Accurate FissiOn data for Nuclear Safety (AIFONS)

Final report

S. Pomp, M. Lantz, A. Solders, A. Mattera, V. Rakopoulos, A. Al-Adili, A. Prokofiev

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Summary

This report summarizes the results of the Accurate FissiOn data for Nuclear Safety project, AlFONS, supported by the Swedish Radiation Safety Authority (SSM), and the Swedish Nuclear Fuel and Waste Management Company (SKB). The formal duration of the project was from 2010-07-01 until 2014-06-30. While the research work discussed here is still continuing, results reported here include work until 2014-12-31.

Within AlFONS we aimed at measuring independent fission yields (sometimes called isotopic yields after the fission process but before subsequent β-decay) in neutron-induced fission of actinides in, primarily, the fast energy range. Reference measurements for thermal neutrons are also aimed for.

The project included extensive research and development to allow for this new type of measurement at the Ion Guide Isotope Separator On-Line (IGISOL) and the Jyväskylä Penning Trap (JYFLTRAP) of the University of Jyväskylä, Finland. The facility has been equipped with a new cyclotron allowing for higher proton beam intensity in an energy range suitable for production of the secondary neutrons that finally induced the fission events. The IGISOL facility and JYFLTRAP had to be moved to a new beamline and commissioned.

The development work at Uppsala University focused on design and characterization of the neutron production target to be used at IGISOL. To this end, measurement campaigns at The Svedberg Laboratory, Uppsala, Sweden, and at IGISOL have been carried out.

Due to various technical problems the project is delayed and it was so far not possible to conduct the planned measurements during the time allocated for the project. However, the new facility, IGISOL-4, is now operational and the neutron production target has been tested on site in 2015. First real measurements will be performed in 2015.

The report gives an introduction including a motivation for the measurements, describes the experimental setup and techniques, including target simulations and test measurements, summarizes recent results and ends with an outlook, an overview of administrative matters, a list of references, and a list of publications resulting from the AlFONS project.
1 Background

1.1 The AlFONS project

The present project, Accurate FissiOn data for Nuclear Safety (AlFONS), supported as a research task agreement by the Swedish Radiation Safety Authority (SSM), and the Swedish Nuclear Fuel and Waste Management Company (SKB), started 2010-07-01. The primary objective is to promote research and research education of relevance for development of the national competence within nuclear energy.

The aim of the project in a wider context is to:

- promote development of the competence within nuclear physics and nuclear technology by supporting licentiate and PhD students,
- advance the international research front regarding fundamental nuclear data within the research area of present and future nuclear systems,
- strengthen the Swedish influence within the mentioned research area by expanding the international contact network,
- provide a platform for Swedish participation in relevant EU projects,
- monitor the international development for the supporting organizations, and
- constitute a basis for Swedish participation in the nuclear data activities at IAEA and OECD/NEA.

The project is operated by the Department of Physics and Astronomy, Division of Applied Nuclear Physics, at Uppsala University (hereafter called TK, the abbreviation of the Swedish division name Tillämpad Kärnfysik).

This document is the final report summing up the activities from the projects start until six months after the formal end of the project on 2014-06-30, and giving an outlook for the future continuation work.
2 Introduction

2.1 The need for nuclear data in future nuclear systems

For nuclear power applications there are a large number of physical properties of nuclides that need to be known. Measurements of these properties have been performed since the 1940's, with focus on cross-sections for different neutron-induced reactions on U-235, U-238 and Pu-239. An important side effect of nuclear fission is the creation of fission products, and substantial experimental efforts have been made to also measure the properties and distributions of these products. Typical properties measured are the mass, the charge and the kinetic energy of individual fission products. There are a number of definitions used, but a common name for these properties is fission yields.

The fission yields for thermal neutrons on U-235 have been measured with relatively good accuracy. However, as illustrated in Fig. 1, in the tails and the valley of the mass distribution the yields are generally not known to better than 40% (relative uncertainty). In the latest ENDF/B-VII.1 evaluation of the thermal neutron fission of U-235 only 106 independent yield ratios, out of the 998 tabulated, have relative uncertainties smaller than 10% [1]. For other yield sets the situation is generally worse.

