 AMeV, 1.0 pμA</td>
</tr>
<tr>
<td>$^{7}\text{H}$ : observation, states, 4n decay</td>
<td></td>
<td>$^{15}\text{N}$, 48 AMeV, 1.0 pμA</td>
</tr>
<tr>
<td>$^{10}\text{Li}$ : E and $\Gamma$ for ground state</td>
<td></td>
<td>$p(^{18}\text{Ne},d)^{17}\text{Ne}^*$ combined mass, zero angle spec.</td>
</tr>
<tr>
<td>$^{10}\text{He}$ :</td>
<td></td>
<td>$d(^9\text{Li},p)^{10}\text{Li}$ combined mass</td>
</tr>
<tr>
<td>$^{11}\text{Li}$ :</td>
<td></td>
<td>$t(^8\text{He},p)^{10}\text{He}$ tritium target, neutron array</td>
</tr>
<tr>
<td>$^{16}\text{Be}$ :</td>
<td></td>
<td>$t(^9\text{Li},p)^{11}\text{Li}$ neutron array</td>
</tr>
</tbody>
</table>

- $^{23}\text{Si}$ : $P(\beta^3\text{He})$ – yes/no/limit
- $^{26}\text{S}$ : observation, states
- $^{17}\text{Ne}$ : 2p decay for $3/2^-$ state, $\Gamma_{2p}/\Gamma_{\gamma} \to 0.0002\%$
- $^{7}\text{H}$ : observation, states, 4n decay
- $^{10}\text{Li}$ : E and $\Gamma$ for ground state
- $^{10}\text{He}$ : $E, \Gamma, J^\pi$ of excited states, search for exotic decays – n, 2n, 4n
- $^{11}\text{Li}$ : search for exotic decays – n, 2n, 4n
- $^{16}\text{Be}$ : $E, \Gamma, J^\pi$ of excited states, search for exotic decays – n, 2n, 4n
### Acculina-2 ‘shopping list’

<table>
<thead>
<tr>
<th>Product name</th>
<th>$T_{\text{min}}$ U400M</th>
<th>Prim. beam, E, I</th>
<th>Method, equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{23}\text{Si}$ : $P(\beta^3\text{He})$ – yes/no/limit</td>
<td>One week</td>
<td>$^{32}\text{S}$, 52 AMeV, 0.2 – 0.5 pμA</td>
<td>OTPC technic $p^{(28}\text{S},t)^{26}\text{S}$ missing mass</td>
</tr>
<tr>
<td>$^{26}\text{S}$ : observation, states</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{17}\text{Ne}$ : 2p decay for 3/2⁻ state</td>
<td>Two weeks</td>
<td>$^{20}\text{Ne}$, 54 AMeV, 1.0 pμA</td>
<td>$p^{(18}\text{Ne},d)^{17}\text{Ne}^*$ combined mass, zero angle spec.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$^{15}\text{N}$, 48 AMeV, 1.0 pμA</td>
<td>$d^{(9}\text{Li},p)^{10}\text{Li}$ combined mass</td>
</tr>
<tr>
<td>$^{7}\text{H}$ : observation, states, 4n decay</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{10}\text{Li}$ : E and $\Gamma$ for ground state</td>
<td>Three or more weeks</td>
<td>$^{11}\text{B}$, 34 AMeV, 4.0 pμA</td>
<td>$t^{(8}\text{He},p)^{10}\text{He}$ ttritium target, neutron array</td>
</tr>
<tr>
<td>$^{11}\text{Li}$ : $E$, $\Gamma$, $J^\pi$ of excited states, search for exotic decays – n, 2n, 4n</td>
<td></td>
<td></td>
<td>$t^{(9}\text{Li},p)^{11}\text{Li}$</td>
</tr>
<tr>
<td>$^{16}\text{Be}$ :</td>
<td></td>
<td></td>
<td>$t^{(14}\text{Be},p)^{16}\text{Be}$</td>
</tr>
</tbody>
</table>
**7H puzzle:** different methods => only limits

*Life time estimation in the case of 4n emission & exp. limits for 7H: $T_{1/2} < 1$ ns, $E(t+4n) \sim 50-100$ keV.*

Golovkov et al.
PLB 588 (2004) 163

---

Golovkov et al.,
EXON-2006 p.32

Fortier et al.,
EXON-2006 p.3

Korsh. et al.,
PRL 90(2003)
Two possible ways are foreseen:

i) crucial force with intense $^8$He for $d(^8$He,$^3$He)$_7^7$H and $p(^8$He,$pp$)$_7^7$H reactions

ii) reactions with $^{11}$Li projectile, namely QFS on $^4$He target or $^4$He transfer
Solving the $^7$H problem with zero angle spectrometer, one should explore also the full potential of the $^2$H($^8$He, $^3$He)$^7$H and $^4$He($^{11}$Li, 2$\alpha$)$^7$H reactions.

