FRONTIER TECHNOLOGIES AND FUTURE DIRECTIONS IN HIGH INTENSITY ISOL RIB PRODUCTION*

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Abstract

The future frontier of the ISOL technique is to increase the intensity of the RIB beams. In the ISOL technique several ways to increase substantially the production of rare isotope beam. The most expedient one is to increase the incident beam. Increasing the overall release efficiency and ionization efficiency are the other two easiest ways to increase the overall RIB intensity.

Now with the TRIUMF/ISAC facility the ISOL RIB facility can operate routinely up to 50 kW, this is 100 μA on target. But, the driver beam intensity cannot increase without considering the radiation damage issues and the challenge to the ion source itself where ionization efficiency is dramatically affected by target out-gazing.

The other technology challenge for the ISOL technique is the target material itself. The main concern is the capability of the target material to sustain high power density deposited by the driver beam. Refractory metals foil target are suitable but nevertheless very limited in the available species we can produce with those targets. We have developed composite target at ISAC that increases the overall target thermal conductivity in order to be able to operate carbide and oxide at full beam intensity for the carbide and at 30 kW for the oxide targets, respectively. The other solution is to use two-step target where the driver beam impinges a converter, which is decoupled from the ISOL target.

INTRODUCTION

The production of Rare Isotope Beam (RIB) is quite a challenge mainly due to fact that the most interesting rare isotopes are the one that lied close to the limit of stability both on the neutron rich and deficient side and most of the time very have short half-life. Making it difficult to make them using techniques such as chemical or mass separation off-line. In the On-Line Isotope Separation (ISOL) method, the isotopes are produced by nuclear reactions in a thick target that is closely coupled to the ion source, allowing them to be quickly turned into an ion beam that can be mass analyzed and transport efficiently to experiments.

The main challenge comes from the fact that the reaction products stop in the bulk of the target and the atoms have to be released efficiently out of the target container before we can make an ion beam. The steps for producing RIB from the ISOL method are:

- A high energy beam impinging onto a thick target material enclosed in a target container, which is directly coupled to an ion source,
- The isotopes are produced in nuclear reactions and come to rest embedded in the target material,
- The rare atoms have to diffuse through the target material grain or foil lattice to the surface, diffusion process,
- The rare atoms have to effuse, meaning bounce around until it reaches the exit hole of the target container leading to the ion source. Each time the rare atom has to desorb from the surface, effusion process,
- The rare atoms has to be ionized and extracted to form an ion beam, ionization process,
- The beam is mass analyzed and transported to the experiment.

The challenge is to optimize each step if to produce an intense, pure ISOL RIB.

The frontier technologies in ISOL RIB production are to achieve higher RIB intensity of nearly all isotopes, especially in the extreme neutron rich area of the nuclear chart. There are several paths to achieve higher RIB intensity,

- Increase of the driver beam intensity on target,
- Improve the release efficiencies out of the ISOL target, especially for the refractory species,
- Improve the ionization efficiency and
- Efficient high charge state breeding.

Increasing the driver intensity will lead directly to higher ISOL RIB intensity, but to do so we need to improve the target material and the target container for higher power deposition, section 1 and 2 describes the advance in target material fabrication and target container at ISAC. Section 3 describes the attempt to improve the release of radioactive isotope from thick target and section 4 describes the advance in the ion source technology to improve the beam purity from Resonant Ionization Laser Ion Source and plasma ion sources, electron impact and cyclotron resonances ion sources. Finally, section 5 describes the future project under construction and the next generation of ISOL target station.

ISOL RIB PRODUCTION

To reach higher ISOL RIB one can increase the incident driver beam on target. This can only be achieved at the condition that the target material and the target container are capable of sustaining reliably the power deposition by the driver beam. Firstly, the target material has to have a thermal conductivity high enough to release the power deposited inside the target material to the target container. Secondly, the target container has to be capable of dissipating the heat from the target material to the

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surrounding while keeping the target material at its optimum temperature.

Target Material for High Power Beam

In the ISOL method the radioactive atoms produced during the interaction of the driver beam onto the target material nucleus come to rest and are embedded into the target material lattice. In order to have a high release efficiency the target material has to be operating at it temperature limit which keep the vapor pressure acceptable for the ion source. It is important to select the target material for:

- Its ability to produce the RIB species desired by the experimentalist,
- High thermal conductivity,
- Low vapor pressure.

