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Summary Report of

1st Research Coordination Meeting

Development of Reference Database for Beta-delayed neutron emission

IAEA Headquarters, Vienna, Austria
26 – 30 August 2013

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March 2014

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Abstract

A summary is given of the 1st Research Coordination Meeting of the new IAEA Co-ordinated Research Project (CRP) on Development of a Reference Database for Beta-delayed neutron emission data. Participants presented their work, reviewed the current status of the field with regards to individual precursors and aggregate data, and discussed the scope of the work to be undertaken. A list of priorities and task assignments was produced.

March 2014

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1 Introduction

1.1.1 Background Motivation

In 2013 the 75th anniversary of the discovery of the nuclear fission process was celebrated. The practical applications of this phenomenon are well known to the citizens of the world. However, from the point-of-view of basic physics and technology, many physical properties of this important phenomenon are not understood or measured well. The beta-delayed neutrons (βn) emitted in the fission process, which essentially drive the current power and research nuclear reactors, is one such topic. Detection of the beta-delayed neutrons is almost as old as the discovery of the fission mechanism and celebrates its 75th anniversary in 2014, but only since the 70's have significant measurements of the neutron emission probabilities (P_n values) from fission products (and also for low-mass nuclei in the non-fission region) been made. During the last decade there has been a renewed interest in the experimental and theoretical study of neutron-rich nuclei far off the stability line at the next generation of radioactive beam facilities. A large number of these neutron-rich nuclei, which could be reached in the future, are potential delayed neutron emitters, quite a number are even $\beta 2n$ - and $\beta 3n$ -emitters. Yet experimental information on neutron emission probabilities is only available for less than half of the identified $\beta 1n$ -emitters, and the ratio of measured vs. known βn -emitters is worse for $\beta 2n$ (<8%), $\beta 3n$ (~5%), and $\beta 4n$ (~2%). Moreover, many of these measurements unfortunately give only upper limits or approximate values.

In recent years novel detectors have been built to operate at major accelerator facilities to measure the delayed-neutron decay characteristics of βn -emitters, in synergy with quantification of aggregate properties involved in the fissile materials. Current research interest in this direction is motivated by the need for better calculations of the decay heat in reactors, planning of future advanced fuel technology, anti-neutrino spectra from reactors, r -process nucleosynthesis, and nuclear structure physics. Although half-lives and P_n data are available in several compiled and evaluated libraries such as ENSDF, NUBASE, NuDat, Wallet Cards, etc., complete documentation of measurements and evaluation procedures is often missing for these properties. Previous dedicated compilations and evaluations^{1,2} suffer from incompleteness as well, and have in the meantime become outdated. Measured neutron spectra are not available in any database. With these aspects in mind, it was felt that there is an urgent need for a modern and comprehensive database where a user could retrieve various types of pertinent information related to beta-delayed neutron activity. A Consultants' meeting to explore these possibilities was organized at the IAEA from 10 to 12 October 2011. The meeting brought together experimentalists, nuclear data evaluators, and theoreticians to discuss, plan and coordinate a focused activity for creating a database as well as to stimulate experimental work on nuclei of interest (see INDC(NDS)-0599)³.

A new Coordinated Research Project (CRP) was approved in August 2012, based on the recommendations of the Consultants' meeting, with the aim of producing a Reference Database of Beta-delayed neutron emission data. The first Research Coordination Meeting (RCM) of the CRP was held from 26 to 30 August 2013 at the IAEA headquarters in Vienna. The meeting was attended by 18 participants from 10 Member States including 3 IAEA-NDS staff (see Participants List in Appendix 2). Paraskevi Dimitriou (IAEA-NDS) was the

¹G. Rudstam, K. Aleklett, and L. Sihver, *At. Data Nucl. Data Tables* 53, 1 (1993).

²B. Pfeiffer, K.-L. Kratz, and P. Möller, *Prog. Nucl. Energy* 41, 39 (2002).

Scientific Secretary of the meeting, Balraj Singh (McMaster University, Canada) and Daniel Abriola (TANDAR, Argentina) were elected Chairmen, and Iris Dillmann (TRIUMF, Canada) agreed to act as rapporteur.

A brief introduction of the scope of the meeting was given by the Scientific Secretary P. Dimitriou. Meera Venkatesh, Director of the Division of Physical and Chemical Sciences (NAPC), welcomed the participants to the IAEA and wished them success in their work. Robin Forrest, Head of the Nuclear Data Section, emphasized the importance of the CRP to reactor applications and basic sciences. The Agenda was approved without changes (see Appendix 1) and the meeting began with participants' presentations. Fifteen presentations covering experimental, theoretical and systematic aspects relevant to beta-delayed neutron activity were presented (See Appendices 4 and 6).

1.1.2 Objectives

The objectives of the CRP on a Reference Database of beta-delayed neutron emission data are to coordinate and track progress over the next 4 years in

- new experimental measurements,
- theoretical model calculations,
- empirical systematics, and
- compilation and evaluation of relevant data

and create a reference database to accommodate various

- microscopic (individual properties of precursors), as well as
- macroscopic quantities (aggregate properties of fissile materials of interest)

based on previously available experimental data, new measurements as outlined in these proceedings, values from different empirical systematics, and values from different theoretical model calculations.

1.1.3 Expected output

The outputs of this CRP for the microscopic and macroscopic quantities are the following:

I. Microscopic quantities:

1. Compilation and evaluation of experimental half-lives and P_{1n} , P_{2n} , P_{3n} and higher if available for delayed neutron precursors in the fission as well as the non-fission region. All newly published results should be included, and results of planned experiments should be communicated to the CRP network members, especially the data evaluators.
2. A list of standard precursors in different mass regions, for which reliable and several independent measurements are available, should be produced. Some work has already been done but some fine-tuning is still needed.
3. Corresponding values from different (three approaches available at present) empirical systematics should be deduced for nuclides where both, half-lives and P_n are known and those where only half-lives are known. These should be made available in the database.
4. Theoretical values (from Borzov, Möller, and possibly others) should be entered in the database for all delayed neutron precursors which have been identified in experiments.
5. Measured neutron spectra including Total Absorption Spectrometer (TAS) spectra, should be made available through links to the EXFOR database. Spectra in graphical

form should be digitized and submitted to EXFOR for compilation. Simulated neutron spectra as in Brady's thesis should also be made available.

6. Complete bibliography in NSR style with linked access to journal articles.

II. Macroscopic quantities:

1. 6- and 8-group representations based on half-lives of precursors should be re-evaluated.
2. The ν_d parameter and delayed neutron constants for fissile materials of importance for reactor technology should be deduced.
3. Measured/evaluated fission yields should be made available.
4. Neutron energy dependence of absolute total yields, relative yields, and half-lives of individual delayed neutron groups should be made available for thermal and fast neutron fission of ^{232}Th , ^{233}U , ^{236}U , ^{239}Pu , and ^{241}Am .

2 Proposed programme

Several items were discussed to define the scope of the work to be undertaken, and as a result specific actions were agreed upon and tasks were assigned.

2.1.1 Standards

At the Consultants' Meeting on Beta-Delayed Neutron Emission, 2011³, and at the Experts Meeting held at McMaster University in 2012⁴, the following β -delayed neutron precursors were selected as "standards" for the purpose of data evaluation and measurements: ^9Li , ^{17}N , ^{87}Br , ^{88}Br , ^{94}Rb , ^{95}Rb , ^{137}I and ^{138}I . Relevant compiled data were provided in the summary report³.

After a review of the above standards, and further discussions, participants agreed to the following:

^{16}C could also be a good candidate for a standard. However, the fact that the delayed neutrons are emitted with a relatively high energy could pose a problem with their detection. The discrepancies observed in the measured P_n -values for ^{138}I (only two independent measurements, see discussion in Ref.³, p. 46) needed to be resolved therefore an **Action** was placed on the experimental groups to propose a TAS (Total Absorption Spectrometer) experiment at JYFL, Jyväskylä/ Finland. There were also suggestions for future measurements at TRIUMF, Vancouver/ Canada.

Determining a standard for delayed neutron spectra could be very useful for calibration purposes. ^{87}Br was suggested as a good candidate precursor as there were at least 4 independent measurements of its delayed neutron spectra (see Ref.³). Delayed neutron spectra included in ENDF/B-VII.1 should not be considered in the evaluation process, as they are based mostly on model calculations using the CGM (Cascading Gamma and Multiplicity) approach⁵. An **Action** was placed on D. Cano-Ott and J.L. Tain to continue to investigate possible candidates for 'neutron spectra standards'.

³ D. Abriola, B. Singh, I. Dillmann, Summary Report of Consultants' Meeting on 'Beta-delayed neutron emission evaluation', www-nds.iaea.org/publications/indc/indc-nds-0599.pdf

⁴ <http://indico.gsi.de/event/bdn>

⁵ T. Kawano, S. Holloway, LANL Report LA-CC-11-018.

Establishing standards for the mass region $A=17-87$ or for $A>150$ would require new measurements since at the moment there are not many available to allow for a robust standardization procedure. The search for a possible standard in the mass region $A=17-87$ is presently ongoing, suggestions will be presented soon. There are several measurements of neutron spectra for nuclides with $A\sim 50$ from VANDLE (“Versatile Array of Neutron Detectors at Low Energy”) at ORNL (R. Grzywacz), which should be looked into. It is not recommended at the moment to attempt to establish a standard for the probability of emission of two delayed neutrons, namely P_{2n} , as there are only a few reliable measurements of P_{2n} -values, mostly with low statistics.

Evaluators should add a ‘flag’ in the database tables about the quality of the data that have been considered in the evaluation procedure, and also some brief comments on standards. Since all present standards are odd-Z nuclei, it was suggested to establish an even-even nuclei a possible standard, e.g. ^{134}Sn ($Z=50$) which has a $P_n=17$ (13) % and measured neutron spectra. ^{16}C was not considered due to the remarks mentioned above.

A uniform nomenclature was adopted by the CRP participants to be used when referring to measured and evaluated delayed neutron emission probabilities throughout the CRP and also in the Reference Database. The definitions of P_n , P_{1n} , P_{2n} were given as follows:

“The P_n value is the % (or # of times per 100 decays) that the β -decay is followed by at least one neutron emission.”

$$P_n = P_{1n} + P_{2n} + P_{3n} + \dots$$

$$P_{0n} = 100\% - P_n$$

“The neutron multiplicity n_n is the average number of neutrons per decay.”

$$n_n = 0 \cdot P_{0n} + 1 \cdot P_{1n} + 2 \cdot P_{2n} + 3 \cdot P_{3n} + \dots$$

“The P_{2n} value is the % (or # of times per 100 decays) that the β -decay is followed by emission of 2 neutrons.” and so on..

Examples: ^{86}Ga

$$P_{1n} = 60\%; P_{2n} = 20\%$$

$$\Rightarrow P_n = 80\%$$

$$\Rightarrow P_{0n} = 20\%$$

$$\Rightarrow n_n = 100 \text{ per } 100 \text{ decays}$$

The following **Actions** were placed with respect to Standards following the discussions described in this section:

- **Action** on K. Rykaczewski/ R. Grzywacz to pursue new measurements at VANDLE on $^{87,88}\text{Br}$, ^{94}Rb .
- **Action** on P. Garrett to extract P_{1n} data from existing 8π measurements at TRIUMF. It could be possible to deduce the P_{1n} of ^{94}Rb from the measured γ -data (work in progress).
- **Action** on J.L. Tain and A. Sonzogni to provide absolute γ -intensities (incl. β - and βn -intensities of daughter, J^π of mother, daughter, and grand-daughter) for nuclides ^{94}Rb and ^{95}Rb , and to verify the same properties for ^{137}I and ^{138}I
- **Action** on B. Singh, D. Abriola, and I. Dillmann to re-evaluate standards as new data become available.

- **Action** on I. Dillmann et al. to identify βn -emitters with the new Atomic Mass Evaluation 2012⁶
- **Action** on IAEA NDS to mark isotopes with $E_\gamma > S_n$ in the Reference Database.

2.1.2 Methods for β -delayed neutron measurements and new data

The methods for β -delayed neutron measurements listed in the Summary Report of the Consultant's Meeting (2011)³ were reviewed. Some new methods were added, and a list of (priority) measurements to be carried out before the 2nd Research Coordination Meeting was produced.

2.1.2.1 Methods for measurements

Notation

Precursor (AZ): **M**, mother

β -decay daughter ($^AZ+1$): **I**, intermediate

β -delayed neutron-daughter ($^{A-1}Z+1$): **F**, final nucleus (**F1** for $\beta 1n$, **F2** for $\beta 2n$)

$$P_n = N_{n\text{-decays}} / N_{\text{decays}}$$

1. “ β/n coincidence method” (replaces “ n/β ” term to account for proper sequence of detection): Beta efficiency not required. Neutron efficiency is determined in absolute terms:

$$P_n = \frac{1}{\varepsilon_n} \frac{N_{\beta n}}{N_\beta}$$

The main assumption in this method is that the number of counted β 's is free of contaminations, i.e. the background is subtracted and the random noise is corrected. This method depends on the β -efficiency ε_β , e.g. Si detectors have a threshold of about 150 keV, so the ε_β -curve increases to typically about 25% detection efficiency at around 2 MeV.

As for the neutron efficiency, the curve is assumed to be constant unless an energy-dependent efficiency curve is given. If the neutron energy distribution is very different from the calibrant isotope, this might induce systematic effects which cannot be corrected.

Evaluators were advised to seek information on the β/n coincidence window. The correlation time should be long enough to capture also the high-energy neutrons which need more time to be moderated down to thermal energies.

Evaluators were also advised that if neutron energy spectra are recommended from such measurements, they should be in linear scale, corrected for the efficiency, and normalized to 1.

Conclusion: “*The n/β method is good if the efficiency of the neutron detector has been measured using a source with similar energy dependence as the precursor of interest.*”

2. “ $n-\beta$ ”: Neutrons and β counted separately (no coincidences) but simultaneously (in the same experiment).

The remarks on the neutron efficiency mentioned in the previous method apply also

⁶M. Wang, G. Audi et al., Chinese Physics C 36 (2012) 1287-2014; online at <http://amdc.impcas.ac.cn/evaluation/data2012/ame.html>

here. In addition, the dependence of ε_β on the β -endpoint energy is not trivial and can cause complications in the determination of the β -efficiency.

It was acknowledged that in the past there was no possibility of correcting for increasing noise in the data analysis afterwards. Nowadays modern digital data acquisition systems have time-stamps which allow these corrections to be made after the measurement.

3. “ γ $^A Z+n$ ”: Abundance of precursor determined via γ -counting of any β -decay daughter. It was suggested that the label of this method be changed to: “ n - γ ”, for n and γ counting.

Several drawbacks of this method were mentioned. First of all, absolute γ intensities have to be known. When fragmentation reactions are used for the production of the precursor nucleus, the βn -daughter might also be produced. The γ counting would then have to be corrected to account for this. Contamination of the sample from the activity of the daughter nucleus would have to be known. Additional problems could arise if isomers are present.

In Ref.³ an upper limit for the half-life of the β -decay daughter nucleus of $t_{1/2}(^A Z+n) \sim 10 * t_{1/2}(M)$ was given to avoid too many decay corrections. After review of this limit, it was decided that this is not necessary if the half-life is well-known because it could then be corrected accordingly.

4. “ P_n $^A Z$ ”: Normalization with respect to a known P_n value from precursor $^A Z$. In this method, care should be taken that the chosen standard has a neutron energy spectrum similar to the investigated isotope.

Only neutron counting is used. The P_n value is deduced by comparison of the investigated neutron rate to the rate of a neutron emitter with known P_n value:

$$P_n = \frac{N_n(\text{isotope})}{N_n(\text{standard})}$$

If the reference isotope is not measured simultaneously then the normalization requires the use of production yields. In the latter case, the results are affected by the uncertainties in e.g. the fission yields.

This method is not recommended for measurements with a cocktail beam in which several unknown neutron-emitters with very similar half-lives can be present.

5. “ion”: Counting of number of precursors N_{ion} . The amount of βn daughters $N_{\beta n\text{-daughter}}$ is determined by any suitable method, and the P_n value deduced from this:

$$P_n = \frac{N_{\beta n\text{-daughter}}}{N_{ion}}$$

The efficiency of the “ion counting device” should be carefully determined and known for both species, mother and daughter. This method also needs corrections for βn -daughters already present in the beam cocktail.

There can be further subdivisions depending on the identification method: Fragmentation ranging-out, ΔE -TOF, ΔE -E, ion- $\beta\gamma$, and the detection methods: traps⁹ and storage rings⁷.

⁷A. Evdokimov, I. Dillmann, et al., Proc. Nuclei in the Cosmos XII, Cairns/ Australia, PoS (NIC XII)115 (2012); http://pos.sissa.it/archive/conferences/146/115/NIC%20XII_115.pdf

6. “fiss”: Determination of the number of precursors by fission yields

As this method is strongly affected by the uncertainties in the fission yields, evaluators were advised not to use it unless it was the only available measurement. In such a case, they should bear in mind that the results would have to be adapted to the most recent evaluations of fission yields.

7. “ γ - γ ”: pure γ -counting technique to determine both the number of mothers and β n-nuclei (granddaughters) produced.

Absolute γ -intensities are required, that means a complete knowledge of the decay scheme including γ 's going to the ground state or eventually competing γ -decays from levels above the neutron separation energy.

$$P_n = \frac{\varepsilon_{\gamma,d} \cdot I_{\gamma,abs,d} \cdot N_{\gamma,gd}}{\varepsilon_{\gamma,gd} \cdot I_{\gamma,abs,gd} \cdot N_{\gamma,d}}$$

where d= “daughter” nucleus; gd= “granddaughter” nucleus.

Another issue with this method is the direct β -feeding of the ground-state. The previous comment about counting time vs. half-life holds as in method 1 and 2: if half-lives are well-known, the granddaughter activity can be decay-corrected.

NOTE: In Rudstam et al.¹, the measurement by K. Okano et al.⁸, was wrongly labeled as “n- γ ”. However, the title was misleading and as mentioned in the CM Summary Report³, this is also a γ -counting method.

Additional methods to be added:

8. Ion-recoil method: This method includes the trap measurements (Yee et al.⁹). It uses the recoil ions and time-of-flight measurement to deduce the neutron spectrum and can be complemented with γ -detectors. However, it is only feasible for P_{1n} measurements.

The aforementioned coincidence methods can be complemented with triple coincidences, e.g. $\beta n \gamma$ or $\beta \gamma \gamma$.

2.1.2.2 New Data

New data that will become available in the near future were discussed. A list of the data that has either been measured and submitted for publication, or is in preparation for publication, or scheduled to be measured by participants of this CRP is presented in Table 1. These data will be compiled and evaluated in the new Reference Database, as and when they become available in regular publications or preprints.

Other programs involving β -delayed neutron measurements were discussed and actions were placed on participants to contact the corresponding groups and make them aware of the CRP and the potential interest in including their data in the Reference Database. These groups are listed below:

- ALTO (France): measurement of ¹³⁶Sb with TETRA neutron detector (contact will be made by M. Fallot)

⁸K. Okano et al., Ann. Nucl. Energy 13, 467 (1986)

⁹R.M. Yee, N. Scielzo et al., Phys. Rev. Lett. 110, 092501 (2013)

- RIKEN (Japan): EURICA campaign measures $T_{1/2}$, maybe P_n values (contact will be done by S. Chiba)
- NSCL (USA), Fernando Montes, S. Linneker, H. Schatz:
New proposals for the NERO setup are foreseen in the near future, discussions ongoing.
- Lohengrin @ILL Grenoble (France), Chiara Mazzochi (Warszawa) and Ludo Mathieu (Bordeaux): new long counter setup “LOENIE” (LONG-counter with ENergy Independent Efficiency)¹⁰, presently analyzing older data, reactor will restart in June 2014.
- Argonne/ Livermore (USA), N. Scielzo: plans to move the trap to the new low-energy CARIBU beamline and make measurement with upgraded array. Measurements of ^{137,138}I and others planned

Table 1. New data to be delivered to the CRP Reference Database in the next 1 ½ years.

