Progress towards new RIB and higher intensities at TRIUMF

Pierre Bricault
Target/Ion source department, TRIUMF
• Production of Rare Isotopes
  • ISOL method
• ISAC Target
  • High power target material, composite target
• ISAC ion sources for high power beam
• Uranium carbide target development
• ARIEL project
  • Photo-fission, converter study.
• Summary
Physics at ISAC

- Symmetry Studies with Fr
- Super heavy
- EDM

- Slow neutron capture process (s-process)
- Proton drip-line
- Doubly magic
- Rapid proton capture process (rp-process)
- Neutron drip-line
- Halo nuclei
- Rapid neutron capture process (r-process)
ISAC at TRIUMF

Driver:
Cyclotron H⁻
500 MeV
100 µA

Laser Beams for Resonant Laser Ion Source

ISAC-I
High Energy Experiments

ISAC-II
High Energy Experiments

Low Energy Experiments
The challenges are located here at the target/ion-source.

Driver:
Cyclotron $^1$H
500 MeV
100 µA

Laser Beams for Resonant Laser Ion Source

ISAC-I
High Energy Experiments

ISAC-II
High Energy Experiments

Low Energy Experiments
RI Production Reaction Mechanisms

- Spallation: products distribution peaks few mass units lighter than target.
  - Neutron deficient
- Fragmentation: product N/Z ratio reflects the target ratio.
  - Neutron rich.
- Induced fission into roughly equivalent mass products.
  - Medium range masse region

500 MeV, proton
ISOL Method

• Rare Isotope Beam are a challenge to produce. Especially, the short-lived ones.
• The ISOL method can be described as the production of RI by bombarding a thick target nucleus by a fast projectile.
• The requirements for producing high intensity RI beams are:
  • High intensity and energy driver
  • A refractory target material inside a high power target container
  • A high resolution mass separator
ISOL Method

This method involves the interaction of light ion beam onto a thick high-Z target material. The fragments are imbedded into the bulk of the target material.

• The rare atoms diffuse out of the target material matrix, => Diffusion process, $\varepsilon_D$.
• Then they effuse out of the “target oven” to the ion source, => Effusion process, $\varepsilon_E$.
• The rare isotope are then ionized in the ion source, => Ionization process, $\varepsilon_I$.

$$ Y = \Phi \sigma \left( \frac{N_A}{A} \tau \right) \varepsilon_D \varepsilon_E \varepsilon_I $$

• High yield can be obtained by increasing the proton beam intensity.
The diffusion process is driven not only by the concentration gradient, but also by the activation energy $E_A$ required to move the atoms from site to site through the solid.

**High temperature operation speed up the diffusion process.**

$D = D_0 \exp(-E_A/kT)$.

$D_0$ is related to the vibrational frequency and lattice parameter of the solid crystal.
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\[
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\]

- High yield can be obtained by increasing the proton beam intensity.
Pure effusion

Once the exotic atom has diffused to the surface of the target material the subsequent effusion step is determined by:

- The mean number of collisions with the surface of the target material and the container before leaving enclosure.
- The mean free flight time $\tau_f$ between two wall collisions.
- The main sticking time $\tau_a$ per wall collision, which depends essentially on the temperature and absorption enthalpy $\Delta H_a$ of the surface of the enclosure.
Target Material For High Power

- Power dissipated into the target is very large demanding very high thermal conductivity target material and a target container capable of dissipating the power.
- Target assembly can be described as consisting of two parts:
  - the target material itself,
  - the target container.
- ISAC High Power target can dissipate up to 25 kW.
High Power Target Material Fabrication