In a supplement to WRENDA 93/94 - World Request List for Nuclear Data [2] the International Atomic Energy Agency (IAEA) concludes that for independent neutron induced fission yields practically all fissioning systems need to be further investigated and that it is recommended to measure the energy dependence of yields for neutron energies ranging from thermal to very high.

Figure 1. Mass yield distribution of thermal neutron-induced fission on U-235 (black squares) from the ENDF/B-VII.1 library [1] together with relative uncertainties of the thermal yields from the same library (red bars) [3].
2.2 The importance of fission yields

Accurate knowledge about fission yields distributions is of importance for a better theoretical understanding of the fission process itself. Besides theoretical development there are also a number of applications related to nuclear power generation where better knowledge is beneficial, for instance:

- information about the composition of the resulting spent fuel (spent fuel repositories, partitioning and transmutation issues, Gen-IV reactor scenarios),
- various safety measures (decay heat, fission gas production, criticality, dosimetry, safeguards, delayed neutrons),
- information about neutron poisoning (significant discrepancies between different evaluations have been identified, especially for Xe-135, Sm-149 and Gd-157), and
- improvement of burn-up predictions.

The well-known shape of the fission yield mass distribution with two peaks around mass number $A = 95$ and $A = 135$ is characteristic for the thermal neutron field in a light water reactor (LWR) with U-235. But, as shown in Figs. 2a and 2b, the mass distribution varies with neutron energy, and it also depends on the initial actinide. Therefore systematic measurements at different neutron energies and for different fission target nuclides are of importance. Furthermore, the mass distributions seen in Figs. 2a and 2b reflect the situation for many experiments where only the masses of the fission products are determined, though usually in combination with other observables such as kinetic energy. Therefore it is valuable to obtain independent fission yields as complementary information to other data. It should be mentioned that independent fission yields are defined as the percentage of atoms of a specific nuclide produced directly in fission reactions, i.e., after emission of prompt neutrons but before radioactive decay has occurred.

**Figure 2a.** Fission yields (in %) as a function of mass as given in the ENDF/B-VII.1 evaluation for neutron-induced fission of U-235 for different incoming neutron energies: thermal (0.0253 eV, red), fast (500 keV, green) and high energy (14 MeV, blue). The plot was produced with JANIS [4].
Figure 2b. Fission yields (in %) as a function of mass as given in the ENDF/B-VII.1 evaluation for fission by thermal neutrons of Th-229 (green), U-235 (blue) and Pu-239 (red). The plot was produced with JANIS [4].

2.3 International outlook

Partly as a result of the call from the 1990’s by the International Nuclear Data Committee of the IAEA for new experimental data [1], the last decades has witnessed an increased interest in measurement of fission products, so that we are presently witnessing a renaissance of experiments on fission yields [5]. This section will cover some of the experimental techniques being used in recent and planned experimental programmes at different laboratories.

2.3.1 Gamma-ray spectrometry

Since 2008, a new effort in the measurement of fission products has been undertaken at the ILL (Institut Laue-Langevin) facility, where the Lohengrin mass separator and a high resolution ionization chamber is installed. This setup was complemented with a moving implantation-tape and gamma-spectrometry station to extend the measurement of isotopic yields to masses A > 42 [6].

2.3.2 Measurement of unstopped fragments

Many of the new experimental efforts in the measurement of fission products yields are aimed at a multi-parametric measurement of the unstoped fission fragments. These use the principle described in the previous section to determine the mass A and the charge Z of the fission products. Since fission products are identified on an event-by-event basis, this opens the way to multi-parameter experiments, where the mass of the fission products are correlated with other observables (such as gamma or neutron multiplicities). This is the case, for example, of the STEFF setup. Here the nuclei are identified measuring their velocity and energy (2E-2v technique) and the emitted prompt gamma energy and multiplicity are measured in coincidence. Experimental runs have already been performed at ILL, showing a mass resolution of 4 AMU. Work is now being performed to improve this figure and new experiments are planned at the new Experimental Area 2 of nTOF, at CERN [7].
At the Joint Research Centre of the European Commission IRMM in Geel, Belgium, there is an extensive programme on measuring fission yields with Frisch-Grid Ionization Chambers. We have an ongoing collaboration on such measurements, especially concerning fission of U-234 [8], and plan to extend this to include measurements with the VERDI setup [9]. The latter uses, like STEFF and SPIDER (see below) the 2E-2v technique and will achieve a mass resolution at about 1 AMU.