Usually, refractory foils made of tantalum and niobium and carbides discs are among the best candidates.

Table 1 gives the list of the target material and the type in used at ISAC and the power on target of the incident beam. To achieve high power density on target the target material has to have large thermal conductivity. For the refractory foils it is possible to go up to 50 kW, while it is more difficult for other target material such carbide or oxide. In those cases we have developed the composite foil target allowing an increase of the power on target by more than an order of magnitude for the oxide and by a factor 5 for the carbide target material.

Table 1: Target Material in Used at ISAC

Material	**Type**	**Backing Support**	**Beam Power kW**
Ta	Foil	-	50
Nb	Foil	-	50
CaO	Pellet	-	0.5 to 1
Al2O3	Composite	Nb foil	12.5
UO2	Pellet	-	1
SiC	Pellet	-	5
SiC	Composite	Graphite foil	35
TiC	Composite	Graphite foil	35
ZrC	Composite	Graphite foil	40
TaC	Composite	Graphite foil	35
UCx	Composite	Graphite foil	5

ISOL Target Container for High Intensity RIB

Challenging experiments forced us to increase the incident driver beam on target with the goal of producing higher RIB intensity. To do so the ISOL target oven has to be capable of dissipating the power deposited by the incident beam very efficiently.

The ISAC high power target[1] (IHPT) was developed to accommodate the TRIUMF 50 kW proton beam. The conventional target at ISOL facilities such as ISOLDE, SPIRAL and HRIBF can only accommodate for less than 1 kW dissipated power inside the target. There were several attempts in developing the ISOL target for higher power dissipation, by Ravn[2], Talbert[3], Nitschke[4] and RIST collaboration[5]. The most promising being the RIST because of the simple cooling design. But, the target fabrication is quite limiting because it required diffusion bounding and can only be applied to a few target materials, Mo, Nb, Ta and W. The ISAC High Power Target, IHPT, utilizes the thermal radiation cooling and is made of a 20 cm long and 2 cm in diameter tantalum tube onto which radial fins are installed. The fins are diffusion bounded to the target container by heating the tube in vacuum at 1500 ºC for a period of approximately 20 hours. The overall emissivity measured is 0.92 which allow operating the target at nominal 2200 ºC up to 20 kW of deposited power by the proton beam.

The challenge with increasing proton beam on target comes in several forms: 1) the radiation damage of the tantalum tube, 2) the thermal shock when the proton beam goes off and 3) chemical reactions between the tantalum container and the target material or the radiological impurities created.

All these processes create cracks in the tantalum container allowing the rare isotope atoms of interest to escape the container reducing the output yield.

ARIEL TARGET STATION TECHNOLGY

The goal of the ARIEL project is to be able to deliver more RIB to experiments. The project is based on a 50 MeV: 10 mA electron LINAC and on another 100 μA proton beam for producing the ISOL RIB. This means that we will have two new target stations, one for the electron beam and one for the proton beam. The target stations will be based on the ISAC technologies developed over the past 10 years.

The target stations are located in a sealed building serviced by an overhead crane. The target maintenance facility includes a hot cell, warm cell, decontamination facilities and a radioactive storage area. The target area is sufficiently shielded so that the building is accessible during operation at the maximum proton beam current.

Beam-line elements near the target are installed inside a large T-shaped vacuum chamber surrounded by close-packed iron shield. This general design eliminates the air activation problem associated with high current target areas by removing all the air from the surrounding area. The design breaks naturally into modules; an entrance module containing the primary beam diagnostics, an entrance collimator and a pump port; a beam dump module containing a water cooled copper beam dump; a target module containing the target/ion source, extraction electrodes and first guiding component and heavy ion diagnostics; and two exit modules containing the optics and the associated diagnostics for the transport of heavy ion beams.

The vacuum design seeks to eliminate the need for radiation-hard vacuum connections at beam level by using a single vessel approach. The front-end components, with their integral shields, are inserted vertically into the T shaped single large vacuum vessel. Most vacuum connections are situated where elastomer seals may be used. Only two beam-level connections exist; one at the proton beam entrance and one at the heavy ion beam exit.

