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Summary Report of the 1st RCM of the CRP on the

Updating Fission Yield Data for Applications

(Virtual Event)

31 August – 4 September 2020

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Abstract

The First Research Coordination Meeting of the CRP on "Updating Fission Yield Data for Applications" was held by video conference from 31 August to 4 September 2020 with more than 50 international experts from 16 countries attending the meeting. The CRP is devoted to evaluation efforts of cumulative and independent fission yields for incident energies from the thermal point up to 14 MeV on actinide targets. Produced fission yield evaluations should include full uncertainty quantification and are expected to combine available experimental data and state-of-art model information. Four working groups were created within the collaboration: 1) Availability of experimental fission product yield data for evaluations; 2) New fission product yield experimental data; 3) Fission product yield evaluation; and 4) Fission product yield validation. Technical discussions and the resulting work plan of the Coordinated Research Programme are summarized in this report. The meeting presentations are available at: https://nds.iaea.org/index-meeting-crp/FissionYields2020/.

April 2021

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1 Introduction

The First Research Coordination Meeting of the CRP on “Updating Fission Yield Data for Applications” was held by video conference from 31 August to 4 September 2020, from 2 to 5pm Vienna local time. More than 50 international experts from CRP-participant institutes in 16 countries attended the meeting.

The meeting opened on Monday with a welcome addresses by the Head of the Nuclear Data Section, A. Koning, and the Scientific Secretary, R. Capote. R. Mills of UKAEA was elected Chairperson. B. Pritychenko (BNL), S. Oberstedt (JRC-Geel), O. Cabellos (UPM), R. Vogt (LLNL) and T. Kawano (LANL) were elected rapporteurs for each day of the meeting, respectively.

R. Capote (IAEA) briefly introduced the CRP, the objectives, goals, expected deliverables, and timeline. In particular, it was stressed that the CRP will be devoted to evaluation efforts of cumulative and independent fission yields for incident energies from the thermal point up to 14 MeV on actinide targets. Produced FY evaluations should include full uncertainty quantification and are expected to combine available experimental data and state-of-art model information. This was followed by a general introduction of the importance of and needs for fission product yield (FPY) data by M. B. Chadwick (LANL). FPY evaluations require both experimental data and theoretical efforts. Measurements often do not cover the entire mass and energy ranges of interest, thus theoretical models can fill the gap to complete evaluations. One focus, a priority of evaluating FY data for neutron-induced reactions on major actinides, was highlighted by M.B. Chadwick. The meeting continued Monday through Thursday with presentations by the participants, followed by some brief discussion. The discussion time was constrained by the limited time for the online meeting due to the wide range of time zones involved. Friday was reserved for more detailed discussions and for assignment of tasks.

The meeting presentations are available at:

https://nds.iaea.org/index-meeting-crp/FissionYields2020/

Finally, NDS acknowledges all participants for their cooperation and contributions to this productive meeting.

2 Presentation summaries

2.1 Fission fragments observables measured at the LOHENGRIN recoil separator

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The CEA, in collaboration with ILL and LPSC, has developed a measurement program of fission fragment observables. The combination of measurements with an ionisation chamber and Ge detectors is necessary to precisely describe the heavy fission fragments as a function of mass and charge. Recently, new measurements of fission yields from different fissioning systems, ^{233,235}U($n_{\rm th}$,f), ^{239,241}Pu($n_{\rm th}$,f), and ^{241}Am($n_{\rm th}$,f), were performed with this detector setup. The focus has been on normalization of the data to provide new absolute measurements, independent of any libraries, and the experimental covariance matrix. Over the past decade, a new experimental procedure was developed, along with a new analysis method, to make more precise measurements.

Currently, mass yield are measuremed within 2-3% accuracy for the heavy and light mass regions. However, some issues remain in the symmetric and far-asymmetric mass regions. A new Time-of-Flight (ToF) detector is under development in order to eliminate contamination from the LOHENGRIN spectrometer in these mass regions. This improvement will be part of an upcoming PhD thesis (2020-2023). We also plan to measure the ^{235}U($n_{\rm th}$,f) mass yields as part of this thesis work.

The achievable uncertainty of isotopic yield measurements depends on the decay data, especially uncertainties on the gamma intensities. However, the measurements can be revised and updated easily in the near future, based on improved decay data.

Finally, isomeric ratio measurements and precise kinetic energy measurements are performed to test models. These measurements are important to validate de-excitation codes such as FIFRELIN.

We would like to take the opportunity to participate to the CRP in order to share our experimental data (average values, uncertainties and associated covariance matrices) with the community.

Probe	Energy	Targets
Neutron	Thermal	^{235,233}U, ^{239,241}Pu, ^{241}Am, possibly, in the near future ^{243,145}Cm

2.2 Experimental results on monoenergetic neutron- and photon-induced fission from the TUNL-LANL-LLNL FPY collaboration

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A joint TUNL-LANL-LLNL collaboration has collected fission product yield (FPY) data using monoenergetic neutron and photon beams. The primary focus of our work is to measure the energy evolution of FPYs using these monoenergetic beams. Cumulative FPYs are determined using the activation technique: post irradiation, fission products are tracked over multiple half-lives and quantified via γ-ray spectroscopy from a thick target with HPGe detectors. A dual fission chamber measures the total number of fissions in two thin targets. The number of fissions in the thick target is then determined by mass scaling. The FPY is then given by

FPY = (HPGe counts / Fission chamber counts)$(m_{\text{thin}}/m_{\text{thick}})C_i$,

where C_i are the conventional corrections associated with an activation experiment. Compared to a typical activation experiment, this approach has the advantage that there is no dependence on a reference cross section or absolute flux measurement. The primary disadvantage is a dependence on the γ-ray intensity. As such, the overall normalization is subject to systematic uncertainties. However, we measure the energy dependence of the FPYs with high confidence. To aid in this effort, we have taken great care to reduce systematic uncertainties by using the exact same actinide targets, fission chambers, and HPGe detectors in each experimental run.

Monoenergetic neutrons are produced by the TUNL tandem accelerator from 0.5 to 7.7 MeV and at 14.8 MeV. Quasi-monoenergetic neutrons are produced from 7.7 to 14 MeV. Corrections are made for the off-energy contributions.

Our first measurements focused on long-lived cumulative FPYs of ^{235}U, ^{238}U, and ^{239}Pu [1]. In this work, 16 FPYs were measured at nine discrete neutron energies from 0.56 to 14.8 MeV. The FPYs of ^{239}Pu(n,f)^{147}Nd shows a positive slope from 0.5 to 4.0 MeV, which confirms data from critical assembly experiments. This is followed by a negative sloped FPY from 4.0 to 14.8 MeV, as expected. Furthermore, this dataset resolved longstanding discrepancies at 14.8 MeV. Additional data at $E_n = 6.5$, 11, and 13 MeV has since been taken. We expect publication of these results in the next year.

We have begun to expand this dataset by including fission products with progressively shorter half-lives. We have measured the FPYs of 45 additional nuclides from ^{238}U, ^{235}U, and ^{239}Pu with $t_{1/2}$ from ≈ 15 minutes to several hours at $E_n = 4.6$ and 9.0 MeV. These are neutron energies not included in the current evaluations. Additional data at $E_n = 14.8$ MeV is currently being analyzed. We expect publication in the next year for these three neutron energies.

In the past year, we have constructed a RApid Belt-driven Irradiated Target Transfer System (RABITTS), a fully automated system for cyclic activation. This enables yield measurements of fission products with half-lives as low as 1 s. Access to these short time scales allows measure-

Table 1: Summary of current measurements.

Probe	Energy	Targets	Status
Neutron	$E_n = 0.5\text{-}14.8$ MeV $\Delta E = 0.1$ MeV	^{235}U, ^{238}U, ^{239}Pu	Measurements at additional neutron energies and of additional fission products expected to be published next year.
Photon	$E_\gamma = 11.2, 13.0$ MeV $\Delta E = 0.25$ MeV	^{235}U, ^{238}U, ^{239}Pu, ^{240}Pu	Expect to publish ^{240}Pu data next year.

ments of isomeric ratios from fission. We continue counting our targets after cyclic activation, which systematically connects our RABITTS FPYs with our previously published values. We have produced 60 preliminary FPYs for ^{238}U(n,f) at $E_n = 2.0$ MeV. Additional data on ^{238}U, ^{235}U, and ^{239}Pu at $E_n = 2.0$ and 4.5 MeV are currently being taken. For some mass chains, there is enough cumulative data to begin constraining independent yields.

Experiments inducing fission with monoenergetic photons were conducted at the High Intensity γ-ray Source, with beam energies from $E_\gamma = 8 - 14$ MeV with a spread of 0.25 MeV FWHM. These experiments use the same techniques, targets, fission chambers, and HPGe detectors as our neutron-induced fission measurements. We have measured photon-induced FPYs of ^{240}Pu as a means of validating the Bohr hypothesis. Our ^{240}Pu(γ,f) FPYs agree very well with our ^{239}Pu(n,f) data for the same excitation energy. We expect publication of these results in the next year. Photon-induced FPYs of ^{235}U, ^{238}U, and ^{239}Pu at $E_\gamma = 13$ MeV were reported for 42 fission products [2]. Since then, additional data has been collected at 11.2 MeV, allowing us to begin investigating the energy dependence of photofission FPYs. We have recently installed a 1 m RABITTS at HIγS, which will allow us to measure FPYs with half-lives from 0.4 s to 4 min. We have completed data taking on ^{235}U, ^{238}U, and ^{239}Pu at $E_\gamma = 13$ MeV, and have started data collection on all three actinides at $E_\gamma = 11.2$ MeV. Preliminary results at $E_\gamma = 13$ MeV show good agreement with the SOFIA data [3].

2.3 Cumulative yields of Bromine, Krypton, Rubidium and Iodine isotopes from fission of ^{233}U, ^{235}U, and ^{239}Pu by neutrons in the energy range from thermal to 5 MeV

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A reliable fission product yield database is of great importance in reactor design and operation, burn-up determinations, decay heat calculations, transmutation studies and many other related applications.

Cumulative fission product yields are needed for calculation of delayed neutron characteristics such as the total delayed neutron yields, relative abundances and energy spectra of delayed neutrons for separate delayed neutron groups.

Experiment

The experimental method employed in the measurements is based on periodic irradiation of the fissionable targets by neutrons generated at the accelerator along with measurements of the composite decay of the gross neutron activity. In the present experiment, an irradiation time of 300.06 s and a counting time of 724.5 s were used. A sample delivery time of 150 ms was used in the measurements.

The decay curve analysis was carried out within the framework of a 12 delayed neutron group model. Two sequences of decay constants were derived on the basis of known half-lives of delayed neutron precursors. The group periods were chosen to properly allocate the appropriate delayed neutron precursors. In the framework of such an approach, the effective periods of composite groups were obtained by an averaging procedure with the relative DN yields employed as a weight. These data were used in further processing of the experimental composite DN decay curves. In the present work 17 delayed neutron precursors were considered. These precursors are responsible for about 70% of the total DN yield.

Determining the cumulative fission product yields - delayed neutron precursors

Our method is based on the ratio linking the value of the cumulative yield of the i^{th}-precursor $\mathrm{CY}_i(E_n)$ to the relative abundance $a_i(E_n)$, the total delayed neutron yield $\nu_d(E_n)$, and the probability of delayed neutron emission $P_{n\,i}$,

$$\mathrm{CY}_i(E_n) = \frac{a_i(E_n)}{P_{n\,i}}\nu_d(E_n)$$

The IAEA Coordinated Research Project on the Development of a Reference Database for beta-delayed neutron emission focused on developing a high quality database of precursor characteristics. These included delayed neutron emission probabilities P_n and half-lives $T_{1/2}$ as well as a compilation of total delayed neutron yields $\nu_d(E_n)$ for a wide range of fissile nuclei and incident neutron energy. This database enables us to expand our delayed neutron measurement technique to obtain the energy dependence of fission product yields from neutron-induced fission.

Model of delayed neutron groups

In the present work, the 12-group model of the time distribution of delayed neutron precursors, based on the known half-lives of 17 precursors, was used. We first obtained information on the relative abundances $a_i(E_n)$ of delayed neutrons related to precursors ^{87}Br, ^{88}Br, ^{89}Br, ^{91}Br, ^{93}Kr, ^{94}Rb, and ^{95}Rb. Next, we determined the abundances of delayed neutrons relative to ^{137}I, ^{138}I, ^{139}I, and ^{140}I precursors.

The group periods were chosen to properly allocate the appropriate delayed neutron precursors, placing each of them in a separate DN group. The remaining groups are composite, comprising several delayed neutron precursors with effective periods obtained by an averaging procedure:

$$T = \frac{\sum_{i=1}^{N} (T_{1/2}\mathrm{CY}P_n)_i}{\sum_{i=1}^{N} (\mathrm{CY}P_n)_i}$$

Estimate of the most probable fission product charge Z_p

The method for determination of the most probable fission fragment charge used in our work is based on the fact that the primary distribution of fission fragments in a given isobaric chain can be described by Gaussian distribution characterized by two parameters: the most probable charge Z_p, and the dispersion σ. For a more careful analysis of the Z_p data it is useful to present the data as a deviation from the unchanged charge distribution, Z_p(UCD), as a function of complementary light and heavy primary fragments A', before neutron evaporation.

Conclusion

Cumulative yields were obtained for Bromine, Krypton, Rubidium and Iodine isotopes from neutron-induced fission of ^{233}U, ^{235}U, and ^{238}U for neutron energies from thermal to 5 MeV. We plan to measure the delayed neutron decay curve from fission of ^{235}U and ^{238}U to obtain the energy dependence of the total delayed yield and average half-life of delayed neutron precursors for neutron energies from thermal to 8 MeV.

On the basis of the cumulative yields we obtain, the most probable charge of isobaric chains with mass numbers (87, 88, 89, 91, 137, 138, 139, and 140) and their complementary light fragment chains were calculated. The data are in good agreement with the data obtained by Wahl in his Z_p model. This observation shows the validity of the approach used to determine the cumulative fission product yields and the DN precursors.

Measurements of fission product yields usually involve expensive mass separator facilities, complicated time of flight methods, and fast radiochemistry. The energy range of incident neutrons available in current fission product yield data is quite restricted. The results obtained in the present work open the possibility to expand our present investigations to systematic studies of cumulative fission product yields, at least for bromine and iodine precursors, and the most probable charges for a range of compound nucleus excitation energies using electrostatic accelerators.

2.4 Decay data measurements to aid in FPY determinations

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A common method for the determination of fission product yields (FPYs), neutron activation analysis followed by gamma-spectroscopy measurements, is the so-called activation method. Samples are exposed to incident particle or photon beams, then taken offline where γ-ray spectroscopy is used to determine the fission fragment yields by measuring γ-rays emitted following their beta decay. This technique relies heavily on knowing the absolute intensity of γ-rays produced in beta-decays and often constitutes a significant fraction of the experimental uncertainty.