- The ceramic powder suspended in a solvent, which contains dissolved polymers that favor the powder dispersion.
- This mixture in suspension is poured into a mold or onto a backing foil and then allowed to dry.
- The dried slip cast is easily cut into the desired shape using LASER cutting.
- These carbide ceramics can be used up to 40 µA.
- For higher beam power it is necessary to increase the effective thermal conductivity of the carbide ceramics.
- We have developed a technique allowing us to pour the solution onto an exfoliated graphite foil.
- These composite carbide targets are capable of dissipating very high power.
- The ceramic layer is typically 0.25 mm thick, while the graphite layer is around 0.1 mm thick.
ISAC HIGH POWER TARGET

Section view of the High Power Target
Composite Target Material Concept

Fins

19.1 mm

200 mm

25.4 mm
High Power Target Material, composite

Fins diffusion bonded on Ta tube

High thermal conductivity foil, graphite, Mo, Nb ...

Target material, carbide, oxide.

Target container window

Good thermal contact between foil and Ta tube.
ISAC “Target Ovens”

Normal Target

High Power Target

$I_{\text{Proton}} \leq 40 \ \mu A$

$55 \leq I_{\text{Proton}} \leq 100 \ \mu A$
Perhaps the most striking result of operating at higher proton beam currents has been the observation of radiation enhanced diffusion (RED).
Possible reasons for degradation of performances

1. Radiation damage of the target container and target,
2. Impurities created move to crystal interstice weakening the matrix.
3. Temperature cycling when proton beam goes off.

Yield ratios of $^8$-$^{11}$Li, $^{20}$-$^{27}$Na and $^{26}$-$^{31}$Al measured 17 day apart. The average ~79% yields decrease is believed to result from loss of target container integrity.
Target container damages

$N_p \sim 1E19$ protons
## Proton Beam Intensity On Target

<table>
<thead>
<tr>
<th>Target Material</th>
<th>High Conductivity Support</th>
<th>Proton Beam Intensity (uA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiC</td>
<td>C (graphite foil, 0.1 mm thick)</td>
<td>70</td>
</tr>
<tr>
<td>TiC</td>
<td>C (graphite foil, 0.1 mm thick)</td>
<td>70</td>
</tr>
<tr>
<td>ZrC</td>
<td>C (graphite foil, 0.1 mm thick)</td>
<td>75</td>
</tr>
<tr>
<td>Ta</td>
<td></td>
<td>75-100</td>
</tr>
<tr>
<td>Nb</td>
<td></td>
<td>80-100</td>
</tr>
<tr>
<td>Nb5Si3</td>
<td>Nb (foil, 0.025 mm thick)</td>
<td>15</td>
</tr>
<tr>
<td>Al2O3</td>
<td>Nb (disk, 0.5 mm thick)</td>
<td>30</td>
</tr>
</tbody>
</table>
• There is no universal ion source for on-line application,
• We must develop ion source for each group of elements,

Hot Surface IS
LASER IS
Negative IS
ECR IS
Ion Sources for High Power Operation

- Ion sources that are not so much affected by the target outgas effect are:
  - The hot cavity surface ion source,
  - The Laser ion source.

- The plasma ion sources are much more affected by the target outgas,
  - ECR IS,
  - Nielsen and Bernas,
  - FEBIAD, is the one, which is less affected by the base pressure.
FEBIAD Ion Source

FEBIAD Xe Ionization Efficiency vs Pressure
R. Kirchner, "Ion Sources for Radioactive Beams", Proceeding ISOL Workshop, Berkely, 1994

Tracer Element Ionization Efficiency (%)

Pressure (mB)

FEBIAD

Nielsen IS
Hot Plasma Ion Source, FEBIAD

- It was used for TUDA $^{18}$F(p, $\alpha$)$^{15}$O experiment,
- We operated the FEBIAD combined with a high power composite SiC/Cgr target at 70 $\mu$A,
  - Nov. 2007, $I^{(18F)}$ = 9E+06 /s
  - May 2008, $I^{(18F)}$ = 5E+07 /s
- ISOLDE, 1E+07/s,
- HRIBF, 2E+06 /s.
- One issue is sometime the outgasing of the carbide produces carbon fiber in the extraction electrode creating shorts.

