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Summary Report of

2nd Research Coordination Meeting

Development of a Reference Database for Beta-Delayed Neutron Emission

IAEA Headquarters, Vienna, Austria
23 – 27 March 2015

Prepared by

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July 2015

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Abstract

The 2nd Research Coordination Meeting of the IAEA Coordinated Research Project (CRP) on the Development of a Reference Database for Beta-Delayed Neutron Emission was held from 23 to 27 March 2015 at the IAEA Headquarters, Vienna. Participants reported and reviewed the overall progress made regarding the objectives and main outputs of the CRP, and discussed future projects and assignments. Summary reports of the presentations by the participants are given. This report contains subsequent discussions, new actions arising out of these discussions, and the new tasks that were assigned in order to achieve the objectives of the CRP, together with details of future measurements related to this CRP.

July 2015

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1. Introduction

A Coordinated Research Project (CRP) was approved in August 2012 with the aim of producing a Reference Database of beta-delayed neutron emission data. The CRP proposal and program was based on the recommendations of the Consultants' Meeting held from 10 to 11 October 2011[1]. The first Research Coordination Meeting (RCM)[2] of the CRP was held from 26 to 30 August 2013 at the IAEA headquarters in Vienna to determine the plan of the experimental, theoretical and evaluation work, assignments to participating groups, and CRP outputs.

The 2nd RCM was held from 23 to 27 March 2015 at IAEA in Vienna, to monitor the progress and revise the work plan accordingly. It was attended by 19 participants from 9 member countries including IAEA-NDS staff (see Participants List in Appendix 2). Paraskevi Dimitriou (IAEA-NDS) was the Scientific Secretary of the meeting, Krzysztof Rykaczewski (ORNL, USA) was elected Chairman, and Iris Dillmann (TRIUMF, Canada) acted as rapporteur.

Robin Forrest, Head of the Nuclear Data Section, welcomed the participants to the IAEA and wished them success in their work. The Agenda was approved without changes (see Appendix 1) and the meeting began with participants' presentations followed by discussions (See Appendices 4 and 6 for summaries and links to the presentations, respectively).

1.1 Objectives

The objectives of the CRP on Reference Database of beta-delayed neutron emission are to coordinate and track progress in

- new experimental measurements,
- theoretical model calculations, and
- empirical systematics

of beta-delayed neutron emission with the purpose of creating a reference database of

- compiled and evaluated microscopic data ($T_{1/2}$, P_n, delayed-neutron (DN) spectra, access to decay scheme in the ENSDF database for precursors) and
- recommended macroscopic quantities (Total delayed neutron yields, group parameters, decay curves and aggregate DN spectra for fissile materials of interest)

In this 2nd RCM, participants reviewed the progress made so far and discussed necessary actions that need to be taken to achieve the overall objectives of the CRP. The complete lists of actions and work assignments are included in Appendix 3.

[1] Summary Report of the CM on beta-delayed neutron emission evaluation, 10-11 October 2011, Vienna, INDC(NDS)-0599
[2] Summary Report of the 1st RCM of the CRP on Reference Database for beta-delayed neutron emission, 26-30 August 2013, Vienna, INDC(NDS)-0643

2. Review of Work Program

2.1 P_{1n} - Standards

A review of the nuclides (^{9}Li, ^{17}N, ^{87}Br, ^{88}Br, ^{94}Rb, ^{95}Rb, ^{137}I and ^{138}I) that were adopted as standards for P_{1n} measurements at the 1st RCM[2] was performed and new proposals were discussed.

^{9}Li: Currently, the adopted P_{1n} value for ^{9}Li has been obtained by considering the data published in four articles, however only three of these sets of data are from independent sources[3]. The resulting recommended value is P_n = 50.5(10)%. Recently, a new measurement of the delayed-neutron branch at TRIUMF with the OSAKA setup was published[4], quoting a net result of P_{1n} = 61.8(54)% which is significantly increased with respect to the above-mentioned evaluated standard. J.L. Tain presented his assessment of this new measurement, noting first that this measurement was primarily dedicated to the study of spin and parity of states in ^{9}Be by using a polarized ^{9}Li beam and measuring the β-asymmetry. The main concern about this work was that the authors used calculated neutron and beta efficiencies without mentioning any experimental verification of either of the associated uncertainties. Another concern was the use of two different detectors for the two different energy regions (plastic scintillator for energies >150keV and ^{6}Li doped glass scintillator for energies < 600 keV) which would give rise to large uncertainties around the matching energy. Also, from the tabulated intensities appeared that they included the contribution (β-feeding) to the 11.81 MeV from a previous work despite the fact that they did not observe it due to their detection threshold issues. However, they did not renormalize the intensities in their decay scheme to account for this feeding. [Sec. note: Subsequent to the RCM meeting, B. Singh contacted the authors to clarify the issue of the unobserved feeding. In reply of May 22, 2015, the first author (Yoshikazu HIRAYAMA) stated "We listed the branch from the 11.81 MeV state as showing the present compilation. In our experiment, we cannot measure the neutron decays from 11.81 MeV due to the low detection efficiency for the low-energy beta-rays. So, we cannot judge the existence of the 11.81 MeV state, and we omitted the 2.7% branch in our result".] The final recommended value of P_n = 50.5(10)% is however not affected by the inclusion of the rather imprecise value of P_n = 61.8(54)% in the 2015-Hirayama paper.

^{95}Rb: A re-evaluation of the half-life of this precursor is necessary.

Action on A. Algora: extract the half-life of ^{95}Rb from the recent BELEN@IGISOL measurements.

^{137}I: The new measurements performed by Scielzo et al[5] using a beta-decay Paul trap should be considered in the evaluation and the tables should be revised accordingly.

^{138}I: New measurements were performed to resolve the observed discrepancies. P_{1n} values were measured using BELEN in November 2014, and TAS measurements were performed in February 2014. The data are being analyzed. As soon as the data analysis is completed the data will be sent to B. Singh for re-evaluation of the standard.

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[3] 1981LA11: Nucl. Phys.A 366, 449 (1981);1981BJ01: Nucl.Phys.A 359, 1 (1981);1992Te03: Zeit. Phys.A 342, 303 (1992);1995ReZZ: Reeder et al., Proc. Arles conf, p587 (1995), 2008ReZZ: priv. comm. from Reeder, supplement to 1995ReZZ report.

[4] 2015HI02: Y. Hirayama et al, Phys.Rev.C 91, 024328, 2015.

[5] 2013Ye02: R.M. Yee, N.D. Scielzo et al., Phys.Rev.Lett.110, 092501 (2013)

^{49}**K:** This nuclide was proposed as a new standard as two independent measurements for the P_{1n} value exist. However, at present the precision of the measurements is at 10%, therefore, new measurements with improved precision down to 5% are required. A proposal to measure delayed neutron (DN) spectra at CERN/ISOLDE has been approved and the experiment will take place in August-October 2015.

^{16}**C:** This nuclide could also be a good candidate for a P_{1n} standard. However, the fact that the delayed neutrons are emitted with a relatively high energy could pose a problem with their detection.

Establishing standards for nuclides with Z>29, in addition to ^{137,138}I, would require new measurements since at the moment there are not many available to allow for a robust standardization procedure. Suggestions were made for ^{135}Sb, and ^{145,146}Cs as possible candidates. ^{135}Sb has been measured by the Valencia group with the BELEN detector and the data are under analysis. The final values will be provided to B. Singh for consideration.