The Evaluated Nuclear Structure Data File (ENSDF) is a complete and comprehensive database of nuclear structure and decay data and a common source of data on the absolute intensities required for the determination of FPYs as described above. While the data in ENSDF are complete, there are many instances where the decay data were last measured decades ago with primitive detector setups. For example, the decay of the long-lived fission product ^{136}Cs was last studied in 1976 and the data published only in a laboratory report [4].

This presentation outlined a campaign of measurements aimed at improving the decay data for fission fragments. Experiments are performed at Argonne National Laboratory using the CARIBU facility. Fission fragments are produced following the spontaneous fission decay of a strong ^{252}Cf source, thermalized in a gas catcher and then mass separated [5]. The current set of measurements have made use of the Gammasphere array consisting of 100 HPGe, Compton-suppressed HPGe detectors or the SATURN array [6] consisting of 5 closely packed HPGe Clover detectors surrounding plastic scintillators.

In the heavy fragment region, decays of ^{141}Cs, ^{142}Cs and ^{144}Cs have been studied along with their daughter nuclei in the $A = 141$, 142 and 144 chains. In the light fission fragment region, experimental efforts have focused on nuclei relevant to predicating the antineutrino flux from a reactor. Using the SATURN array, the absolute intensity of the decay of ^{92}Rb was precisely determined and found to be in good agreement with recent total absorption gamma-ray spectroscopy measurements.

Decay data are an integral component in the determination of FPYs measured through the activation method. ENSDF evaluators can always be consulted to provide an assessment of the quality of the decay data currently available in ENSDF. Furthermore, the NNDC welcomes suggestions for isotopes of interest to FPY measurements which require new measurements using modern detectors arrays.

2.5 ^{238}U(n,f) induced by fast neutrons, the prototype for a modern and comprehensive database of experimental fission yields

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A new compilation of fission yields data from fast neutron-induced fission of ^{238}U (^{238}U(n_{F},f)) is underway at the National Nuclear Data Center. In the following we will describe the steps taken so far and the future work that will contribute to the effort of the IAEA Coordinated Research Project on Fission Product Yields. The work performed so far focused on ^{238}U(n$_{\mathrm{F}}$,f) as a prototype of future efforts working towards the creation of a comprehensive database of experimental fission product yields. Data for ^{238}U are only a fraction of those available for other major actinides which allows us to implement, test and troubleshoot a working framework that can later be extended to all other fissioning systems. At the same time, the interest in ^{238}U for reactor antineutrino applications makes a revision of available data for this fissioning system very timely. The work already performed at the NNDC has proceeded along three main avenues: collecting and compiling available experimental FY data; developing a storage and working format for experimental FY data; and updating and correcting FY data using the most current decay data.

Compilation

We started collecting and compiling available experimental data from the Nuclear Science References (NSR) database. A list of all available publications containing information on experimental FYs from ^{238}U was the starting point of the compilation effort, which resulted in more than 200 references, filtered down to about 150 of interest for ^{238}U(n$_{\mathrm{F}}$,f). The bibliographical list led to the identification of related EXFOR entries, which constituted the source of most experimental data. A few recent experimental data were obtained directly from the original publication or from the authors.

A working format for FY data

In order to simplify the storage, retrieval and management of an experimental FY database, we developed a new working format where all the extracted experimental points could be compiled. The format is based on JSON, a modern, standard and programming language-independent format to archive and transmit data using text-based files. The new format does not try to replicate the corresponding EXFOR entries, but makes the parameters useful for the evaluation of FYs easily accessible and allows for the correction of FY data (based on, e.g., updated nuclear data) without modifying the original EXFOR entry.

A total of 535 EXFOR datasets have been converted to the new JSON format, using the EXFOR-TO-JSON.FY code developed by V. Zerkin, and available at https://nds.iaea.org/exfor/.

Bringing FY data up to date

The data sets which included decay data in the original publication underwent careful corrections to bring the measured values up to date. This involved - in nearly all cases - correction of the γ-ray intensities using the current values available in ENSDF. A total of 1850 decay data points were corrected for several dozen EXFOR entries. The large majority of the corrections changed the original FY values by less than 5%, with only the oldest measurements (often dating back to the 1960s) changing by more than 10-15%. Current work is focused on collecting and compiling experimental data for Isomeric Yield Ratios, starting from references available in NSR and datasets compiled in EXFOR, and on studying the effect of new ^{238}U(n_F,f) experimental data on the reactor antineutrino spectrum.

2.6 Status of Experimental FPY Compilation for EXFOR

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for the International Network of Nuclear Reaction Data Centres (NRDC)

1. Completeness of EXFOR

NDS found that 63% of the articles cited in the ENDF and UKFY reports [7, 8] are in EXFOR. We checked the contents of the rest of the articles, and concluded that: 17% should be added to EXFOR; 15% are irrelevant to EXFOR (e.g., private communications); and 5% should be checked further because they are e.g., laboratory reports not available at NDS [9].

From this assessment and an independent completeness survey done with NSR by NNDC, NDS prepared a list of 625 experimental FPY articles. NDS prepared copies of these articles and assigned them to nine data centres (China, India, Japan, Russia, Ukraine, USA, NEA and IAEA) for their compilation in the NRDC 2019 meeting. Until now 27% of these articles have been compiled in EXFOR.

2. Extension of EXFOR

(1) Fission following Coulomb excitation

We started to compile the fission yields from Coulomb excitation of a secondary beam produced by fragmentation (such as at the GSI FRS) as photon-induced fission yields.

Example: Charge yield from Coulomb excitation of a ^{226}Th secondary beam by a Pb target.

`90-TH-226(G,F)ELEM,CHG,FY,,SPA`

where `SPA` indicates that the data set is not for a monoenergetic photon beam. Such data can be compiled only when the excitation energy (or an estimate) is available from the experimentalists.

(2) Fission following transfer reactions

The yields from transfer-induced fission are currently being compiled as:

Example: Secondary fragment mass yields from ^{238}U(^{18}O,^{19}O)^{237}U*.

`92-U-238(8-O-18,8-O-19+F)MASS,ISP/SEC,FY`

where `ISP` indicates that the yield is specific for an excitation energy of an intermediate nuclide (= ^{237}U). We are aware that some neutron-induced fission yield evaluators would prefer to define this data set as the ^{236}U(n,f) mass yield, namely

`92-U-236(N,F)MASS,SEC,FY`

This question can be discussed further among the CRP and NRDC members. Note that:

1. the EXFOR policy allows the `(N,F)` option only if the authors agree with it;
2. the EXFOR rules also should cover data from transfer-induced fission (a) other than $1n$ transfer, and (b) other than fission yields (e.g., cross sections).

2.7 Current status of FY Compilations (Area #1)

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Nuclear reaction data collection, evaluation and dissemination have been pioneered at Brookhaven National Laboratory since the early 50s. These activities gained popularity worldwide and, around 1970, the experimental nuclear reaction data interchange or exchange format (EXFOR) was established. As shown in Fig. 1, the original EXFOR compilation scope consisted only of neutron reactions and spontaneous fission data while many other nuclear data sets were ignored.

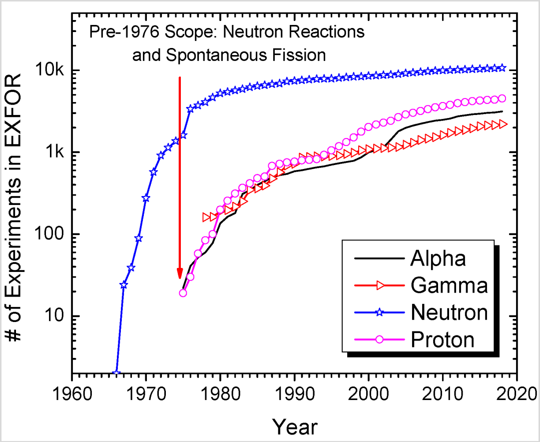

Figure 1: EXFOR compilation timeline showing the evolution of the library compilation scope and data content over time.

Fission yields play a very important role in applied and fundamental physics and such data are essential in many applications. The comparative analysis of the Nuclear Science References (NSR) and the Experimental Nuclear Reaction (EXFOR) databases show a large number of experiments unaccounted for and provides a guide to the recovery of fission cross sections yields and covariance data sets. Due to the high cost of new experiments, it is very important to find and recover the previously-disregarded data using scientific publications, data evaluations and nuclear database comparisons. The dedicated fission yield data compilation effort is currently underway in the Nuclear Reaction Data Centers (NRDC) network and includes identification, compilation, storage and Web dissemination of the recovered data sets. The current status of missing FY compilations at NNDC is shown in Fig. 2.

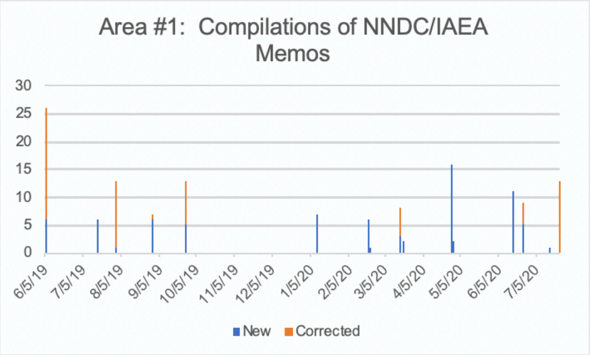

Figure 2: Present status of missing fission yields compilations at NNDC.

2.8 Available fission product yield experimental data from the UK database and its analysis for evaluations

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In the nuclear fission industry, fission product yields are used in many different reactor and spent fuel calculations including decay heat, shielding, dosimetry, burn-up, fuel handling, waste management and disposal. The availability of verified fission product yields with well understood uncertainties are vital to such calculations for important nuclides that fission in energy or other applications. There have been many evaluations of fission yields from the Crouch (UK) and Rider (USA) from the 1970's to the current CENDL, ENDF/B, JEFF and JENDL evaluations of today. These rely upon the available experimental data, its analysis, models to predict unmeasured yields and, finally, application of nuclear physics constraints to produce complete and physically-consistent datasets for use in simulations. The required data include the independent (direct) yields as well as the cumulative yields. The independent yields are usually produced by splitting the terms into the mass yield, the charge dispersion for a given mass, and the isomeric splitting ratio. The cumulative yields are determined from the independent yields using a consistent set of decay data. In addition, it is necessary to consider light charged particle emission from fission (^{1}H, ^{3}H, ^{3}He, ^{4}He, ...). This emission is usually handled separately from the binary fragments and then combined to produce a complete dataset of fission fragmentation.

There are several problems with this approach. The principle issue is that although independent yields are the most necessary data for general calculations, most measurements are of cumulative yields, sometimes using relative or "ratio of ratio" techniques. In addition, delayed neutron and long-lived alpha emission implies that the cumulative yields and mass yields may be different depending on the time scales considered. Finally, changes to nuclear states and decay data will change the yields produced and thus care must be taken to ensure consistent data is employed in the analysis, modelling and use of the yield data.

The UK analysis technique using weighted and unweighted means with an automatic down-weighting procedure (James, 1991; James 1992 and Mills, 1995) on a database has been used to produce the JEFF-2.2, JEFF-3.1.1 and JEFF-3.3 fission yields. The methods include handling cumulative yields of isomeric states to improves estimates of the mass yields. The latest database UKFY3.7 includes 12924 direct measurements of yields, 1442 yield ratio measurements and 1471 "ratio of ratio" measurements. These are used to determine 15837 yields. This database was frozen in 2017 to produce JEFF-3.3.

The planned work will consist of: (i) Review and analyse the UK fission product yield database, leading to a journal publication and release of the UK database. (ii) Contribute recommended analysed values from experimental measurements to the CRP. (iii) Review to ensure the data sources in the UK database are captured correctly in the IAEA EXFOR database.

The workplan is:

1. Review and analyse the UK fission product yield database vs published data and the IAEA EXFOR database.
2. Supply database and comments on EXFOR to the CRP participants.
3. Analyse database to produce a set of recommended fission yields.

4. Supply recommended FYs to the CRP participants for review.
5. Produce a journal paper on the UK FY database and publish database (by end of March 2021).
6. Contribute to the final CRP publication.

2.9 FPY data at 8 MeV equivalent neutron energy on ^{235}U (SOFIA) and new GANIL experiment

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The measurement of fission yields in reverse kinematics provides some new and high accuracy information that usual studies can not.

The beam kinematical boost reduces the emittance of the fission fragments and transfers enough energy to the fragments to allow for a full in-flight isotopic identification, before any beta decay.

The SOFIA project, aims, at GSI, at getting such very high accuracy fission yields. Data for the coulex fission of ^{236}U were collected and yields with an accuracy as good as 1% could be extracted over the full Z and A range. The excitation mechanism does not allow for any adjustability of the compound system excitation energy. The distribution is relatively broad and the mean value correspond to 8.2 MeV neutron induced fission on ^{235}U. The obtained dataset covers the full range of fission fragment or provides a very nice validation of the neutron induced fission measurement exploiting the activation technique for instance.

Another facility can be used fkor similar studies. The GANIL hosts the VAMOS spectrometer and can provide with uranium beams at the coulomb barrier energy. Our collaboration is currently designing a silicon telescope array dedicated to transfer reaction from the uranium beam on a carbon target. When collecting the light ejectile from the transfer reaction, one can identify the compound (fissioning) system and the associated excitation energy with 300 keV resolution. Additionally, the target/projectile combination is chosen so that 2 most populated compound systems are the ^{236}U and the ^{240}Pu corresponding to the neutron induced fission of ^{235}U and ^{239}Pu. Thus, we expect that we will collect fission yield data for both fissioning system in one experiment. This experiment will be presented to the next GANIL PAC and could possibly run as early as 2022.

2.10 Experiments on Fission Yields and neutron multiplicities for enhanced fission modelling

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- At Uppsala we are experimentally studying the fission process including primary fission yields, product yields, independent yields, cumulative yields and isomeric yields. In addition, we study prompt fission neutron emission.
- The main goal of our CRP participation is to compile all our existing data and to make sure they are reported fully with uncertainties. We also wish to discuss what possible impact our data has on fission yield evaluations.
- A secondary goal is to work on incorporating GEF into the TALYS code to further improve the evaluation process.
- Our measured data include:
  - yields and TKE for ^{234}U from 0.2 to 5 MeV;
  - yields and TKE for ^{238}U from 10 to 60 MeV;
  - Sn and Sb isotopic yields from ^{238}U(n,f) at an average energy of 12 MeV;
  - isomeric yields for ^{238}U(p,f) at a proton energy of 25 MeV for isotopes of In, Ge, Cd, Y, Sn, Sb;
  - $\overline{\nu}(A)$ for ^{235}U($n_{\rm th}$,f) and ^{252}Cf(sf)
- We use three techniques for measured the yields: the $2E$ and $2E - 2v$ methods as well as the ISOL method at IGISOL. We are working on developing the VERDI $2E - 2v$ instrument which is able to measure fission yields with mass resolution below 2 amu. Hopefully, within the time frame of this CRP, the first measurements with VERDI will be carried out.
- We are also involved in modeling isomeric populations and thus the angular momentum of fission fragments, using TALYS. We have recently introduced the Total Monte Carlo method to carry out these de-excitation calculations.
- The codes developed within this project will be calibrated using Monte Carlo and machine learning regression tools for new evaluations.

