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Nuclear Data

M. Kerveno et al (IPHC), M. Fallot et al (SUBATECH), L. Mathieu et al (LP2i-Bordeaux), F.R. Lecolley et al (LPCC), L. Audouin (IJCLab), C. Sage et al (LPSC)

1/ Summary

Nuclear data is a fundamental issue in the field of nuclear energy. Indeed, all studies of nuclear systems, current or future, require the ability to simulate the interaction of particles with the material contained in the reactor core. Nuclear databases are then the basic ingredient of these simulations. For 30 years, IN2P3 has been involved in this research, which is governed by various laws since 1991 and the Bataille law. The teams of the institute have taken advantage of their expertise in instrumental nuclear physics to try to meet the challenges of improving the databases. Today, it is within the OPALE Master Project that the IN2P3 teams produce new measurements of effective sections, fission products yields and their decay to meet the needs of nuclear energy applications. Within national and international collaborations and involved in the work of international agencies that coordinate this theme, the OPALE teams have a recognized place today. Beyond the measurement itself, which remains our main activity, our actions have more recently turned towards evaluation with a will to be a more proactive actor in the chain of nuclear data production. A rapprochement with the IN2P3 reactor physicists is also under construction in order to participate in the definition of the needs in terms of new measurements.

This report first presents the general theme of nuclear data as well as the international context in which these activities take place. A brief history of the theme at IN2P3 is mentioned followed by the description of the Master Project OPALE. The heart of this report then concerns the description of the scientific projects carried out in OPALE as well as our ambitions for the next years. Before the conclusion which presents our strengths and weaknesses, some "accounting" elements are indicated.

LEXICON

OCDE/AEN Organisation de coopération et de développement/Agence pour l'Energie Nucléaire
AIEA Agence Internationale pour l'Energie Atomique
ARIEL Availability and use of nuclear data Research Infrastructures for Education and Learning
CIELO Collaborative International Evaluated Library Organization
CRP Coordinated Research Project (AIEA)
EUFRAT European facility for nuclear reaction and decay data measurements
IRSN Institut de Radioprotection et de Sûreté Nucléaire
NACRE Le Noyau Au Coeur du RéactEur
NEEDS Nucléaire Energie Environnement Déchets Société
NFS Neutrons For Science - SPIRAL2
OPALE des dOnnées exPérimentAles à l'évaLuation pour les réactEurs
SANDA Supplying Accurate Nuclear Data for energy and non-energy Applications
SciNEE Sciences Nucléaires pour l'Energie et l'Environnement
WPEC Working Party on International Nuclear Data Evaluation Co-operation (AEN)

2/ Scientific issues and challenges

The future of nuclear energy necessarily involves improving the performance of production systems and scenarios. The optimization of the operation of 3rd generation reactors with respect to current and future fuel cycles (U-Pu, Th-U) or the development of new reactor concepts are the subject of numerous studies. To make them possible, 4th generation reactors will have to meet stringent requirements regarding their operation throughout the nuclear power cycle. All these studies on the optimization of the operation and safety of nuclear power plants, the fuel cycle, waste inventories, etc., as well as studies on the development of new reactors (generation IV), new reactors and even complete scenarios, are based on the use of simulation codes. These codes make it possible to follow the evolution of the neutron population or of the different materials present in the reactor core, in the fuel or in the structures. The simulations then give access, for example, to reactor control parameters such as the multiplication coefficient, flux distributions, power slicks, etc., or to the inventory of waste produced, residual heat, etc. (cf. contribution by X. Doligez).

Whatever the codes used, these simulations require as input data the use of evaluated databases, which gather the nuclear physics observables essential to the simulation of the particle-matter interaction. An evaluated nuclear data of a physical quantity (cross section, angular distribution, spectrum of emitted particle, fission yield...) is built from its experimental knowledge (microscopic and integral measurement) and theoretical knowledge (modeling by nuclear reaction codes for example) and represents its best estimate at a given time. Currently, the typical time for an update of an assessment is about ten years if we consider the whole process (measurement and evaluation). The evaluated data are compiled in databases managed by nuclear data centers. There are five main databases in the world: one American (ENDF[1]), one European (JEFF[2]), one Japanese (JENDL[3]), one Chinese (CENDL[4]) and one Russian (ROSFOND[5]), which are constantly evolving.

Indeed, in the last few years, computational resources have progressed so much that they are no longer the only limiting factor for more and more accurate reactor studies. This accuracy depends, today, to a large extent on the quality of the evaluated data bases used by the simulation software. Several international studies, for example under the aegis of the NEA and the IAEA, have shown that many entries in the evaluated databases do not allow reaching the accuracy required for an application level. As a result of these studies, a list of reactions and related observables that require improvement has been created at the NEA. This is the High Priority Request List[6], which is regularly updated according to the progress made, or new requests to be integrated. In addition, a large sensitivity study on several innovative reactor concepts, carried out within the framework of WPEC-subgroup 26[7] (OECD/NEA) and published in 2008, was used to feed this priority list.

To qualify and quantify the needs for improvement, reactor physicists have developed methodologies based on perturbation theory to estimate the impact of the lack of knowledge of an input

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[1] https://www.nndc.bnl.gov/exfor/endf00.jsp
[2] https://www.oecd-nea.org/dbdata/jeff/
[3] https://wwwndc.jaea.go.jp/jendl/j40/update/
[4] https://en.cnnc.com.cn/2020-06/17/c_501119.htm
[5] https://vant.ippe.ru/en/year2007/neutron-constants/774-1.html
[6] OECD/NEA, Nuclear Data High Priority Request List, http://www.nea.fr/dbdata/hprl/
[7] M.Salvatores and R.Jacqmin, Nuclear Science-NEA/WPEC-26, Volume 26, NEA N° 6410 (2008)

observable (e.g. reaction cross section or fission yield) on a core parameter of interest (e.g. multiplication coefficient or residual heat). The recent developments of numerical methods for the calculation of uncertainties and sensitivities (analytical methods, Total Monte Carlo and sensitivities) now make it possible to bring reactor physics closer to nuclear physics upstream of the evaluations and their processing. The contribution of Xavier Doligez goes into more detail on the description of these methods and the new ways they open for the study of the impact of the in-certainties of the databases on the reactor calculations.

Once the need for improvement has been identified and quantified for an observable, the entire evaluation chain must be questioned (from microscopic measurement to theoretical modeling to the evaluation itself). For example, an experimental effort may be required for quantities for which existing measurements are contradictory, inaccurate and/or unreliable, or simply do not exist. Improvement of theoretical models may also be necessary, for example, when phenomenology shows its limits. It is important to underline that the key link of the evaluation is the development of good and sufficiently predictive theoretical models. The nuclear data theme is therefore in essence strongly linked to fundamental nuclear physics, whether for the theoretical understanding of reaction mechanisms, for example fission, or for the knowledge of the nuclear structure of nuclei of interest for nuclear energy.

Today, the challenges to be met in order to produce modern and optimal databases affect all aspects of the evaluation cycle: the production of quality experimental data (precise, explicit, binding ...), the development of predictive theoretical models (from the phenomenological to the microscopic) and modern evaluation methods. Furthermore, an optimization of the evaluation cycle time is also an objective.

A large international community from all continents is involved in the nuclear data problem. From the experimental point of view, large national laboratories contribute to the production of new nuclear data measurements. Without being exhaustive, we can mention in the United States, the LANL, the BNL, in Japan, the JAERI. We could see in 2019, during the international conference of our field "Nuclear Data for Science and Techno-logy" held in Beijing, that a rich activity takes place in China. In Europe, many countries also contribute to the production of data such as Spain, Belgium, Sweden, Italy, ..., and of course France via the teams of IN2P3 and CEA. At the level of the evaluated databases, the nuclear data centers are in charge of the activities. In Europe, the Nuclear Energy Agency (NEA) of the OECD hosts the JEFF (Joint Evaluated Fission and Fusion) Nuclear Data Library project in which the European community participates. The International Atomic Energy Agency (IAEA) also plays a very important federating and coordinating role at the global level. In particular, it hosts the EXFOR[8] experimental database and coordinates numerous concerted actions through its nuclear data service[9].

In this panorama, France plays an important role through the work carried out at CEA and IN2P3. More recently, IRSN has also become involved in the nuclear data theme. The following section describes the involvement of IN2P3 in this field, as well as its interactions with the major French and international actors in the field, with respect to the different structuring and funding frameworks in which the IN2P3 teams evolve.

