Overview of High Energy/Intensity Accelerator Production of Biomedical Radionuclides in Europe

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Main uses of High Specific Activity No-Carrier-Added (NCA) radiotracers in the life-sciences

- Some NCA radiotracers applications
  - Metallo-biochemistry
    - Behaviour of different chemical forms of trace elements
  - Environmental toxicology
    - Low Level and Long Term Exposure (LLE) to ultra-trace elements
  - Nuclear medicine
    - Radiodiagnostics (SPECT, PET)
    - Systemic radionuclide tumour therapy
THE IUPAC PROJECT #2003-015-2-500
“Terminology, Quantities and Units concerning Production and Applications of Radionuclides in Radiopharmaceutical and Radioanalytical Chemistry”
Chair Mauro L. Bonardi, and 7 Task Group members

Due to the relevance of the Project for several IUPAC Divisions and other international bodies, the Project Proposal was delivered to the General IUPAC Project Committee (PC).
The new IUPAC Project has been approved by IUPAC PC and financed during the IUPAC General Conference in Ottawa, Canada, Aug 2003.


http://wwwGIR.mi.infn.it
### Selected examples of No-Carrier-Added radionuclide research and production at Milano UNIMI and INFN in the last 35 years

(see IAEA-NDS TECDOC 2011, 2001)

#### Specific Activity

\[ A_s \ (\text{GBq} \cdot \mu\text{g}^{-1}) \]

#### Isotope Dilution Factor,

\[ \text{IDF}^\circ \ (\text{dimensionless}) \]

