HORIZON 2020

HORIZON 2020 RESEARCH AND INNOVATION FRAMEWORK PROGRAMME OF THE EUROPEAN ATOMIC ENERGY COMMUNITY

Nuclear Fission and Radiation Protection 2018 (NFRP-2018-4)

Project acronym:	**SANDA**
Project full title:	**Solving Challenges in Nuclear Data for the Safety of European Nuclear facilities**
Grant Agreement no.:	**H2020 Grant Agreement number: 847552**

Workpackage N°:	***WP3***
Identification N°:	***D3.1***
Type of document:	***Deliverable***
Title:	Report on the meetings performed in the frame of ("Producer - user - interaction")
Dissemination Level:	***PU***
Status:	***VERSION 1***
Comments:	The details of the online meeting and the actual contributions to the meeting can be found at the CERN indico web page (https://indico.cern.ch/event/1064846/ also reachable from the calendar of the SANDA web)

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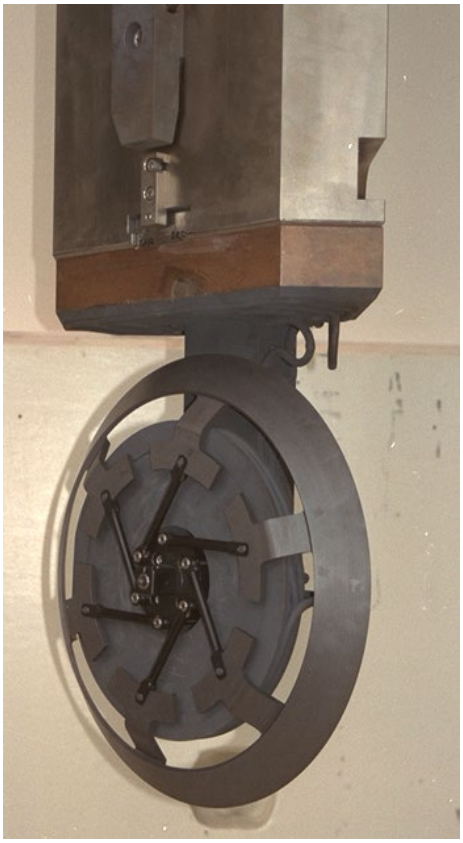
PAUL SCHERRER INSTITUT

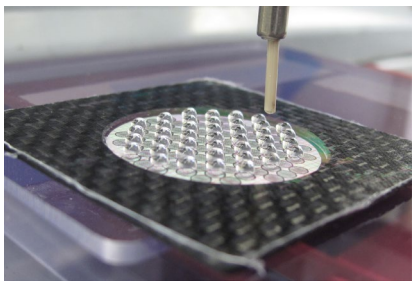
PSI

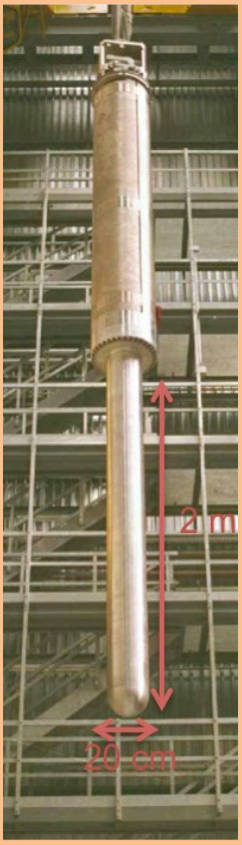
SANDA

2020/21

SANDA workshops for target production: Part I and II







Dorothea Schumann;Goedele Sibbens

SANDA WP3 - Target Preparation for Improvement of Nuclear Data Measurements
2020/21

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EDITORIAL

Dear participants of the SANDA I/II workshop,

I warmly welcome you to the target user-producer-interaction meeting in the frame of the SANDA project. SANDA means "**S**upplying **A**ccurate **N**uclear **D**ata for energy and nonenergy **A**pplications" (Horizon 2020 funding under Grant agreement 847552 — SANDA — NFRP-2018). To reach this ambigious goal, one of the indispensable tools in experimental research aimed to determine reaction cross sections is - besides a beam, a detector and an analytics system – a suitable and well-characterized target. In the NUPECC Long Range Plan 2017, this importance of isotope and target production is emphasized and supporting target makers is strongly recommended. In order to produce tailored targets meeting the specific requirements of the envisaged experiments, a tight interaction of the target makers with the "end-users", e.g. the researchers performing the experiment, is necessary. Target makers should learn as much as possible about the scientific background and the technical aspects of the planned experiment. In addition, researchers should know how the isotopes and targets for their experiments are produced to be sure to get the wanted material in the requested quality and quantity and without unwanted by-products and side effects. Target production on the nowadays requested level is never a routine operation. Every target is unique and its manufacture requires several steps of development and interaction with the user. In particular, if radioactive substances are involved, the procedures are cost-intensive and time consuming. Users should be aware that they should foresee funding for target preparation in their proposals (as is common already for a long time for detectors, analysis or beam developments).

Unfortunately, due to the pandemic, we could not perform the SANDA I workshop, originally planned for March 2020, and the second try to perform it in July 2020 failed as well. Instead of this, we collected the applications, partially started to manufacture some of the targets and we launched a second call this year.

The present combined SANDA I/II workshop will be performed online in order to give the target makers the opportunity to learn more about the envisaged experiments and specify requirements on target production. Instead of an intensive detailed discussion during the meeting, both users and producers are requested to intensify their bilateral contacts to ensure target manufacturing tailored to the experiment requirements. Hopefully, there will be a later opportunity in the frame of SANDA to perform a workshop in person reporting on first successful measurements using the targets manufactured by us.

Altogether, with these actions we hope to improve the quality of delivered targets and samples and thus, contribute to the improvement of nuclear data in general.

Not all partners, who submitted an abstract, were able to attend the workshop. In the present booklet we collected all submitted experiment proposals

We would like to thank the European Union for the support provided.

D. Schumann (Chair)

Program workshop SANDA I/II

18.8.2021

Via Zoom

Wednesday, 18.8.2021

8:50	Welcome	D. Schumann (PSI)
Session 1	**Target production and characterisation**	
9:00	JRC-Geel target preparation laboratory	G. Sibbens (JRC)
9:30	Isotope production and targetry at PSI	E. Maugeri (PSI)
10:00	Isotopic thin films preparation laboratory for nuclear physics; IFIN-HH, Bucharest, Romania	N. M. Florea (IFIN-HH)
10:30	Coffee break	
Session 2	**Applications (SANDA I)**	
11:00	243-Americium targets for the study of neutron induced fission cross section at the n_TOF facility of CERN	Z. Eleme (Univ. Ioannina)
11:30	Need in radioactive targets for fission studies at NFS	D. Tarrio (UU)
Session 3	**Applications (SANDA II)**	
12:00	Test of a novel Frisch-Grid chamber, and measurement of the ^{236}U(n,g) cross section	G. Lorusso (NPL)
12:30 -	Lunch break	
13:30	A ^{59}Ni target for neutron-induced gamma-ray spectroscopy	C. Michelagnoli (ILL)
14:00	A ^{179}Ta target for (n,gamma) spectroscopy relevant for the astrophysical origin of ^{180}Ta	C. Michelagnoli (ILL)
14:30	Production of a ^{10}Be target for nuclear structure experiments	L. Tetley (Uni York)
15.00	Coffee break	
15:30	^{10}B targets for the production of ^{11}C in deuteron induced reactions	J. Benlliure (Uni Santiago)
16:00	Preparation of ^{50}Cr and ^{53}Cr targets for neutron capture and transmission experiments for criticality safety	C. Guerrero (CNA)
16:30	Radiative capture measurement on ^{79}Se at n_TOF: sample preparation and future perspectives	C. Domingo-Pardo (IFIC)
17:00	First measurement of ^{94}Nb neutron cross section at n_TOF: Sample preparation and future perspectives	C. Domingo-Pardo (IFIC)
17:30	Closing remarks	D. Schumann

Abstracts for SANDA II

presented on 18.8.2021

JRC-GEEL TARGET PREPARATION LABORATORY

G. Sibbens, A. Moens, D. Vanleeuw, D. Lewis

European Commission, Joint Research Centre, Directorate G

Retieseweg 111, B-2440 Geel , Belgium

The JRC-Geel target preparation laboratory of the Joint Research Centre prepares and characterizes a range of tailor made targets for neutron-induced reaction measurements, e.g. cross-sections and particle emission yields. An overview of the different techniques with examples of produced targets is presented in [1].

The target laboratory is equipped with separate evaporators to prepare thin deposits of ^{6}LiF, metallic Li, ^{10}B, tristearin ($C_{57}H_{110}O_6$), Au, $^{235}UF_4$ and $^{238}UF_4$ by physical vapour deposition (Fig. 1) on a plastic or metal substrate and with separate electrolytic cells for the deposition of U-, Pu-, Am- and Np-isotopes on an aluminium substrate (Fig. 2) by molecular plating in isopropanol. For each isotope, a cell is fabricated in the JRC-Geel workshop according to the required dimensions of the substrate and the deposit.

In addition, the laboratory also has the capability to prepare thick metal samples like discs and foils by rolling and punching. There are several types of press tools to compact powders into pellets. Polyimide foils with a typical areal density of 35 µg/cm^2 can be produced by spin coating glass plates and in-situ poly-condensation.

Fig. 1: Loading the tantalum filament of the ^{238}U-evaporator with $^{238}UF_4$ powder for the preparation of a $^{238}UF_4$ deposit by physical vapour deposition.

The areal density of the deposited material is calculated from the mass and the inner diameter of the mask positioned in front of the substrate during deposition. The deposited mass of the actinides is derived from the alpha-activity measured by low-solid angle alpha-particle counting and the isotopic composition determined by the JRC-Geel mass spectrometry laboratory. The mass of the stable deposits is determined by weighing the substrate before and after deposition.

The areal density of the polyimide foils is measured by spectrophotometry. The other targets are characterized for the mass by substitution weighing and for the dimensions by measuring the diameter and thickness with a calliper and thickness gauge respectively.

All radioactive targets are prepared in a nuclear controlled area in a glove box dedicated to the material and the oxidizing material in an argon glove box as far as possible.

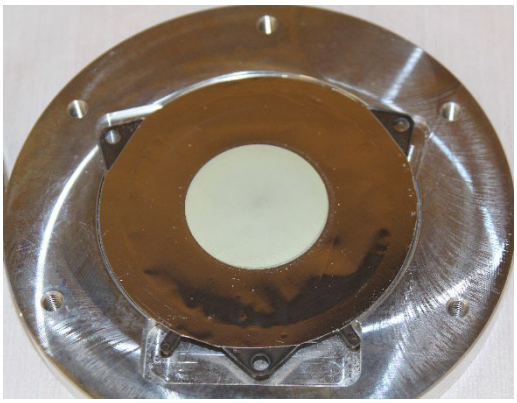

Fig. 2: ^{235}U deposit with a diameter of 33 mm and an areal density of 255 µg/cm^2 prepared by molecular plating on an Al foil with a thickness of 25 µm ; target is positioned in a container for transport.