New experimental setups are also being built at Los Alamos Neutron Science CEnter (LANSCE) - with the SPIDER spectrometer, a development based on the 2E-2v technique that was behind *Cosi fan tutte* [10] - and at the NFS facility, at GANIL, where the FALSTAFF spectrometer will be installed [11].

**2.3.3. Experiments in inverse kinematics**

New experimental programs are also being developed exploiting the availability of new heavy ions beams to perform experiments in inverse kinematics. In this concept, a beam of actinides or pre-actinides is impinged on a heavy mass target, where it fissions. The SOFIA (Study On Flssion with Aladin) experiment at GSI [12] and the VAMOS spectrometer at GANIL [13] both aim at extensive and systematic studies of fission in a mass range spanning from pre-actinides (A = 180-210) up to heavy actinides (A > 238). The great advantage of this technique is the possibility to study the fission of very exotic and/or radioactive actinides, that usually are very difficult or even impossible to produce in the amounts and purities needed for a neutron-irradiation experiment.

**2.3.4 European projects and framework collaborations for transnational access**

There are a number of projects within the 6th and 7th European framework programmes, and within the new Horizon-2020 programme, with focus on fission-related experiments. Some recently finished programmes are EFNUDAT (European Facilities for Nuclear Data Measurements), EUFRAT (European Facility for innovative reactor and transmutation neutron data), ERINDA (European Research Infrastructures for Nuclear Data Applications) and ANDES (Accurate Nuclear Data for nuclear Energy Sustainability). The Applied nuclear physics division at Uppsala university has had some involvement in all of these programmes, partly with direct relation to the AlFONS project.

A new project within the 7th European framework program is CHANDA (solving CHAllenges in Nuclear Data). We are one of the 35 partners within the CHANDA project which supports our activities in model developments with the TALYS and GEF code, and our experimental work at NFS, GANIL and at IGISOL.
2.4 Scientific scope of AlFONS

The group being involved in the AlFONS project at the Applied Nuclear Physics Division (TK) collaborates mainly with the IGISOL group at University of Jyväskylä (JYFL). The purpose is to measure neutron-induced independent fission yields of different actinides of relevance for partitioning and transmutation of spent fuel and for other aspects where information on nuclear fuel inventories is important. The project will use the upgraded IGISOL-JYFLTRAP facility at the accelerator laboratory of the University of Jyväskylä. The Jyväskylä group is on the forefront when it comes to accurate measurements of reaction products from nuclear interactions involving short lived nuclei. With the Ion Guide Isotope Separator On-Line (IGISOL) technique high yields of reaction products are selected and in the JYFLTRAP Penning trap the mass of the selected species can be accurately determined. This method has also proven to be very useful for the determination of independent fission yields using the trap as a high precision mass filter. So far experiments have been performed with 20-50 MeV protons on Th-232 and U-238, and with 25 MeV deuterons on U-238 [14].

The objective of the AlFONS project is to develop a neutron source to be coupled to the IGISOL-JYFLTRAP facility, enabling measurements of independent fission yields from fast and thermal neutrons on different actinides of relevance for present and future nuclear systems. The neutron source is realized as a neutron converter where a proton beam from an accelerator impinges on a beryllium disc, knocking out neutrons. The main focus of the project has so far been on the design of the neutron converter in order to characterize the neutron fields and ensure that the structural integrity of the converter is not compromised due to heat deposition, chemical effects or structural damage. Details on the experimental work will follow in the next section.
3 Experimental setup and techniques

3.1 The IGISOL-JYFLTRAP facility

The description of the experimental technique applies both for charged particle beams and neutron beams, and the principles are the same irrespective of if it is fission products or other kinds of reaction products that are measured. The principle layout of the IGISOL-JYFLTRAP facility is shown in Fig. 3 for the case of using a neutron converter in order to measure independent fission yields with fast or moderated neutrons down to thermal energies. The considerations for a neutron converter are discussed in Section 3.2.