<table>
<thead>
<tr>
<th>Target Nuclide</th>
<th>Nuclear Reaction</th>
<th>RadioNuclide produced</th>
<th>Energy range</th>
<th>SA(CF)</th>
<th>IDF°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al-27</td>
<td>(d,αp)</td>
<td>Na-24</td>
<td>19-15</td>
<td>323</td>
<td>nd</td>
</tr>
<tr>
<td>Sc-45</td>
<td>(α,n)</td>
<td>V-48</td>
<td>23-11</td>
<td>6</td>
<td>170</td>
</tr>
<tr>
<td>Sc-45</td>
<td>(p,n)</td>
<td>Ti-45</td>
<td>15-9</td>
<td>837</td>
<td>nd</td>
</tr>
<tr>
<td>Ti-nat</td>
<td>(p,n)</td>
<td>V-48</td>
<td>21-7</td>
<td>6</td>
<td>7-60</td>
</tr>
<tr>
<td>V-nat</td>
<td>(p,xn)</td>
<td>Cr-51</td>
<td>15-8</td>
<td>3</td>
<td>46</td>
</tr>
<tr>
<td>V-nat</td>
<td>(p,αd)</td>
<td>Sc-46,47</td>
<td>45-20</td>
<td>1.3; 31</td>
<td></td>
</tr>
<tr>
<td>Cr-nat</td>
<td>(p,xn)</td>
<td>Mn-52g</td>
<td>16-13</td>
<td>18</td>
<td>290</td>
</tr>
<tr>
<td>Cr-nat</td>
<td>(d,xn)</td>
<td>Mn-52g</td>
<td>14-9</td>
<td>18</td>
<td>nd</td>
</tr>
<tr>
<td>Mn-55</td>
<td>(n,γ)</td>
<td>Mn-56</td>
<td>(\phi = 9 \times 10^{12})</td>
<td>803</td>
<td>6 \times 10^5</td>
</tr>
<tr>
<td>Fe-nat</td>
<td>(p,xn)</td>
<td>Co-55,56,58</td>
<td>45-5</td>
<td>120; 1.1; 1.2</td>
<td>10,50</td>
</tr>
<tr>
<td>Co-59</td>
<td>(p,xn)</td>
<td>Ni-56,57</td>
<td>45-10</td>
<td>14; 57</td>
<td>500</td>
</tr>
<tr>
<td>Co-59</td>
<td>(p,αd)</td>
<td>Mn-54</td>
<td>45-25</td>
<td>0.3</td>
<td>9400</td>
</tr>
<tr>
<td>Zn-nat</td>
<td>(p,xn)</td>
<td>Ga-66,67</td>
<td>29-15</td>
<td>187; 22</td>
<td>37,13</td>
</tr>
<tr>
<td>Zn-nat</td>
<td>(d,xn)</td>
<td>Ga-66,67</td>
<td>19-10</td>
<td>187; 22</td>
<td>NCF</td>
</tr>
<tr>
<td>Zn-nat</td>
<td>(d,αxn)</td>
<td>Cu-64</td>
<td>19-5</td>
<td>143</td>
<td>200</td>
</tr>
<tr>
<td>Ga-nat</td>
<td>(p,xn)</td>
<td>Ge-69</td>
<td>30-15</td>
<td>43</td>
<td>NCF</td>
</tr>
<tr>
<td>Ge-nat</td>
<td>(p,xn)</td>
<td>As-71,72,74,76</td>
<td>16-4</td>
<td>25; 62; 3.7; 58</td>
<td>10,5</td>
</tr>
<tr>
<td>As-75</td>
<td>(p,xn)</td>
<td>Se-73,75</td>
<td>32-17</td>
<td>224; 0.5</td>
<td>10-30</td>
</tr>
<tr>
<td>Kr-nat</td>
<td>(p,xn)</td>
<td>Rb-81,82m,83,84</td>
<td>40-30</td>
<td>313; 222; 0.7; 1.8</td>
<td>NCF</td>
</tr>
<tr>
<td>Mo-nat</td>
<td>(p,xn)</td>
<td>Te-94g,95m,96g</td>
<td>40-20</td>
<td>131; 0.8; 61; 12</td>
<td>10-50</td>
</tr>
<tr>
<td>Ag-nat</td>
<td>(p,xn)</td>
<td>Cd-107,109</td>
<td>35-25</td>
<td>144; 0.1</td>
<td>20,6</td>
</tr>
<tr>
<td>Cd-nat</td>
<td>(p,xn)</td>
<td>In-111,114m</td>
<td>27-15</td>
<td>15; 0.9</td>
<td>3,10</td>
</tr>
<tr>
<td>Sb-nat</td>
<td>(p,xn)</td>
<td>Te-119m,121g</td>
<td>40-23</td>
<td>9; 2.4</td>
<td>nd</td>
</tr>
<tr>
<td>Te-nat</td>
<td>(p,xn)</td>
<td>I-123,124,etc.</td>
<td>28-17</td>
<td>71; 9; etc.</td>
<td>NCF</td>
</tr>
<tr>
<td>Te-124</td>
<td>(p,2n)</td>
<td>I-123</td>
<td>28-17</td>
<td>71</td>
<td>10</td>
</tr>
<tr>
<td>Hg-nat</td>
<td>(p,xn)</td>
<td>Tl-201</td>
<td>25-15</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>Hg-202</td>
<td>(p,2n)</td>
<td>Tl-201</td>
<td>19-10</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>Tl-203</td>
<td>(p,3n)</td>
<td>Pb-201/Tl-201</td>
<td>27-19</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>Tl-nat</td>
<td>(p,xn)</td>
<td>Pb-203</td>
<td>35-20</td>
<td>11</td>
<td>120</td>
</tr>
<tr>
<td>Pb-nat</td>
<td>(p,xn)</td>
<td>Bi-205,206</td>
<td>44-22</td>
<td>1.5; 3.8</td>
<td>100</td>
</tr>
<tr>
<td>Bi-209</td>
<td>(p,3n)</td>
<td>Po-207</td>
<td>45-25</td>
<td>96</td>
<td>NCF</td>
</tr>
<tr>
<td>U-235</td>
<td>(p,n)</td>
<td>Np-235</td>
<td>35-10</td>
<td>0.05</td>
<td>NCF</td>
</tr>
</tbody>
</table>
### Some proton/deuteron Cyclotron nuclide production (*enr. target*)

