Experiments with RIBs at ACCULINNA-1 and ACCULINNA-2 fragment separators

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Feb. 2018, ACC-1. β-delayed particle emission of $^{11}\text{Be}$ ($T_{1/2} = 13.76$ s) was studied. The other isotopes, $^8\text{Li}$ ($T_{1/2} = 0.84$ s), $^8\text{B}$ ($T_{1/2} = 0.77$ s) and $^9\text{C}$ ($T_{1/2} = 0.126$ s), were used for the crosscheck measurements.

→ The method OTPC works well even in the case of long-lived nuclei.
→ New data with a good statistics were obtained for $^{11}\text{Be}$ and $^9\text{C}$.

Proposal has been done by Warsaw Univ.
Preliminary results: examples of $^9$C ($T_{1/2} = 0.126\, s$) and $^{11}$Be ($T_{1/2} = 13.76\, s$) decay

$^{11}$Be case ($\sim 10^3\, 1/s$): so-called “saturation mode”

Example of one events which contains 8 frames ($\Delta t \sim 600\, ms$)

$\alpha_1$, $\alpha_2$, $\alpha_3$

standard mode ($\Delta t \sim 0.5\, s$)

2s break needs to get rid from $^8$Li

$\beta$-delayed alpha emission: $P \sim 3\%$
First experiments with \(^6\)He and \(^9\)Li on CD\(_2\) target were carried out at ACC-2 in spring:
- elastic and inelastic scattering of \(^6\)He;
- \(d(\text{^6He,}^3\text{He})\text{^5H}\) reaction;
- \(d(\text{^9Li,}p)\text{^10Li} \rightarrow n + \text{^9Li}\) run.
ACCULINNA-2 provides a good quality of $^6$He and $^9$Li obtained in the $^{15}$N (49.7 AMeV) + Be (2 mm) reaction:

$I \sim 10^5$ pps @ 0.1 p$\mu$A & $\Delta p/p = 6\%$ (Be wedge 3 mm)

$P \sim 92\%$, $E \sim 25$ AMeV, beam spot $\sim 17$ mm (FWHM)
Preliminary results of elastic and inelastic scattering of $^6$He on $^2$H: $d\sigma/d\Omega$ in a wide angular range (4 runs, $\theta_{CM} \sim 30\div140^\circ$) with a good statistics.
\( d(\text{^6He,} \text{^3He})^\text{5H} \) reaction as a tool for the main run \( d(\text{^8He,} \text{^3He})^\text{7H} \)

i) \( \Delta E-E \) plot for low-energy \(^3\text{He} \) (E=8.5 ÷ 11.5 MeV) identification;

ii) coincidences between \(^3\text{He} \) and \(^3\text{H} \) (E= 117 ÷ 121 MeV);

iii) triggering for \(^3\text{He} \) moving forward at \( \theta_{\text{lab}} < 20 \) deg.

Preliminary results:

* \(^3\text{He} \) separation should be improved;

** several \(^3\text{He}-t \) coincidences/day;

*** 200 triggers/telescope @ 10^5 pps
Key points for 22 µSi:

- Thickness uniformity and energy resolution

Energy resolution:
~ 250 keV (~ 4%) for E_\(\alpha\) = 6.0 MeV

Thickness distr.:
from 19 µ up to 26 µ (instead of ±1.5 µ)

\(^{226}\)Ra source
Thickness correction for 22 $\mu$ Si will give us significant improvement in the identification plot.

Simulation of the ID-plot with energy resolutions: 250 keV for 22 $\mu$ Si and 50 keV for 1000 $\mu$ Si.
E. Nikolskii's simulations

$\mathrm{d}^\left({}^{8}\mathrm{He}, {}^{3}\mathrm{He}\right)^7\mathrm{H} \mathrm{g.s.} \left(\mathrm{E}^* = 0.5 \ \mathrm{MeV}\right)$ at 30 AMeV, cross sections by R. Wolski

- $\mathrm{D}_2$ gas target: 6 mm, 1 atm, 30K (2.96 x $10^{20}$ cm$^{-2}$), 6μ Fe foils
- Si- Telescope: 5x5 cm$^2$ dE(22 μ) + 6x6 cm$^2$ E(1mm), $I(\mathrm{^8He}) = 10^5$ s$^{-1}$