Figure 3. Layout of the IGISOL-JYFLTRAP facility (schematic view in the inset). A particle beam enters from the top left impinging on a neutron converter, resulting in a neutron field causing fission in an actinide target. The fission products are accelerated by an electrostatic field, and transported through a dipole magnet for mass selection, followed by an RFQ cooler and buncher for improvement of the beam properties. The cooled ions are injected into the Penning trap for accurate mass determination and finally the count rate is determined by sending the ions to a Multi-Channel Plate detector (MCP). CAD drawing by Tommi Eronen.

3.1.1 Particle beams

The IGISOL facility was moved in 2011 to a new experimental area within the JYFL laboratory, and a general upgrade of the facility was performed. An important addition is a new MCC30/15 cyclotron providing protons in the energy range 18-30 MeV and deuterons of 9-15 MeV [15]. For protons a beam current of 100 μA or more is expected, making it possible to consider high intensity neutron beams. After some initial tuning problems the new cyclotron commenced operation during the spring of 2013. Together with the older K-130 cyclotron, that provides protons at energies up to 130 MeV, more than 4000 hours of beam time can be provided annually for the IGISOL facility.
3.1.2 Reaction (fission) chamber and ion guide

The reaction chamber contains the beam target from which reaction products or fission products are ejected. The target has to be thin enough to allow the fission products to escape from it. Helium or other noble gases are used as buffer gas that flows through the reaction chamber. The gas pressure in the chamber is about 200 mbar, which is enough to stop fission products with energies less than 2 MeV. Fission products with higher energies are lost as they will hit the chamber walls. The fission products are initially completely ionized, but rapidly change their charge state through interactions with the buffer gas. Due to the high ionization potential of noble gases, a large fraction of the products retain a 1+ charge state. The gas flow transports the fission products out of the chamber into an ion guide that centers them on the axis and accelerates them by means of an electrostatic potential in steps to a kinetic energy of about 30 keV.

3.1.3 Mass selection, beam refinement, and mass determination

The accelerated ions are sent through a 55° dipole magnet with mass resolving power up to 500 for a first mass selection. At this stage the ions have a relatively large transverse emittance and energy spread. Therefore they are refined in a gas-filled Radio Frequency Quadrupole (RFQ) buncher and cooler before being injected to the JYFLTRAP two stage Penning trap. The Penning trap can be used to determine the mass of an ion by finding its cyclotron frequency in a strong magnetic field. The cyclotron frequency of the oscillating ion can be probed by applying an alternating quadrupole potential to a set of segmented ring electrodes and the mass can be determined through the relation \( f_c = \frac{1}{2\pi} \left( B \cdot q/m \right) \). Here \( f_c \) is the cyclotron frequency of the ion with charge \( q \) and mass \( m \), oscillating in an external magnetic field \( B \).

The trap can also be used as a high resolution mass filter. By first subjecting the ions to a dipole oscillating field, followed by a mass selective quadrupole field combined with a buffer gas, only those ions for which the frequency of the applied field matches the cyclotron frequency are selected. Finally the selected ions are ejected from the trap through a narrow aperture and are detected at a Multichannel Plate Detector (MCP) where the count rate is measured as a function of the quadrupole frequency. This method selects ions with a mass resolving power of up to \( 10^5 \) which means that it is possible, through peak fitting, to resolve metastable states that are 0.5 MeV apart.

The total time from fission product emission in the reaction chamber to detection in the MCP is a few hundred milliseconds, enabling the determination of the independent fission yields for a large selection of nuclides.

3.1.4 Potential difficulties with the ion guide technique

The experimental method has some potential limitations that need to be considered:

- The low stopping power of the helium gas only stops about 1% of all fission products. This could potentially lead to a bias in which fission products that are being studied.

- To a first approximation the ion guide technique is insensitive to chemical properties as ions of any element can be produced. But some elements rapidly form oxides, and there are several elements that tend to be extracted as 2+ ions.

- It may be relevant to consider whether there is some sort of mass dependence in how well different fission products are transported by the ion guide.