FEBIAD Ion Source, section view.
More RI with recent addition of ZrC and UO$_2$ targets since 2008.

To improve yield of Fr and Rn we need a UC$_x$ target.
UCx as Target Material

**Advantage:**
- Good thermal conductivity, compared to UO$_2$
- Low vapour pressure at high temperatures

**Concerns:**
- Exothermic oxidation
- Operation safety
- Long-term stability after use
- Storage of irradiated targets
Fabrication of UC\textsubscript{x}

- UC\textsubscript{x} was produced by from UO\textsubscript{2} + graphite,
- Using a ball mill machine they are ground to fine power in a plasticiser solution,
- Carbonization is done under vacuum,
- The resulting sheet is milled in a plasticiser solution again,
- The solution is then cast onto a graphite foil
- Target disks are then cut from the “green” cast.
- Target disks are then load into the target container for thermal conditioning under vacuum.

“raw” UC\textsubscript{2}
Test Chemical Stability of UC\textsubscript{x}

- Test the chemical reactivity in air
  - Exposure of raw and sintered UC\textsubscript{x} to air for different periods of time.

- Chemical reactivity in air at higher temperatures
  - Heating the raw and sintered UC\textsubscript{x} up to 400 degree Celcius.

- Chemical reactivity in water
  - Exposure of the raw and sintered UC\textsubscript{x} to water.
UCx exposure to air

- Two samples were exposed in air at room temperature,
- No visible effect after one day,
- After 5 days we see some discoloration on the surface.
“raw” UCx at 400°C

- Exposure to air at 400°C for one hour results in a slow decomposition of the carbide back into oxide.
- No rapid oxidation.
Exposure to water at 20°C results in the decomposition of the product.

This picture shows the “raw” UC\textsubscript{x} after 22.5H in water.

No rapid oxidation observed.
Same tests for the sintered material show that the chemical reactivity is even slower.

- No rapid oxidation observed in all tests.
SEM of “raw” and sintered UC$_x$

“raw” UC$_x$

Sintered UC$_x$
Status U Target and Future Plan

• First two runs with UO₂ at 1 and 2 µA.
  • Results of the assay for the noble gases, Kr, Xe and Rn are in good agreement with the FLUKA prediction,
  • No contamination in the pump filters pass the first mass selecting slit.
  • No evidence of significant alpha or beta air activation in the target hall.
• We have received the authorization for the Canadian Nuclear Safety Commission to operate U target 1000 µA-H.
• First UCₓ test is scheduled for December 2010.
Future Projects

• ISAC facility can deliver on one RI beam at the time, single user facility,
  • Backlog ~ 2-3 years

• In the last five-year plan proposal we proposed to build two new target stations,
  • Using electron for photo-fission
  • 500 MeV from existing beam port on the H-cyclotron,

• Combined with the actual ISAC we will be able to deliver 3 RI Beams simultaneously.
More RI Beams To Users

• ARIEL project

• Add two target stations will allow to have multiple users.

• Electron Superconducting LINAC

• New 500 MeV, 200 µA proton beam line from H-Cyclotron
ARIEL project, Target stations concept
Shielding Simulation With FLUKA

- Simulations show that the separation and shielding between the target stations meet the operation requirement,
- Operating one target station while the other is being maintained.
Target Station Concept

• Uses Target Module similar as for ISAC
  • Sealed containment box.
  • Simplified vacuum system.
  • Quick disconnect vacuum envelope using pillow seals technique developed for T2K.
Characteristics of the induced photo-fission

Schematic of the photofission

Electron Beam → Converter → Gamma Rays → $^{238}$U Target
Bremsstrahlung spectrum and GDR

Braking Radiation and $^{238}$U photofission

Cross Section (mb) vs. $E_\gamma$ (MeV)