Note that the limit achieved before for the $^2$H($^8$He, $^3$He)$^7$H reaction makes $30 \, \mu b/sr$.
Real will be to reach a cross-section limit $d\sigma/d\Omega = 1 \, \mu b/sr$.
Trend towards the so low cross section limit is justified because the relatively compact configuration inherent to $^8$He hinders the formation of the $^7$H structure assumed to be huge in its dimensions.

Suggestion has been put forward to try $^{11}$Li as the source nucleus for the $^7$H production.
The enormously big two-neutron halo of $^{11}$Li might be a positive factor in that case.
Search for $^7$H in the reaction of quasi-free scattering $^4$He($^{11}$Li,2$\alpha$)$^7$H

Schemes of QFS: initial (a) and final (b) states prescription

$I(^{11}$Li $@ ~30$ AMeV) $\sim$ $10^4$ pps $\Rightarrow$ $\sim 200$ $^7$H events / day at $E_T = 2$ MeV

Complete MC simulation of the experiment
**26S in 2011:** search via implantation method

**NNDC:** $T_{1/2} \sim 10$ ms
**Acculinna:** $ToF_{F_1-F_4} \sim 0.0003$ ms

**Experiment:**
$T_{1/2} < 79$ ns, $Q_{2p} > 640$ keV

*Fomichev et al.,* IJMP E20 (2011) 1491

Acculinna-2:
missing mass for $p(^{28}S,t)^{26}S$
$I(^{28}S) \sim 10^3$ pps, $P \sim 12\%$, $E \sim 38$ MeV/A,
1 mm liquid $H_2$, $\sigma \sim 200 \mu b/sr$ =>
~ 10 events $^{26}S$ per week

---

**Graph:**

- **Yields** vs $Q_{reaction}$ (MeV)
- **E, AMeV**
- **26S - via spectrometer**
- **ttritons**

$p(^{28}S,t)^{26}S$
Search for the $2p$ radioactive decay of $^{26}$S in the $p(^{28}$S,$t)^{26}$S reaction

- The $2p$ decay of $^{26}$S will be measured in-flight using the zero-degree spectrometer.
- Decay energy will be measured with around 50 keV resolution.
- Measurable will be decay time in a range of 0.1 – 30 ns.
$^{23}\text{Si}$: $\beta$ delayed $^3\text{He}$ emission with the use OTPC

$^{32}\text{S} (@52 \text{ AMeV, 100 pnA}) \rightarrow 8 \text{ pps} \ ^{23}\text{Si} \ (T_{1/2} = 42.3 \text{ ms})$

"... $^{23}\text{Si}$ has an open channel for the $\beta$ delayed $^3\text{He}$ emission - never seen before. Moreover, this channel should be relatively easy to see, because the $\beta$-alpha decay leads to the unbound $^{19}\text{Na}.$"

Proposed by M. Pfützner et al.
T-company

$^{10}\text{He} \text{ @ Acc1: } ^3\text{H}(^8\text{He},p)^{10}\text{He}$

\[ E_T \sim 2.1 \pm 0.2 \text{ MeV} \quad 4.5 < E_T < 6 \text{ MeV} \quad E_T > 6 \text{ MeV} \]
\[ \Gamma \sim 2.0 \text{ MeV} \quad J^\pi = 1^- \quad J^\pi = 2^+ \]

$^{16}\text{Be} \text{ @ Acc2: } ^3\text{H}(^{14}\text{Be},p)^{16}\text{Be}$

\[ Q_{2n} = 1.35 \]

PRL 108, 102501 (2012) First observation of g.s. dineutron decay: $^{16}\text{Be}$.
“Acculinna-2” will be put into operation in 2016 and first experiments with RIBs will be possible (\(^7\)H, \(^{16}\)Be, \(^{26}\)S etc).

The scientific program implies an extensive use of advantages of intermediate RIB energies (E\textasciitilde10-50 MeV/nucleon) and additional equipment (zero angle spectrometer, RF-kicker, cryogenic gaseous targets including tritium) for the study of exotic nuclei with Z\textless=36.

Intense radioactive beams available at the new facility (especially after U-400M cyclotron upgrade) will allow us to do world level experiments.

