Development of a neutron converter for studies of neutron-induced fission fragments at the IGISOL facility

M. Lantz[1], *D. Gorelov*[2], *A. Al-Adili*[1], *A. Jokinen*[2], *V. Kolhinen*[2], *A. Mattera*[1], *S. Rinta-Antila*[2], *H. Penttilä*[2], *S. Pomp*[1], *V. Rakopoulos*[1], *V. Simutkin*[1] *and A. Solders*[1]
[1] Uppsala University, Uppsala, Sweden
[2] University of Jyväskylä, Jyväskylä, Finland

Abstract

The ERINDA funded scientific visit has enabled the groups at Uppsala University and University of Jyväskylä to work closer together on the design of a neutron converter that will be used as neutron source in fission yield studies at the IGISOL-JYFLTRAP facility at the University of Jyväskylä. The design is based on simulations with both deterministic codes and Monte Carlo codes, and an ERINDA funded benchmark measurement. In order to obtain a competitive count rate the fission targets will be placed very close to the neutron converter. The intention is to have a flexible design that will enable neutron fields with different energy distributions. In this report the progression and the present status of the design work will be discussed, together with an outlook of the future plans.

1 Background

The IGISOL-JYFLTRAP facility was recently moved to a new location within the accelerator laboratory at the University of Jyväskylä. A high intensity MCC30/15 cyclotron that gives 100 μA protons in the energy range 18-30 MeV, and about 50 μA deuterons of 9-15 MeV, has been installed, eventually the intensities can be increased even further. The high intensity beams of charged particles allow the production of a high neutron flux through some (p,xn) or (d,xn) reaction by using a suitable material as neutron production target. The resulting neutron field can be used for high precision studies of neutron-induced fission-fragment distributions, where the Ion Guide Separator On-Line (IGISOL) technique is combined with the JYFLTRAP Penning trap. The method has been successfully used for proton-induced fission yields [1, 2] and it is therefore of interest to extend the use with a neutron source. This opens up new possibilities for fundamental research on nuclides far from stability, and for systematic studies of fission yield distributions in view of present and future nuclear fuel cycles.

2 Objectives

The aim of the ERINDA scientific visit was to allow closer interaction between the groups at Uppsala university and University of Jyväskylä with the purpose of determining a feasible design for a neutron production target, a so called neutron converter. The converter is to be used for measurements of neutron-induced independent fission yields at the new IGISOL-JYFLTRAP facility.

It should be mentioned that there are two seemingly conflicting goals that need to be fulfilled for the neutron converter:

- The Jyväskylä group has a long and proud history of fundamental research with radioactive nuclides, and the intention is to perform nuclear structure studies on neutron-induced fission-fragments far from the stability line. In order to be competitive with other experimental facilities the neutron converter should be able to deliver 10^{12} fast neutrons (E > 1 MeV) per second on a ^{238}U target.
- The mutual interest of the Jyväskylä and Uppsala groups to provide nuclear data of relevance for society, in particular within the objectives of the ERINDA framework, requires neutron fields with

energy distributions that resemble those in nuclear reactors, i.e. thermal spectra as well as fast reactor spectra.

There are also some other boundary conditions that have to be fulfilled:

- The use of a 30 MeV proton beam with 100 μA intensity that fully stop in the neutron converter means that about 3 kW of heat is deposited in a very small volume of material. Cooling requirements may limit the options for suitable materials and geometries.
- Activation of the neutron converter will have to be handled. The IGISOL experimental chamber will also be used for other experiments so it is important to find a solution where the induced activation does not reduce access too much. There is also the concern that the neutron converter may suffer problems with structural integrity due to hydrogen buildup from the absorbed protons or deuterons.

With these goals and constraints in mind the aim has been to reach a flexible design that is relatively easy to assemble and remove, that allows different neutron fields, that will maintain its structural integrity, and that will not compromise safety when it comes to induced radioactivity and chemical toxicity.

3 Initial approach and some lessons learned

Some preliminary studies were initiated by the Uppsala group during 2010, before the ERINDA funded scientific visit had been approved. The initial approach was to start from the geometry of the ANITA white neutron source that is available at TSL [3]. The ANITA target is made of tungsten, which has a very high melting point, high thermal conductivity and give relatively little residual radioactivity at the proton energies of interest [4]. The dimensions of the ANITA target is a cylindrical disc with 5.0 cm diameter and 2.5 cm thickness.