Name/ Group	Submitted	In preparation (measured but not yet published)	Scheduled
KR/ ORNL, UTK	^{85,86} Ga, ⁸⁶ Ge, ⁷² Fe	<ul style="list-style-type: none"> • 29 neutron energy spectra (VANDLE) • ⁷⁷Cu, ⁸⁴Ga • 22 isotopes, decay heat (MTAS) 	<ul style="list-style-type: none"> • ⁷⁹⁻⁸¹Ga, ⁸³Ge (3Hen@TRIUMF) • A≈110, 136 (3Hen@CARIBU) • NSCL/ MSU
PG/ Guelph, TRIUMF	• ¹⁰² Rb	• ^{98,100,101} Rb, ^{52,53} K	• ^{32,33} Mg
JLT/ Valencia & BELEN collaboration	<ul style="list-style-type: none"> • ⁸⁵Ge, ^{85,86}As, ⁹¹Br • ⁸⁶⁻⁸⁸Br, ⁹¹⁻⁹⁴Rb (TAS) 	A<128, A>210 (BELEN@GSI)	<ul style="list-style-type: none"> • ¹³⁵⁻¹³⁷Sb, ⁸⁶Ge, ^{98,99}Y (+ isomers), ^{139,140}I (BELEN@Jyväskylä) • ¹³⁸I (TAS)
DCO/ CIEMAT			• ^{94,95} Rb, ⁸⁸ Br, ¹³⁷ I (MONSTER@Jyväskylä)

2.1.2.3 List of priorities for new measurements

Based on the needs of the two communities (reactor physics and nuclear structure/ astrophysics), the priority lists are different. Reactor physics needs aggregate parameters as six-group (Keepin) or eight-group parameters and nubar, whereas nuclear astrophysics requires microscopic quantities like half-lives and P_n for individual isotopes in the neutron-rich region. The priorities are likely to be shifted from P_{1n} to P_{2n} (or even P_{3n}). An important task of this CRP is to provide a list of priorities for evaluation and new experiments.

For reactor kinetics important information was provided in the thesis of M. Brady¹¹. For

¹⁰L. Mathieu et al., Journ. of Instr. 7, P08029 (2012), doi: 10.1088/1748-0221/7/08/P08029

¹¹M.C. Brady, T.R. England, “Delayed neutron data and group parameters for 43 fissioning systems”, Nucl. Sci. Eng. 103 (1989) 129.

minor actinides such detailed studies or information are not widely available.

An **Action** was placed on D. Cano-Ott to provide a list of priorities for measurements for lead- and sodium-cooled reactors using minor actinides as fuel.

From a sensitivity study of the value of nubar for different actinides in the thermal region, J.L. Tain has produced a table of the most important delayed neutron precursor nuclides. The values of nubar were calculated using the fission yields from ENDF/B-VII.1, and P_n -values from Pfeiffer 2002¹² or Möller 2003¹³.

Table 2. Most important contributors to ν_d (at least 1%). Those which contribute by at least 3% are marked in boldface.

²³⁵ U $E_n = \text{thermal}$	⁵⁶Ge, ^{85,86}As, ⁹¹Br, ⁹⁸Y, ¹³⁹I ⁸⁸ As, ⁹³ Rb, ⁹⁶ Rb, ^{98m} Y, ⁹⁹ Y, ¹³⁵ Sb, ¹³⁷ Sb, ¹⁴⁰ I, ¹⁴³ Cs
²³⁷ Np $E_n = \text{thermal}$	⁸⁵As, ^{98,98m}Y, ⁹⁹Y, ¹³⁵Sb, ¹³⁹I ⁹¹ Br, ^{93,96} Rb, ¹³⁶ Te, ¹⁴⁰ I, ^{143,144} Cs
²³⁹ Pu $E_n = \text{thermal}$	^{98,98m}Y, ⁹⁹Y, ¹³⁹I ⁸⁵ As, ⁹³ Rb, ¹⁰⁵ Nb, ¹³⁵ Sb, ¹⁴⁰ I, ¹⁴³ Cs
²⁴¹ Am $E_n = \text{thermal}$	^{98,98m}Y, ⁹⁹Y, ¹³⁹I ⁸⁵ As, ⁹¹ Br, ^{93,96} Rb, ¹⁰⁵ Nb, ¹³⁵ Sb, ¹³⁶ Te, ¹⁴³ Cs
²⁴² Cm $E_n = 500 \text{ keV}$	⁸⁵As, ⁹³Rb, ^{98,98m}Y, ⁹⁹Y ¹⁰⁵ Nb, ¹³⁹ I
²⁴³ Am $E_n = 500 \text{ keV}$	⁸⁵As, ^{98,98m}Y, ⁹⁹Y, ¹³⁹I ⁹¹ Br, ^{93,96} Rb, ^{105,106} Nb, ¹³⁵ Sb, ¹³⁶ Te, ¹⁴⁰ I, ¹⁴³ Cs
²⁴⁴ Cm $E_n = 500 \text{ keV}$	^{98,98m}Y, ⁹⁹Y, ¹³⁹I ⁸⁵ As, ⁹¹ Br, ^{93,96} Rb, ¹⁰⁵ Nb, ¹³⁵ Sb, ¹⁴³ Cs

The result of this study showed that the delayed neutron fraction was overestimated, and that top priority nuclides for new measurements are as follows:

1st priority: ⁸⁶Ge, ^{85,86}As, ⁹¹Br, ⁹³Rb, ^{98m,98}Y, ⁹⁹Y, ¹³⁵Sb, ¹³⁹I
2nd priority: ⁸⁸As, ⁹⁶Rb, ^{105,106}Nb, ¹³⁷Sb, ¹³⁶Te, ¹⁴⁰I, ^{143,144}Cs

For **Nuclear Astrophysics**, sensitivity studies depend strongly on the astrophysics scenario of the r-process nucleosynthesis, as the actual reaction path is influenced largely by the astrophysical conditions, such as neutron density and temperature etc. If the classical model is used to describe the r process, then the progression of the path depends solely on the masses of the contributing isotopes and the neutron density and temperature at the site. In such a case, it may be possible to identify special key isotopes around the solar r-process peaks or at neutron shell closures. The most important isotopes are located at the neutron shell closures $N=50, 82, \text{ and } 126$ and produce the three r-process abundance peaks at $A \sim 80, 130, \text{ and } 195$.

Modern descriptions with neutron star mergers as possible scenario are more complicated and produce reaction paths along the neutron dripline. These nuclei are another 10 or more mass units away from the present limits of the chart of nuclides and out of reach for the present and

¹² B. Pfeiffer, K.-L. Kratz, P. Möller, Prog. Nucl. Energy 41 (2002) 39.

¹³ P. Möller, B. Pfeiffer, et al., Phys. Rev. C 67 (2003) 055802;
<http://t2.lanl.gov/nis/molleretal/publications/rspeed2002.html>

near-future radioactive beam facilities. However, as astrophysicists have pointed out, the β -delayed neutron emission influences the neutron economy in the later stages of the r process, namely during the “freeze-out” phase when the material decays already back to stability. Thus not only the decay parameters of the most neutron-rich nuclei are important but also the parameters of the isotopes “in between”.

An **Action** was placed on P. Dimitriou, K. Rykaczewski, and J.L. Tain to contact nuclear astrophysicists working in this field, namely S. Goriely, R. Surman, M. Mumpower, and A. Arcones, for their advice and recommendations.

For **Nuclear Structure** physics, it is of particular interest to investigate the nuclear structure properties of exotic nuclides lying near the neutron drip line. Beta-delayed neutron data may be the only source of information for these exotic cases, therefore an **Action** was placed on B. Singh, and I. Dillmann to identify nuclides for which $P_{1n/2n/3n}$ is possible based on the Atomic Mass Evaluation tables⁶, and check which ones have and/or are planned to be measured.

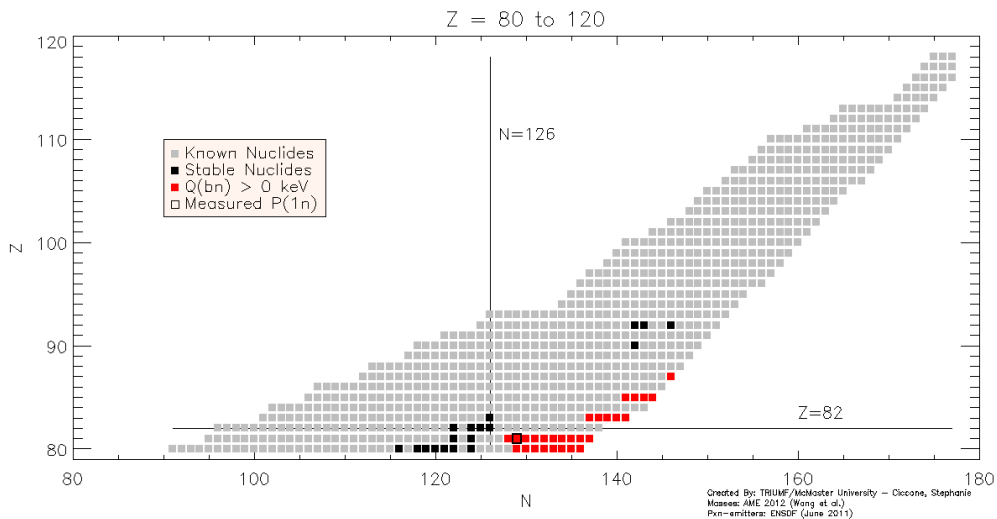
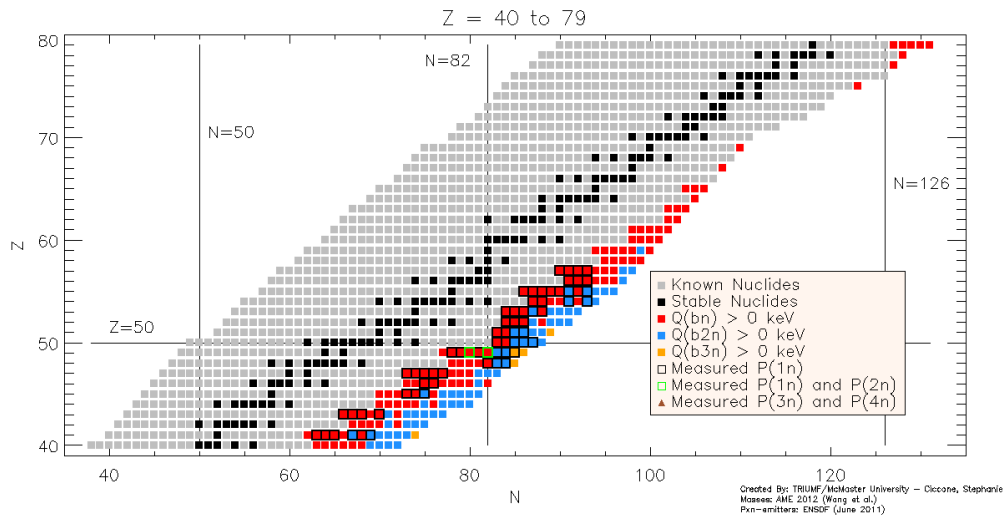
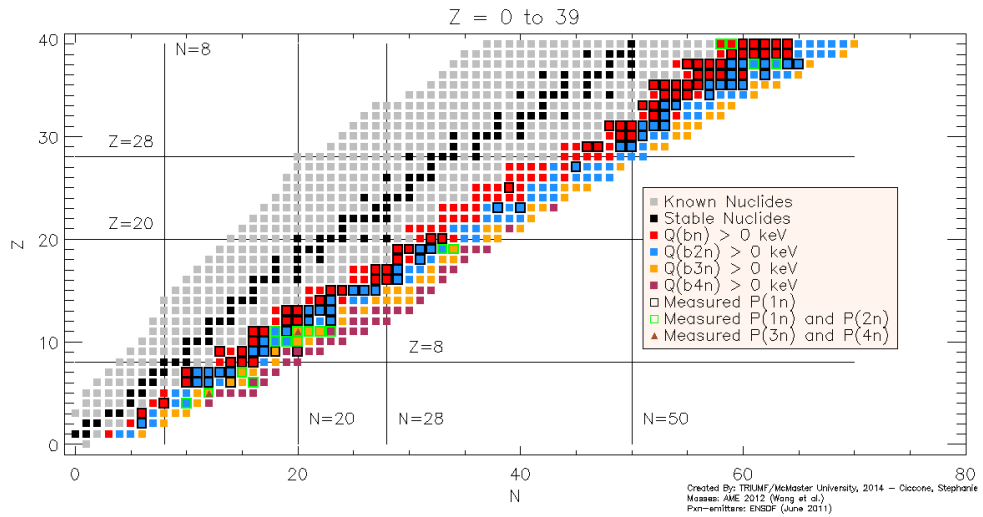


FIG 1. Chart of nuclides with the indication of isotopes with measured P_{xn} -values, and energetically possible P_{xn} -emitters (derived using masses from the AME2012¹⁴).

2.1.3 Evaluators Guidelines

The evaluators will have to first make a comprehensive assessment of the measurement method following the guidelines outlined in the Summary Report³. After careful consideration of the data, the evaluator will have to

- evaluate the recommended value,
- evaluate the uncertainty of the data, and
- comment on possible correlations between the evaluated values ($T_{1/2}$, P_n).

Specific issues the evaluators would have to pay attention to when performing the above-mentioned evaluations are the following

- Type of detector used
- Production method of radioactive isotopes
- Fine structure branching ratio
- Provide E_{level} , J^π , P_n (partial) of precursor
- The uncertainty cannot be lower than the lowest (reasonable) given experimental uncertainty
- Compare precision vs. accuracy
- Suitable averaging method is used for the evaluation of $T_{1/2}$
- If P_n and $T_{1/2}$ have been measured in parallel, they are correlated. The uncertainty of the P_n depends thus on the uncertainty of the $T_{1/2}$. This work cannot be done by evaluators. A recommendation should be given to experimentalists:
Try to include as much information as possible about the correlations and give an estimation of the correlation matrix, if details are given by the original authors.

Participants who will be responsible for the evaluation of existing and new measurements of $T_{1/2}$ and P_n values are B. Singh, D. Abriola, I. Dillmann, T. Johnson, E. McCutchan, A. Sonzogni, G. Mukherjee, H. Xiaolong, and J.L. Tain.

The evaluation of $T_{1/2}$ and P_n for nuclides in the mass region $A < 72$ is almost finished, while the effort for mass region $A > 72$ has started recently.

A careful review of the standards will be undertaken by B. Singh, D. Abriola and I. Dillmann.

Publications made by a collaborative effort within the CRP should include the following acknowledgement: *“This work has been done in the framework of a Coordinated Research Project of the International Atomic Energy Agency (IAEA) on the Development of a Reference Database for β -delayed neutron emission data.”*

2.1.4 Format of database

A possible format for the database for microscopic data was suggested. Two files should be considered: one for compilation of measured data and one for evaluated (adopted) values. The file for each isotope should contain all the fields that are included in the evaluation spreadsheets used by the evaluators. These are, among others

- ground-state/isomer spin and parity of precursor
- Q-values for β decay, β_n -decay, β_{2n} -decay, β_{3n} -decay

- $T_{1/2}$
- $P_{n,1n,2n,3n}$ etc.
- Comments on measurements and evaluation of $T_{1/2}$, $P_{n,1n,2n,3n}$
- Active link to NSR (Nuclear Science References); copies of references should be available to the network members, while taking care of copyright issues
- Add link to program “Visual Averaging Library” from M. Birch (McMaster University, Canada)¹⁵ at NNDC website; to be used by evaluators (it is a Windows 7 program, working on Java for other systems)
- Link to delayed neutron energy spectrum
- Asymmetric error bars
- Dynamic set of Q-values
- Average number of neutrons per β -decay: neutron multiplicity n_n
- Links to TAS spectrum \Leftrightarrow antineutrinos
- Flags for “Pandemonium” isotopes (check WPEC 25 definition and list)
 - Compare last known level with Q-value
 - JENDL: tried to use Gamow Teller (GT) contribution to repair “Pandemonium” isotopes

An example is given below:

Adopted Values

	J^π	$t_{1/2}$	P_{1n} (%)	P_{2n} (%)	Q_β	$Q_{\beta n}$	$Q_{\beta 2n}$	$Q_{\beta 3n}$
<u>Precursor1</u> (<u>hyperlink</u>)			86.4 (5)	0.34 (56)				
<u>Precursor2</u> (<u>hyperlink</u>)			23.4 (56)	-				

Hyperlink to Precursor1:

Compiled Values

Precursor1	P_{1n} (%)	P_{2n} (%)	Spectra E_n, E_β
Experiment 1 (Ref)	x (y) %	a (b) %	<u>link1</u> , <u>link2</u>
Experiment 2 (Ref)			
Experiment 3 (Ref)			
Recommended:	86.4 (5) %	0.34 (56)%	
Systematics 1			
Systematics 2			
Theory 1			
Theory 2			

The following actions were decided following the discussions about the database format:

¹⁵http://www.nndc.bnl.gov/nndcscr/ensdf_pgm/utility/

Action on A. Sonzogni to collect neutron energy spectra from other sources such as ENDF/B-VII.1

Action on IAEA NDS to make the fission yields from the IAEA TECDOC, 2007 available on the CRP webpage.

2.1.5 Inclusion of delayed neutron data in the EXFOR Database

Although total average delayed fission neutron yields ($\bar{\nu}$) are extensively compiled in EXFOR, and several energy spectra for specific delayed neutron groups are also available, data for delayed-neutron emission probabilities (P_n -values) and delayed neutron spectra for individual fission product precursors are rather scarce. This is to a certain extent due to the fact that those data are on the border between reaction data and decay data, and were not considered a priority for the EXFOR compilation in the past.

Presently, the (β ,n) branching fractions (P_n -values) and delayed fission neutrons are considered within the scope of the EXFOR database, and corresponding compilation formats are provided in the EXFOR manuals. However, delayed neutron emission spectra for individual precursors are not included in the database and the corresponding coding has not yet been identified. In order to respond to the need to include delayed neutron data in a database, the current situation was assessed at IAEA NDS (significance of data for reactor applications, number of articles, other available resources), and a Memo was prepared with the request to have both delayed neutron emission probabilities and energy spectra compiled in the EXFOR database (Memo to be submitted to NRDC Technical Meeting, May 2014).

The REACTION coding proposed for delayed neutron data for individual precursors was revised in the Memo as follows:

1. Delayed-neutron emission probability for a given precursor (P_n value)

- a. (Z-S-A(0,B-),,PN) for a single fragment
where: Z-S-A is the fission product nucleus (precursor nucleus before β decay);
- b. (ELEM/MASS(0,B-),,PN) for a series of fragments
The precursor nucleus is entered as a variable in the data table (see EXFOR Chapter 6: Variable Nucleus).
- c. (Z-S-A(0,B-),NUM,PN) when partial P_n values (P_{1n}, P_{2n}, \dots) are given
The multiplicity (1, 2, ...) are coded under the heading PART-OUT.
(This case must be added to the manual when needs arise.)

Units: a code from Dictionary 25 with dimension PN (e.g., PC/DECAY)

2. Delayed-neutron energy spectrum for a given precursor

- a. (Z-S-A(0,B-)Z'-S'-A',,NU/DE) for a single fragment
or (Z-S-A(0,B-)0-NN-1,,DE)
where: Z-S-A is the precursor nucleus before β decay
- b. (ELEM/MASS(0,B-),,NU/DE) for a series of fragments
or (ELEM/MASS(0,B-)0-NN-1,,DE)
The precursor nucleus is entered as a variable in the data table (see EXFOR Chapter 6: Variable Nucleus).

Units: a code from Dictionary 25 with dimension PND (e.g., PC/DEC/MEV)

The proposal will also suggest ways of making retrieval of delayed neutron data from EXFOR easier for the users, e.g. including a relevant example.

