Experimental studies using radioactive beams at European large-scale facilities

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European large-scale facilities:

<table>
<thead>
<tr>
<th></th>
<th>Facility</th>
<th>City</th>
<th>Country</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>CERN</td>
<td></td>
<td></td>
<td>Isolde and n_TOF CH ISOL+postacc., sec.neutrons</td>
</tr>
<tr>
<td>2.</td>
<td>CRC/UCL</td>
<td>Louvain-la-Neuve</td>
<td>B</td>
<td>ISOL+postacc.</td>
</tr>
<tr>
<td>3.</td>
<td>GANIL</td>
<td>Caen</td>
<td>F</td>
<td>fast sec. beams, ISOL+postacc.</td>
</tr>
<tr>
<td>4.</td>
<td>GSI</td>
<td>Darmstadt</td>
<td>D</td>
<td>fast sec. beams</td>
</tr>
<tr>
<td>5.</td>
<td>JYFL</td>
<td>Jyväskylä</td>
<td>FIN</td>
<td>IGISOL</td>
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<td>6.</td>
<td>KVI</td>
<td>Groningen</td>
<td>NL</td>
<td>fast stable beams</td>
</tr>
<tr>
<td>7.</td>
<td>LNL</td>
<td>Legnaro</td>
<td>I</td>
<td>stable beams</td>
</tr>
</tbody>
</table>
**General remarks:**
- there is no clear distinction between nuclear-structure research and nuclear-astrophysics studies;
- many activities at LSF to measure masses, half-lives, level schemes, spin assignments etc. with relevance for astrophysics not presented in this overview;
- overview is given by a non-specialist ➔ comments and clarifications welcome!

**Presentation of each facility:**
- overview over the facility, beams, equipment;
- summary of astro-related activities;
- presentation of selected example(s);
- future plans to be discussed in the round-table discussion.
1. CERN-ISOLDE

implantation and decay

radioactive ion beams

no astro activities so far with postaccelerated REX-ISOLDE beams

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### Astrophysical activities at CERN: ISOLDE

1. **Decay spectroscopy** of mass-separated nuclei to study level schemes
   e.g.: $^{12}\text{Be} \rightarrow \beta^- \rightarrow ^{12}\text{B} \rightarrow \beta^- \rightarrow ^{12}\text{C}^* \rightarrow \alpha\alpha\alpha$
   ➔ relevant for triple-α process

2. **Decay spectroscopy** ($\beta^-, \gamma-, \beta n$-decay) of mass-separated p- and n-rich nuclei to obtain $Q_\beta$-values, half-lives, $P_n$ values, and level schemes
   e.g. properties of $^{130}\text{Cd}, ^{129}\text{Ag}$ waiting points
   ➔ relevant for rp- and r-process path, isotopic anomalies

3. **ISOLTRAP mass measurements** of mass-separated nuclei
   ➔ relevant for r- and rp-process path
$^{12}$C from the $\beta$-decays of $^{12}$N and $^{12}$B

ISOLDE

JYFL

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Combined fit of $^{12}$B and $^{12}$N

1. Select 8Be 0+ channel
2. Divide by different detection efficiency
3. Divide by different $\beta$-phase space
4. Normalize

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Implications for the triple-α rate

interference of $0^+ @ 10$ MeV with Hoyle res.

no $2^+$ res. at 9.1 MeV
The n_TOF facility at CERN

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton beam momentum</td>
<td>20 GeV/c</td>
</tr>
<tr>
<td>Intensity (dedicated mode)</td>
<td>$7 \times 10^{12}$ protons/pulse</td>
</tr>
<tr>
<td>Repetition frequency</td>
<td>1 pulse/2.4s</td>
</tr>
<tr>
<td>Pulse width</td>
<td>6 ns (rms)</td>
</tr>
<tr>
<td>n/p</td>
<td>300</td>
</tr>
<tr>
<td>Lead target dimensions</td>
<td>80x80x60 cm$^3$</td>
</tr>
<tr>
<td>Cooling &amp; moderation material</td>
<td>H$_2$O</td>
</tr>
<tr>
<td>Moderator thickness in the exit face</td>
<td>5 cm</td>
</tr>
<tr>
<td>Neutron beam dimension in EAR-1 (capture mode)</td>
<td>2 cm (FWHM)</td>
</tr>
</tbody>
</table>

www.cern.ch/n_TOF
n_TOF beam

Neutron intensity

Monte Carlo Simulation
- $^{235}$U(n,f) with PPACs
- $^{238}$U(n,f) with PPACs
- $^{235}$U(n,f) with PTB ionisation chamber
- $^{238}$U(n,f) with PTB ionisation chamber
- $^6$Li(n,a) Silicon Flux Monitor 2001
- $^6$Li(n,a) Silicon Flux Monitor 2002
- $^{197}$Au(n,g) with $C_6D_6$ detectors
- $^{nat}$Fe(n,g) with $C_6D_6$ detectors

