Design and test of an Accelerator Driven Neutron Activator at the Joint Research Centre of the European Commission

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Outline

- ARC concept and previous experiments
- Motivation – the INBARCA project
- New design for an ARC neutron activator
- Installation and preliminary results
- Concluding remarks
Adiabatic Resonance Crossing (ARC) concept

- ARC was introduced by C. Rubbia for transmutation and radioisotope production (by neutron capture)
- The ARC method consists of moderating neutrons in lead
- Pb has the lowest capture cross section in the fast neutron field

- In Pb fast neutrons are moderated in small energy degradation steps therefore neutron capture in the epithermal range (resonance range) is enhanced
Use of ARC Concept for Transmutation or Radioisotope Production

1 - Fast neutrons are generated in a target bombarded with accelerated charged particles

2 - Then they are incrementally slowed by scattering with relatively little energy absorption in lead down to the resonance energy range of the material to be transmuted

3 - Finally, they are captured in the material to be transmuted (neutron captures take place)
Transmutation by Adiabatic Resonance Crossing (TARC) Experiment at CERN (1996-1999)

1 - Facility installed in the CERN PS proton beam line

2 - Neutrons produced by spallation with proton beam (2.5-3.5 GeV)

3 - Neutrons slowed down in Lead (3.3 m x 3.3 m x 3 m, ~334 tons)

4 - TARC Conclusions:
   - ARC can be used to transmute large amounts of $^{99}$Tc or $^{129}$I (long lived f. products)
   - ARC can be used as an alternative method (alternative to nuclear reactors) for radioisotope production for medical or other applications
ARC experiment at the Cyclotron of Louvain-La-Neuve (Belgium)

1 – Aim: Feasibility study for industrial production of $^{99}$Mo (generator of $^{99m}$Tc) and $^{125}$I using the ARC concept in a cyclotron (University of Louvain)

2 – Neutron generated by proton beam (65-75 MeV) bombarding Be target

3 – Neutron slowing down in pure lead (1.6 m x 1.6 m x 1.63 m, 47 tons)

4 – Conclusion: The results were very encouraging and seem to confirm that the ARC concept can be used for radioisotope production for nuclear medicine
Aim of the current project
- partially funded by the EUREKA programme, project INBARCA -
(Innovative Nanosphere Brachytherapy by Adiabatic Resonance Crossing with Accelerators)

1 – Test of a new ARC design concept at low energy (Cyclotron)

2 – Measurement of activation yields and validation of MC calculations

3 – Activation of nanoparticles for Brachytherapy (Ho and Re)

4 – Investigation of other potential uses (other radioisotopes, activation of nanoparticles for tracer studies, etc.)
List of radioisotopes used in brachytherapy (in black) and the ones proposed in this project (in red)

<table>
<thead>
<tr>
<th>Radioisotope</th>
<th>Symbol</th>
<th>$T_{1/2} \text{ (h)}$</th>
<th>Decay mode</th>
<th>Mean energy</th>
<th>Current production method</th>
<th>Main applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>125-Iodine</td>
<td>$^{125}\text{I}$</td>
<td>1425.6</td>
<td>$\epsilon$</td>
<td>35 keV</td>
<td>Reactor</td>
<td>Prostate cancer</td>
</tr>
<tr>
<td>103-Palladium</td>
<td>$^{103}\text{Pd}$</td>
<td>407.76</td>
<td>ec</td>
<td>21 keV</td>
<td>Reactor &amp; Accelerator</td>
<td>Prostate cancer</td>
</tr>
<tr>
<td>90g-Yttrium</td>
<td>$^{90}\text{Y}$</td>
<td>64.104</td>
<td>$\beta^-$</td>
<td>930 keV</td>
<td>Reactor</td>
<td>Live cancer</td>
</tr>
<tr>
<td>192g-Iridium</td>
<td>$^{192}\text{Ir}$</td>
<td>1771.92</td>
<td>$\beta^-\text{(95.24%)}$</td>
<td>317 keV</td>
<td>Reactor</td>
<td>HDR brachytherapy</td>
</tr>
<tr>
<td>188g-Rhenium</td>
<td>$^{188}\text{Re}$</td>
<td>16.98</td>
<td>$\beta^-$</td>
<td>2 MeV</td>
<td>Reactor</td>
<td>Bone cancer, rheumatoid arthritis, prostate...</td>
</tr>
<tr>
<td>186g-Rhenium</td>
<td>$^{186}\text{Re}$</td>
<td>89.25</td>
<td>$\beta^-$</td>
<td>1 MeV</td>
<td>Reactor</td>
<td>Bone cancer, rheumatoid arthritis, prostate...</td>
</tr>
<tr>
<td>166-Holmium</td>
<td>$^{166}\text{Ho}$</td>
<td>26.80</td>
<td>$\beta^-$</td>
<td>2 MeV</td>
<td>Reactor</td>
<td>Liver Tumour</td>
</tr>
</tbody>
</table>
New design for an ARC neutron activator
System design: calculations

