Statement on French nuclear data needs and activities for the period May 2018 – March 2021

Prepared for the 33th INDC meeting, March 28- April 1, 2021

C. De Saint Jean, CEA, France

with M. Kerveno (CNRS/IN2P3), D. Bernard, G. Noguere and X. Mougeot (CEA), L. Leal (IRSN)

1. Nuclear Data needs

French Nuclear data needs are coming mainly from CEA, CNRS and IRSN physicists working on nuclear data evaluation, measurements, benchmarking, or directly users of nuclear data. Physicists and engineers are involved in fission related applications (reactors, fuel cycle…), nuclear physics, astrophysics, medical applications, etc. The following needs concerns experimental, theoretical and evaluation activities.

Accurate and validated nuclear data are a crucial ingredient of various studies on nuclear system design and related fuel cycle (GEN 2, 3 and 4 concepts, in nominal and accidental conditions), experimental reactors (JHR, CABRI…) and naval propulsion reactors. Improvement of nuclear data precision, reduction of biases in neutronic simulation codes devoted to reactor applications is expected. In reactors, the energy range of interest (for neutron energy and related induced reactions) is from thermal energies up to several tenths of MeV.

France nuclear data needs have not changed much since last few years. As a result, the following needs are close to previous INDC meetings.

1.1. Microscopic/Differential/integral measurements

An improved knowledge of **angular distributions** is necessary for basic cross section evaluation and the related nuclear reaction parameters (spin and parity of resonance for example, fission channels decorrelation). The impact is important for large size core (fast and thermal spectrum) as well as heterogeneous cores, where transport effects are crucial.

Inelastic cross sections (and the related angular distributions) of major fuel components (^{235,238}U, ^{239,240,241}Pu) as well as some structural materials (such as Iron, MgO,…) are insufficiently well-known due to a lack of precise measurements; there are still inconsistencies in evaluated files (JEFF, ENDF, JENDL). These uncertainties and biases contribute highly to the neutronic parameters uncertainties for reactors.

To validate evaluations in the resolved range, precise time of flight experiments are still very much needed, in the temperature interval from **a few K to 2000K**. Low temperature measurements could disentangled the effect of crystal lattice on the knowledge of resonance parameters for major isotopes (^{238}U,$^{239,240,241}Pu$) and high temperature measurements could validate models for resonant scattering.

Neutron induced Capture measurements of fissile isotopes (especially for uranium and plutonium) in the whole energy range are needed, these cross sections being major contributors to reactor calculations.

Lastly, for **short-lived** isotopes, cross sections measurements are needed (fission products, isomers). This activity (theory/evaluation/measurement of short-lived isotopes) may be a good candidate for a CRP or TM at AIEA. In addition, it seems that at the N-TOF installation, a dedicated isotopes production is discussed.

New **nu-bar(E), eta(E), alpha(E)** microscopic measurements in thermal and epithermal range for fissile nuclei are necessary to exhibit fluctuations on nu-bar as well as temperature effect on cross sections slopes (capture/fission). It should be accompanied with theoretical development explaining observed fluctuations (**(n,γ ,f)** process).

New measurements of delayed neutron data are very much welcomed.

Thermal data (phonon spectrum, $S_{\alpha\beta}$), for various moderators and structural materials are crucial for the proper knowledge of light water reactors spectrum. In addition, resonant scattering of heavy isotope (^{238}U) was proved to be a first order effect on reactivity of PWR/BWR reactors by having an induced effect on ^{238}U capture and thus ^{239}Pu build-up. Proper modeling of this effect is still a challenge when both resonant scattering and crystal lattice effects are taken into account. A follow up to WPEC SG 42, SG 48 was initiated which is a good idea. **Anyway, it could be interesting to have an international and collaborative effort on molecular dynamics models as well as phonon spectrum measurements**.

Neutron induced reactions suffer in the unresolved resonance range of a lack of both integral and microscopic measurements even for well-known isotopes (uranium and plutonium).

Dpa data are important for fuel designs using innovative structural materials; Iron is important as well as other steel components (Cr, Ni…); Conclusion of the dedicated CRP is very much welcome on nuclear data as well as proposition of standard DPA calculation and evaluation procedure.