$\frac{dN}{dlnE} / 7 \times 10^{14}$ protons

$E_n$ (eV)
<table>
<thead>
<tr>
<th>Target</th>
<th>Motivations &amp; Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{24,25,26}$Mg</td>
<td>Isotopic abundance ratios in stellar grains. Importance of $^{22}$Ne($\alpha$,n)$^{25}$Mg for the s-process neutron balance. Light nuclei, small cross sections.</td>
</tr>
<tr>
<td>$^{90,91,92,93,94,96}$Zr</td>
<td>s-process branching at A=95 &amp; observed abundance patterns in stellar grains. Sensitivity to neutron flux during the s-process. $^{93}$Zr($\tau_{1/2} = 1.5$ Myr) to be measured in 2004.</td>
</tr>
<tr>
<td>$^{139}$La</td>
<td>Bottleneck in the s-process flow. N=82 neutron shell closure.</td>
</tr>
<tr>
<td>$^{151}$Sm</td>
<td>s-process branching at A $\approx 150$. $^{151}$Sm is radioactive ($\tau_{1/2} = 93$ yr).</td>
</tr>
<tr>
<td>$^{186,187,188}$Os</td>
<td>Nuclear cosmochronology (Re/Os clock). s-process branching at A $\approx 185$.</td>
</tr>
<tr>
<td>$^{204,206,207,208}$Pb, $^{209}$Bi</td>
<td>Termination of the s-process. Small $\sigma_\gamma/\sigma_{el}$.</td>
</tr>
</tbody>
</table>
The s-process path at $^{151}\text{Sm}$

- $^{151}\text{Sm}$ is radioactive with a half-life of 93 years.
- The $\beta$-decay rate of $^{151}\text{Sm}$ depends on $T$.

- New cross section plus realistic s-process modelling can explain 71% of solar $^{152}\text{Gd}$ yield;
- Missing yield provided by p-process;
- Main uncertainty: $T$-dependent half-life of $^{151}\text{Sm}$.

$\text{MACS-30} = 3100 \pm 160 \text{ mb}$
2. The RIB facility at Louvain-la-Neuve

Production & acceleration of isobarically pure and intense low-energy radioactive ion beams – specially suitable for nuclear astrophysics

RIB intensities up to $5 \times 10^9$ pps on target

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Experimental equipment at CRC/UC Louvain-la-Neuve

\[ ^{7}\text{Be}(d,p)^{2}\alpha \]

(2-10) \times 10^6 /s

\(^{7}\text{Be}\) beam \( \rightarrow \) \( \alpha \) \( \rightarrow \) \( p \)

CD\(_2\) target

FC

Cup

(4-6) \times 10^6 /s

\(^{18}\text{F}\) beam

\( p \)

\( \alpha \)

LAMP

CD\(_2\) target

LED

\( ^{15}\text{N} \)

\( +40 \text{ cm} \)

\( -9 \text{ cm} \)

\[ d(^{18}\text{F},p\alpha)^{15}\text{N} \]

"LEDA" type

16 strips in \( \theta \)

300 \( \mu \text{m} \) or 500 \( \mu \text{m} \)

Solid angle: 10% of \( 4\pi \)

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ARES recoil separator at CRC/UC Louvain-la-Neuve

beam rejection factor: $5 \times 10^{-6} ... 5 \times 10^{-7}$

$E = 0.2 - 0.8 \text{ MeV/A, intense RIB (}10^8-10^{10}\text{ pps)}$

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Astrophysical activities at CRC/UC Louvain-la-Neuve
(non-exhaustive...)