- Red: 50 MeV
- Dotted Red: 25 MeV
- Blue: GDR

Gamma

$^{238}$U $\rightarrow$ Neutron

$^{99}$A

$^{138}$X
GEANT4 Simulation

- Number of fission as a function of the electron beam energy

50 to 75 MeV seems to be optimum energy for photo-fission.
100 kW converter study

- Power distribution for a 100 kW beam onto Ta converter and UC₂ target.
  - 37 kW in converter
  - 22 kW in target

Water cooled Ta disks
500 kW power distribution

- Rotating water-cooled wheel, Pb and Ta converter and UC$_2$/C target.
  - 274 kW in the converter
  - 66 kW in the target
Cooling Concept, ARIEL High Power Target

Active cooling concept under study for power in the range of ~ 30 to 70 kW.
Use GEANT4$^1$ and FLUKA$^2$ to simulate the photo-fission.

- 50 MeV, 100 kW yields to $\sim 2 \times 10^{13}$ photo-fissions/s.
- 50 MeV, 500 kW yields to $\sim 6.5 \times 10^{13}$ photo-fissions/s.


2) Copyright Italian National Institute for Nuclear Physics (INFN) and European Organization for Nuclear Research (CERN)("the FLUKA copyright holders"), 1989-2007.
Summary and Concluding Remarks

- We are developing new techniques for target material fabrication capable of operating at very high power,
  - Composite targets, carbide bonded on graphite successfully operate routinely up to 70 µA.
- The technique has been used to new target material,
  - High power oxide target, Al2O3 on Nb, EURISOL target test March 2009
  - Nb₃-Si₅ disks on Nb foil,
- Development of high power UC₂ target for ISAC and for future ARIEL project.
- Development of ion source capable of operating at such high power,
  - Surface ion, Laser and FEBIAD work under target outgas.
- Building on existing expertise and success in high power target will allow us to expand RI beam production using;
  - e-LINAC for 238U photo-fission,
  - New proton beam line, BL4N. => multi users facility
Thank You

List of collaborators
Marik Dombsky,
Friedhelm Ames,
Jens Lassen,
Vicky Hanemaayer,
Aurelia Laxdal,
Rick Maharaj,
Maico della Valle
ARIEL Project

• ARIEL project phase 1,
  • TRIUMF received funding for electron superconducting LINAC through a the Canadian Foundation for Innovation,
  • and British Columbia government has allocated $30.7 M for the building.

• Phase 2
  • 100 kW target for photo-fission of $^{238}$U.

• Phase 3
  • proton beam line to a second target station,
  • 500 kW for photo-fission.
Second target station
2017
Electron only
P ~ 500 kW

New tunnel for beam lines
200 µA proton; 450–500 MeV
10 mA electron; 25–75 MeV

First target station 2013
Electron and proton
P ~ 100 kW

200 µA Proton Beam Dump
# ISAC Target Station Technology

<table>
<thead>
<tr>
<th>ISAC/TRIUMF</th>
<th>ISOLDE/CERN</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Proton CW:</strong> 500 MeV</td>
<td><strong>Proton Pulsed:</strong> 1.4 GeV</td>
</tr>
<tr>
<td>$\Phi \sim 100 \mu A$</td>
<td>$\Phi \sim 2 \mu A$</td>
</tr>
</tbody>
</table>

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[Images of ISAC/TRIUMF and ISOLDE/CERN facilities]
• Contrary to other ISOL facility we do have a complex vacuum system.
  • Containment box is not hermetically sealed.
  • The HI port on containment box closed during transport, but not sealed.
• Primary and secondary vacuum are separated by differential pumping only.
Concrete & Steel

Steel

Concrete

Target

Beam Dump

Ion Beam

Slits

Pre-separator

LASER OPENING

BL2A
Module de la Cible

Grue contrôlée à distance

Cellules des Manipulateurs

Stockage de cibles

Puits des cibles
Target Exchange Process

• Hands On target module connection and disconnection
  - Need one week cool-down after beam off before starting services disconnection

• Target exchange takes from 3 to 4 weeks requiring proton beam off periods, ~ 200 H.