- For fast neutrons there may be non-isotropic effects on the spatial distribution of fission products due to the fact that the incident particle brings high momentum into the fissioning system.
A dedicated investigation was performed by comparing the isotopic yields of Rb and Cs isotopes obtained in proton-induced fission of U-238 with high quality data from a different experimental method. The results were found to be in good agreement. Further cross checks have been performed by comparing results with some experiments performed at Tohoku University. The Tohoku experiments use a similar ion guide technique, but the different geometry compared with IGISOL allows useful inter-comparisons of several of the concerns, usually with reasonable agreement [16].

Also the Penning traps have chemical effects to consider. Several cross checks, including calibration with alpha recoil sources or fission sources placed inside the ion guide, have been performed or have been suggested. Other concerns are corrections for decaying isomers, the accumulation of decay products in the trap, and time dependent variations of the count rate. An important remedy for the latter uncertainty is that for all measurements there are data taken during the same run for known reference masses, enabling data renormalization.
3.2 The nIGISOL project

Although most fission yield experiments at IGISOL were performed with protons, two attempts have been made with neutrons, showing that the ion guide technique is feasible also for such measurements. In those tests the $^{12}$C(d,xn) and $^{13}$C(p,xn) reactions were used, and the incident beam currents were a few $\mu$A. In the present project higher neutron yields are sought through proton- or deuteron-induced reactions on other target materials, and with the new MCC30/15 cyclotron that provides higher beam currents.

3.2.1 Design considerations

For the introduction of a neutron source to the IGISOL facility there are several issues to consider:

- **Neutron yield:** In order to be competitive in comparison with other experimental facilities, in studies of nuclides far from the stability line, the neutron converter should be able to deliver about $10^{12}$ fast neutrons ($E_n > 1$ MeV) on a U-238 target.

- **Neutron energy spectra:** For studies of independent fission yields of relevance for nuclear power applications the incident neutrons should have an energy distribution resembling those in light water reactors (LWR) or fast reactors. This objective may be difficult to achieve, and there may be background effects due to scattered neutrons within the experimental area. Mono-energetic neutrons are also considered.

- **Cooling issues:** With 30 MeV protons of 100 $\mu$A beam intensity or more, at least 3 kW of heat is deposited into a very small volume of the neutron converter. Therefore sufficient cooling of the converter has to be provided, and the number of suitable converter materials becomes limited.

- **Activation and structural integrity:** The neutron converter will become activated through the reactions with protons or deuterons, and the produced neutrons will activate surrounding materials. This may reduce access to the facility after irradiation. Furthermore, the converter may suffer structural problems through hydrogen buildup if it is thick enough to fully stop protons or deuterons. For thinner targets the residual beam may activate other material.

- **Flexible design:** Several of the issues above can be handled by using different materials and thicknesses. This requires a design where the converter easily can be replaced with a new one, without complicated issues of breaking vacuum and risk of leakage of the cooling media. Furthermore, for toxic materials such as Be, a design is required that reduces the amount of handling and machining of the converter material.

With these issues in mind Be and W converters with different geometries have been considered. Both materials have high melting points and heat transfer properties, and may be coupled mechanically to a cooling device. The requirement of high neutron intensity may be fulfilled by placing the converter very close, 5-10 cm, to the fission target. Monte Carlo codes have been used in order to estimate the neutron flux for different options. Figure 4 shows neutron spectra for Be and W converters, with and without moderating materials for the use of neutrons down to thermal energies.

It should be mentioned that due to the close proximity of the fission target the overall neutron yield will be much higher than for many other facilities, where the flight path between the neutron source and the target usually is several meters. As clearly seen in both figures, a Be converter gives many more fast neutrons than W and therefore it was decided to use it for the converter, in spite of slightly worse heat resistance and more difficult handling of the material.
3.3 Simulation codes

Various computer codes are routinely being used throughout the AlFONS project, not the least for the design and validation of the neutron converter. Here the use of a few of them, and related issues, will be briefly described.