1. Direct measurements of fusion reactions with radioactive beams
detected with ARES recoil separator
   e.g.: $^{19}\text{Ne}(p,\gamma)^{20}\text{Na}$
   ➔ relevant for hot-CNO→rp process

2. Direct measurements of fusion reactions with radioactive beams
detected in kinematic coincidences (LEDA,LAMP)
   e.g.: $^{18}\text{F}(p,a)^{15}\text{O}$
   ➔ relevant for γ-astronomy on $^{18}\text{F}$
   e.g.: $^{7}\text{Be}(d,p)^2\alpha$
   ➔ relevant for $^7\text{Li}$ abundance used as a baryometer

3. Elastic-scattering reactions with radioactive beams
   e.g.: $^{7}\text{Be}(p,p)^7\text{Be}$
   ➔ relevant for $^7\text{Be}(p,\gamma)^8\text{B}$

   etc.
BBN nuclear reactions affecting $^7\text{Li}$ production?

- About 100 other reactions involved in SBBN from H to B
- About 40 remain whose uncertainty on rate is not available
- Systematic check by varying the rates by factors of 10, 100, 1000.

An interesting case: $^7\text{Be}(d,p)2\alpha$

$^7\text{Li}/^7\text{H}$ vs. $\Omega_B h^2$

$t(\alpha,\gamma)^7\text{Li}$ and $^7\text{Li}(p,\alpha)\alpha$

$^3\text{He}(\alpha,\gamma)^7\text{Be}(n,p) \leq 30\%$

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$^7\text{Be}(d,p)^2\alpha$ S-factor measured at BBN energies

but: no solution for the $^7\text{Li}$ problem!
3. The GANIL/SPIRAL radioactive beam facility
### Examples of RIB at SPIRAL1/GANIL

<table>
<thead>
<tr>
<th>Primary beam</th>
<th>secondary beam</th>
<th>Max Intensity pps</th>
<th>Emin-Emax A.MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{16}$O</td>
<td>$^{15}$O</td>
<td>$3 \times 10^7$</td>
<td>4-25</td>
</tr>
<tr>
<td>$^{26}$Ne</td>
<td>$^{18}$Ne</td>
<td>$10^7$</td>
<td>3-20</td>
</tr>
<tr>
<td>$^{36}$Ar</td>
<td>$^{34}$Ar</td>
<td>$10^6$</td>
<td>4-12</td>
</tr>
<tr>
<td>$^{36}$Ar</td>
<td>$^{35}$Ar</td>
<td>$3 \times 10^7$</td>
<td>4-12</td>
</tr>
<tr>
<td>$^{48}$Ca</td>
<td>$^{44}$Ar</td>
<td>$2 \times 10^5$</td>
<td>4-11</td>
</tr>
<tr>
<td>$^{48}$Ca</td>
<td>$^{46}$Ar</td>
<td>$2 \times 10^4$</td>
<td>4-11</td>
</tr>
</tbody>
</table>

He, Na, Kr beams…

Production of post-accelerated secondary beams:
- optical quality similar to primary beams
- used in existing experimental areas

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Astrophysical activities at GANIL

1. Decay spectroscopy ($\beta^-, \gamma^-, \beta n$-decay) of stopped nuclei after in-flight separation
   ➔ $Q_\beta$-values, half-lives, $P_n$ values, level schemes ....
   e.g. nuclear structure around $N=28$
   ➔ relevant for $r$-process, isotopic anomalies

2. Study of $(n,\gamma)$ cross sections on unstable isotopes via HI(d,p)
   e.g. $^{40,44,46}$Ar(d,p)
   ➔ relevant for $r$-process, isotopic anomalies

3. Study of fusion reactions via resonant elastic scattering (RES)
   e.g. $^{18}$F+p→$^{19}$Na*→$^{18}$F+p, $^{15}$O+α→$^{19}$Ne*→$^{15}$O+α
   ➔ relevant for hot CNO→rp-process
(d,p) reactions with $^{40,44,46}$Ar beams

$^{40,44,46}$Ar
11A.MeV

GANIL/SPIRAL

170°

CD$_2$
380$\mu$g.cm$^{-2}$

SPEG

10cm.

41,45,47Ar

Identification detectors

BEAM: ~ parallel optics (Angular aperture < 2mrad; $\phi = 2$ cm)

MUST: - Si Strip detector.
- Proton impact localisation.
- Proton energy measurement.

- 60mm x 60mm.
- X,Y resolution: 1 mm.
- Intrinsic resolution: 50 KeV.

CATS: - gas filled beam-tracking detector
- Proton emission point.

- 70mm x 70 mm.
- X,Y resolution: ~0.6 mm.