In view of the task involved in compiling all existing articles with relevant delayed neutron emission data, CRP participants volunteered to contribute to the effort by (i) undertaking the digitization of neutron energy spectra available published in graphical form only and (ii) preparing sample EXFOR files for measurements of delayed neutron emission probabilities and energy spectra. In the latter case, useful information would include TOF spectra, time-of-flight path length, neutron energy, neutron spectra background correction, efficiency correction, range (thresholds), method of measurement.

Accordingly, the following actions were taken:

An **Action** was placed on B. Singh and G. Mukherjee to involve their groups in this digitization effort and to use digitization software distributed by the IAEA NDS (NRDC software: http://www-nds.iaea.org/nrdc/nrdc_sft).

An **Action** was placed on J.L. Tain to prepare a sample EXFOR file on measurements of delayed neutron emission probabilities, and on K. Rykaczewski and D. Cano-Ott to prepare a sample EXFOR file on measured delayed neutron energy spectra.

The possibility of including delayed neutron emission probabilities and spectra from other data libraries, such as ENDF/B VII.1, JENDL, and JEFF in the Reference Database was also discussed. As the latter data libraries contained mostly P_n from the compilation of Rudstam et al.¹, and calculated neutron energy spectra obtained from the CGM model⁵, the conclusion was that they could be of use mainly for performing systematic comparisons.

2.1.6 Systematics and Theoretical Predictions

Not all decay properties of neutron-rich nuclei (as $T_{1/2}$, P_n , energy spectra) required for applications in reactor technology and nuclear astrophysics can be measured, as the nuclei cannot be produced by present day technologies. For these cases, the decay properties must be obtained from theoretical models. The adjustable parameters of the models have to be fitted to experimental data, with the majority of these data being nuclei close to the valley of stability. The reliability of the extrapolative power of the models will be improved considerably with the availability of experimental data on extremely neutron-rich nuclides from the future radioactive ion-beam facilities.

Empirical formulas have been widely used in the past to describe the systematics of β -delayed P_n -values. At present, the available systematics are as follows

- 1) Kratz-Herrmann formula¹⁶, which is still widely applied today, and describes the P_n values in terms of energies Q_β and the neutron separation energies S_n
- 2) McCutchan et al.¹⁷, which is similar to the approach of (1) but describes P_n in terms of $(Q_\beta - S_n)$ and the β -decay half-life $T_{1/2}$.
- 3) Miernik¹⁸, which describes the P_n values in terms of nuclear level density of the β -decay daughter nucleus.

¹⁶ K.-L. Kratz, G. Herrmann, Z. Phys. 263 (1973) 435.

¹⁷ E.A. McCutchan, A.A. Sonzogni, T.D. Johnson, D. Abriola, M. Birch, and B. Singh, Phys. Rev. C 86 (2012) 041305(R).

As it would be useful to compare the predictions of these different approaches with the measured and adopted P_n values, it was agreed that an effort would be made to make these results available on the Reference Database. The development of an online calculation tool to provide and/or re-calculate these values ‘on-the-fly’ will also be considered.

More sophisticated calculations have been performed by several groups:

- a) Möller et al.¹⁹ have calculated ground state decay properties for all particle-stable nuclides with the macroscopic-microscopic QRPA model²⁰. A drawback of these calculations is the fact that only the Gamow-Teller (GT) β -decay mode is included. Near magic numbers, e.g., the first-forbidden decay branches can dominate the gross decay properties half-lives and delayed-neutron branching ratios. In a subsequent paper from 2003¹³, first-forbidden β -strength from the Gross-theory of β -decay²¹ was added heuristically to the calculated GT-strength.
- b) Borzov²² calculated β -decay $T_{1/2}$ and β -delayed neutron emission probabilities applying the finite range droplet mass (FRDM) model and a continuum-QRPA approach based on the self-consistent ground state description in the framework of the nuclear-energy density functional theory (DFT). Until now, the algorithms are restricted to spherical nuclei, and should only be applied to isotopes near magic numbers which have only small ground-state deformations.
- c) Marketin et al. are working on producing a comprehensive table of β -delayed neutron emission probabilities for all nuclei, both spherical and deformed, across the whole neutron-rich region of the nuclear chart. They are using the covariant density functional theory (DFT) for the description of the ground state of the nuclei, with the proton-neutron relativistic QRPA to describe the excited states and the transition strengths between the two, in a completely self-consistent way.

CRP participants I. Borzov and T. Marketin will provide their calculated $T_{1/2}$ and P_n values for comparison with the evaluated/adopted values in the Reference Database. A link to the online version of the article of Möller et al.¹³ will also be provided.

Apart from the nuclear structure models mentioned above, there have also been efforts to combine nuclear structure and decay models for the description of emitted γ - and delayed-neutron spectra simultaneously. The Neutron and Gamma Decay Code “CGM” (Cascading Gamma and Multiplicity) developed by Kawano⁵ is based on the combination of the QRPA model^{19,20} for β -decay and the Hauser-Feshbach statistical model for γ -decay. This method allows calculation of not only the gross decay properties ($T_{1/2}$ and P_n), but also delayed-neutron energy spectra. In Kawano et al.²³ energy spectra for 271 precursors are calculated and compared with the 36 measured spectra contained in the ENDF decay library.

This effort will be extended by exploring the possibility of coupling other β -decay models, such as the Gross Theory and (b)-(c) mentioned above, with other statistical model codes, namely, EMPIRE and TALYS. A systematic comparison of the γ and delayed-neutron emission spectra produced by the various codes will provide insight into the performance of

¹⁸ K. Miernik, Phys. Rev. C 88 (2013) 041301(R).

¹⁹ P. Möller, J.R. Nix, K.-L. Kratz, At. Data Nucl. Data Tables 66 (1997) 131.

²⁰ P. Möller, J. Randrup, Nucl. Phys. A 514 (1990) 1.

²¹ K. Takahashi, Prog. Theoret. Physics 47 (1972) 1500.

²² I.N. Borzov, Nucl. Phys. A 777 (2006) 645.

²³ T. Kawano, P. Möller, W.B. Wilson, Phys. Rev. C 78 (2008) 054601.

the nuclear structure models, and also shed light on the capabilities of the codes to describe the competition between γ and neutron emission. This will improve our understanding and description of the measured delayed neutron spectra.

New efforts to measure delayed-neutron energy spectra will also be undertaken within the CRP (see Appendix 3).

2.1.7 Aggregate delayed-neutron data

Aggregate data directly associated with the kinetics and safety operations of nuclear reactors (including the Accelerator-driven systems, ADS) are the absolute total yield of delayed neutrons, the relative abundances of delayed neutrons and half-lives of their precursors, and the energy spectra of delayed neutrons. Despite all the efforts devoted to improving the time-dependent delayed neutron data, the problem of choosing the most adequate delayed-neutron parameter set for a reactor with a specific neutron spectrum still persists. As a result, the recommended set of delayed neutron parameters for major fissile isotopes is still the one derived from one experiment (Keepin^{24,25}). The reason for this is the high quality of Keepin's data and the absence of a reliable procedure for averaging the appropriate data obtained in experiments with different experimental conditions such as background, different time sequence, data processing method etc.

One of the major tasks of this CRP is to re-evaluate the delayed-neutron parameter set on the basis of new measurements and systematics of delayed neutron constants (a_i, T_i)²⁶. These results will also be compared with the results of the microscopic approach which is based on applying the summation method on the P_n and $T_{1/2}$ values of the individual fission fragments proposed by the reference database, and the cumulative fission yields from an existing library such as ENDF/B-VII.1 and/or JEFF. Nubars and delayed-neutron group spectra will also be compared with those produced by the summation method. This systematic comparison will thus provide a means of validating the $P_n, T_{1/2}$ values and delayed-neutron spectra recommended in the reference database.

These comparisons could be displayed in the macroscopic data section in a tabular format as follows:

Thermal ($n+^{238}\text{U}$): delayed neutron properties

Fission Product	P_n (adopted)	$T_{1/2}$ adopted	neutron spectra (yes/no)	$Y_i(\text{JEFF})$	ν_d contribution
^{136}Xe					
Total			(Total n spectrum)		(Total ν_d)

²⁴ G.R. Keepin, T.F. Wimett, and R.K. Zeigler, Phys. Rev. 107 (1957) 1044.

²⁵ G.R. Keepin, "Physics of Nuclear Kinetics", Addison-Wesley Publishing Company, Inc., series in Nuclear Science and Engineering, Library of Congress Catalogue card no. 64-20831 (1965).

²⁶ V.M. Piksaikin, A.S. Egorov, K.V. Mitrofanov, INDC(NDS)-0646, Vienna, October 2013.

The database could also provide tables of calculated v_d (summation method) from different sources as follows:

Thermal ($n+^{235}\text{U}$): v_d

Fission Yields →	JEFF	ENDF/B
Source for P_n ↓				
Möller 2003				
Pfeiffer 2002				
ORNL2013				
Wilson/ Brady				

The problem of fission yields was extensively discussed as it was widely accepted that they are the source of the largest uncertainties when applying the summation method. In particular, it was noted that the independent fission yields of ^{235}U were low by a factor of 3, therefore it was recommended that cumulative fission yields be used for the summation method, and that they should be taken from the JEFF library.

An **Action** was placed on R. Mills, V. Pikaikin, and A. Sonzogni to provide input on the sensitivity of aggregate delayed-neutron data on the microscopic data for individual precursors.

3 Conclusions

The First Research Coordination Meeting (RCM) on the development of a Reference Database for β -delayed neutron emission data was held at the IAEA, Vienna, from 26 – 30 August 2013.

Participants reviewed the current status with respect to measured and evaluated delayed-neutron data, and the emerging data needs for reactor applications, and basic sciences such as nuclear astrophysics and nuclear structure.

It was agreed that the new database would consist of two separate sections, one for microscopic delayed-neutron data for individual precursors, and the other for macroscopic data delayed neutron data such as nubar, group parameters, and delayed group spectra. These two sections would be linked through a validation process, by which the recommended P_n and $T_{1/2}$ microscopic data and individual precursor neutron spectra would be combined with suitable fission yields through the summation method to provide estimates of the corresponding aggregate quantities. The database format, as well as the creation of a common workplace for CRP participants to access documents, evaluation spreadsheets and codes was proposed.

Regarding the evaluation of standards and existing data for individual precursors, the participants discussed the methodology, produced a list of new data to be included in the database and also agreed on a priority list for new measurements. It was also recommended that predictions of delayed-neutron systematics and theoretical models be included in the database.

The work plan of the participants was presented and a list of assignments to be completed until the next RCM was produced and adopted (see Appendix 3). The next RCM was proposed to take place in early spring of 2015.

**1st Research Coordination Meeting on
Reference Database of Beta-Delayed Neutron Emission**

IAEA, Vienna, Austria
26-30 August 2013

Meeting Room VIC A0742

AGENDA

Monday, 26 August

08:30 - 09:00 **Registration** (IAEA Registration desk, Gate 1)

09:00 - 9:30 **Opening Session**

Welcoming address and Introduction
Election of Chairman and Rapporteur
Adoption of Agenda
Administrative matters

9:30 - 12:30 **Presentations by participants (about 40 min each)**

1. *A comprehensive approach to determine delayed-neutron data – mass yield measurement, calculations of independent yield, decay heat and delayed neutrons*, S. Chiba, Tokyo Inst. of Technology, Japan
2. *An analysis of incident neutron energy dependence of β -delayed neutrons*, F. Minato, JAEA, Japan
3. *Systematics of Pn and P2n decay*, T. Johnson, BNL, USA

Coffee break as needed

12:30 – 14:00 **Lunch**

14:00 – 18:00 **Presentations by participants (cont'd)**

4. *Emission of β -delayed one- and two-neutrons including neutron-gamma correlations studied at Oak Ridge*, K. Rykaczewski, ORNL, USA
5. *Recent results on Pn-values with the BELEN 4pi neutron counter and future measurements*, J. Tain, IFIC-Univ. Valencia, Spain
6. *Opportunities for measurements of β -delayed neutron emitters at the TRIUMF radioactive beam facility and the GRIFFIN and DESCANT spectrometers*, P. Garrett, Univ. of Guelph, Canada
7. *Measurements of β -delayed neutron emission probabilities: possibilities at VECC, Kolkata*, G. Mukherjee, VECC, India

Coffee break as needed

Tuesday, 27 August

09:00 - 12:30 Presentations by participants (about 40 min each)

8. *Towards a reference database for β -delayed neutron precursors*, B. Singh, McMaster Univ., Canada
9. *Components of a reference database for β -delayed neutron emission*, D. Abriola, Tandem Lab., Argentina
10. *Plans for evaluation of β -delayed neutron emission data for some FP nuclides*, X. Huang, CNDC, China
11. *Simple estimates of β -delayed neutron spectra*, A. Sonzogni, BNL, USA

Coffee break as needed

12:30 – 14:00 Lunch

14:00 – 18:00 Presentations by participants (cont'd)

12. *Beta delayed neutron data for advanced reactor technologies*, D. Cano-Ott, CIEMAT Madrid, Spain
13. *Absolute total delayed neutron yields, relative abundances and half-lives of delayed neutron groups in 6- and 8-group model format from neutron induced fission of ^{232}Th , ^{233}U , ^{236}U , ^{239}Pu , and ^{241}Am in the energy range from 0.35 MeV (or threshold energy) to 5 MeV*, V. Piksaikin, IPPE, Russia
14. *Calculation of delayed neutron emission from fission and fitting results to few group approximations*, R. Mills, National Nuclear Laboratory, UK
15. *Beta-delayed neutron emitters for reactor antineutrino energy spectra*, M. Fallot, SUBATECH-Univ. Nantes, France

Coffee break as needed

19:00 Dinner in a restaurant (see separate information)

Wednesday, 28 August

09:00 - 12:30 Round Table Discussion

Following presentations made by K. Rykaczewski

16. *North-American Workshop on Beta-delayed neutron emission: Summary*
17. *Microscopic Approach to β -delayed-neutron emission*, I. Borzov, IPPE
18. *Energy-resolved β -delayed neutron spectroscopy of fission fragments with VANDLE*, R. Grzywacz, UTK/ORNL
19. *New statistical formula for β -delayed neutron emission probability*, K. Miernik, ORNL/U. of Warsaw

Coffee break as needed

12:30 – 14:00 Lunch

14:00 – 17:30 Round table discussion (cont'd)

Coffee break as needed

Thursday, 29 August

09:00 - 12:30 Round Table Discussion

Coffee break as needed

12:30 – 14:00 Lunch

14:00 – 17:30 Round table discussion (cont'd)

Coffee break as needed

Friday, 30 August

09:00 - 13:00 Drafting of the meeting summary report

Coffee and lunch break(s) in between

13:00 Closing of the meeting

**1st Research Coordination Meeting on
Reference Database of Beta-Delayed Neutron Emission**

IAEA, Vienna, Austria
26 – 30 August 2013

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List of Actions

As of 30-08-2013

No.	Responsible	Action
1	NDS-IAEA/P. Dimitriou	Collect conf. proceedings on bDN and upload on CRP website
2	I. Dillmann, B. Singh, K. Rykaczewski, J.L. Tain	Provide IAEA with list and links and files of older and current PhD theses concerned with P_n data
3	All participants with access to aggregate data	Send aggregate data to NDS-IAEA/P. Dimitriou
4	I. Dillmann, P. Garrett, M. Fallot J.L. Tain, K. Rykaczewski,	Keep evaluators updated about new data
5	J.L. Tain, D. Cano-Ott, G. Mukherjee, K. Rykaczewski	Review the DN energy spectra which have been used as a reference for efficiency calibration purposes
6	D. Abriola, I. Dillmann, B. Singh	Check for possible DN P_n standards for A=20-72 mass region
7	P. Garrett (TRIUMF)	Send new ^{94}Rb data on DN P_n and $T_{1/2}$ to Abriola-Dillmann-Singh for re-evaluation of standards
8	D. Abriola, I. Dillmann, B. Singh	Re-evaluation and addition of standards
9	B. Singh	Make sure that fine-structure DN data branches are made available in ENSDF or XUNDL
10	T. Johnson, A. Sonzogni	Provide experimental and evaluated DN energy spectra existing in other databases and relevant references to NDS-IAEA/P. Dimitriou
11	G. Mukherjee, X. Huang	Select nuclei in A=72-150 region for evaluation and send to B. Singh
12	D. Abriola, I. Dillmann, B. Singh, A. Sonzogni, E. McCutchan, T. Johnson, M. Birch	Publish Evaluation of DN $P_n+T_{1/2}$ of A<72 nuclei
13	All participants	Send relevant articles on DN P_n and energy spectra to NDS-IAEA (P. Dimitriou) for compilation
14	J.L. Tain, K. Rykaczewski, D. Cano-Ott	Prepare sample EXFOR files for DN P_n and energy spectra from different types of measurements
15	B. Singh, G. Mukherjee	Contribute to effort of digitizing DN spectra
16	NDS-IAEA (P. Dimitriou, M. Verpelli)	Prepare preliminary version of bDN Database with microscopic

		data for $A < 72$
17	V. Piksaykin, R. Mills, A. Sonzogni, D. Cano-Ott, K. Rykaczewski, S. Chiba, F. Minato, M. Fallot	Prepare high-priority list of nuclides important for applications (reactor kinetics and equilibrium) based on an inter-library comparison (JEFF, ENDF/B, JENDL) and sensitivity check of macroscopic data (ν -bar, group parameters) with respect to the microscopic quantities such as P_n and fission yields included within each library
18	P. Dimitriou, K. Rykaczewski, J.L. Tain, F. Minato	Contact astrophysics community for recommendations on nuclei or mass regions where bDN has impact on r-process nucleosynthesis
19	I. Dillmann, P. Garret, J.L. Tain, K. Rykaczewski,	Prepare a priority list of nuclides with DN P_n that are important for nuclear structure studies

Work Plan
Until 2nd RCM

Participant	Institute	Countryry	Proposed Work
I. Borzov	IPPE	Russia	New DF3+CQRPA calculations of β -decay rates and DN P_n for key quasi-spherical nuclei. Comparison s of new calculations with data from HRIBF and GSI. Combine with HF code to get DN P_n and energy spectra
D. Cano	CIEMAT	Spain	Experiment using BELEN at IGISOL-JYFL (proposal by Gomez-Hornillos, Tain). Experiment with MONSTER at IGISOL-JYFL (Sps: Cano and Tain). (to be scheduled) Review of different sensitivity studies on bDNs for reactors. Characterization of new scintillators to be used as neutron detectors at metrology labs.
S. Chiba	Tokyo Inst. Techn.	Japan	Construction of apparatus for surrogate method to measure FFMD. Extension of Langevin Eqs to predict independent FYs. Use DN P_n and $T_{1/2}$ data produced by CRP to improve the Gross Theory.
M. Fallot, A. Porta	SUBATECH-Nantes	France	Preparation of a new TAS experiment proposal on bDN emitters in collaboration with IFIC (Tain) and submission to JYFL PAC or ALTO facility.
P. Garrett I. Dillmann A. Chen B. Singh	Univ. Guelph TRIUMF McMaster Univ.	Canada	Commissioning of DESCANT and GRIFFIN Publications of 8π results on n-rich Rb isotopes Measurements @ TRIUMF (3Hen) Evaluation of bDN with $A < 72$ -start on fission mass region
G. Mukherjee	VECC	India	Literature survey and compilation-evaluation of existing bDN data. Characterization and testing of neutron detector systems developed at VECC which will be part of MONSTER.
V. Piksaikin	IPPE	Russia	Least-squares fit of DN decay curves for each isotope to obtain 6- and 8-group models at E_n . Obtain Covariance data for delayed neutron parameters (a_i, T_i). Produce new data: 1) (a_i, T_i) for main reaction

			nuclides for energies 14-18 MeV and 2) DN spectra from thermal fission of ^{235}U
K. Rykaczewski, R. Grzywacz	ORNL	USA	Submission of HRIBF data on fission products. Preparation of approved experiments at TRIUMF ISAC-1 and CARIBU-ANL.
J.L. Tain	CSIC-U. Valencia	Spain	Exp. With BELEN at IGISOL-JYFL in 2013 (same as Cano) to measure Ge, As, Br, Y and Sb isotopes. Contribution to new evaluation of old DN P_n data. New sensitivity study to identify additional DN emitters of interest in advanced nuclear reactors. Provide data on DN emitters, $T_{1/2}$ and P_n from GSI measurements.
X. Huang	CNDC	China	Evaluation of selected potential FP nuclides (A=100-150 region to be shared with VECC and McMaster): review and collection of measured data, assessment of exp. technique and use of suitable averaging method.
F. Minato	JAEA	Japan	Calculate DN emission with Ohsawa's approach: make computer code to calculate DNY and investigate energy dependence of FF. Provide results of Skyrme-Hartree-Fock calculations of DN $T_{1/2}$ values (even-even nuclei)
T. Marketin	Univ. of Zagreb	Croatia	Extend Covariant DFT to treat FF transitions. Employ finite amplitude method to solving relativistic QRPA eqs., including deformation. Goal is to calculate β -decay rates for all nuclei, both spherical and deformed.
Advisors			
D. Abriola	Tandar Lab	Argentina	Evaluation of bDN with A<72
A. Sonzogni, T. Johnson E. McCutchan	BNL	USA	Systematics for P_{2n} . Sensitivity study to identify most relevant bDN emitters to delayed nu-bars. Perform first experiment for ^{138}I to measure decay and $T_{1/2}$ (provided the exp. is scheduled at CARIBU). Calculation of DN energy spectra. Contribute to evaluation and documentation effort.