Action on B. Singh, A. Algora: check when evaluating the higher-mass region if enough independent measurements exist for any nuclide to allow for a standard to be established. [Note: for Z>57, Alejandro Algora has taken the responsibility of compiling and evaluating $T_{1/2}$ and P_n data since he and his collaborators are involved with most of the measurements in this region.]

The search for additional standards in the mass region A=17-87 will also continue in parallel.

2.2 Standards for Delayed Neutron (DN) Spectra

Delayed neutron spectra in the fission mass region used as references for efficiency calibration purposes were reviewed by J.L. Tain. His assessment focused on the DN spectra of ^{87,88}Br, ^{94,95}Rb, ^{137,138}I, which are included in Brady's thesis[6], Greenwood et al (1997)[7], Reeder et al (1985)[8] and ENDF/B VII.1[9].The DN spectra in Ref.[6] were obtained from three different types of measurements (Kratz[10], Rudstam[11], Greenwood[12]) covering different energy ranges. The complete assessment can be found in Appendix 4. The main conclusion is that it is difficult to make any thorough and meaningful assessment of these spectra as they are available only in graphical form, and that an effort should be made to digitize them and make them available to the experts for detailed study and comparison with other data and model calculations.

Action on K. Banerjee and G. Mukherjee in collaboration with IAEA NDS: digitize all the spectra included in Refs.[6,7] [They have already digitized the spectra in Refs.[8,12]].

Action on P. Dimitriou: upload all digitized DN spectra produced from previous action on bDN Connect site for participants to access.

Action on A. Sonzogni: provide DN spectra from ENDF/B VII.1 for comparison.

[6] M. Brady, PhD Thesis; M.C. Brady, T.R. England, Nucl.Sci.Eng.103, 129, 1989.
[7] Greenwood et al. Nucl.Sci.Eng.126, 324, 1997.
[8] Reeder et al. Nucl.Sci.Eng.75, 140, 1980.
[9] ENDF/B VII.1: Nuclear Data Sheets xxx
[10] K.-L. Kratz, figures in Brady Thesis; K.-L. Kratz, "Review of Delayed Neutron Energy Spectra", Proc. Consultants Mtg. on Delayed Neutron Properties, Vienna, Austria, March 26-30,1979 [IAEA report INDC NDS-l07/G+Special]
[11] Rudstam, private communication.
[12] Greenwood et al. Nucl.Sci.Eng.91, 305, 1985.

Action on V. Piksaikin: compare these digitized DN spectra with his compilation and benchmark against his measured composite spectra. Make the results of this study available on bDN Connect site.

Action on J.L.Tain, D. Cano Ott, R. Grzywacz, V. Piksaikin: assess the digitized DN spectra and the results of the comparison with the composite DN spectra of V. Piksaikin with a view to making recommendations of reference DN energy spectra.

Regarding DN spectra for Z=2-28 region, B. Singh and collaborators are digitizing about 20 spectra and have sent a few of them to IAEA NDS (V. Semkova) for checking and compilation in either the EXFOR or the bDN reference database, depending on whether such spectra are energy versus intensity or time-of-flight (or some other parameter) versus intensity. Note that only the energy versus intensity spectra can be entered in the EXFOR database according to the policies for this database. Other kinds of neutron spectra will be stored in the bDN reference database. All available spectra will be made accessible through the bDN database either as data files or links to the EXFOR.

^{85}As and ^{135}Sb were also discussed as possible candidates for reference DN spectra. They have been measured by VANDLE@CARIBU (Argonne National Lab) by R. Grzywacz and collaborators and the data analysis is in progress.

The following actions from the 1st RCM[2] were reviewed and further recommendations were made with respect to Standards:

Action on K. Rykaczewski and R. Grzywacz: pursue new measurements at VANDLE on ^{87,88}Br, ^{94}Rb. Remains continuous.

Action on P. Garrett: 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 is in progress.

Action on J.L. Tain and A. Sonzogni: 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. These data should be checked together with B. Singh and then the responsible ENSDF evaluators should be contacted.

Action on P. Dimitriou: mark isotopes with $E_{\gamma}> S_n$ for gamma-neutron competition in the CRP bDN Reference Database. To be done using data from ENSDF and XUNDL.

2.3 Measurements and new data

The methods for β-delayed neutron measurements listed in the Summary Report of the 1st RCM[2] were reviewed and additional remarks and clarifications were introduced for methods 1 and 7 mentioned therein as follows.

2.3.1 Methods for measurements

Notation

Precursor (^{A}Z): **M**, parent
β-decay daughter ($^{A}Z+1$): **I**, intermediate
β-delayed neutron-daughter ($^{A-x}Z+1$): **Fx**, final nucleus (**F1** for β1n, **F2** for β2n with x=1,2,3 for delayed 1n-, 2n-, 3n-decay modes)

$$P_{xn} = N_{xn\text{-}decays} / N_{decays}$$

- "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:

$$P_{xn} = \frac{1}{\varepsilon_n} \frac{N_{\beta xn}}{N_{\beta}}$$

  The number of counted β's and βn correlations has to be free of contaminations, i.e. the contribution from background activities is subtracted and the random noise is corrected. The main assumption in this method is that the β efficiency for decays to states above S_n is the same as the efficiency for any decay and cancels. However β detectors have a threshold, typically of about 50-150 keV, so the ε_{β}-curve has a steep increase in the range of about 2 MeV. This might introduce a systematic error if the calibrating isotope has a small $Q_{\beta n}$ window.
  As for the neutron efficiency, the energy dependency of the efficiency curve is often ignored. If the neutron energy distribution is very different from the calibrant isotope, this might induce systematic effects which should be corrected.

- "γ counting" technique: determines both the number of β- and βn-daughter nuclei produced by measuring the emitted γ rays (see Fig. 1). Absolute γ intensities are required, that means a complete knowledge of the decay scheme including the β- or βn-direct feedings of the ground states. The absolute γ intensities should be verified preferentially with a method adequate for solving complex decay schemes, namely total absorption spectroscopy. Also, the number of nuclei produced in the isobaric decay chains has to be measured and monitored.

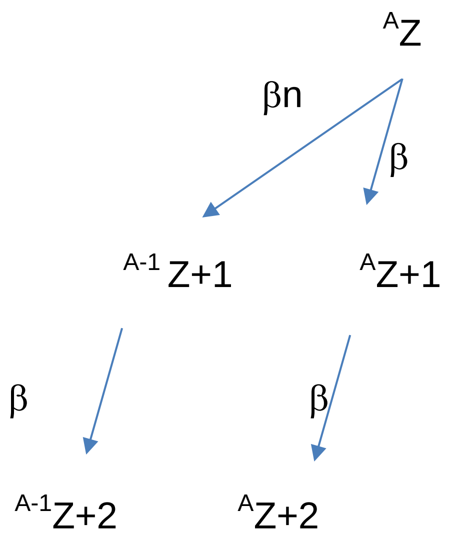

FIG 1. "γ counting" decay scheme: for simplicity we assume that the parent nucleus (^{A}Z) has only P_{1n} and that daughter nuclei ($^{A-1}Z+1$ and $^{A}Z+1$) have P_n=0.