[8] https://www-nds.iaea.org/exfor/
[9] https://www-nds.iaea.org/

3/ Nuclear Data at IN2P3

3.1 - 30 years of nuclear data at IN2P3

Research on nuclear energy was initiated at IN2P3 in the 1990s by the 1991 Bataille law on nuclear waste management (see Sylvain David's presentation). At that time, nuclear physicists of the institute were able to use their skills to try to answer the scientific questions raised by the law. One of the natural lines of research taken in charge by our colleagues was the development of experimental programs in order to answer the needs of new nuclear data measurements for reactors. At the time, given the context, the activities were focused on the problems of transmutation (fission cross section, for example) and spallation (linked to studies on accelerator-driven reactors).

To organize and finance activities around this new nuclear energy theme at IN2P3, a research group GEDEON (GEstion des DEchets par des Options Nouvelles), which later became GEDEPEON (Gestion des DEchets et Production d'Energie par des Options Nouvelles) and was financed by the interdisciplinary PACEN program (Programme pour l'Aval du Cycle et l'Energie Nucléaire) of the CNRS, was created. This structure brought together the CNRS, the CEA, EDF and FRAMATOME and enabled the various teams from the institutes to work on joint projects in line with the needs of industrial and academic players in the nuclear energy sector. The teams were also quickly involved in the European projects of the various EURATOM programs, which, in addition to providing additional funding, allowed them to participate in the European coordination of research on nuclear energy. Among the past achievements, we can mention the involvement of IN2P3, via a team from IPNO, to the start of the n-TOF installation at CERN for the measurement of fission cross sections and the angular distribution of fission fragments. The institute has also greatly contributed, within the framework of the nuclear data for energy theme, to the development of fission and capture measurements by the substitution method (team from LP2i-Bordeaux) but also to the development of the GEF[10] code for the description of fission yields, a code now widely used by the academic community but also by an industrial company (EDF).

3.2 - 2022: the OPALE Master Project

Today, nearly 30 years after their birth at IN2P3, our research is part of the institute's "Innovative channels and techniques for nuclear energy production" research program. Since 2016, the nuclear data activities concern the Master Project (MP) OPALE (des dOnnées exPérimentAles à l'evaLuation pour les réactEurs) which gathers the activities of 6 teams from 6 laboratories (IJCLAb, IPHC, LP2i-Bordeaux, LPCC, LPSC, SUBATECH) around projects of cross section measurements and studies of fission products and their decay. Today, 18 researchers (7 CNRS, 11 Ens. Ch.), 6 PhD students and 1 post-doc are involved in OPALE. The experimental activities take place on various European sites. We can mention for example, for the major installations, EC-JRC Geel (Belgium), Jyväskylä (Finland), ILL (France), GSI (Germany) and more recently SPIRAL2/NFS (France). Within the GdR SciNEE (cf. Presentation of A. Billebaud), the MP OPALE is part of the pole 1: Nuclear systems and associated scenarios[11].

[10] K.-H. Schmidt, B. Jurado et al., Nuclear Data Sheets 131 (2016) 107-221
[11] http://lpsc.in2p3.fr/index.php/fr/poles

Each project relies on national and/or international collaborations for the realization of experimental programs. At the national level, historically, we have always collaborated with our colleagues at CEA. Since 2016 and thanks to the creation of the structuring project NACRE of NEEDS (Le Noyau Au Cœur du REacteur, led by CNRS and co-lead by CEA), collaborations have been strengthened with 4 directions of CEA (DES, DAM, DSM, DRT) and some projects have been able to evolve towards more integrated activities from experiment to evaluation. At the international level, the teams are currently involved in the European SANDA[12] project. This EU project, also built in an integrated way, from experiment to evaluation through validation, allows the meeting of all the European actors of the theme of nuclear data for applications. Whether it is NACRE or SANDA, these two projects also allow us to collect the complementary financial resources necessary for the realization of our projects. (See section 5/ resources and means).

Finally, it is important to note that, in recent years, IN2P3 teams have significantly increased their interactions with international agencies such as the NEA or the IAEA through, for example, participation in the animation of the JEFF project or involvement in IAEA CRPs[13] and NEA WPEC subgroups. The structuring in MP at IN2P3 and the visibility of the structuring project NACRE have certainly contributed to this.

At the teaching level, the teachers-researchers evolving in the OPALE MP are obviously involved in the training of the universities or schools to which they are attached for teachings related to nuclear physics. Each year, since 2018, between two and three theses are started in the MP teams and we also welcome many trainees. OPALE researchers are also involved in the organization committees of IN2P3 schools such as the Ecole Energie & Recherche or the Ecole Joliot Curie. They can give lectures or answer to specific invitations from French or foreign schools.

4/ OPALE: achievements and ambitions

This part is devoted to the description of the scientific activities that make up the OPALE MP. It is divided into three sections respectively dedicated to the observables of interest, namely the reaction cross sections, the fission products and the decay of the fission products.

4.1 - Reaction cross sections

The reaction cross sections provide information on the probability of interaction of particles with matter. They are an essential ingredient in simulations of the evolution of the reactor core and its environment. Neutron parameters, for example the multiplication factor, the power and various reactivity coefficients (sodium drain, doppler...), depend directly on these quantities. As mentioned in the previous section, the evaluated databases compile these cross sections and are used for the simulation of the reactor cores. These data must therefore describe all the reactions over a very wide range in

[12] www.sanda-nd.eu
[13] https://www.iaea.org/projects/crp/f41030

neutron energy (from thermal energy, 0.025 eV, to several tens of MeV) and for a wide variety of nuclei.

The example of the evaluation of major neutron cross sections in the case of the ^{233}U nucleus compared to the available experimental data is presented Figure 1. We can see, for the same nucleus, how the situation can be different according to the considered reaction.

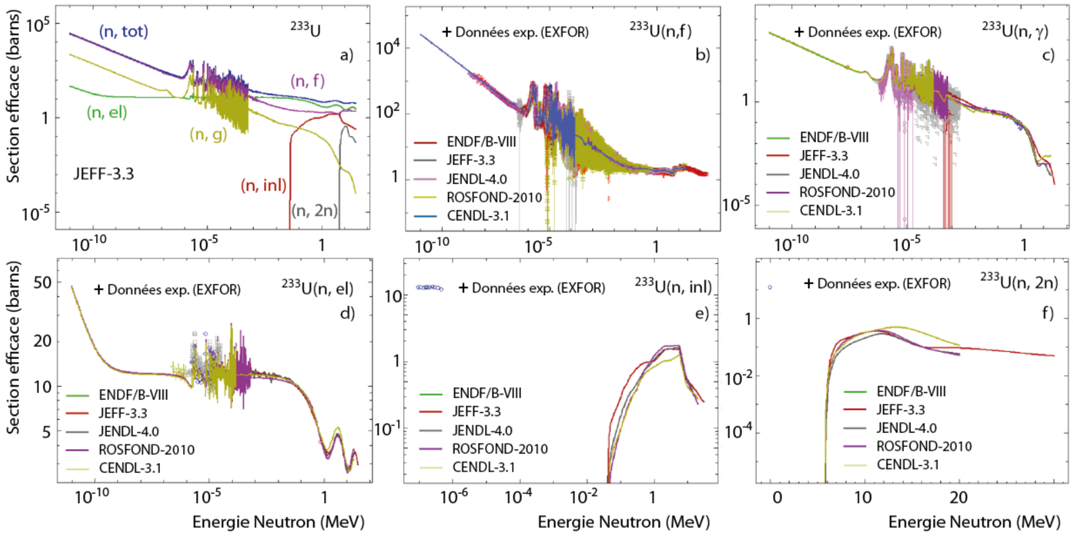


Figure 1 : Reaction cross-sections of n+^{233}U reactions from the evaluated databases compared to experimental data from the EXFOR database (https://www.nndc.bnl.gov/exfor/)

The evaluation of all these processes relies on different theoretical models depending on the energy range and the reaction studied (neutron capture, fission, elastic or inelastic scattering, (n,xn) or (n,pcl[14]) reaction, etc.). These models come into play and are combined in nuclear reaction codes such as TALYS or EMPIRE, used for data evaluation. The issues concerning the improvement of the quality of the evaluated data for cross sections concern in particular the improvement of the quality of the experimental data sets used to constrain the evaluation and the development of more predictive theoretical models. In this area, the actions of the OPALE teams are motivated by the following main points: the lack of basic data (for the Thorium cycle for example), high uncertainties (e.g. fissile isotopes created in the reactor such as $^{240,242}Pu$, threshold reactions) or requiring the resolution of strong challenges in terms of experimental set-ups and theoretical modelling (e.g. inelastic neutron scattering cross section measurements).