R. Mills	NNL	UK	Benchmarking studies of new evaluated DN P_n database for nu-bar using existing fission product yields and potentially 8-group parameters
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**Experimental Data
to be delivered by 2nd RCM (winter/spring 2015)**

	Experimental Data	Isotopes
1	K. Rykaczewski	Submitted: $^{85,86}\text{Ga}$ (^{86}Ge) (P_n) To be submitted: ^{72}Fe , ^{86}Ge (decay schemes) In preparation: ^{84}Ga , ^{77}Cu +27other (DN energy spectra) MTAS in preparation: 22 nuclei (decay heat) TRIUMF scheduled: $^{79,80,81}\text{Ga}$, ^{83}Ge (P_n) CARIBU to be scheduled: $^{109,110}\text{Mo}$, A=136,137 (All)
2	P. Garret	To be submitted: ^{102}Rb (P_n) To be analyzed: $^{98,100,101}\text{Rb}$ (P_n) To be analyzed: $^{52,53}\text{K}$ (P_n) Scheduled: $^{32,33}\text{Mg}$ (P_n)
3	J.L. Tain	BELEN To be submitted: ^{85}Ge , $^{85,86}\text{As}$, ^{91}Br (P_n) Few isotopes \sim ^{132}Sn , ^{210}Tl ($P_n+T_{1/2}$) Approved: ^{86}Ge , $^{98+m,99}\text{Y}$, $^{135-137}\text{Sb}$, $^{139,140}\text{I}$ (P_n) TAS To be submitted: $^{86-88}\text{Br}$, $^{91-94}\text{Rb}$ (All)
4	D. Cano-Ott	MONSTER (spectra) Approved: $^{94,95}\text{Rb}$, ^{88}Br , ^{137}I (spectra)
5	M. Fallot	TAS To be measured: ^{138}I (All)
6	RIKEN	bDN emitters $T_{1/2}$ (to be added later)
7	CARIBU	bDN trap (to be added later)

Summary of Presentations

A comprehensive approach to determine delayed-neutron data – mass yield measurement, calculations of independent yield, decay heat and delayed neutrons (Satoshi Chiba, Tokyo Institute of Technology, Japan)

Delayed neutron data is one of the key information for evaluation of kinetics and reactivity of nuclear reactors and other nuclear facilities including accelerator-driven systems for nuclear-waste transmutation. Estimation of the delayed-neutron data requires a comprehensive knowledge on the fission of relevant nuclei, namely, how the fission fragments are populated in nuclear chart (independent yield) and how these neutron-rich nuclei decay toward stable ones. They are also related closely to the problems of decay heat and emission of reactor antineutrinos, the latter attains strong recent interest since it is related to the reactor-neutrino oscillation and possibility of reactor monitoring for non-proliferation of nuclear materials. However, there are still many open problems left in this field because the physics of fission and neutron-rich nuclei are complicated and actually are matters of the front-edge nuclear physics.

In our approach, we will conduct the following comprehensive researches systematically to improve our knowledge on the delayed neutrons as collaboration between Tokyo Tech. and JAEA as a 4-year project supported by MEXT:

1. Measurement of fission fragment mass distribution (FFMD) data by the surrogate method with heavy-ion projectiles [1]. It will yield excitation energy dependence of FFMD and data for minor actinides which are hard to be obtained by other methods.
2. Estimation of the independent fission yield by a multi-dimensional Langevin model calculation which is tuned to reproduce the FFMD data obtained in item 1[2].
3. Gross theory of β -decay will be extended to reproduce available up-to-date data for the half lives of β -decay, spectra of β -rays and γ -rays, and delayed neutron emission probabilities of relevant nuclei. Then, it will be used to estimate the decay heat, delayed-neutron emission and emission of antineutrinos (including their spectra) of nuclei for which no data are available.

After these researches yielded some results, the following will be done successively:

4. A statistical decay model based on the Hauser-Feshbach formula will be fully employed in conjunction with items 2 and 3. In item 2, it will be used to estimate prompt neutron emission which modifies the independent fission yields. In item 3, the statistical decay model estimates the delayed-neutron emission probability and spectra of delayed neutrons.
5. A temporary evaluated nuclear data library will be generated and tested against integral data. This information will then be used to further update various components emerging from items 2 to 4 until a satisfactory agreement is obtained.

In the present RCM, present status of items 1 to 3 will be introduced.

References

- [1] S. Chiba et al., Nuclear Data Sheets (in print).
 [2] Y. Aritomo and S. Chiba, arXiv:1305.6132 (submitted to Phys. Rev. C).

Summary Report on “An Analysis of Incident Neutron Energy Dependence of beta-delayed Neutron” (F. Minato, Japan Atomic Energy Agency, Japan)

We discussed incident neutron energy (E_n) dependence of beta-delayed neutron yields (DNYs) produced by neutron-induced fission. According to nuclear data evaluations on the open market and several theoretical calculations, the energy dependence can be separated into three parts. The first part is moderate change from thermal and resonance regions to $E_n \sim 4$ MeV, and the second is steep decrease from $E_n \sim 4$ to 7 MeV. The third is slow decrease at high E_n region.

We first discussed the moderate change from thermal to MeV region. In this energy region, Y_i at resonances were totally smaller than that at the thermal neutron energy. As a result of this resonance dependence, the DNY gave slight increase toward $E_n \sim$ MeV region. Next, we discussed the steep descent from $E_n \sim 4$ to 7 MeV. We gave several examples which were able to explain the energy dependence. First one was the effect of second- & third-chance fissions, but it did not give any conclusive influences on the energy dependence. “Would-be Precursor” and Odd-Even effect provided a reasonable result for the energy dependence. In particular, excitation energy and charge distributions to fission fragments were shown to be important to obtain accurate energy dependence. We also pointed out the effect of decrease of fission fragment being precursor. Then, we discussed the slow decrease at high E_n region. In this energy region, there are only a few experimental values. Therefore, simulation calculation may be a powerful tool. Considering the energy dependence of Y_i , namely, increasing fraction of symmetric fission, the energy dependence of DNY should give a slight decrease. We plan to examine this energy dependence by the next CRP meeting.

We also introduced some preliminary results of our microscopic calculations. Our formalism is based on SHF+BCS & proton-neutron QRPA. $T_{1/2}$ of $Z=50$, 82 isotopes and $N=126$ isotones were calculated. In addition, P_n of $Z=50$ isotopes and $N=82$ isotones were shown. $T_{1/2}$ were reasonably reproduced, while the results of P_n were not good accuracy comparing with experimental data. We also showed problems in the decay-scheme around heavy nuclei where first-forbidden transition becomes important. The microscopic calculation may help providing P_n data, however several improvements were still required. We plan to calculate all the even-even nuclei systematically and extend our formalism to odd-nuclei, looking for appropriate improvements.

Microscopic approach to beta-delayed neutron emission (I.N. Borzov, Institute of Physics and Power Engineering, Russia)

Reliable decay data for neutron-rich fission products are of value for supercomputer modeling of the processes in nuclear power reactors and in astrophysical environments. In particular, inadequate decay data for short-lived nuclei reduce an accuracy of summation codes in estimating the absolute delayed neutron yields or reactor decay heat for the short cooling times. The complete set of beta-decay data for short-lived nuclides is needed for the FRIB applications and astrophysical r-process modeling. The vast majority of these nuclides are still experimentally unknown. Thus, a new reference database of evaluated half-lives and beta-delayed neutron emission rates should include reliable theoretical data obtained via large scale nuclear structure calculations.

The beta-decay models based on the Gross Theory use schematic treatment of nuclear structure but have a global applicability. Extreme sensitivity of the beta-rates to nuclear structure effects calls for the microscopic approaches based on the shell-model and charge-changing quasiparticle random-phase approximation (pnQRPA). The macroscopic-microscopic finite-range droplet models FRDM+RPA(deformed) [1a], FRDM+RPA(spherical) [1b] are restricted by the allowed Gamow-Teller decays. The FRDM+RPA+GrossTheory [2] inconsistently applies a quantum description for allowed β -decay transitions and statistical “gross theory” treatment for the first-forbidden decays. These models have added a lot to our understanding of the global beta-decay properties. They were based on schematic nuclear structure framework (P. Moeller, J. Randrup, 1990) constrained by computer performance limitations existed at that time. In contrast to the extended pnQRPA model [3], these models ignore particle-particle NN-interaction.

A reliable extrapolation of nuclear spin-isospin response far off stability is based on the universal nuclear density functional and efficient supercomputer techniques (*see e.g. <http://www.unedef.com>*). Both self-consistent studies (see Refs.5-6) and experimental β -decay measurements far from stability (see e.g. Refs. 10, 12-15) often have shown deviations from the FRDM+BCS+RPA predictions, especially near the closed shells. Our self-consistent approach [5] treats the β -decay half-lives ($T_{1/2}$) and β -delayed neutron emission probabilities (P_n) on the same microscopic footing both for the Gamow-Teller (GT) and first-forbidden (FF) decays. The masses and other ground state properties are derived self-consistently with the Fayans density functional DF3 [4a] and its modification DF3a [4b]. The excited states are treated in the continuum QRPA (CQRPA) approach which is free of the single-particle basis truncation. The (A -independent) effective nucleon-nucleon (NN) interaction contains the contact Landau-Migdal part and one-pion and rho-meson exchanges in the ph channel. An important role is played by the effective NN-interaction in the proton-neutron “ $T=0$ pairing” channel.

The DF+CQRPA model [5] is tailored to (near) spherical nuclei. It provides agreeable description of about 400 isotopes near closed shells with small ground-state deformations including the fission products and r-process nuclei near the “waiting points”. The approach is non-relativistic. Self-consistent relativistic HFB+pnRQRPA calculations with DD-ME1 functional [6] using the allowed GT-approximation have been applied to the of the beta-decay half-lives of the even-even nuclides in $Z\sim 28$, $N\sim 50$ region.

The demanding extension of the self-consistent framework would be inclusion of the deformation. Deformed self-consistent Skyrme-Hartree-Fock calculations of the beta-decay

properties for even-even nuclides in Zr, Mo region were performed in [7]. The allowed GT approximation and separable NN ph and pp interactions were used. Non-self-consistent GT+FF deformed calculations of the beta-rates with Bonn-CD interaction have been recently performed [8] for $Z=36-43$ region. The framework includes a number of strong approximations, namely restricted ph and pp bases, phenomenological shifts to the excitation energies in odd-A and odd-odd nuclei, local fitting of the pp-interaction strength. Finally, a valuable “data behavior check” is given by the artificial neural network (ANN) modeling [9] which can be treated as a complement to microscopic studies of the beta-rates.

Performance of fully microscopic approach can be exemplified by comparison with extremely neutron-rich nuclides in the region of light fission products. Unusual nuclear structure features have been found in the recent experimental beta-decay studies beyond $Z=28$ and $N=50$ shells: new sub-shell closure at $N=58$ [10]; weakening of the 78Ni core which causes ground-state spin inversion [11]. A drastic change of the single-particle pattern (inversion of the $1f_{5/2}$, $2p_{3/2}$ ground states) has a significant impact on the **β -decay half-lives and β -delayed neutron emission probabilities**. First, with neutrons filling the positive parity $1g_{9/2}$, $2d_{5/2}$ and $3s_{1/2}$ states and protons occupying negative parity $1f_{5/2}$, $2p_{3/2}$ states, the high transition energy first-forbidden (FF) decays start to compete with the allowed decays due to their higher phase spaces. In a fully microscopic framework such a concurrence results in reduction of the half-lives and total Pn-values compared to a pure Gamow-Teller (GT) approximation. Second, in the region beyond $N=50$, the beta-rates reveal a strong sensitivity to both parent ground-state spin inversion and level ordering in the neutron and proton shells.

The half-lives and delayed neutron probabilities (DN Pn-values) of the Cu to As isotopes beyond $N=50$ shell have been measured recently at HRIBF ORNL using radioactive beam purification and tagging technique with efficiency calibrated γ -ray detectors [12-15]. The experiments have clearly shown that the reference global GT model [1], as well as semi-statistical GT+FF model [2] fail to reproduce both old and newly measured half-lives and DN Pn-values of neutron-rich Zn and Ga nuclei beyond the shell closure at $N=50$ (see Fig 1).

The new data for Zn [8] and Ga isotopes [9] call for refinement of the microscopic DF+CQRPA approach [5]. It was augmented by blocking approximation allowing one to fix the odd proton in $1f_{5/2}$ orbital and, thus properly describe the ground state spins of the parent (and daughter) isobaric companions. In this way we have explained an increased delayed neutron emission in Cu isotopes found in purified radioactive beam experiments [12]. In Zn, Ga, Ge and As isotopes an agreement with both known and new experimental half-lives [12-15] gives some confidence in extrapolation to more exotic nuclides. In Ga isotopes (Fig.1) a slowing down of the half-lives near new sub-closure of $N=58$ agrees with the measured half-

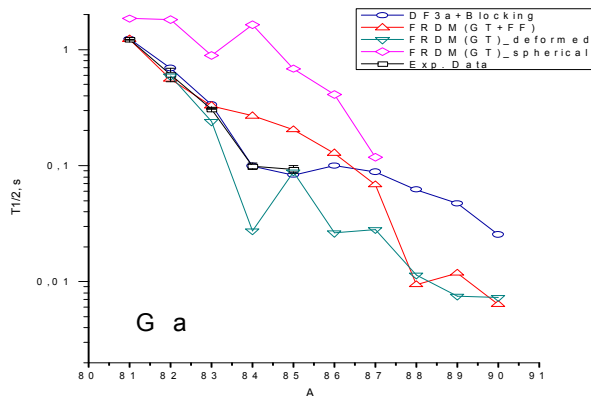


Fig. 1 Beta-decay half-lives of spherical Ga isotopes calculated in DF3a+CQRPA for 1f5/2 g.s. spin-parity assignment for the parent Ga nuclei. Comparison is given to the FRDM (deformed GT approximation) [1a], FRDM (spherical GT approximation) [1b], FRDM (GT+FF approximation) [2], experimental data from NUBASE and new data from HRIBF ORNL for A=84,85 [10].

life of ^{85}Ga [14]. The new data support a **reduction of the total delayed neutron emission probabilities** due to the high-energy FF transitions. It was predicted in [5] in the regions beyond the N=50, 82 shells [5, 16] and especially near N=126 shell [17]. Multi-neutron delayed neutron emission rates in these regions are also reduced. Important physics is “hidden” in detailed distribution of the beta-strength within the multi-neutron emission subspaces confined by the $Q_{\beta xn}$ windows. The uncertainties in the $Q_{\beta xn}$ windows and fragmentation of the GT and FF beta-strengths are directly translated to the DN P_{xn} values. High probability of delayed 2n-emission in ^{86}Ga recently obtained in [18] is in agreement with our calculations both with exact [19] and a simple account for spreading width in the CQRPA [20]. A prescription by [20] is implied to estimate of the lower and upper limits of DN Pn-values (see Table).

Plans. The calculations of the β -decay rates and delayed neutron emission probabilities for key quasi-spherical nuclei near $Z\sim 28$, $N\sim 50$, $Z\sim 50$, $N\sim 82$, $Z\sim 60-80$, $N\sim 126$ will be used for the present evaluation. Implementing the new DF3a functional into the HFB ground state code for deformed nuclei is planned. The link of the DF+CQRPA output is foreseen to the statistical Hauser-Feshbach framework for better treatment of delayed neutron (and delayed cluster) emission and delayed particle spectra. A sensitivity check with respect to the microscopic beta-strength functions will be performed for the nuclear structure characteristics (DN Pn values and spectra), macroscopic reactor data (absolute DN yields for different fissioning systems and group parameters) and the r-process abundances.

References

- [1a] P. Moeller et al., At. Dat. Nucl. Dat. Tab. 66, 131 (1997).
- [1b] B. Pfeiffer et al., Ann. Nucl. Energy 41, 39 (2002).
- [2] P. Moeller et al., Phys.Rev. C 67, 055802 (2003).
- [3] K. Grotz, H.-V. Klapdor, “Die Schwache Wechselwirkung in Kernteilchen- und Astrophysik”, Stuttgart, 1989.
- [4a] S.A. Fayans, S.V. Tolokonnikov, E. Trykov, D. Zawischa, Nucl. Phys. A 676, 49 (2000); I.N. Borzov, S.A. Fayans, E. Kromer, D. Zawischa, Z. Phys. A335, 117 (1996)
- [4b] S. V. Tolokonnikov, E. E. Saperstein, Phys. At. Nucl. 73, 1684 (2010).
- [5] I.N. Borzov, Phys. Rev. C 67, 025802 (2003); Phys. Rev. C 71, 065801 (2005).
- [6] T. Marketin, D. Vretrenar, P. Ring, Phys.Rev. C 75, 024304 (2007).
- [7] P. Sarriguren, J. Pereira, Phys. Rev. C 81, 064314 (2010).
- [8] D. Fang, B.A. Brown, T. Suzuki, Phys. Rev. C 88, 024314 (2013).

- [9] N.J. Costiris, E. Mavromatis, K.A. Gernoth, J.W. Clark, Phys. Rev. C 80, 044332 (2009); nucl-th 1309.0540v1 (2013)
- [10] J.A. Winger et al., Phys.Rev. C81, 044303 (2010).
- [11] K.T. Flanagan et al., Phys.Rev.Lett. 103, 142501 (2010).
- [12] J.A. Winger et al., Phys.Rev.Lett. 102, 142502 (2010).
- [13] S. Padgett et al. Phys. Rev. C 82, 064314 (2010).
- [14] M. Madurga et al., Phys.Rev.Lett. 109, 112501 (2012).
- [15] C. Mazocchi et al., Phys. Rev. C 87, 03415 (2013).
- [16] I.N. Borzov, et al., Nucl.Phys. A 814, 159 (2008).
- [17] I.N. Borzov, Phys. At. Nucl. 74, 1435 (2011).
- [18] K. Mernik et. al., in Phys.Rev.Lett. 111, 132502 (2013).
- [19] A.P. Severukhin, V.V. Voronov, I.N. Borzov, N. Van Giai, JINR-Report-E4-2012-136.
- [20] G.F. Bertsch, Phys. Let. B95, 157 (1980).

Beta-decay half-lives and P_n -values in Ga isotopes with $N>50$.