<table>
<thead>
<tr>
<th>radionuclide</th>
<th>target</th>
<th>reaction</th>
<th>p energy MeV</th>
<th>σ&lt;sub&gt;max&lt;/sub&gt; mbar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu-64</td>
<td>Zn/ZnO</td>
<td>natZn(p,spall)</td>
<td>70-140</td>
<td>35</td>
</tr>
<tr>
<td>*Cu-64</td>
<td>Ni</td>
<td>⁶⁴Ni(p,n)</td>
<td>15</td>
<td>675</td>
</tr>
<tr>
<td>Cu-67</td>
<td>ZnO</td>
<td>⁶⁸Zn(p,2p)</td>
<td>70</td>
<td>25</td>
</tr>
<tr>
<td>Ge-68</td>
<td>Ga₂O₃ / Ga</td>
<td>⁶⁹Ga(p,2n)</td>
<td>45</td>
<td>100</td>
</tr>
<tr>
<td>*Ge-68</td>
<td>Ga₂O₃ / Ga</td>
<td>⁶⁹Ga(p,2n)</td>
<td>20</td>
<td>550</td>
</tr>
<tr>
<td>Sr-82</td>
<td>RbCl / Rb</td>
<td>natRb(p,4n)</td>
<td>50</td>
<td>100</td>
</tr>
<tr>
<td>I-124</td>
<td>Te</td>
<td>natTe(p,n)</td>
<td>53</td>
<td>150</td>
</tr>
<tr>
<td>*I-124</td>
<td>TeO₂</td>
<td>¹²⁴Te(p,n) , (d,2n)</td>
<td>12</td>
<td>590</td>
</tr>
<tr>
<td>*Re-186</td>
<td>WO₃</td>
<td>¹⁸⁶W(p,n) , (d,2n)</td>
<td>10</td>
<td>17</td>
</tr>
<tr>
<td>Pd-103</td>
<td>Rh</td>
<td>¹⁰³Rh(p,n) , (d,2n)</td>
<td>10</td>
<td>500</td>
</tr>
<tr>
<td>Th-228</td>
<td>ThO₂</td>
<td>²³²Th(p,X)</td>
<td>70</td>
<td>60</td>
</tr>
<tr>
<td>Ac-225</td>
<td>ThO₂</td>
<td>²³²Th(p,X)</td>
<td>60</td>
<td>3</td>
</tr>
<tr>
<td>Pa-230</td>
<td>ThO₂</td>
<td>²³²Th(p,3n)</td>
<td>30</td>
<td>260</td>
</tr>
</tbody>
</table>
Radionuclides for metabolic radiotherapy and theragnostics

<table>
<thead>
<tr>
<th>radionuclide</th>
<th>Half-life days</th>
<th>$\beta$-max MeV</th>
<th>R soft tissue mm</th>
<th>$E_\gamma$ keV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dy-165</td>
<td>0.1</td>
<td>1.29 (83%); 1.19 (15%)</td>
<td>5.7</td>
<td>95 (4%)</td>
</tr>
<tr>
<td>Sm-156</td>
<td>0.4</td>
<td>0.7 (51%); 0.4 (44%)</td>
<td>2.6</td>
<td>none</td>
</tr>
<tr>
<td>Re-188</td>
<td>0.7</td>
<td>2.12 (72%); 1.96 (25%)</td>
<td>11</td>
<td>155 (15%)</td>
</tr>
<tr>
<td>Ho-166</td>
<td>1.2</td>
<td>1.85 (51%); 1.77 (48%)</td>
<td>8.5</td>
<td>81 (6%)</td>
</tr>
<tr>
<td>Rh-105</td>
<td>1.5</td>
<td>0.57 (75%); 0.25 (20%)</td>
<td>2.0</td>
<td>319 (19%)</td>
</tr>
<tr>
<td>Sm-153</td>
<td>1.9</td>
<td>0.67 (78%); 0.81 (21%)</td>
<td>2.5</td>
<td>103 (28%)</td>
</tr>
<tr>
<td>Au-198</td>
<td>2.7</td>
<td>0.96 (99%)</td>
<td>3.6</td>
<td>411 (96%)</td>
</tr>
<tr>
<td>Y-90</td>
<td>2.7</td>
<td>2.28 (100%)</td>
<td>11</td>
<td>none</td>
</tr>
<tr>
<td>Re-186g</td>
<td>3.7</td>
<td>1.07 (74%); 0.93 (21%)</td>
<td>3.6</td>
<td>137 (10%)</td>
</tr>
<tr>
<td>Yb-175</td>
<td>4.2</td>
<td>0.47 (87%)</td>
<td>1.7</td>
<td>396 (7%)</td>
</tr>
<tr>
<td>Lu-177g</td>
<td>4.2</td>
<td>0.48 (78%)</td>
<td>1.7</td>
<td>208 (11%)</td>
</tr>
</tbody>
</table>
Main steps in accelerator (or reactor) production of a labelled compound (e.g. radiopharmaceutical)

The Quality Control (QC) and Good Manufacturing Practice (GMP) are mandatory for each step of the procedure.