Simulations of the neutron flux have been performed with the Monte Carlo codes FLUKA [17] and MCNPX [18]. As seen in Fig. 4b it is relatively easy to moderate neutrons in such a way that the low energy part resembles that of an LWR, while Fig. 4a shows that it is difficult to obtain fast neutron spectra similar to those in fast reactors. For the fast spectra in Fig. 4a the simulations also reveal some significant discrepancies between the two Monte Carlo codes. The reasons for these discrepancies have not been determined, but as the codes have different physics models and handle the simulations in different ways it is important to use more than one code, and compare with existing experimental data, in order to determine which simulations to rely on. The two codes will be further used for studies of the neutron flux and for verification that the radiation shielding of the IGISOL facility is sufficient for the planned measurements with high intensity beams.

Studies of the need for cooling of the converter have been performed with COMSOL Multiphysics [19]. Both for Be and W it has been possible to identify geometries thick enough to fully stop 30 MeV protons that can be sufficiently cooled by a flow of water in a closed loop.

The Monte Carlo codes GEANT [20] and SRIM [21] have been used for initial studies of the ion guide efficiency. During these studies certain limitations in the models were identified. Therefore further work and model development is planned in order to optimize the capture of the fission products.
3.4 Approaching a final design

Taking into account all the initial criteria given in Sec 3.1 and 3.2, and the results from the simulations, a design has been agreed on that fulfills most of the criteria. The design is inspired by the LENS target developed at Indiana University Cyclotron Facility (IUCF), where a Be target slightly thinner than the full proton stopping length is used [22]. The target is assembled in a holder and acts as a window between the evacuated beam pipe on the upstream side, with a 0.5 cm thick layer of cooling water on the downstream side. By not stopping the protons within the target itself the cooling requirement is drastically reduced, as is the risks of structural degradation from hydrogen buildup. The reduction in neutron yield is about 5%. The main drawback is that there may be chemical effects in the cooling water due to the stopping of protons in it, and possibly also some induced radioactivity. In order to avoid exposure to beryllium dust, target cylinders are bought at standard dimensions from commercial utilities and are used without any further machining. The holder uses O-rings on both sides of the plate in order to ensure an airtight assembly. Furthermore a second window, made of steel or havar, will be inserted in the beam pipe in order to reduce the effects in case of a water leak. The principle design of the prototype converter is shown in Fig. 5.

Figure 5. Left: Principle geometry for the neutron converter, having a 5 mm thick beryllium disc so that 30 MeV protons are stopped in the water layer after the disc. Right: Design of the prototype used for the benchmark experiment at TSL and for the first tests at IGISOL.
3.5 Benchmark experiment at TSL

Due to the discrepancies in predictions between FLUKA and MCNPX it was necessary to compare the simulations with experimental data. The few experiments performed in the relevant energy range all have some question marks of relevance, and none of them cover the full energy range. Therefore, it was deemed necessary to perform a reference measurement that could provide some guidance on how to interpret the simulated results.

Through the EU-funded ERINDA framework programme, beam time was obtained for a measurement of the neutron energy spectra from a Be converter resembling the preliminary design.

The experiment was performed in 2012 at The Svedberg Laboratory (TSL), using a cyclotron beam of 37 MeV protons degraded to 30 MeV at the position of the Be converter. Outgoing neutrons were measured with Bonner Sphere Spectrometers, covering the range from thermal energies up to about 20 MeV, with a \(^7\)Li(Eu) scintillator as thermal neutron detector. In parallel a NE-213 liquid scintillator, allowing n-\(\gamma\) pulse shape discrimination, was used for a Time-of-Flight (ToF) measurement in the energy range 5-30 MeV, thus providing a good overlap region for intercomparisons between the two methods. The ToF data were saved on two different data acquisition systems, one with pre-set thresholds, and one where the detector pulses were saved event by event for off-line analysis. Figure 6 shows a time-of-flight spectra from the analysis with pre-set thresholds, where the detector pulse shape enables the discrimination of gammas from neutrons. The identified photons are used for the time calibration.

![Figure 6. Pulse-shape discriminated time-of-flight spectra showing the photon (blue) and neutron (red) events detected in the NE-511 liquid scintillator. Photons from different objects along the proton beam line are clearly identified.](image)

The experiment was performed with different settings, including background measurements with shadow cones and with slow neutrons moderated through polyethylene. For the ToF measurement it was also possible to vary the thickness of the Be converter. It is important to stress that the background conditions at TSL are very different from those at IGISOL due to different geometries around the converter. By having a controlled experiment to compare the simulations with the intention was to make better predictions of the neutron spectrum that induces the fission yields measured at IGISOL.