A, Z		N	$J^\pi \square$ g.s.)	$T_{1/2}$ (exp)		Branching (%)	$T_{max-min} / P_n \text{ tot } min-max ;$ P_{xn}^* (DF3a+CQRPA)
82					β^-	100	
31	Ga	51	(1,2,3)	0.599 s 2	β_n	19.8 (10) 21.3 (13) ORNL	0,691 / 28,06
83					β^-	100	
31	Ga	52	5/2- Exp	0.308 s 10	β_n	62.8 (25) 37(17) ORNL	0,335 / 50,67
84					β^-	100	
31	Ga	53	(0-1,-)	0.085 s 10	β_n	47(10) ALTO 74(14) ORNL	0.099-0.087 / 16.1 – 37.6
85					β^-	100	
31	Ga	54	5/2- Exp	0.093 s 7 ORNL	β_n	-	0.106-0.083 / 35.5 - 76.1
86					β^-	100	
31	Ga	55	(0-,1-)	0.043 s+25-10 ORNL	β_n	60(10) P2n=20(10) ORNL	0,100-0.072 / 19.7 – 51.3; P_{1n}= 6.43 -27.9* P_{2n}= 11.5 – 22.05 P_{3n}= 1.56 – 0.9

If not labeled, the experimental data are from the NUBASE.

Emission of beta-1n and beta-2n including beta-neutron-gamma correlations studied at Oak Ridge (K.P. Rykaczewski, ORNL, USA)

Motivation for our decay studies of neutron-rich nuclei including beta-delayed neutron emitters

Decay rates of neutron-rich nuclei are important for understanding the origin of atoms and nuclei. Over 50% of nuclei heavier than iron were created in the process of multiple neutron captures and following β -decays that increase the atomic number with respect to parent activity. Therefore, β -decay rates are among critical input parameters to the simulations of rapid neutron capture process (r-process) path [1,2]. The neutron budget during the r-process is increased by the emission of neutrons from highly excited states populated in β -decay. The β -decay energies Q_β far from beta stability often exceed 10 MeV and reach the states populated by allowed Gamow-Teller (GT) transformation of a neutron into a corresponding proton state. These states are typically located above the neutron separation energy S_n in the daughter isotopes. Such β -decays are followed by emission of a neutron, or even multiple neutrons when the emission energy window $Q_\beta - S_{xn}$ has a positive value [3]. Most importantly, the β -delayed neutron emission is changing the r-process abundance pattern by changing the population of isobaric chains. The final abundance pattern is explored experimentally and often used a signature for the physics of Super Novae explosions. Therefore, the measurements of βn -emission are helping to analyze the mechanism and path of the r-process nucleosynthesis.

Beta-delayed neutron emission with a large energy window may end up at the excited state of the final nucleus. Further de-excitation towards the ground state results in the emission of gamma radiation, which is relatively easy to detect with good energy resolution. Such observation of γ -lines, in particular in time correlations with neutrons, unambiguously establishes and assigns the nuclear levels, i.e., it contributes to the tracking of nuclear structure evolution towards neutron-rich isotopes [3,4]. Beta-delayed neutron emission is directly related to the β -strength pattern and can help to determine the β -strength to unbound states.

Decay spectroscopy of neutron-rich nuclei, in particular of fission products has societal applications. Fission is powering nuclear reactors, and β -delayed emission plays an important role during the nuclear fuel cycle. The emission of γ -rays and electrons contributes about 8% to the total energy release in a nuclear reactor and it remains the only source of heating after the reactor shutdown. Beta-delayed neutron emission contributes at the level of 1% to the overall neutron budget in a power reactor. However, since it is a delayed emission with respect to the fission event, it allows us to control the criticality level during reactor operation. Since there are new designs using new nuclear fuel components pursued world-wide, the existing integral measurements might be not adequate. An ultimate solution would be to have a correct microscopic picture of the β -delayed neutron time dependence obtained from well-established fission yields and correct β -delayed neutron branching ratios P_n , preferably experimentally verified P_n values.

Holifield Radioactive Ion Beam Facility (HRIBF)

The experiments on neutron-rich radioactive nuclei described in the following sections were performed at the Holifield Radioactive Ion Beam Facility (HRIBF). HRIBF was operating at

Oak Ridge National Laboratory (ORNL) between 1996 and 2012 using the on-line isotope separation technique to produce radioactive ion beams. The HRIBF operation ceased recently, on 15th April 2012. HRIBF was producing beams of proton-induced ^{238}U fission products, at low energies of 40 keV to 200 keV, as well as beams post-accelerated in the 25 MV TANDEM to several MeV per nucleon [5]. The production of fission products was facilitated by protons at about 50 MeV energy and 15 μA intensity provided by the Oak Ridge Isochronous Cyclotron (ORIC) to irradiate about 6 to 7 grams of $^{238}\text{UC}_x$ target [5,6]. The radioactive beam intensity and isobaric purity for fission products was superior among the ISOL facilities world-wide. Interestingly, the intensity of 200 keV ^{86}Ga pure ion beam achieved in April 2012, was about 1000 ions per hour [3]. Gallium-86 is located 15 neutrons away from stable Ga isotope (^{71}Ga). This HRIBF rate was larger than the rate of ^{86}Ga achieved so far at RIKEN (Wako, Japan). RIKEN is presently the most powerful facility for fast neutron-rich beams resulting from the fragmentation and fission of 345 MeV/u ^{238}U beam at about 10 pA intensity [7].

There were several methods of radioactive beams purification developed at the HRIBF. First selection could be done at the ion source level. For some decay studies of beta-delayed neutron emitters, the extraction of molecular beams was performed [2]. Beams of $^A\text{GeS}^+$ were obtained by adding H_2S gas to the ion source cavity. The $^A\text{GeS}^+$ positively charged molecules had mostly mass (A+32), since ^{32}S has a 95% content in natural sulfur. The first stage mass separation selected (A+32) molecular ions and transmitted this low energy beam through a charge-exchange cell [5,6]. These molecular beams were contaminated by fission products of mass (A+32), e.g., ^{118}Ag abundantly produced in fission in $^{86}\text{Ge}^{32}\text{S}$ beams. The $^A\text{Ge}^{32}\text{S}$ molecule was broken in the charge-exchange cell and $^A\text{Ge}^-$ negative ions were extracted towards the second stage high-resolution mass separator. Second separator was suppressing ions originally present at (A+32) beams (like ^{118}Ag) selecting pure Ge (and As) beams for decay studies. Several beta half-lives of βn -emitters were measured and verified using this technique at the HRIBF. It included the first measurement of the ^{86}Ge half-life of 226(21) [2].

Laser ionization of fission products was also developed and applied on-line at the HRIBF, to select beams of Ga isotopes [8,3]. The intensities of sub-second activities of beta-delayed neutron emitters ^{83}Ga , ^{85}Ga and ^{86}Ga reached 12,000 pps, 100 pps and 1000 pph, respectively. A powerful beam purification technique employing post-acceleration of fission product beams was developed few years ago at the HRIBF. It is so called “ranging-out technique” based on the range difference in matter of ions with the same energy but of different atomic numbers [9-11]. The isobaric cocktail of post-accelerated ions at 2-3 MeV/u was transmitted through a gas cell. By adjusting the gas pressure, the beam component with the lowest atomic number among the isobars, but having the largest range, was transmitted beyond a thin exit window of the gas cell. Other higher-Z isobars were stopped in the gas and exit window. The gas cell was simultaneously acting as an ionization chamber detector allowing us to identify and count ions. It resulted in the measurements of absolute β -delayed neutron and β -delayed gamma branching ratios for neutron-rich Cu and Ga isotopes. The deduced branching ratios were based on the implanted ion count and γ -radiation measured by the detectors with well-calibrated efficiency [10,12].

Detectors

A suite of efficient detectors has been constructed and commissioned at the HRIBF to study the decays of neutron-rich nuclei, in particular the properties of β -delayed neutron emission.

The basic configuration of Clover Array for Radioactive Decay Spectroscopic Studies (CARDS) includes four Ge clovers and two plastic β -counters surrounding the activity implanted into a moving tape. Two different versions of a Moving Tape Collector (MTC) made by E. Zganjar (LSU) were used for decay studies of β n-emitters, see [1-3, 10, 12-15]. The 3Hen array consists of 74 ^3He ionization chambers at 10 atm pressure embedded in a high-density polyethylene moderator (HDPE) [16,17]. Beta-delayed neutron events are detected through a capture reaction $^3\text{He} + n \rightarrow p + t + 0.76 \text{ MeV}$ after slowing in the HDPE moderator. The estimated efficiency of the full 3Hen array reached nearly 80% between 1 keV and 1 MeV neutrons. The hybrid version of 3Hen including plastic beta counters and two Ge clover detectors was recently used to study β 1n and β 2n emission from ^{86}Ga [3].

The VANDLE array was designed to measure the energies and intensities of emitted β -delayed neutrons. A low energy threshold, around 100 keV, was achieved thanks to the use of sophisticated digital signal processing system described in [18, 19].

The Modular Total Absorption Spectrometer (MTAS) has been constructed from 19 large NaI(Tl) detectors of hexagonal cross section and 21" length. The detector and composite shielding weight is about 2200 and 12,000 pounds, respectively. Very high total absorption efficiency, between 98% at 300 keV to 96% at 4 MeV for single γ -ray transition, was achieved. MTAS measurements reveal the true distribution of the β -strength followed by β - and γ -radiation [20-22], while VANDLE and 3Hen measurements contribute to our knowledge of the beta-strength located above the neutron separation energy. All beta-decay studies at the HRIBF were performed using data acquisition based on digital signal processing methods [18,19].

Results

Several results related to the beta-delayed neutron emission have been achieved at the HRIBF [1-4, 10, 12-15, 23]. The studies applying "ranging-out" of post-accelerated fission fragments and using pure beams at 200 keV energy led to the determination of β n-branching ratios P_n of 7.2(5)% for ^{76}Cu , 30.3(22)% for ^{77}Cu , 65(8)% for ^{78}Cu , 12(4)% for ^{81}Zn , 62.8(25)% for ^{83}Ga , 74(14)% for ^{84}Ga , 45(15)% for ^{86}Ge , 60(10)% and 20(10)% for β 1n and β 2n for ^{86}Ga , respectively, and 53(+11,-8)% for ^{93}Br . These branching ratios were generally larger than those previously reported that were obtained with contaminated beams of fission products and without on-line counting of implanted ions.

New β n-rates were well reproduced by the microscopic model by I. Borzov including Gamow-Teller and First Forbidden beta transitions, see [10]. A new statistical formula for the β n-probability was recently developed by K. Miernik [24]. It is based on the statistical level density function with an effective density parameter derived from experimental P_n values. The quality of the β n-rates description is better than earlier models. In particular, the calculated P_n values fit the properties of β n-emitters near magic neutron numbers.

β -decay half-lives have been corrected and measured for the first time for several fission products like ^{78}Cu , ^{79}Cu , ^{82}Zn , ^{83}Zn , ^{85}Ga , ^{85}Ge , ^{86}Ga , ^{86}Ge and ^{93}Br . The half-lives, systematically shorter than global model expectations [25], were found to be well reproduced by Borzov's microscopic modeling. The influence and newly measured and calculated half-lives on the post r-process abundances was modeled by R. Surman in [1]. The resulting mass distributions demonstrated a mass flow towards higher mass numbers in comparison to earlier analysis, but closer to the reference data around $A > 140$ and a peak at $A \sim 190$.

Fine structure in βn -emission, namely βn -transitions populating excited states in the daughter nuclei, was observed and analyzed for several emitters. The competition of γ - and neutron - emission can result in the presence of γ -transitions de-exciting the states located well above the neutron separation energy – an effect usually not included in theoretical calculations of P_n values, see [4, 12-15, 23]. The fine structure in βn -emission represents an experimental observable which can be used to test theoretical predictions. So far, it is difficult for βn -modeling to consistently reproduce experimental data [23]. An added bonus of the observation of γ -radiation following neutron transitions is related to the firm assignment of the resulting level structure in exotic nuclei [3, 4].

VANDLE measurements performed at the HRIBF resulted in the neutron energy spectra from nearly 30 fission products, see R. Grzywacz contribution to this meeting. These energy spectra revealed the presence of high energy neutrons, around 1.5-2 MeV energy, for exotic nuclei like ^{84}Ga with a large energy window for neutron-emission, the $Q_\beta - S_n$ of about 8.6 MeV. These high energy components were not seen or expected in earlier experiments.

The decays of 22 fission products including seven decays of highest priority for decay heat analysis in power reactors [26] were measured using MTAS at the HRIBF. The observed increase of the average gamma energy per decay $\langle E_\gamma \rangle$ was often at the level of 20% to 50% with respect to previously accepted data. For example, the analysis including ground-state to ground-state feeding yielded an increase of $\langle E_\gamma \rangle$ values by 26% for ^{86}Br , 47% for ^{89}Kr and 43% for ^{139}Xe decays [21]. In two test cases of ^{142}Ba and ^{142}La decays, where the beta strength function was measured before with a different total absorption spectrometer TAS [27], good agreement between MTAS and TAS results was observed [22]. Interestingly, MTAS can help to simultaneously analyze $\beta\gamma$ - and βn signals, the latter related to the neutron full energy signal, neutron inelastic scattering and ~ 6.8 MeV energy deposited after the capture of a neutron in the NaI scintillator [28].

Conclusions

The results of studies performed at the HRIBF contributed to a change in our understanding of decay patterns of fission products. Large βn -branching ratios were observed for nuclei near ^{78}Ni suggesting the need of new measurements and theoretical studies of the beta decay properties of fission products. New half-lives, shorter than expected, triggered a new model of the beta decay process within a fully microscopic approach. The beta decay level schemes have been obtained for several fission products, often leading to corrections, or at least substantial extension of previous data. New data pointed to the evolution of single particle levels around ^{78}Ni that is triggered by the excess of neutrons over protons. New and extrapolated decay properties were used to perform a sensitivity study of the r-process abundances.

The results from the HRIBF can be the inspiration for the future facility and programs designed to study the decay of fission fragments, to get data important for understanding of nuclear structure evolution and related beta decay properties relevant for nuclear power applications and astrophysics of the r-process.

References

- [1] Madurga et al., PRL 109, 112501, 2012.
- [2] Mazzocchi et al., PR C 87, 034315, 2013.
- [3] Miernik et al., PRL 111, 132502, 2013.

- [4] Korgul et al., PR C, 2013, in press.
- [5] Beene et al., J. Phys. G; NPP 38, 024002, 2011.
- [6] Stracener, W.D., NIM Phys. Res. B 204, 42, 2003.
- [7] Kubo, T., in contr. to the 33rd Mazurian Lakes Conf., Piaski, Poland, 1-7 Sept. 2013.
- [8] Liu et al., NIM Phys. Res. B 298, 5, 2013.
- [9] Gross et al., EPJ A 25, S01, 115, 2005.
- [10] Winger et al., PRL 102, 142502, 2009.
- [11] Gross et al., PR C 85, 024319, 2012.
- [12] Ilyushkin et al., PR C 80, 054304, 2009.
- [13] Padgett et al., PR C 82, 064314, 2010.
- [14] Ilyushkin et al., PR C 83, 014322, 2011.
- [15] Miernik et al., PR C 88, 014309, 2013.
- [16] Rykaczewski et al., <https://www.phy.ornl.gov/hribf/equipment/leribss/3hen-prop.pdf>
- [17] Liddick et al., BABS 50,no. 6, 103, 2005.
- [18] Grzywacz K., NIM Phys. Res. B 204, 649, 2003.
- [19] Grzywacz et al., NIM Phys. Res. B 261, 1103, 2007.
- [20] Rykaczewski K., McGraw-Hill, Yearbook of Science and Technology, p. 92, 2013.
- [21] Fijałkowska et al., Nuclear Data Sheets, 2013, in press; and contr. to the 33rd Mazurian Lakes Conf., Piaski, Poland, 1-7 Sept. 2013.
- [22] Wolińska et al., Nucl. Data Sheets, 2013, in press; and contr. to the 33rd Mazurian Lakes Conf., Piaski, Poland, 1-7 Sept. 2013.
- [23] Korgul et al., PR C 86, 024307, 2012.
- [24] Miernik K., Phys. Rev. C, Rapid Comm., 2013, in press.
- [25] Moeller et al., PR C 67, 055802, 2003.
- [26] Nuclear Science NEA/WPEC-25, NEA No. 6284, OECD 2007.
- [27] Greenwood et al., NIM Phys. Res. A 390, 95, 1997.
- [28] Rasco et al., in contr. to the 33rd Mazurian Lakes Conf., Piaski, Poland, 1-7 Sept. 2013.

Status of the measurement of P_n -values with the BELEN 4π neutron counter and future plans (J.L. Tain, CSIC - Univ. Valencia, Spain)

The BEta deLayEd Neutron (BELEN) detector is a 4π neutron counter consisting on an array of ^3He proportional tubes embedded in a polyethylene moderator. It was developed by collaboration between UPC-Barcelona, IFIC-Valencia, GSI-Darmstadt and CIEMAT-Madrid for the DESPEC/NUSTAR experiment at the future FAIR facility. Meanwhile it is being used at several existing installations to measure beta-delayed neutron emission probabilities P_n of interest in reactor technology, astrophysics and nuclear structure.

The concept of the detector is a modular one, which allows easy transportation and more importantly reconfiguration of counters to trim the detection efficiency to experimental needs (for example maximizing efficiency or minimizing efficiency variations with neutron energy). The major advantage compared to previous similar detectors is a self-triggered acquisition system, which allows recording independently for every counter, time and amplitude of any signal above threshold. This DACQ has very small dead time and allows for flexible time delayed correlations and accurate threshold corrections in the off-line analysis. All these features redound to the accuracy of result.

The detector with 20 ^3He tubes was commissioned in 2009 (B. Gomez-Hornillos et al., UPC) at the Cyclotron Laboratory of the Jyväskylä University (JYFL). This facility includes the IGISOL Mass Separator, which allows the extraction of refractory elements and the JYFLTRAP Penning Trap, which filters IGISOL beams to produce pure isotopic beams. This feature boosts the quality of results in this type of measurements. During this run, improved measurements on ^{94}Rb and ^{138}I were performed and were included already in the evaluation of standards in the first Consultant Meeting [1]. It was subsequently used in 2010 (J.L. Tain et al., IFIC) in a measurement of fission products which are important contributors to the fraction of delayed neutrons per fission (ν_d) and have relatively large P_n uncertainty (see also elsewhere in this CRP report) or are important for astrophysical calculations of the r-process. The analysis of data taken during this campaign for ^{85}Ge , $^{85,86}\text{As}$ and ^{91}Br were presented and will be published soon [2]. The results improve significantly the P_n values for these important neutron emitters. Comparison with theoretical calculations [3,4] has allowed to identify shortcomings of the models and might lead to their improvement. Comparison to systematic parameterizations [5] points to a significant structure in the beta strength distribution for ^{85}Ge and ^{85}As , which should be further investigated.

In the year 2011 a measurement was performed at GSI (Darmstadt, Germany). An improved version of BELEN with 30 ^3He tubes was utilized. The detector was installed at the of FRagment Separator (FRS) which allows in-flight separation and identification of isotopes produced in the reaction of a high energy U beam with a Be target. The isotopes are implanted onto a stack of DSSSD at the center of BELEN. Two experiments were carried out: one for nuclei that will contribute significantly to the formation of the 2nd abundance peak in r-process abundance distribution (F. Montes et al., MSU) and another for those contributing to the 3rd abundance peak (C. Domingo-Pardo et al., IFIC). Very preliminary data on half-lives for the latter were presented, together with evidence for delayed neutron emission in the Hg-Tl region [6]. Apart from a very weak branching reported in the case ^{210}Tl decay this is the first evidence for delayed neutron emission in the heavy mass region. Data analysis will continue.

Two new experiments with BELEN (already approved) will be scheduled shortly at IGISOL.

One is the continuation of the 2010 experiment with the aim of measuring ^{86}Ge , $^{98,98\text{m},99}\text{Y}$, $^{135,137}\text{Sb}$, $^{139,140}\text{I}$. The second one is a new proposal (I. Dillman et al., Giessen/GSI) to measure the two-neutron emission probability in ^{136}Sb beta decay. In this experiment an updated version of BELEN with 48 ^3He tubes will be employed. The new geometry will have a larger efficiency with less energy dependent variation, with respect to the older ones. Efficiency calibration runs with the new detector have been performed very recently at PTB (Braunschweig, Germany) in order to verify the energy dependence.