IN2P3, through the work of the DNR team of the IPHC, is currently a leader in the study of inelastic neutron scattering. This reaction is still poorly known because it is not well measured and theoretical models have difficulty in predicting its cross section correctly. For example, a request is listed in the HPRL concerning a new measurement of the neutron inelastic scattering cross section on 238U. This measurement should reduce the uncertainties from the current 20% to only a few percent. The development of the GRAPhEME spectrometer (in collaboration with JRC-Geel and IFIN HH Bucharest) at the EC-JRC-GELINA facility has allowed the realization of several measurement campaigns of

[14] lcp : light charged particles (p, d, t, alpha)

the (n, n'γ) reaction on the following nuclei ^{233,235,238}U[15,16], ^{232}Th[17], ^{182,183,184,186}W[18]. These campaigns have allowed the collection of many cross sections never before measured and with an accuracy of a few percent in the 0-10 MeV energy range. Once the data are analyzed and published, the cross sections are transmitted to the EXFOR experimental database. The prompt gamma-ray spectroscopy method is a powerful but indirect method for the study of inelastic scattering. Indeed, deducing the latter from our measurements requires either a very good knowledge of the nuclear structure of the nucleus studied or the use of theoretical models to complete the missing experimental information. The team has thus developed a strong link with the theoreticians of the CEA/DAM of Bruyères-le-Châtel. This collaboration, extended to a theoretician from LANL and a theoretician-evaluator from the IAEA, has led to a significant progress in the description of the cross sections (n, n'γ) in particular in the study of the nucleus ^{238}U[15].

To illustrate one aspect of this work, Figure 2 shows the improvement obtained for the description of the cross sections for high spin transitions in the fundamental band by the implementation of a microscopic pre-equilibrium model (model A TALYS) which allows a more realistic description of the spin distributions obtained during the inelastic interaction of the neutron with ^{238}U. The work on this nucleus was also the occasion for the team to co-direct a thesis (CEA funding) with the CEA/DES/Cadarache, part of the subject of which concerns the preparation of a new evaluation of nuclear data for the ^{238}U nucleus taking into account recent theoretical advances.

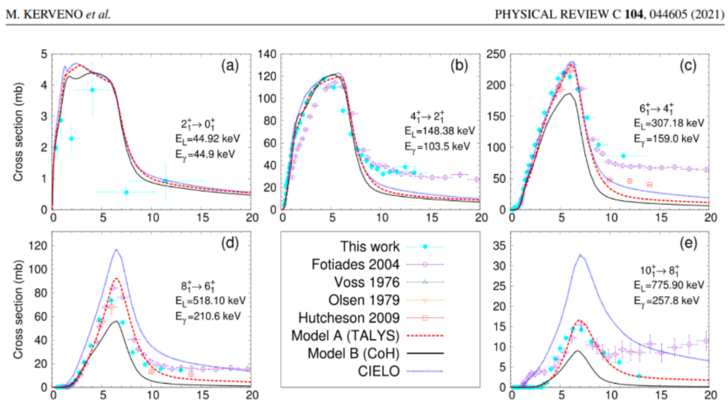


Figure 2 : Measured ^{238}U(n, n'γ) cross sections for transitions in the fundamental band compared to predictions of 3 nuclear reaction codes.

Following the obtaining of an ANR funding in 2007, the team was able to develop GRAPhEME by adding a segmented HPGe detector which allows difficult measurements on very radioactive isotopes such as 233U and 239Pu. Indeed, these measurements must be performed with a high counting rate due to the activity of the target. Moreover, the gamma spectra are very strongly contaminated by the radioactivity gammas and those resulting from the decay of the fission products (fission cross section much higher than that of the inelastic scattering). The analysis of ^{233}U data is being finalized and will produce unique experimental data as never measured before. The challenge of measurement on ^{239}Pu is posed as soon as the search of the target begins. The team was able to benefit from the network of target laboratories of the European project SANDA (WP3) and a sufficiently pure sample is about to be obtained. At GELINA, to complete the measurements with GRAPhEME, the team is also developing a new instrument (DELCO) for the detection of conversion electrons coming from the de-excitation of low energy levels in actinides.

With the arrival of the new NFS facility, a large program of (n, xn) reaction cross sections measurement is envisaged, initially on low active actinides such as ^{238}U and ^{232}Th. The team has submitted letters of intent to the PAC GANIL in this sense. These new measurements will provide very important

[15] M. Kerveno et al., Phys. Rev. C 87, 24609 (2013)
[16] M.Kerveno et al., Phys. ReV C 104, 044605, (2021)
[17] E. Party et al., EPJ Web of Conferences 211, 03005 (2019)
[18] G. Henning, et al. EPJ Web of Conferences 247, 09003 (2021)

complementary data sets to constrain the evaluations but also to test and improve the theoretical models (mainly pre-equilibrium ones) describing these reactions. We can also note the strong technical involvement of the IPHC team in the development of the NFS time-of-flight experimental area[19].

Although studied for many years, the fission process, obviously central to nuclear energy applications since it contributes to energy production, cannot yet be completely described by theoretical models. For nuclear energy applications, the fission cross sections are an observable of undeniable interest. IN2P3, via the LP2i-Bordeaux team, is involved in measurements of the ^{242}Pu nucleus. Indeed, this nucleus is a key element in the formation of very radiotoxic nuclear waste that is difficult to incinerate, such as Am or Cm. Moreover, this nucleus was chosen for the deposit of the fission chambers of the Occitane device of the Jules Horowitz irradiation reactor. The fission cross section of ^{242}Pu is present in the HPRL and the request concerns a new measurement on the energy range 200 keV-20 MeV. The expected improvement on the accuracy of the cross section is of the order of 5 to 10% over the energy range of interest. The team has therefore taken up the challenge and the project includes a measurement and evaluation component, and an instrumental development one. The experimental technique used for the measurement is based on two specificities of the LP2i-Bordeaux team: the use of photovoltaic cells for the detection of fission events, and the use of the recoil proton technique to measure the neutron flux. A photovoltaic cell is a simple, robust and cheap detector, allowing the detection of Fission Fragments with high efficiency. The recoil proton technique uses a hydrogen-rich "radiator" to convert the neutron flux into a proton flux based on the ^{1}H(n,n) cross section which is a very accurate standard. This allows to get rid of the references usually used for this kind of experiment (^{235}U(n,f), ^{238}U(n,f)...), and thus to produce nuclear data independent of the existing data. This point is fundamental to bring an added value to the databases and theoretical models. The measurement of ^{242}Pu(n,f) between 1 and 2 MeV was carried out by the group. The existing data showed discrepancies in this energy region, and the presence of a structure around 1 MeV was in question (see Figure 3). The analysis was conducted mainly between 2015 and 2017, and led to several new points at the level of the fission plateau, results published in PRC[20]. These results confirm the "low hypothesis" of the cross section, but do not discriminate the presence of the structure. A work has been carried out during a thesis in 2020-2021 (financed by CEA/DES and co-directed

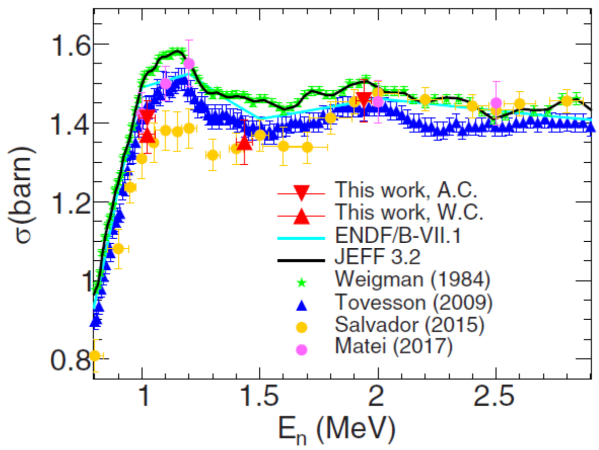


Figure 3 : ^{242}Pu(n,f) cross section with the main evaluations and experimental data. The data from LP2i-Bordeaux (red triangles) validate the low assumption of the cross section.