The main advantage of this technique lies in the relative simplicity of detecting γ rays as compared to detecting neutrons. The γ-ray background, and γ-ray detection efficiency can be characterized very well as a function of energy, and when γ rays are detected from the de-excitation of both the β- and βn-daughter nuclei ${}^{A}Z{+}1$ and ${}^{A-1}Z{+}1$ the technique does not require the knowledge of the β-decay efficiency which can introduce large uncertainties. Therefore, when this technique can be applied, it results in small systematic uncertainties. On the other hand, since the γ-ray detection efficiency is small, and the number of specific γ rays may represent only a fraction of the total decays, this method requires high counting statistics.

Also, in case β-decaying isomers are present, γ rays provide a uniquely selective tool to discriminate them from the ground state, and measure correctly the P_n values of both the states. In these cases, measurements of P_n values via direct neutron detection maybe difficult, especially if the isomer and the ground states have similar half-lives.

In case of short lived nuclei ($T_{1/2}$ ~100 ms) where parent (${}^{A}Z$) decay can be correlated not only to β-daughter nuclei (${}^{A}Z{+}1$; ${}^{A-1}Z{+}1$) but also to the βn-daughter nuclei (${}^{A}Z{+}2$; ${}^{A-1}Z{+}2$), and in experiment where nuclei ${}^{A}Z{+}1$ and ${}^{A-1}Z{+}1$ are independently produced and transmitted with the beam, the knowledge of absolute γ intensity, in principle, is no longer required. This is because one can compare the number of γ rays correlated to nuclei [Z] (i.e., from the decay chain [Z] → [Z+1] → [Z+2]* → [Z+2]) to the number of the same γ rays correlated to implanted nuclei [Z+1] (from the decay chain [Z+1] → [Z+2]* → [Z+2]). This method bypasses the need for knowing the decay scheme, but at the cost of introducing a dependence on the β-decay efficiency. This is because the nuclei [Z] and [Z+1] may be implanted in different parts of the detectors where the β−decay efficiency may be different.

2.3.2 New Data

New data that are expected to be measured during the remaining course of the CRP are presented in Table 1. These data will be provided to the evaluation coordinator (B. Singh) for compilation and evaluation in the new Reference Database, as and when they become available in regular publications or preprints or when the researchers feel confident to submit them.

Table 1. Experiments expected to be performed in the future:

Name/ Group	Isotopes	Expected date
BRIKEN@RIKEN Proposal 1 (Rykaczewski, Tain, Grzywacz, Dillmann) Proposal 2 (Estrade, Lorusso, Montes)	First measurement of P_{1n}: ^{76}Co, ^{78,79}Ni, ^{80,81}Cu, $^{83-85}$Zn, ^{85,87}Ga, $^{87-90}$Ge, $^{88-91}$As, ^{90,92}Se First measurement of P_{2n}: $^{80-82}$Cu, ^{83,84}Zn, ^{84,85,87}Ga, ^{87,88}Ge, $^{88-91}$As First measurement of P_{1n}, P_{2n}, and P_{3n}: $^{121-127}$Rh, $^{128-129}$Pd, $^{130-131}$Ag, $^{133-134}$Cd, $^{135-136}$In, $^{138-140}$Sn, $^{140-141}$Sb, $^{142-143}$Te, $^{144-146}$I, $^{147-148}$Xe, $^{149-151}$Cs, $^{150-152}$Ba	2016-2017
VANDLE@ ISOLDE	$^{130-132}$Cd, $^{49-53}$K	July 2015 Oct. 2015
VANDLE@ CARIBU	^{109,110}Mo, A=136,137	April 2015
BPT @ CARIBU (Scielzo)	^{134,135,136}Sn, ^{98m,99,100,101,102,103}Y	2016-2018
GRIFFIN+DESCANT@ TRIUMF	^{145,146}Cs,[^{49}K,^{9}Li], $^{130-132}$Cd, ^{133,134}In	2015-2016
TAS@ ALTO	$^{130-134}$In, ^{133,134,136}Sn	2015-2016

2.3.3 List of priorities for new measurements

Based on the needs of the research communities (reactor physics, nuclear structure and astrophysics), the mass regions of importance are different for various applications.

For **Fission Reactor** technologies, one needs to consider a variety of applications and systems for both power production and actinide burning. This includes all possible future reactors types (e.g. light-water reactors and fast reactors) and novel systems (such as Accelerator Driven Systems) with fuels including UOX, MOX, and MOX with high minor actinide content and Th232/U233 fuels. In all these fission systems, beta-delayed neutron emitters in the fission product region are nuclides that lie far from stability. Therefore, they have short half lives and are produced with low yields making the measurement of their yields more difficult. Consequently, the fission product yield evaluations have to rely upon the predictions of empirical and semi-empirical models that are difficult to validate due to scarcity of data. It is thus accepted that evaluated fission yields have large uncertainties and will have a larger effect on delayed neutron emission than the P_n values and half-lives. Nevertheless, a priority list of beta-delayed neutron emitters is still needed to allow for a review of the recommended P_n values and half-life data for these applications. The first step in that direction would be to identify which nuclide yields and neutron spectra contribute to each fissioning system (neutron-induced and spontaneous fission). Once the βDN precursors are identified, sensitivity studies are required to assess the quality of the existing βDN data (P_n and half lives) and, if needed, recommend new measurements. It is recognised that covariance data for uncertainty assessments are not available to date, but a sensitivity analysis to identify important precursors should be possible.

Action on R. Mills, D. Cano, A.Sonzogni, S. Chiba and V. Piksaikin: perform complete sensitivity studies for all the above-mentioned systems to identify important precursors and submit a report to the CRP by the end of 2015.

For **Nuclear Astrophysics**, the conclusions of sensitivity studies depend strongly on the astrophysics scenario that is assumed for the r-process nucleosynthesis, since the actual reaction path is influenced largely by the astrophysical conditions such as neutron density, and temperature. It has been shown that half-lives are required for all scenarios, whereas the influence of delayed-neutron emission probabilities is strongest for so-called "cold" scenarios. P_{1n} values influence the r-process abundances in the 'cold' r-process models such as neutron-star mergers, cold neutrino-driven wind r-process, but do not affect substantially the outcome of the 'hot' r-process paths. In any case, r-process calculations involve large-scale calculations of nuclear properties that extend all the way out to the neutron drip line, therefore it is of paramount importance to develop physically sound global nuclear models that would provide reliable data for beta decay rates and delayed-neutron emission probabilities, and could be safely extrapolated to the very neutron-rich nuclei for which measurements are not yet possible. To test and validate these global models, half-lives and P_{xn} data are needed for a wide range of nuclei across the neutron-rich side of the nuclear chart.

For **Nuclear Structure** physics, beta-delayed neutron data is a unique source of information for studying exotic nuclei near the neutron drip line. The measurement of beta-delayed neutron energy spectrum is practically the only way to assess the competition between Gamow-Teller and first forbidden beta transition in the energy region between neutron separation energy in a daughter nucleus and the decay energy of the precursor. The nuclear structure community has produced a priority list of nuclides for measurements of P_n branching ratios at BRIKEN (BRIKEN Workshop 2012, Valencia). Some of these nuclides have already been measured or accepted for measurements at BRIKEN in the near future. It was agreed that an effort should be made to establish contact with this community and gain insight in their priorities.

A priority list of measurements should also be proposed for cases where existing data are discrepant.

2.4 Compilation and Evaluation

The compilation and evaluation of nuclides in the region Z=2-28 has been completed and an article has been submitted for publication in Nuclear Data Sheets[13]. The compiled and recommended data for $T_{1/2}$ and P_{xn} values, along with new systematics and comments on the evaluation method, have been made available to the CRP participants through the bDN Connect site and have also been incorporated in the new CRP bDN database. The bDN database will be updated when the article goes through journal review procedures and finally gets published.