The initial studies with Monte Carlo codes started with characterizing the neutron flux with respect to energy and angular distributions. The geometry was varied in different ways and moderator materials were introduced in order to imitate light water reactor spectra. There were also studies with different geometries of the fission target and heavy metal reflectors in order to enhance the neutron flux on the fission target. Focus was on tungsten as converter material although studies on beryllium were performed for comparison. Only protons were considered due to the ambition of maximising the neutron flux and the difficulty of properly simulating the (d,xn) reaction with the Monte Carlo codes. Below are some conclusions drawn from the initial studies [4, 5]:

- The neutron flux does not vary significantly with the geometry of the target. Incident projectile energy and neutron scattering angle determines the flux roughly within a factor of two, no matter which geometry is used.
- The flexibility with the target geometry allows for enough surface area to be in contact with some sort of cooling circuit in order to provide sufficient cooling.
- It is relatively easy to imitate a light water reactor spectra by introducing layers of water or polyethylene as moderator, while a fast reactor spectra can only be approximated very roughly. In both cases there will be an excess of fast neutrons depending on the incident proton energy and neutron scattering angle, see Fig. 1.
- The excess of fast neutrons can be reduced by using protons at lower incident energy, or deuterons, though with the consequence of reducing the total number of fast neutrons.
- The goal of 10^{12} fast neutrons on a fission target can be fulfilled with tungsten by placing a foil of ^{238}U in the forward direction, spanning a cross sectional area of about 10 cm x 10 cm approximately 10 cm from the neutron converter.

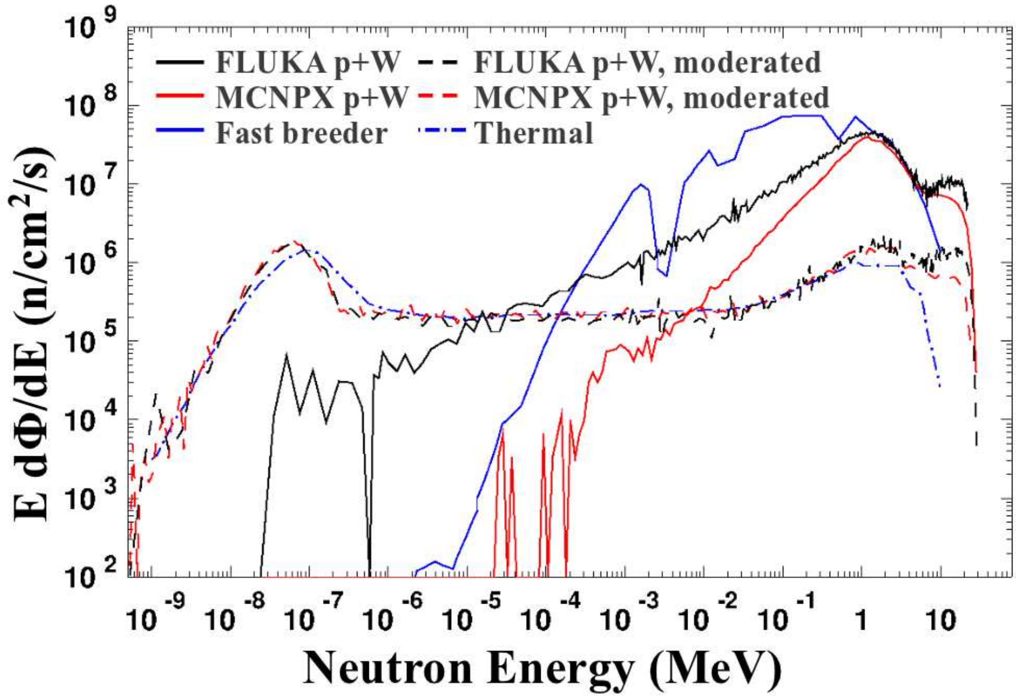

Fig. 1: Simulated neutron spectra for 30 MeV protons on a thick tungsten targets, with and without 10 cm of moderator, compared with typical spectra for light water (thermal) and fast breeder reactors. The discrepancy between MCNPX and FLUKA is clearly seen for the unmoderated spectra. There is an excess of high energy neutrons in comparison with the reactor spectra, due to the high energy of the incident protons.