Counts / 1.5 MeV

$E_{t+4n}$ (MeV)

Resolution:
- $\sim 1.2_{\text{n.e.g.}}$
- 1.15, 1.28, 1.23

$\sim 5$ $^7\mathrm{H}$/day (two telescopes) @ 5 x $10^4$ $^8\mathrm{He}$/s $\rightarrow \sim 140$ $^7\mathrm{H}$ during 4 weeks
Energy & position:
decay tritons & RIB
$B_\rho = 0.4 \sim 1.0 \text{ Tm}$
Cone $0 \sim 14^\circ$

Neutrons,
Cone $0 \sim 14^\circ$

Advantages: good energy resolutions ($\sim 1.2 \text{ MeV}$) & $^3\text{He}$-t-n coins.

$d(^8\text{He},^3\text{He})^7\text{H}$: 7 weeks are requested (effect + background)
Moving ahead to the flagship experiment $^7H$
Moving ahead to the flagship experiment $^7\text{H}$

Radiation shell around $\text{F1-F2}$ area will be completed in July-August.
ACCULINNA-2 fragment separator commissioned in 2017 is now ready for day-one experiments.

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

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

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

Thanks for your attention
Energy resolution in the flagship experiment $^7H$

$d(^8\text{He},^3\text{He})^7\text{Hg.s.}(E^*=0.5\text{ MeV})$ at 30 AMeV, cross sections by R. Wolski

- $D_2$ gas target: 6 mm, 1 atm, 30K (2.96 x 10^{20} \text{ cm}^{-2}), 6\mu \text{ Fe foils}$
- Si- Telescope: $5 \times 5 \text{ cm}^2 \text{ dE(22 } \mu \text{ + 6\times6 cm}^2 \text{ E(1mm) dx=1.9 mm, dy=3.1 mm}$

**Contributions to resolution**

- **FWHM (MeV)** (E*=0.5 MeV)
  - $D_{\text{tel}} = 20 \text{ cm, } \Theta_{\text{lab}} = 15^\circ$
  - **Total** \~ $1.2 \text{ n.e.G.}$
  - **TOF** 0.05
  - **MWPCs** 0.124
  - **D2 empty** 0.071
  - **D2 gas** \~ $1.15 \text{ n.e.G. (flat)}$
  - **Si(dX_dY)** 0.121
  - **MS+Si_dX_dY** 0.620
  - **Si E-resolution** 0.282
**7H puzzle: each time only limits of σ were observed**

- \( p(^{8}\text{He}, pp)^7\text{H} \)
- \( E=61\ \text{AMeV} \)

- \( d(^{8}\text{He}, ^3\text{Het})^7\text{H} \)
- \( \sigma \sim 30 \mu \text{b/sr} \)

- \( d(^{8}\text{He}, ^3\text{He})^7\text{H} \)
- \( \sigma \sim 10 \mu \text{b/sr} \)

- \( E=25\ \text{AMeV} \)

- \( E=15.3\ \text{AMeV} \)

**Korsheninnikov et al., PRL 90(2003)**

**Nikolskii et al., PRC 81 (2010)**

**Caamaño et al. PRL 99(2007)**

\[ ^{12}\text{C}(^{8}\text{He}, ^{13}\text{N})^7\text{H} \implies E = 0.57^{+0.42}_{-0.21} \text{ MeV, } \Gamma = 0.09^{+0.94}_{-0.06} \text{ MeV} \]

**Drastically improvement of sensitivity in \( d(^{8}\text{He}, ^3\text{He})^7\text{H} \) or \( p(^{8}\text{He}, pp)^7\text{H} \)**

**\( ^{11}\text{Li} \) as a projectile and alpha transfer reaction \( d(^{11}\text{Li}, ^6\text{Li})^7\text{H} \)**
**ACC-2 @ U400M advantages:**

- Room temperature operating
- Relatively low cost beam time
- Runs during 3 and even more weeks are possible
- Cryogenic targets $^3$He, $^4$He and all hydrogen isotopes
- ToF length $\sim 15$ m