[13] M. Birch, B. Singh, et al., Nuclear Data Sheets, in review, 2015

The next task is to compile and evaluate the nuclides in the region Z=29-57 region and also additional nuclides in Z>57 region for which new data may become available. It is estimated that the work involved for this Z region is about double of what was required for the Z=2-28 region:

$T_{1/2}$: ~300 nuclides are known to be potential bDN emitters in this region, 41 of these have isomers which may be relevant to bDN emission. For Z>57, it is possible that new P_{xn} data will become available for about 40 more nuclides in the next 2 years or so, adding to approximately 380 nuclides.

P_n data: there are currently data for 160 nuclides, and in addition for about 20 isomers; as mentioned above, 40 new P_n values are expected to become available for nuclides with Z>57 in the next 2 years, adding to a total of 220 nuclides. P_{2n} data currently are available for only 3 nuclides (^{98,100}Rb, ^{134}In), but it is possible that some P_n values have admixture of P_{2n} component which may be difficult to unravel. No P_{3n} has been reported so far.

The main task of compilation and evaluation will be the responsibility of B. Singh (McMaster, Canada), G. Mukherjee and K. Banerjee (VECC, India), and X. Huang (CIAE, China), D. Abriola (CNEA, Argentina), A. Algora (Valencia, Spain) for Z>57 region. The reviewing/checking of the compiled and evaluated data will be distributed among a larger group: I. Dillmann (TRIUMF, Canada), G. Lorusso (NPL, UK), S. Chiba (Tokyo Institute of Technology), E. McCutchan, T. Johnson and A. Sonzogni (NNDC, BNL, USA). The BNL group will also provide systematics for Z>28 region. It is estimated that a first draft of the compiled and evaluated data tables could become available by March 2017.

2.5 Beta-delayed neutron data in EXFOR

Following discussions about the importance of βn-emission probabilities and neutron spectra from individual precursors for reactor applications[1,2], a Memo was submitted to the Network of Nuclear Reaction Data Centers (NRDC) by IAEA NDS with the request to have both delayed neutron emission probabilities and energy spectra compiled in the EXFOR database (Memo CP-C/429). The decision to include both types of data in EXFOR was taken at the NRDC Technical Meeting, Smolenice, May 2014. Note however, that only energy versus intensity spectra can be considered for compilation in the EXFOR database. In cases where experimentalists supply TOF and corresponding energy spectra then both can be included in the EXFOR files. Otherwise, spectra that are given as TOF vs intensity or Channel number vs intensity only, will be stored in the bDN database as digitized (x.y) tables.

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

Delayed-Neutron Emission Probability (P_n value)

Definition: Probability for emission of at least one ・ -delayed neutron

REACTION Coding: `(Z-S-A(0,B-)[Z+1]-S'-A,,PN)`
Units: `NO-DIM`

Probability of emission of N・ -delayed neutrons (P_{Nn})

Definition: Probability to emit N neutrons after ・ ・ decay

REACTION Coding: `(Z-S-A(0,B-)[Z+1]-S'-A,NUM,PN)`
Units: `NO-DIM`

The number of emitted neutrons is given under the data heading `PART-OUT` with units `NO-DIM`.

Delayed-neutron emission multiplicity <n>

Definition: Multiplicity of delayed neutrons per decay

$\langle n \rangle = P_{1n} + 2 \cdot P_{2n} + 3 \cdot P_{3n} + \ldots.$

REACTION Coding: `(Z-S-A(0,B-)[Z+1]-S'-A,MLT,DN)`
Units: `PRT/DECAY` or `PC/DECAY`

Energy spectrum of delayed neutrons emitted by a specific precursor

REACTION Coding: `(Z-S-A(0,B-)[Z+1]-S'-A,,PN/DE)`
Units: a code from Dictionary 25 with dimension `1/E` (*e.g.*, `1/KEV`)

Digitization of delayed neutron (DN) energy spectra for individual precursors: the effort has been undertaken by B. Singh and M. Birch for nuclides in the low mass region (Z=2-28) and K. Banerjee and G. Mukherjee for nuclides in the fission mass region. Several digitized spectra have already been submitted to IAEA NDS for inspection and have been approved (nuclides in 1980Re03[8] and 1985Gr15[12]). These spectra have now been forwarded to the NRDC EXFOR compilers for inclusion in the EXFOR database, and once they have been assigned an EXFOR entry they will be linked to the CRP bDN database.

V. Piksaikin has also digitized DN spectra from the literature and has created a library containing a total of 47 spectra including DN spectra from JEFF 3.1, and Greenwood data. He has used these DN spectra in combination with the summation method to produce composite spectra to compare with his measured spectra for neutron-induced fission on ^{235}U.

Priority in the digitization effort will be given to the DN spectra included in Refs.[6,7] (^{87,88}Br, ^{94,95}Rb, ^{137,138}I)-note that Refs.[8,12] have already been digitized. These digitized spectra will be made available on the bDN Connect site for the experts to access and assess.

Action on V. Piksaikin: look at the components of his composite spectra and ascertain which sets of individual precursor spectra are most suitable for reproducing his measured spectra.

Action on K. Banerjee/G. Mukehrjee and IAEA NDS: digitize the remaining original graphical spectra in Refs.[6,7]; make these digitized spectra available on the bDN Connect site. Notify J.L. Tain, R. Grzywacz, D. Cano and V. Piksaikin.

Action on J.L. Tain, R. Grzywacz, D. Cano and V. Piksaikin: study the digitized spectra mentioned above carefully and make an assessment.

Action on V. Piksaikin: benchmark the digitized spectra mentioned above against his measured integral spectra and provide results and conclusions on the bDN Connect site.

Action on R. Mills: check where the DN spectra in JEFF 3.1 library originate from.

Action on A. Sonzogni: make available the DN spectra in ENDF/B VII.1 library.

One important conclusion from the discussion on DN spectra was that to better understand the neutron energy spectra one also needs to have experimental information on the subsequent gamma emission so as to understand where the neutrons come from.

Participants also discussed the usefulness of Total Absorption Spectroscopy (TAS) measurements to accurately determine the β-feeding (and β-strength functions) in cases of beta-decay to a daughter nucleus that suffers from Pandemonium. It was emphasized that in such cases only TAS measurements are reliable. In spite of the importance of these types of measurements, there is no systematic effort yet to compile the TAS spectra and relevant experimental information (response function etc). One possible solution would be to compile them in the Experimental Unevaluated Nuclear Data Library (XUNDL).

Action on J.L. Tain and A. Algora: provide an example of TAS spectra (XY tables) and Detector Response Function from recent publication to B. Singh for compilation in XUNDL.

Action on NDS-IAEA: send sample EXFOR files with both TOF and converted energy spectra to experimentalists to consider how TAS spectra could potentially be compiled in EXFOR. Note that as mentioned above, TOF spectra alone cannot be accommodated in EXFOR.

2.6 Systematics and Theory

Empirical formulas and their predicted values will be included in the CRP bDN database. At present, the following systematics are available:

1) Kratz-Herrmann formula[14], 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[15], which is similar to the approach of (1) but describes P_n in terms of (Q_β-S_n) and the β-decay half-life $T_{1/2}$.
3) Miernik[16], which describes the P_n values in terms of nuclear level density of the β-decay daughter nucleus.