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[1] G. Sibbens et al., Target preparation for neutron induced reaction measurements, submitted to Eur. Phys. J. AG

ISOTOPE PRODUCTION AND TARGETRY AT PSI

E. A. Maugeri, D. Schumann

Laboratory of Radiochemistry, (Paul Scherrer Institute, Villigen, Switzerland)

The Paul Scherrer Institute, PSI, hosts one of the most powerful proton accelerators worldwide with a beam of 590 MeV in energy at a current up to 2.4 mA, feeding different facilities such as a proton therapy station, a meson production facility, and a neutron production source (Swiss Spallation Neutron Source (SINQ)), where neutrons are produced via spallation of a solid high Z target. Both high energetic neutrons and protons impinge on different structural materials and these interactions could result in formation of radioisotopes, some of which are very exotic and could be used for important applications e.g. in nuclear physics and astrophysics, and environmental science. The ongoing project ERAWAST (Exotic Radionuclides from Accelerator Waste for Science and Technology) [1] aims to identify and separate these scientifically relevant radioisotopes. Furthermore, both proton accelerator and SINQ offer the opportunity of production of specific radionuclides via *ad hoc* irradiation campains.

In the last decades the Isotope and Target Chemistry group at PSI has gained unique and world-wide recognized experience in radionuclide separation and purification from irradiated material, and target preparation.

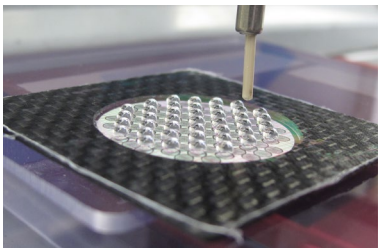

Fig. 1: Droplets of $^{7}Be(NO_3)_2$ placed onto the sLD-PE film, from [2].

This contribution presents the most important techniques that have been recently developed and implemented at PSI for target preparation, based on molecular plating and casting. These techniques allowed producing several targets, which have been used or are going to be used in different nuclear physics and astrophysics experiments, such as the production of ^{7}Be targets, see Figure 1 and 2 [2-3], used for the measurement of $^{7}Be(n,\alpha)^{4}He$ [4] and $^{7}Be(n,p)^{7}Li$ [5] cross sections in the energy range of interest for the Big-Bang nucleosynthesis.

Another important aspect that will be presented in this talk is the importance of implementation of new target characterization methods. In this context, two methods, based on alpha spectrometry coupled with the advanced alpha-spectroscopy simulation program, and radiographic imaging, respectively, will be presented.

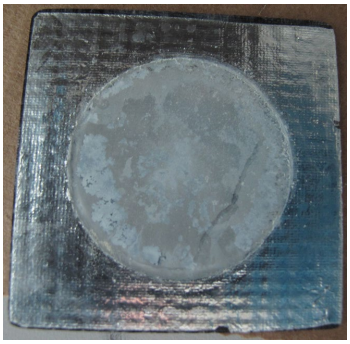

Fig. 2: Be molecular plated onto 5 µm Al backing, from [3].

This presentation will end with an extended discussion about what the authors consider necessary for a productive collaboration between target maker and target user.

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[1] D. Schumann et al., Radiochim. Acta **101**, 501 (2013).
[2] E.A. Maugeri et al., JINST **12**, P02016 (2017).
[3] E.A. Maugeri et al., Nucl. Instrum. Methods Phys. Res A **889**, 138 (2018).
[4] M. Barbagallo et al., Phys. Rev. Lett. **117**, 152701 (2016).
[5] L. Damone et al., Phys. Rev. Lett. **121**, 042701 (2018).

ISOTOPIC THIN FILMS PREPARATION LABORATORY FOR NUCLEAR PHYSICS, IFIN-HH, BUCHAREST, ROMANIA

N.M. Florea, A. Mitu

Horia Hulubei National Institute for R&D in Physics and Nuclear Engineering (IFIN - HH Bucharest, Romania)

The "Isotopic thin films preparation laboratory for nuclear physics", from Nuclear Physics Department of Horia Hulubei National Institute for R&D in Physics and Nuclear Engineering (IFIN-HH Bucharest, Romania), produces thin films of various thicknesses made from both naturally occurring materials and stable enriched isotopes [1]. Such thin films are used as "targets" for different types of nuclear structure experiments - nuclear structure and lifetimes measurements of excited nuclear states using γ-ray spectroscopy techniques (Doppler shift attenuation, plunger, and fast-timing), nuclear structure studies using the activation technique, cross-section measurements of interest for nuclear astrophysical processes, etc., performed mainly at the IFIN-HH 9 MV Tandem Accelerator or at other international research facilities in the frame of scientific collaborations (CERN, IN2P3 France, EU JRC-Geel, TUM Germany, IKP Poland, JINR Russia, etc.).

To assure good target quality the laboratory includes state-of-the-art equipments used for thin-film fabrication technology and consist of Physical Vapor Deposition (PVD) and mechanical rolling techniques. In the last years, different approaches and experimental protocols were applied for the preparation of high quality isotopic thin films with selected properties that perfectly answer nuclear physics experiments requirements.

Some examples: Self-supported ^{13}C solid thick targets (400 mg/cm^2 thickness and 2 cm diameter) using amorphous ^{3}C powder and also ^{14}N target with similar geometry features using $LiNH_2$ compound, for IKP Poland were prepared by pressing using a hydraulic 25T press. Other methods involve metallothermic reduction reaction of different oxides with dedicated reducing agents (Zr, Hf, La, CaH_2, Mg, C, H_2), which subsequently leads to obtaining of high purity metallic form of the deposited thin film ($^{144,147,149,152,154}Sm_2O_3$, $^{140}CeO_2$, $^{46}TiO_2$, $^{30}SiO_2$, $121Sb_2O_5$, $^{72,73}GeO_2$, etc.). Reliable thin films made of ^{nat}Ca, ^{nat}Ba, ^{nat}Sr, ^{24}Mg in metal form that can resists oxidation by air were also produced [2].

To obtain durable ^{82}Se layers that preserve their physical and chemical properties while irradiated with intense accelerated particle beams, a thermal treatment to convert the condensed ^{82}Se layers that exhibit unstable amorphous structure to hexagonal crystal structure was performed. This is very important because an intense fast heating of Se films with amorphous structure rapidly induces the conversion to hexagonal crystal structure and so the obtained foils shrink and tend to crack or curl.

To remove the oxygen layer (as contamination) from the surface of different metallic isotopic foils (^{64}Ni, ^{65}Cu, ^{208}Pb) resulted during the fabrication process a thermal treatment using a hydrogen oven was successfully applied. The process of removing the surface oxygen contamination is very useful for sub-barrier neutron transfer reactions with ^{18}O or ^{13}C beams.

To produce reliable thick targets from refractory materials as Os, W with extremely high vaporization temperatures (4500-5500°C) using Pulsed Lased Deposition (PLD) technique was also developed in collaboration with the National Institute for Laser, Plasma and Radiation Physics (INFLPR) [3].

Other self-supported or backed targets were also produced through high vacuum evaporation methods or by mechanical rolling: ^{130}Te, $^{182,184}W$, Au, Ta, Y, Nb, Sn, etc.

Target characterization methods (e.g. PIXE, PIGE, RBS, AFM, SEM-EDX, thickness determination using energy-loss of α-particles) were also employed to determine the features of the obtained targets.

This work was supported by a grant of the Ministry of Research, Innovation and Digitization, CNCS/CCCDI – UEFISCDI, project number PN-III-P1-1.1-TE-2019-0337, within PNCDI III.

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[1] N.M. Florea, L. Stroe, R. Marginean, D.G. Ghita, D. Bucurescu, M. Badea, C. Costache, R. Lica, N. Marginean, C. Mihai, V. Mosu, C.R. Nita, S. Pascu, T. Sava, J Radioanal Nucl Chem **305**, 707 (2015).

[2] A. Mitu, A. Oprea, M. Dumitru, N.M. Florea, T. Glodariu, R. Suvaila, C. Luculescu, N. Marginean, M. Dinescu, Gh. Cata-Danil, J Radioanal Nucl Chem **316**, 725 (2018).

[3] A. Mitu, M. Dumitru, R. Suvaila, A. Oprea, I. Gheorghe, P. Mereuta, S. Brajnicov, I. Burducea, N.M. Florea, N. Marginean, T. Glodariu, M. Dinescu, G. Cata-Danil, Vacuum **161**, 162 (2019).

243-AMERICIUM TARGETS FOR THE STUDY OF NEUTRON INDUCED FISSION CROSS SECTION AT THE N_TOF FACILITY OF CERN

Z. Eleme (University of Ioannina- Greece), N. Patronis (University of Ioannina- Greece), M. Diakaki (CEA- Cadarache- France), A. Tsinganis (Extreme Light Infrastructure- Czech Republic), N. Colonna (Instituto Nationale di Fisica Nucleare, Bari- Italy), R. Vlastou (National Technical University of Athens- Greece)

The design, feasibility and sensitivity studies on new generation of nuclear reactors, such as Acelerator Driven Systems- ADS [1] and Generation IV Fast Neutron Reactors [2], require high- accuracy cross section data for a variety of neutron -induced reactions, at energies ranging from thermal up to several tens of MeV.

In this scope, recent attention has lead to the investigation of the effect of Americium isotopes as burnable actinides on a variety of nuclear reactors [3]. Among the Americium isotopes, the ^{243}Am isotope is the one that has the least studied neutron -induced fission cross section in the thermal and the resonance region.

Among the last years, the n_TOF facility at CERN, has provided the scientific community with high precision cross section data for neutron -induced fission reactions covering almost 10 orders of magnitude from thermal up to the MeV neutron energy region [4]. Subsequently, we can profit from the expertize of JRC- Geel for the production of high purity ^{243}Am targets aiming at measurement of the neutron induced fission cross section of ^{243}Am.

In the present contribution, an overview about the characteristics of the requested ^{243}Am targets will be given so as to cope with the requirements and the challenges of a possible future measurement at the n_TOF facility at CERN.

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[1] A. Stanculescu, Annals of Nuclear Energy 62 (2013) 607-612
[2] Generation-IV International Forum, www.gen-4.org/
[3] I. Shaaban, M. Albarhoum, Annals of Nuclear Energy 109 (2017) 626–634
[4] N. Colonna et al., The fission experimental programme at the CERN n_TOF facility: status and perspectives, accepted for publication at EPJ A (2019).

NEEDS IN RADIOACTIVE TARGETS FOR FISSION STUDIES AT NFS

A. V. Prokofiev, D. Tarrío, and S. Pomp (Uppsala University, Division of Applied Nuclear Physics)

1. Introduction

Uppsala University is active in EU-funded projects SANDA and ARIEL aimed at nuclear data measurements, nuclear education, as well as development of new facilities for these purposes, in particular NFS at GANIL in Caen, France [1, 2]. These activities, initiated in framework of the CHANDA project, were postponed because of a delay with the licensing of the NFS facility.