Prompt neutron and gamma fission spectrum and multiplicities are still of major interest for plant lifetime extension considerations, nuclear heating and in terms of uncertainties on reactivity as well as power map tilts on reactor cores. Innovative experiments are needed. In particular, for induced neutron energy between 1keV and a few MeV, very few experiments are existing. Furthermore, reduction of experimental uncertainties are very important for low and high energy part of spectra. Breakthroughs in terms of experimental devices are needed.

For challenging nuclear models, global fission experiments such as fission yields with neutron prompt spectrum and multiplicities, cross sections/fission yields (as proposed in NFS at GANIL by FALSTAFF, FIPPS at ILL and ChiNu in the US) are of first interest.

1.2. Structure data and basic nuclear physics

Efforts on nuclear structure data are needed for:

- The interpretation of existing and future inelastic cross sections for heavy isotopes. They appeared to be a major source of uncertainties (lack of knowledge).
- Fission observables evaluations ,
- Neutrino studies using nuclear reactors or fuel component as sources: need of precise beta and antineutrino spectrum. **A collaborative international** effort should continue: specialist of beta spectrum calculation as well as experimentalist may contribute at the end to an **evaluated data base**.

This effort is related to basic compound nucleus physics (level densities, spin densities…), gamma and x ray intensities for dosimetry analysis, beta spectra…

Furthermore, decay data evaluation databases **international effort** could be pursued as decay data specialists are lacking.

1.3. Theoretical calculations

For fission yields, neutron/gamma multiplicities and spectra, there is a necessity to have an overview of the state of the art in evaluation and related codes (GEF, FIFRELIN, SPY, Moller propositions …) by a **dedicated international effort**. For Fission Yields, there is a major concern to propose a dedicated evaluation data base sharing all experimental (old and recent) results with a comprehensive description of the experiments (calibrations to standards or any data that has evolved). The proposed CRP at AIEA is going in the good direction.

From a general point of view low energy nuclear fission breakthrough in terms of theoretical approaches are needed. The calculation of fission barriers as well as their penetrability factors is based on approximations related to phenomenological theories. Progress is needed and the **international experts should continue to collaborate** to estimate the state of the art, the potential issues (theoretical as well as experimental) and some hints of what could be feasible in a short/mid/long term.

Surrogate reactions measurements (aiming at producing a targeted compound nucleus by other entrance channel than neutron) exhibits difficulties in term of theoretic interpretation (P_f, P_γ) due to spin/parity distributions issues. This activity may be part of the previous general physics issue or could be worthily discussed in dedicated meetings.

As for experiment, the unresolved resonance range need real progress in terms of nuclear reaction models and the associated representation in nuclear data files. In particular, its connection to resonance range and fast range is still a puzzling theoretical question.

1.4. Uncertainties

Uncertainties for all nuclear data are expected. In this framework, various efforts need to be pursued:

- Full energy range covariances → correlation between different energy ranges : **bridging the gap between thermal and continuum range**
- Multi-observable correlations (spectra/multiplicities/cross sections…)
- Model defects: incapacity of phenomenological models to reproduce experimental results.

1.5. Deep Learning

Since recently, there is a high interest in deep learning techniques not only for nuclear data evaluation, but also for basic nuclear science (theoretical and experimental). Few workshops took place in France and various international conferences or workshop highlighted this growing interest. This very promising activity could be pursued at an international level at IAEA (follow up of a 2020 meeting) and NEA for example.

1.6. Specific Evaluation

The CRP on Updating the Photonuclear Data library and generating a reference database for photon strength functions was appreciated.

1.7. Miscellaneous

With the decommissioning of various experimental reactors in France (EOLE/MINERVE/MASURCA at CEA for example), the status of existing ZPRs and their abilities for proposing analytic experiments (one may think of new integral experiments for inelastic and elastic cross section of iron, uranium and plutonium) is of great concern for nuclear data physicists in France.

Furthermore, there is a real concern related to the shortage of international radio-isotope production capabilities for medical diagnostics. Also, for nuclear medicine, emergent radioisotopes are studied and a need for their related decays data is reported.