Systematics (1) and (2) will be revised on the basis of the new evaluation of Birch et al[13] for Z=2-28 and will be made available for uploading on the database.

The empirical Miernik model (3) will be made available with current parameterization for sake of comparison.

More sophisticated theoretical models have been developed by several groups:

a) Möller et al[17] have calculated ground state decay properties for all particle-stable nuclides with the macroscopic-microscopic QRPA model. Their calculations treat the Gamow-Teller transitions and add the first-forbidden β-strength heuristically from the Gross-theory of β-decay[18].

b) Borzov[19] calculated β-decay $T_{1/2}$ and β-delayed neutron emission probabilities applying a continuum-QRPA approach based on the self-consistent ground state description in the framework of the nuclear-energy density functional theory (DFT).

[14] K.-L. Kratz, G. Herrmann, Z. Phys. 263, 435, 1973.
[15] E.A. McCutchan, A.A. Sonzogni, T.D. Johnson, D. Abriola, M. Birch, and B. Singh, Phys.Rev.C 86, 041305(R), 2012.
[16] K. Miernik, Phys.Rev.C 88, 041301(R), 2013; Phys.Rev.C 90, 054306, 2014.
[17] P. Möller, B. Pfeiffer, et al., Phys.Rev.C 67, 055802, 2003.
[18] K. Takahashi, Prog.Theor.Physics 47, 1500, 1972.
[19] I.N. Borzov, Nucl.Phys.A 777, 645, 2006; presentation at this meeting (Appendix 4 and 6).

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.
Results will be published as an INDC(NDS) report and will be included in the database.

c) Marketin et al[20] 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.
A table will be provided with beta-decay rates and P_{xn}, and by end of year correlations between model parameters and decay observables and r-process abundances.

d) Minato et al[21] is calculating beta-decay half-lives and strength functions using the quasiparticle random phase approximation (QRPA). The Skyrme-Hartree-Fock + BCS model with a SkO effective interaction is used for ground-state properties assuming axial and reflection symmetric deformation. Odd nuclei are treated within independent particle model. The βn-emission probability from excited states is estimated by the Hauser-Feshbach statistical model. Calculated $T_{1/2}$, P_{xn} and DN spectra for P_{xn} and P_n will be provided fort he CRP bDN database. Also β-strength functions and -intensities for fission products. There are plans to extend calculations to the drip line in the future.

e) Grzywacz[22]: calculated β-strength functions using the shell model for nuclei between ^{76}Ni and ^{90}Br. Future plans are to add first-forbidden strengths and statistical model calculations to obtain P_{xn} values.

CRP participants will provide their calculated $T_{1/2}$ and P_n values using models (b-d) for comparison with the evaluated/adopted values in the Reference Database. A link to the article of Möller et al[17] will also be provided.

The need to review existing microscopic models and in particular, how they treat isoscalar pairing interaction was recognized at the meeting. The following action was therefore recommended:

Action on I. Borzov, T. Marketin, and F. Minato: review existing microscopic (and macroscopic) models used to calculate β-decay properties and submit conclusions/recommendations by the 3rd RCM.

Efforts to combine nuclear structure and statistical models to describe the competition between neutron and γ- emission following beta-decay are ongoing. Minato[21] and Tain[23] have been performing such calculations and in the case of Tain et al., the comparison with experimental data has revealed serious discrepancies (see summaries and presentations in Appendices 4 and 6, respectively). The “CGM” code (Cascading Gamma and Multiplicity) developed by Kawano[24] which combines the QRPA model[25] for β-decay and the Hauser-

[20] T. Marketin, presentation at this meeting (Appendix 4 and 6).
[21] F. Minato, presentation at this meeting (Appendix 4 and 6).
[22] R. Grzywacz, presentation at this meeting (Appendix 4 and 6).
[23] J.L. Tain: presentation at this meeting (Appendix 4).
[24] T. Kawano, P. Möller, W.B. Wilson, Phys.Rev.C 78, 054601, 2008.

Feshbach statistical model for γ-decay has been used to produce DN energy spectra for 271 precursors, many of which have already been incorporated in the ENDF/B VII.1 decay-data sub-library. This effort will be extended by coupling the various β-decay models (a-d) mentioned above with other statistical model codes, namely, EMPIRE[26] and TALYS[27]. A systematic comparison of the γ and delayed-neutron emission spectra produced by these codes and those of Minato, Tain and Kawano would be most useful in providing insight into the nuclear structure models used as input to the codes, and also shed light on the capabilities of the codes to describe the competition between γ and neutron emission.

2.7 Macroscopic (integral) data

Participants agreed to include the following integral data in the database:

1. Existing experimental data on total DN yields, decay parameters, integral DN energy spectra.

New measurements on minor actinides in the 14-18 MeV energy range will be provided by V. Piksaikin by the 3rd RCM.

2. Re-evaluated decay parameters for $^{233, 235,238}$U, ^{239}Pu, ^{232}Th in both 6-group and 8-group format obtained by using more precise measurements in the energy range from thermal to 5 MeV by the 3rd RCM.
3. Systematics for decay parameters.
4. Summation calculations of: Total DN yields, average $T_{1/2}$ of DN precursor

Summation calculations will be performed using the following input data libraries:

a) FPYs: JEFF 3.1, ENDFB/VII.1, JENDL –fixed
b) P_n, $T_{1/2}$: JEFF 3.1, ENDFB/VII.1, JENDL –fixed; current ENSDF; recommended bDN database generated by CRP

Summation calculatons will be performed by: V. Piksaikin, R. Mills, D. Cano, A. Sonzogni, F. Minato, and S. Chiba.

To begin with, calculations will be performed for: ^{235,238}U and ^{239}Pu, for thermal and fast neutrons. An inter-comparison of the codes to be used in the calculations will be carried out first.

2.8 Reference Database

A preliminary version of the microscopic database for Z=2-28 nuclei based on preliminary data provided by the coordinator of the compilation/evaluation effort was presented at the meeting by IAEA NDS (P. Dimitriou, M. Verpelli). Improvements were suggested and recommendations were made to include the different systematics (Kratz-Hermann[14], McCutchan et al[15], Miernik[16]) derived from these new data and distinguish them from older versions by the year of publication. Model calculations of Möller et al[17], Borzov et al[19], Marketin[20] and Minato[21] will also be incorporated in the database. A complete and improved

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[25] P. Möller, J.R. Nix, K.-L. Kratz, ADNDT 66, 131, 1997.
[26] EMPIRE-3.2 Malta, Modular system for nuclear reaction calculations nad nuclear data evaluation, Herman et al, INDC(NDS)-0603
[27] A.J. Koning, S. Hilaire, M.C. Duijvestijn, TALYS-1.0: Proceedings of the International Conference on Nuclear Data for Science and Technology, April 22-27, 2007, Nice, France, editors O.Bersillon et al, EDP Sciences, 2008, p. 211-214.

version of the database should become available to CRP participants for testing by the end of 2015.

The macroscopic database will be generated including existing experimental data, systematics, and summation calculations, and evaluated libraries for total DN yields, decay parameters and DN energy spectra as described in Sect. 2.6. The preliminary version will be made available to participants for comments and feedback by end of 2015.

3. Conclusions

The Second Research Coordination Meeting (RCM) on the development of a Reference Database for β-delayed neutron emission data was held at the IAEA, Vienna, from 23 to 27 March 2015.