This contribution follows up on the Target Preparation Request submitted by our group in 2015, concerning needs in radioactive targets for fission studies at NFS.

2. Target specifications

We are going to employ neutron beams at the NFS facility for measurements of neutron-induced fission cross sections (CS) and fission fragment angular distributions (FFAD) [1, 2]. The present experimental programme comprises the measurements for ^{235}U and ^{238}U nuclei in the energy range of 1 – 40 MeV. The CSs will be measured relative to each other as well as relative to the H(n,p) cross section. Our goal is to measure the CSs with overall uncertainty ≤2%.

The development work initiated during CHANDA, in collaboration with the target producers at JRC, has allowed us to define the following specifications for the targets of ^{235}U and ^{238}U:

- 3 targets for each nuclide, with areal density of 400 μg/cm² for each nuclide of interest, ^{235}U and ^{238}U.
- 3 empty backings for background measurements.
- Shape and size of the fission material layer: circular, Ø25 mm.
- Diameter tolerance: ±0.5 mm.
- Uncertainty in diameter determination: ±0.1 mm.
- Isotopic purity: as good as reasonably achievable, and in any case ≥99.9% for 238U.
- Fissile contaminants in ^{238}U targets should be avoided.
- Overall uncertainty in the measurement of the average thickness and/or the target mass: as good as reasonably achievable, and preferably <1%.
- Homogeneity of the target thickness: as good as reasonably achievable, and preferably ≤3%.
- Chemical form and preparation method: any, optimized for the durability and the mechanical stability of the targets.
- Backing: a polyimide (PI) backing with areal density of 40 μg/cm².

The type of backing has been suggested by the target producers. Each backing has to be attached to a 1-mm thick aluminium frame (ring) with the inner and outer diameter of 70 and 90 mm, respectively. The proposed dimensions result from tests performed at JRC in 2017-2018, aimed at checking long-term mechanical stability of the backings. A frame with a backing under test [3], with a larger inner diameter, is shown in Fig. 1.

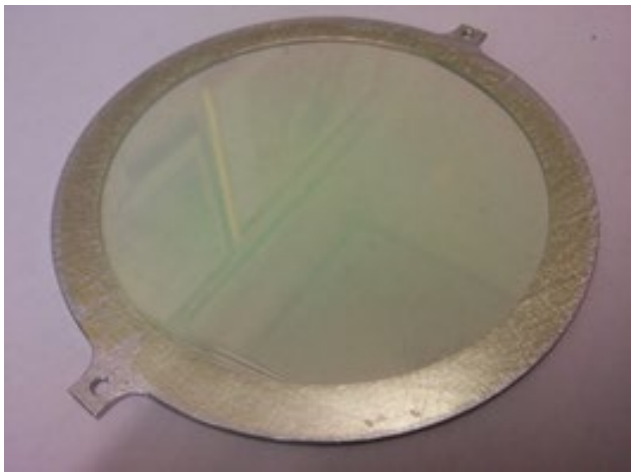

Fig. 1: A frame with an empty backing, manufactured according to [3].

The thickness of each backing should be known with as good accuracy as reasonably achievable; this applies both to the working targets as well as to the empty backings for background measurements.

3. Outlook and further work

We expect to hear back concerning the viability of the targets and the time line, taking into account that the NFS facility will become available for experiments in September 2021. Knowing the time line for the target production will make it possible for our group to apply for:

- a transnational access grant in framework of the ARIEL project,
- a beam-time allocation, to be granted by the GANIL Program Advisory Committee.

[1] D. Tarrío et al., EPJ Web of Conf. **146**, 03026 (2017)
[2] K. Jansson et al, NIM **A794**, 141 (2015), and references therein.
[3] Drawing Ref. Nr. TP 2016-004 & 005, EC-JRC; G. Sibbens, private communication (2016).

TESTS OF A NOVEL FRISCH-GRID IONISATION CHAMBER, AND MEASUREMENT OF THE ^{236}U(n,f) CROSS SECTION

G. Lorusso, M. Bunce, D. Thomas, M. Birch (National physical Laboratory, Teddington, UK), S. Bennet, A. McFarlane, A. Smith, G. Smith, T. Wright (University of Manchester), Emilio Maugeri (PSI)

Summary

The present proposal is for the fabrication of ^{238}U and ^{236}U thin targets for neutron-induced cross-section measurements that we plan to carry out at the National Physical Laboratory (NPL), in collaboration with the University of Manchester (UoM) and the Paul Scherrer Institute (PSI).

Test of the UoM fission chamber

A new Frisch-grid ionisation chamber has recently been developed at the University of Manchester (UoM) for fission studies [1]. The novel aspect of the detector is the use of segmented anodes allowing measurements of fission fragments angular distributions based on the time distribution of signals recorded in different anode segments. The advantage of the technique is that the measurements depend only on the detector geometry and electron drift velocity in the fill gas. Modelling the interaction of fission fragments with the counting gas is not required. Furthermore, since the amplitude of signals are not employed, Frisch-grid inefficiency correction is also not required. Initial tests with a point-like ^{252}Cf source an angular mask to restrict the polar angle were promising, but more tests are required to drive the next steps of the detector development. We need to demonstrate the capability of measure neutron-induced fission cross sections and angular distributions in in-beam experiments and with a finite sized target. For these tests we plan to use an isotope with well-known cross section such as ^{238}U.

^{236}U(n,f) cross section

A second goal of our measurements is to provide new data for the ^{236}U(n,f) cross section. The isotope of ^{236}U is relevant for the design of fast reactors and especially for development of new nuclear fuel cycles such as the Th/U cycle [2], where ^{236}U builds up in the equilibrium stage and constitutes a large fraction of the cycle long-lived waste. In this case, the largest discrepancies among nuclear data libraries, up to one order of magnitude are below fission thresholds. Above threshold, discrepancies between existing measurements are typically <10% up to 5 MeV [3] but become larger above such energy. In this proposal we aim to measure cross sections at fast neutron energies, and in particular the region above 10 MeV (2^{nd} and 3^{rd} fission channel), where only few measurements exist.

Experimental setup

We plan to carry out both measurements at the monoenergetic neutron facility at the National Physical Laboratory (NPL), UK. We will use a 3.5 MeV Van de Graff accelerator and a large low neutron scattering experimental area. The UoM fission chamber will be installed at the centre of the area and will be irradiated with neutrons in the energy range 0.5-16.5 MeV.

^{236,238}U targets

An essential element of the measurements is the manufacture of high-quality targets. These need to be deposited on a thin backing that allows for both fission fragments to be detected and should have active ^{236,238}U layers with thickness of no more than 100 μg/cm^2. To collect enough statistics, at least a mass of 600 μg is required, resulting in 3 cm diameter targets.

We plan to produce these at PSI by molecular plating using ^{238}U available at PSI, and ^{236}U available at NPL. The mass of both samples will be characterised at NPL using a defined solid angle alpha counter [4]. At NPL we will also analyse target material before deposition to confirm its isotopic composition using ICP-MS.

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[1] S.A. Bennett, P.T. MacGregor, A.G. Smith, R.L. Kennedy-Reid, T. Wright., Nucl. Instrum. Methods Phys. Res., A 951 (2020) 162846.

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[3] R. Sarmento et al., Phys. Rev. C 84, 044618 (2011).

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A ^{59}Ni TARGET FOR NEUTRON-INDUCED GAMMA-RAY SPECTROSCOPY

C. Michelagnoli (ILL), A. Garnsworthy (TRIUMF), U. Köster (ILL)

A recent experimental campaign employing different techniques identified impressively the shape coexistence in ^{64}Ni [1]. Here a ≈1 mg ^{63}Ni sample prepared at PSI played a central role for a (n,γγ) angular correlation experiment performed at the FIPPS instrument at ILL.

A similar physics case should now be studied by following the migration of low-spin states along the line of Ni isotopes. The experiment has been accepted by the ILL subcommittee fort he FIPPS instrument. While the ^{61}Ni(n,γγ)^{62}Ni could be performed with a stable target, the study of ^{59}Ni(n,γγ)^{60}Ni requires again a radioactive target. Thanks to the threefold larger (n,γ) cross-section a smaller quantity of about 0.3 mg ^{59}Ni (0.9 MBq) would provide a similar count rate (and even somewhat lower masses could be compensated by a prolongation of the measurement time).

Due to the excellent selectivity of gamma ray spectroscopy with high resolution Ge detectors admixtures of other stable nuclides to the target can be tolerated as long as they don't overwhelm the total neutron capture rate. Even a hundredfold excess of ^{58}Ni or ^{60}Ni over ^{59}Ni would still be acceptable.

Thus, different possibilities exist to produce the required ^{59}Ni target: either irradiation of natural nickel or enriched ^{58}Ni in a high flux reactor or spallation of e.g. a copper target.

The only showstopper would be an excessive content of ^{60}Co because its beta decay populates a gamma ray cascade proceeding through the first 2+ state of ^{60}Ni. This would pollute the coincidence gate of the 1333 keV transition and limit the accuracy of angular correlation studies. Residual ^{60}Co activity should not exceed ≈10 kBq per mg of ^{59}Ni.

No particular physical form is required for this target, any powder, grains or deposit dried in a Teflon bag is well suitable. Usable chemical forms are e.g. metal, oxide, fluoride, carbonate, nitrate, etc. only chlorides or other elements with high neutron capture cross-section should be avoided.

The experiment at FIPPS will last about 2 weeks, is non-destructive and leads to negligible activation. Thus the target could be reused afterwards for other applications.

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A ^{179}Ta TARGET FOR (n,γ) SPECTROSCOPY RELEVANT FOR THE ASTROPHYSICAL ORIGIN OF ^{180}Ta

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The nucleosynthesis process leading to ^{180}Ta, the rarest "stable" isotope in the solar system is still under debate. Despite the considerable theoretical and experimental effort, a mechanism producing sufficient amounts of this isotope has not yet been identified [1]. The most promising scenario is the one of an s-process origin [2], but the production of this isotope through the p-process [3] and nu-process [4] has been also proposed. One of the most likely scenarios within the s-process nucleosynthesis is that under typical s-process conditions, ^{179}Hf becomes unstable and undergoes β decay, allowing the production of ^{180}Ta^{m} through neutron capture on the unstable ^{179}Ta. In the hot stellar environment, the quasi-stable Jpi=9- isomeric state would be easily destroyed by thermally induced population of the short-lived ground state. This thermal coupling between the isomer and the ground state has been demonstrated in photoactivation experiments [5]. This experiment demonstrated the possibility of resonant photon absorption through a possible intermediate state (IS) at 1.01 MeV energy. As pointed out by the authors, the resulting lifetime is still long with respect to the times typical of the s-process scenario and a detailed spectroscopy of ^{180}Ta is needed in order to identify all the possible IS candidates.