[19] M. Kerveno, invited talk, 22nd colloque GANIL, sept. 2021 https://ganil2021.sciencesconf.org/resource/page/id/9

[20] P. Marini et al., Phys. Rev. C 96, 054604 (2017)

between the two laboratories) on the evaluation of this nucleus, more specifically on theoretical calculations around this structure at 1 MeV (Figure 4). This work highlighted errors/blunders in the previous evaluation, and led to a more precise description (realized with the TALYS code) of the passage of the fission barrier but also of the daughter nucleus after neutron emission (inelastic diffusion of the incident neutron). This last reaction path, marking a pronounced dip around 1 MeV, would then be responsible for the structure observed on the fission cross section. This work tends to confirm the presence of this structure around 1 MeV. A new experiment has been proposed through the EUFRAT calls[21] to carry out a new and more precise measurement, specifically around the 1 MeV structure, at EC-JRC-Geel (Belgium). The proposal has been accepted, and an agreement between the different partners (EC-JRC-Geel, LP2i-Bordeaux, CEA/DES) is being drafted.

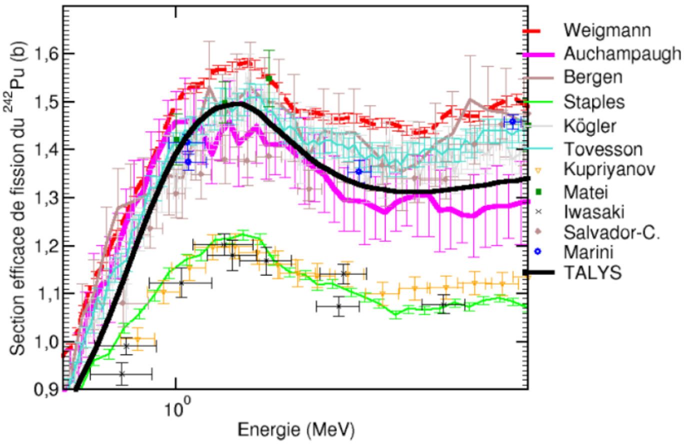


Figure 4 : ^{242}Pu(n,f) cross section with many experimental data sets and the latest theoretical calculation of LP2i-Bordeaux and CEA to reproduce the structure around 1 MeV.

The other side of the project includes the development of a new recoil proton detector aiming at the normalization of fission cross sections to ^{1}H(n,n) elastic scattering. Under the usual very noisy experimental conditions (generation of a large amount of neutrons, gamma and electrons by the source point), the recoil protons can only be detected and counted accurately with a simple silicon detector above 1 MeV because of an intense signal at low energy. The group has therefore been developing for several years the Gaseous Recoil Proton Detector[22] (DGPR) (Figure 5), which is a mini Time Projection Chamber based on a segmented Micromegas detector.

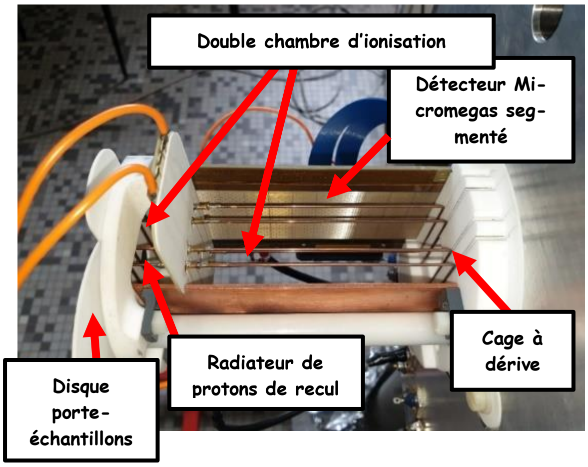


Figure 5 : Photo of the Recoil Proton Gas Detector.

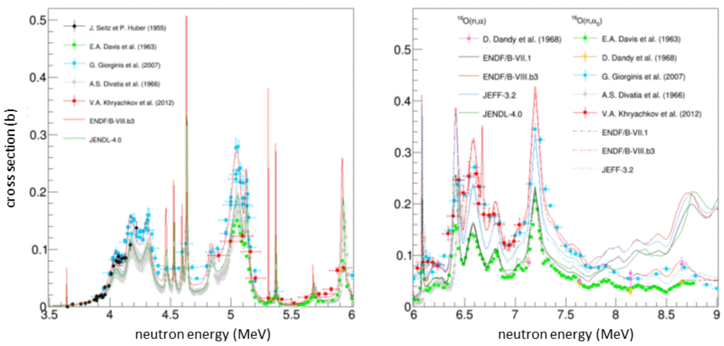
The interest of DGPR is to be much less sensitive to gamma/electrons, by adapting the gas pressure to the path of the recoil protons. The segmentation of the detector into 64 pads allows discriminating the good trajectories (recoil protons coming from the radiator with a nominal energy) from the bad ones (recoil protons coming from other hydrogenated materials, or coming from the radiator with an abnormal energy, cosmic rays...). Several test experiments have been performed on the AIFIRA platform of LP2i-Bordeaux, and have allowed to validate or to improve the different aspects of the detector. The whole experimental system gives satisfaction: low sensitivity to gamma/electron noise, trace reconstruction, stability of the electric field under irradiation...

A last problem remains at the level of the DGPR acquisition system. This system was adapted by the Electronics Department of LP2i-Bordeaux from the GET electronics, for use with 64 detection

[21] https://publications.jrc.ec.europa.eu/repository/handle/JRC114118
[22] P. Marini et al., Rad. Meas. 124 (2019)

channels. However, the various tests have revealed a serious deficiency in the processing of events, with an abnormally high dead time, which reduces the detection efficiency for significant count rates (30% at 300 pps). This problem, prohibitive for the exploitation of the detector, is under investigation. This detector will be used later to measure the fission cross sections of other nuclei, of interest for the production of radiotoxic radioactive waste, such as ^{240}Pu or ^{241}Am.

The LPC Caen team has taken up another experimental challenge which concerns the measurement of the cross section of the $^{16}O(n,alpha)^{13}C$ reaction. This reaction is one of the key reactions in reactor studies because it affects the knowledge of helium production in the fuel. Indeed, 25% of the helium is produced by the $^{16}O(n,alpha)$ reactions inducing an uncertainty of a few hundred pcm on the neutron multiplication factor (k_{eff}) which is a fundamental parameter for the control of the reactor[Erreur ! Signet non défini.,23,24]. Therefore, since 2005, this reaction has been part of the NEA HPRL, which requires more measurements for this reaction from its threshold up to 20 MeV; this need was again clearly expressed at the International Conference on Nuclear Data for Science and Technology (Beijing, China, 2019)[Erreur ! Signet non défini.]. Indeed, despite the recent measurements[25,26], many discrepancies between measurements and evaluations (Figure 6) persist. In addition, there are also discrepancies between the evaluations themselves, which are more or less important depending on the energy range. This highlights the need to perform as many new measurements as possible with new configurations using several facilities across Europe to provide new data sets for the evaluation process. The SCALP detector was designed and



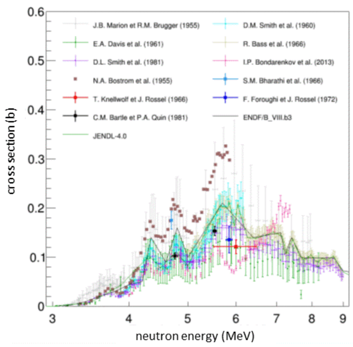


Figure 6 : Experimental and evaluated cross section for the $^{16}O(n,)^{13}C$ (left and center) and for the $^{19}F(n,)^{16}N$ reactions (right).