SPEG: Energy loss spectrometer: recoil ion identification (background suppression)
$^{18}\text{F}(p,\alpha)^{15}\text{O}$ studied via $^{15}\text{O}+\alpha$ RES

$^{18}\text{F} + p \rightarrow ^{15}\text{O} + \alpha$

Destruction of $^{18}\text{F}$ in novae

Use of $^{15}\text{O} + \alpha \rightarrow ^{19}\text{Ne}^* \rightarrow ^{15}\text{O} + \alpha$ RES

$^{15}\text{O}$ beam from SPIRAL
$E/A = 1.74 \text{ MeV}$
$I > 10^7 /s$

run in April 2005

$J^\pi = 5/2^+$

$J^\pi = 3/2^-$

$^{15}\text{O} + \alpha$ fed by RES

bound states

Stellar reaction

$E_\alpha$

$2.9 \text{ MeV}$
4. SIS/FRS at GSI as a radioactive beam facility

stable and secondary beams
100 < E/A < 1500 MeV

FRS: high-resolution zero-degree spectrometer
ALADIN: large-acceptance spectrometer
ESR: 11 Tm storage ring
Astrophysical activities at GSI

1. **Coulomb-dissociation** at relativistic energies
   - KaoS: \( A + Pb \rightarrow B + p + Pb \)
   - LAND: \( C + Pb \rightarrow D + n + Pb \)
   - relevant for pp and r-, p-process

2. **In-ring \( \beta \)-decay** of stored bare nuclei
   - e.g. bound-state \( \beta \)-decay of \( ^{163}\text{Dy} \) and \( ^{187}\text{Re} \)
   - relevant for s-process and cosmo-chronometer

3. Introduction of realistic fission-fragment distributions into r-process calculations
   - relevant for r-process
Coulomb-dissociation of $^8$B to study $^7$Be(p,γ)

Theory: P. Descouvemont's cluster model of $^8$B

Seattle (p,γ) data: $S_{17}(0) = 21.2 \pm 0.6 \pm 0.6 \text{ eV b}$

GSI-2 CD data: $S_{17}(0) = 20.6 \pm 1.3 \pm 1.5 \text{ eV b}$

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In-ring detection of bound-state $\beta$ decay ($^{187}\text{Re}^{75+}$)

stored $^{187}\text{Re}^{75+}$ ions $\approx 10^8$

'lifetime' $\approx 2.5$ hours

$^{187}\text{Os}^{75+}$ $\beta_b$-daughters/hour

$N_d = \lambda_{\beta_b} <N_m> \approx 200$

storage times: 0....5 hours

stripping off the electron of H-like $^{187}\text{Os}^{75+}$ in a $\text{N}_2$ gas jet ($10^{13}$ p/cm$^2$) switched-on for about 2 minutes

recording the bare $^{187}\text{Os}^{76+}$ ions as function of storage time

$\rightarrow T_{1/2}(^{187}\text{Re}^{75+}) = (33 \pm 2) \text{ yr}$

$T_{1/2}(^{187}\text{Re}^{0+}) = 42.5 \text{ Gyr}$

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Bound-state $\beta$-decay and branching points in the $s$-process: the case $^{163}$Dy/$^{163}$Ho

$s$-process at $T_s \approx 30$ keV:
- pathwya determined by:
  - neutron flux $n_n$,
  - n-capture cross-sections $\rho_e$,
  - $\beta^-$ decay probabilities $\lambda$

branching points:
- for $\lambda \neq \lambda$ ($T_s$) $\rightarrow n_n$
- for $\lambda = \lambda$ ($T_s$) $\rightarrow T_s, \rho_e$

from Dy-, Ho-, and Er- abundances and from $\lambda_{\beta b} (^{163}$Dy$^{66+}) = 1.72 \times 10^{-7}$ s$^{-1}$
→ at the $A = 163$ branching point*: $T_s = (3.3 \pm 0.5) \times 10^8$ K; $\rho_e = (3.9 \pm 2) \times 10^{27}$ cm$^{-3}$

Fission plays an important role in the r-process ⇒
- yields of transuranium isotopes and age of the universe
- may have a strong influence on the formation of the majority of heavy nuclei due to fission recycling
- r-process end point
- $\nu$-induced fission is irrelevant for r-process progenitors in the mass range $A \sim 200-215$, but becomes more and more important with increasing mass number.  
- The calculated mass and charge distributions show pronounced peaks coming from symmetric and asymmetric fission. These peaks are in agreement with patterns observed in the r-process abundance distributions in metal-poor stars at mass numbers $A \sim 90$ and $\sim 135$. 