In order to validate one of the possible astrophysical scenarios, both a precise cross-section measurement on the radioactive ^{179}Ta [6] and a detailed structure study of the ^{180}Ta are needed. The latter will be possible by using a radioactive ^{179}Ta target at FIPPS, the new gamma ray spectroscopy instrument at Institut Laue Langevin, Grenoble. An intense, well collimated and halo-free thermal neutron beam induces (n,γ) reactions on the target. The emitted gamma rays are detected with an array of 8 Ge clover detectors. The transition multipolarities are assigned via angular distribution measurements of the emitted gamma radiation and the parity by Compton polarimetry with the clover detectors. BGO shields for improved Compton suppression and LaBr3(Ce/Sr) detectors for fast timing measurements of intermediate level lifetimes down to few ps will complement the setup. The FIPPS experimental zone is equipped with a dedicated casemate at slight underpressure and filtered ventilation, thus permitting the use of radioactive targets.

A ^{179}Ta target with about 1 GBq activity (100x the French exemption limit), corresponding to 8.3E16 atoms, will provide a neutron capture rate of about 8 kHz which is suitable for the intended experiment. ^{179}Ta decays by electron capture with 665 days half-life, emitting only X-rays. These will be strongly attenuated by a heavy metal shield to keep the count rate of the gamma ray detectors at an acceptable rate.

Such a target is best produced by the ^{180}Hf(p,2n)^{179}Ta reaction with subsequent radiochemical Hf/Ta separation [7]. Fig. 1 shows the (calculated) cross-sections of the TALYS based evaluated nuclear data library TENDL-2015 and the derived thick target yield for an enriched metallic ^{180}Hf target. A 24 MeV proton beam is well matched to cover the excitation function of the (p,2n) reaction. Energies below about 12 MeV should be avoided to minimize co-production of ^{180}Ta that cannot be chemically separated from ^{179}Ta. Irradiating a water-cooled 0.7 mm thick metallic ^{180}Hf target (950 mg/cm^2) will integrate the excitation curve from 24 down to 12 MeV and provide a physical yield of about 3.4E13 atoms/μA h. An irradiation for 24 hours at 100 μA should produce about 1 GBq of ^{179}Ta.

Alternatively also natural Hf targets can be used. The ultimate purity of the ^{179}Ta is barely changed, but the yield would be threefold lower, requiring still longer irradiation times.

Also lower proton energies can be used, e.g. 18 MeV protons with a correspondingly thinner target and longer irradiation time. Due to the long lifetime of ^{179}Ta this irradiation could be divided up into several separate irradiations spread over many months. Thus, the required beam dose could be accumulated by using the (safely encapsulated) target as "beam dump" whenever the accelerator beam is not required for other purposes.

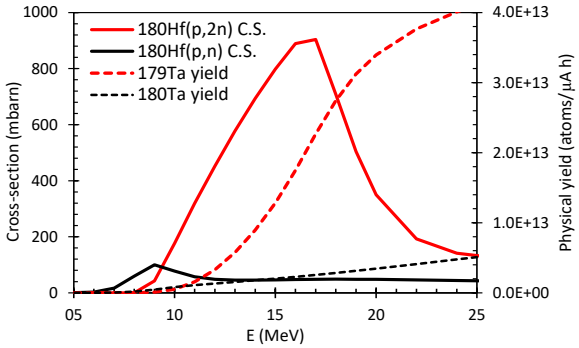

Fig. 1: Calculated cross-section from TALYS

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PRODUCTION OF A ^{10}Be TARGET FOR NUCLEAR STRUCTURE EXPERIMENTS

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Understanding nuclear structure and dynamics in terms of the fundamental interactions between protons and neutrons is one of the overarching goals of nuclear science. To this end, nuclear theory is developing chiral effective field theory (EFT) [1,2], a unified approach to nuclear forces, where two-nucleon (NN), three-nucleon (3N) and higher-body forces are derived within a consistent, systematically improvable framework. Neutron-rich oxygen isotopes are particularly fruitful candidates to test ab initio theory. First valence-space calculations with NN+3N forces were able to explain, for the first time, the location of the oxygen dripline at ^{24}O [3]. More recently, large-space ab initio calculations, where all nucleons are treated as explicit degrees of freedom, have confirmed those early results [4-6]. An important next step is to benchmark these calculations and the role of 3N forces against other observables, which are sensitive to physics beyond what is relevant for excitation energies alone. Indeed, previous work on the structure of ^{21}O has demonstrated the sensitivity of the 3N forces to spectroscopic observables such as level lifetimes [7]. We will perform an ambitious measurement of lifetimes of excited states in ^{22}O, populated via the ^{10}Be(^{14}C,2p)^{22}O fusion-evaporation reaction, employing a radioactive ^{10}Be target [8]. Measuring these lifetimes with high accuracy will provide a stringent test for ground-breaking first-principles calculations, pivotal in our understanding of life.

A first target has been produced at PSI (see Fig. 1) by molecular plating of $Be(OH)_2$ solution on thin Pt foils (ranging from 1 to 2 um thick). The beryllium solution used for this deposition had an isotopic composition of ^{9}Be/^{10}Be = 2.110 $\pm$ 0.063, as per a ICP-MS measurement in 2017. We deposited 192ug of solution on a 7mm diameter area of the Pt backing, corresponding to a ~0.5mg/cm^2 Be target (~160ug/cm^2 ^{10}Be target). The yield of the deposition is estimated at 30-40% (from approximate activity measurements), reducing the areal density of ^{10}Be to less than 50ug/cm^2, a number that challenges the feasibility of the experiment. The unknown composition of the target, i.e., how much oxygen and hydrogen were deposited in the target and whether more contaminants were formed during the deposition, together with the low ^{10}Be amount, posed significant constraints to the experiment [8]; the latter was performed in April 2021 at Argonne National Laboratory, USA. Indeed, there was no observation of the 2-proton exit channel leading to ^{22}O, questioning the amount of ^{10}Be in the target and/or the thickness of the target which would affect the experimental settings of the spectrometer that was used for channel selection. In order to better understand this target, a Rutherfod Back Scattering (RBS) experiment will be performed at the Dalton Cumbrian Facility in the UK for its characterisation.

Going forward, we need to develop a robust procedure to produce thin ^{10}Be targets suitable for nuclear structure experiments with high fidelity. A higher concentration of ^{10}Be is needed in order to be able to produce and observe weak channels at the neutron drip line. In addition, pure Be targets are also needed in order to minimize contamination from other elements. The production and characterisation of a high-quality, high areal-density, and homogeneous ^{10}Be target, represents the last challenge to the experiment going forward successfully. In addition, the successful production of this ^{10}Be target will lead to a greater experimental accessibility of the light neutron-rich region for future nuclear structure experiments. This proporal addresses this need by further investigating and refining the technique for the production of ^{10}Be targets for nuclear structure experiments.

Fig. 1: Be target on a 1um thick Pt foil, ready to be irradiated at the Argonne National Laboratory.

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^{10}B TARGETS FOR THE PRODUCTION OF ^{11}C IN DEUTERON INDUCED REACTIONS

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^{11}C is a widely used radiotracer for positron-emission tomography produced in (p,n) reactions on ^{11}B targets using compact cyclotrons. Since a few years, laser-accelerators are being cosidered as an alternative technology for radiotracer production [1-3]. The broad Maxwelliam-like energy spectrum of laser-accelerated ions favors the use of reactions with small or negative Q-value. According to this argument, reactions induced by deuterons for the production of radiotracers are being proposed [4]. In the particular case of ^{11}C the proposed reaction is ^{10}B(d,n)^{11}C.

Unfortunately, the existing measurements on the production cross sections of ^{11}C in reactions induced by deuterons are scarce and even contradictory [5]. The different measurements are depicted in Fig. 1, showing some clear inconsistencies at energies below 10 MeV that become particularly large below 5 MeV. Because this is the energy range of interest for laser accelerators, the assesment on the production of 11C with laser accelerated deuteron beams clearly requires a precise evaluation of these cross sections.

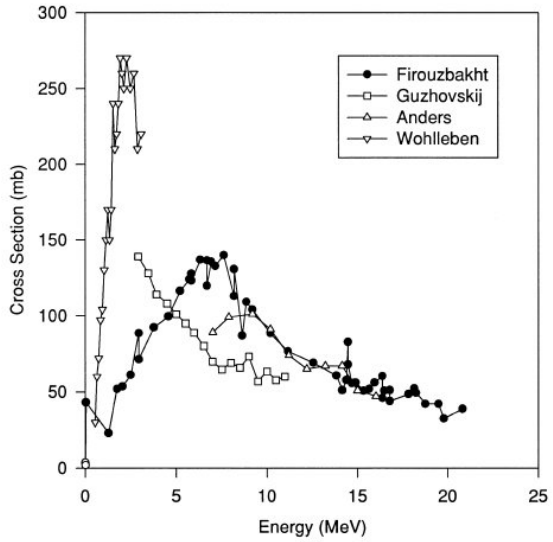

Fig. 1: Diferent measurements of the production cross section of ^{11}C in reations induced by deuterons on ^{10}B reported in literature.

One of the major difficulties for the precise determination of these cross section is the use of thin enough ^{10}B targets to minimize the uncertainty in the reaction energy, induced by the slowing down of the deuteron projectiles in the target material. According to our stopping power calculations, 235 μg/cm^2 of ^{10}B would induce some 10% uncertainty for deuterons with energies around 1 MeV.

On the contrary, the use of those thin targets requires to increase the irradation time and the time for the measurement of the γ–γ activity. This is the reason why we need several targets for an effcient scaning in energy, combining irradiations and decay times.

The requirements for the targets are then the following :

- Around 96% enriched ^{10}B material.
- Few microns aluminium substrate.
- ^{10}B thicknesses ; 235 and 470 μg/cm^2.
- Target size: ~1 cm^2.
- Number of targets: 4 targets for each thickness.

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PREPARATION OF ^{50}Cr AND ^{53}Cr TARGETS FOR NEUTRON CAPTURE AND TRANSMISSION EXPERIMENTS FOR CRITICALITY SAFETY

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In nuclear technology, criticality safety benchmarks allow performing sensitivity analysis of the nuclear data used as input for nuclear reactor calculations. Based on such studies, the Nuclear Energy Agency (NEA) has recently called in its High Priority request List (HPRL) for new measurements on neutron capture of the neutron capture cross section on ^{50,53}Cr isotopes in the 1 to 100 keV energy range, as chromium is a major component of stainless steel [1,2].

In response to this request, we have proposed [3] to perform such measurements at the n_TOF EAR1 measuring station with a set of carbon fiber C6D6 detectors using high purity targets specially designed to reduce the multiple interaction effects, which are behind the disagreement of previous measurements. The proposal was submitted to the CERN INTC in January 2021 and approved in the CERN Governing Board of March 17th, 2021. The n_TOF experiment will be complemented by transmission and activation campaigns at the GELINA and HISPANOS facilities, respectively.