In a selected number of cases, it is possible to avoid the radiochemical processing step, which happens in target itself: recoil labelling with "hot atoms"
Production, Radiochemical Processing and QC / QA of No-Carrier-Added (NCA) radionuclides and labelled compounds

MAIN STEPS

Nuclear Reaction Studies
- thin-target excitation functions
- thick-target yields
- irradiation conditions optimisation

N.C.A. radiochemical processing
- Ultra-high purity chemicals
- Ultra-high purity targets
- Ultra-high purity equipments

Quality Control

Radionuclidic Purity

Radiochemical Purity

Specific Activity

Chemical Purity

NCA labelled compound

Radionuclidic Purity
Mauro Bonardi, Claudio Birattari, Flavia Groppi, Enrico Sabbioni, Thin-target excitation functions, cross-sections and optimised thick-target yields for $^{nat}Mo(p,xn)^{94g,95m,95g,96(m+g)}Tc$ nuclear reactions induced by protons from threshold up to 44 MeV. No Carrier Added radiochemical separation and quality control, Appl. Radiat. Isot., 57 (5) (2002) 617-635.

Other radionuclides of technetium produced in a proton cyclotron via $Mo(p,xn)$ reactions for research purposes (Milano and Ispra 1982 - 2004)

Mauro Bonardi, Claudio Birattari, Flavia Groppi, Enrico Sabbioni, Thin-target excitation functions, cross-sections and optimised thick-target yields for $^{nat}Mo(p,xn)^{94g,95m,95g,96(m+g)}Tc$ nuclear reactions induced by protons from threshold up to 44 MeV. No Carrier Added radiochemical separation and quality control, Appl. Radiat. Isot., 57 (5) (2002) 617-635.

Gamma-emitting technetium radiotracers production for waste disposal studies at Milan AVF Cyclotron, Report INFN, INFN/TC-84/24, Frascati, Roma, 1984


- Mauro Bonardi e Flavia Groppi, Masurio-99m, Masurio-99, Renio-186g, Renio-188: Radioelementi chimici isomorfi, ma con attività specifica e proprietà chimico-fisiche differenti. Storia e produzione di radiotraccianti. Metodiche di produzione e controllo di qualità, Rapporto INFN/TC-01/04, Frascati, Roma, 2001
**High Energy/Intensity Accelerators, why? I part**

- In this mainframe, as “high energy accelerator” we mean a charged particle accelerator with a beam energy larger than some 60 up to 150 MeV/nucleon.
- In practice, most of them accelerate only protons, with “increasing” beam current, up to 1.5 mA (i.e. 1500 µA expected).
- In selected cases alpha and deuteron beams (of lower intensity) could be useful.
High Energy/Intensity Accelerators, why?  II part

- The main nuclear reactions involved are:
  \[ T(\ p, \ x \ n) \text{ with } x \text{ up to } 6, \ 7, \ 8 \text{ and } \]
  \[ T(\ p, \ \text{spallation}) \text{ with emission of several nucleons and clusters of nucleons (like } d \text{ and } \alpha). \]

2 facilities (+1) in EUROPE are established:
1 Linac of 160 (of 600) MeV, in Troitsk, Moskow region, Russia, operating since 1972.
2 cyclotrons:
- ARRONAX of \( K = 70 \), in Nantes, FR (2010) and
- SPES-INFN of \( K = 70 \), in Legnaro (Pd), IT (bought Oct 2010, delivered 3-4 years from now).
In radionuclide production, light ion energies larger than *some tens MeV / nucleon* are non desirable.
Cyclotron Co., Obninsk (at IPPE site, Russia)
(Courtesy B. Zhuikov, INR; bz@inr.ru)

23 MeV and 15 MeV protons, deuterons, \( \alpha \)-particles ( > 1 mA )
The 1st acceleration section at 160 MeV is used for radionuclide production. At LANL (USA) a new but very similar facility at 100 MeV started operations in 2004.
Floor Plan of INR Isotope Production Facility
(Courtesy B. Zhuikov, INR)
INR Isotope Production Facility
(Courtesy B. Zhuikov, INR)
TARGET IRRADIATION CELL
WITH GRAPHITE COLLIMATORS
AND LITHIUM BEAM WINDOW