2.11 Measurements of fission-fragment yield and prompt decay properties

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JRC-Geel operates three laboratories where fission research is conducted. The three laboratories are a neutron-TOF facility (GELINA), a fast-neutron source (MONNET) and the VERDILab, studying spontaneous fission.

The goal of the present activity is to investigate prompt neutron and γ-ray emission in fission in correlation with fission fragment properties. The first step, if deemed necessary, is to accurately measure the primary fission fragment mass and total kinetic energy distributions, $Y(A, \mathrm{TKE}; E^*)$, where E^* usually ranges from 0 to about 11 MeV.

- Investigations at GELINA were performed in response to a nuclear data request on the OECD-NEA high priority request list for new measurements of prompt neutron multiplicities from ^{239}Pu(n,f) for incident neutron energies from thermal to 5 eV (HPRL-99H). There is experimental evidence of strong fluctuations in the average neutron multiplicity, $\overline{\nu}$, from resonance to resonance in ^{239}Pu(n,f). These fluctuations have been shown to impact nuclear reactor benchmarks by reducing the criticality. One explanation for the fluctuating neutron multiplicity may be the competition between direct fission and the $(n, \gamma$f) process. However, there is also evidence for fluctuations of the fission fragment mass yields from resonance to resonance. The mass yield fluctuations may also contribute to fluctuations of the neutron multiplicity averaged over all fission fragment masses. Two experiments were already performed, the first, with ^{235}U(n,f), where the observed variation of $\overline{\nu}$ could be attributed to variations of the mass and total kinetic energy (TKE) distributions with incident neutron energy. In a second experiment, studying ^{239}Pu(n,f), variations due to fission-fragment characteristics turned out to be much smaller and thus unable to explain the $\overline{\nu}$ changes reported in the literature. Since resonances suspected of carrying a significant fraction of the $(n, \gamma$f) process are usually small, a setup providing a sufficiently high fission rate needed to be developed. Presently, we measure neutron-energy dependent prompt neutron emission using a compact multi-target chamber containing 28 mg ^{239}Pu to provide the fission tag. Statistically significant $\overline{\nu}(E_n)$ data, together with accurate pre-neutron fragment yields, are expected to be available in about two to three years.

- In the VERDILab we have set up an array of LaBr$_3$(Ce) detectors of various size and different orientation relative to the symmetry axis of a position-sensitive twin Frisch-grid ionization chamber (VESPA++) to measure prompt fission neutron (PFN) and γ-ray (PFG) characteristics as a function of fission fragment mass and TKE. Of particular interest are mass-dependent PFN and PFG spectral characteristics, neutron-neutron correlations and the time dependence of PFG emission. During the meeting, mass and TKE-dependent average PFG multiplicity data, $M_\gamma(A)$ and M_γ(TKE), were presented. The high number of events, collected with three different detectors at three different angles relative to the ionization chamber, allows removal of discrepant data in the literature. The accuracy and precision of the new $M_\gamma(A)$ and M_γ(TKE) data will help benchmarking fission models that attempt to describe fission-fragment de-excitation, such as through models of the initial spin distributions.

- MONNET, the new mono-energetic fast-neutron source was presented. The facility received its operations permit in June 2020 and is one of the JRC EUFRAT Open Access

> Instruments. The laboratory will offer neutron beams with energies up to 24 MeV, with a kinematical gap between about 10 to 13 MeV. Production of photon beams is foreseen at a later stage. In the coming years, measurements of pre-neutron fragment characteristics as a function of excitation energy is planned for fission of ^{230,232}Th and ^{236}U. All this is subject to the deteriorating manpower situation and the availability of spectroscopic targets.

Our contribution to this CRP will be accurate pre-neutron mass and TKE distributions for thermal and resolved-resonance neutron energies for the reactions ^{235}U(n,f) and ^{239}Pu(n,f). In addition, mass and TKE-dependent PFN and PFG characteristics will be provided for benchmarking fission models. Additional fission yield data from fast-neutron induced fission on ^{230,232}Th and ^{236}U could be delivered, if the available resources do not continue to deteriorate.

2.12 New Experimental Method for Measuring Isotopic Fission Yields and Isomer Yields Ratios Based on Mass Measurements at the FRS Ion Catcher

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We will develop and quantify a new method to measure independent isotopic fission yields (FYs) and isomer yield ratios (IYRs) based on direct ion counting, using a spontaneous fission (SF) source installed in the FRS Ion Catcher (FRS-IC) at GSI. The FRS-IC is a well-established scientific instrument developed, maintained and operated by the international FRS-IC Collaboration. It has already generated numerous technical and physics publications on rare, short-lived isotopes. In the FRS-IC, fission fragments are generated by a SF source inside a cryogenic stopping cell (CSC), thermalized and stopped within it, and then extracted and transported to a multiple-reflection time-of-flight mass spectrometer (MR-TOF-MS). The relative mass yield accuracy ($\sim 6 \times 10^{-8}$) and resolving power ($\sim 10^{6}$) of the MR-TOF-MS are sufficient to separate all isobars and low-lying isomers, down to excitation energies as low as $\sim$200 keV, of fission fragments.

The system is essentially element, Z, independent and can measure up to $\sim$20 isotopes at ond3, making it an excellent instrument for broad range FY distribution studies and isomer yield ratios. The extraction time of the CSC, $\sim$10 ms, will enable direct measurements of independent isotopic fission yields down to half-lives of tens of ms.

The FRS–IC CSC's high stopping power and extraction efficiency, along with the compact RF-focusing beam line, will enable access to relatively low-yield fission products. With a 10 kBq ^{252}Cf SF source already installed and a ^{248}Cm 30 kBq source to be installed in the second year of the CRP, we will reach independent fission yields as low as 10^{-6}. With a future 10 MBq ^{252}Cf SF source that we plan to install in the later years of the CRP, we may reach fission yields as low as 10^{-8}.

We will develop the method and produce data for SF of ^{252}Cf and ^{248}Cm. Known SF data from ^{252}Cf will serve to develop and quantify the method. New data for isotopic FPYs and IYRs will be generated for both SF sources and compared systematically. We will further compare the measured SF FPYs and IYRs to those obtained from ^{238}U inflight fission [5] and proton induced fission on ^{238}U and ^{232}Th. Such comparisons will produce important systematic insights about fission product generation in these cases where the IYRs will particularly shed light on their angular momentum upon generation.

In preliminary runs during 2019 and 2020, performed with the 'standard' CSC, with the SF source mounted in its corner, we were able to detect and identify 150 fission fragments by their masses down to yields of 10^{-5}. We have recently installed a dedicated internal component of the CSC (DC cage). The SF source is mounted on the axis and is easily replaceable. The enhanced specifications of this DC cage will reach yields of 10^{-6} for the same SF sources. Analysis to extract the FYs and IYRs from these measurements is ongoing. These FY measurement methods could be used in the future for measuring neutron-induced fission yields on various actinides over a wide range of neutron energies at Phase II of the Soreq Applied Research Accelerator Facility (SARAF II), under construction at Soreq NRC, Israel.

2.13 Fission yields with GEF

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The GEF code [10, 11, 12] (General description of fission observables) covers the entire fission process from the formation of an excited system, for example by neutron capture, to the generation of the fission fragments, their de-excitation process by neutron evaporation and gamma emission, including consecutive radioactive decays towards beta-stable end products. It calculates practically all fission quantities using a semi-empirical approach in a consistent way, thus establishing correlations between fission quantities. The calculated fission fragment yields mainly rely on the potential-energy surface on the fission path. The relevant characteristics of the potential-energy surface are deduced from empirical fission fragment yields, originally from the ENDF/B-VII evaluation, because it was possible to include a large number of systems in a consistent way. As demonstrated in Ref., a rather good description of the fission yields for practically all fissioning systems is obtained with only four proton shells in the nascent fragments, the origin of the different fission modes.

In the last year, the very accurate fission yields, measured with the Lohengrin spectrometer since about 1980, which have only rarely been used in current evaluations, along with additional constraints imposed by measured decay heat and antineutrino spectra were exploited to appreciably improve the accuracy of the GEF fission yields. By exploiting the inherent regularities provided by the theoretical framework of GEF, it became possible to identify many suspicious or erroneous yield values in ENDF/B-VII, JEFF- 3.1.1 and JEFF-3.3 for a number of fissioning systems and, thus, to purify the data used to determine the GEF parameters, further improving the quality of the GEF results. In addition, some remaining deficiencies of the GEF code became evident from the appearance of rather small but systematic discrepancies between the GEF yields and the very accurate Lohengrin data.

From our careful comparative study of yields from GEF, the Lohengrin data and different evaluations, it will be possible to establish extensive tables of improved guess values for many fissioning systems. Furthermore, we propose to make the GEF code available for future evaluations to improve the quality of fission yield tables.

2.14 Potential use of the FIFRELIN Monte Carlo code for the future Fission Yield evaluations

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Over the last 10 years, CEA-Cadarache has been developing the FIFRELIN Monte-Carlo code, for FIssion FRagment Evaporation Leading to an Investigation of Nuclear data. This code, calculating fission observables (spectra and multiplicities of prompt neutrons and gammas; energy release; and fission product yields...), is a useful tool for nuclear reactor applications as well as for investigating correlations between fission observables in order to improve our understanding of the fission process. A typical FIFRELIN calculation is performed in two steps:

Step 1: determination of the two pre-neutron fission fragment characteristics (mass, nuclear charge, kinetic energy, excitation energy and spin-parity);

Step 2: simulation of the de-excitation of each fission fragment by prompt particle emission (neutrons, gamma and electrons).

These two steps were briefly discussed and all the models that can be chosen by the user were described. Three examples of the capabilities of FIFRELIN were then discussed.

- The first example is related to the post-neutron mass yields from the ^{239}Pu(n_{th},f) reaction. Here, we compare two different FIFRELIN calculations. The difference between both calculations comes from the way the characteristics of the pre-neutron fission fragments are determined (Step 1): for the first calculation (called FIFRELIN/Dematté), we used the Demattë's experimental data, while for the second one (called FIFRELIN/GEF), pre-neutron characteristics were provided by the GEF code. Both calculations show relatively good agreement with the recent experimental data obtained from the Lohengrin recoil mass spectrometer and emphasize the impact of the pre-neutron mass yields on the calculated post-neutron mass yields. We also showed the isotopic fission yields extracted from the FIFRELIN/Dematté calculation that still must be compared with experimental data. From a pragmatic point of view, when no pre-neutron experimental data are available, we believe that the combination between the GEF code (for Step 1) with the FIFRELIN code (for Step 2) can be useful for future FY evaluations (especially for fast neutron-induced reactions).
- Example two was dedicated to the branching ratio of the thermal-neutron capture reaction on ^{151}Eu. Here, we show the impact of several models available in FIFRELIN on the gamma cascade simulation. We noted that we could nicely reproduce the experimental data and observed that the calculated branching ratio is much more sensitive to the level density than to the γ-strength function.
- The third example concerned the determination of the fission product spin (after prompt neutron emission) from the isomeric ratio measured by our group on ^{132}Sn. The procedure of the spin extraction was described and then compared with the GEF and Madland-England models. Strong disagreements between these models are shown. The construction of an isomeric ratio database should be very useful in order to test and validate our models.

Lastly, we mention some evolutions planned employing FIFRELIN in the near future. In particular, we will develop the capability to perform cumulative fission yields (via the Q-matrix) and calculate the average delayed neutron multiplicity which can aid in the validation of fission yield evaluations.

2.15 Energy-Dependent Fission Product Yields: Modelling and Evaluation

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We first summarized a multi-laboratory effort in the US to produce a new ENDF fission product yield (FPY) data library involving LANL, BNL, PNNL, LBNL, and LLNL. The main objective is to evaluate the energy dependence of the FPY data, in contrast to current libraries which include only a few energy points. LANL leads the FPY theoretical modeling and data evaluation efforts. Some preliminary studies of energy-dependent FPY calculations were reported in collaboration with IAEA [13].

The LANL FPY model consists of four stages;

(a) the Hauser-Feshbach (HF) model for the fissioning actinides,

(b) HF decay of the fission fragments,

(c) beta-decay of prompt fission products, and

(d) optimization of model parameters.

The first stage is carried out using the LANL HF code CoH3, which gives the fission probabilities for each multi-chance fission contribution. The code also provides the pre-fission neutron spectrum along with its average energy, and the distribution of excitation energies of the compound nucleus prior to fission. These quantities are some of the inputs to the HF fission fragment decay process [14], followed by the cumulative FPY calculation. This model performs a detailed numerical integration over the excitation energy, spin, parity, primary fission yields, etc. distributions without requiring Monte Carlo sampling. A deterministic approach is particularly suited for FPY evaluations since some of the fission yields are extremely small. The LANL FPY model produces all the fission observable simultaneously, facilitating adjustment of the model parameters. Many different types of experimental data are employed to fit a limited number of model parameters.

We demonstrated an application of the Bayesian technique for parameter optimization in calculations of ^{235}U($n_{\rm th}$,f) and showed that modest adjustments of the parameters indeed improve the reproduction of the cumulative FPY data, as well as the prompt and delayed neutron multiplicities. By introducing energy-dependent model parameters, together with the multi-chance fission data, the calculated cumulative FPYs are extrapolated to higher energies. The calculated results agree very well with the experimentally measured energy-dependent FPY data below 10 MeV, as well as the LANL radiochemistry data in the fast energy range. LANL and IAEA are extending these calculations to complete the new FPY data evaluation.

2.16 Microscopic determination of fission fragment distributions

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The determination of the fission properties is of particular importance in a large number of nuclear applications. Most of the existing theoretical analyses of the fission fragment distribution rely on empirical or phenomenological models essentially fitted to experimental data. Although such adjustments respond to the high accuracy needs of some nuclear applications, their predictive power remains poor due to the large number of free parameters and often nonphysical approximations considered. It is now possible to use the microscopic quantum mechanical approach starting from the sole Gogny or Skyrme effective nucleon-nucleon interaction as input to model the fission process. Recently, a fully quantum mechanical model has been proposed to describe the nuclear dynamics. It is known as the time-dependent generator coordinate method (TD-GCM) with the Gaussian overlap approximation [15, 16, 17] and has been succesfully applied to the calculation of fission yields in the actinide region as well as proton-rich thorium. It has also been shown to robustly predict the symmetric/asymmetric yield transition in the neutron-rich Fm isotopes [17]. In this approach, the static properties of the system are obtained by a standard Hartree-Fock-Bogolyubov (HFB) calculation with the effective Gogny interaction. The collective Schrödinger-like equation of the TD-GCM can then be solved to obtain the fission fragment yields [18, 19]. This highly sophisticated method has only been applied so far to a few even-even systems and represents the most promising microscopic method to provide fission yields and corresponding total kinetic energies.