The collaboration started also a new project to bring the BELEN detector to the BigRIPS spectrometer at RIKEN (Japan). Colleagues from ORNL (USA) and JINR-Dubna (Russia) have joined also the project in such a way that we will have a total of 172 ^3He tubes to mount the largest neutron counter of this type ever. A total of 50 scientists from 19 institutions are participating with proposals to measure one- and several-neutron emission probabilities of interest in astrophysics and nuclear structure along the nuclear chart. Experiments could be performed in 2014/2015.

References

- [1] D. Abriola et al., Summary Report of Consultants Meeting, INDC(NDS)-0599
- [2] J.L. Tain et al., Proceedings ND2013 (New York) and to be published
- [3] P. Moeller et al., Phys. Rev. C 67 (2003) 55802
- [4] I.N. Borzov, Nucl. Phys. A 777 (2006) 445
- [5] E.A. McCutchan et al., Phys. Rev. C 86 (2012) 041305(R)
- [6] C. Domingo-Pardo et al., Proceedings NPA6 (Lisbon)

Opportunities for β -delayed neutron measurements at the TRIUMF-ISAC facility and the GRIFFIN and DESCANT spectrometers (P. E. Garrett, University of Guelph, Canada)

The TRIUMF radioactive beam facility, ISAC, produces neutron-rich nuclei primarily through the bombardment of uranium-based targets (both UO_x and UC_x) with 500 MeV protons. The uranium-oxide target has been used with beam currents up to 2 μ A, while the uranium-carbide target can be used up to 10 μ A. The radioactive nuclei produced must diffuse to the surface of the foils where they can be ionized. Because of the diffusion process, the availability of specific beams is strongly chemistry dependent. In general, refractory elements are extremely difficult, although for some specific ones, molecular forms can be used to provide beams. For the actinide targets, the ion sources that have been used to date are a surface-ion source, a laser-ion source, and a FEBIAD-ion source. These three ion sources provide the potential to ionize essentially any species that can migrate to the surface of the target foils, although the laser-ion source TRILIS must have a definite ionization scheme developed that may not be applicable to all elements. The list of already developed and measured yields are provided by the database accessible at <https://mis.triumf.ca/science/planning/yield/beam>.

The Canadian community operates the 8π spectrometer that can be used to study β -delayed neutron emitters. The 8π consists of 20 HPGe detectors, with BGO suppression shields, arranged in an icosahedral geometry. The beams from ISAC are deposited onto the tape of a Moving Tape Collector within a vacuum chamber at the center of the 8π spectrometer. The length of the beam-spill time, and movement of the tape to a location outside of the spectrometer is controlled via the data acquisition computer. Since the beam is deposited directly to the center of the 8π , it is capable of performing measurements of the shortest-lived species without losses associated with the movement of the tape. In a typical mode of operation, the decay is studied for a specified period of time and then the tape position is moved. This removes any long-lived activity that could build up on the tape to a position outside of the detector field of view. Inside the vacuum chamber, in view of the tape, are 20 plastic scintillators that can be used for tagging on the β -particles. By removing 10 of these, 5 Si(Li) detectors can be included. These high-resolution detectors are excellent for very low-energy photons (both X rays and γ rays) that would be highly attenuated in the target chamber material and thus not otherwise detected, and also as electron detectors. Because of the high-resolution, the conversion electrons are observed as discrete peaks on the broad β -particle background. The array and the data acquisition have been optimized for use in β -decay experiments, and individual γ -ray branchings from an individual level on the order of 10^{-4} have been observed. Spectroscopy with beam rates as low as a few ions/second have been studied.

As powerful as the 8π -spectrometer is, we are replacing this device with the new GRIFFIN array – a spectrometer based on 16 large-volume HPGe detectors. The individual detectors of the 8π spectrometer are based on so-called “25%” crystals, i.e., Ge crystals that have 25% of the efficiency of a 3 in \times 3 in NaI detector, whereas the individual GRIFFIN detectors will have 4 crystals each with more than 40% relative efficiency, for a total of 64 such crystals. The calculated efficiency of the new spectrometer will reach as high as $\approx 20\%$ for 1 MeV γ rays, or a factor of 17 greater than the 8π for γ -ray singles, and a factor of 300 greater for γ - γ coincidences. This will enable experiments with beam rates as low as 1 ion/minute. Coupled to the device will be a state of the art data acquisition system capable of achieving

throughput's of 300 MB/s – equivalent to trigger rates of 1 MHz, although the new system will be triggerless.

Another major advance in the spectrometers available at the TRIUMF facility will be the DESCANT array. Based on deuterated liquid scintillators, the 70 detectors of DESCANT were designed to be used in in-beam reaction studies accelerated beams coupled to the TIGRESS array, but can equally be coupled to the GRIFFIN array to enable the measurement of neutrons followed β decay. DESCANT covers 1.08π sr solid angle, and has demonstrated neutron detection down to 60 keV neutrons. The deuterated scintillator, BC537 from St. Gobain, possesses excellent pulse-shape discrimination abilities, and further the pulse-height spectrum has a more distinctive shape than with normal hydrogen-based scintillators that may benefit the ability to discriminate between multiple-scattering events and $n > 1$ multiplicity events.

The current 8π spectrometer will be decommissioned beginning in Jan. 2014, with the new GRIFFIN spectrometer commissioning expected in Aug./Sept. 2014. The full 16 detector array will be available by spring 2015. The first DESCANT in-beam test will be performed in Nov. 2013, with full commissioning in spring 2014, and will be available for coupling to GRIFFIN shortly thereafter. The main program envisioned for DESCANT will be the coupling with GRIFFIN and measurements of β -delayed neutron emitters, specializing in γ -neutron coincidences.

In the near term, data collected with the 8π spectrometer on the heavy Rb isotopes, ^{98,100,101,102}Rb, will be analyzed to extract the P_n values using the γ - and γ - γ technique. Further, the collaboration has data on ^{52,53}K, and a small amount of data on ⁹⁴Rb that will also be analyzed. In reality, the time scale for producing a significant number of new, published results with the GRIFFIN-DESCANT combination will likely exceed the duration of this CRP, although a large number of measurements will be undertaken which will include those isotopes identified as high-priority.

While significant resources will be directed towards the commissioning and use of the GRIFFIN and DESCANT spectrometers, the Canadian collaboration will also provide a strong support to the ORNL team in pursuing measurements with the 3HEN device at TRIUMF.

Measurements of beta delayed neutron emission probabilities: possibilities at VECC, Kolkata (G. Mukherjee, VECC, India)

There are several methods for the measurements of beta delayed neutron emission probabilities (P_n), which is given by the ratio of number of beta-delayed neutron decays to the total number of beta decays i.e N_n/N_β . Therefore, this involves the measurements of beta, neutron and gamma depending on the method. The experimental facilities available at the Variable Energy Cyclotron Centre, Kolkata, India has been presented in the light of the possible measurements of beta delayed neutron emission probability.

Accelerators

There are two cyclotrons at VECC. The first one is a K-130 cyclotron which is running since late 70's and the new one is a superconducting K-500 cyclotron. The K-130 cyclotron was started with light ion beams and later on heavy ions were also delivered. At present the light ion beams like p, d, and α can be obtained from the K-130 cyclotron. The K-500 cyclotron will start delivering high energy (≥ 50 MeV/A) heavy ion beam soon. A radioactive ion beam facility is also being developed at VECC using the ISOL method. Low-energy RIB (few 100s of keV/nucleon) will be obtained by using the primary beams from the K-130 cyclotron. A 50 MeV, 2 mA SC e- LINAC is being developed in collaboration with TRIUMF, Canada. This will be used to produce RIBs using photo-fission.

Major Experimental Facilities

Several experimental facilities are available and are under development at VECC, Kolkata. These include scattering chambers, charged particle detector array (CPDA), gas detectors, neutron detectors, LAMBDA array for high energy gamma detection (162 BaF₂ detectors), high-resolution gamma detectors (6 Clover HPGe and a segmented clover HPGe), Low Energy Photon Spectrometer (LEPS) detectors for low energy gamma and X-ray measurements, Modular Total Absorption Spectroscopy setup (consisted of 50 elements of BaF₂ detectors). A mini orange spectrometer for electron measurement is under development.

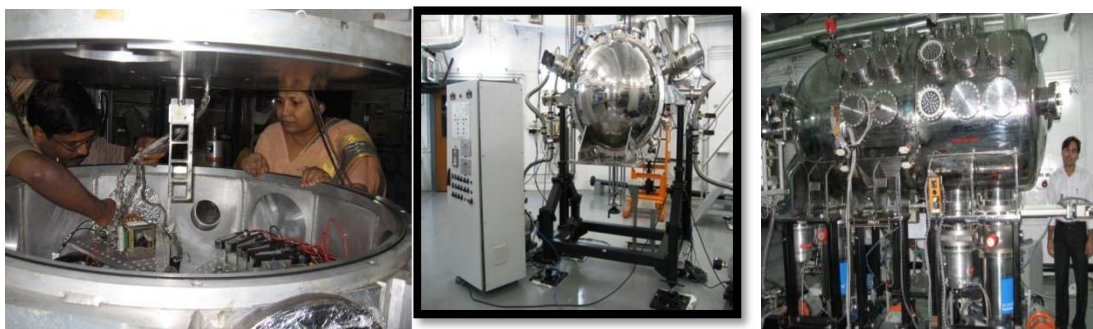


FIG. 1; *Scattering Chambers at VECC.(Left) 1m diameter general purpose chamber, (middle) a thin-walled chamber for neutrons and (right) large general purpose fully auto control chamber.*

Scattering Chambers: For any experimental investigation on nuclear reaction mechanism, a versatile and well equipped scattering chamber is very essential. At VECC, we have several scattering chambers to meet different needs. The main work-horse is a 1m-diameter cylindrical chamber shown in Fig. 1 (left) below. It has two movable arms with automatic operation for the movements of the arms as well as the target holder. These can also be done manually. This chamber, placed in the beam hall of K-130 cyclotron, is serving the nuclear

reaction community for several decades. Two more scattering chambers, one a general purpose large (2.2 m long 1 m diam) chamber and another a thin walled spherical chamber (Fig. 1 (right)) for neutron measurements have been installed in the beam hall of K-500 cyclotron.

The CPDA (developed for the utilization of high energy heavy ion beams from K-500 cyclotron) consists of three parts, forward, extreme forward and backward. The forward part consisted of 24 numbers of 3-element telescopes with single sided Si strip ($\Delta E1$), double sided Si strip ($E/\Delta E2$) and CsI(Tl) (E) detectors. The extreme forward part consists of plastic scintillators and the backward part consists of CsI(Tl) detectors.

Two kinds of *neutron detectors* have been fabricated at VECC, (i) time of flight detectors and (ii) neutron multiplicity detector (see Fig. 2). About 30 time-of-flight detectors have been fabricated and in use at VECC. As a part of the FAIR-MONSTER collaboration we will deliver several MONSTER detectors. One prototype of such detectors has been fabricated recently and is being tested.



FIG 2: Neutron detectors at VECC. VECC TOF, MONSTER and neutron multiplicity detectors.

The *TAS setup* has been tested using different radioactive sources, like ^{137}Cs , ^{60}Co , ^{22}Na and ^{152}Eu which are 1-, 2-, 3- and multi gamma emitting sources. The unique modular setup has enabled us to get the sum spectra gated by different multiplicity folds. It has been shown that it is possible to separate out the single peaks from the summed peaks by using such fold-gated sum spectrum. It is also possible to identify the possible number of gamma rays contributing to a sum peak.

Several *experimental programs* are underway using these facilities and the light ion beams from the K-130 cyclotron at the moment. These include the study of excited Hoyle state, level density parameters, fusion-fission dynamics, fragment emission, nuclear structure at zero and finite temperature, decay spectroscopy etc. The decay spectroscopy of neutron rich fission fragments have been performed by using chemical separation of fission fragments produced by light ion induced fission on heavy targets.

In *summary*, several experimental facilities for the detection of all types of particles (charged particles, neutrons, gammas) are available at VECC. Most of these facilities are routinely used for several nuclear physics experimental program using the cyclotron beams at VECC and some of the facilities are under development. Several time-of-flight neutron detectors are being fabricated at VECC under the FAIR-MONSTER collaboration. It is possible to use the facilities for the beta-delayed neutron measurements.

Towards a Reference Database for Beta-delayed neutron emitters (B. Singh, McMaster University, Canada)

Following topics were discussed: Current user access to B-n data; contents of new B-n database; what features this database should have; compiled and evaluated experimental data; what has been compiled/evaluated so far with examples; future plan for continuation of evaluation effort. Collaborative effort: B. Singh, M. Birch (McMaster, Canada); I. Dillmann (Triumf, Canada); D. Abriola (CNEA, Argentina); T. Johnson, E. McCutchan, A. Sonzogni (NNDC, BNL, USA)

Current User Access to B-n data:

- * ENSDF database, NUDAT, Wallet Cards (NNDC webpage): much information is outdated; full documentation of available experimental data is often missing. Evaluation procedure often not too clear. Live-Chart (IAEA) of nuclides has same data as in ENSDF.
- * NUBASE-12: mostly taken from ENSDF; very little documentation.
- * Dedicated evaluations/compilations: see NDC(NDS)-0599 p. 47 (2012).

Contents of new B-n reference database?

Nuclide ID: A, Z, N: restrict to experimentally identified nuclides. Mass excess, S(n), S(2n), Q(β^-), Q(β -n) from AME-12 or later. S(3n), Q(β -2n), Q(β -3n): deduced from AME. Experimental: compiled and evaluated data for $T_{1/2}$ and β (B-n), β (B-2n) or higher. Complete documentation available experimental measurements, methodology, evaluation procedure, bibliography. Information about the existence of experimental neutron and TAGS (TAS) spectra should be indicated. Web links to databases such as EXFOR for measured neutron spectra, ENSDF/XUNDL for details of β^- and β -xn daughter decay schemes, and NSR for bibliographic access. Systematics: based on recommended experimental $T_{1/2}$ and β -xn values, generate systematics using empirical global/regional fits, such as Kratz-Hermann formula or more recent approaches. Parameters of delayed neutron groups such as Keepin's 6-group parameters for nuclei in A=73-150 fission-region. Theoretical: available theoretical values of $T_{1/2}$ and β -xn for all nuclides. Theoretical neutron/TAS spectra using QRPA and Hauser-Feshbach model.

Display/File access Features of B-n Database

Search by single nuclide or range of nuclides by A, Z or N (or all nuclides where β -n mode is possible).

Search by half-life or β -n value or range. Combined searches such as β -xn, $T_{1/2}$ and Z or A.

Search by Author. Access to complete bibliography, linked to journal/other web-pages. Downloads of data files in different formats such as ASCII, EXCEL, HTML, XML, (CSV, HDF5).

Access to measured and calculated neutron/TAS spectra.

Access to decay schemes of β^- and β -n daughters.

Compilation and Evaluation %B-xn and T_{1/2} data

Mass Region	Decay Mode	Predicted	Measured
A < 72	1n	203	110
	2n	127*	19
	3n	76*	4
	4n	39*	1 (?)
A=72-150	1n	287	150
	2n	131*	3
	3n	28*	0

A<72 region: **110 nuclides** and A=73-150: **150 nuclides** with %β-xn and T_{1/2}

*Note: 2n emitters are also 1n emitters, 3n both 2n and 1n, and so on.

What has been done so far?

December 2011: INDC(NDS)-0599 report of Oct 10-12, 2011 Consultants' meeting at IAEA: Li-9, N-17, Br-87, Br-88, Rb-94, Rb-95, I-137, I-138 were compiled and evaluated by B. Singh and D. Abriola (see above report for results). May 22-23, 2012: McMaster workshop: A<72 nuclei: progress on compilation of nuclei in this region reported. Complete first draft was prepared October 2012. Currently being reviewed by A. Abriola and I. Dillmann. Later it will be sent to NNDC for further review. May 2-3, 2013: Oak Ridge workshop: policies, work on A<72 region, systematics reported. A=73-150 (fission) region: work started at McMaster in early May 2013. About 35 nuclides have been compiled and evaluated so far. Couple of examples are presented.

Compilation and Evaluation policies

Compile all experimental data, including T_{1/2}, P_n, methodology, problems

- * For details of methods, see NDC(NDS)-0599 p. 47 (2012). The preferred method is γ-γ, β-γ, β-γ-n. Not just averaging, critical assessment of individual measurements.
- * Recommended value is the weighted average of the most reliable measurements.
- * When an average is taken, the assigned uncertainty is not lower than the lowest experimental uncertainty in the dataset that is being averaged.

Example: see Table 1.

Table 1: Compiled data for ⁸⁷Se

Reference	T _{1/2} (s)	%P(n)	Method	Comments
1960Sa05	16(3)	-	β,γ	Grow-in; Assignment "remains in doubt"
1968To06	5.8(5)	0.8(LE)	Pn,fiss	Superseded by 1971To13; 15 s curve
1969WaZS	-	0.44(20)	Pn,fiss	Measured (1968To06)/cumulative yield
1970De08	5.9(2)	0.26(7)	Pn,fiss	25 s, least-squares; Adjusted 1993Ru01; Original: 0.23(7)
1970Kr05	5.85(15)	0.51(17), 0.24(8)	Pn,fiss	32 s; Adjusted 1993Ru01 from fiss; From P(n) of ⁸⁷Br; Original=0.25(6)
1970ToZT	5.5(2)	0.18(4)	Pn,fiss	Also 1970TOZW; Superseded by 1971To13
1971To13	5.41(10)	0.17(3)	Pn,fiss	Adjusted 1993Ru01; Original=0.16(3); 30 s; P(n)<0.26 (fit)
1975Hu02	6(+3-1), 5(+3-2)	-	β,γ	20 s curve (3 points); 468 keV γ 1498 keV γ; Also 1971To13
1977Pf01	2(AP)	-	γ	469.1 keV γ
1977Ki14	5.6	-	γ	main study on Mo isotopes
1978Ze08	5.8(3)	-	γ	29 s; 334 keV γ
1993Ru01	5.29(11)	0.60(12)	β,n	Multiscaling

Recommended (Present Work):

Recommendations:

T_{1/2}=5.65 (12) s; Un-weighted Average;

Discrepant data

P(n)=0.356 (84) %; Un-weighted Average;

Discrepant data

Other

Reference	T _{1/2} (s)	%P(n)
1993Ru01	-	0.36(8)
2002Pf04	5.50(14)	0.36(8)
ENSDF/NUBASE-12	5.50(12)	0.20(4)

1960Sa05: J. E. Sattizahn, J. D. Knight, J. Inorg. Nucl.Chem. 12, 206 (1960).

1968To06: L. Tomlinson, M. H. Hurdus, J. Inorg. Nucl.Chem. 30, 1995 (1968).

1969WaZS: A. C. Wahl, A. E. Norris, R. A. House, J. C. Williams, Proc. Symp. Phys. Chem. Fission, 2nd,

Vienna, Intern. At.En.Agency, Vienna, p. 813 (1969).

1970De08: P.del Marmol, D.C.PerricosJ.Inorg.Nucl.Chem. 32, 705 (1970).

1970Kr05: J.-V. Kratz, G .Herrmann, J. Inorg.Nucl.Chem. 32, 3713 (1970) . Other: 1970KrZX,1974KrZG

1971ShZD: S. Shaley, IAEA-R-611-F (1971).

1971To13: L. Tomlinson, M. H. Hurdus, J. Inorg .Nucl. Chem. 33, 3609 (1971). Other: 1970ToZW,1970ToZT

1975Hu02: M. H. Hurdus, L. Tomlinson, J. Inorg. Nucl.Chem. 37, 1 (1975).

1977Pf01: B. Pfeiffer, et al., J.Phys. (Paris) 38, 9 (1977).