- Rod
- Thermocouple
- Targets
- Graphite collimators in stainless steel radiator
- Li-window
graphite collimator after high-power irradiation with slanted proton beam
Target Inserted in the Facility before Irradiation
(Courtesy B. Zhuikov, INR)
The maximum damage is located on target backing due to the higher power density.

aluminum target after high-power irradiation with slanted proton beam
very high melting point titanium target after high-power irradiation with slanted proton beam
In target surface beam power density $P_S$ vs. volumic beam power density $P_D$

For a beam of normalized diameter $D$, the dissipated power (in W) and the surface power density (in W.cm$^{-2}$) are:

$$P \text{ (watt)} = \frac{\Delta E \text{ (MeV)} \times I \text{ (\mu A)}}{\gamma z}$$
(for protons and deuterons $\gamma z = 1$)

$$P_S = \frac{P}{\pi (D/2)^2} = \frac{\Delta E \text{ (MeV)} \times I \text{ (\mu A)}}{\pi (D/2)^2}$$

is less relevant than the (volumic) power density (in W.cm$^{-3}$), due to the non-linearity of beam energy loss in target material (i.e. stopping-power, by improved Bethe-Bloch eq.)

$$P_D = \frac{P}{\Delta S \times \pi (D/2)^2} = \frac{P_S}{\Delta S}$$
Beam profile and power deposition into a thick target

Rotating, wobbling or sweeping ......

The beam multiscattering is a minor effect into solid targets

\[ R(E) = \text{range} \]
\[ S(E) = \text{stopping power} \]

\[ R(E) = - \int dE \frac{1}{S(E)} \]
With beam of energy of 70-150 MeV/nucleon the twin targets are effective for simultaneous production of several radionuclides

- 3 optimized energy windows for 3 radionuclides of similar half-life
- 3 radionuclides plus 1 radionuclide obtained by fast neutron irradiation on beam dump
- 1 radionuclide produced by different nuclear reaction in different optimized energy windows (e.g. Tl-201 by (p,3n) + (p,5n) nuclear reactions)
Energy Straggling and Beam Scattering of Protons Passing through a Target
(Courtesy B. Zhuikov, INR)
Beam power dissipation systems for solid-liquid targets

- Beam **defocussing** to avoid hot spots ($D = 10-20$ mm)
  - “plug” beam vs. gaussian beam shaping
- **Slanting** the beam on the target with an angle of $12-15 \, ^\circ$
- **Rotating** the beam on a circular or elliptical orbit by a wobbler
  - **Sweeping** the beam on a large surface ($D = 70-80$ mm)
  - Cooling the target holder by **high speed water** (Newton’s law, Nusselt’s number) or in minor extent by **liquid metals** (e.g. Hg, LBE, Pb, alkaly salts)
Beam power dissipation systems for solid-liquid targets

- Cooling the **double window** target by **high-speed He gas**
- Cooling the target by **tight contact** with a high thermal conductivity material (**Fourier’s laws**)
- Self-cooling the target by irradiation (**Stefan-Boltzmann**’s law)
  - Use of high melting point and thermal conductivity **intermetallic target compounds and alloys**
  - Use of **recirculating molten target material**
Various high-power Sb-targets

Sb in graphite shell

Sb in molybdenum shell

Targets from TiSb intermetallic compound

Intermetallic compounds and alloys are an effective solution for thermal dissipation into high-power targets, in spite of a more complex radiochemical processing.
Liquid Rubidium (50 g !) Target Irradiated by high-power intense Proton Beam at INR (Courtesy B. Zhuikov, INR)
CardioGen-82®
USA Sr/Rb-82 Generator

Russian Sr/Rb-82 Generator in W Container

Ion-exchange chromatography column
Nano-crystal structure of SnO$_2$-sorbent (TDO) (distribution of crystal dimension)

Generator column assembly with flange

Amount on the surface

![Graph showing the distribution of crystal dimension](image)
Production and Transportation Scheme of Sr-82/Rb-82 for PET cardiology
(Courtesy B. Zhuikov, INR)