An improved static and statistical scission-point model called the Scission Point Yield (SPY) model has also been recently proposed [20, 21]. This model assumes thermodynamic equilibrium at scission, neglecting the evolution between the saddle and the scission point. The model is based on two pillars, namely the absolute available energy balance at the scission configuration and the statistical description of the phase space available. An upgraded version of the SPY model has been published recently [22]. It extracts all the information that can be defined at the scission point such as the potential enegy surfaces of the fission fragments, their charge densities and microcanonical probabilities excited, on the basis of state-of-the art ingredients derived from a mean-field model. This approach does not have any free parameters and has proven its capacity to predict rather well known fission fragment mass and charge distributions [22] as well as new behaviours like the unexpected asymmetric fission of the light nucleus ^{180}Hg which is consistent with the predicted transition between the symmetric fission of ^{198}Hg and the asymmetric fission of ^{180}Hg [21]. Though this approach is essentially static in nature, it has proven its predictive power and can easily be applied systematically to a large set of fissioning systems with even or odd numbers of nucleons. The present research project will consist in

1. providing fission fragment distributions employing TD-GCM [16, 17] for the nuclei of special interest in the present CRP, namely ^{235,238}U, ^{239,241}Pu and ^{252}Cf. Systematic HFB calculations of potential energy surfaces will be performed with the D1M finite-range Gogny interaction. As soon as such energy surfaces are available, it will be possible to make a microscopic analysis of the collective dynamics through a study of the time evolution of the compound system on the basis of the TD-GCM approach using the FELIX code [18, 19].

2. providing fission fragment distributions systematically for all fissioning systems of rel-

evance to nuclear applications on the basis of the SPY model [22]. This objective will require the upgrade of the SPY model in two directions. First, consider all nuclear ingredients obtained by the Gogny-HFB mean-field model with the D1M interaction and second, extend the deformation space towards the octupole deformations of fission fragments for a detailed account of the entire configuration space.

2.17 FREYA Capabilities

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This talk is meant to show how the complete fission model FREYA [23] can be used as part of a FPY evaluation effort. It shows how FREYA can be used to study sensitivity of results to various inputs, including the minimal FREYA input parameters, the variation of prompt fission fragment yields, changes in TKE(A$_H$), and the variation of all input distributions $Y(A, Z,\text{TKE})$. Indeed for the purposes of neutron and photon observables, the uncertainty in TKE has a larger effect on e.g. the average neutron multiplicity than $Y(A)$ alone. Thus, for effective modeling of the fission product yields, knowledge of the distribution of energy in fission is at least as important, if not more so, than the input fragment yields themselves. The cumulative yields follow on from those independent fission product yields.

The first part of the talk gives a brief overview of the fission physics in FREYA. It is noted that FREYA was meant to be a fast code to be adopted into transport models. Many events can be simulated quickly. FREYA keeps track of the energy, linear and angular momentum of fragments, emitted neutrons and emitted photons. Energy, momentum, angular momentum, mass and charge are conserved at each step. FREYA can do neutron-induced fission for incident neutrons of up to 20 MeV and spontaneous fission for select actinide isotopes. Based on the compound nucleus and excitation energy, photofission and other types of fission, e.g. (d,p), can also be studied.

FREYA takes $Y(A)$ of fission fragments, TKE(A_H) as inputs. $Y(Z)$ is determind from the unchanged charge distributiono and the width of the TKE distribution is determined by thermal fluctuations in the excitation energy. (Energy is conserved by removing the thermal flucutations from the total kinetic energy.) FREYA allows for pre-equilibrium neutron emission and multi-chance fission for neutron-induced fission. After mass and charge are selected, the fission Q value is obtained, the TKE is sampled from the TKE(A_H) distribution and the total excitaiton energy is obtained. This TXE is divided between the two fragments, first based on level densities, then modified by a parameter x to give more energy to the light fragment. (This x is similar to the R_T parameter in FIFRELIN and CGMF when they use a fixed value – the $\nu(A)$ obtained is quite similar. It is also possible to manufacture an A dependent x, like their $R_T(A)$, as done in the study of $Y(A, Z,\text{TKE})$, but this is not broadly done in FREYA.) Note that x has a strong influence on $\nu(A)$ – another observable strongly dependent on x are neutron-neutron correlations and, if these have been measured but $\nu(A)$ has not, it is possible to use this observable to extract x. As already mentioned, thermal fluctuations are introduced to modify the excitation energy. These are included in the c parameter, which strongly affects $P(\nu)$ and the multiplicity moments but not other observables. The excitation energy for a given fragment is split between rotational and intrinsic. The x parameter is related to the intrinsic excitation. The rotational energy primarily affects photon emission. The amount of spin (angular momentum) is controlled by the parameter c_S which multiplies the scission temperature. This parameter primarily affects photon observables. There are two other parameters, e_0, the asymptotic level density parameter, $a_i = A_i/e_0$, and dTKE which is used to tune the total kinetic energy to reproduce the average neutron multiplicity. While certain parameters most distinctly affect specific observables, we note that e_0 and dTKE only indirectly affect observables. All parameters have some effect on the prompt fission neutron spectrum and on the neutron multiplicity. In addition, there are external, detector-related parameters, $g_{\rm min}$ and $t_{\rm max}$ that refer to the minimum measured photon energy and total measurement time respectively. FREYA uses Weisskopf-Ewing spectra for neutron emission, the GDR dominates statistical photon emission and the RIPL-3 lines are included to account for low energy photon emission.

After the fission physics in FREYA is introduced, the sensitivity of observables to variations in c, x and e_0 are shown for ^{252}Cf(sf), particularly for $\nu(A)$ and $P(\nu)$ as well as the neutron multiplicity moments. An unrealistically large range of parameter values is employed to show the level of effects. The sensitivity of the variants in the first moment is shown for all three parameters as well.

The next part of the talk shows the sensitivity of FREYA results to various changes in the inputs. First a global fit to the parameters for spontaneous fission is briefly discussed and results given for all spontaneously fissioning actinides included in FREYA. It is clear that e_0, x and c_S do not change significantly from one isotope to another. The c parameter is strongly dependent on the neutron multiplicity distribution. For ^{238}U(sf), $c < 1$ because $\overline{\nu}$ is small and $P(\nu)$ is narrow and sharply peaked. It is 2-3 for ^{238,240,242}Pu(sf) where $\overline{\nu}$ is around 2 but $P(\nu)$ is fairly wide. For isotopes with larger multiplicity, ^{244}Cm(sf) and ^{252}Cf(sf), it is a bit larger than unity. The value of dTKE is typically negative to adjust to fit $\overline{\nu}$, some of the TKE(A_H) distributions used as input either have no uncertainties given or have very low statistics which could lead to poorer input distributions, requiring some adjustment. The exception is ^{252}Cf(sf) where dTKE is small and positive. Uncertainties on neutron observables based on a variation of all five parameters are shown [24].

Some results are shown for exchanging the input $Y(A)$ for ^{239}Pu($n_{\rm th}$,f) based on microscopic calculations by Nicolas Schunck and collaborators. The TKE(A_H) remains the same. Although the yields differ substantially, almost no change in the PFNS, $\nu(A)$ and $\nu({\rm TKE})$ are visible to the naked eye. The exception is $\nu({\rm TKE})$ at low TKE where the result with the higher yield at symmetry gives more weight to the second valley in the potential energy surface, resulting in a larger contribution to low TKE, where there is also then lower overall excitation (lower Q value) and thus lower neutron emission at low TKE.

A study was also made with a variation of TKE(A_H). Patrick Talou generated 1000 TKE(A_H) distributions which were fed into FREYA while keeping $Y(A)$ fixed. Larger variations in the neutron observables were seen than from much larger relative changes in $Y(A)$, as seen before. In particular, changing the average TKE within the measured uncertainties gave a huge variation in the average neutron multiplicity $\overline{\nu}$.

The results of this preliminary study prompted us to generate an ensemble of 15,000 yield functions, $Y(A, Z, {\rm TKE})$ in ^{252}Cf(sf) based on available data on $Y(A)$, TKE(A_H) and σ(TKE). (Since σ(TKE) was used as input, there was no c parameter and the thermal fluctuations were replaced by the given σ(TKE).) Only small changes in the neutron observables could be seen over all 15,000 yield functions. Strong correlations betweek the average TKE and $\overline{\nu}$ were observed: larger average TKE increases average neutron multiplicity. On the other hand, increasing σ(TKE) also increases the dispersion on $\overline{\nu}$. To try and limit the resulting $\overline{\nu}$ dispersion closer to the measured (evaluated) value, a biased weight was introduced. The experimental variance on nubar reduces the TKE width to 17.2% of the value from the data. The evaluated $\sigma(\overline{\nu})$ is close to the minimum calculated width of the biased TKE distribution [25].

The last part of the talk describes how FREYA is being used with FPY evaluations. It is clear from what has already been shown that FREYA can quickly explore sensitivity of results such as FPYs to calculated or evaluated fission fragment yields. To reduce its reliance on a measured TKE(A_H) distribution, FREYA can also be refactored to test empirical formulations or theoretical calculations of the fragment excitation energy in density functional theory or other approaches. The FIER code data on β decay [26] has been introduced in FREYA, allowing calculations of the cumulative fission yields.

FREYA could also be used, with the beta decay information, where available, to study the energy spectrum of antineutrino emission. What is notable is the sensitivity to the input energy, either TKE or, turning it around TXE, which produces a larger variation of observables than $Y(A)$ alone.

2.18 ^{235}U($n_{\rm th}$,f) Fission Yield evaluation: status and perspectives

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The study of fission yields has a major impact on the characterization and understanding of the fission process and is mandatory for reactor applications. The mass and isotopic yields of the fission products have a direct influence on the predictions of fuel burn-up and decay heat. Moreover, these data are required for other studies such as delayed neutron evaluations, antineutrino flux assessments and reactor programs. Currently, the lack of covariance matrices associated with evaluated fission yields leads to an overestimate of the uncertainties on the mass yields because these uncertainties are determined from the sum of the uncertainties associated with the isotopic and isomeric yields.

Our collaboration starts a new program in the field of the evaluation of fission products in addition to the current experimental program. The goal is to define a new methodology of evaluation based on statistical tests in order to provide the best estimate based on consistent sets of measurements. Results on pure experimental mass yield evaluations were presented at this meeting. A ranking of solutions with associated correlations based on Shannon's entropy criterion is proposed for the mass yields from ^{235}U($n_{\rm th}$,f). Of all solutions, the maximum of Shannon's entropy corresponds to the minimum of variances and correlations values. This result is consistent with the Cramer-Rao theorem, which fixes the limits on minimal variances as the maximum of Fischer's information. Shannon's entropy corresponds to another quantification of information of the analysis and we expect that the optimal solution corresponds to the minimum of variance-covariance and the maximum of information. In this method, a complete evaluation (values, variances, and correlations) is produced consistently.

The second step corresponds to the evaluation of the variance-covariance matrix for isotopic yields. Based on the JEFF3.1.1 evaluation, for example, we have deduced the charge distribution $(P(Z|A)$. Coupling this charge distribution to our evaluation of the mass yields, $Y(A)$, we obtain a solution of $Y(A,Z)$, the isotopic yield evaluation, which is consistent with our evaluated mass yield uncertainties of $\sim$1–2%. Solutions with different variance-covariance matrices exist and can be proposed based on conservation laws. Nevertheless, the correct result has to be consistent over all stages of the analysis and for all fission yield observables.

In this work, consideration of experimental data is crucial for defining the mass yield evaluation, its uncertainties and correlations. The lack of experimental covariance information could result in an underestimate of the evaluated mass yields uncertainties The lack of correlations in the data limits the knowledge provided by a data set. This work aims to build an a priori experimental correlation matrix to fill gaps in the analysis and propagate the matrix to the complete evaluation.

Proposal: ^{233}U, ^{235}U, ^{239}Pu, ^{241}Pu($n_{\rm th}$,f) mass, isotopic and isomeric yields evaluations.

2.19 Bayesian Monte Carlo for FY evaluation with GEF: example and plan

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Paul Scherrer Institut (PSI), Switzerland

In this presentation the basis of the Bayesian Monte Carlo method are succinctly explained. In our case, the method is applied employing the GEF code, for which a number of model parameters are randomly varied (in the first iteration). The resulting random fission yields (independent and cumulative) are compared with a selection of evaluated yields (from ENDF/B-VIII.0, but the same method can be applied to EXFOR yields) and weights are calculated based on the agreement between the calculated random yields and the evaluated ones. A weight is calculated for each random yield. Based on the weight distribution, the second iteration is started, using the (updated) weighted model parameter distributions. This is repeated until convergence of the parameter distributions is achieved. An example is presented in for the case of ^{235}U thermal neutron-induced fission.

For the CRP, we are planning to apply this method to neutron-induced reactions on a selection of actinides. One possibility is a chain of Cm isotopes.

2.20 Evaluation of FPY and associated covariance data

S. Chiba
Laboratory for Advanced Nuclear Energy (LANE), Tokyo Institute of Technology, Japan

In Japan, fission product yield (FPY) data have not been evaluated before. Instead, the data were imported from ENDF and some corrections were applied.

In this work, we report Japan's first attempt to populate evaluated FPYs and associated covariance data. to do this, we have excavated the experimental data in EXFOR. There are ample data but, due to complexity of the fission process, the data are quite complex and sometimes independent and cumulative yields are misassigned. We have made a careful categorization of the data. However, we still could not achieve as precise an evaluation of the mass chain yields as that obtained in historic work such as England & Rider, Wahl, and Mills. We therefore adopted the mass chain yield and uncertainties from England and Rider.

We instead placed our emphasis on determining the Z distribution, introducing a new form of the odd-even correction with branching ratios calculated in Hauser-Feshbach theory. Finally, we considered five obvious physical constraints, such as conservation of mass and charge, and applied the generalized least-squares method to obtain the final FPY values and associated covariance matrices.

We verified the new FPY evaluation against decay heat, delayed neutron yield, PIE and aggregate electron and antineutrino spectra. The evaluation procedure is explained in recent publication [27]. The table below shows the list of nuclei for which we have obtained new FPYs and their associated covariance matrices.