The key for improving upon previous experiments is the use of targets as thin as necessary to achieve enough statistical accuracy but minimizing the multiple scattering/interaction corrections. As the scattering and capture cross sections change with the neutron energy, two different thickness are considered, for each isotope a thin one for low neutron energy and thicker one for higher energies, where the capture cross sections are smaller, and more mass is needed to acquire the statistics needed. In all cases, a diameter of 40 mm, large enough to cover the n_TOF neutron bean, has been considered.

In particular, the targets properties considered included in the proposal are summarized in Table 1. The raw material will be borrowed from *ORNL Isotopes,* which offers highly enriched ^{50}Cr (96,42(2)% enriched) and ^{53}Cr (97,2(2)% enriched) material as metal powder, instead of the usual oxide form. The targets, if not self-sustained, need to be provided in the target holder's used for capture experiments at n_TOF: a thin mylar backing mounted on a 50 mm diameter PCB ring frame.

	Purity (%)		Thickness at/barn	mg/cm^2	μm
^{50}Cr	96,42	Thin	0.6x10^{-3}	50	69
		Thick	5x10^{-3}	415	577
^{53}Cr	97,2	Thin	1.2x10^{-3}	106	147
		Thick	8x10^{-3}	704	979
^{nat}Cr	-	Thin	1.0x10^{-3}	86	120
		Thick	7x10^{-3}	604	841

Tab. 1: *Summary of the targets and their properties.*

Summarizing, the target request within SANDA consists of:

- Elemental and isotopic characterization of the raw material.
- Preparation of 6 targets with diameter of 40 mm and the thickness listed in Tab. 1.
- Characterization of the targets I terms of geometry, total mass, thickness, and homogeneity.
- Recovery and characterization of the raw material in order to return it to ORNL.

The targets must be ready by June 2022, for the n_TOF experiment is planned for Summer/Fall 2022.

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RADIATIVE CAPTURE MEASUREMENT ON ^{79}Se AT n_TOF: SAMPLE PREPARATION AND EXPERIMENT PROPOSAL

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Neutron capture cross sections are a crucial ingredient for innovative nuclear technologies as well as for the improvement of stellar models in nucleosynthesis studies. For the particular case of the unstable ^{79}Se, its capture cross section is of interest in both fields because ^{79}Se is one of the main contributors to the long-term radiotoxicity of spent fuel due to its long half-live (~300 ky). This fact on its own motivates the first measurement of the ^{79}Se(n,γ) cross section mainly for nuclear transmutation studies [1]. Additionally, measuring the neutron capture cross section of this isotope will provide a crucial test for the understanding of s-process nucleosynthesis in the mass region around A=80 [2]. The s-process branching point at ^{79}Se is especially well suited for determining the thermal conditions of the stellar site thanks to the strong thermal dependency of its beta-decay rate [3].

In this context, a measurement (LoI) was already proposed to the Isolde and n_TOF Committee at CERN (INTC) and approved in 2014 [4]. Meanwhile, a sample of ^{79}Se for this measurement has been produced in collaboration between IFIC, PSI, ILL and CERN. The production method is based on the irradiation of a ^{78}Se sample in the high-flux reactor at ILL. For the neutron irradiation at ILL a Pb-Se eutectic alloy was prepared to avoid safety issues related to the low melting point of pure Se. Among other possible alloys, lead was chosen due to the very small cross section of ^{208}Pb (0.36 mb at 30 keV). For the final sample, 3 g of metallic powder enriched to 99.34% in ^{78}Se were mixed with highly enriched lead (99% ^{208}Pb) to produce a pellet-alloy of 3.9028 g with a diameter of 14 mm and a thickness of 5 mm. The sample was encapsulated in a laser-welded casing of aluminum with a thickness of 0.5 mm (totaling a 1.0240 g of 6N Al) before being irradiated at ILL for a total time of 51 days and a power-weighted fluence of 42 full power days. The expected amount of ^{79}Se is about 3 mg.

This contribution will first present the results of the ^{79}Se sample characterization carried out at PSI at the end of 2019, mainly focused on the accurate determination of sample contaminants to estimate the realistic background conditions in the actual neutron capture experiment. In addition, an update will be given on the upcoming ^{79}Se(n,γ) measurement. Its final proposal was already approved by the INTC in November 2020 [5] and the measurement will be carried out in 2022 at n_TOF-EAR1 [6] using i-TED, a novel detection system which exploits the Compton imaging technique to achieve an enhanced sensitivity [7]. Last, we aim at discussing during the workshop the possible methods for an accurate quantification of ^{79}Se mass after the experiment

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FIRST MEASUREMENT OF ^{94}Nb NEUTRON CAPTURE CROSS-SECTION AT n_TOF: SAMPLE PREPARATION AND FUTURE PERSPECTIVES

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One of the crucial ingredients for current and future innovative nuclear technologies, as well as for the improvement of stellar models in the framework of nucleosynthesis studies is the neutron capture cross section. In the particular case of the radioactive ^{94}Nb, the ^{94}Nb(n,γ) cross-section is of interest in both nuclear astrophysics and nuclear energy applications. It could play a critical role constraining the s-process production of ^{94}Mo in AGB stars, which presently cannot be reproduced by state-of-the-art stellar models[1]. As today, there exists no previous ^{94}Nb(n,γ) experimental data for the resolved and unresolved resonance regions.

Motivated by this situation, an experiment to measure ^{94}Nb(n,g) at CERN n_TOF was proposed [2]. The latter was approved by the CERN INTC and it will be carried out in 2022 using the high-flux beam-line of n_TOF EAR2 [3].

The conventional methodology of producing ^{94}Nb from activation of ^{93}Nb materials was not applicable in this case. Although ^{93}Nb is naturally mono-isotopic, there is no supplier that can certificate less than about 100ppm of Ta. This quantity is far too high because it would take many years to sit out the ^{182}Ta produced in the neutron irradiation. Therefore, an alternative methodology was followed for this specific experiment. A hyperpure sample of ^{93}Nb, originally produced at the Institute of Solid State and Materials Research of Dresden [4], was made available for this project thanks to a collaboration with ILL. The final ^{93}Nb material available for this experiment has a mass of 304 mg and <1 ppm of Ta. It was afterwards activated at ILL for 51 days and a power weighted fluence of 42 full-power days, thereby yielding 9.24×10^{18} atoms of ^{94}Nb. This represents ~1% of the total number of atoms present in the bulk of the sample. A careful characterization of the activated sample was performed at PSI by means of HPGe gamma-ray spectroscopy. The activity of ^{94}Nb found in the sample was 10.1 MBq with no additional trace of contaminants. This is therefore a rather unique sample, and its characterization became also of pivotal importance for a realistic assessment of the background level expected in the proposed experiment and to validate its feasibility.

This contribution will first present the preliminary results of the ^{94}Nb sample characterization carried out at PSI at the end of 2019, focused mainly on the accurate determination of sample contaminants to estimate the realistic background conditions in the foreseen neutron capture experiment.

Finally, the sample-related experiment strategy will be discussed, which also includes the production of a dummy natNb sample with a spiral shape, similar to the one intended for the ^{94}Nb sample. The impact of this sample conditioning for the actual experiment to improve the intercepted fraction of the neutron beam will be discussed in the context of a novel Bayesian-based analysis strategy optimized for the very small ^{94}Nb isotopic contribution to the capture yield.

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Abstracts for SANDA II

(without presentation)

RECONDITIONING AN OXIDIZED ^{87}Sr SAMPLE

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A neutron capture experiment on ^{87}Sr has been carried out several years ago at the n_TOF facility with the 4π calorimeter in order to determine the spins of a number of neutron resonances [1]. The sample was an initially metallic sample of 287 mg Sr, enriched to 87.7% of ^{87}Sr, obtained from LANL, Los Alamos. This sample was then sealed between two layers of capton under an inert atmosphere in order to prevent oxidation. Nevertheless, some oxygen seemed to be present because during the measurement the sample oxidized substantitally as can be seen in figure 1. While this was not an issue to exploit the data for the purpose of spin assignments based on low-level populations, the measurement could not be used to extract in addition the neutron capture cross section. For this purpose, typcially a reference sample is used with the same shape as the Sr sample. Because of the changing form of the Sr sample during the measurement, it was not possible to deduce a reliable normalization. A neutron capture cross section measurement allows to obtain the Maxwellian averaged capture cross sections at several temperatures, which is of interest for the astrophysical s-process and for the ^{87}Rb-^{87}Sr cosmochronometer [2].

We propose to recondition the oxidized sample into a well-defined container suitable for subsequent measurements in neutron beams like JRC-Geel or n_TOF at CERN. Several of such containers have already been produced at JRC-Geel and are available. The sample would ideally be pressed into a pallet of 20 mm diameter in order to obtain a material with a homogeneous areal density.

Prior to this operation it may be needed to fully oxidize the remaining material, and measure the mass of the oxide to verify its composition. An indication of the homogeneity of the material would be needed as well but could be estimated after the sample production.

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Fig. 1: The existing ^{87}Sr sample before (left) and after the previous measurement (right). One can clearly observe the oxidation of the initially metallic sample

Abstracts for SANDA I

(without presentation)

TARGET CHARACTERIZATION BY ICP-MS MEASUREMENTS

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Accurate experimentally determined nuclear property data are crucial in the fields of astrophysics, nuclear structure and medicine, geoscience, fundamental nuclear physics, safe nuclear power generation, and secure long-term storage of radioactive waste. Target production for nuclear data determination faces high quality demands concerning target purity as well as the quantitative characterization of the number of atoms of the target-nuclide in question. Successful target preparations can be assisted greatly by Inductively Coupled Plasma Mass Spectrometry (ICP-MS), an extremely versatile and sensitive analytical technique for concentration and isotope abundance determinations.

For most ICP-MS analyses, analytes in liquid form are required. ICP-MS owes its prowess to the potency of the plasma ion source to efficiently ionize almost all elements of the periodic table, the ever-increasing sensitivity of modern mass spectrometers, and the ability to resolve most molecular interferences either by high mass resolution capabilities (Sector Field ICP-MS, SF-ICP-MS) or reactive collision (Quadrupole-ICP-MS, Q-ICP-MS). Compared to single-collector SF-ICP-MS, Multi-Collector SF-ICP-MS (MC-ICP-MS) has the added advantage to detect several ion beams simultaneously, allowing isotope ratio determinations down to single-ppm level precision. Using gravimetric standard addition with an additional internal standard [1] ("St.Add") or reverse isotope dilution [2] ("ID"), MC-ICP-MS allows concentration determinations for most target-nuclides at sub-% uncertainty and consuming ca. 10^{13} to 10^{14} atoms of the nuclide. Using St.Add and ID, only slightly less precise concentration data for target-nuclides can be obtained by SF-ICP-MS with its much better "peak shapes" compared to Q-ICP-MS. The great power of single-collector SF and particularly Q-ICP-MS, however, lies in their ability to scan repeatedly and rapidly across wide mass ranges which makes these techniques ideal to evaluate targets for stable and radioactive impurities. SF-ICP-MS analyses are usually associated to element and matrix-specific detection limits at low ppt levels and below [3]. Q-ICP-MS, particularly "triple-Quad" versions having more than one mass filter, now can reach detection limits that are similar to only ca. 10-times worse [4], [5]. Typical purity evaluations can reach an uncertainty of 10% at best and depend on comparison of impurity signals to a calibration line established by analyzing multi-element standard solutions at different concentrations. Ideally, the purity of reagents and starting materials should be monitored by ICP-MS before target preparation to eliminate possible sources of impurities. To preserve the option of refining the purification scheme before target preparation, purity evaluation by ICP-MS is advisable before target preparation.