Participants reviewed the current status with respect to measured, compiled and evaluated delayed-neutron data, systematic approaches and theoretical models, as well as integral data obtained from summation calculations using state-of-the-art data libraries on fission product yields, P_n and $T_{1/2}$.

A preliminary version of the microscopic database for Z=2-28 nuclei was presented and the format of the macroscopic database was proposed and agreed upon.

The work plan of the participants was reviewed and revised to ensure that the objectives of the CRP are met in time. The revised lists of actions are included in Appendix 3.

Participants were encouraged to publish their work acknowledging the CRP.

The next RCM was proposed to take place in early spring of 2017.

2nd Research Coordination Meeting on CRP on
Reference Database for Beta-delayed Neutron Emission

IAEA Headquarters, Vienna, Austria
23-27 March 2015
Meeting Room M0E75

ADOPTED AGENDA

Monday, 23 March

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)**

"A comprehensive approach to determine delayed-neutron data - mass yield measurement, calculations of independent yield, decay heat and delayed neutrons: Progress Report"
S. *Chiba, Tokyo Inst. of Technology*

"Theoretical calculations of beta-delayed neutrons and sensitivity analyses"
F. Minato, Japan Atomic Energy Agency

"Beta-delayed neutron emission near the shell-closures"
I. Borzov, RNC Kurchatov Institute

"Large scale evaluation of beta-decay rates of r-process nuclei"
T. Marketin, Univ. Zagreb

Coffee break as needed

12:10 – 14:00 ***Lunch***

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

"Update on bdn-relevant proposals and experiments (ORNL, RIKEN, TRIUMF) and recently evaluated data"
K. Rykaczewski, Oak Ridge National Laboratory

Progress Report of the Valencia group activities, *J. Tain, IFIC-Univ. Valencia*

"Nuclear structure insights from Pn measurements"
A. Algora, IFIC-Univ. Valencia (15')

"Update on GRIFFIN and DESCANT and bDN measurements via gamma-ray spectroscopy"
P. Garrett, U. of Guelph (30')

"Pn value measurements with EURICA, *G. Lorusso", NPL*

Coffee break as needed

Tuesday, 24 March

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

"Completed compilation and evaluation of Pn and half-lives for Z=2-28 region nuclei" + a few words about Z>29 nuclei,

B. Singh, McMaster University

"Progress report of IAEA project on beta-delayed neutron emission"

K. Banerjee, VECC (30')

"Nuclear Astrophysics and beta-delayed neutrons"

I. Dillmann, TRIUMF

"Visualizing beta-delayed neutron emission"

S. Ciccone, McMaster Univ. (30')

"bDN database + CONNECT PLATFORM"

P. Dimitriou-M. Verpelli (IAEA)

Coffee break as needed

12:30 – 14:00 Lunch

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

"Verification of the evaluated fission product yields data from the neutron-induced fission of 235U, 238U and 239Pu based on the beta-delayed neutron characteristics" (25')

"High-resolution measurements of aggregate delayed neutron spectra in different time intervals from neutron-induced fission of 235U (Comparison with data obtained by summation calculation) (25')

V. Piksaikin, Institute of Physics and Power Engineering

"Beta delayed neutron data and reactor calculations"

D. Cano-Ott, CIEMAT Madrid

"Delayed neutron calculations using available evaluated files and study of the components to identify important delayed neutron emitters for reactor applications"

R. Mills, National Nuclear Laboratory

"Synergy btw antineutrino spectra and beta-delayed neutron emission-Report of the Nantes group", *M. Fallot, SUBATECH-Univ. Nantes*

"Beta delayed neutron covariances",

A. Sonzogni, BNL

Coffee break as needed

Wednesday, 25 March

09:00 - 12:30 Round Table Discussion

Coffee break as needed

12:30 – 14:00 Lunch

14:00 – 14:40 Presentations

"Gamow-Teller Beta-decays in nuclei beyond N>50", *R. Grzywacz, Univ. Tennessee (40')*

"bDN Pn and spectra in EXFOR database", *V. Semkova (10')*

14:40 – 18:00 Round Table Discussion (cont'd)

Coffee break as needed

Dinner at local restaurant (19:00)

Thursday, 26 March

09:00 - 12:30 Round Table Discussion

"Review of DN spectra of reference isotopes", *J.L. Tain*
"9Li Pn value as a standard", ' '
"Issue of beta efficiency on Pn determination", ' '

Coffee break as needed

12:30 – 14:00 Lunch

14:00 – 17:30 Round Table Discussion (cont'd)

Coffee break as needed

Friday, 27 March

09:00 - 12:30 Drafting of summary report

Coffee break as needed

12:30 Closing of the meeting

2^{nd} Research Coordination Meeting on

Reference Database for Beta-delayed Neutron Emission

IAEA, Vienna, Austria

23 – 27 March 2015

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Appendix 2

List of Actions

1st RCM Actions: Revised at 2nd RCM		
No.	**Responsible**	**Action**
1	NDS-IAEA/P. Dimitriou	Collect relevant articles from literature on bDN data and upload on CRP website **Continuous** (also Lab Reports) In case of conf. proceedings, also include comments about existence of published article
2	I.Dillmann, B. Singh, K. Rykaczewski, J.L. Tain, R. Grzywacz	Provide IAEA with list and links and files of older and current PhD theses concerned with P_n data **Continuous**
3	All participants with access to aggregate data	Send aggregate data to NDS-IAEA/ P. Dimitriou **Continuous**
4	All experimentalists ($T_{1/2}$, P_n, neutron spectra (singles TOF or energy spectra))	Keep evaluation coordinator B. Singh updated about new analyzed data which researchers feel confident to communicate **Continuous**
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 **Continuous**
6	I. Dillmann, B. Singh	Check for possible DN P_n standards for fission mass region. **In progress**
7	P. Garrett	Send new ^{94}Rb data on DN P_n and $T_{1/2}$ to Dillmann-Singh for re-evaluation of standards **In progress**
8	B. Singh	Check if fine-structure DN data branches are made available in ENSDF or XUNDL A<21: checked and found complete files Z<28: reasonably complete **Continuous**

Appendix 3

Actions cont'd		
No.	**Responsible**	**Action**
9	T. Johnson, A. Sonzogni	Provide experimental and evaluated DN energy spectra existing in other databases and relevant references to NDS-IAEA/P. Dimitriou **Continuous** (also provide useful links with comparisons)
10	B. Singh, K. Banerjee	Contribute to effort of digitizing DN spectra **Continuous**
11	NDS-IAEA (P. Dimitriou, M. Verpelli)	Prepare preliminary version of bDN Database with microscopic data for Z=2-28 **Continuous-**updating and maintenance
12	R. Mills (coordinator), V. Piksaikin, 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 (nu-bar, group parameters) with respect to the microscopic quantities such as P_n and fission yields included within each library. To be completed by end of 2015. **In progress**
13	I. Dillmann, P. Garrett, J.L. Tain, K. Rykaczewski, R. Grzywacz	Provide feedback from nuclear structure community on nuclides with DN P_n that are important for nuclear structure studies **Continuous**