1977Ki14: Y .Kiso, R. Matsushita, J. Takada, H. Takemi, T. Tamai, J. Nucl. Sci. Technol. 14, 482 (1977).

1978Ze08: M. Zendel, E. Stender, N. Trautmann, G. Herrmann, Nucl. Instrum.Methods 153, 149 (1978). Other: 1977ZeZY

1993Ru01: G. Rudstam, *et al.*, ATNDT **53**, 1 (1993).

2002Pf04: B. Pfeiffer, K. Kratz, P. Moller, Prog. Nucl. Energy **41**, 39 (2002)

Future plans for evaluation: Submit $A < 72$ region for publication in NDS by Dec 2013.

- * Continue $A=73-150$ region: expect to complete another 35 nuclides by May 2014.
- * Try to have a first draft of $A=73-150$ region by December 2014
- * Checking/review/edit by collaborators
- * Generate systematic plots and data files.

Components of a reference database for β -delayed neutron emission (Daniel Abriola, CNEA, Argentina)

A reference database is a database that is considered the state of the art standard by a user community. Three reference databases are presented as examples, namely the Fukushima Monitoring Database, FMD (<https://iec.iaea.org/fmd/>), the Reference Input Parameter Library, RIPL-3 (<http://www-nds.iaea.org/RIPL-3/>) and the Ion Beam Analysis Library IBANDL (<http://www-nds.iaea.org/exfor/ibandl.htm>). The structure, organization and ways to display and filter data are tailored in each case taking into account the needs and preferences of the user community. On one hand, the FMD has a very diverse user community and had little time to adapt to user needs, which explains its structure and limited display capabilities, on the other hand the RIPL and the IBANDL databases have been around for some time adapting to user needs. In fact, the RIPL database has been the standard for the neutron and light ion-induced nuclear reactions since 1993 (n, p, d, t, He-3, He-4, g up to 100 MeV), while the IBANDL database is the default standard for the Ion Beam Analysis community since 2002. Both databases present the user the data organized in "segments" according to the content of the database. For instance the RIPL database has 7 data segments where data about atomic masses, nuclear levels, nuclear resonances, optical model parameters, nuclear densities, giant dipole resonances and fission are available. The IBANDL database divides the data according to the kind of experimental data such as Elastic Backscattering, Nuclear Reaction Analysis and Particle Induced Gamma-ray Emission. In this CRP we will have to think about the potential user community of the Reference Database for β -delayed Neutron Emission. Possible communities that would be involved are: reactor, decay heat, astrophysics, safeguards and security (antineutrinos), nuclear theory etc. Possibly each community will require not only different kind of data, but also different software to filter and display the relevant information. The type of data needed for the different communities can roughly be separated in two segments: Macroscopic and Microscopic.

The Macroscopic (Global or aggregate) data are from fission (neutron induced or spontaneous fission) and should be organized according to the fissioning isotope (U-235, U-238, Th-232...) and examples of relevant data are: Nubar, Group parameters (λ_i and A_i), Delayed neutron yields...etc. Figure 1 shows group one spectra for U-235, U-238 and P-239.

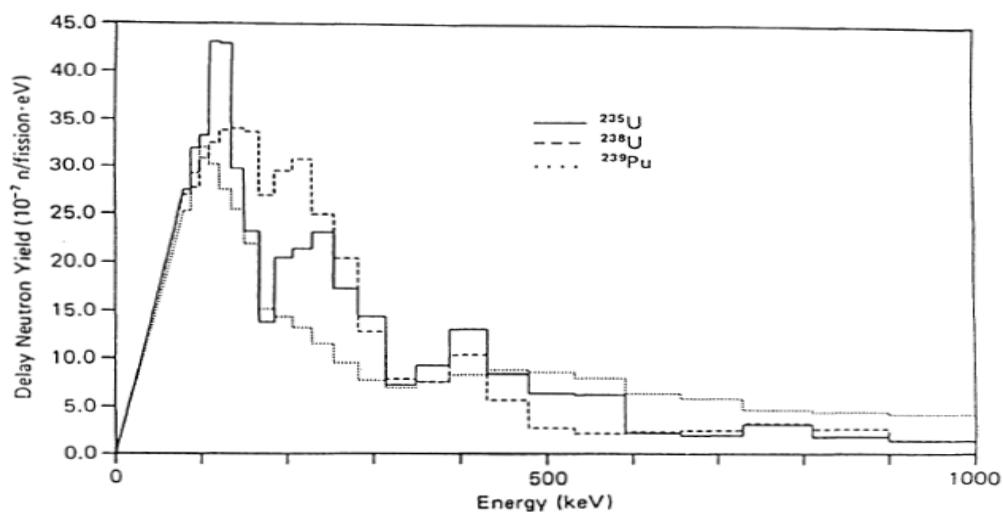


Fig. 4. ENDF/B-V group-one spectra.

FIG. 1. Delayed neutron Yields for ^{235}U , ^{238}U and ^{239}Pu (taken from [1]).

The Microscopic data are precursor-based and include the probabilities of neutron emission P_{1n} , P_{2n} ..., $Q(\beta\text{-}n)$, $Q(\beta\text{-}2n)$..., the half-life and J^π (g.s) of the precursor, neutron spectra etc. An example of some of those data is shown in Table 1. The corresponding table for this CRP would be much larger including data from different origin and different kind.

Table.1 Example of microscopic data taken from [2].

Precursor	J^π (g.s.)	Half-life (s)	%P(n)	$Q(\beta^-)$ (keV)	S(n) (keV)	$Q(\beta^-n)$ (keV)
Li-9	3/2-	0.1783(4) s	50.8(2)	13606.47(11)	1664.55(8)	11941.92(9)
N-17	1/2-	4.173(4) s	95.1(7)	8679(15)	4143.08(01)	4536(15)
Br-87	(5/2-) ^a	55.65(13) s	2.60(4)	6818(3)	5515.17(25)	1303(3)
Br-88	(2-)	16.29(6) s	6.58(18)	8975(4)	7053.1(26)	1922(3)
Rb-94	3(-)	2.702(15) s	10.5(4)	10281(8)	6828(10)	3453(8)
Rb-95	5/2-	0.3777(8) s	8.73(20)	9229(20)	4352(9)	4877(21)
I-137	(7/2+)	24.5(2) s	7.14(23)	5877(27)	4025.53(11)	1851(27)
I-138	(2-)	6.23(3) s	5.56(22)	8070(100) SY	5663(3)	2410(100) SY

SY – systematic value

According to the origin the data can be divided as Experimental (compiled or evaluated data) and Theoretical (nuclear model-based or systematic).

The database should include all previous data, if possible with comments plus recommended (evaluated values). Theoretical models and systematics should be included to allow the user to extrapolate to regions where no experimental data are available. Of course in principle some quantities of the Macroscopic segment can be calculated from the Microscopic data, but some software has to be designed to do that.

The software component of the database should allow the user to search, filter and display different data in a user friendly way. Evaluated data should be highlighted but in absence of such evaluation experimental data or theoretical estimations should be presented.

Data and Software should be developed simultaneously to maximize the integration between the two and simplify the development process.

References

[1] M.C.Brady, Thesis, Texas A-M Univ. (1989); LA-11534-T (1989)

[2] D. Abriola, B. Singh and I. Dillmann, Summary Report of Consultants' Meeting Beta-delayed neutron emission evaluation (2011), INDC(NDS)-0599.

Plans of evaluating the beta-delayed neutron emission data for FP nuclides (Huang Xiaolong, China Nuclear Data Center, China)

The plan of this work is to compile and evaluate the half-life($T_{1/2}$), the delayed neutron emission probability (Pn) for the selected nuclides with $T_{1/2} > 1$ s in the fission product nuclide (FP) region ($66 \leq A \leq 172$). The primary evaluated method is the Limitation of relative statistical weights (LRSW) described below.

Evaluated contents

In order to determine the potential nuclides which could emit a delayed neutron after β^- decay, the following equation will be considered:

$$Q_{\beta-n} = Q_{\beta}(A,Z) - S_n(A,Z+1) \quad (1)$$

Where $Q_{\beta}(A,Z)$ is Q-value of the β^- decay parent; $S_n(A,Z+1)$ is the neutron separation energy of the decay daughter.

If $Q_{\beta-n} > 0$, it means a delayed neutron emission will be occurred. Accordingly the β^- decay parent is a precursor nuclide.

According to the evaluated mass values from Wang (2012Wa38) and $Q_{\beta-n} > 0$, the potential precursors for FP nuclides ($66 \leq A \leq 172$) have been calculated. About 452 potential nuclides with $Q_{\beta-n} > 0$ were found.

Based on the NSR and EXFOR library, there found about 145 FP nuclides, which have measured half-life($T_{1/2}$) and/or delayed neutron emission probability(Pn). Among these 145 FP nuclides, there found 20 nuclides with measured delayed data (neutron energy & intensity).

In present work, we plan to compile and evaluate two kinds of physics quantities: the half-life($T_{1/2}$) of precursor and the delayed neutron emission probability (Pn). In most cases, the Limitation of relative statistical weights(LRSW) evaluated method is primary adopted.

Evaluated method

To get the reasonable recommended half-life($T_{1/2}$) of precursor and delayed neutron emission probability (Pn), the following evaluated guideline will be considered.

(1) Based on the NSR and EXFOR library, all measurements including which quantity was measured (in particular half-lives, neutron emission probabilities and neutron spectra) will be reviewed and collected. Then compile the existing measured data.

(2) Assess the measured data. According to the adopted measurements method, to determine the advantages and weakness of these measurements. Analysis and comments the methodology of the experiment, to judge which results are most reliable. If possible, assess the potential sources of systematic uncertainties.

(3) Evaluation. After a careful consideration of the experimental data, the most reliable results will be selected. Then the data processing method & procedure (when several independent measurements may be considered) will be decided. Usually the average value will be adopted.

(4) Recommend. When the evaluation is completed, a comparison with measured and recommend data will be carried out. Finally the results will be documented.

Data processing procedure

When several independent measurements are selected, the data processing procedure are

considered. Several averaging method were proposed. The typical method is the Limitation of relative statistical weights(LRSW) described below. In additional, COVC(systematic uncertainty determined) and Statistical Model (SM) are also introduced below.

Limitation of relative statistical weights(LRSW)

A relative statistical weight is defined as w_i/W . To avoid any single datum having too much influence on determining the weighted mean, LRSW prescribes that no single datum should have a relative statistical weight greater than 0.50 when determining the weighted mean of a data set. The uncertainty of any datum should be increased until its relative statistical weight is reduced to 0.50. Then LRSW procedure compares the unweighted mean with the new weighted mean. If their uncertainties overlap, i.e.

$$|x_u - x_w| \leq \sigma_u + \sigma_w \quad (2)$$

The weighted mean should be adopted. If their uncertainties did not overlap, the data were inconsistent and it would be safer to use the unweighted mean. In either case the uncertainty is increased, if necessary, to cover the most precise value in the data set.

COVC(systematic uncertainty determined) method

If the measured uncertainties are not statistically independent, that's correlations between measured uncertainties are determined. The COVC method could be considered.

Let express the measured data assembly with $\{x_i, y_i\} \quad i=1, 2, \dots, N$, namely $\{X, Y\}$ and the covariance matrix of Y is V_Y . The vector Y can be fitted with a linear function of vector X , namely should be $Y = aX + b = c_1X + c_2$, and the parameter vector $C^T = (c_1, c_2)$.

According to the least squared method, the optimum value of the parameter vector is

$$C = (F^T V_Y^{-1} F)^{-1} F^T V_Y^{-1} Y \quad (3)$$

The fit values is $Y = FC$. If C is CONSTANT, the COVC method is the normally weighted average method.

Work Plan

The plan of this work is to compile and evaluate the half-life($T_{1/2}$), the delayed neutron emission probability (Pn) for the selected precursors with $T_{1/2} > 1$ s in the fission product nuclide (FP) region ($66 \leq A \leq 172$). In most case, the Limitation of relative statistical weights(LRSW) will be adopted to process the selected measured values.

References

ENSDF: <http://www.nndc.bnl.gov/ensdf>

The absolute total delayed neutron yields, relative abundances and half-lives of delayed neutron groups in 6- and 8-group model format from neutron induced fission of ^{232}Th , ^{233}U , ^{236}U , ^{239}Pu , and ^{241}Am in the energy range from 0.35 MeV (or threshold energy) to 5 MeV (V.M. Piksaikin, Institute of Physics and Power Engineering, Russia)

The latest evaluation of delayed neutron constants was made for main fuel nuclides (^{235}U , ^{238}U , ^{239}Pu) within an working group under the auspices of the Nuclear Energy Agency's (NEA) Working Party on International Evaluation Cooperation (WPEC), Subgroup 6 (SG6) in 1999 [1]. As a result of this work the total delayed yields for the above nuclides were essentially corrected as compared with Tuttle's recommended data set [2]. For the total delayed yields from ^{238}U correction is +5.6%, for thermal induced fission of ^{239}Pu - +3.4% and for fast neutron induced fission of ^{239}Pu - +3.2%. This is a direct indication that there is a need for a continuing effort on delayed neutron data improving. From now, this will be mainly directed at satisfying new requirements emerging from the current trends in reactor technology, such as: the use of high burn-up fuel, the burning of plutonium stocks, the general growing interest in fuel recycling strategies, and new concept of actinide burners.

The main objective of the present work is the measurements of the energy dependence of the absolute total yield, relative yields and half-lives of individual delayed neutron groups at thermal and fast neutrons fission of ^{232}Th , ^{233}U , ^{236}U , ^{239}Pu , and ^{241}Am . The basic experimental method employed in these experiments is based on periodic irradiations of the fissionable samples in a well defined neutron flux followed by the measurement of the time dependence of delayed neutron activity. For this purpose a tube of sample transfer system with samples under investigation was placed between two fission chambers close to tritium or deuterium accelerator targets on the beam line of the CG-2.5. The measurements included two different types of experiments. The first one consists of the measurements of the delayed neutron abundances and periods. In this type of experiments the measurements with different irradiation and delayed neutron counting time intervals were foreseen to enhance the contribution of certain delayed neutron groups in the composite delayed neutron decay curve. In the second type of experiments intended for measurements of the total delayed neutron yields the irradiation time of fissionable samples was several times longer as compared with the longest half-life of delayed neutron precursors. In both types of experiments the measurements of delayed neutron activity of a fissionable sample were made by the neutron detector placed at 3 m aside from accelerator target. The irradiation time intervals were 15, 180 and 300 s. Depending on background conditions the delayed neutron counting intervals were 424.5 and 724.5 s with the time channel sequence after the end of sample irradiation: 0.01 s (150 channels), 0.02 s (150 channels), 0.1 s (200 channels), 1 s (200 channels) and 10 s (30 or 50 channels).

The neutron detector represents a assembly of 30 counters SNM-11 distributed in the polyethylene moderator block possessing an external shield from the neutron background in the experimental room of accelerator. The time of sample transfer is about 150 ms that allows to obtain information on the most short-lived delayed neutron groups. The PC computer serves as a central processor controlling the irradiation and counting time, the number and width of the time channels for the delayed neutron activity measurements. The system makes it possible to measure the following parameters: pulse height distributions from two fission chambers located in front of and behind the sample at the irradiation position, time dependence of the neutron flux from the target, time dependence of the ion current on the target, the time dependence of the delayed neutron activity from the irradiated sample,

number of counts from each row of neutron detector, time delay of the sample on the irradiation position, transportation time of the sample. The personal computer controls also the operation of the pneumatic transport system and the accelerator mode switches.

Analysis of delayed neutron decay curves for each isotope was performed using an iterative least-squares fitting procedure to estimate the temporary delayed neutron parameters both for the 6- and 8-group models at each incident-neutron energy. Measurements were performed on the proton and deuteron beam of CG-2.5 cascade generator (SSC RF-IPPE). Flux of mono-energetic neutrons was obtained from T(p,n) and D(d,n) reactions.

The obtained data are presented both in numerical and graphical forms. As a result of the work made on the processing of the experimental information gathered in the above experiments the following characteristics of delayed neutron have been obtained:

- the energy dependence of the relative abundances and periods of delayed neutrons in 6-groups model presentation from fission of ^{232}Th in the energy range 3.2-5.1 MeV;
- the energy dependences of the relative abundances and periods of delayed neutrons in 6- and 8- groups model presentation from fission of ^{233}U in the energy range from thermal to 4.72 MeV;
- the energy dependence of the relative abundances and periods of delayed neutrons in 6- and 8- groups model presentation from fission of ^{236}U in the energy range 1.01-4.72 MeV;
- the energy dependences of the relative abundances and periods of delayed neutrons in 6- and 8- group model presentation from fission of ^{239}Pu in the energy range from thermal to 4.97 MeV;
- the energy dependence of the relative abundances and periods of delayed neutrons in 6- model presentation from fission of ^{241}Am in the energy range 0.62-4.97 MeV;
- the energy dependence of the total delayed neutron yields from fission of ^{232}Th in the energy range from 3.2 to 5.1 MeV;
- the energy dependence of the total delayed neutron yields from fission of ^{233}U in the energy range from 0.34 to 4.90 MeV.
- the energy dependence of the total delayed neutron yields from fission of ^{236}U in the energy range from 1.01 to 4.72 MeV;
- the energy dependence of the total delayed neutron yields from fission of ^{239}Pu in the energy range from 0.34 to 4.90 MeV;
- preliminary data on the energy dependence of the total delayed neutron yields from fission of ^{241}Am in the energy range from 0.86 to 4.85 MeV.

References

- [1] A. D'Angelo, J.L. Rowlands, Progress in Nuclear Energy, 2002, v. 41, № 1-4, p. 391-412.
- [2] R.J. Tuttle, INDC(NDS)-107/G, IAEA, Vienna., 1979, p. 29-67.

Calculation of delayed neutron emission from fission and fitting results to few group approximations (R. Mills, National Nuclear Laboratory, UK)

Introduction

The total number of delayed neutrons per fission, $\bar{\nu}_d$ and the time dependence of the delayed neutron emission rate are important parameters for reactor design and safety studies, as they determine the behavior of reactors to rapid changes in operation. The parameters for fissioning systems important for current reactor technology have been determined experimentally, for others, important for potential future technologies, where accurate measurements are difficult to make they can be determined from estimates of fission product yields and decay data, by the summation method. This submission describes delayed neutron validation work carried out on JEF-2.2 in the 1990's [1, 2] with some small recent additions [3] that attempts to gauge the accuracy of this method for delayed neutron time dependence against experiment.

Delayed neutron emission following a fission event is where the decay of a fission product leaves a daughter nucleus with sufficient excitation energy to throw off a neutron. For nuclides where this occurs the fraction of decays that produce at least one neutron per beta decay is called the P_n value; these nuclides are short-lived and on the neutron rich. In this work, the number of neutrons per decay D_n will be used, which is the sum of all neutron emitting decay modes whether 1, 2, 3, ... neutrons are emitted ($D_{1n}, D_{2n}, D_{3n}, \dots$).

The delayed neutron emitters exist on the extremely neutron rich side of the fission yield distribution, where few fission product yield measurements have been made except for the more common actinides such as ^{235}U and ^{239}Pu . Thus the models used to predict the charge distribution of the fission yields will have a significant effect on the results. Also the different chain yield distributions for the fission of the higher actinides mean that some precursors, relatively unimportant for ^{235}U fission, become much more significant. Especially important is the movement of the light mass peak towards higher mass as the mass of the fissioning nuclide increases. However, measurements of the P_n/D_n values have historically been based mainly upon ^{235}U fission so theoretical estimates of the P_n/D_n branching ratios become much more important when considering the higher actinides.