Next step of the facility development is foreseen. It will include the complex of modern technique (gas catcher, RFQ ion guide, cooling trap, charge breeder and LINAC) needed for RIB injection into a storage ring.

Summary and outlook
“Acculina-2” will be put into operation in 2016 and first experiments with RIBs will be possible (\(^7\)H, \(^{16}\)Be, \(^{26}\)S etc). The scientific program implies an extensive use of advantages of intermediate RIB energies (E~10-50 MeV/nucleon) and additional equipment (zero angle spectrometer, RF-kicker, cryogenic gaseous targets including tritium) for the study of exotic nuclei with Z≤36.

Intense radioactive beams available at the new facility (especially after U-400M cyclotron upgrade) will allow us to do world level experiments.

Next step of the facility development is foreseen. It will include the complex of modern technique (gas catcher, RFQ ion guide, cooling trap, charge breeder and LINAC) needed for RIB injection into a storage ring.
$^{10}$Li excitation spectrum is being considered to be the subject of the first-day experiment at Acculinna-2.

Two papers showing new experimental results of the $^{10}$Li study were published in 2015:


$^{10}$Li reconstructed excitation energy from the d($^{9}$Li,p)$^{10}$Li reaction at 11 AMeV.

Fit made with three states at 110 ±40, 500 ±100, and 1100 ±100keV decay energy.
$^9$Li ($\sim 25$ AMeV, $I \sim 10^5$ 1/s) + $D_2$ ($\sim 0.5$ mm @ 20K) $\Rightarrow 10^\text{Li} + p$

i) conditions of cinematically completed measurements ($p$-$n$ coincidences) could provide high energy resolution for the $^{10}\text{Li}^*$ spectrum $\delta E \sim 200$ keV (FWHM);

ii) relative contribution of s-wave and p-wave components will be defined even in the case of the levels overlap (as a result of sufficient statistics and data analysis of the angular correlations).
**$^17\text{Ne}$**

- **$^{15}\text{O}(2p,\gamma)^{17}\text{Ne}$** astrophysical appl.
  - $3/2^-$ at 1288 keV, $Q_{2p} = 344$ keV

- **$^{18}\text{Ne}(t)^{16}\text{Ne}$**
  - Level structure of $^{16}\text{Ne}$ (by product)

**ACCULINNA-2 advantages:**
- $^{18}\text{Ne}$ RIB quality and zero angle spectrometer

---

**Graphs and Data:***

- **MSU PRC66,024313(2002)** $\Gamma_{2p}/\Gamma_\gamma < 0.77\%$
- **FLNR EXON2014 Proc., p.171** $\Gamma_{2p}/\Gamma_\gamma < 0.025\%$
- **Theory PRC76,014008(2007)** $\Gamma_{2p}/\Gamma_\gamma \sim 0.0002\%$

---

**Diagram Details:**
- $^{18}\text{Ne} + ^1\text{H} \rightarrow ^{17}\text{Ne} + d$
- $^{18}\text{Ne} + ^1\text{H} \rightarrow ^{16}\text{Ne} + t$
Long term plan with RIBs

RIB injection in a storage ring

beam bunch
every 10 – 300 ms

Since 2020:
R&D for RIB injection system
Conceptual project of the HI-electrons rings complex


Acc-2 Gas  RFQ  Trap  ESIS
catcher  ion guide  ion cooling  charge breeder

LINAC
E >10 MeV/n

RIB injection

RIB injection in
a storage ring

~30 MeV/n  30 keV  10 keV/n

Acc-2

Gas
catcher

RFQ
ion
guide

Trap
ion
cooling

ESIS
charge
breeder

LINAC
E >10 MeV/n

beam bunch
every 10 – 300 ms

Acc-2

Gas
catcher

RFQ
ion
guide

Trap
ion
cooling

ESIS
charge
breeder

LINAC
E >10 MeV/n

beam bunch
every 10 – 300 ms

Since 2020:
R&D for RIB injection system
Conceptual project of the HI-electrons rings complex


Acc-2 Gas  RFQ  Trap  ESIS
catcher  ion guide  ion cooling  charge breeder

LINAC
E >10 MeV/n

beam bunch
every 10 – 300 ms

Since 2020:
R&D for RIB injection system
Conceptual project of the HI-electrons rings complex
$^5$H structure with the use $t + T$

$E_T(J^\pi = 1/2^+) = 1.8$ MeV
$E_T(J^\pi = 3/2^+, 5/2^+) \sim 4.5 - 5.0$ MeV

M.S. Golovkov et al., PRC 76, 021605(R) (2007)