– The use of heavy metal reflectors behind the fission target only slightly increases the effective neutron flux, and mainly at low energies. Furthermore it means that more material will be exposed to neutron activation, increasing the radiotoxicity of the assembly.
– The use of beryllium instead of tungsten increases the fast neutron flux with about a factor of seven, and the total neutron flux with about a factor of four.

The simulations of neutron production were initially performed with MCNPX [6], and later on the work was cross checked through independent simulations with FLUKA [7, 8]. FLUKA has also been used for determining the geometrical distribution of the heat deposition within the target, and for calculations of induced radioactivity within the target and surrounding material. Heat transfer and the need for cooling has been studied with COMSOL Multiphysics [9].

Some discrepancies between MCNPX and FLUKA have been observed both in the shape of the neutron fields and in their absolute magnitude, see Fig. 1 for an example with 30 MeV protons on tungsten. So far, the reasons for the discrepancies have not been fully sorted out, but it should be pointed out that incident proton energies below 50 MeV are relatively challenging for the models used in the Monte Carlo codes. Whatever the reason, the discrepancies do not change any conclusions regarding the design of the neutron converter, but may impact the information used for normalization of experimental results. The reference measurement (see Sec. 5) and comparison with other measurements will help to reduce these uncertainties.

4 Towards a final design

The option of using beryllium was initially discarded due to concerns about its toxicity, but when it became clear that it would significantly increase the fast neutron flux the issue was reconsidered. It was decided to aim for a design where factory made pieces of beryllium can be used in a flexible target holder without any further machining, and where the structural integrity would be preserved as far as possible.

When the development of the LENS target at Indiana University Cyclotron Facility [10] came to our knowledge a similar approach was pursued. In brief, the idea is to make the target slightly thinner than the full stopping length, and to have the cooling media (water) directly on the back side of the target plate. The effect is that the noninteracting protons stop in the cooling water instead of in the target, thus significantly reducing hydrogen buildup. Furthermore the main part of the Bragg peak will occur in the cooling water, reducing the need of a high flow rate of cooling water. The neutron production will only be reduced by less than 10% as the energy of the outgoing protons are near the neutron production threshold.

A design has been proposed and decided upon, where the beryllium disc is pressed against an O-ring that ensures a vacuum tight assembly where no water will leak into the beam pipe, see Fig. 2. The risk can be further reduced by having the beam pipe ending with a thin window of havar or steel in front of the target assembly [11]. With such a design the target assembly can be positioned relatively freely within the IGISOL experimental chamber, without any need of tight attachement to the beam pipe [12]. This will speed up the procedure of removing the assembly, thus reducing exposure of personnel to radioactivity.

The design will allow the use of different target materials and target thicknesses. It may be feasible to construct several identical target assemblies, if need be one can then quickly replace the entire assembly instead of wasting time with opening the assembly for exchange of the target disc. By using thinner beryllium targets, or targets of other materials, different neutron fields can be used for intercomparison.