• The overall process limit RIB development due to large overhead require by the target exchange
  - Create schedule issue for RIB development
Remote Services Connection/Disconnection

- More than 65 connections,
  - Electrical
  - Cooling
  - Signal
  - Vacuum
- Prototype under development
- Implementation spring 2012.
Pure effusion

Profile distribution depends on the number of collisions on the target inner surface and on the activation energy to remove the wanted species from the target surface.

- \( x \) is the number of collisions,
- \( \Delta H_a \) is the activation energy,
- \( t_0 \) is the mean sticking time, it depends on the lattice vibration (T dependent)
- \( t_f \) is the meantime between two collisions.

\[
p_v(t) = v e^{-vt} .
\]

\[
\tau_{\text{del}} = 1/v = \chi(\tau + \tau_f).
\]

\[
\tau = \tau_0 e^{-\Delta H_a / kT}
\]
Release properties of ISOL target material

• The release efficiency of rare isotopes is not the same for all elements. This play in our advantage by improving the selectivity or to our disadvantage by not releasing the element we want.

• The requirement for fast release of short-lived rare isotopes species from the target material involves operating the target/ion source at high temperature.

• The target must be a refractory material having a low vapor pressure at elevated temperature to avoid vaporization of the target material.
  - refractory metal foils, Ta, Nb, ...
  - refractory carbide discs, SiC, TiC, ZrC, TaC, ...
  - refractory oxide, Al$_2$O$_3$, UO$_2$ ...

• => need of R&D.
This example shows the progress made over the year for $^{26}\text{gAl}$. SiC composite target and high power “target oven” allows us to increase the $^{26}\text{gAl}$ yield by two order of magnitude.

Addition of the RILIS improved the yield by another factor 7.

SIS, surface ion source
PP: pressed powder target material
NT: normal ISAC target
CF: composite foil, carbide target material bounded to graphite foil
HPT: high power target oven
RILIS: Resonant Ionization Laser Ion Source
High Power Target

- Low power target oven can dissipate up to 4 kW of beam deposition power.
- The high power target oven has fins attached to the Ta tube and can dissipate up to 20 kW beam power.
- How do we compare with other,
  - ISOLDE/CERN, 1 kW,
  - SPIRAL/GANIL, 1 kW,
  - HRIBF/Oak Ridge, 500 W
Laser Ion Source progress

1) Resonant steps and populating an auto-ionization level.
2) Two resonant steps and one non resonant step.
3) Three resonant steps to Rydberg level and field ionization.
4) One resonant step and to continuum non resonant ionization.

Resonant Ionization LIS
- element selective
- isobar free beams

- The development of new resonant ionization laser schemes is done in collaboration with several institutions and laboratories: Mainz U, Oak Ridge-HRIBF, Jyväskulä-Finland, CERN-ISOLDE.

See Posters
Andrea Teigelhofer, “Grating Ti:Sa Laser”
Jean Philippe Lavoie, “Production of pure RIB using Laser Ion Source”
RFQ-RLIS

• Ion sources development
  • RFQ-LIS
    • Suppress surface ion from target and transfer tube,
    • Final prototype operational,
    • Pure beam from Resonant Laser Ion Source,
      • Modules are ready for the RFQ-LIS,
      • Test on-line can take place
The other option is using a liquid metal as a converter

- Lead is a good option, preferable to Mercury from the point of view of personnel safety and environmental considerations
- Liquid lead circulated by an electromagnetic pump
- The power is then removed through two step heat exchanger: Pb- GaInSn- Water
New Proton Beam Line

- Second proton beam line, BL4N, to be installed by 2014.
- This new beam line will allow to operate ISAC target up to 200 µA.
500 kW converter study

• For beam power above 150 kW we cannot apply the static target solution for a converter.

• Options for a ½ MW converter under study,
  • Water-cooled rotating wheel,
  • Liquid metal converter.