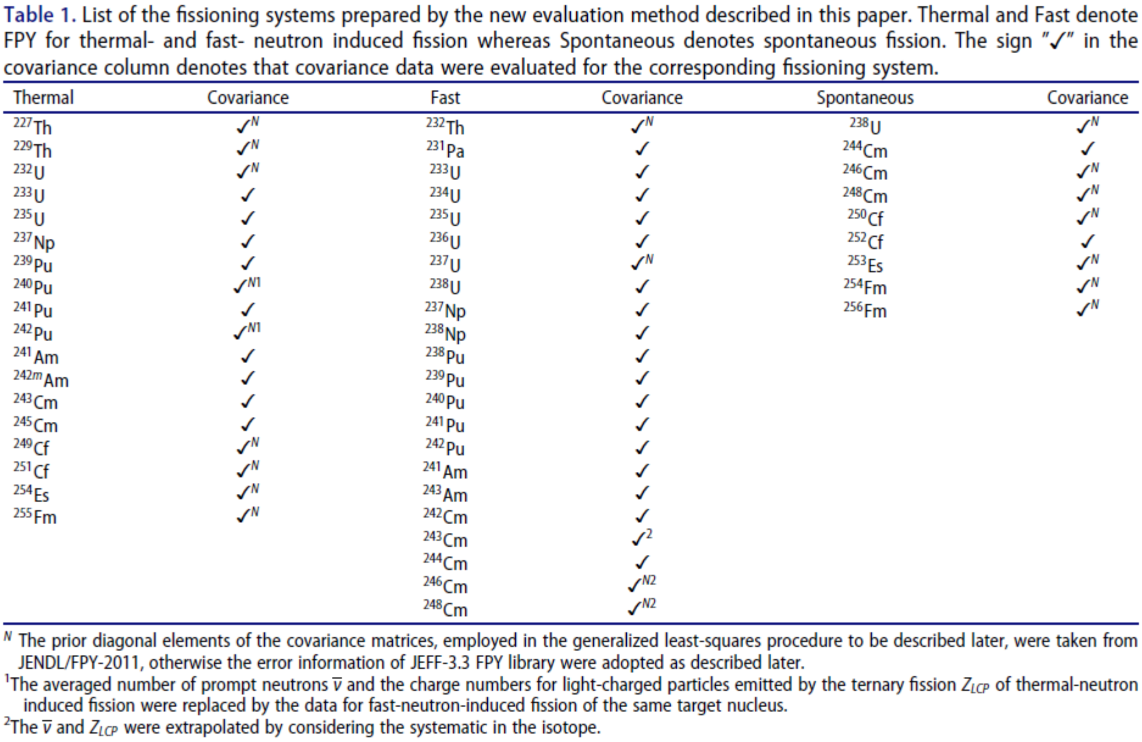

Table 1. List of the fissioning systems prepared by the new evaluation method described in this paper. Thermal and Fast denote FPY for thermal- and fast- neutron induced fission whereas Spontaneous denotes spontaneous fission. The sign "✓" in the covariance column denotes that covariance data were evaluated for the corresponding fissioning system.

Thermal	Covariance	Fast	Covariance	Spontaneous	Covariance
^{227}Th	✓^{N}	^{232}Th	✓^{N}	^{238}U	✓^{N}
^{229}Th	✓^{N}	^{231}Pa	✓	^{244}Cm	✓
^{232}U	✓^{N}	^{233}U	✓	^{246}Cm	✓^{N}
^{233}U	✓	^{234}U	✓	^{248}Cm	✓^{N}
^{235}U	✓	^{235}U	✓	^{250}Cf	✓^{N}
^{237}Np	✓	^{236}U	✓	^{252}Cf	✓
^{239}Pu	✓	^{237}U	✓^{N}	^{253}Es	✓^{N}
^{240}Pu	✓^{N1}	^{238}U	✓	^{254}Fm	✓^{N}
^{241}Pu	✓	^{237}Np	✓	^{256}Fm	✓^{N}
^{242}Pu	✓^{N1}	^{238}Np	✓		
^{241}Am	✓	^{238}Pu	✓		
^{242m}Am	✓	^{239}Pu	✓		
^{243}Cm	✓	^{240}Pu	✓		
^{245}Cm	✓	^{241}Pu	✓		
^{249}Cf	✓^{N}	^{242}Pu	✓		
^{251}Cf	✓^{N}	^{241}Am	✓		
^{254}Es	✓^{N}	^{243}Am	✓		
^{255}Fm	✓^{N}	^{242}Cm	✓		
		^{243}Cm	✓^{2}		
		^{244}Cm	✓		
		^{246}Cm	✓^{N2}		
		^{248}Cm	✓^{N2}		

[N] The prior diagonal elements of the covariance matrices, employed in the generalized least-squares procedure to be described later, were taken from JENDL/FPY-2011, otherwise the error information of JEFF-3.3 FPY library were adopted as described later.

[1] The averaged number of prompt neutrons $\overline{\nu}$ and the charge numbers for light-charged particles emitted by the ternary fission Z_{LCP} of thermal-neutron induced fission were replaced by the data for fast-neutron-induced fission of the same target nucleus.

[2] The $\overline{\nu}$ and Z_{LCP} were extrapolated by considering the systematic in the isotope.

2.21 Present status and perspectives of JENDL Fission Product Yield data

F. Minato
Nuclear Data Center, Japan Atomic Energy Agency, Japan

The present status and future perspectives of fission product yield (FPY) evaluations by the JENDL group was presented. So far, two evaluated FPY data libraries were released by the JENDL group. The first is the JENDL-4.0 Fission Yield Sub-library released in 2010 [28]. Soon after its release, the JENDL Fission Product Yield 2011 (JENDL/FPY-2011) [29] library was published. Both evaluated data sets are based on the ENDF/B-VII FPY data [30]. However, some corrections are included in order to be consistent with the evaluated decay data of JENDL/FPD-2000 and JENDL/FPD-2011, respectively. In 2017, fission fragment yields of ^{86}Ge, ^{88}As, ^{100}Rb, and ^{131}Cd from thermal neutron-induced fission of ^{235}U were corrected [31] because of their anomalously large yields compared to those of neighboring fission products. Now we are developing the third evaluated FPY data set for JENDL5, to be released in 2022.

We have a project to evaluate FPYs in parallel with JENDL5 FPY data through the CRP. In the project, we pay attention to experimental data not only of the fission yields themselves but also of fission gamma and neutron data. Up-to-date regression analysis based on Bayesian approaches will be adopted for parameter optimization in nuclear models. In this talk, one of the examples using Bayesian optimization was presented. Optionally, we plan to study FPYs beyond thermal, fast, and 14 MeV neutron energies through this CRP.

We have developed the CCONE code [32], used for nuclear data evaluation in JENDL for the FPY evaluations. CCONE is able to calculate physical quantities resulting from fission, such as prompt fission gamma and neutron emission, which will be important for a consistent and systematic evaluation of fission yields. Determination of parameters of phenomenological models used to calculate optical models, fission barriers, statistical models, and the 5-Gaussian model of fission yields, etc., will be a key component of this study. We need to appropriately choose which parameter should be determined from which observables. We also plan to include physical insights obtained from Langevin models through collaboration with Tokyo Institute of Technology. This collaborative effort will reduce shortcomings of the phenomenological methods used in CCONE.

We will contribute to the CRP by sharing information about our evaluation method with the CRP participants.

2.22 Fission yield studies at CNDC

S. Nengchuan
China Institute of Atomic Energy (CIAE), China
China Nuclear Data Center (CNDC), China

Since CENDL-2/FPY was released in 1987, many studies have been made of the fission yields from ^{235,238}U(n,f) and ^{239}Pu(n,f) at the CNDC, including measurements of cumulative yields via the direct gamma method; yield evaluations with Wahl systematics, and developing semi-empirical models using the multi-modal random neck rupture model. Presently, the main efforts are focused on theoretical studies with tje Langevin approach and independent fission yield measurements.

A three-dimensional Langevin model, including a constraint on the heavy fragment deformation, is used to study fission dynamics of uranium and plutonium isotopes at low excitation energies. The potential energy surface is calculated with the macroscopic-microscopic model based on the two-center shell model. The calculated fission fragment mass distributions (FFMDs) are close to the data from ENDF/B-VIII.0 and calculations using GEF, as shown in Fig. 3. This model is very promising since it involves only a few parameters.

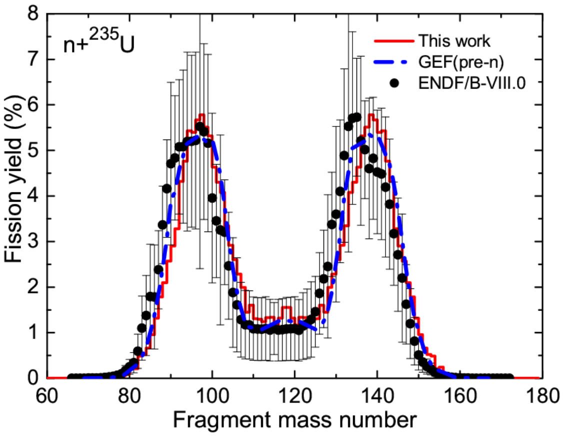

Figure 3: The calculated mass distribution of n(14MeV)+^{235}U fission compared to GEF calculation and ENDF/B-VIII.0.

On the experimental side, the Energy-Velocity-X-ray coincidence methodology is adopted to measure the independent yields. The energy–Velocity coincidence method gives a mass resolution of 0.6% a.m.u for light fragments. Using fragment-X-ray coincidences, the fragment charge could be deduced from the measured $Y(Z|A)$ distribution. A test measurement has been performed for ^{252}Cf spontaneous fission. The results are quite satisfying, as shown in Fig. 4 and Fig. 5

During this CRP, yields from ^{235}U(n,f) and ^{239}Pu(n,f) will be studied. We will continue to improve the Langevin model and expect it could produce results applicable to studies of the trends of the energy-dependent yields. Experiments will be carried out, with results available by the end of 2022, for incident neutron energies of thermal and 14 MeV. Fission yield evaluation work will also be concurrently performed based on experimental data, using models or codes like GEF. Model parameters will be optimized using the least-square fitting method. The yields and covariances could also be calculated.

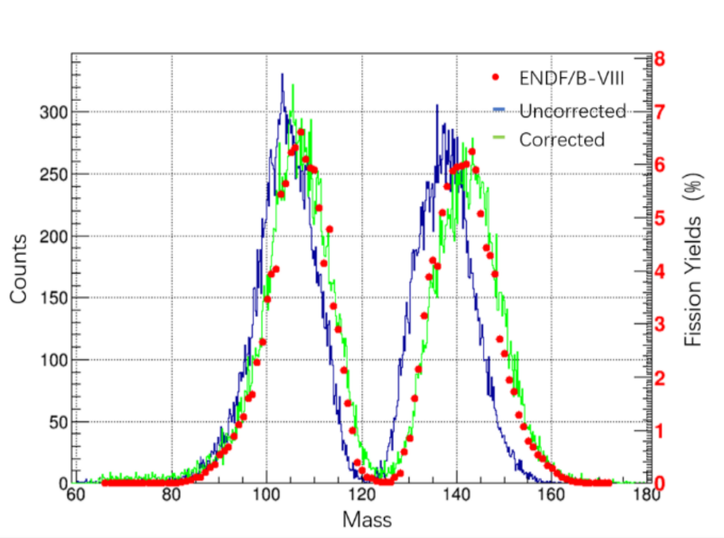

Figure 4: Measured ^{252}Cf(sf) fragment mass distribution compared with evaluated data from ENDF/B-VIII. The green and blue lines are the yields with and without energy loss corrections, respectively.

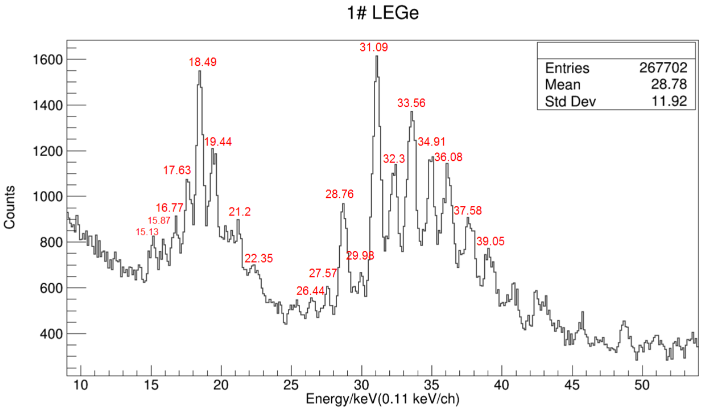

Figure 5: The measured energy spectrum. The peak position and area correspond to the charge number (in red) and the independent fission yields respectively.

2.23 A re-evaluation of the energy released in fission that is converted into heat in a nuclear reactor

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Because fission yields form a highly correlated set of random variables, uncertainty quantification of observables that use fission yield input can be particularly complex. There are two such cases in nuclear reactor antineutrino research, the inverse beta decay (IBD) antineutrino yield, and the energy release in fission that is eventually converted into heat. These two cases are related because the energy release requires knowing the energy carried away by antineutrinos, the first moment of the antineutrino spectrum.

The correlations among independent fission yields arise from physics constraints, such as conservation of mass and charge as well as competing fission modes, in conjunction with measurement techniques. In the case of cumulative yields, additional correlations arise from the topology of the decay network formed by the fission products. Evaluated yields have additional correlations arising from the particular procedure used to produce recommended fission yield values. Unfortunately, we currently do not have correlation matrices in ENDF/B, JEFF, or JENDL yields. Thus our solution has been to use the GEF code to obtain independent fission yield correlations.

We have applied these correlations to the above-mentioned cases and obtained what we considered to be improved uncertainty estimates. We also observed a few issues with previous calculations as well as with current evaluated libraries. Some concerns have emerged when looking into future evaluated fission yield libraries, for example, can the evaluated uncertainties be smaller than the lowest uncertainty achievable experimentally? Also, if correlation matrices are included, a document describing the benchmark of these matrices should be produced.

2.24 Checking, Processing & Verification, Benchmarking & Validation of Fission Yields data

O. Cabellos
Universidad Politécnica de Madrid (UPM), Spain

This presentation summarizes Processing & Verification (P&V) and Benchmarking & Validations (B&V) activities for evaluated fission yield files.

First, P&V activities are introduced. For some specific codes, such as the ACAB code, processing evaluated FYs into a completely different format is needed. This P&V is performed for both nominal values and their uncertainties. Another important P&V issue is the consistency between decay data and fission yield evaluations through the Q-matrix, used to transform independent FYs (IFYs) to cumulative FYs (CFYs).

A comparison between evaluated and raw data from different EXFOR compilations may play an important role in checking and verification of evaluated FYs. Such a comparison can identify potential outliers and/or errors.

B&V activities were also presented. This process should be automated by employing different tools/scripts to quickly assess new evaluations. A repository with different types of benchmarks would be valuable to enlarge the scope of validation to different applications such as decay heat, waste management, burnup credit, and delayed neutron emission. This repository should contain “models” and inputs which allow reproducibility, traceability, and transparency of results.

Data for B&V applications have been collected through two international projects: SFCOMPO-2.0: Database of measured isotopic concentrations of spent nuclear fuel, with operational histories and design data (NEA/NSC), and CoNDERC: Compilation of Nuclear Data Experiments for Radiation Characterisation (IAEA/NDS). The compilation of integral benchmark experimental data into a standardized format will make these data easy to incorporated into tests of FY evaluations.

Integral benchmark experiments were presented to provide a global overview of the FY performance for different applications: depletion calculations in PWR/BWR reactors; fission pulse decay heat (FPDH); and fission pulse delayed neutron emission (FPDN). Activation and/or depletion codes are used with different evaluations of IFY in these calculations. The resulting C/E values show general good agreement with current FY evaluations.

Finally, a Sensitivity & Uncertainty (S&U) analysis was presented to examine the overall effects of nuclear data uncertainties. The impact of fission yield uncertainties is highlighted in criticality, decay heat and isotopic inventory (e.g. burnup indicators). The large impact of cross correlations in these applications was emphasized, highlighting the necessity to provide such correlations in future FY evaluations.