[23] M.B. Chadwick et al., The CIELO collaboration, Nuclear Data Sheets 118 (2014)
[24] A. Courcelle, working document, CEA Cadarache (2005)
[25] G. Giorginis et al., Conf. On Nuclear Data for Science and Technology, Nice, 1, 525 (2007)
[26] V.A. Khryachkov et al., EPJ Web of Conferences, 21, 3005 (2012)

The ^{19}F(n,alpha)^{16}N reaction should also be considered one of the key reactions: there are many discrepancies between experimental and evaluated data (Figure 6) and fluorine is present in the molten salt reactor (MSR) fuel salt. To our knowledge, however, there is no sensitivity analysis for this reaction, which is mainly due to the absence of MSR as a study case in the NEA-WPEC 26[Erreur ! Signet non défini.]. The first step of the SCALP experimental program is the study of this reaction in order to be able to manage the important background noise during the data acquisition (n,alpha) on oxygene 16 with the SCALP detector. SCALP (Scintillating ionization Chamber for ALPha particle production in neutron induced reaction) is a new scintillating ionization chamber [27,28] used as an active target to measure the reaction cross section (n,alpha) on various gaseous targets such as ^{19}F or ^{16}O, from the reaction threshold to 20 MeV (Figure 7). It consists of an ionization chamber filled with CF_4 (for fluorine measurements) or CF4+CO2 (for oxygen measurements) allowing the detection of the energy deposited by the light charged particles emitted during the reaction (n,alpha). In parallel, four photomultiplier tubes detect the scintillation light produced by the interaction of particles in the active volume of the gas. By taking advantage of the fast scintillation response, the kinetic energy of the neutrons can be deduced by time-of-flight measurements. SCALP is therefore well suited for single-energy neutron beams or white neutron beams. Thanks to its good resolution in deposited energy and time of flight, SCALP discriminates the different channel outputs, allowing to identify the different reaction pathways[29].

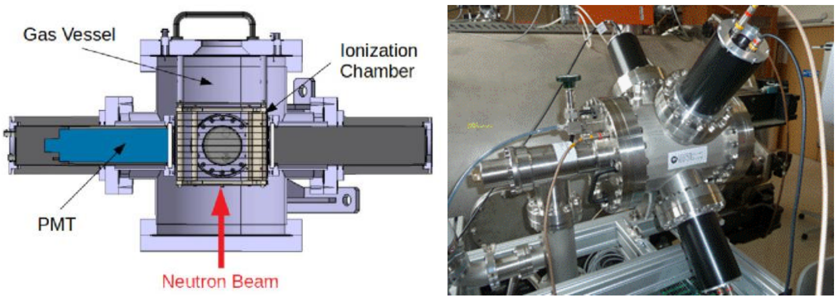


Figure 7 : Schematic (left) and photo (right) of the SCALP device designed and built at LPC Caen.

To carry out the experimental program associated to the SCALP device, proposals for experiments have been submitted and accepted at the nELBE (HZDR, Dresden, Germany), GELINA (JRC-Geel, Belgium) and NFS (GANIL, Caen, France) facilities in 2019. The first measurement was planned on the nELBE facility in March 2020. Due to the COVID19 pandemic, this experiment had to be cancelled. The experiment with NFS was performed in October 2020 and data analysis for (n,alpha) production on fluorine-19 and oxygen-16 is underway.

In addition to this experimental program, a collaboration has been initiated with the LePH (Cadarache, CEA) with the objective of taking into account these new measurements of the (n,alpha) excitation functions on oxygen-16 and fluorine-19 in a multichannel modeling in 4th generation nuclear power. This collaboration is taking shape through a thesis whose subject is the analysis of the data from the different experiments carried out with SCALP as well as the first studies on the implications of these new measurements in the multichannel modeling. The direction of this thesis is ensured jointly by the LPC Caen and the LePH Cadarache.

4.2 - Fission yields

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[27] G. Lehaut et al., Nucl. Instr. Meth. A 797 (2015), 57-63

[28] G. Lehaut et al., EPJ Web of Conferences 225, 01001 (2020)

[29] B. Galhaut et al., EPJ Web of Conference 146 (2017) 03014

Fission is a complex process, which splits a nucleus containing typically more than 200 nucleons into a large number of possible fragments, with emission of neutrons and other particles. Understanding the emission probabilities of fission particles and fragments is essential for the modeling and simulation of all nuclear systems. The study of fission physics has a long and rich history, but no theoretical Detailed measurements are required and in combination with semi-empirical models, they allow the creation of evaluated nuclear data files that can be used in application studies. Uncertainties in these fission product yields must also be quantified and, due to the fundamental nature of the fission process (two fragments in binary fission, conservation of mass and charge, etc.), these data are highly correlated. Quantifying these correlations and using these matrices to quantify the uncertainty in the assessment is one of the major challenges for nuclear data today. The physics of fission product reactions is also crucial for advanced modeling of nuclear reactors, but since these are almost always radioactive and exotic isotopes, few measurements have been made and these data are generally less well known.

Among the fission observables under study, the quantities directly related to the fragments figure prominently: production rate, recoil energy, emitted neutrons. As for the cross sections, this information is a valuable probe for understanding the physics, and has a direct impact on the application field, whether it is the prompt energy released in the reactor, the residual heat, or the production of radiotoxic or neutron-pathogenic nuclei.

The SOFIA collaboration, in which the IJCLab is involved, is based on a unique method: measuring the charge and mass of two prompt fission fragments in coincidence. The SOFIA experiments take place at GSI (Darmstadt, Germany), the only laboratory in the world to offer uranium beams up to 1A GeV. They are based on inverse kinematics: the fissioning system acts as a projectile. This technique makes it possible to measure the fission of any system, since the nucleus of interest is produced by a first nuclear reaction and then selected "in flight" using a recoil spectrometer, the FRS. In the case of SOFIA, the fission is triggered by coulomb interaction, resulting in an excitation energy of 14 MeV on average, equivalent to a neutron of about 8 MeV. This choice is imposed by the relativistic nature of the secondary beam (a nuclear interaction with the 600A MeV projectiles would lead to tens or even hundreds of MeV of excitation) and by the need to compensate for the moderate intensity of the secondary beam by a high interaction cross section; the disadvantage is that the excitation energy is not known event by event, only in average value.

SOFIA combines 9 detectors to track and identify the secondary beam and the fission fragments. The charge is determined by an ionization chamber: total separation is obtained for the fission fragments, a resolution unique in the world. The mass is deduced from the combination of the charge, the deflection in a magnetic field and the velocity. Another technical achievement of SOFIA is to reach a time resolution of 20 ps (FWHM), offering a mass resolution of 0.55 u FWHM (cf. Figure 8).

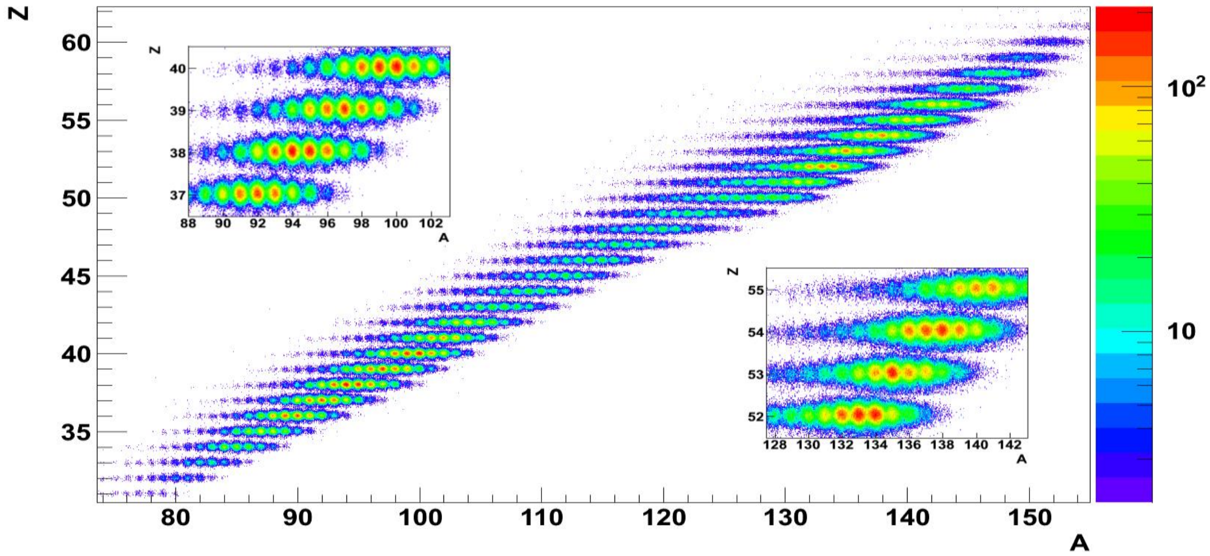

Figure 8 : Identification matrix of $^{236}U^*$ fission fragments. We note the complete separation of the charges, and a mass resolution between 0.55 and 0.7u FWHM.

IN2P3's contribution to SOFIA is mainly the responsibility of the MWPCs, currently 4 in number, dedicated to the tracking of the primary beam and fission fragments. These chambers, entirely manufactured in the laboratory, are regularly maintained and updated. Their performance means that they are also used by other NUSTAR/R3B teams.