Simulations showed that the low energy neutron background at TSL was significant. This is also expected at IGISOL and has to be taken into account. For measurements on actinides such as U-238
with a high energy threshold for fission the background is of no importance, while for actinides with high fission cross sections at thermal energies, such as U-235, the effects may be significant. Furthermore, high energy photons may induce photofission. While having relatively low cross sections, the effect should be estimated from the measurements and from simulations. The analysis from the measurements has been finalized during the fall 2014 and is the basis for the Phil. Licentiate thesis of Andrea Mattera.

Figure 7. FLUKA simulation of neutron flux at the experimental setup in the Blue Hall at TSL. The 37 MeV protons enter through a beam pipe from the left and goes out in open air (at x = 0), followed by a degrader (x = 50 cm). Then it passes through a rectangular collimator (x = 100 cm) followed by a cylindrical collimator (x = 180 cm) and the neutron converter (x = 200 cm). To the right of the neutron converter the shape of a shadow cone is seen. The protons produced within the shadow cone come from neutrons absorbed within it.
3.6 Calibration measurement at IGISOL

In March 2014 the first test with a prototype neutron converter was performed within the IGISOL chamber at JYFL. 30 MeV protons from the new MCC30/15 cyclotron impinged on the beryllium disc, producing a neutron field that was measured with two different methods. A time-of-flight measurement was performed, using Thin-Film Breakdown Counters (TFBC) [23]. During the same experiment metal activation plates were used at four different scattering angles from 0 to 135 degrees.

![Image](image_url)

Figure 7. The prototype neutron converter, mounted on the end of the beam pipe (center of the picture), in a calibration measurement where activation plates (white squares wrapped in tape) were positioned at 0, 45, 90 and 135 degrees scattering angle. The proton beam enters from left through the beam pipe. In a full assembly the ion guide is positioned on the stand with bolts, and the reaction products are transported out through the hole in the top of the picture.

3.7 Other activities

After several years without access to laboratory facilities in Uppsala, the local infrastructure has started to be improved since a new laboratory for detector development has been taken into operation in late 2012. The division is also constructing a small 14 MeV neutron beam facility on the Ångström Campus site for detector testing and small size experimental studies. This facility is planned to be taken into operation during fall 2015.
4 Recent results

4.1 Neutron flux at TSL
The experimental setup was explained in Section 3.6. Two different measurement techniques were used, Time-of-Flight and Bonner Sphere Spectrometers, and for the TOF measurement two different data acquisition systems were used. The TOF part is the main content of Andrea Mattera’s Phil. Licentiate Thesis. Besides testing the prototype neutron converter, with and without moderator material, measurements were also performed with a thin (1 mm) and a thick (6 mm) Be target. Preliminary results have been presented at a conference, but the analysis will be finalized during 2015.

4.2 Fission yields from 25 MeV p+Th
In April 2010 and March 2014 an experiment to measure the fission yields from 25 MeV protons on a Th-232 target was performed at IGISOL. Data are presently being analyzed and will be part of the PhD thesis of Dmitry Gorelov at JYFL. An important aspect of this experiment is that both the old and new IGISOL facility were used. This will enable cross checks of the data, in order to sort out any systematic background effects.

4.3 Isomeric yield ratios from 25 MeV p+U
An ERINDA funded experiment was performed in June 2013 in order to measure isomeric yield ratios for a few selected nuclides. This was the first experiment with fission yields at the new IGISOL facility, and was seen as an important stepping stone before running a full experimental programme.

Besides full mass measurements with JYFLTRAP, nuclides were also analyzed with gamma spectroscopy. The data are being analyzed and will be part of the Phil. Licentiate thesis of Vasileios Rakopoulos during the spring 2015.