2.25 Approaches for validation CY databases using delayed neutron macroscopic characteristics

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State Scientific Center of Russian Federation Institute of Physics and Power Engineering,
Obninsk, Russia

This presentation describes the approaches used in the IPPE to validate fission product yield data using summation calculations and experimental delayed neutron (DN) data. The IPPE has great experience in measurements of macroscopic delayed neutron data such as ν_d, the total DN yield; $\langle T \rangle$, the average half life of DN precursors based on the relative abundances a_i and half lives $T_{1/2}$ of separate DN groups. The newly-introduced quantity $\langle T \rangle$ has shown itself to be a very reliable macroscopic DN parameter for comparing different DN data sets. The present validation approaches are based on the comparison of the macroscopic DN data, ν_d and $\langle T \rangle$, obtained with the help of summation techniques using the microscopic DN data (P_n, $T_{1/2}$ of the individual precursors) and cumulative yields (CY) from data libraries (ENDF/B, JENDL, JEFF, ROSFOND) with the appropriate recommended macroscopic DN data.

The first approach for validation of the cumulative yields (CY) data is related to the CY data from the ENDF/B-VII.1, JENDL-4.0, JEFF-3.1.1 and ROSFOND-2010 databases and CY data from Wahl calculation. In these databases the CY data are presented only for the thermal, fast (0.5 MeV) and 14 MeV neutron-induced fission. We have considered the data for thermal and fast neutron-induced fission of 5 fissioning systems (^{235}U(n_th,f), ^{238}U(n,f), and ^{239}Pu(n_th,f)). To calculate ν_d and $\langle T \rangle$, ϕ and $T_{1/2\,i}$ four different data sets have been used (Wilson & England, 2002; Pfieffer, Kratz, and Moller, 2002; Rudstam et al, 1993; IAEA – Abriola et al., 2013). Comparison of the calculated values of ν_d and $\langle T \rangle$ with the recommended ones helps identify the best CY database. We concluded that JEFF-3.1.1 has the best CY dataset.

The second approach is focused on validation of the energy dependence of the CY data, employing simulations over a wide range of energies. We performed an experiment that obtained temporal delayed neutron data on a_i and T_i from fission of ^{235}U(n,f) for incident neutrons of energies from thermal to 8 MeV. These data could be used as a benchmark data set to validate CY data sets in different codes. In particular, these data were used to validate CYs from the GEF code. Comparative analysis shows that the $\langle T \rangle$ values obtained using CYs from GEF with data (P_n and $T_{1/2}$ for 368 precursors) from the IAEA Beta-Delayed Neutron CRP (2016-2019) agrees rather well with our data for thermal neutrons up to 1 MeV but differs significantly for $1 < E_n < 8$ MeV. We note that the values of $\langle T \rangle$ from the GEF CYs increases above 5 MeV while our data increases at 6 MeV. This increase is consistent with the energy dependence of the fission cross section and is related to the onset of second chance fission, (n, n',f). Thus, based on our data for $\langle T(E_n) \rangle$, the GEF ^{235}U CYs are underestimated. We noted that the experimental energy dependence of $\langle T \rangle$ makes it possible to determine the structure of the fission cross section across the second chance fission threshold, important to evaluate the fission product yields for energies above the second chance fission threshold.

We are planning to extend our DN experiments to other fissile nuclei such as ^{238}U, ^{239}Pu, ^{233}U for incident neutron energies up to 8 MeV. These results will help improve models of the FPYs.

2.26 Fission Yield Applications at ETRR-2

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Atomic Energy Authority (AEA), Egypt

Fission product yields are required at several stages of the nuclear fuel cycle and the reliability of related calculations depends on the accuracy of fission yield data. At Egypt's second research reactor (ETRR-2) three codes are used for neutronics calculations: WIMS-5B and CITVAP, based on the 1986 WIMS-69 group library, and MCNPX 2.7.0, based on the ENDF/B-VII.0 library. These codes are used for fuel management, evaluation of spent fuel issues and other neutronics calculations. Recently, ETRR-2 participated in the CRP "Benchmarks of Computational Tools against Experimental Data on Fuel Burnup and Material Activation for Utilization, Operation and Safety Analysis of Research Reactors" to evolve the accuracy of these codes. ETRR-2 produces ^{99}Mo and ^{131}I radioisotopes in fission. At ETRR-2, these fission products are used in measurements of fuel burnup, detection of fuel failure, and nuclear materials safeguards. The applications of fission products at ETRR-2 are based on the nuclear data for neutron energies from thermal to 20 MeV.

Our participation in the CRP has four main aims:

1. To evaluate the accuracy of the available fission yield data by simulating a series of benchmarks in the areas of nuclear reactor calculations and spent fuel evaluations. Different data libraries, such as ENDF/B-VIII.0 and JEFF-3.3, will be considered.
2. To work with CRP participants to produce a recommended set of fission yield data.
3. To take part in the validation of the CRP-recommended fission yield data files against a series of benchmarks.
4. To update the data libraries used in the neutronic calculations at the ETRR-2 research reactor.

2.27 Influence of fragment distributions $Y(A$,TKE) on PbP model results

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The primary results of both the deterministic prompt emission PbP model [33, 34] and a model treating sequential emission [33, 35] are multi-parametric matrices (as functions of the A, Z and TKE of the initial/pre-neutron emission fragments) of different prompt emission quantities (e.g. $\nu(A, Z$,TKE), $E_\gamma(A, Z$,TKE), $\langle\epsilon\rangle(A, Z$,TKE)) generically labeled $q(A, Z$,TKE) (in the case of PbP) and $q_k(A, Z$,TKE) (in the case of sequential emission with k denoting the emission sequence). The very good agreement of such matrices with the existing experimental data constitutes the validation of the prompt emission model itself (see e.g. Refs. [33, 36] for ^{235}U($n_{\rm th}$,f)). Single distributions of different prompt emission quantities such as $q(A)$, q(TKE) and total averages $\langle q\rangle$ are obtained by averaging the primary results of these models over the fission fragment distributions $Y(A$,TKE). The good agreement of such single distributions (e.g. $\nu(A)$, ν(TKE), $\langle\epsilon\rangle(A)$, $\langle\epsilon\rangle$(TKE), $E_\gamma(A)$, E_γ(TKE)) and total average quantities (e.g. $\langle\nu\rangle$, $\langle E_\gamma\rangle$, prompt neutron and γ-ray spectra) with the experimental data constitutes a secondary validation of the prompt emission model, together with the $Y(A$,TKE) distribution.

In order to illustrate how the differences between different $Y(A$,TKE) distributions are reflected in the model results of different prompt emission quantities an exercise is presented in which the primary results of the PbP for ^{235}U($n_{\rm th}$,f) (already validated, see Refs. [33, 35]) are averaged over three experimental $Y(A$,TKE) distributions measured at JRC-Geel by Al-Adili et al. [37], Straede et al.[38], Göök et al.[39] and a calculated distribution from GEF [10]. The comparison of these four distributions showed significant differences in TKE(A), $\sim 10\%$ at lower TKE values, in $Y(A)$ near symmetry and very asymmetric splits, and a shift of Y(TKE) of Ref.[39] compared to other Y(TKE) data. The ν(TKE) results based on the input yields $Y(A$,TKE) are close to each other and describe the experimental data very well. The $\nu(A)$ results exhibit similar sawtooth shapes (based on the same TXE partition of PbP) and are in overall good agreement with the data. ν(A) based on the distributions of Refs. [37, 38] are close to each other over the entire A range but significant differences between $\nu(A)$ based on the $Y(A$,TKE) distributions of Refs. [39, 10] are visible at $105 < A < 118$ and for $A > 155$. The $\nu(A)$ behaviour is inversely correlated with the behaviour of TKE(A). The differences in shape and magnitude between TKE(A) are reflected in the TXE(A) distributions and consequently in prompt emission quantities of fragment pairs (e.g. $\nu_{\rm pair}(A)$, $E_{\gamma\,\rm pair}(A)$). Hereafter these differences in TKE(A) are reflected (together with the TXE partition) in distributions as a function of A of different quantities, e.g. $E^\star(A)$, $\nu(A)$, and $E_\gamma(A)$. The total average values of different quantities are very sensitive to the $Y(A$,TKE) distributions. Such total average values, i.e. $\langle\mathrm{TKE}\rangle$ and the total average temperatures of initial light and heavy fragments $\langle T_i\rangle_{L,H}$ are input parameters of the Los Alamos model (LAM). The PFNS results in the center-of-mass and laboratory frames of both versions of the LAM (with or without sequential emission [40]) using the values of $\langle\mathrm{TKE}\rangle$ and $\langle T_i\rangle_{L,H}$ based on $Y(A$,TKE) from Ref. [37, 38, 39] as input describe the experimental data well. Differences are visible in the high-energy tail of the spectrum. The highest sensitivity of PFNS is to $\langle T_i\rangle_{L,H}$: even small differences, up to 1.3% in $\langle T_i\rangle_L$ and up to 0.7% in $\langle T_i\rangle_H$, induce differences as large as $\sim 14\%$ in the high-energy tail of the spectrum.

3 Summary of discussions and recommendations

The meeting participants recognized that many activities related to the new FPY evaluations will be incorporated into this CRP, as shown in all the presentations, including experimental measurements, modeling, evaluation, and validation. Some new ideas for sharing experimental data for evaluations — whether or not the data are currently available in EXFOR — were discussed, such as extending the data format to facilitate easier access to these data by the CRP participants. It was noted that some measurements employing new experimental techniques could be available either within the CRP timeline or beyond. Such measurements would benefit the FPY data library in later updates. New theoretical understanding of the fission process, together with uncertainty quantification, can improve the evaluations.

The meeting presentations can be separated into four categories which coincide with those to be addressed in the CRP, namely

a Availabity of experimental fission product yield data for evaluations,

b New fission product yield experimental data,

c Fission product yield evaluation,

d Fission product yield validation.

Coordinators were nominated in each category: (a) B. Pritychenko (BNL); (b) O. Serot (CEA/DEN); (c) R. Capote (IAEA); and (d) O. Cabellos (UPM). In addition, because modeling plays a key role in the FPY evaluations, F. Minato (JAEA) was appointed coordinator of a modeling subgroup under evaluations, category (c). These coordinators will work closely with the CRP participants to promote international collaborations and facilitate production of the CRP deliverables.

Category (a), historic data, encompasses experimental data already compiled in EXFOR, as well as other, derived data, that are no longer in their original form. It is important to ensure that the CRP participants have access to all available legacy FPY data and that this experimental database is available to everyone interested in carrying out evaluations.

Category (b) is dedicated to recent experimental data, typically measured with advanced techniques at more modern facilities. It was acknowledged that it might be difficult to make these new data available in EXFOR in a timely manner. However, the CRP will facilitate coordination between the experimental and evaluation groups to make these data available to participants. Even though many of these experiemntal programs may extend far beyond the timeline of the CRP, the importance of maintaining the momentum of ongoing experimental activities was noted.

The evaluation effort in category (c) will involve investigation of currently available FPY evaluations and determining how much these prior evaluations will influence the CRP work. Modeling is a crucial part of the FPY evaluations and the determination of their uncertainties. The needs of FPY users will play an important role in the FPY validations that encompass category (d). Because independent and cumulative FPYs are connected by decay data, coordination with the nuclear structure data community is required. It was emphasized by FPY users that not only the FPY data alone but also an assessment of realistic uncertainties in the evaluated FPYs are crucial for the final data library. Because no correlation matrix is included with the current evaluations, a new covariance format was proposed to be provided at the request of the user community. In particular, the covariance data for the three major actinides, as well as for ^{241}Pu, are critical in applications.

The rest of this section presents a summary of the talks given by the participants and the subsequent discussions, organized according to the above categories.

3.1 Availabity of experimental fission product yield data for evaluations

The first compilations of experimental nuclear reaction data were produced during the Manhattan project. The compilations were later expanded at Brookhaven National Laboratory [41]. These pioneering efforts led to nuclear data developments worldwide, including the four neutron centers agreement on compilation data interchange (EXFOR) format in 1970. The scope of the initial EXFOR compilations was restricted to neutron cross sections and spontaneous fission. Fission yield (FY) data were not compiled until 1976. The original compilations strongly relied on published data as well as tabulated data obtained directly from the authors. Figure 6 illustrates the evolution of the EXFOR library over time.

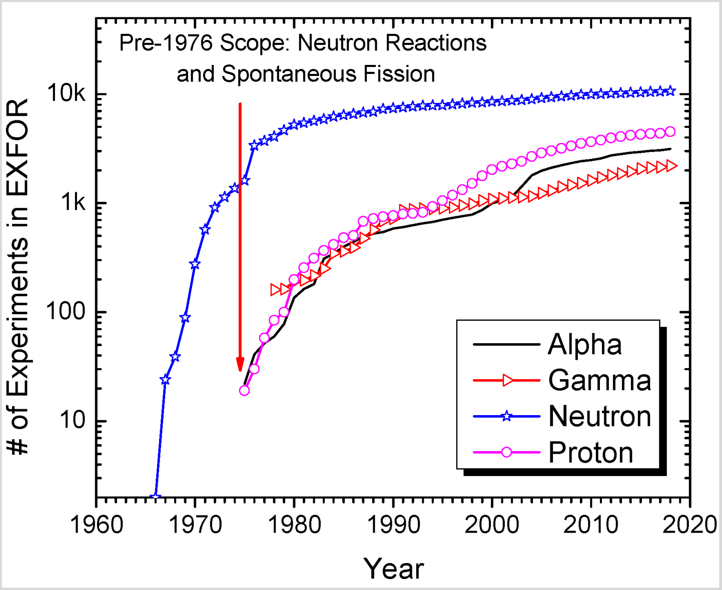

Figure 6: Evolution of the EXFOR library data compilations scope with time [42].

Due to a variety of historical and technological reasons, not all experimental data were submitted to EXFOR and a large amount of data were missed by compilers. The importance of these missing data was recognized by the IAEA Coordinated Research Project on Compilation and Evaluation of Fission Yield Nuclear Data [43] in the 90s. This CRP requested the four neutron data centers to compile the missing fission yield data from the 1981 Meek & Rider file [44]. The Meek & Rider data were later added into EXFOR as STATUS RIDER. These additions helped to improve the completeness of EXFOR for fission yields. However, the problem of missing data was left unresolved.

Presently, new FY measurements are very expensive [45]. Thus, it is cost effective to recover previously-published results before conducting new measurements. The development of modern computer tools and bibliographical databases provide new avenues to improve the completeness of EXFOR. In 2017 the National Nuclear Data Center (NNDC) launched a project to collect missing fission yield data using the Nuclear Science References (NSR) database, largely overlooked by users. The initial data search and analysis revealed a large number of previously missed neutron-, photon-induced and spontaneous fission yield data [46, 47, 48, 49]. Further analysis of the NSR database identified 384 neutron-induced, 142 spontaneous and 126 photo-induced fission yield experiments [42] missing from EXFOR. To simplify the compilation work, 540 fission yield PDF files were produced and added to the joint EXFOR-NSR PDF database.

In the following year, the Nuclear Data Section (NDS) of the IAEA initiated a complementary project [9, 50, 51] based on a detailed analysis of the England & Rider evaluation and In the following year, the Nuclear Data Section (NDS) of the IAEA references in R. Mills Ph.D. thesis [7, 8]. The IAEA NDS assessed availability of these experimental data in EXFOR and reported that 80% of these data entries were already included. It was determined that

- 63% of the data entries were already included in EXFOR,
- 17% were missing,
- 5% required further checks, and
- 15% were not relevant.