- **Murmansk Region, RUSSIA**
  - Rb target material production

- **INR, Troitsk, Moscow Region, RUSSIA**
  - Irradiation of Rb-targets at LINAC
  - 160 MeV Protons

- **Los Alamos National Laboratory, NM, USA**
  - Chemical recovery of Sr-82 from Rb-targets

- **GE Healthcare, NJ, USA**
  - Loading of Sr/Rb-82 generators

- **IPPE, Obninsk**
  - Sr-82 recovery

- **IPPE, Obninsk**
  - Future Chemical Laboratory at INR
  - Sr-82 recovery

- **CRIRR, St-Petersburg**
  - Other hospitals

- **Medical Preparations Co., Moscow, RUSSIA**
  - Loading of Sr/Rb-82 generators

- **Hospitals in USA**
Isotopes exported by INR, (Courtesy B. Zhuikov, INR)

Sr-82  Pd-103  Sn-117m  Ge-68  Na-22  Cd-109

Targets

Rb  Ag  Sb  Ga  Al  In

-Los Alamos, USA
-IPPE, Obninsk

-Karpov, Obninsk
-Mayak, Ozersk

Cyclotron Co., Obninsk
IPPE, Obninsk

Los Alamos, USA

- IPPE, Obninsk
- Brookhaven, USA

Applied Chemistry, St-Petersburg
Beam power dissipation systems into gas targets

- Beam **defocussing** to avoid hot spots (D = 10-20 mm)
  - “plug” beam shaping vs. gaussian beam
- Shaping the target to pseudo-conical geometry to compensate multiscattering phenomena
  - Cooling the target holder by **high speed water** (Newton’s law, Nusselt’s number) or in minor extent by **liquid metals** (e.g. Hg, LBE, Pb, alkaly salts)
- Cooling the **double window** target by **high-speed He gas**
- Use of **recirculating gas targets**

Navier-Stokes’s eqs. Are very hard to solve for most practical purposes

In gas targets the **beam divergence by multiscattering** is a major concern
PROPOSAL

A CYCLOTRON ISOTOPE PRODUCTION CENTER
FOR BIOMEDICAL RESEARCH

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Department of Physics of the University of Padua and INFN

Ulderico Mazzi
Department of Pharmacology of the University of Padua

Mauro L. Bonardi, Flavia Groppi Garlandini
Department of Physics of the University of Milano and INFN

Dante Bollini
University of Bologna and INFN

Dario Casara
Istituto Oncologico Veneto
The Legnaro National Laboratory of INFN, Padova, Italy

- The K = 70 proton accelerator was purchased on Oct 2010 from Best Theratronics, Canada for 10.5 MEuros. It will be delivered in 3-4 years.
  - In total, for Cyclotron (only protons) and cyclotron bunker 20 MEuros already invested.
- 30 MEuro more are necessary for hot nuclear and radiochemistry facilities.
- The machine is similar to ARRONAX (IBA).
LNL-INFN Cyclotron $K = 70$ - protons 70 MeV
Guarantee extracted beam current 750 µA (expected 1500 µA)

Similar to ARRONAX
Nantes, France
(protons, deuterons and alpha)
Double proton beam of 300 + 300 µA obtained on Oct 2010
Recent Research Projects funded by INFN and UNIMI, in collaboration with JRC-Ispra Cyclotron Laboratory and several other foreign institutions

- **RAME-64 (2001-03):** optimization of deuteron cyclotron production, radiochemical processing and quality control of *no-carrier-added* $^{64}\text{Cu}$ from Zn, $^{66}\text{Zn}$ and $^{64}\text{Zn}$ targets
- **ASTATO (2003-05):** alpha cyclotron production, radiochemical processing and QC of $^{211}\text{At}/^{211}\text{gPo}$ by wet- and dry-chemistry methods from $^{209}\text{Bi}$ target and $^{210}\text{Po}$ impurity
- **RENIO (2005-08):** proton and deuteron cyclotron production, radiochemical separation and QC of *no-carrier-added* $^{186}\text{gRe}$ from natural W and highly enriched $^{186}\text{W}$ targets
- **LUTETIUM-177 (2009 - 11):** deuteron cyclotron production, radiochemical separation and QC of *no-carrier-added* $^{177}\text{gLu}$ from natural Yb and highly enriched $^{176}\text{Yb}$ targets
INFN RAME-64 EXP (2001-03): Deuteron irradiation on natural zinc targets (energy range up to 19 MeV, JRC-Ispra, EU)