After measuring with unprecedented accuracy the fission yields in the region of application interest[30], and in particular the fission yields of $^{236}U^*$, illustrated in Figure 9 (analog of ^{235}U+n, the essential reaction of today's nuclear power) as well as the transition to symmetry in Th[31], the collaboration conducted a more fundamental measurement in 2021, to shed light on our understanding of the fission phenomenon: the exploration of a new fission mechanism, brought to light by the observation of an asymmetric fission of ^{180}Hg. The experiment has mapped the neutron-deficient pre-actinide region, measuring the yields of about 50 very exotic nuclei, in order to study in detail the transition region between symmetric and asymmetric fission. For this purpose, many upgrades of the setup have been carried out, including the change of the MWPC electronics, the fabrication of an additional MWPC, and the deployment of new photomultipliers on the time-of-flight wall.

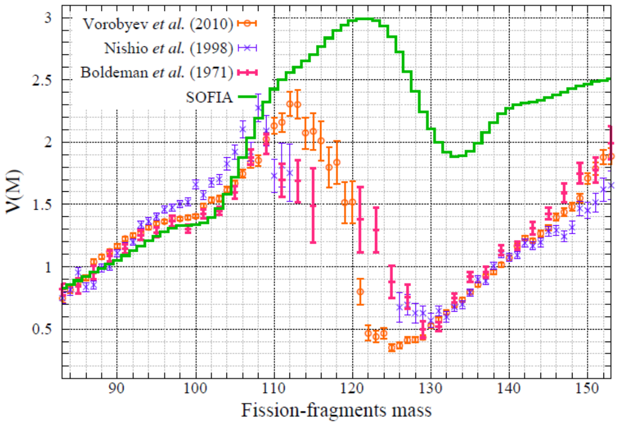

Figure 9 : Prompt neutron rate in the fission of $^{236}U^*$, compared to thermal neutron results on ^{235}U. This measurement confirms in a spectacular way that the additional exiting energy is captured by the heavy fragment.

Future SOFIA experiments rely on the development of the FAIR (Super-FRS and associated detectors) and R3B (CALIFA and NEULAND in particular) facilities. A medium-term perspective, ambitious

[30] E Pellereau et al., Phys. Rev. C 95 (2017) 054603
[31] A. Chatillon et al., Phys. Rev. Let. 124 (2020) 202502 et Phys. Rev. C 99 (2019) 054628

but costly, is the development of a ^{242}Pu beam at GSI, which would open the door to measurements of fission yields of all Pu isotopes and possibly of Am, of interest for 4th generation reactors.

With the ILL facility in Grenoble and the Lohengrin spectrometer, IN2P3 via the LPSC team has also been involved for about ten years in direct measurements of independent fission yields. Within a collaboration with the CEA, several fissioning nuclei (^{233}U, ^{235}U, ^{239}Pu, ^{241}Pu and ^{241}Am) have been the object of new work dedicated to the measurement of fission observables, with a complete data analysis (experimental correlation matrices) allowing their interpretation and the testing of models (cf. Figure 10). Beyond the application aspects, these data also allow constraining the fission models and thus participate to the improvement of the understanding and the theoretical description of the fission process. For example, the experimental measurement of the isomeric ratios gives indirect information on the spin distribution and the excitation energy available during the fission. The work carried out concerns in particular the measurements of mass and charge of fission yields induced by thermal neutrons with a particular focus on the region of heavy and symmetric fragments. The latter is often poorly supplied with experimental data. We have therefore developed a complete measurement and analysis protocol, which includes the evaluation of systematic corrections and instrument biases, as well as experimental variance-covariance matrices[32]. Our method of analysis also provides fission yields that are independent of any external standardization, as our measurements cover the entire study area.

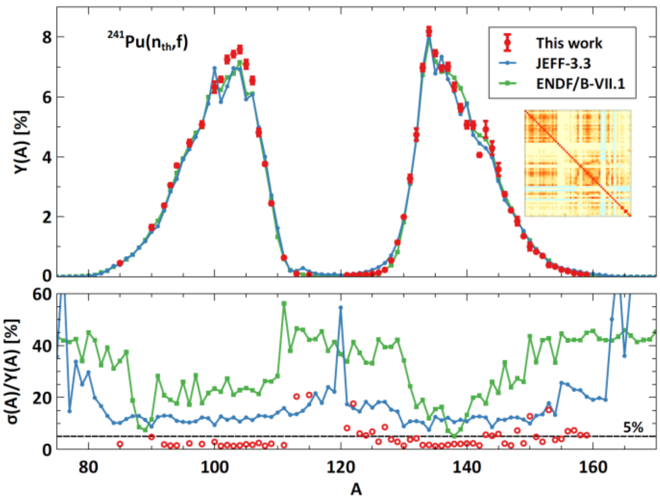

Figure 10 : Mass yields for the $^{241}Pu(n_{th},f)$ reaction with evaluation of the experimental correlation matrix and associated uncertainties.

In parallel, experimental work on the analysis and interpretation of the isomeric ratios produced by fission is carried out[33] (Thesis J. Nicholson 2021). Among other things, it shows the need to replace in the evaluations the empirical Madland-England model, which is found to be insufficient to reproduce our experimental results. The use of the Monte Carlo code FIFRELIN developed by the CEA to interpret and predict isomeric yields for future libraries of evaluated data such as JEFF now seems much more relevant.

The measurement of yields in the region of symmetric fragments is an interesting challenge, because of the very low yields and therefore the great influence of the possible contamination by masses of higher yields. We have highlighted the presence in this region of two components in the kinetic energy distributions, which opens a perspective on the question of the existence or not of modes in low energy fission, and which may result in the validation of some phenomenological and/or microscopic models useful for the evaluation. The LPSC continues its experimental program with the aim of to perform a new reference measurement of the fission yields of the $^{235}U(n_{th},f)$ reaction. Currently, mass yield measurements at ILL are performed by a dual Frisch grid ionization chamber (E x E). The collaboration is developing a new time-of-flight (TOF) detector with the goal of adding a velocity filter to the

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[32] A. Chebboubi et al., Eur. Phys. J. A 57 (2021) 335
[33] A. Chebboubi et al., Phys. Lett. B 775 (2017) 190

current selection of (E x E) x TOF events. The time-of-flight measurement will be realized by using metallized Si_3 N_4 foils and electrostatic lenses to guide the electrons emitted as the fission products pass through the foils to a detection system. Different electron detectors are under study to sign the start and stop of the TOF system, such as channeltrons or SiPM. The development of this new detector is done in collaboration with the technical services of LPSC, CEA and ILL. This new filter will allow to check and/or correct by a direct method the contaminated masses at the output of the spectrometer and the corresponding analysis method will replace the indirect method consisting in the correction by subtraction of the contaminants.

A prototype of this TOF detector has been initiated and tested during an experimental campaign in July 2021 at the Lohengrin spectrometer. Two types of detectors are being studied: channeltrons and fast scintillators mounted on SiPM. These choices are dictated by the constraint of operating with the degraded secondary vacuum (10^{-5} - 10^{-6} mbar) that prevails at the end of the Lohengrin instrument. At present, the results on the detectors indicate an insufficient time resolution (500 ps). The use of a dedicated time-of-flight line in ultra-high vacuum (10^{-8} mbar) to guarantee a vacuum of a few 10^{-7} mbar is essential to use MCP (Microchannel plate) detectors having the necessary time resolution (100 ps) for the project. It is thus planned in 2022 to be equipped with two MCP detectors and a dedicated time-of-flight line. Once the latter is characterized, it is planned to first measure precisely the symmetric region of the $^{235}U(n_{th},f)$ yields, followed by a similar study on different isotopes such as ^{239}Pu and ^{241}Pu, whose heavy peak yields have already been fully measured on Lohengrin by the collaboration.