At last, a general concern is expressed regarding the lack of young physicists working in the nuclear data area. PhD students and post-docs are very hard to find

2. Recent French Nuclear Data activities

2.1. Experimental activities

French nuclear data activities rely on a close collaboration with national and international organizations. Thus, collaborations were established between CEA, CNRS (IN2P3), ILL (Institut Laue Langevin of Grenoble), JRC/Geel in Belgium and N-TOF at CERN for using experimental devices related to specific measurements of interest for France.

Because of the covid-19 pandemic, many experimental activities were in stand-by in 2020.

Fission Yields

At **ILL**, since 2008, a large collaboration has started (CEA/CNRS) with the aim of studying various fission fragments aspects, mainly in the heavy fragment region. New experimental setups and new procedures for the data analysis were developed (allowing a proper experimental covariance matrix evaluation). Excellent results were obtained with decreased uncertainties compared to other experiments and evaluated data. The symmetric mass region was studied for ^{233}U(nth,f) and ^{239,241}Pu(nth,f) reactions. Ongoing analysis are made to finalize experimental campaigns. In addition, development of time of flight capabilities is underway with a first experiment on ^{235}U(nth,f) in the near future.

CEA/CNRS are highly involved in **SOFIA** experiment (at **GSI**) based on inverse kinematic. The set-up allows accurate measurement of the fission yields after prompt neutron emission and before any β^- decay and gives nuclear charge, nuclear charge and kinetic energy of each fragment. After several years of experiments, recent electronic and detector enhancements were proposed and tested in 2020. New experiments are scheduled at 2021.

An innovative CEA program is in preparation at GANIL (called **VAMOS**) for Plutonium fission yields and excitation energy measurements.

Furthermore, **FALSTAFF** program scheduled at **GANIL** in a near future, is underway with various electronic/ detectors developments and test (at GANIL and CEA-Saclay).

Thermal data

The correct understanding of the thermalization process in light water reactors is important for safety applications. Efforts are still underway (CEA/IRSN/Argentina-Bariloche) to improve the neutron thermal cross sections of light water down to the cold neutron energy range, where the evaluated cross sections in the nuclear data libraries JEFF-3.1.1 and ENDF/B-VII.1 show sizeable disagreements from measurements. New measurements of the double-differential cross sections of light water were done at **ILL** (CEA/IRSN) and in the US (IRSN) as a function of the temperature and pressure. Such new data are essential for producing reliable evaluation with covariance matrices for light water.

<u>Cross sections, spectra and multiplicities</u>

At **JRC/Geel**, recent contributions of French laboratories (CEA/CNRS) were devoted to time of flight measurements (^{233,235,238}U,^{239}Pu(n,n'γ), Luthétium…), experimental device testing (micromegas, set-up for capture/fission measurements). Major objectives are to measure the capture cross section of fissile isotopes such as ^{239,241}Pu, ^{233,235}U, as well as inelastic cross sections of major actinides. Due to the pandemic spread, major experiments scheduled in 2020 are postponed in 2021 or 2022.

A new Micromegas detector development using a Time Projection Chamber devoted to time of flight measurements is underway at CEA. Is aims at providing a novel detector that could be used at **N-TOF** for actinides cross sections measurements.

French laboratories are involved in planned experiments at **NFS** (GANIL), in ongoing chi-nu program at LANSCE (US) and on innovative fission experiments (cross sections, spectra/multiplicities and fission yields measured all together). One can notice recent CEA/Los Alamos high precision spectra/multiplicity experiment for 239Pu, 235U giving very promising constraints for future evaluations (~0.5% nu-bar uncertainty achieved for example).

Day one experiment in **NFS** is scheduled in 2021. French laboratories will propose measurements for fission studies (σ, fragments, yields, neutron and gamma multiplicities), (n,xn) and reactions (σ and $d^2\sigma/dEd\Omega$), deuteron and proton induced reactions, detector developments. In particular, **SCONE** program is proposed by CEA for nxn measurement of Actinides. A fission chamber development is underway (collaboration between CEA and CNRS) and first test are proposed and accepted by GANIL on NFS with beam time allowed in 2021. In addition, CNRS propose a program (with SCALP detector) devoted to **^{16}O(n,α)** cross section measurement with some beam time accepted by NFS for the end of 2021. The experimental results will be analyzed and tested for evaluation with a CEA collaboration.