MCNPX, FLUKA and STAR-CD codes were used for designing the new ARC facility

Components taken into account in the simulations:

- Be target (quality, thickness, shape)
- Proton irradiation (energy, charge, shape)
- The cooling water of the Be target (shape, flow)
- The lead buffer and Graphite reflector (quality, shape)
- Irradiation channels (positions)

The final design was optimised for maximum activation yield (with thermal and epithermal neutrons) of Ho and Re in the irradiation channels
# JRC Cyclotron (Ispra, Italy)

## Scanditronix MC 40

<table>
<thead>
<tr>
<th>Particles</th>
<th>Minimum Energy (MeV)</th>
<th>Maximum Energy (MeV)</th>
<th>Maximum Extracted Current (μA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>8</td>
<td>40</td>
<td>60</td>
</tr>
<tr>
<td>α</td>
<td>8</td>
<td>40</td>
<td>30</td>
</tr>
<tr>
<td>$^3$He$^{2+}$</td>
<td>8</td>
<td>53</td>
<td>30</td>
</tr>
<tr>
<td>d</td>
<td>4</td>
<td>20</td>
<td>60</td>
</tr>
</tbody>
</table>

## Technical Specifications

- **RF cavities**: 2, lambda/4
- **Dees**: 2, 90 degrees
- **Beam aperture**: 20 mm
- **Tuning**: Moving shorts/trim cap.
- **RF range**: 12.5 – 27 MHz
- **Frequency stability**: $< 10^{-6}$
- **Amplitude stability**: $< 10^{-3}$
- **Max. Dee peak voltage**: 44 kV
- **Ion source**: P.I.G. Type
- **Pole diameter**: 115 cm
- **Magnet weight**: 60 tons
- **Main coils Max. Curr.**: 850 A
- **Sectors**: 3
- **Hill gap**: 100 mm
- **Valley gap**: 180 mm
- **Max. magnetic field**: 2.1 Tesla
- **Extraction radius**: 50 cm
- **Trim coils**: 8
- **Harmonic coils**: 84 sets
Installation of the neutron activator

Dimension: 60 cm x 60 cm x 60 cm
Weight: ~600 kg
Control system of the neutron activator
Preliminary Results
Activation of foils of Mo and Au

\[ ^{98/100}\text{Mo}(n,\gamma/2n)^{99}\text{Mo} \]

\[ ^{197}\text{Au}(n,\gamma)^{198}\text{gAu} \]

\[ ^{197}\text{Au}(n,2n)^{196}\text{gAu} \]
Preliminary Results
Activation of foils of Re and Ho

\[ ^{185/187}\text{Re}(n,\gamma/2n)^{186}\text{gRe} \]
\[ ^{187}\text{Re}(n,\gamma)^{188}\text{gRe} \]