Present ICP-MS do not have the resolution power to resolve isobars. For some combinations of interfering element(s) and target-nuclide(s), elimination of the interference via reactive collision is possible (mostly Q-ICP-MS). Alternative mathematical corrections for isobaric interferences are an additional source of uncertainty and depend on known isotope abundances of the interfering element. Thus, to ensure high-quality quantitative results, it is ideal to analyze highly pure analytes deficient of interfering species. Analyzing nuclear materials, cases will arise in which interferences cannot be reduced to insignificance but the isotope abundances of the interfering element cannot be assumed to be "natural", i.e., as reported in [6], with certainty. In these cases, separately determining the isotope abundances of the interfering element using a purified fraction of the interfering element is a viable option, e.g., [7]. Alternatively, recurrent adding of the same element in large amounts and having "natural" isotope abundances followed by renewed purification, e.g., [8] can reduce the induced error of assuming "natural" isotope abundances of the interfering element reduced to insignificance.

Laser Ablation (LA) of solids in a gas stream and direct introduction of the dry aerosole into the plasma source has vastly expanded the use of ICP-MS to obtain spatially resolved chemical data. In particular, ultra-fast LA systems using laser pulse-widths in the femtosecond range (fs-LA) are almost ideal sampling tools that allow for virtually non-destructive in-situ analyses of targets. Given this ability, 2D LA-ICP-MS imaging of targets by analyses across its diameter can help evaluate target homogeneity in a swift fashion, if autoradiography is not possible.

I will give a short introduction into the topic and discuss some examples of work concède at PSI.

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RADIOISOTOPE PRODUCTION AT INSTITUT LAUE-LANGEVIN

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Institut Laue-Langevin (ILL) in Grenoble, France, operates a 57 MW high-flux reactor. Its main purpose is the distribution of thermal, hot, cold, very cold and ultracold neutron beams to over 40 instruments. Every year, some 1500 researchers from over 40 countries visit the ILL to use these instruments for research, mainly by neutron scattering in the fields of condensed matter physics, chemistry, biology, materials science, etc. In addition dedicated instruments exist for nuclear and particle physics, the latter studying properties of the neutron or neutrino respectively.

The highest neutron flux at ILL's reactor with up to $1.5 \cdot 10^{15}$ n.cm 2s 1 can be reached in the vertical beam tube V4. It can be loaded with irradiation shuttles or fission chambers, e.g. for cross-section measurements of actinides [1-3]. This irradiation position provides the highest thermal neutron flux in Western Europe and is also ideally suited for production of radionuclides with high specific activity.

The achievable specific activity of a produced radionuclide (which basically measures the atomic ratio of this isotope of interest to all isotopes present after irradiation) scales to first order proportionally with the thermal neutron flux, at least for cases which are not limited by target- or product burn-up respectively. Only target isotopes with a particularly high neutron capture cross-section can be transmuted in a long irradiation quasi completely into a product with very high specific activity. Thus an isomeric target of the K isomer ^{177m}Lu target had been produced [4].

For target isotopes with low cross-section the achievable specific activity of the product is still limited, e.g. for the recently produced ^{79}Se[PbSe] and ^{94}Nb[Nb] targets that will serve for the measurement of cross-sections of astrophysical interest. If required, the specific activity can be further increased by electromagnetic mass separation of the produced radionuclides from the remaining target atoms. Recently ^{169}Er and ^{175}Yb with high specific activity have been produced by first irradiating the stable enriched precursors ^{168}Er and ^{174}Yb in ILL's V4 beam tube, then boosting the specific activity by off-line mass separation at MEDICIS (CERN) [5]. Also a HfO_2 target was irradiated in V4, then the produced ^{181}Hf was off-line mass-separated and ion implanted at the BONIS separator (Bonn University). ^{181}Hf is an excellent nuclide for measuring via time differential perturbed angular correlation spectroscopy (TDPAC) the electronic and magnetic environment of the probe atom in a solid or liquid [6].

Still higher specific activities, so-called non-carrier-added (n.c.a.) quality, can be achieved by exploiting neutron capture reactions to short-lived precursors that decay quickly to longer-lived daughters which are obviously isotopes of an element different from the target element. Consequently a subsequent radiochemical separation of the produced radionuclide from the target material leads to very high specific activity. Examples are ^{176}Yb(n,γ)^{177}Yb(β$^-$)^{177}Lu (commercially available from ITG Garching), ^{102}Pd(n,γ)^{103}Pd(EC)^{103m}Rh [7] or ^{160}Gd(n,γ)^{161}Gd(β-)^{161}Tb [8,9] for nuclear medicine applications, ^{110}Pd(n,γ)^{111}Pd(β$^-$)^{111}Ag for producing ^{111}Ag, another TDPAC nuclide [10], ^{146}Nd(n,γ)^{147}Nd(β-)^{147}Pm and ^{170}Er(n,γ)^{171}Er(-)^{171}Tm for producing targets for astrophysical cross-section measurements [11] and ^{162}Er(n,γ)^{163}Er(EC)^{163}Ho for projects aiming at determining the electron neutrino mass [12,13]. When the intermediate radionuclide is longer-lived, the radiochemical separation can also be performed multiple times as a radionuclide generator. Examples are ^{46}Ca(n,γ)^{47}Ca(β$^-$)^{47}Sc [14], ^{98}Mo(n,γ)^{99}Mo(β$^-$)^{99m}Tc [15] or ^{130}Ba(n,γ)^{131}Ba(β$^-$)^{131}Cs [16].

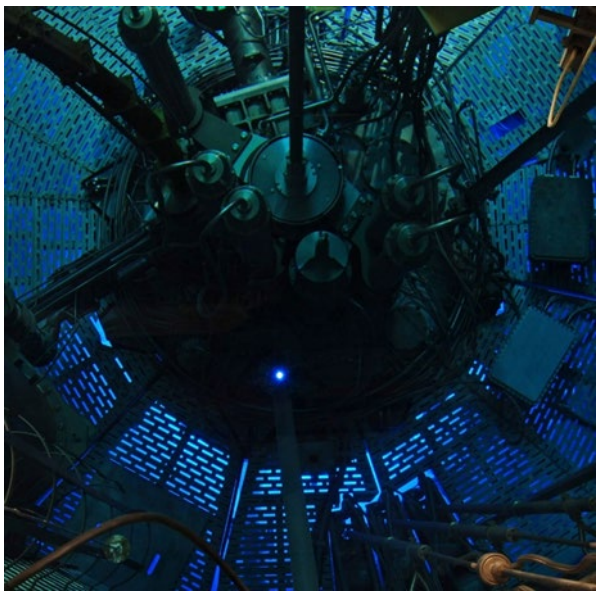

Fig. 1: Top view of ILL's high flux reactor. The Cherenkov radiation in the V4 beam tube can be seen

as the bright blue spot in the center of the image.

A very high neutron flux is particularly important for double neutron capture reactions where the product isotope is reached from the stable target isotope via an intermediate, relatively short-lived isotope. In this case the achievable specific activity of the product scales roughly with the square of the neutron flux. Examples are $^{164}Dy(n,\gamma)^{165}Dy(n,\gamma)^{166}Dy$ [12], $^{186}W(n,\gamma)^{187}W(n,\gamma)^{188}W$ [17] and $^{192}Os(n,\gamma)^{193}Os(n,\gamma)^{194}Os$. These generator isotopes serve in turn for multiple extractions of the shorter-lived daughters ^{166}Ho, ^{188}Re and ^{194}Ir respectively in non-carrier-added quality.

In addition to the examples given before practically all radionuclides accessible by thermal neutron capture can be produced at V4.

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ISOTOPE PRODUCTION AT PSI

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High-energetic protons and secondary particles induce in matter the production of a big variety of radionuclides, some of them being very rare, exotic, and, in several cases, difficult to obtain by complementary reactions. These isotopes are of high importance in research fields like nuclear astrophysics, basic nuclear physics or environmental science, and sufficient sample material for scientific experiments is urgently needed.

Highly activated components stemming from the surroundings or parts of a high-power particle accelerator are a unique possibility to gain such valuable isotopes. The advantage of "mining" isotopes from waste materials consists in their principal availability, not requiring "extra" beam time. The challenge is their radiochemical isolation from the matrix.

PSI operates the Spallation Neutron Source SINQ, which is driven by one of the most powerful high-energetic proton accelerators world-wide (590 MeV, up to 2.4 mA), and is therefore best-suited as a producer of such rare exotic radionuclides. In the frame of the ERAWAST (Exotic Radionuclides from Accelerator Waste for Science and Technology [1]) initiative a complex program for isotope separation from different matrices has been established at PSI within the past decade.

In figure 1, a schematic view of the PSI accelerator facilities is presented. The arrows point on special positions, from which useful material can be extracted. Several sources for isotope extraction are discussed in the talk.

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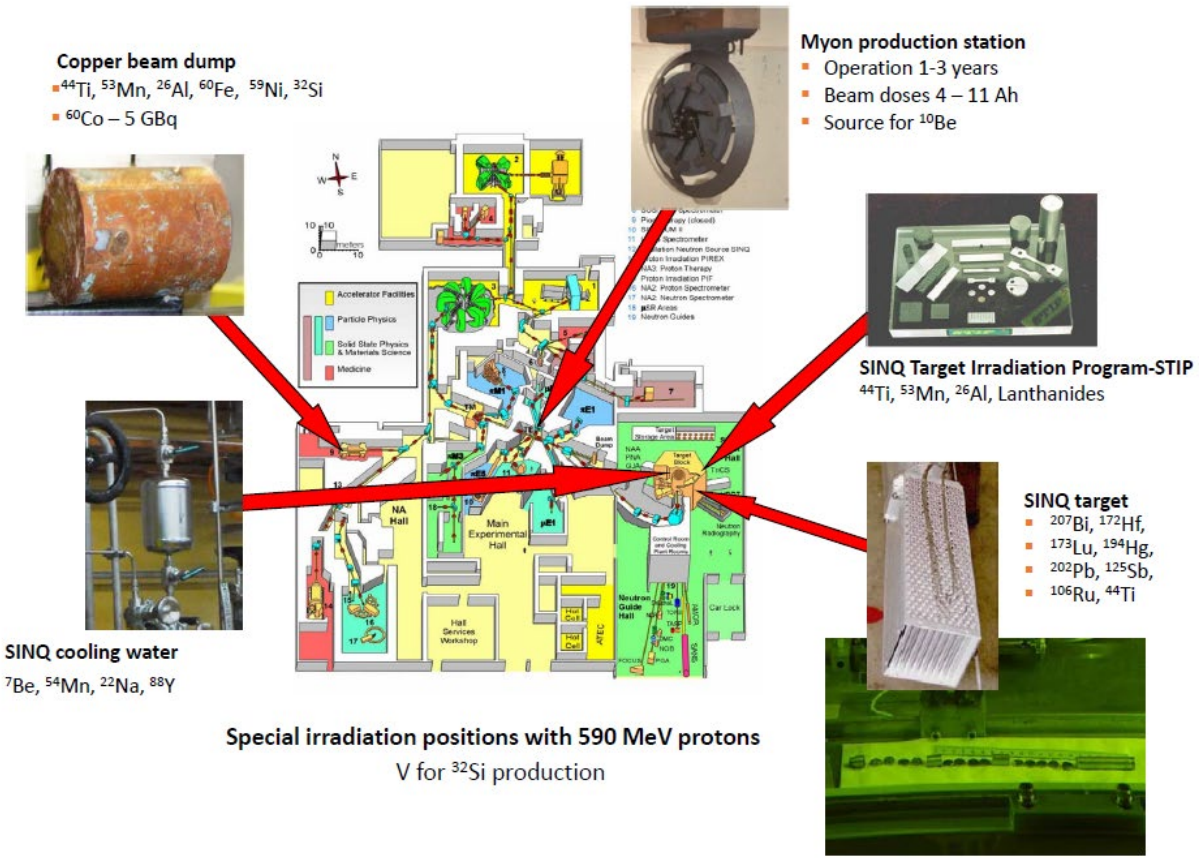