4.3 - Fission products decay

The beta decay properties of fission products play a major role in the estimation of important observables for the safety of nuclear reactors as well as in fundamental or applied neutrino physics. Indeed, the beta decay of the nuclei produced during the fission process is at the origin of most of the residual power which represents about 7% of the nominal power of a reactor and which must be evacuated under penalty of melting the fuel cladding (cf. Fukushima accident in 2011). Beta decay is also responsible for the emission of delayed neutrons, without which it is not possible to operate a reactor. Finally, it is at the origin of the emission of antineutrinos which is studied both for fundamental physics and for the monitoring of nuclear reactors. The estimation and understanding of these three quantities for current and future reactor designs relies on the quality of nuclear data and theoretical models. Many data are missing or affected by the Pandemonium effect[34], an experimental bias due to the low efficiency of the Germanium detectors used for the measurements. Our expertise, developed at IN2P3 by the SUBATECH team, is based on the use of the Total Absorption Gamma Spectroscopy (TAGS) technique, which avoids this bias, and on the development of simulations to test the impact of the measurements and to establish new lists of priority measurements.

[34] J. C. Hardy et al., Phys. Lett. 71 B, 307 (1977).

We have carried out two TAGS measurement campaigns at the Jyväskylä facility in collaboration with the IFIC in Valencia during the last decade. More than 25 important contributors to antineutrino spectra, reactor residual power and delayed neutron emitters have been measured. Our model based on nuclear data (fission yields and beta decay data) including these TAGS measurements is currently the one that best compares with measurements from reactor neutrino experiments[35]. The difference between the flux predicted by this model and the flux measured by Daya Bay is reduced to 1.9% which strongly disadvantages the « reactor anomaly[36,37]» (cf. Figure 11).

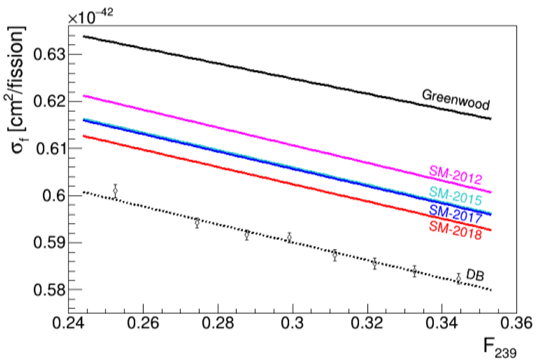

Figure 11 : Comparaison des flux des antineutrinos détectés. Labels : DB : Daya Bay ; Greenwood : avant nos contributions (6% d'écart avec DB), autres labels cf. [42].

One of the main future challenges of the reactor antineutrino spectra concerns the determination of the spectrum beyond 4.5 MeV, a region still very much affected by the Pandemonium effect but also by the lack of data concerning more exotic nuclei. It is also the region of the "shape anomaly", a distortion of the spectra observed by neutrino experiments that is still unexplained. This detailed understanding will be all the more important as it will allow the interpretation of the "high resolution" neutrino measurements of the JUNO-TAO project[38] and make reliable predictions for reactor monitoring[39]. The study of the shape of electron spectra from non-unique forbidden first decays is currently one of the tracks considered to explain the "shape anomaly". For this we have built an electron detector (E-Shape experiment: Subatech, IFIC of Valencia, University of Surrey), whose commissioning took place in 2019 (experiment postponed to January 2022 by the sanitary crisis).

Our TAGS measurements also significantly improved the predictions of the residual power emitted after the fission of ^{239}Pu[40] while the ^{235}U case still raises questions, as well as the more innovative systems. In order to determine new priority lists of measurements and to test the impact of beta decay measurements[41] and fission yields, we have recently developed the ability to simulate the residual power by the summation method with the SERPENT code. This work is strongly coupled with simulations of generation IV reactors (LPSC collaboration, NEEDS TeamFrance and SUDEC, European project SAMOSAFER).

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[35] M. Estienne et al., Phys. Rev. Lett. 123, 022502 (2019). A fait l'objet d'un « fait marquant » de l'in2p3.

[36] un déficit significatif entre les prédictions réalisées à partir d'estimations récentes des spectres en énergie des antineutrinos et les flux mesurés par les expériences de neutrino à moins de 100 m d'un cœur de réacteur. Cette problématique est à l'origine de nombreuses nouvelles expériences de physique des neutrinos proches de réacteurs de recherche dans le monde.

[37] Pour la « reactor anomaly » : Th. A. Mueller et al., Phys. Rev. C 83, 054615 (2011). P. Huber, Phys. Rev. C84, 024617 (2011). G. Mention et al., Phys. Rev. D 83, 073006 (2011). Impact de notre modèle : J. M. Berryman and P. Huber Phys. Rev. D 101, 015008 (2020).

[38] TAO Conceptual Design Report, A Precision Measurement of the Reactor Antineutrino Spectrum with Sub-percent Energy Resolution, JUNO Collaboration, arXiv:2005.08745v1 (2020).

[39] Talks invités aux Workshops Snowmass et WONDRAM, conf. invite Neutrino 2020

[40] A. Algora, B. Rubio, J.-L. Tain, M. Fallot, W. Gelletly, Eur. Phys. J. A 57, 85 (2021)

[41] Thèse A.-A. Zakari-Issoufou, univ. de Nantes (2015). Thèse L. Le Meur univ. de Nantes (2018).

Publications[42] and invitations to expert meetings and international conferences[43,44] testify to the important role of IN2P3 in this research via our TAGS measurements and associated simulations. The official lists of relevant nuclei for the reactor antineutrino spectra are the ones we have established. The results of our measurements and their impact on the residual power and antineutrino spectra have been published in a journal article in 2021[40]. We also collaborate with evaluators of decay data and fission yields [45] in particular via the IAEA meetings and within the framework of the NACRE projects of NEEDS and SANDA.

Experimental challenges await TAGS measurements for the estimation of reactor resistive power and antineutrino spectra with more exotic and often delayed neutron emitting nuclei. It is with these scientific objectives coupled with objectives of nuclear structure and astrophysics that we carry the project (NA)^{2}STARS[46], upgrade of the DTAS consisting of 18 NaI crystals by adding 16 LaBr3 crystals (coll. Subatech, IFIC, Ciemat, IP2I). Thanks to (NA)^{2}STARS, the TAGS technique would see an important part of its current limitations lifted.

Finally, to predict the highest energy part of the antineutrino spectrum and the residual power at short times, theoretical models are also essential to complete the databases. We have been collaborating with S. Péru-Désenfants from CEA-DAM since 2013, in order to compare in particular TAGS measurements with pn-QRPA model predictions.

4.4 - Beyond nuclear data measurements

As previously mentioned, the nuclear data theme is, in essence, very much linked to fundamental nuclear physics. This is true for example for the study of the fission process and the proximity of the teams with other teams/colleagues studying these phenomena is a real asset for our activities (example of the development of the GEF code). Recently, the efforts are concentrated around the problem of the knowledge of the nuclear structure necessary to lift the barriers when using experimental techniques which depend on this knowledge (prompt gamma spectroscopy for the study of inelastic neutron scattering, TAGS measurement for the study of beta decay, gamma spectroscopy for the measurement of fission yield). Within the structuring project NACRE, an action has been launched in 2020 to initiate meetings of the two communities (nuclear data and structure) and an article is in preparation to establish a list of priority nuclei (of interest for reactors) for new nuclear structure measurements. These first steps have already led to the participation in two upcoming experiments. One at ALTO for the next campaign of ν-ball2 and which will allow a new measurement of the structure of ^{238}U (interest for the inelastic diffusion of the neutron). The other one at NFS, to study the possibility of nuclear structure measurements via (n, 3n) reactions with the EXOGAM multidetector.

In recent years, the OPALE teams have shown a willingness to anchor their experimental projects more downstream towards evaluation and more upstream towards the definition of needs. The

[42] M. Fallot et al. PRL 109,202504 (2012), « SM-2012 ». A.A. Zakari-Issoufou et al. PRL 115, 102503 (2015), «SM-2015». E. Valencia et al., PRC 95, 024320 (2017) et S. Rice et al. PRC 96 (2017) 014320 "SM-2017". V. Guadilla et al. PRL122, (2019) 042502 « SM-2018 ». APS Viewpoint: M. Fallot, Physics 10, 66 (2017).

[43] P. Dimitriou et al. INDC(NDS)-0676 (2016). M. Fallot, B. Littlejohn and P. Dimitriou, Summary of the Technical Meeting about Antineutrino spectra and their applications, IAEA, Vienna, Austria (2019), INDC(NDS)-0786. CRP IAEA: P. Dimitriou et al. Nuclear Data Sheets 173 (2021) 144-238.

[44] Meetings JEFF. Workshops WONDRAM 2021 et SNOWMASS 2020. Conférence internationale Neutrino 2020.

[45] K.-H. Schmidt, M. Estienne, M. Fallot et al. Nuclear Data Sheets Volume 173, (2021), Pages 54-117.