The target stations are shielded by approximately 2 m of steel placed above the target. Outside this steel shielding the operating radiation fields will be sufficiently low so that radiation damage to equipment is not a concern. The steel shielding is surrounded by an additional 2-4 m of concrete, which provides the required personnel protection during operation. To service the targets, shielding above the target station is removed giving access to the services at the top of the steel shielding plugs. Residual radiation fields at this level will be low enough to allow hands-on servicing.

With ARIEL new target stations we have an opportunity to improve the current target station design and bring it to the next level. We have learn so much from the past ten years of operation at ISAC and this is why the next generation of ISOL target station will not be an exact copy of the ISAC target station. At the time we had to invent most of the technologies without very much experience. Before designing the design of the new target stations we must evaluate the existing ISAC target concept. To do the analysis of the ISAC target station technologies we used a type of analysis used in product manufacturing, it is called design failure mode effect analysis, DFMEA. Each item or function of the system is analyzed. A list of potential or experienced failure, potential or experienced effect of the failure mode, the causes of the failure are described. Then the severity (S) of the failure is given a number from 1 to 10, 1 being benign and 10 severe. The occurrence (O) of the failure is also given a number from 1 to 10, 1 being 1 in 10^3 cycle and 10 is a failure that arise 1 every running period. The ease of detection (D) to prevent the failure is given a number from 1 to 10, 1 being easy to detect the failure and 10 being very difficult. The product of S*O*D represent the risk priority given for that failure mode. From there we decide of the criticality of that failure mode and recommend action and record the Engineering Change Order associated with the action. The person responsible for the action and the date of completion is also recorded in the DFMEA documents. This document follows the product in its life cycle. The following findings were made during a design failure mode effect analysis, DFMEA, of the target station and target module.

On the pros side:

1) The modular approach allows us to operate at the design proton beam intensity, 100 µA. The non radiation resistant components, such as o-rings, turbo pumps, actuators, cable, … are well protected by the module and target station steel shielding.
2) The two stage mass separator composed of a low and a high-resolution separator in cascade. The first set of selection slit located at the focal plane of the first separator inside the heavily shielded target hall allow the elimination of most of the unwanted radioactive beam isotopes in a well defined manner, limiting the contamination.
3) We never had to change the optics in the two modules for the heavy ions beam transport from the ion source to the pre-separator and the entrance and beam dump modules.

On the cons side:

- Vacuum system is very complex. There two different pressure volumes, the primary and the secondary vacuum envelopes. Pillow seals are used to seal the target box volume to the exit module vacuum for the heavy ions beam line.
- The target box housing the target/ion source assembly is not hermetically sealed. This makes the target module transfer of the spent target from the target station to the hot cell is done at atmospheric pressure. There is a risk of spreading contamination during the transfer of volatile species. Or more importantly, target materials that are sensitive to moisture in air may reacts strongly and become flammable. In that case the fumes may exit the target box and contaminate the target hall.
    - In the new design the target box will be an hermetically sealable vessel preventing the contamination during the transfer of the irradiated target from the target station to the hot-cell.
    - The fact that the target box is hermetically sealable will allow the elimination of the two vacuum zones. Only one single zone is necessary.
    - This will allow us to condition fully the high voltage of the target module equipped with the new target and keep the target module under vacuum during the transfer limiting the risk of spreading contamination and delay in the start up of a new target.
- The mechanical and electrical service connections necessary to operate the target/ion source assembly have to be disconnected manually. In order to permit a person to disconnect the services we have to allow for a cool down period. A complete cycle for the target exchange takes about 3 to 4 weeks.
    - A built in remote service connection and disconnection has to be incorporated into the design at the beginning. T
- Since the target exchange take so long we are forced to operate the target / ion source much longer than desired. We have notices that after two weeks of continuous operation at 70 µA and above the production yield drop significantly. Radiation damages are clearly visible on the target container

and it reduces the overall target performances. We can see cracks on the target container, which can lead to radioactive atoms to leave the target container before reaching the ion source.

- The servicing of the selection slits is made using human intervention in the present design. This limits greatly the maintenance to the minimum until it breaks creating reliability issues.
    - In the new design the selection slits as well as all the target station beam diagnostics will be accessible with the overhead crane, allowing maintenance and repair in the hot-cell.