Appendix 3

New Actions adopted at 2nd RCM		
No.	**Responsible**	**Action**
14	B. Singh (Coordinator) with X. Huang, K. Banerjee, G. Mukherjee, D. Abriola, A. Algora, and with I. Dillmann, E. McCutchan, A. Sonzogni, T. Johnson,S. Chiba, G. Lorusso	Compilation and evaluation of $T_{1/2}$ and P_n data for nuclides with Z=29-57 and selected higher mass nuclides Reviewing/checking effort
15	I. Dillmann, P. Garrett, R. Grzywacz, J.L. Tain, K. Rykaczewski,	Same as Action 13 but for DN spectra
16	R. Grzywacz	^{49}K possible new standard for Z=2-28 region: measurement at ISOLDE in Fall 2015
17	I. Dillmann	Upload nuclear astrophysics papers on sensitivity studies related to bDN data in bDN site
18	I. Dillmann, P. Garrett, K. Rykaczewski	Produce priority list of nuclides in Z=2-28 region that need to be re-measured because of discrepant data
19	R. Grzywacz	Contact the authors of the recent article on ^{9}Li, Y. Hirayama et al, PRC 91, 024328 (2015), for more information about the measurement and data analysis to clarify their results for P_n – send feedback to B. Singh
20	A. Algora	Extract $T_{1/2}$ of ^{95}Rb from data measured by BELEN@IGISOL in 2014
21	B. Singh	Check when evaluating ^{135}Sb and ^{144,145}Cs if existing data are adequate to propose them for ‘standards’ in the mass region of fission products
22	A. Algora, J.L. Tain	Send TAS data to B. Singh who will explore how best to compile them in XUNDL
23	NDS-IAEA/P. Dimitriou	Send sample EXFOR files with TOF spectra for experimentalists to comment and provide feedback

New Actions cont'd		
No.	**Responsible**	**Action**
24	K. Banerjee, NDS-IAEA/P. Dimitriou	Digitize DN spectra of Rudstam, Greenwood and Kratz included in thesis of Brady as a top priority
25	NDS-IAEA/P. Dimitriou	Upload digitized DN spectra from Action 23, as well as 47 DN spectra provided by V. Piksaikin, to bDN CONNECT site and notify CRP participants
26	R. Mills, NDS-IAEA/P. Dimitriou	Inform CRP the source of DN spectra available in JEFF library
27	V. Piksaikin	Benchmark digitized DN spectra from Actions 23-24 against his measured composite DN spectra
28	V. Piksaikin, J.L. Tain, D. Cano, R. Grzywacz	Make detailed assessment of DN spectra made available through Actions 23-25 taking into account the results of Action 26
29	I. Borzov (coordinator), T. Marketin, F. Minato	Review existing theoretical models and in particular how they treat the isoscalar pairing interaction

Appendix 3

REVISED WORK PLAN (2nd RCM: 23-27 March 2015)

Participant	Institute	Country	Proposed Work
I. Borzov	IPPE	Russia	New DF3+CQRPA calculations of beta-decay rates and DN P_n for key quasi-spherical nuclei. Comparisons of new calculations with data from HRIBF, GSI, RIKEN, TRIUMF. Combine with HF code to get DN P_n and energy spectra. **Done except for combination with HF code. Preliminary (beta) version to be published in INDC(NDS) report and include in NSR and database.**
D. Cano	CIEMAT	Spain	Experiment using BELEN at IGISOL-JYFL (proposal by Algora, Cano, Gomez-Hornillos, Jokinen). **Preliminary data sent. Final data to be published as PhD thesis and paper.** Same experiment with MONSTER at IGISOL-JYFL (Sps: as above). **(uncertain)** Experiment with Li-9, 11 at ISOLDE (Sps. Delaunay, Cano Ott). **Done. Data under analysis.** Review of different sensitivity studies on bDNs for reactors. **Done-including benchmarking.** Characterization of new scintillators to be used as neutron detectors at metrology labs. **Experiments done and analysis in progress. Also done summation calculations. Next: Analysis of data. Sensitivity studies.**
S. Chiba	Tokyo Inst. Techn.	Japan	Construction of apparatus for surrogate method to measure FFMD. **Done-data on ^{238}U, ^{232}Th, ^{248}Cm to be published). Next: ^{237}Np.** Extension of Langevin Eqs to predict independent FYs. **In progress (need to correct calculation of prompt neutrons).** Use DN P_n and $T_{1/2}$ data produced by CRP to improve the Gross Theory. **To be done when CRP database is complete. Contribute to checking of evaluations in fission mass region (coordinated by B. Singh)**
M. Fallot, A. Porta	SUBATECH-Nantes	France	Preparation of a new TAS experiment proposal on bDN emitters in collaboration with IFIC (Tain, Algora) for submission to JYFL PAC or ALTO facility. **Done. Experiments will take place in 2015-2016 on following nuclides: $^{130-134}$In, ^{133,134,136}Sn. Spokespersons:** A. Algora, M. Fallot, A. Porta, B. Rubio and J.-L. Taín**. Measured ^{138}I. Analysis ongoing.**

WORK PLAN cont'd

Participant	Institute	Country	Proposed Work
P. Garrett I. Dillmann A. Chen B. Singh	Univ. Guelph TRIUMF McMaster Univ.	Canada	Commissioning of DESCANT and GRIFFIN. **Coming up in May 2015.** Publications of 8π results on n-rich Rb isotopes. **^{102}Rb submitted for publication.** Measurements @ TRIUMF (3Hen). **Not done- currently status of proposal degraded to LoI.** Evaluation of bDN with Z=2-28. **Completed. Submitted for publication.** **Next: B. Singh will continue with compilation and evaluation of P_n and $T_{1/2}$ data for selected nuclei in Z=29-57 region and additional nuclei in the higher mass regions where new data become available. He will also coordinate this effort for Z=29-57 region with the CIAE group (Huang) and VECC group (Banerjee).** **I. Dillmann will participate in this effort in checking the evaluated and compiled data, and publication of a paper of this work.**
G. Mukherjee, K. Banerjee	VECC	India	Literature survey and compilation-evaluation of existing bDN data in fission region. **In progress.** Digitization: **Rb, Cs isotopes submitted to NDS IAEA.** Characterization and testing of neutron detector systems developed at VECC which will be part of MONSTER. **Done.** **Next: Compilation/evaluation of mass region A=111-136 (subject to modification). Digitization. Develop a few more MONSTER modules.**

WORK PLAN cont'd

Participant	**Institute**	**Country**	**Proposed Work**
V. Piksaikin	IPPE	Russia	Least-squares fit of DN decay curves for each isotope to obtain 6- and 8-group models at different incident neutron energies. **In progress.** Obtain Covariance data for delayed neutron parameters (a_i,T_i) . Produce new data: 1) (a_i,T_i) for main fissile materials and minor actinides (Np, Am) for neutron energies 14-18 MeV and 2) Composite DN spectra from thermal neutron-induced fission of ^{235}U **In progress.** **Measured DN energy spectra and corresponding INDC(NDS) report in preparation.** **Verification of FPYs to be published in Prog. Nucl. Energy.** **Next: Complete (1), re-evaluation of 6- and 8-group models with the purpose to produce new recommendations for some nuclides. Contribute to Macroscopic database.**
K. Rykaczewski, R. Grzywacz	ORNL, U. of Tennessee	USA	Submission of HRIBF data on fission products. **Done-14 papers and conf. proceedings sent.** Preparation of approved experiments at TRIUMF ISAC-1 and CARIBU-ANL. **TRIUMF experiment deferred-status is currently that of LoI. CARIBU experiments almost complete. Data under analysis.** **Next: More data ready for submission for publication on A = 82, 83, 86, 87.** **CERN and NCSL proposals: approved for 2015-2016. CERN: nuclear orientation for ^{87}Br, ^{137}I. Cd and very neutron rich K decays.** **NSCL: Co decays.** **BRIKEN: joint proposal of Rykaczewski, Tain, Dillmann, and Grzywacz was approved.**