4.4 Neutron flux at IGISOL
Preliminary data are given in Andrea Mattera’s Phil. Licentiate thesis. Further analysis and a follow-up experiment are planned for the spring 2015.
5 Outlook

The first experiments at the upgraded IGISOL-JYFLTRAP facility were performed in June 2013, including a measurement of isomeric yield ratios from 25 MeV protons on U-238. The first test of the neutron converter in March 2014 will be followed by dedicated experimental campaigns during 2015. The plan thereafter is to begin a measurement programme with neutron-induced fission from a large U-238 foil with neutrons from the Be converter. Then a number of parameters can be changed in order to obtain different neutron energy distributions; reduced proton energy, use of deuterons, use of thin target, and use of different converter material. For thin target measurements semi-monoenergetic neutron beams will provide reference points. None of the neutron fields will agree with those in a reactor, but from measurements with different fields the energy dependence of the independent fission yields can be obtained and used in unfolding.

Another parameter to change is the fission target. Although it is the most obvious thing to change, it may be very difficult to obtain different target actinides of interest. Besides the practical difficulty of obtaining and manufacturing targets from some fissile nuclides, there may be regulatory restrictions making transfer of the material between different countries difficult or even impossible. It may seem a bit ironic that research of relevance for the development of safer nuclear power and safer handling of used fuel may be hindered due to rules regulating the safe handling of the very same nuclides. A preliminary wish list includes the following actinides:

- Relatively easy to access and handle: U-235, U-238, Th-232
- Somewhat more difficult to obtain: Np-237, Pu-239, U-234
- Very difficult to manufacture or handle: Pu-240, Am-243

In spite of these challenges there will be plenty of experiments to be done starting with U-238, both from an applications point of view and for fundamental research in nuclear structure. It is the ambition of the groups in Jyväskylä and Uppsala to make a long term commitment to this project. For a long term dedicated effort follows some challenges with respect to securing funding and to have continuity in manpower, not the least in order to attract talented students. It should be emphasized that the EU-funded programmes for transnational laboratory access (as, e.g., provide through CHANDA) are increasingly important in order to enable these kinds of projects, and for providing people with relevant expertise both for research and industry.
6 Administrative matters

6.1 Staff and students

The AlFONS project was led by Prof. Stephan Pomp.

Dr. Mattias Lantz, researcher, and Dr. Andreas Solders, researcher, shared the responsibilities for running the project. Dr. Ali al-Adili, researcher, has been involved in the experimental work, and is developing methods for analyzing the capture of fission yields in the setup.

Dr. Alexander Prokofiev from The Svedberg Laboratory, Uppsala University, expert on neutron field characterizations and TFBC detectors, was also involved in the project.

Two PhD students are directly involved and financed by the present project:

Andrea Mattera thesis work focuses on the characterization of the neutron converter for nIGISOL. He has presented and defend his licentiate thesis in December 2014 with Dr. Luca Zanini from ESS as external reviewer.

Vasileios Rakopoulos focuses on the obtained data from the fission yield experiments, and the gamma spectroscopy. He will defend his licentiate thesis during the spring 2015.

6.2 MSc student projects

Sara Wiberg, a student in the Engineering Physics programme, performed a pilot study of the efficiency of fission yield capture at IGISOL. The work was the basis for further studies, led by Ali al-Adili.

Arya Tavana, a student in medical nuclide techniques, has performed studies of the radiation shielding at IGISOL, using the MCNP Monte Carlo code.

Two MSc students, Joel Blomberg and David Gabro, have during the fall 2014 performed Monte Carlo calculations of the neutron shielding for the IGISOL facility.
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We thank the IGISOL team in Jyväskylä, especially Dr. Heikki Penttilä, Dimitri Gorelev, and Dr. Vasily Simutkin for their continued support and the fruitful collaboration. Vasily was also involved in the experimental work in Uppsala during his time as postdoctoral fellow in Uppsala.

The teams of Dr. Roberto Bedogni from INFN Frascati, Rome, Italy, and Dr. Andrea Pola from Politecnico di Milano, Milano, Italy, have contributed to the project with their Bonner sphere measurements at TSL.

Finally, special thanks to the staff of TSL for providing a suitable beam for our measurements and for the general support during preparation and performance of the campaign. We note with great sorrow that this unique and highly valuable facility will close down by the end of 2015.
References

References referred to in the document


Peer reviewed articles and conference proceedings within the AIFONS project


Oral presentations at conferences, workshops and meetings that are not peer reviewed


Oral presentations at conferences, workshops and meetings without any printed text


Student reports