The new target station design addresses the mentioned findings by implementing new vacuum joint technology and remote services connection.

The remote vacuum seal requirements specification are:

- Provide vacuum seal with a leak rate lower than 5×10^{-9} mbar liter/s,
- Remote actuation, connection and disconnection,
- Robust and reliable, since the area will be highly active due to the high neutron flux, maintenance shall be minimum around these vacuum seals.

In the next generation the steel plug module will be replace by beam pipe section. Each section will have its own vacuum pumping station composed of two turbo pumps connected to the main beam pipe by a large tube. The rationale is to keep the turbo pumps as far as possible from high radiation field. The beam dump and the entrance module are also replaced by standalone diagnostics box, and beam water-cooled copper plug, respectively. Again the rationale is that we never had to replace any of these devices since starting ISAC operation 12 years ago. These decisions make the vacuum envelope of the target station much simpler than it is for the ISAC case. It also makes the target station much cheaper since 4 module steel plugs are replaced by less expansive shielding, like cast steel plug and concrete block.

The vacuum envelope will comprise the target module containment box, heavy ion beam line and pre-separator to the mass separator. The heavy ion beam line will be built in section that can fit into the hot-cell for maintenance and repair of the sections. The vacuum envelope will be sealed using all metal vacuum joints.

Figure 1 shows a 3-D view of the next generation of target station proposed for the ARIEL project. The new target station will be made of a target module, heavy ion beam line, pre-separator and beam dump. Contrary to the actual ISAC target station there will be only one module, which is the target module. The entrance diagnostics and beam dump will be stand alone device which will not share the same vacuum envelope as the target station.

Vacuum Joint Options

There two vacuum joint technologies envisaged for the ARIEL target stations. The pillow seal, which was originally developed at Paul Scherrer Institute (PSI) in Switzerland[6] uses a single thin foil to make the vacuum seal. The pillow seal is made using a thin metal foil electron beam welded on a flange. The pillow is inserted between two flanges. High pressure He is pump to inflate the thin foil, also called pillow. The seal joint is made than of two flanges equipped with pillows and two concentric bellow welded on each side to the flanges. The helium gas used to inflate the pillow is also injected into the concentric bellows pushing the flanges outward toward the fixed flanges on each side. A newer design developed for T2K beam window[7] uses a double pillows setup allowing a pump down in between the pillows. They reported in reference 2 a leak rate of 10^{-8} Pa m^3/s. Unfortunately, this is larger than desirable for constructing the whole heavy ion beam line with this technology. There will be fours of these vacuum joints in the heavy ion beam line, making the total leak rate much larger than acceptable.

Another option is to use HELICOFLEX®, C-FLEX™ seals. This seal technology relies on elastic deformation of the metal “C” shape metal. During compression we obtain a contact point of each sealing surface. The key of success of this joint is to provide the proper, compression force and surface finish.

NEUTRON RICH ISOTOPES

At TRIUMF we are fortunate to have a high energy and high intensity proton driver with the H^- 500 MeV Cyclotron and a high intensity, 50 MeV: 10 mA, electron driver under construction[8]. We can produce neutron rich isotopes using three different techniques, 5 kW direct proton onto the UCx target, 500 kW two-stage photo-fission using the electron driver and a 50 kW two-stage neutron induced fission using the proton beam on a converter and UCx target. Figure 2 shows all the possible options available at TRIUMF to produce neutron rich rare isotope beams.

5 kW Proton on UCx

This is the actual situation, where the high energetic proton beam impinges onto the UCx target discs. There is several reaction processes as mentioned earlier. This setup is less suitable since the spallation reaction produces isobars that contaminate the desired neutron rich species. Further more, the high energetic proton beam induces fission that yield to less neutron rich isotopes than pure low energy neutron induced fission. The limitation to 5 kW is only due to regulatory consideration not due to the capability of power dissipation of the UCx target, which can go up to 20 kW.