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5. JYFL Accelerator Laboratory @ Jyväskylä

K130 MeV Cyclotron
ECR & light-ion sources
IGISOL
RITU

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IGISOL floor plan

Ion Guide
Stopping in gas → mostly 1+
Fast, universal
Refractories

RFQ

Nuclear Spectroscopy

Laser Spectroscopy

Ion Guide Technique
• Fission reaction
• Light-ion reactions
• Heavy-ion fusion reactions
• Transfer reactions
• Singly charged DC beam @ 40 kV
• Energy spread even 100 eV → cooling and bunching in RFQ

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Astrophysical activities at JYFL/IGISOL

1. **Decay spectroscopy** ($\gamma$, $\beta p$, $\beta \alpha$-decay) of mass-separated nuclei to study level schemes/resonance strengths
   
   e.g.: $^{12}\text{N} \rightarrow \beta^+ \rightarrow ^{12}\text{C}^* \rightarrow \alpha\alpha$
   
   $\Rightarrow$ relevant for triple-$\alpha$ process
   
   e.g.: $^{23}\text{Al} \rightarrow \beta\gamma/\beta p \rightarrow ^{23}\text{Mg}$ to study $^{22}\text{Na}(p,\gamma)^{23}\text{Mg}$
   $^{31}\text{Cl} \rightarrow \beta\gamma/\beta p \rightarrow ^{31}\text{S}$ to study $^{30}\text{P}(p,\gamma)^{31}\text{S}$
   
   $\Rightarrow$ relevant for nova nucleosynthesis

2. **Decay spectroscopy** ($\gamma$-decay, $\beta n$-decay) of mass-separated n-rich nuclei to obtain half-lives and $P_n$ values
   
   $\Rightarrow$ relevant for extrapolation to r-process path

3. **Mass measurements in JYFLTRAP** of short-lived fission products
   
   $\Rightarrow$ relevant for extrapolation to r-process path
BREAKOUT OF THE NeNa CYCLE THROUGH THE $^{22}\text{Na}(p,\gamma)^{23}\text{Mg}$ CAPTURE REACTION STUDIED BY BETA DECAY OF $^{23}\text{Al}$

$t_{1/2} = 470(30)\text{ ms}$

$Q_{EC} = 12.240(25)\text{ MeV}$

Beta-delayed protons and gammas observed in the $\beta$ decay of $^{23}$Al

6. The AGOR + BBS facility at KVI

Big Bite Spectrometer (BBS):
- \( \text{dp/p} = \pm 9.5\% \)
- focal plane detectors: 4\( \pi \) coverage, particle id
- high resolution: FWHM = 90 keV

AGOR cyclotron (K=600):
- light and medium-heavy stable beams
- plus tritium beams (2\( \times \)10\(^7\)/s)
- E/A < 90 MeV/nucleon
Astrophysical activities at KVI

1. **Transfer reactions** in inverse kinematics
   e.g.: $p(^{21}\text{Ne},t)^{19}\text{Ne}$ to study $^{15}\text{O}(a,\gamma)^{19}\text{Ne}$
   $p(^{24}\text{Mg},t)^{22}\text{Mg}$ to study $^{21}\text{Na}(p,\gamma)^{22}\text{Mg}$
   → relevant for hot CNO→rp process

2. Probing $GT^+$ strength with $\text{HI}(d,^2\text{He})$
   high resolution data!
   → relevant for EC in supernova
Studying $^{15}\text{O}(\alpha,\gamma)^{19}\text{Ne}$ via $p(^{21}\text{Ne},t)^{19}\text{Ne}$ at KVI

$\alpha$-branching is very small: $^{15}\text{O}(\alpha,\gamma)^{19}\text{Ne}$ is too slow to feed the rp process

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Studying EC on $^{58}$Ni via $^{58}$Ni(d,${}^2$He)$^{58}$Co at KVI

Strong influence of GT strength on calculated EC rate!
Conclusions,
Topics to be discussed

- Contributions to astrophysics from all methods available (ISOL, ISOL+postacceleration, fast fragmentation);

- High degree of networking! (Nuclear theory, stellar theory, and Improvements? experiment)

- Competitive instrumentation? (Recoil separator, Si arrays,...) Combine forces?

- Small-scale vs. large-scale facilities?

- Future developments at LSF? REX-ISOLDE, n_TOF, SPIRAL-II, FAIR.....
Special thanks to ..... 

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• Ari Jokinen, JYFL;
• Ad van den Berg, KVI.