<u>Delayed neutron experiment</u>

^{235}U(nth,f) delayed neutron decays were measured in 2018 and 2019 at ILL with the LEONIE experimental device conceived by CEA in the framework of a CEA/CNRS collaboration called ALDEN. A 0.8 % uncertainty was obtained. U233 and 239 Pu were scheduled and thus postponed at ILL. In addition, a proposal was made to have equivalent measurements on major actinides but for fast neutrons at JRC/Geel with the MONET accelerator.

Integral experiments

EXCALIBUR, an integral transmission experiment based on the fast neutron source produce by the highly enriched critical facility CALIBAN, located in Valduc (France) was proposed by CEA. Two experimental campaigns were performed. The 1st objective of this program is to validate the ^{238}U inelastic scattering cross section in the 1-8 MeV energy range which is relevant for both thermal and fast reactor applications. The analysis of these experiments was performed with the TRIPOLI4 continuous energy Monte Carlo code.

To pursue this kind of integral advances, a program called **INTEGRAAL** is still underway with JRC using the GELINA target hall to measure the integral transmission of fast neutrons coming from the source through different thicknesses of Uranium 238, using neutron dosimeters with different threshold energies. After a first promising experimental campaign, a second experiment is proposed.

The investigation of the feasibility of doing both microscopic and integral measurements with common targets are underway. The idea is to compare microscopic measurements (at JRC/Geel) and integral measurements (at MINERVE) with the same sample to avoid unexpected samples issues that were seen in the past for these isotopes. A large experimental program was proposed to combine properly MINERVE (CEA) and GELINA (JRC/Geel) measurements. More than 30 fission products which have been measured in MINERVE reactor are going to be investigated at GELINA.

Structure data

CEA carried out specific measurements in order to improve the decay data of some radionuclides. In collaboration with other National Metrology Institutes, new half-lives have been precisely established for ^{231}Pa and ^{166}Ho, as well as new relative gamma emission intensities for ^{166}Ho and the probability of electron-positron pair production in ^{90}Y decay. Studies were also performed on ^{103m}Rh/^{103}Pd, which are of importance for neutron dosimetry in reactors, and on ^{147}Nd, a fission product commonly used as an indicator of nuclear explosion. Absolute photon emission intensities, down to low-energy X-rays, have been improved for these radionuclides, leading to a strong reduction of the discrepancy between neutron transport codes and experimental data in the case of ^{103m}Rh.

CNRS physicist participate to **TAS** measurements where 23 nuclei were measured, mainly interesting for decay heat and anti-neutrino spectra. Interpretation are underway. Detailed analysis of ^{99}Zr, ^{95}Y and ^{93}Rb are close to final results. Two TAGS experiments at Jyväskylä programmed in 2020 are postponed.

2.2. Evaluation activities

International effort

In the evaluation of nuclear data, as well as for nuclear physics modelling, collaborations exist between CEA, IRSN and American laboratories such as Los Alamos, Oak Ridge and Brookhaven. French physicist did contribute also to various CRPs or IAEA project (PFNS, standards, DPA, Beta decay, Fission Yields, INDEN) and to OECD/WPEC subgroups. WPEC SG37, SG38, SG39, SG40, SG41, SG42 (CEA coordinator), SG43 (CEA monitor), SG44 (CEA monitor) were closed or closing. Participation is underway for SG45 (CEA coordinator), 46, 47 (IRSN monitor), 48 (CEA coordinator), 49 and 50. The whole activity is reported in the context of the JEFF (Joint Evaluated Fission and Fusion file) OECD group. CEA/IRSN are preparing the future JEFF4 release: activities are underway on ^{235,238}U, ^{239,240}Pu, ^{241}Am, light elements (Be9), fission products and structural material.