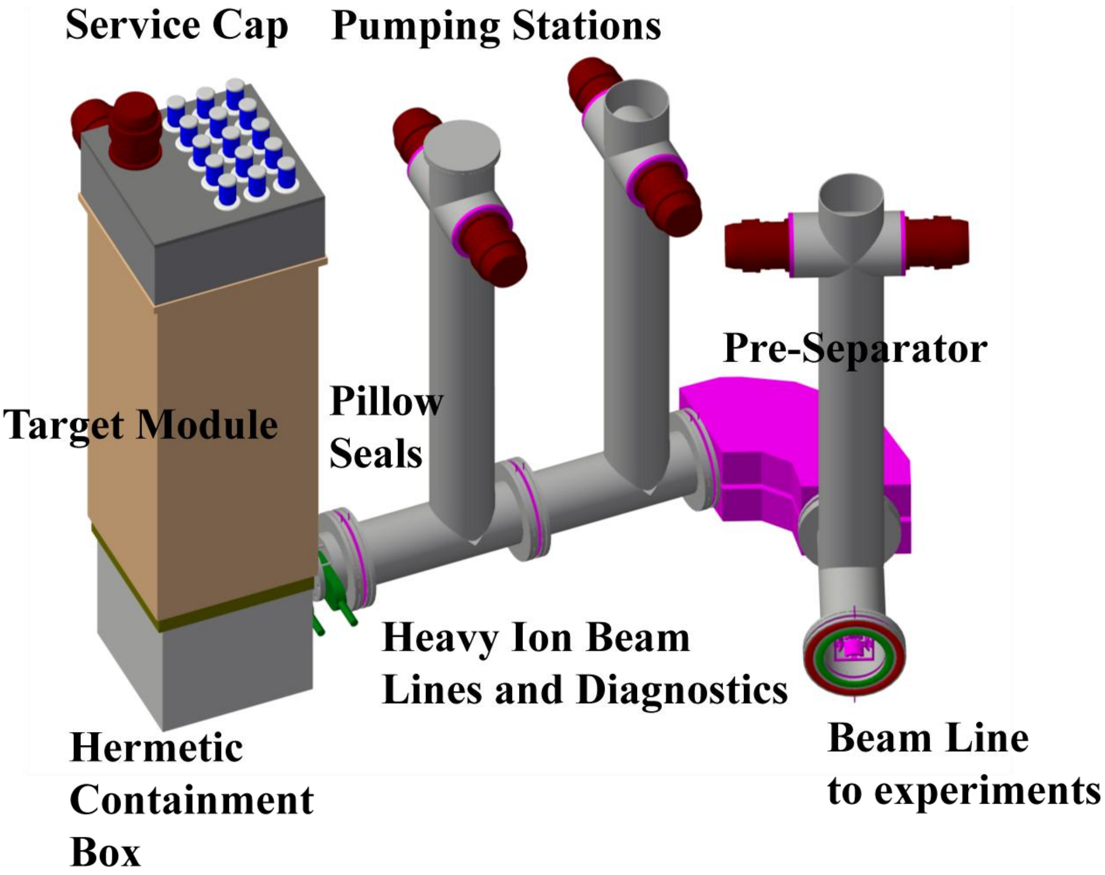

Figure 1: 3-D view of the next generation of target station proposed for the ARIEL project.

500 kW Electron, Two-stage Photo-fission of ^{238}U

ARIEL as mention aims to accelerate electron beam up to 50 MeV and 500 kW total beam power. The converter for such power can only be made using liquid lead. Simulation shows that 375 kW is deposited into the converter and 75 kW in the target itself. This is 7 times larger than the power we can handle in one single target. To handle the power deposition in the UCx we will use the composite target technique as described earlier, the uranium carbide will be deposited onto an exfoliated graphite foil. Furthermore, we will divide the target into seven smaller target containers and we will use helium gas to cool the whole target assembly. The minimum flow rate is estimated at 18 He mole/s.

50 kW Proton on Two-stage U Target

In this option the proton beam impinges onto a converter material, for example W, Nb, Mo or Ta. The U target is made as an annulus into which the proton beam goes without interacting with the U target. This target is placed in the backward position in such a way that only low energy neutrons can reach the U target. In this case the power deposited in the U target is small since its mainly coming from the fission products stopping in the target material. It is estimated to be only 400 Watts.