(d,xn)$^{66}$Ga, $^{67}$Ga, $^{65}$Ga($T_{1/2}=15$ min $\rightarrow$ $^{65}$Zn)

(d,αxn)$^{64}$Cu($T_{1/2}=12.70$ h), $^{61}$Cu($T_{1/2}=3.3$ h)
(d,2p)$^{64}$Cu

(d,pxn)$^{69m}$Zn, $^{65}$Zn

Zn target self-labelling
1. irradiated target dissolution

2. liquid / liquid extraction

3. anion exchange chromatography

Scheme of Radiochemistry and QC for NCA radio-Cu and radio-Ga separation from irradiated Zn target at INFN-LASA
Production of $^{67}$Cu and $^{64}$Cu from Zn-target (M.L. Bonardi, B.L. Zhuikov, et al.)

the same radiochemistry developed at LASA had been used in Troitsk, RU,

for cross-section determination in the proton energy range from 30 up to 140 MeV

**INR (Troitsk, Russia)**

Proton energy: 145 MeV, 100 µA

$^{67}$Cu from nat. Zn-target
- Irradiation time: 3 d
- Decay/processing time: 3 d
- RCY: 90%
- Activity: 1.5 Ci (56 GBq)

$^{64}$Cu from nat. Zn-target
- Irradiation time: 12 h
- Decay/processing time: 2 d
- RCY: 90%
- Activity: 2 Ci (74 GBq)

IMI-2010-ANS Las Vegas Nov-08-2010

**ARRONAX (Nantes, France)**

Proton energy: 70 MeV, 200 µA

$^{67}$Cu from nat. Zn-target
- Irradiation time: 3 d
- Decay/processing time: 3 d
- RCY: 90%
- Activity: 0.7 Ci (26 GBq)

$^{64}$Cu from nat. Zn-target
- Irradiation time: 12 hr
- Decay/processing time: 2 d
- RCY: 90%
- Activity: 1.5 Ci (56 GBq)
Nuclear renaissance in Italy
Cyclotron $K = 70$

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IMI-2010-ANS
LasVegas Nov-08-2010

The End
Prossimi eventi Internazionali in Italia

Gruppo Interdivisionale di Radiochimica e Chimica delle Radiazioni, applicate all’ambiente, alla salute ed all’industria,
GIR della Società Chimica Italiana, SCI
http://wwwGIR.mi.infn.it

- 18-23 Sept, 2011, Città del Mare, Palermo, Sicilia, Italy, 3-rd International Nuclear Chemistry Congress, http://3rdincc.mi.infn.it, Chairwoman Prof. Flavia Groppi, Flavia.groppi@mi.infn.it, Flavia.Groppi@unimi.it

- 17-21 Sept, 2012, Como, Italy, 8-th International Conference of Nuclear and Radiochemistry, http://NRC8.mi.infn.it (under construction), Chairman Prof. Mauro L. Bonardi, Mauro.Bonardi@mi.infn.it, Mauro.Bonardi@unimi.it
**No-carrier-added, n.c.a.**: A preparation of a given radionuclide where special attention has been paid to procedures, equipment and materials in order to minimise the introduction of isotopes (both stable and radioactive) of the element in question in the same chemical form or as a species enabling isotopic exchange reactions.

Notes: (i) whether this minimisation was effective indeed, should be tested by a chemical analysis.

**Carrier-free, c.f.**: A preparation of a given radionuclide, which is free from isotopes (both stable and radioactive) of the element in question.

Notes: (i) whether virtual freedom from amounts of other isotopes really is achieved should be seen against the amount of element associated with the radionuclide in question. (ii) Where possible, this virtual freedom should be tested by a chemical analysis. (iii) Carrier-free actually also implies no-carrier-added, while the reverse is not true.

**Isotope dilution factor, IDF (t)**: the ratio at time $t$ after end of radiochemical processing, including labelling, if applicable, of a radionuclide, between the number of all atoms (both stable and radioactive) isotopic with radionuclide of interest and the number of atoms of radionuclide itself, i.e.: $\text{IDF (t)} = \frac{A_{S(c.f.)}}{A_s(t)}$ (normally > 1)