<table>
<thead>
<tr>
<th>Установка</th>
<th>ACC</th>
<th>ACC-2</th>
<th>COMBAS</th>
<th>LISE</th>
<th>A1900</th>
<th>RIPS</th>
<th>BigRIPS</th>
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<td>Институт</td>
<td>FLNR, JINR</td>
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<td>GANIL</td>
<td>MSU</td>
<td></td>
<td>RIKEN</td>
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<tr>
<td>$\Delta \Omega$, msr</td>
<td>0.9</td>
<td>5.8</td>
<td>6.4</td>
<td>1.0</td>
<td>8.0</td>
<td>5.0</td>
<td>8.0</td>
<td>0.32</td>
<td>5.0</td>
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<td>$\delta_P$, %</td>
<td>2.5</td>
<td>6.0</td>
<td>20</td>
<td>5.0</td>
<td>5.5</td>
<td>6.0</td>
<td>6.0</td>
<td>2.0</td>
<td>5.0</td>
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<tr>
<td>$p/\Delta p$, a.u.</td>
<td>1000</td>
<td>2000</td>
<td>4360</td>
<td>2200</td>
<td>2915</td>
<td>1500</td>
<td>3300</td>
<td>8600</td>
<td>3050</td>
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<tr>
<td>$Bp_{\text{max}}$, Tm</td>
<td>3.2</td>
<td>3.9</td>
<td>4.5</td>
<td>4.3</td>
<td>6.0</td>
<td>5.76</td>
<td>9.0</td>
<td>18</td>
<td>18</td>
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<tr>
<td>Length, m</td>
<td>21</td>
<td>38</td>
<td>14.5</td>
<td>42</td>
<td>35</td>
<td>21</td>
<td>77</td>
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<td>$E_{\text{min}}$, AMeV</td>
<td>10</td>
<td>5</td>
<td>20</td>
<td>40</td>
<td>110</td>
<td>50</td>
<td>350</td>
<td>220</td>
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<tr>
<td>$E_{\text{max}}$, AMeV</td>
<td>40</td>
<td>50</td>
<td>80</td>
<td>80</td>
<td>160</td>
<td>90</td>
<td>350</td>
<td>1000</td>
<td>1500</td>
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The $\beta$-decay properties of $^{11}$Be are summarised in Table 1. Of the several $\beta$-delayed particle channels that are opened in the decay of $^{11}$Be, only $\beta$-delayed $\alpha$ ($\beta\alpha$) emission was observed directly, with a branching ratio of about 3% [6, 7]. The knowledge of the branching ratio for $\beta\alpha$ emission is a crucial first step for success in the challenging direct measurement of $\beta p$ decay of $^{11}$Be that is planned later with the Optical Time Projection Chamber (see Section 2) [8]. The experimental approach of detecting $^{11}$Be delayed protons by means of the OTPC detector seems at present the most promising, since standard silicon detector arrays would suffer from the overwhelming electrons and noise background in the 200 keV energy region (the proton spectrum is expected to peak at about 180-200 keV). It is important to have not only a precise and accurate value for it, but also the same systematic uncertainty in the measurement, as can be achieved by using the same detection set-up.

Table 1: Decay properties of $^{11}$Be. Upper part: Q-value for $\beta$ decay, half-life and $\alpha$ and proton delayed emission probabilities. Lower part: Q-values for the opened $\beta$-delayed particle channels in the decay of $^{11}$Be and respective separation energies in the daughter nucleus $^{11}$B.

<table>
<thead>
<tr>
<th>$Q_{\beta}$ [keV]</th>
<th>$T_{1/2}$ [s]</th>
<th>$b_{\beta\alpha}$ 3.47(12)$^a$</th>
<th>$b_{\beta p}$ 8.3(9)$\cdot 10^{-6}$ $^b$</th>
</tr>
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<tbody>
<tr>
<td>11509.3(5)</td>
<td>13.81(8)</td>
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</table>

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<thead>
<tr>
<th>$S_x$($^{11}$B) [keV]</th>
<th>$Q_{\beta x}$ [keV] $^c$</th>
<th>p</th>
<th>n</th>
<th>$\alpha$</th>
<th>t</th>
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<tr>
<td>11228.6(4)</td>
<td>280.7(3)</td>
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<td>11454.12(16)</td>
<td>55.2(5)</td>
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<td>8664.1(4)</td>
<td>2845.1(2)</td>
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<td>11223.6(4)</td>
<td>285.7(2)</td>
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