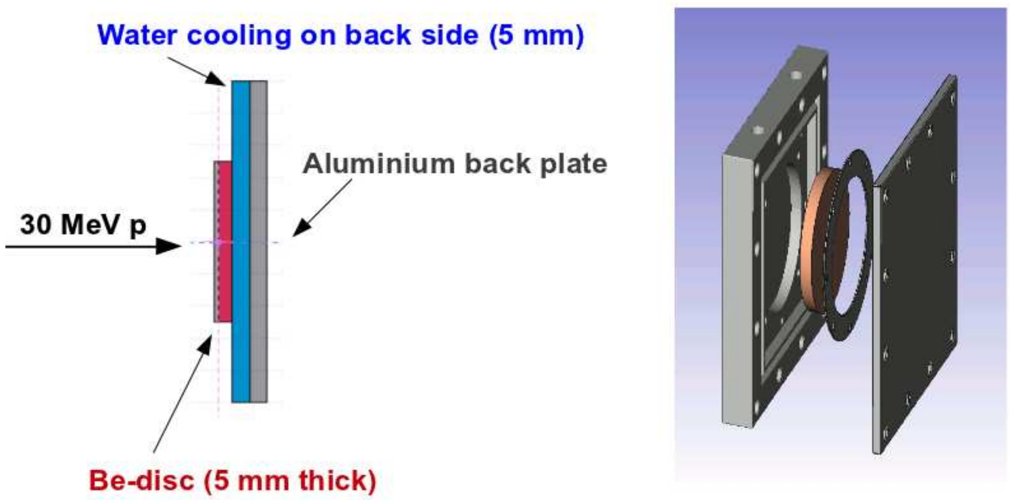

Fig. 2: Principle drawing (left) of a beryllium neutron converter for the IGISOL project. Protons will loose most of their energy within the target, the neutrons that do not cause any nuclear reaction will be fully stopped in the water layer behind the target. CAD drawing of the target assembly (right) by D. Gorelov.

5 Reference measurement at TSL

Besides sorting out the observed discrepancy between the predicted neutron fields from the Monte Carlo codes MCNPX and FLUKA, it is of importance to have a reference measurement from a target assembly of similar design as the one that will be used at the IGISOL facility. Therefore an ERINDA funded experiment [13] was performed with a mockup of the target assembly. The neutron field in the forward direction was measured, varying several parameters. Two different measurement methods were used, Bonner Sphere Spectrometers (BSS) for energies from the thermal range up to about 20 MeV, and a Time-of-Flight measurement with a liquid scintillator for the energy range 5-30 MeV. Analysis is approaching the final stages and some preliminary results and status reports have been reported at different occasions [14–16]. More details are given elsewhere in these proceedings [17].

6 Present status and outlook

In June 2013 the first experiment with the new IGISOL-JYFLTRAP facility was performed, where isomeric yield radios from selected proton-induced fission products were measured in an ERINDA funded experiment [18, 19]. This was an important first step of improving the performance of the JYFLTRAP, and the experimental results will be assessed before introducing the neutron converter, which is being constructed during the winter 2014.

Although a the general design and the selection of beryllium as target material has been decided, there are still a number of issues to look closer at:

- Activation of the target and surrounding material: Preliminary studies were initally performed using FLUKA and are now being followed up in more detail. This is of importance in order to work out strategies for how to handle the target and planning for other experimental work in the IGISOL chamber.
- Radiation protection during experimental runs: The IGISOL experimental hall is situated behind heavy concrete shielding, with the data taking area being on the outside of the concrete, adjacent to the JYFLTRAP. Due to the high intensities from the new MCC30/15 cyclotron the neutron flux in the full geometry of the experimental facility is being simulated as a precaution.
- The MCNPX/FLUKA discrepancy: We are performing a systematic intercomparison between the two codes, varying different parameters in order to try to pinpoint the reasons for the discrepancy. Earlier discussions with members of the FLUKA development team did not reveal any user error, but a close scrutiny of how both codes are handled will be performed. If no reason is found the issue will be brought up again with the FLUKA and MCNPX development teams in order to find out the reason. It should be mentioned that both development teams expect better agreement between the two codes.
- Neutron background: The neutron flux within the IGISOL chamber will have a background that is dominated by scattering from the chamber itself. To a smaller extent there will be a contributions from different objects and surrounding concrete in the IGISOL experimental hall. The magnitude of these background sources will have to be assessed and eventually corrected for, depending on the type of experiment. In Fig. 3 is an example from FLUKA simulations where the neutron field from the bare target assembly (both options of beryllium and tungsten are shown) is compared with the same target inside the IGISOL chamber. The figure also show the effect of introducing a polyethylene moderator between the target assembly and the fission target. As seen there will be a thermal neutron peak due to scattering in the IGISOL chamber itself. In spite of this, a moderator material may still be useful in order to modify the neutron spectrum.
- Gamma-induced effects: So far only rough estimates have been made on the effects of intense gamma flux from the converter, mainly on the fission rate. The contribution is relatively small but not negligible and needs to be assessed.