The EXFOR compilations based on the NNDC findigs are almost complete while the IAEA compilations are still in progress. In addition, NNDC has proactively compiled charged-particle-induced fission yield experiments in the USA and Canada. These projects will provide sufficient data to account for missing yields in EXFOR. The NNDC and NDS work was presented by B. Pritychenko (NNDC/BNL) and N. Otuka (NDS/IAEA) respectively.

In parallel with EXFOR, R. Mills (UKAEA) maintains his own experimental fission product yield (FPY) database, originally created by Crouch [52]. This database is occasionally updated by including more recent experimental data, such as selected LOHENGRIN data sets, discussed by Chebboubi in a separate presentation. It was noted that the historical experimental data are generally cumulative FPYs. An iterative adjustment of the independent FPYs must be carried out to match the measured cumulative FPYs.

There were broad technical discussions of EXFOR compilation rules, data storage techniques, and nuclear structure data. Several extensions of EXFOR rules to cover some recent FPY experiments, such as Coulomb excitation in heavy-ion (HI) induced reactions and photon-induced fission were discussed. A recommendation to compile these data as photon-induced fission was proposed. On the other hand, FPY data produced in transfer reactions could be treated as HI-induced fission. Although the HI reactions can be viewed as equivalent to neutron-induced reactions, compiling these data in this category contradicts standard EXFOR rules and procedures. These issues will be further clarified at the next Nuclear Reaction Data Centre (NRDC) network meeting. A. Mattera (NNDC/BNL) presented the work of G. Fabricate (NNDC/BNL) and V. Zerkin (NDS/IAEA) on possible storage of EXFOR FPY data in a new JSON format. Mattera also discussed nuclear structure and decay data used in legacy FPY experiments. When updated nuclear decay data and γ-ray intensities become available, it will be prudent to renormalize old experimental data by applying these values. Data renormalization is currently underway at NNDC for ^{238}U, including a complementary measurement proposed for Argonne National Laboratory.

3.2 New experimental data on fission product yields

Recent FPY measurements are being made throughout the world. This meeting involved presentations of LOHENGRIN at Grenoble and SOFIA at GANIL, both in France; TUNL in the United States; JRC at Geel, Belgium, GSI in Germany; and Uppsalla University in Sweden. Although there was no presentation of cumulative FPY measurements by LANL in the US, the availability of FPY measurements in critical assemblies was noted during the meeting.

The fission fragment observables measured by the LOHENGRIN recoil separator was reported by A. Chebboubi (CEA/DEN). Cadarache also performs FPY data evaluations, including the isomeric ratios and covariances, by combining the LOHENGRIN data with theory. He summarized currently available experimental data on ^{241}Am, ^{233}U, and ^{239,241}Pu, and compared the measurements with various model calculations. He noted that the experimental data obtained are relative measurements.

The TUNL-LANL-LLNL FPY collaboration, as reported by S. Finch (TUNL), measures cumulative FPYs from monoenergetic neutron- and photon-induced fission using activation techniques. The TUNL Van de Graaf accelerator produces quasi-monoenergetic neutrons in the 0.5 – 14.8 MeV range for neutron-induced fission measurements. The photo-fission measurements are carried out at the High Intensity Gamma-ray Source (HIγS) facility at TUNL. The energy dependence of FPYs for neutron-induced fission measurements of ^{235,238}U and ^{239}Pu were published in Gooden et al. [1]. The monoenergetic photon measurements at $E_\gamma = 13$ MeV were published by Krishichayan et al. [2]. The ^{239}Pu(n,f) and ^{240}Pu(γ,f) measurements, resulting in the same compound nucleus, give very similar FPYs, confirming the Bohr hypothesis. Finch also discussed new measurements with RABBITS, a rapid transfer system, to obtain shorter-lived FPYs.

An alternative method of obtaining cumulative FPYs by delayed neutron measurements was reported by Mitrofanov (IPPE). The cumulative Br, Kr, Ru, and I isotope yields were measured for neutron-induced fission of ^{233}U, ^{235}U, and ^{239}Pu for neutrons of energies from thermal to 5 MeV. A model for delayed neutron emission is required to obtain the cumulative FPYs. Their model employed a group-representation of the delayed neutrons.

Coulomb-excitation measurements at SOFIA and transfer-reaction measurements at VAMOS were reported by J. Taieb (CEA/DAM). The SOFIA measurement, which can be considered equivalent to neutron-induced fission of ^{235}U at 8 MeV, demonstrated extraordinary mass and charge resolution. Although the excitation energy distribution has noticeable peaks near 11 and 14 MeV, the distribution is rather broad. The VAMOS measurements, on the other hand, are sensitive to initial excitation energies over the range from thermal up to 20 MeV.

A. Al-Adili (Uppsala U.) reported measurements at JRC and IGISOL at U. Jyväskylä. His presentation included measurements of correlations between fission fragments and prompt neutrons as a function of incident neutron energy at the new fast-neutron source MONNET; development of the high-resolution fission-fragment spectrometer VERDI; and isomeric yield measurements performed at IGISOL.

S. Oberstedt (JRC) summarized experimental measurements of prompt fission neutron and γ-ray correlations with fission fragment properties at GELINA; ($\overline{\nu}$ fluctuations at resolved neutron resonance energies for incident thermal neutrons); and VESPA++ (spontaneous fission isotopes). He reported that new, accurate FPY data for neutron-induced fission on ^{235}U and ^{239}Pu are already available for neutron energies from thermal to 50 eV. In addition, FPY measurements for ^{230,232}Th and ^{236}U are currently planned at the new fast-neutron source MONNET.

T. Dickel (GSI) and I. Mardor (Soreq) described ongoing work at GSI to measure independent isotopic fission yields and isomer yield ratios employing direct ion counting, using a spontaneous fission source installed in the Fragment Separator Ion Catcher (FRS-IC) at GSI. The fragments are transported to a multiple-reflection time-of-flight mass spectrometer able to resolve yields as low as $\sim 6 \times 10^{-8}$ with resolving power sufficient to separate all isobars and low-lying isomers for energies as low as 200 keV. They will measure the fission yields and isomeric ratios for ^{252}Cf(sf) and ^{248}Cm(sf) duirng the CRP. They have recently installed a DC cage that will allow them to measure lower yield fragments with the same sources. The same measurement methods will be applied at the Soreq Applied Research Accelerator Facility (SARAF II), under construction in Israel.

3.3 Fission product yield evaluations

The present status and future plans for FPY data evaluations and libraries for each major nuclear data library project were briefly summarized by F. Minato (JAEA) for JENDL, N. Shu (CIAE) for CENDL, and T. Kawano (LANL) for ENDF. In addition, because modeling is expected to play a key role in the FPY evaluations, F. Minato (JAEA) was appointed coordinator of a modeling subgroup under evaluations, category (c).

3.3.1 FPY modeling and fission codes

In general, FPY evaluations rely on theories for nuclear fission, prompt and β-decay of the fission fragments for independent and cumulative yields respectively, and experimental data for input. At this meeting, a variety of physics models for the formation of fragments and their de-excitation were presented, including the GEF code by K.-H. Schmid; the HF^{3}D model by T. Kawano (LANL); the SPY and TD-GCM models by S. Goriely (ULB) and S. Hilaire (CEA/DAM); the FIFRELIN code by O. Serot (CEA/DEN); the FREYA code by R. Vogt (LLNL) and J. Randrup (LBNL); and the PbP model by A. Tudora (U. Bucharest). In addition, employing TALYS for FPY calculations was mentioned by some speakers. Semi-empirical to fully quantum-mechanical descriptions were involved in modeling fragment yields in GEF, SPY and TD-GOM. Complete event models such as FIFRELIN, FREYA and GEF, as well as deterministic models like PbP and HF^{3}D, all take fission fragment yields as input, although GEF generates the fragment yields it employs. Most models rely on some number of adjustable parameters. Adjusting these parameters or the input yields could be a useful means of assessing the sensitivities of the models to the input physics. For example, some models may exhibit larger sensitivities to the level densities while others are more sensitive to the photon strength. Such studies could also prove interesting for other nuclear data communities.

The theoretical models should also be capable of calculating and improving upon the prediction of isomeric ratios in the FPYs. Presently, a simple model by Madland and England [53] is widely employed. Another important component of advanced modeling is to expand the dependence of FPYs on incident neutron energy since the current FPY data libraries are limited to a small number of energy points, usually no more than three: thermal, fast, and high energy. Some discussion of each model presented is given below.

K.-H. Schmidt summarized the capabilities of the GEF code, which describes the whole process from prompt decay of an excited compound nucleus through statistical neutron and photon emission, followed by β-decay, to stability. Thus GEF can be used to determine both the independent and cumulative fission product yields. The empirical parameters in the FPYs in GEF typically come from radiochemical data, direct kinematics and inverse kinematics with an emphasis on radiochemical data. The LOHENGRIN data has recently been included in the parameter determinations because it provides better constraints than the radiochemical data. The structures in the potential energy surfaces used in GEF to determine the yields depend on the proton and neutron shells in the fragments, dominated by the proton shells. The Z and N systematics of the FPYs are determined from the FPY data by adjusting the parameters in the potential energy surface to fit the FPYs. Yield systematics when using four shells, dominated by $Z = 36$ (deformed) and $Z = 50$ (spherical), 55 and 58 describes most of the data except near the transition between asymmetric and symmetric fission. This empirical approach has been used to adjust the FPYs for about 100 systems.

O. Serot (CEA/DEN) discussed some of the possibilities for using the FIFRELIN Hauser-Feshbach code in FPY evaluations. FIFRELIN does not calculate the yields from a potential energy surface but instead samples mass yields from experimental data. If no data are availabe, the GEF yields and kinetic energies are used. Once the fission fragment characteristics (mass, charge, kinetic energy, excitation and spin/party) are determined, the fission fragments are de-excited by Hauser-Feshbach theory. Conversion electrons are being added to calculate cumulative yields. In addition to several fitted parameters, including how the statistical excitation is partitioned between the light and heavy fragments and the width of the spin distribution for each fragment, FIFRELIN has several options for physics inputs such as the nuclear level densities, photon strength functions and the neutron and photon transmission coefficients. FIFRELIN results on isomeric ratios were presented to show the sensitivity of the results to various inputs. He showed that the ^{152}Eu$(n_{\rm th}, \gamma)$ branching ratio is sensitive to the level density. He also discussed using Bayesian statistics to fix the initial spin $J_{\rm rms}$ required to match the ^{132}Sn isomeric ratio.

The Hauser-Feshbach Fission Fragment Decay (HF^{3}D) model [14] from LANL was presented by T. Kawano (LANL). The model gives the independent and cumulative FPYs as a function of neutron energy. He demonstrated the energy dependence of some selected FPY data, as well as the delayed neutron multiplicity $\overline{\nu}_d$.

S. Goriely (ULB) and S. Hilaire (CEA/DAM) proposed a microscopic determination of fission fragment distributions. They propose to determine the FPYs based on two different approaches: the Scission Point Yield (SPY) model and the dynamical time dependent generator coordinate method (TD-GCM). The SPY model is based on first-chance fission, neglects evolution from saddle to scission, and assumes isolated fragments at rest with a fragmentation probability proportional to the number of available systems. It uses the BSk27 Skyrme interaction. Raw yields from this approach show large fluctuations, requiring smoothing the distributions. They suggested that changing the distance between nucleons can improve $Y(A)$ considerably. The fragment kinetic energies have also been extracted in this approach but it was not discussed how changing the distance between nucleons would affect the TKE distributions. The TD-GCM uses a fully quantum mechanincal approach with nucleon-nucleon interactions, a constrained Hartree-Fock Bogilyubov approach, collective variables, and assuming adiabaticity to obtain the potential energy surface and its evolution equation to reach the scission configuration. Neither approach currently includes prompt neutron or photon emission; they would take the input yields and use TALYS for the decays. They plan to try to study ^{236,239}U, ^{240,242}Pu and ^{252}Cf with both SPY and TD-GCM. They will also use the SPY model over the full table of isotopes.

R. Vogt (LLNL) described how the LBNL-LLNL FREYA code could be used to test FPY evaluations. FREYA takes fission fragment yields from data or models and uses Weisskopf-Ewing neutron emission, followed by photon emission to produce fission product yields. The possibility to obtain cumulative fission yields has been developed for FREYA as well. Various tests of FREYA's sensitivity to model inputs were shown. In particular, effects on several neutron observables were presented for several scenarios: replacing $Y(A)$ for ^{239}Pu(n,f) with model distributions; generating 1000 TKE(A_H) distributions and studying prompt emission with fixed $Y(A)$ for ^{252}Cf(sf); and using an ensemble of 15,0000 $Y(A, Z, \mathrm{TKE})$ distributions generated from a least squares fit to $Y(A)$, TKE(A_H) and $\sigma(\mathrm{TKE})$ data and the associated covariances. The talk showed that FREYA is flexible and fast so that the consequences of appropriately modified input can readily be studied.

A. Tudora (U. Bucharest) discussed the influence of the fission fragment distributions, $Y(A, \mathrm{TKE})$, on point-by-point (PbP) model calculations. She implemented four different distributions of $Y(A, \mathrm{TKE})$ based on three sets of experimenta data from Geel and one distribution taken from GEF. She then compared the calculated $\mathrm{TKE}(A)$, $\nu(A, \mathrm{TKE})$, and $\nu(A)$. She noted that the PbP model can be employed for validating fragment distributions $Y(A, \mathrm{TKE})$.

3.3.2 FPY evaluations and covariances

The quality of any new FPY evaluation depends on information available regarding the fissioning system (neutron-induced, photon-induced, and spontaneous), incident energies in the case of induced fission, and the target nuclei (for example ^{233}U, ^{235}U, ^{238}U, ^{239}Pu, and ^{241}Pu). Since the evaluation will be based both on experimental data and modeling, it is important that the experimental data are available in EXFOR or in some other easily accessible databases. Decay data, connecting the independent and cumulative yields, also play important roles in the evaluations.

Models are not only utilized to evaluate the FPYs themselves, but also to produce self-consistent variances and correlations of the FPYs. As repeatedly mentioned, it is crucial to provide the FPY covariances (correlations), which allows users of FPY data to perform uncertainty quantification in applications. A variety of correlation matrices have been proposed previously. However, depending on the evaluation methodology and the constraints applied, not all of them will lead to a unique solution. A goal of the CRP should be to develop a methodology for a consistent evaluation. It is also important that any new FPY evaluation is tested in different applications.

Ongoing FPY data evaluation efforts were reported by several groups. The talks pertaining to these efforts are summarized in the remainder of this section.

G. Kessedjian (CEA/DEN) reported on their attempt to define a new methodology of evaluation based on statistical tests in order to provide the best estimate based on consistent sets of measurements. In their method, a complete evaluation (values, variances, and correlations) would be produced consistently, minimizing entropy and maximizing information content. Their work combines FIFRELIN with input yields from GEF to evaluate, for example, the ^{235}U(n_{th},f) FPYs and associated covariances.