[46] Neutrinos, Applications and Nuclear Astrophysics with a Segmented Total Absorption with higher Resolution Spectrometer.

evaluation subject has been able to be invested in particular thanks, among other things, to the collaborations with the CEA carried out by the NEEDS/NACRE project. The reinforcement of these collaborations has allowed the financing of theses by the CEA under joint supervision with IN2P3 teams. The funded subjects almost systematically include a part on nuclear data processing and another on evaluation. For our students, these theses are very interesting because they are trained in a complete way to the nuclear data theme. For the IN2P3 teams, it is also an opportunity to transfer knowledge on evaluation. As for the definition of needs, collaborations with reactor physicists have been set up and within the framework of the GDR SciNEE an animation takes place around these questions (see Xavier Doligez report). We can also mention a collaborative work between the IPHC and the IJCLab in the framework of a thesis to develop tools for the calculation of sensitivity to the sections of interest for the thorium cycle and in particular the inelastic diffusion of the neutron measured by the IPHC team. As mentioned previously, the SUBATECH team is also developing its own codes to simulate Generation IV reactors in order to estimate the residual power and associated uncertainties.

4.5 - Review of OPALE publications for the last 4 years

	TOTAL OPALE	
	since 4 years	**year 2021**
publications	**25**	**8**
proceedings	**36**	**4**
publications in preparation		**10**
communications	**50**	**8**

Cf. in appendix, the list of major publications of the OPALE MP.

5/ Resources and means

OPALE Human Resources feb-22

IJCLAb	*permanents*	*%*[47]	*non permanents*	*%*
	L. Audouin (EC)	100		
IPHC	*permanents*	*%*	*non permanents*	*%*
	Ph. Dessagne (Ch)	95	Carole Chatel (Post doc)	100
	G. Henning (Ch)	100	François Claeys (doc)	100
	M. Kerveno (Ch)	100	Nicolas Dari Bako (doc)	100

[47] % = % du temps de recherche dédié au projet

LP2i-Bordeaux	*permanents*	*%*	*non permanents*	*%*
	M. Aiche (EC)	80		
	P. Marini (Ch)	30		
	L. Mathieu (Ch)	50		
LPCC	*permanents*	*%*	*non permanents*	*%*
	F.R. Lecolley (EC)	40	A. Chevalier (doc)	100
	J.L. Lecouey (EC)	10		
	N. Marie (EC)	5		
LPSC	*permanents*	*%*	*non permanents*	*%*
	O. Meplan (EC)	40	M. Houdouin Quenault (doc)	100
	M. Ramdhane (EC)	90		
	C. Sage (EC)	100		
SUBATECH	*permanents*	*%*	*non permanents*	*%*
	E. Bonnet (Ch)	15	A. Beloeuvre (doc)	60
	M. Estienne (Ch)	70	Y. Mola (doc)	15
	M. Fallot (EC)	70		
	L. Giot (EC)	15		
	A. Porta (EC)	85		

Financial resources:

As mentioned previously, the financial resources of the OPALE project come from 3 main sources: IN2P3, the NEEDS program via the NACRE project and European projects, actually the SANDA project. It should also be noted that, from time to time, the OPALE teams may receive financial support to carry out experiments at facilities belonging to the consortium of the European project ARIEL[48] (to which IN2P3 facilities contribute) or EC-JRC grants via the EUFRAT "Open Access" calls. These grants finance the participants' missions. Some international collaborations have also benefited from calls for international scientific cooperation projects (PICS or LIA).

Main financial resources of OPALE activities

For the last 4 years

	2018	2019	2020	2021	% average buget/year
IN2P3	44 000 €	45 000 €	39 000 €	50 000 €	25%
NEEDS/NACRE	69 500 €	65 000 €	76 000 €	39 500 €	35%
EU-SANDA	73 750 €	73 750 €	73 750 €	73 750 €	40%
TOTAL	**187 250 €**	**183 750 €**	**188 750 €**	**163 250 €**	

6/ Technical achievements

48 https://www.ariel-h2020.eu/

First of all, it is necessary to mention that the technical achievements concern mainly the design and the realization of measurement instruments. These developments or regular updates of our instruments (detectors and acquisition system) require needs of mechanical, computing or electronic services of the laboratories over the years as well as recurrent financing. For the whole OPALE MP, this continuous work represents a few FTE/year. More substantial investments are also sometimes necessary. For example, the mechanical department of the IPHC has been involved in the realization and assembly of the beamline and the second collimator of NFS (about 6 FTE for this realization).

To date, there is no "major" technical achievement planned but needs could emerge depending on responses to ANR calls for projects (DTAS $(NA)^2$STARS upgrade project) for example or the choices of collaborations/facilities to engage in a particular measurement program (e.g. SOFIA).

7/ Conclusions

In the field of nuclear data for energy, the IN2P3 teams are now internationally recognized. We have developed competitive instruments, some of them within international collaborations, to measure the observables of interest with precision. We participate actively in the elaboration of European projects and in their management. We have also increased our involvement in NEA and IAEA working groups. Our expertise is solicited to integrate experimental committees such as those of the European projects (CHANDA, ARIEL) or INTC of CERN.

The complementarity of our measurement programs, from cross sections to fission observables, allows us to have a global and coherent view on the general problem of nuclear data for energy applications. The strengthened links with the CEA (via the NEEDS/NACRE project) allow us a closer relationship with the community of evaluators on the one hand, and on the other hand access to the demands of industry. However, we have the freedom, at IN2P3, to explore systems that are not directly linked to the current industrial demands but that could be in the future (data from the thorium cycle) which will save precious time in the studies. We have also taken advantage of the new European facilities to propose our next measurement programs. The experimental data that we produce are unpublished and can now be used rapidly in the evaluations thanks to the links that we have been able to establish with the inter-national evaluators. The proximity, within the institute and sometimes within the teams themselves, of our colleagues in fundamental nuclear physics allows us to feed our discipline and to lift fundamental barriers more quickly, as for example for nuclear structure issues.

It must be emphasized that the structuring of our activities into a Master Project has been very beneficial to us. The vagueness that has reigned for the last two years concerning a "restructuring" of the so-called "applied" activities is harmful and the disappearance of the MP would be detrimental to the visibility and dynamism of our community. The creation of the GDR has brought us closer to our colleagues in reactor physics, which is an undeniable asset and which we would like to use to develop new projects, particularly around sensitivity studies.

The funding of our activities comes from several sources, which requires us to respond to calls for proposals and to report on our activities, but it also requires that these sources be renewed. NEEDS, for example, is a key structure for our activities, both for project funding and for our interactions with the CEA. The presence of calls dedicated to nuclear data in European programs is crucial. This aspect is directly linked to the intentions of European partners regarding the maintenance/development of nuclear energy.

The human resources allocated to the project are certainly not in line with our ambitions. Indeed, the low budgets coupled with the low number of doctoral and post-doctoral students generate a prejudicial slowdown of our scientific production and can penalize the activities exposed to the international competition.

APPENDIX: Major OPALE publications

Cross sections

"Measurement of 238U(n, n'γ) cross section data and their impact on reaction models"
M. Kerveno, M. Dupuis, et al. Physical Review C 104, 044605 (2021) 2
https://doi.org/10.1103/PhysRevC.104.044605

"How to produce accurate inelastic cross sections from an indirect measurement method?"
M. Kerveno, G.Henning, et al. European Physical Journal N 4, 23 (2018) 1
https://doi.org/10.1051/epjn/2018020

"From γ emissions to (n,xn) cross sections of interest: the role of GAINS and GRAPhEME in nuclear reaction modeling"
M. Kerveno, et al., European Physical Journal A 51, 167 (2015) 1
https://doi.org/10.1140/epja/i2015−15167−y

"Measurement of 235U(n,n' γ) and 235U(n,2n γ) reaction cross sections"
M.Kerveno, et al., Physical Review C 87, 24609 (2013)
http://link.aps.org/doi/10.1103/PhysRevC.87.024609

" ^{242}Pu neutron-induced fission cross-section measurement from 1 to 2 MeV neutron energy"
P. Marini et al., Phys. Rev. C 96, 054604 (2017)
https://doi.org/10.1103/PhysRevC.96.054604

"Development of a gaseous proton-recoil telescope for neutron flux measurements between 0.2 and 2 MeV neutron energy. "
P. Marini et al., Rad. Meas. 124 (2019)
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