Comparison

It is interesting to compare the production of some key nuclei with the actual ISAC 5kW proton beam on UCx target, the ARIEL 500 kW electron beam producing photo-fission and the 50 kW proton beam, two-stage target using a W converter and U target. Table 2 gives the production yield in target for the three different setups.
As we can see from the table 2 there is not very much difference in the production of the key isotopes between the three options. While option 2 with the photo converter is not readily feasible, option 1 and 3 using 5 and 50 kW, respectively, are readily possible using the actual technologies developed at ISAC.

The main concern for the option 2 is the feasibility of the converter itself. The power density at the entrance window is quite large and we are far from being sure that such window will work. One option is to operate the liquid lead converter without the entrance window.

ARIEL FIRST BEAM

A ½ MW electron LINAC accelerator, e-linac , will be built in phases[9,10]. The main components of the eLinac are, an injector cryomodule composed of two capture cavities, and a 5 cell cavity capable of accelerating the electron beam up to 10 MeV and two cryomodules composed of two 9 cell cavities capable of 20 MV each.

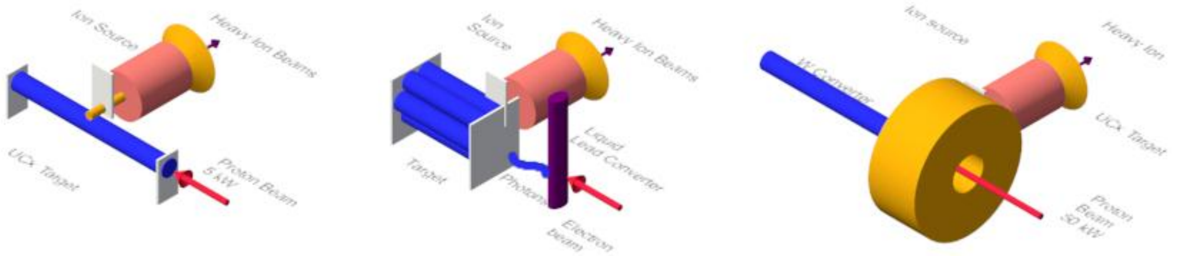

Figure 2: Schematic of the three options available at TRIUMF for producing neutron rich isotopes. From the far left, this represents the actual 5 kW proton beam on UCx target, the middle one is the 500 kW electron beam on a liquid lead converter producing gammas inducing photo-fission and the last one on the right is the two stage target concept. The 50 kW proton beam impinges onto a converter and the UCx target is placed in the backward direction in such way that only slow neutron that are emitted can reach the UCx target.

Table 2- In target production of key nuclei using a 5 kW proton, 500 kW electron and two stage using 50 kW proton on W converter, beam on UCx target.

Nuclei	5 kW proton	500 kW electron	50 kW proton two-stage
Ni-72	3.8E+08	2.0E+08	8.0E+07
Zn-78	1.4E+09	3.4E+09	8.9E+08
Kr-91	5.3E+10	2.3E+11	2.7e+11
Kr-94	1.3E+10	1.3E+11	6.7E+10
Rb-97	7.4E+09	1.1E+11	1.9E+10
Sn-132	1.1E+10	2.5E+10	1.5E+11
Sn-134	1.0E+09	2.4E+09	1.3E+10
Xe-142	1.1E+10	5.2E+10	1.2E+11
Xe-144	1.0E+09	7.9E+09	9.5E+09
Cs-144	6.8E+09	6.0E+10	7.7E+10
Cs-146	5.0E+07	9.2E+08	9.8E+09

Table 3 gives the main specifications for each of the phases.

The electron linear accelerator is due to be fully commissioned by end of 2013 but the target hall will not be ready for uranium target for the photo-fission before the fall of 2017. In the mean time we can produce low activity rare isotope, namely, 8-Li from a beryllium oxide target using the 9-Be(γ, p)8-Li.

Figure 3 shows the results of FLUKA[11] simulations showing the 8-Li production as a function of electron energy for a fixed beam intensity of 4 mA.