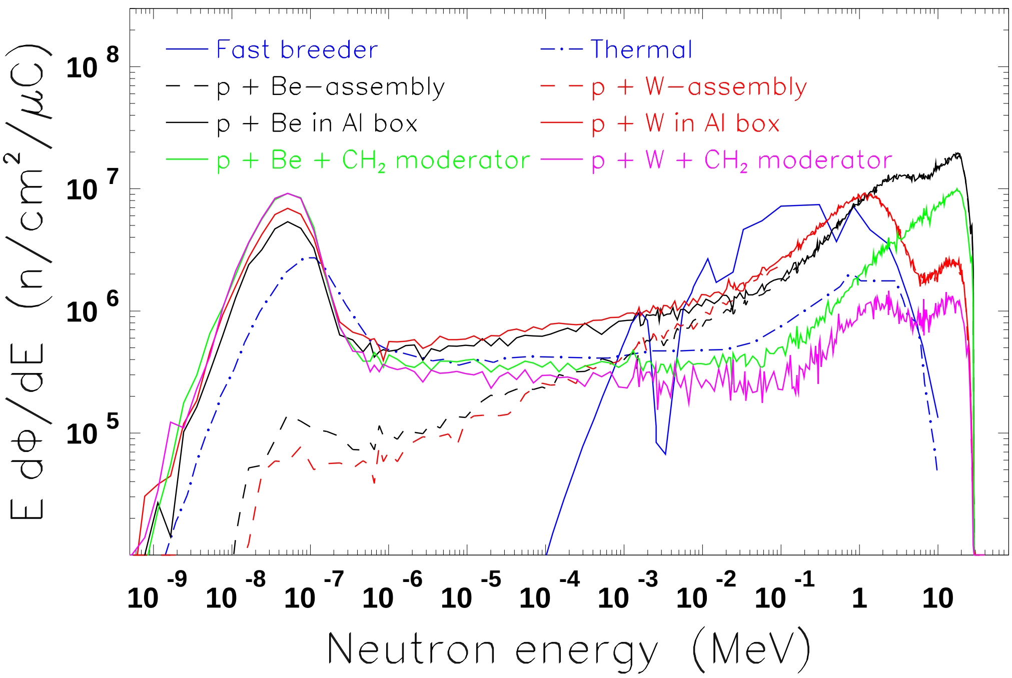

Fig. 3: FLUKA simulation with example of how the neutron spectrum from the target assembly (dashed lines) is affected by the IGISOL target chamber (solid lines) and the inclusion of a 10 cm thick CH_2 moderator block (solid green and magenta lines). The difference in neutron spectra between beryllium (black and green lines) and tungsten (red and magenta lines) is also shown.

– Varying beam and geometries: With a relatively flexible target assembly one can use deuteron beams in order to vary the neutron spectrum. Reduction of proton energy is also a possibility in order to vary the neutron energy distribution. One can also consider placing the fission target at a different angle with respect to the beam direction, within the geometrical constraints given by the ion guide and the IGISOL chamber. These options need to be studied closer before being implemented.

It should be noted that a neutron converter with the suggested design can be constructed and used for measurement campaigns with relatively short notice, disregarding some of the study areas mentioned above. But for absolute normalization and disentangling of the energy dependence of the fission yields, there is plenty of work left to do, both through simulations and through further analysis of the experimental data from the measurement at TSL. It may also be fruitful to verify the actual neutron field within the IGISOL experimental chamber. Thin-film breakdown counters (TFBC) [20] in combination with neutron activation methods, similar to how they were used in another ERINDA funded experiment [21] could be a suitable solution. The use of TFBCs may also be considered as a permanent monitor of the actual neutron flux as they are small and rather radiation resistant.

7 Deliverables

The preliminary designs have been presented at various scientific meetings, one purpose being to obtain feedback from other researchers based on their experiences. References [5, 11, 12] discuss directly technical details around the design of the neutron converter, while refs. [14–17] are status reports on the analysis work of the data from the measurement on a mock-up target at the ERINDA funded experiment at TSL in June 2012 [13]. A more extensive article on the design is being prepared [22]. The ERINDA scientific visit has also enabled members of the Uppsala group to participate in stable ion-beam tests at IGISOL-JYFLTRAP as part of the recommisioning of the new facility [23].

8 Conclusions

The objective of the scientific visit to Jyväskylä has been met as the basic properties for the design of a neutron converter have been determined. A flexible design has been proposed that can fulfil some essential boundary conditions and the somewhat contradictory requirements for fundamental research versus nuclear data taking in view of applications. Further work is necessary in order to obtain better knowledge of the neutron flux and other properties, but most of these issues are of importance mainly in the analysis step. Therefore the neutron converter is ready to be constructed.

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