Uncertainties and covariances

Continuous efforts were made by CEA/IRSN physicists on Fission Yields (for ^{235,238}U, ^{239,241}Pu), prompt neutron spectra and multiplicities (^{235,238}U, ^{239}Pu) and of course neutron induced cross sections of interest (see previous chapter). A noticeable grow of activity was made since 2018 on other nuclear data evaluation such as dpa, delayed neutrons and thermal data (recent use of CAB model for phonon spectra gave promising also for uncertainties estimations of $S_{\alpha\beta}$ for H in H_2O).

Nuclear Structure and decay data

Over the last decades, CEA has been highly involved in decay data evaluations for metrology purposes and has coordinated a dedicated international effort, the Decay Data Evaluation Project (DDEP). Evaluations have been pursued and specific developments have been prioritized to increase the availability of DDEP data. The new website (www.lnhb.fr/nuclear-data) presents for each evaluation the data tables, detailed comments on the evaluation procedure, ENSDF files, beta spectra and capture probabilities, and other useful computer-readable ASCII files. The

Lara web module has been improved with new tools, for example a) on-the-fly simplification of the decay scheme according to thresholds given by the user and b) a decay chain calculation tool. Efforts have also continued in the production and verification of the decay data sub-library in the JEFF (Joint Evaluated Fission and Fusion file) project.

2.3. Theoretical activities directly related to evaluation of nuclear data

For prompt neutron and gamma fission spectra and multiplicities, advances have been made in the developments of the GEF (collaboration between CNRS/K.H. Schmidt), FIFRELIN (CEA) and SPY (CEA) codes. FIFRELIN, for example, is now able to give theoretical evaluation of prompt fission neutron spectra for various actinides (mainly 235,238U, and 239Pu) which exhibit good behaviour as compared to existing experiments. In the future, semi-microscopic analysis tools will be more and more used for evaluations. GEF results were extensively shown in various JEFF meeting since 2014. Its ability to give theoretical (but adjusted on experiments for major isotopes) fission yields was noticed.

QRPA calculations (based on Gogny effective force) performed by CEA exhibited very good agreement with recent CNRS/JRC-Geel $^{238}U(n,n'\gamma)$ measurements allowing reliable use of more microscopic ingredient in the evaluation process. The use of this kind of ingredient for gamma strength function and thus evaluation of cross sections is underway.

Participation of French physicist in two CRP's devoted to RIPL fission parameters and strength function estimations are very promising (QRPA based evaluations are underway).

For nuclear reaction codes, the implementation of the Eigenbrecht-Weindemuller transformation was developed and tested at CEA with TALYS code. Its final release in TALYS as soon as the impletion is fully validated. In addition, strength function tables coming from CEA QRPA microscopic calculations are provided with latest version of TALYS. A noticeable development in CONRAD code (CEA) was done to allow not only charged particle treatment for R-Matrix (which was traduced by participation to IAEA related technical meetings and INDEN) but also the possibility of treating all incoming channels giving the same compound nucleus.

CEA released a new version of the BetaShape code, whose purpose is to improve the data related to low-energy weak interaction decays. This program takes as input an ENSDF file and calculates beta and neutrino spectra, electron capture probabilities, mean energies and log ft values. The physical modelling is much more sophisticated than in the LogFT code, which has been the reference code for the last 50 years in decay data evaluations. CEA has also developed a specific radioactive decay module, called Nuclide++, for the Monte Carlo simulation code

Geant4. Starting only from the radionuclide name, this module automatically creates all the primary events that are generated in the decay, including nuclear emissions from the decay scheme and atomic emissions from the atomic relaxation. The decay data are taken from DDEP evaluations. This new module complements the already existing CEA-developed module for the code PENELOPE.

Conclusions

Some of the reported work was/is supported by EC-funded such SANDA/ARIEL projects as well as French partnerships (CEA-CNRS-EdF-AREVA-IRSN) such as the NEEDS/NACRE framework.

Various conferences or workshops were the occasion of fruitful discussions with the nuclear data specialists (**ND2019**, PHYSOR2020 …). For 2021 and 2022, depending of the pandemic crisis, several interesting conferences should take place.