Fig. 1: Schematic view of the PSI accelerator complex and possible sources for rare exotic isotopes.

DESIGN OF AN ISOTOPE SEPARATOR FOR TARGET PRODUCTION

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With the rising demand for isotopically pure targets for the study of specific nuclear reactions, the construction and installation of a high-throughput isotope separator has been identified as a long-term goal in the nuclear data community. Specifically the handling and purification of radioisotopes is mandatory and will be enabled by installation of the whole setup within a radiologically supervised working area in close contact to a radiochemisty laboratory. In the current project phase, partially funded by SANDA, the design of the apparatus and establishment of a suitable commissioning site, located at PSI, is planned.

The isotope separator will be specifically tailored for efficient production of isotopically pure targets of stable or radioactive isotopes for end users. The design will be derived from experiences with the laser resonance ionisation set up RISIKO at Mainz University. The RISIKO isotope separator has been successfully used for radioisotope purification and implantation, e.g. within the ECHo and further projects [1,2]. It features a hot-cavity laser ion source implying the principle of resonant laser ionization, which is inherently element-selective and highly efficient at the same time.

The laser system is based upon home-built, tunable pulsed Ti:sapphire lasers with high repetition-rate of 10 kHz [3]. Ion extraction from the reservoir/source region with about 30 to 50 kV, electrostatic beam focussing and separation with a conventional double focussing 60° sector field magnet seem most suitable for the task. After passing the separation slit, the ion beam can be re-focused to well below mm size for implantation into detectors, collectors or targets within a dedicated collection chamber with sub millimeter control and resolution.

In this contribution we present the principles, capabilities and limitations of the RISIKO separator with regard to improvements which can be implemented in the new SANDA isotope separator.

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SAMPLES FOR FISSION MEASUREMENTS ON ACTINIDES AT THE CERN n_TOF FACILITY

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The n_TOF facility at CERN was built, among other motivations, with the aim of addressing the increasing needs of new, accurate fission data, suitable for many applications and mainly the nuclear energy production in current and future reactors. Since the start of its operation in 2001, a vast experimental programme has been carried out, which has led to a wealth of high quality results [1].

One of the most important ingredient for a successful fission measurement is the target(s) used, and more specifically the purity of the material, the quality of the thin actinide deposit, the appropriate backing (thin but robust) and the detailed characterisation. All these factors have a direct impact on the uncertainty of the final data of a fission experiment, thus need to be carefully considered before the experiment and during the target preparation. Furthermore, a major challenge nowadays is to find the suitable actinide material with the required isotopic and chemical purity.

At n_TOF, mainly after 2010, most of the actinide targets used for fission measurements come from JRC-Geel and high quality results have been obtained so far, as for example in ref. [2-6].

The aim of this presentation is to give an overview of the target characteristics that are important for this kind of measurements and to show how they affect the quality of the experimental results. Furthermore, future needs will also be presented.

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INDIRECT MEASUREMENT OF NEUTRON CROSS SECTIONS OF SHORT-LIVED NUCLEI WITH SURROGATE REACTIONS ON A ^{242}Pu TARGET

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Neutron-induced cross sections of radioactive nuclei are crucial ingredients for the simulation of advanced nuclear energy systems and for the production of diagnostic or therapeutic radionuclides for medicine and industrial quality control. However, their direct measurement is very complicated or even impossible due to the radioactivity of the targets involved. This issue can be overcome by using surrogate reactions. In this approach, the excited nucleus produced by the neutron-induced reaction of interest is formed by a surrogate reaction involving a light projectile nucleus impinging on a target that is stable or much less radioactive than the one of the desired neutron-induced reaction. The decay probabilities induced by the surrogate reaction are particularly useful to constrain key parameters of model calculations that will then provide much more accurate predictions of the desired neutron-induced cross sections.

Our objective is to use the surrogate-reaction method to indirectly infer the ^{240}Pu(n,γ), ^{240}Pu(n,f), ^{241}Pu(n,γ) and ^{241}Pu(n,f) differential cross sections. The three last cross sections are entries of the High Priority Request List. The direct measurement of these cross sections is particularly difficult due to the short half-life of required targets ^{240}Pu ($T_{1/2}$=6561 y) and ^{241}Pu ($T_{1/2}$=14.329 y). To derive the desired cross sections we will measure simultaneously the fission and γ-emission probabilities of the excited ^{241}Pu and ^{242}Pu nuclei produced by surrogate reactions between ^{4}He and ^{3}He beams impinging on a ^{242}Pu target ($T_{1/2}$ =3.7·10^{5} y). Of particular interest is the measurement of the fission and γ-emission probabilities of ^{242}Pu below the neutron separation energy. This excitation energy region is only accessible with surrogate reactions and is essential for determining key information such as the fission-barrier and level-density parameters, which are of outmost importance for accurately predicting the ^{241}Pu(n,γ) and ^{241}Pu(n,f) cross sections. The experiments will take place at Tandem accelerator of the IPN Orsay in France with an already existing setup [1]. To account for angular-momentum effects and infer the desired ^{240,241}Pu cross sections, we will benefit from the knowledge acquired during the study of very similar surrogate reactions carried out with a ^{240}Pu target within the CHANDA project [2].

The present project is part of SANDA. We have initiated discussions with the target laboratory of the JRC Geel, the radiochemistry group of the IPN Orsay and the University of Mainz for the production of the ^{242}Pu target, which is quite challenging. A significant difficulty is that the radioactive material has to be electrodeposited on a very thin natural carbon backing of 100 μg/cm^{2}, but the radiochemistry group of the IPN of Orsay already managed to produce a ^{240}Pu target with such a backing for our last experiment. Moreover, one has to ensure the best possible chemical purity, i.e. contaminants like Cl, Ca, etc. have to be avoided.

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SIMULTANEOUS MEASUREMENT OF THE ^{239}Pu FISSION AND CAPTURE CROSS SECTIONS

D. Cano-Ott, V. Alcayne, E. Mendoza (CIEMAT), J. Andrzejewski, J. Perkowski (Univ. Lodz), J. Heyse, P. Schillebeeckx, A. Plompen (JRC-Geel)

The design of new critical nuclear systems such as Gen IV reactors and Accelerator Driven Systems requires to decrease the uncertainties on neutron capture and fission cross-sections of major and minor actinides [1]. In particular, ^{239}Pu plays a dominant role in the operation of fast reactors and is also very important for the operation thermal reactors, especially when loaded with MOX fuels. More accurate ^{239}Pu capture and fission cross section data are needed [2] and those measurements have been listed in the NEA/OCDE High Priority Request List.

The measurement of neutron capture cross sections of fissile isotopes involves significant difficulties due to the strong competing γ-ray background. For this reason, the fission tagging technique [3] has been developed and applied at the n_TOF facility at CERN [4]. After the successful measurements on ^{235}U(n,γ) and (n,f) cross sections with the Total Absorption Calorimeter and micromegas fission tagging detector [5], we want to perform a new measurement on ^{239}Pu. Such an activity is part of the experimental program funded by the H2020 SANDA project.

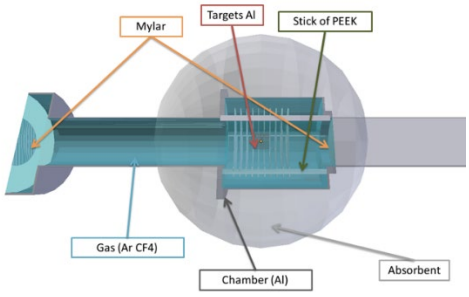

Fig. 1: Schematic view of the elements of the compact ionisation chamber.

For this purpose, a new ionisation chamber with less dead material in the beam is being constructed at the University of Lodz. The optimisation of the chamber has been made by considering the following criteria:

- Separation of the α and fission fragment (FF) components in the fission detector. The α-decay rates in the detector will be of the order of 10^6-10^7 decays/s.
- Maximisation of the FF detection efficiency.
- Minimisation of the dependence of the FF detection efficiency on the angular and (A,Z) distributions.
- Time resolution and pulse width for reducing the pileup of neighboring events.
- Minimisation of the background introduced by the fission detector in the TAC.
- Capability of accommodating a stack of targets.

In addition, the performance of the TAC has been evaluated by performing a new set of simulations and re-analysing previous experiments, by placing the focus on the quantitative understanding of the background production mechanisms.

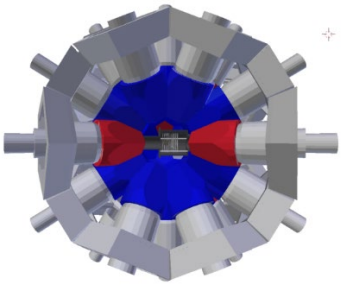

Fig. 2: Geometry of the TAC and the ionisation chamber in its center.

The last and remaining part of the optimisation procedure is related to the ^{239}Pu targets in terms of diameter, thickness, homogeneity, purity and backing (thickness and material). Such an activity needs to be done in strong collaboration with the radiochemistry laboratories and scientists, since they have the knowledge and expertise for producing the best possible quality targets.

During the workshop, we will present all the important aspects related to the measurement and, in particular, what are the desired characteristics of the targets and their impact on the quality of such a challenging measurement.