Table 3: ARIEL eLinac construction phases

Final Energy (MeV)	Currrent (mA)	Configuration	Status/ expected date for completion
25	1	Injector + 1 cryomodule	Funded/ 2013 commissioning
25	4	Injector + 1 cryomodule	Funded/ 2014 operational for 8-Li
50	10	Injector + 2 cryomodule	Proposed /2017 photo-fission

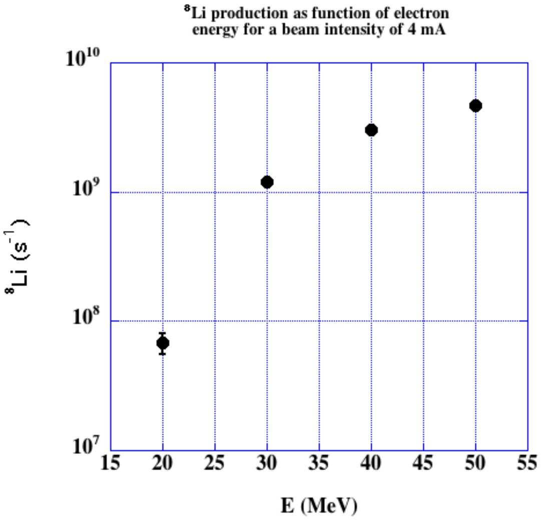

Figure 3: Results of FLUKA simulations of the 8-Li production in target as a function of electron energy for a fixed intensity of 4 mA on a BeO target.

The advantages of using 8-Li from a BeO target are:

- The level of radiation is not extremely large and the 8-Li has a very short half-life of 840 ms only.
- The longest half-life nuclei produced in the target is 7-Be, $T_{1/2}$ is 53 days.
- We can start an early experimental program with the ARIEL facility.

This mean that the whole target station operation commissioning can be accomplished without risking to contaminate the beam lines as it will be the case for an uranium target.

The 8-Li beam is used by the beta-NMR material science community. High nuclear spin polarization is achieved using a collinear optical pumping method in which polarized light from a laser is directed along the beam axis. The method is well established for the case of alkalis such as 8Li where the neutral atom can be excited with visible laser light. The first step in the procedure is to neutralize the ion beam by passing it through a Na vapor cell. The neutral beam then drifts 1.9 m in the optical pumping region in the presence of a small longitudinal magnetic holding field of 1 mT. Then the beam goes through a helium gas where the neutral 8-Li is ionized and then it is send to the beta-NMR experimental setup[12].

CONCLUDING REMARKS

To satisfy the demand for higher RIB intensity we raise the incident proton beam intensity on target. This was only possible by pushing the technologies for material target and target container to sustain the high power deposition in the ISOL RIB production.

We have developed a technique to make composite target material capable of dissipating larger power deposition. This technique increases the overall thermal conductivity of the target material. The target material is deposited onto a highly conductive substrate, exfoliated graphite foil for the carbide target material and metal foil for oxide target material. Now we are routinely operating the proton beam at 35 to 50 kW.

The target container has to take the heat coming from the target material and dissipate that heat to the target cooling system. We use radiative cooling to get the heat out of the target. A fin target container has been developed for this purpose and it is capable of dissipating up to 20 kW of beam power deposited in the target[13].

With the ARIEL project we have an opportunity to built the next generation of high power target station for producing high intensity ISOL RIB. An analysis of the actual ISAC target station has been performed and the findings will be applied to the design of the next generation of target station.

The ARIEL first beam will be made using a BeO target to produce 8-Li for the material science community. We used FLUKA to obtain the production rate of 8-Li in target, the estimated intensity is well above the need for performing beta-NMR studies.

There are several new projects around the world with the aim of producing intense RIB using fission reaction. The power density inside the U target in all of these projects are exciding the actual capability of carbide material thermal conductivity. A high thermal conductivity target material is mandatory for the success of these projects final goals.

The development of composite target material at TRIUMF/ISAC is a good way to achieve such high thermal conductivity allowing high power RIB production ISOL facility.

Furthermore, the dissipation of the power to the cooling system must use a target oven capable of dissipating the power release from the target material to the cooling environment. The IHPT has proven it capability to dissipate up to 20 kW. To go beyond that we need to use other means like helium gas cooling as anticipated at ARIEL photo-fission target.

Finally, one of the frontier in physics is the capability of producing intense and pure neutron rich RIB. These beams can be produced using fission reaction. At TRIUMF we will have access to the fission products by using the photo-fission and a two-stage target system using 50 kW proton beam on a converter.

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