D. Rochman (PSI) discussed the importance of the FPY data covariances, noting that the currently available FPY data libraries include only uncertainties, no correlations. He proposed a Bayesian Monte Carlo method employing GEF to evaluate the covariance data for FPYs. He has so far modified 22 parameters in GEF 2020 v1.1, which also includes β decays. This approach can be applied to minor and possibly also major actinides but the model parameters have to be tuned to data in each case.

S. Chiba (Tokyo Tech) presented their recent FPY evaluation, the first such effort in Japan, as well as their associated covariance data [27]. A newly-developed model of odd-even staggering in FPYs was applied to obtain $Y(A, Z)$. The generalized least-squares method enabled them to implement all the required conservation constraints (mass, charge, normalization) in the FPY data.

F. Minato (JAEA) presented the status and perspectives of JENDL FPY data. The group plans to release JENDL5 in 2022 with FPY data as a major feature. They want to use FPY data based on data provided through the CRP. The evaluation will consider prompt and delayed fission neutron and gamma spectra and will determine the model parameters with regression based on a Bayesian approach to try to study FPYs at other energies beside thermal, fast, and 14 MeV. As part of this effort, they have developed the CCONE code in collaboration with the Tokyo Institute of Technology. CCONE includes nuclear reaction models (optical model, pre-equilibrium, evaporation from compound nucleus) for the cross section, obtaining the prompt fission yields based on Wahl systematics. It then does statistical decays of prompt neutrons and gammas to get the independent product yields. Finally, it uses the Batemann equation for delayed neutron and gamma emission to calculate the cumulative fission yields. He gave examples of fits to specific model parameters using their Bayesian method.

Nengchuan Shu (CIAE) discussed fission yield studies at CNDC, both experimental and modeling work. Experimentally, they use energy-velocity-x-ray spectroscopy to measure fission fragments and identify the fragment charge by a fit to the Z and A yeilds. Such a fit is good for the light fragment but not for the heavy fragment because of degraded mass resolution. They use x-ray spectroscopy to identify gammas from the fragments. They have measured ^{235}U(n,f) and ^{239}Pu(n,f) for thermal neutrons and 2.5 and 14 MeV neutrons. They model FPYs by calculating the potential energy surface and obtain the fission dynamics from a Langevin approach to produce fission trajectories and mass distributions. They have calculated $Y(A)$ for ^{235}U(n,f) for thermal, 0.5, 0.8 and 14 MeV; ^{232}Th, ^{233,234}U, and ^{239}Pu (n,f) at 14 MeV; and thermal yields for ^{233,238}U(n,f) and ^{237}Np(n,f). Their effort also includes an evaluation component.

3.4 Fission product yield validation

Benchmarking and validation activities in current fission yield evaluations have received less attention than neutron-induced nuclear reaction evaluations. However, the nuclear industry strongly relies on the fission yields to assess decay heat, delayed neutron yields and criticality issues related to burnup credit.

The development of a new fission yield evaluation should be performed in close collaboration with benchmarking and validation (B&V) activities which can provide valuable feedback and identify trends to improve the final FPY evaluations.

First, B&V activities can be employed to validate fission yields for fuel cycle applications. These include:

- comparison of nuclide inventory of spent fuels (e.g. the SFCOMPO-2.0 database [54]);
- decay heat measurements of spent fuels [55];
- dose rate calculations in spent fuels [56];

- new measurements in experimental research reactors like ETTR-2 provide valuable information such as the ratio of the effective delayed neutron fraction to prompt neutron generation time;
- antineutrino spectra measurements generated by nuclear reactors like the Daya Bay spectral measurements [57].

Second, experimental measurements of fission burst are needed for different nuclides of interest in reactor operations, including at fast and thermal neutron energies:

- γ-ray, β, and total decay heat [58, 59, 60, 61, 62];
- multiplicity and average energy of delayed neutrons [63].

In addition, other comparative analyses can be performed with delayed neutron data: total delayed neutron yields [64, 65], average half-lives, and emission rates [65].

Finally, Sensitivity/Uncertainty (S/U) and Uncertainty Quantification (UQ) analyses cand determine the impact of fission yield uncertainties in different response functions like isotopic inventory, criticality, decay heat and delayed neutron emission. This CRP will include activities devoted to assessing the importance of fission yield cross-correlations in those responses.

Alejandro Sonzogni (BNL) discussed the impact of fission yields on antineutrino spectra. He started out discussing a re-evaluation of energy release in fission, converted to heat in a nuclear reactor. They instigated the re-evaluation because of the small uncertainites given for the currently available energy release. Results were presented relative to Kopeikin (2004) where uncertainties were evaluated from mass conservation based on the prompt $\overline{\nu}$, $\overline{\nu} = A_t + 1 - \sum_i C_i A_i$ where C_i is a coefficient related to the cumulative yield for isotope i. Keeping events that only give $\overline{\nu}$ within its evaluated uncertainties, they found large legacy uncertainties on ^{90}Zr and ^{135}Cf for ^{235}U(n,f) and ^{109}Ag for ^{239,241}Pu(n,f). If these ENDF values are corrected, the yield uncertainties are reduced and become closer to Kopeikin's values. He noted that the uncertainties on the energy removed by antineutrino emission dominate the uncertainties in the energy release which include the covariance on the cumulative yields; isomers; and β-delayed neutrons. The GEF code is generally used for their study. It includes correlations between the yields of nearby nuclei with positive correlations for yields in the same Brosa modes. FInally, he discussed the inverse beta decay (IBD) antineutrino yields from Daya Bay and RENO, obtained from measured spectra. There are some discrepancies between these results and summation calculations for ^{235}U(n,f), indicating either an issue with the Daya Bay data or the cumulative yields. In addition, the ^{239}Pu(n,f) antineutrino spectra obtained is not smooth, which is unphysical: the spectra should be smooth. Even more precise data should be coming soon, especially with the start of the JUNO experiment.

Oscar Cabellos (UPM, Spain) presented a talk on checking, processing and verification of data. He noted that there is a need to identify FPYs important for safety-related fuel applications and criticality safety, e.g for spent fuel burn up, which is very important for the user community. He also stressed the need for handbooks for benchmarking and validation of FYs and mentioned several international projects: CoNDERC (compilation of nuclear data experiments for radiation characterization); SFCOMPO (isotopic concentration of spent fuel, operational histories and design data); and EXFOR (data compilation). Handbooks compile data in a standardized format to more conveniently validate calculational techniques and fission yield data; evaluate data and quantify uncertainties through sensitivity studies; and streamline code validation. SFCOMPO-2.0 benchmarks were released in June 2017 with entries from 44 different reactors

(8 types of reactors representing 750 fuel samples). He showed some SFCOMPO benchmark comparisons exhibiting good agreement with integral experiments in some places but also some large disagreements. He also compared with EXFOR differential data for statistical verification to identify outliers and errors and then score EXFOR data sets for evaluation projects. He then turned to methodology for Sensitivity/Uncertainty calculations (S/U) and uncertainty propagation using Monte Carlo techniques. One can calculate sensitivity coefficients using the sandwich formula for S/U calculations. He also noted that one can do Monte Carlo calculations with and without correlations. He showed sensitivities and uncertainties propagated in the UAM/pin-cell benchmark with uncertainties in $k_{\rm eff}$ as a function of burnup. He also showed results for FP decay heat. The uncertainty decreases when correlations are included employing Bayesian methods.

Dmitry E. Gremyachkin (IPPE, Russia) described their approach for validating FY databases and computer codes using delayed neutron macroscopic data. They use a summation method to calculate delayed neutron characteristics. The delayed yield is obtained from the sum of cumulative yields times the probability of delayed neutron emission by the $i^{\rm th}$ precursor. They summed over 368 precursors in an appropriate data set. The average half life is calculated by multiplying this sum by delayed neutron half life divided by the delayed neutron multiplicity. He compared the delayed neutron yield and average half life using England-Wilson; Rudstam, IAEA and Pfeiffer-Kratz-Muller data with different databases. He found ENDF and JENDL are higher relative to delayed neutron yields while ROSFOND and JEFF are better for thermal ^{235}U. All databases give higher than recommended results for fast neutrons. The best agreement for ^{239}Pu($n_{\rm th}$,f) is with JEFF while, in the case of fast neutrons, all databases are in relatively good agreement with recommended values. With fast neutrons on ^{238}U, JEFF with Pfeiffer-Kratz-Muller agrees best but all databases are somewhat low relative to the recommended values. This study suggests that delayed neutron properties should be investigated over a wider energy range.

Nader Mohamed (AEA, Egypt) discussed fission yield applications at the ETRR-2 reactor. He reminded that FPYs are required at several stages of nuclear fuel cycle. Related calculations rely on the accuracy of the FY data such as fuel reactivity, criticality, burnup and core cycle length (^{135}Xe and ^{149}Sm); evaluated delayed nenutron precursors like ^{87}Br, ^{142}Cs, ^{137}I; spent fuel processing; environmental impact, transport and storage; as well as verification. He noted that fuel element failure can be used to deduce detected fragments in coolant and/or moderator. Assessments of accidents also requires evaluation of source terms for the fission fragments. Calculating the accumulation of fission products at various stages requires fission yields, decay schemes, and neutron cross sections for produced fragments. He gave some examples of studies done with their reactor. To measure burnup, they measured the concentration of ^{137}Cs by measuring activity correlated to time of discharge of the fuel element and thus determined the number of ^{235}U nuclei that fission. They measured four fission products: ^{139}Ba, ^{135}Xe, ^{101}Tc and ^{138}Cs to verify fuel safety by comparing samples to reference values. He remarked that, in the case of fuel failure, the FPYs will increase by a factor of 5-10 relative to the reference values. He also discussed safeguurd verification and described an analytical model of ^{134}Cs production based on the ^{134}Cs/^{137}Cs ratio, important for evaluating burnup of LEU targets. Their goal is to produce a set of recommended reactor benchmarks.

3.5 Next meeting

This CRP will have two more RCMs within 4 to 5 years. We tentatively planned for the next meeting to be held in 2022, either in summer or autumn.

We plan to publish at least one CRP report in a peer-reviewed, open access journal. More publications may be produced if they are warranted. In addition to the journal articles, the final products, including any documentation, will be made available online.

Finally, there was discussion about the data sharing policy. Some data could be restricted by institute, sponsors, etc, which may prevent public release of the data we produce in the CRP. The data sharing issues will be carefully considered before we store data on an openly-accessible website.

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Appendix A List of participants

1st RCM of the CRP on the

Updating Fission Yield Data for Applications

(Virtual Event)

31 August – 4 September 2020

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Appendix B Agenda

1st RCM of the CRP on the
Updating Fission Yield Data for Applications
(Virtual Event)
31 August – 4 September 2020

Agenda (Complete)

Monday, August 31th

(DAY 1: Introduction, FPY experiments and available data)

13:50-14:00	Technical setup and checks	
14:00-14:10	Opening of the meeting by Head of the Nuclear Data Section	Arjan Koning (IAEA)
14:10-14:20	Election of chair, rapporteurs	Roberto Capote (IAEA)
14:20-14:40	Goals and expected deliverables of the Project, timeline	Roberto Capote (IAEA)
14:40-15:00	FPY needs and comments	Mark Chadwick (LANL)
1. 30min	Fission fragments observables measured at the LOHENGRIN recoil separator	Abdelhazize Chebboubi (CEA)
2. 30min	Experimental results on monoenergetic neutron- and photon-induced fission from the TUNL-LANL-LLNL FPY collaboration	Sean Finch (TUNL)
3. 30min	Cumulative yields of Bromine, Krypton, Rubidium and Iodine isotopes from fission of ^{233}U, ^{235}U, and ^{239}Pu by neutrons in the energy range from thermal to 5 MeV	V.M. Piksaikin (IPPE)
4. 15min	Absolute FY by precise gamma spectrometry	Elizabeth McCutchan (BNL)
5. 15min	^{238}U(n,f) induced by fast neutrons, the prototype for a modern and comprehensive database of experimental fission yields	Andrea Mattera (BNL)

Tuesday, September 1st

(DAY 2: FPY experiments and available data)

1. 20min	Status of Experimental FPY Compilation	Naohiko Otuka (IAEA)
2. 20min	Current status of FY Compilations (Area #1)	Boris Pritychenko (BNL)
3. 30min	Available fission product yield experimental data from the UK database and its analysis for evaluations	Robert Mills (UKAEA)
4. 30min	FPY data at 8 MeV equivalent neutron energy on U-235 (SOFIA) and new GANIL experiment	Julien Taieb (CEA/DAM)
5. 30min	Experiments on Fission Yields and neutron multiplicities for enhanced fission modellin	Ali Al-Adili (UU)
6. 20min	Measurements of fission-fragment yield and prompt decay properties	Stephan Oberstedt (JRC-Geel)

7. 30min	New Experimental Method for Measuring Isotopic Fission Yields and Isomer Yields Ratios Based on Mass Measurements at the FRS Ion Catcher	Timo Dickel (GSI) and Israel Mardor (Soreq)

Wednesday, September 2nd

(DAY 3: FY codes and theory, FPY evaluation)

1. 25min	Fission yields with GEF	Karl-Heinz Schmidt
2. 25min	Potential use of the FIFRELIN Monte Carlo code for the future Fission Yield evaluations	Olivier Serot (CEA)
3. 25min	Energy-Dependent Fission Product Yields: Modelling and Evaluation	Toshihiko Kawano (LANL)
4. 25min	Microscopic determination of fission fragment distributions	Stephane Goriely (ULB, Belgium) and Stephane Hilaire (CEA/DAM)
5. 25min	FREYA capabilities	Ramona Vogt (LLNL)
6. 25min	^{235}U(n_{th},f) Fission Yield evaluation: status and perspectives	Groegoire Kessedjian (CEA)
7. 25min	Bayesian Monte Carlo for FY evaluation with GEF: example and plan	Dimitri Rochman (PSI)

Thursday, September 3rd

(DAY 4: FPY evaluations and applications)

1. 25min	Evaluation of FPY and associated covariance data	Satoshi Chiba (Tokyo Institute of Technology)
2. 25min	Status and perspectives of JENDL Fission Product Yield data	Futoshi Minato (JAEA)
3. 25min	Fission yield studies at CNDC	Shu Nengchuan (CIAE/CNDC)
4. 25min	A re-evaluation of the energy released in fission that is converted into heat in a nuclear reactor	Alejandro Sonzogni (BNL)
5. 25min	Checking, Processing & Verification, Benchmarking & Validation of Fission Yields data	Oscar Cabellos (UPM)
6. 25min	Approaches for validation FY databases and computer codes using delayed neutron macroscopic data	Dmitry E. Gremyachkin (IPPE)
7. 25min	Fission Yield Applications at ETRR-2	Nader Mohamed (AEA)

Friday, September 4th

(DAY 5: Coordination of the work, summary of discussions, deliverables)

1. 25min	Influence of fragment distributions Y(A,TKE) on PbP model results	Anabella Tudora (University of Bucharest)
	Review of the meeting summary	All

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