\[ ^{165}\text{Ho}(n,\gamma)^{166}\text{gHo} \]
**Preliminary Results Summary**

<table>
<thead>
<tr>
<th>Radioisotope</th>
<th>$T_{1/2}$</th>
<th>Reaction</th>
<th>Yield (MCNPX)</th>
<th>Yield Measured (Ispra)</th>
<th>Yield Measured (LLN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{198}\text{Au}$</td>
<td></td>
<td>$^{197}\text{Au}(n,g)^{198}\text{Au}$</td>
<td>553.83</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{196}\text{Au}$</td>
<td></td>
<td>$^{197}\text{Au}(n,2n)^{196}\text{Au}$</td>
<td>1.99</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{198}\text{gAu}$</td>
<td>2.69 d</td>
<td>$^{197}\text{Au}(n,\gamma)^{198}\text{gAu}$</td>
<td></td>
<td>724.20</td>
<td>194.46 * (526.99 **)</td>
</tr>
<tr>
<td>$^{196}\text{gAu}$</td>
<td>6.2 d</td>
<td>$^{197}\text{Au}(n,2n)^{196}\text{gAu}$</td>
<td>1.58</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{24}\text{Na}$</td>
<td>14.96 h</td>
<td>$^{27}\text{Al}(n,\alpha)^{24}\text{Na}$</td>
<td>5.37</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{99}\text{Mo}$</td>
<td>66 h</td>
<td>$^{98/100}\text{Mo}(n,\gamma/2n)^{99}\text{Mo}$</td>
<td>7.13</td>
<td></td>
<td>1.85 * (5.02 **)</td>
</tr>
<tr>
<td>$^{166}\text{Ho}$</td>
<td></td>
<td>$^{165}\text{Ho}(n,\gamma)^{166}\text{Ho}$</td>
<td>1650.00</td>
<td></td>
<td></td>
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<tr>
<td>$^{166}\text{gHo}$</td>
<td>26.8 h</td>
<td>$^{165}\text{Ho}(n,\gamma)^{166}\text{gHo}$</td>
<td>2520.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{186}\text{Re}$</td>
<td></td>
<td>$^{185}\text{Re}(n,\gamma)^{186}\text{Re}$</td>
<td>693.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{188}\text{Re}$</td>
<td></td>
<td>$^{187}\text{Re}(n,\gamma)^{188}\text{Re}$</td>
<td>1150.00</td>
<td></td>
<td></td>
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<tr>
<td>$^{186}\text{gRe}$</td>
<td>3.7 d</td>
<td>$^{185/187}\text{Re}(n,\gamma/2n)^{186}\text{gRe}$</td>
<td>385.00</td>
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<td></td>
</tr>
<tr>
<td>$^{188}\text{gRe}$</td>
<td>0.71 d</td>
<td>$^{187}\text{Re}(n,\gamma)^{188}\text{gRe}$</td>
<td>2100.00</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Yield corrected for proton energy bombardment, ** Yield for 65 MeV proton energy as published (LLN),
  * Yield unit: kBq/(µA.h.g),  Measured yield uncertainties: < 10%
Conclusions

1 - A new concept of an ARC neutron activator was designed and tested. With respect to previous designs it is much more compact (60 x 60 x 60 cm³, weight ~ 600 kg)

2 - Preliminary results on activations of foils of various materials were in good agreement with calculations

3 - With reference to previous work, slightly higher production yields of \(^{99}\text{Mo}\) (generator \(^{99m}\text{Tc}\)) and \(^{198}\text{Au}\) were obtained (factor ~4)

4 - The promising activation yields accomplished in this work open interesting perspectives for brachytherapy studies using Ho and Re based radioactive nanoparticles

5 - The ARC activator developed in this work may constitute an attractive alternative to nuclear reactors for production of certain radioisotopes for medical or other applications
THANK YOU FOR YOUR ATTENTION