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STUDYING THE ASTROPHYSICAL PRODUCTION OF ^{180m}Ta VIA NEUTRON CAPTURE ON RADIOACTIVE ^{179}Ta

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^{180m}Ta is the rarest isotope in nature with an unusually low abundance considering the yields of various processes in its mass region [1]. Its astrophysical origin is still an open question. It is thought to be produced during the slow neutron capture process in Asymptotic Giant Branch stars through two mechanisms : via the β-decay of ^{180m}Hf (formed via n-capture on ^{179}Hf) [2], and via the n-capture on ^{179}Ta (formed via the β-decay of thermally excited ^{179}Hf) [3]. The former route has been studied previously and it was shown that this mechanism alone is not sufficient to explain the observed abundance of ^{180m}Ta [4]. In the present project, we aim to investigate the latter of mechanism, and this requires the cross-section measurement of the n-capture reaction on the ^{179}Ta isotope which is unstable with a half life of 1.82 years.

We have performed a test irradiation at the Birmingham cyclotron to produce ^{179}Ta via ^{180}Hf(p,2n) reactions using the same approach as ref [5]. ^{179}Ta will be extracted at PSI from the mix of various nuclei produced during irradiation. Depending on the net mass and the purity achieved after separation, the sample will be used for an initial activation measurement at thermal neutron energies at a nuclear reactor.

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SEPARATION OF TANTALUM FROM A PROTON IRRADIATED HAFNIUM MATRIX FOR TARGET PREPARATION

I. Kajan, D. Schumann (Paul Scherrer Institute, Villigen, Switzerland)
R. Garg, C. Lederer-Woods (University of Edinburgh, United Kingdom)

In the last years an increasing demand for accurate nuclear data can be observed from different areas of science, including radiopharmacy, astrophysics or basic nuclear physics. In order to perform successful measurements of the nuclear properties of the specific isotope chemical separations are often necessary. Such separations present a chemical challenge with respect to the amount of atoms of the isotope within the bulk matrix.

In this presentation, the efforts towards the separation of nanogram amounts of ^{179}Ta from a proton irradiated hafnium metal are described. For the separations three different chromatographic systems were developed and applied. Processing of the hot sample included removing of the hafnium matrix and application of extraction chromatography in order to obtain the pure ^{179}Ta fraction. Performed separations led to very high decontamination factors of Ta from Hf (>1E6) yielding the pure ^{179}Ta sample. The sample will be used for the following radioactive target preparation for thermal n-capture cross section measurements.

RADIATIVE NEUTRON CAPTURE ON ^{205}Pb AT N_TOF (CERN): MOTIVATIONS AND STRATEGIES FOR THE PRODUCTION OF A ^{205}Pb TARGET

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The ^{205}Pb(n,γ) cross section, which has never been measured experimentally beyond thermal energy, is of great relevance for some proposed designs of Generation IV reactors, like Accelerator Driven System (ADS). Specifically, ^{205}Pb is produced in nuclear reactors which use a lead-bismuth eutectic alloy as a coolant and/or in the spallation target [1]. The foremost example of this reactor would be the projected ADS reactor MYRRHA, under development in Belgium. In these reactors, ^{205}Pb is produced by neutron irradiation of ^{204}Pb, which accounts for 1.4% of all natural lead. Due to its long half-life, it accumulates during the working cycle of the reactor and thus, an accurate and precise knowledge of the neutron capture cross section is necessary both to quantify the amount of ^{205}Pb in the radioactive waste, and for a reliable determination of the reactor neutronics.

In astrophysics, neutron capture cross sections are also one of the fundamental nuclear data in the study of the s (slow) process of nucleosynthesis. More interestingly, the competition between the capture and the decay rates in some unstable nuclei determines the local isotopic abundance pattern. Since decay rates are often sensible to temperature and electron density, the study of the nuclear properties of these nuclei can provide valuable constraints to the physical magnitudes of the nucleosynthesis stellar environment. Following the successful capture measurement campaigns at n_TOF of the thallium, lead and bismuth isotopes in the last two decades [2][3], ^{205}Pb is the last piece to complete the puzzle of the s-process nucleosynthesis at its endpoint. The importance of ^{205}Pb is based on that it is radioactive, with a half-life of 17.3 My, and it is only produced by the s-process. This two features make ^{205}Pb a possible candidate for dating the last s-process events that contributed to the solar system elemental abundances [4][5]. After the 2018 measurement of the ^{205}Tl(n,γ) cross section, the unknown ^{205}Pb(n,γ) capture cross section is the last obstacle hindering an accurate determination the ^{205}Pb abundance produced during s-process nucleosynthesis.

While being of particular interest, the study of the neutron capture cross sections of radioactive nuclei, like ^{205}Pb, is severely limited by the complexity of producing enough quantity of sample material to perform viable experiments. The usual technique employed is thermal neutron irradiation of a stable seed isotope in nuclear reactors. But afterwards, in order to achieve a high purity sample, a process of isotope separation from the stable seed nucleus is necessary. However, in most cases this is not feasible, which adds even more complexity to the measurement and the posterior analysis.

In this contribution, we would like to propose for discussion the use of alternative methods, such as those based on (p,n) or (p,xn) reactions, for the production of a ^{205}Pb sample. Such methods have been employed successfully to produce samples of the isotope for other purposes [6]. By using a seed nucleus with different atomic number, it is possible to apply advanced chemical separation processes. This should make achievable the production of a ^{205}Pb sample, with both the purity and the quantity -a few milligrams- required for capture experiments. In addition, such measurement could strongly benefit from the use of the iTED detection concept, currently in development [7]. The latter will deliver much improved background rejection capabilities for samples with large scattering-to-capture ratios, which is the case for heavy species like lead.

In this context, we would like to propose the funding, and manufacturing, of a ^{205}Pb target to the SANDA project. We believe SANDA offers the ideal framework, in terms of human and technological resources, to tackle the production of such a challenging sample.

Once the production of a viable sample is arranged, a proposal for a capture measurement will be sumitted to the neutron time-of-flight facility n_TOF, at CERN, for the Phase IV of the experiment (2022-24). n_TOF is characterized by a very high instant neutron luminosity, spanmning over a broad neutron energy range from 1 eV up to 1 MeV, which covers the energies of interest for nuclear technology and astrophysics applications. This makes the facility one of the best suited for capture measurements of very

low mass radioactive samples. Recent exemples are the successful measurements of ^{171}Tm(n,γ)[8] and ^{204}Tl(n,γ)[3].

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SAMPLE REQUIREMENTS FOR NEUTRON INDUCED CROSS SECTION MEASUREMENTS

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Several different types of experiments on neutron reactions are performed at the European Commission's Joint research Centre in Geel, Belgium. These experiments study neutron transmission and capture, elastic and inelastic neutron scattering, and neutron induced fission and charged particle reactions. The obtained experimental data can be parametrized using nuclear reaction theory. The resulting model parameters serve as input for evaluated nuclear data libraries such as JEFF or ENDF/B. Nuclear data libraries are used for safety assessments of nuclear systems. They are of interest for nuclear security and safeguards, nuclear physics, nuclear astrophysics and cultural heritage. The experimental observables, i.e. transmission and reaction yields, depend on the areal density of the samples used during measurements. Production of high-quality cross section data therefore relies on the quality and characterization of the samples. An overview will be given of general considerations relevant for sample preparation. Specific requirements and limitations related to the samples for the different types of measurements at JRC Geel will be discussed. Examples of sample characterization techniques of relevance for neutron induced reactions will be given.

PRODUCTION OF PbSe TARGETS FOR NEUTRON CAPTURE CROSS SECTION STUDIES

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Being ^{79}Se a branching point in the *s-process* path, the measurement of the cross section of the ^{79}Se(n,γ) neutron capture reaction will allow for better understanding the *s*-process nucleosynthesis occurring in massive stars.

In this project, it is suggested to study the ^{79}Se(n,γ)^{78}Se reaction by using two complementary techniques, namely the "direct method" and the "surrogate method". With the first approach, an enriched ^{79}Se target will be used for a direct (n,γ) cross section measurement *via* the TOF technique at the CERN n_TOF facility, Geneva. With the surrogate method, instead, the (2n) transfer reaction ^{78}Se(^{18}O,^{16}Oγ)^{80}Se will be studied at the Piave-Alpi INFN facility, Legnaro, Italy.

For the accomplishment of these studies, ^{79}Se and enriched ^{78}Se targets are required. However, due to its relatively low melting point, a pure Se target is not suitable. Hence, a selenium compound more resistant to fusion was selected, namely PbSe (melting point 1079 °C). PbSe targets will be prepared, starting from Se and Pb in their elemental forms, in three steps: 1- Synthesis of PbSe, 2- Purification of the synthesized PbSe, 3- Physical vapor deposition of PbSe on the target support foil.

Here, preliminary results on the preparation and characterization of such targets will be presented.

REACCELERATION OF LONG LIVED ISOTOPES FOR NUCLEAR ASTROPHYSICS

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Since 2018 the reaccelerating facility SPIRAL 1 at GANIL includes a new target ion source which allows one to reaccelerate many more isotopes than previously available. A recent interest of our community has been expressed towards long lived beams, such as 85Kr and 79Se. These beams could valuably be reaccelerated off-line, using isotopes separated from spent nuclear fuel.

Thanks to this contribution we would like to discuss potential solutions for these beams with the SANDA project partners.

PRODUCTION OF A ^{163}Ho TARGET FOR NEUTRON CAPTURE CROSS SECTION EXPERIMENTS AT N_TOF AND HISPANOS

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The unstable isotope ^{163}Ho (4567 years [1]) is a branching point along the *s*-process. However, it was not known until 1987, when it was observed that the stable ^{163}Dy becomes unstable with a half-life of only 47 d at high temperatures like those in the stars, when it is fully ionized [2]. Given its particular interest as a *s*-process branch in the proton rich region, a 0.18 mg ^{163}Ho target was produced in 1993 and its capture cross section measured via activation in a quasi-stellar spectrum at kT=25 keV. The resulting MACS value at 30 keV was of 2125(95) mb [3] (re-nornalized to 2118(98) mb in the current verson (v1) of KADONIS). This is, to date, the only measurement available, thus requiring for nucleosynthesis calculations extrapolation to lower and higher temperatures by means of theoretical cross sections obtained with the Hauser-Feshbach statistical model that are typically affected by uncertainties of 25 to 30%.

In this context, we propose to produce within the SANDA project a ^{163}Ho target of at least 5 mg, enough to perform a time-of-fligh measurement at the n_TOF-EAR1 [4] facility that would cover the resonance region up at few keV. This will allow for a more accurate extrapolation of the MACS data to lower temperatures of 8 keV, characteristic of H-burning in AGB stars. The resonance data will allow as well to estimate the MACS by means of the Hauser-Feshbach statistical model, hence provideing an «overlap» between the low (H-burning) and high (He-burning) enery regions of interest. The ToF experiment would be complemented by an activation measurement similar to that of Jaag and Käppeler [3], to be perfomed at the HISPANOS facility [5]. The target will be produced following the procedure developed recently by Heinitz et al. [6,7]: irradiation of ^{162}Er at a high flux reactor followed by the separation, purification and target making at PSI.

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