From the fission products present at a specific time the delayed neutron emission rate, n_{emit} , can be determined from the activity of these precursors:

$$n_{\text{emit}}(t) = \sum D_{ni} \lambda_i N_i(t)$$

The total delayed neutron emission rate per fission, $\bar{\nu}_d$, can be calculated by considering a case with a fission rate of 1 fission per second. Using the equilibrium condition where the production rate integrated over a long period (i.e. cumulative yield) equals the decay rate. The equilibrium rate of neutron emission is given by:

$$\bar{\nu}_d = \sum_i D_{ni} R_i = \sum_i D_{ni} c_i$$

where c_i is the cumulative yield of nuclide i and D_{ni} is the average number of neutrons emitted per decay. The uncertainty on this can be estimated as

$$\sigma_{\bar{v}_d}^2 = \sum_i D_{ni}^2 \sigma_{c_i}^2 + \sum_i \sigma_{D_{ni}}^2 c_i^2$$

The Keepin 6 group model

As described above the neutron emission rate following a neutron irradiation can be calculated provided that the number density of each nuclide with time can be calculated. However, in practice, reactor kinetics codes consider a small set of “lumped fission products” with a set of a representative decay constants and yields. This approach was pioneered by Keepin [4] who found that a set of six “lumped fission products” gave a good approximation to measurements.

The six group representation of the delayed neutron activity following a single fission pulse, of one ‘average’ fission, was thus approximated by Keepin as:

$$n_{\text{emit}}(t) = \bar{v}_d \sum_{k=1}^6 \alpha_k \lambda_k e^{-\lambda_k t}$$

and similarly for a long constant irradiation, producing 1 fission per second, as:

$$n_{\text{emit}}(t) = \bar{v}_d \sum_{k=1}^6 \alpha_k e^{-\lambda_k t}$$

where t is the time after the irradiation, α_k are the normalized group strengths and the λ_k are the decay constants for the six delayed neutron emitting groups. For these conditions to be applicable the pulse must be too short for any precursor to decay significantly during the irradiation. Similarly the long irradiation condition only applies if all precursors have reached equilibrium before the end of the irradiation.

Fitting of Keepin model parameters

To generate the Keepin six group constants using the JEF-2.2 data it was first necessary to use the inventory code FISPIN [5] to generate the n_{emit} for all 39 fission systems in JEF-2.2. Both a single fission pulse (10^{10} fission/s for 10^{-10} s) and a ‘long’ irradiation (1 fission/s for 10^{13} s) were modeled. The cooling time steps after the irradiation ranged from zero to 500 seconds. 204 time steps were chosen to reproduce accurately the rapidly changing curves. The FISPIN calculations used no actinide content or flux but assumed a constant fission rate that produced fission products. This ignores neutron cross-section effects on the fission products but due to the short half-lives of the delayed neutron precursors this is not considered to be an issue as λ will dominate the $\phi\sigma$ terms in the product/destruction equation unless the cross-section is very large.

The Keepin’s six group model was fitted to the pulse and infinite irradiation data simultaneously (i.e. 408 data points) using the Levenberg-Marquardt method [6] as applied by Press et al [7]. The λ values were constrained to be in value order, the α values constrained to sum to unity and the function minimized was the sum over all points of $((\text{Fitted}-\text{Calculated})/\text{Calculated})^2$ [this avoids the minimization being dominated by the largest components]. The results of the fits for the thermal fission of ^{235}U and ^{239}Pu are shown in

figures 1 and 2. Figure 3 and 4 show the fits plotted as the difference from the fitted parameters. These show the fitted parameters allow a good representation of the summation calculation results with percentage differences of less than 1% over several orders of magnitude. The Keepin experimental data [4] show an offset to these calculations with some variation at longer times that is very good considering the neutron emission changing by several orders of magnitude.

As part of the original work a larger number of groups (7) was tried but this gave no significant improvement in the fits. In addition, it was tried to fit the different fissioning systems to a single set of λ values but this gave considerably worse fits. In recent work by other authors, it is suggested that an 8 group parameterization allowed a single set of λ values to fit many fissioning systems to similar accuracy as unconstrained 6 group fits.

Figure 1: The delayed neutron emission rate following a pulse and long irradiation for the thermal neutron fission of ^{235}U .

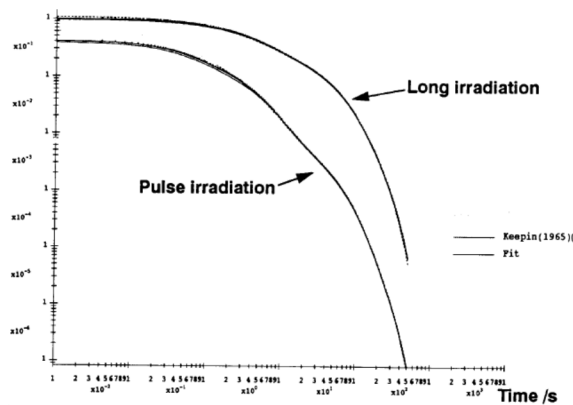


Figure 2: The delayed neutron emission rate following a pulse and long irradiation for the thermal neutron fission of ^{239}Pu .

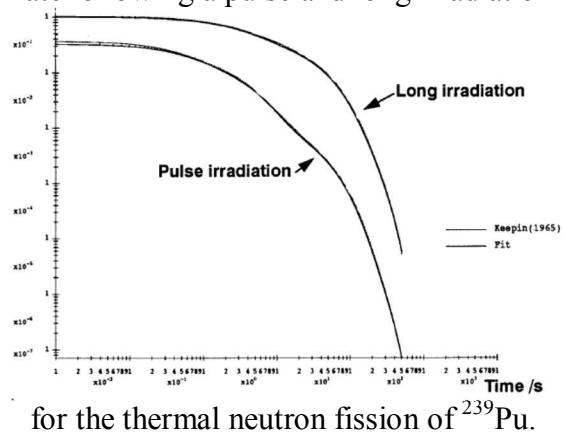


Figure 3: Percentage difference between the long irradiation FISPIN calculations and 6 group parameters for the thermal neutron fission of ^{235}U .

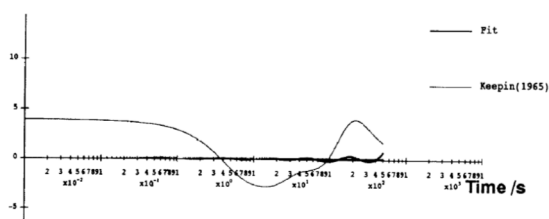
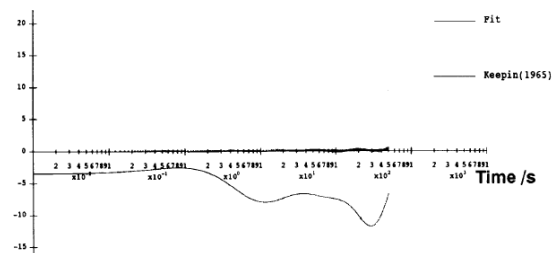


Figure 4: Percentage difference between the long irradiation FISPIN calculations and 6 group parameters for the thermal neutron fission of ^{239}Pu .



References

- [1] “Study of the Delayed Neutron Yield and its Time Dependence by the Summation Method, and the Sensitivity of the Yield to Parameters of the Independent Yield Model and the Decay Data”, by RW Mills, MF James, DR Weaver, International conference on Nuclear Data for Science and Technology, 86-88 (1992).
- [2] JEF/DOC-830 “Summary of JEF-2.2 validation- Delayed Neutron Summation Calculations”, R. W. Mills (1999)
- [3] JEF/DOC-1451 “delayed neutron calculations using JEFF-3.1.1 and other files” (2013)
- [4] G.R. Keepin, Physics of Nuclear Kinetics, Addison-Wesley(1965).
- [5] UKAEA Report ND-R-328(R) “FISPIN- A computer code for nuclide inventory calculations”, R.F. Burstall (1979).
- [6] J. Soc. Ind. Appl. Math., vol. 11, p431-441. D.W. Marquardt (1967).
- [7] “Numerical Recipes: The art of scientific computing”, W.H. Press, B.P. Flannery, S.A. Teukolsky and W.T. Vetterling. ISBN 0521308119. CambridgeUniversity Press (1989).

NNDC Beta-delayed Neutron Research Activities (A.A. Sonzogni, BNL, USA)

The NNDC has been active in the field of beta delayed neutrons emitters, mainly due to our role in the production of the ENDF/B decay data sublibrary. Beta delayed neutrons are of importance in the operation of nuclear reactors and in the calculation of abundances following the r-process in stellar environments. Two presentations were made at the first CRP meeting.

The first presentation was on a new systematics of beta delayed neutron probabilities (P_n) which not only uses the energy available for the neutron after beta decay (Q_{bn}) but also the half-life of the precursor ($T_{1/2}$). This work was recently published by E.A. McCutchan et al. in Phys. Rev. C. Plots of $P_n/T_{1/2}$ vs Q_{bn} are more compact than those using the traditional Kratz-Hermann systematics, resulting in smaller chi-square values in the fitting procedure and in the observation of anomalous cases. This work was also extended to light nuclides.

The second presentation was on the neutron energy spectra in beta-delayed neutron emitters. The role of the beta strength function, Fermi function, and level densities was discussed. A comparison with the evaluated data in ENDF/B-VII.1 was presented and the presence of sharp peaks near closed shells was discussed.

During the discussions, we talked about summation calculations to obtain delayed neutron multiplicities ($\bar{\nu}$) for different systems. The neutrons are generated following the decay of a relatively small group of fission products, less than 50 and mainly neutron rich Br, Rb, I and Cs isotopes. These calculations need fission yields data, ENDF/B or JEFF, and P_n values, which can be obtained from different decay data sources. A comparison of the different calculations with recommended delayed $\bar{\nu}$ was mentioned and the case of ^{238}U was discussed.

We also discussed the delayed neutron activity following fission, which is typically parameterized as a sum of 6 or 8 exponential terms. The ENDF/B library, for instance uses 6 terms, while JEFF uses 8. The delayed neutron activity can also be calculated by solving the corresponding Bateman's equations using fission yields and decay data. One goal of the CRP is to produce recommended group parameters, which will require a careful evaluation of experimental data, comparison with calculations and performing benchmark calculations.

Additionally, the calculation of delayed neutron activity can be incorporated into a Monte Carlo scheme to obtain covariance matrices for the delayed neutron activity as well as the parameters in the 6- or 8-group parameterizations. We have done some work on this area in the past and we plan to contribute to this effort.

BETA-DELAYED Neutron Emitters for Reactor Antineutrino Energy Spectra (M. Fallot, CNRS-IN2P3-Univ. Nantes, France)

Introduction

At this meeting, we have summarized the actual problematic of reactor antineutrino energy spectra in the frame of fundamental and applied neutrino physics. Nuclear physics is an important ingredient of reactor antineutrino experiments. On the basic science side, these experiments are motivated by neutrino oscillations, i.e. the measurement of the θ_{13} mixing angle. This parameter is linked, in the lepton flavor mixing matrix, to the phase characterizing the violation of the CP symmetry. In 2012, the three new generation reactor neutrino experiments, Double Chooz, Daya Bay and Reno [1-3] have released their first results, evidencing a non-zero θ_{13} mixing angle. These experiments use multi-detectors at reactors, with one or several near detectors placed close to the reactor cores in order to measure the emitted antineutrino flux before it oscillates, and one or several far detectors at a location chosen to maximize the oscillation probability. The design of the detectors should be identical in order to eliminate most of the systematics. In the frame of the Double Chooz experiment, new calculation of reactor antineutrino energy spectra were performed in order to predict the emitted antineutrino energy spectrum that was compared with the far detector measurement during the first phase of the experiment, while the near detector is being built.

These new calculations [4, 5], based on the conversion of the very precise integral beta spectra measured by Schreckenbach et al. at the ILL reactor [6], have led to a reinterpretation of the results of the short baseline reactor neutrino experiments [7], evidencing a deficit of the measured reactor antineutrino flux w.r.t. the prediction, @3%. This deficit was called the "reactor anomaly". Several possible explanations can be invoked to explain the newly observed deficit of reactor antineutrinos at experiments placed closer than 100m away from reactor cores. There is a large uncertainty associated to the weak magnetism term entering in the computation of beta decay spectra, which could change the normalization of the predictions of the detected antineutrino flux if revealed too far from the adopted value [5]. In addition, these converted spectra rely entirely on the normalization of the ILL data, for which no other measurement exists. These data are still nowadays the data of reference for reactor neutrino experiments. The third potential explanation is the presence of short baseline oscillations, with the mixing of the three standard neutrino flavors into sterile neutrinos [7, 8]. The latter hypothesis has triggered since numerous new experimental projects aiming at shedding light on these short baseline oscillations [8]. In this context, an independent evaluation of the antineutrino energy spectra would be necessary, as no other measurement of the integral beta spectra associated to the fissions of ^{235}U and $^{239,241}\text{Pu}$ has been performed up to now. The antineutrino spectra computed with the summation method (SM), relying on the summation of the contributions of the beta decay of all fission products in a reactor core, could constitute a possible independent evaluation. It was first revisited in [4], taking advantage of the huge nuclear data information present nowadays in the nuclear data bases. But it appeared that the obtained spectra exhibited shape distortion at the level of 10% w.r.t. the reference ILL beta spectra, and that above 7-8 MeV the obtained energy spectra overestimate substantially the reference spectra. This trend can be attributed to the Pandemonium effect [10], which affects the data of nuclei contributing importantly in the antineutrino energy spectra. It is a similar problem found in the decay heat estimates through the summation method [11].

The determination of reactor antineutrino energy spectra is also important in the field of applied neutrino physics. In the seventies, was born the idea that reactor antineutrino detector could provide a direct image of the fuel content inside the core, as a function of time [9] While experiments during the eighties evidenced experimentally the relationship between the antineutrino flux and energy spectrum with the fuel content and the power of the reactor [12, 13] this idea was only developed lately with the development of dedicated projects worldwide [14, 15] and the recent creation of dedicated Working Groups at the IAEA and at the ESARDA Novel Approaches/Novel Technologies WG [14-16].

It is mandatory in this field to be able to predict the antineutrino emission characteristics associated to various reactor designs [17]. The SM is the only predictive method that could allow such calculations. Antineutrino detection for reactor monitoring is thus another motivation to improve the quality of the beta decay properties stored in the evaluated databases for fission products.

On the Nuclear Data Side: Synergy with Decay Heat, Pandemonium Effect, Total Absorption Spectroscopy Technique

A description of the summation method can be found in the recent updated calculation of [18]. The MCNP Utility for Reactor Evolution (MURE) code [19] is used to extract the fission rates and the fission product activities as a function of time. The Fermi theory and required corrections have been implemented in MURE in order to calculate the beta or antineutrino spectra of each fission product, following Huber's prescriptions [5]. The needed beta decay properties have been extracted from the selected nuclear databases. Details can be found in [18, 20]. The choice was carefully made in order to avoid as much as possible Pandemonium-biased data. The Total Absorption Spectroscopy technique is an alternative to the use of Ge detectors allowing circumventing the Pandemonium effect. Provided the significant improvement in the ^{239}Pu electromagnetic decay heat estimate obtained thanks to the TAS measurement of 7 nuclei ($^{102;104;105;106;107}\text{Tc}$, ^{101}Nb and ^{105}Mo) [21], we have decided to include these very recent measurements in our antineutrino energy spectra.

The final calculated spectra obtained with the SM for $^{235;238}\text{U}$ and $^{239;241}\text{Pu}$ with 100 keV bins and with the last TAS data can be found in [18]. A comparison with the last Huber's computations over the range 2 to 8 MeV has also been proposed. It shows reasonable agreement in the normalization and shape. We reach at maximum 10 % discrepancy up to 7 MeV.

But the influence of the new TAS data of the quoted 7 nuclei revealed to be larger than expected. The ratio of the new predicted spectra and the ones obtained with the same data set but the latest TAS data for $^{102;104;105;106;107}\text{Tc}$, ^{101}Nb and ^{105}Mo published in [21], previously simulated with JEFF exhibit noticeable deviations from unity (reaching an 8% decrease) for Plutonium isotopes, and a non-negligible deviation of 3.5% as regards the ^{238}U spectrum (see Fig. 2 in [18]). These results illustrate how strongly the Pandemonium effect affects the global antineutrinos energy spectra of $^{235;238}\text{U}$ and $^{239;241}\text{Pu}$.

Moreover, by convolution with the detection cross section (inverse beta decay), the resulting antineutrino flux corresponding to pure fissions of ^{235}U , ^{239}Pu , ^{241}Pu and ^{238}U is 99.1%, 94.53%, 94.76% and 98.09% respectively relative to previously obtained flux.

It stresses again the importance of the Pandemonium effect and the necessity to multiply TAS data measurements to improve the prediction capability of the method.

Future Plans on Beta-Delayed Neutron Emitters

To circumvent the Pandemonium problem, the Total Absorption Spectroscopy technique could be employed, and new measurements have been performed or are planned [22, 23] at the University of Jyväskylä, using the Penning trap and TAS detectors. The analysis of $^{92,93}\text{Rb}$, which have been identified as important nuclei for the antineutrino energy spectra, is on going and should be finalized in the coming year [22]. Another 9 nuclei, which have also been identified as a priority for the calculation of the antineutrino energy spectra, will be measured at the JYFL by end of 2013 or start of 2014. In the list of important nuclei that we have established, some nuclei are beta-delayed neutron emitters. At the next planned experiment in Jyväskylä for instance the beta feeding of ^{138}I should be measured. We propose in the coming year to submit a new experimental proposal for experiments focused on beta-delayed emitters of interest for neutrino physics to be performed at the ALTO facility in Orsay [24] by the TAS collaboration. In order to perform TAS experiments at ALTO, the purity of the beam will have to be ensured by the Laser Ion source and a TAS spectrometer such as for instance the set of 12 BaF₂ detectors designed by the Surrey-Valencia collaboration could be installed on site.

References

- [1] Y. Abe et al. (Double Chooz collaboration), Phys. Rev. Lett. 108, 131801, (2012).
- [2] F. P. An et al., Phys. Rev. Lett. 108 (2012) 171803.
- [3] J. K. Ahn et al., Phys. Rev. Lett. 108 (2012) 191802.
- [4] Th. Mueller et al., Phys. Rev. C 83, 054615 (2011).
- [5] P. Huber, Phys. Rev. C 84, 024617 (2011).
- [6] A. A. Hahn et al., Phys. Lett. B218, 365 (1989) and references therein.
- [7] G. Mention et al., Phys. Rev. D83, 073006 (2011).
- [8] K. N. Abazajian et al., <http://arxiv.org/abs/1204.5379>.
- [9] L.A. Mikaelian, 1977, Proc. Int. Conf. Neutrino-77, v.2, p.383.
- [10] J. C. Hardy et al., Phys. Lett. B 71, (1977) 307.
- [11] WPEC-SG25: <http://www.nea.fr/html/science/wpec/volume25/volume25.pdf>
- [12] Klimov, Yu.V., Kopeikin, V.I. . Rev, Mikaélyan, L.A., et al., Atomic Energy, 76, 123-127 (1994).
- [13] Y. Declais et al., Nucl. Phys. B434, 503 (1995).
- [14] M. Fallot, Proc. of the 35rd ESARDA annual meeting, Brugge, Belgium (2013).
- [15] M. Fallot, Proc. of the International Nuclear Data conference, (2013) New York, US.
- [16] IAEA Report SG-EQGNRL-RP-0002 (2012) and IAEA Report STR-361, (2009).
- [17] S. Cormon et al., Proc. of the International Nuclear Data conference, (2013) New York, US.
- [18] M. Fallot et al., Phys. Rev. Lett. 109, 202504 (2012).
- [19] MURE, <http://www.nea.fr/tools/abstract/detail/nea-1845>. O. Meplan, Tech. Rep. LPSC 0912 and IPNO-09-01 (2009).
- [20] M. Estienne et al., Proc. of the International Nuclear Data conference, (2013) New York, US.
- [21] A. Algora et al., Phys. Rev. Lett. 105, 202501 (2010).
- [22] A.-A. Zakari-Issoufou et al., contribution to these conference proceedings (2013).
- [23] A. Algora et al., Proc. of the International Nuclear Data conference, (2013) New York, US.
- [24] ALTO facility, F. Ibrahim et al. Nucl. Phys. A787, 110c (2007).

Group Photo



Links to Presentations

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