Appendix 3

WORK PLAN cont'd

Participant	**Institute**	**Country**	**Proposed Work**
J.L. Tain A. Algora	IFIC Valencia	Spain	Exp. With BELEN at IGISOL-JYFL in 2013 (same as Cano) to measure Y and Sb isotopes. **Done in 2014.** Contribution to new evaluation of old DN P_n data**. Done.** New sensitivity study to identify additional DN emitters of interest in advanced nuclear reactors. **Done and submitted.** Provide data on DN emitters, $T_{1/2}$ and P_n from GSI measurements. **Data to be published.** **Upgrade of BELEN to BELEN-48.** **BRIKEN: joint proposal mentioned above and preparation of experiment.** **Evaluations for Z>57 in fission mass region (Coordinated by B. Singh)**
X. Huang	CNDC	China	Evaluation of selected potential FP nuclides (A=139-151): review and collection of measured data, assessment of exp. technique and use of suitable averaging method. **In progress.**
F. Minato	JAEA	Japan	Calculate DN emission with Ohsawa's approach: make computer code to calculate DNY and investigate energy dependence of FF**. Now using existing Japanese code. Results will be published in a JAEA report.** **Provide results of Skyrme-Hartree-Fock calculations of DN $T_{1/2}$ values (even-even nuclei). Done also including P_{xn} values and Total DN spectra for individual precursors for odd and odd-even nuclei as well. Will extend to drip-line nuclei. To be published in ARIS conf. proceedings and submitted to CRP bDN database.**
T. Marketin	Univ. of Zagreb	Croatia	Extend Covariant DFT to treat FF transitions. **Done. Data to be submitted to CRP bDN database.** Employ finite amplitude method to solving relativistic QRPA eqs., including deformation. **In progress.** Goal is to calculate beta-decay rates for all nuclei, both spherical and deformed**. Done for spherical (incl. P_n). To be submitted to CRP bDN database.** **Continue on deformed and correlations.**

WORK PLAN cont'd

Participant	**Institute**	**Country**	**Proposed Work**
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. **Pending on CRP data becoming available in relevant mass region.** **Performed Nubar and <$T_{1/2}$> calculations for recent FPYs and DD sets. Provided component contribution for major evaluations (JEFF 3.1.1, ENDF/B 7.1, JENDL 2011).**
Advisors			
A. Sonzogni, T. Johnson E. McCutchan	BNL	USA	Systematics for P_{2n}. **Data not adequate. To be revisited as database grows. Performed systematics for new evaluations in Z=2-28 region.** Sensitivity study to identify most relevant bDN emitters to delayed nu-bars. **Done.** Perform first experiment for ^{138}I to measure decay and $T_{1/2}$ (provided the exp. is scheduled at CARIBU). **Cancelled.** Calculation of DN energy spectra. **Cancelled.** Contribute to evaluation cand documentation effort. **Done.** **Next: calculate covariances for DN group parameters and contribute to macroscopic database. Contribute to checking of evaluations in fission region (Coordinated by B. Singh)**
G. Lorusso	NPL	UK	**Provide data from EURICA experiments for inclusion in the CRP bDN database.** **Contribute to checking the evaluations in the fission mass region (coordinated by B. Singh)**

Appendix 3

List of Experimental Data

to be delivered by 3rd RCM (winter/spring 2017): Revised at 2nd RCM (23-27 March 2015)

No	**Experimental Data**	**Isotopes**
1	K. Rykaczewski, R. Grzywacz	Submitted: ^{85,86}Ga (^{86}Ge) (**P$_n$**) **- ok** To be submitted: ^{72}Fe **-ok,** ^{86}Ge (**decay schemes) -to be submitted for publication** In preparation: 83,^{84}Ga, ^{77,78}Cu +27other (**DN energy spectra**) **-to be submitted for publication** MTAS in preparation: 22 nuclei (**decay heat**)**-5 published in conf. proceedings. The rest in preparation for publication (2015-2016)** TRIUMF scheduled: ^{79,80,81}Ga, ^{83}Ge (**P$_n$**) **-deferred**
2	P. Garrett	To be submitted:^{102}Rb (**P$_n$**) **-to be sent to B. Singh** To be analyzed: ^{98}Rb (**P$_n$**) - **underway** ^{100,101}Rb - **insufficient data**
3	J.L. Tain	BELEN To be submitted: ^{85}Ge, ^{85,86}As, ^{91}Br (**P$_n$**) **-ok** Few isotopes A ~ **126 (Ag and Pd isotopes), ^{210}Tl (P$_n$+T$_{1/2}$)-to be submitted for publication by end of 2015** Approved: ^{86}Ge **- not possible**, $^{98+m,99}$Y, $^{135\text{-}137}$Sb, 138,^{139,140}I (**P$_n$**) **- under analysis** TAS $^{86\text{-}88}$Br, $^{91\text{-}94}$Rb (**All**) - **to be submitted for publication (2015-2016)**
4	D. Cano-Ott	MONSTER (spectra) ^{94,95}Rb, ^{88}Br, ^{137}I (**spectra**) **-most likely will not be measured** **^{85,86}As and ^{91}Br P$_n$ to be provided for inclusion in database.**
5	M. Fallot	TAS ^{138}I: measured in 2014 @ Jyväskylä, (spokespersons: Fallot, Tain and Algora) **-analysis ongoing in Nantes.** **^{99}Y: also measured and under analysis.**
6	A. Algora	TAS data on $^{86\text{-}88}$Br, $^{91\text{-}94}$Rb (see Tain). **Measured in 2014@ Jyväskylä, (spokespersons Fallot, Tain and Algora): ^{137}I, analysis ongoing in Valencia.**

Appendix 3

Experimental Data cont'd

No	Experimental Data	Isotopes
7	G. Lorusso (RIKEN)	bDN emitters $T_{1/2}$ (EURICA): **Z=26-32 region (20 isotopes) submitted for publication by end of 2015** **Z=42-46 region (20 isotopes) to be submitted for pubication in 2016** **Z~65: 15 isotopes in 2016 (upper limits)- to be submitted for pubication in 2016**
8	N. Scielzo (CARIBU@ANL)	bDN Pn and DN spectra: **^{137,138,140}I, ^{135,136}Sb, ^{144,145}Cs: to be submitted for publication in next couple of years**

Appendix 3

4. Summaries of presentations

4.1 A comprehensive approach to determine delayed-neutron data, S. Chiba (Tokyo Inst. Technology)

The experimental setup for measurements of fission fragment mass distributions by the multi-nucleon transfer (surrogate) method was prepared, and experiments using ^{18}O beam on ^{238}U, ^{232}Th and ^{248}Cm were carried out. Data obtained for ^{238}U and ^{232}Th targets were presented at the meeting. These data are under analysis, and will be submitted for publication in a couple of months. Data obtained for the ^{248}Cm target are under analysis, and we plan to perform an experiment with ^{237}Np target in the next fiscal year. Though we have to be careful how we interpret these data obtained with a surrogate reaction instead of the neutron-induced fission reaction, many new data on the fission fragment mass distributions are going to come out, including dependencies on excitation energy and isotopes.

The Gross theory of beta-decay is going to be extended to include recent data on $T_{1/2}$ and P_n values. Some nuclear structure effects will be taken into account by using the shell correction energy of the Koura-Tachibana-Uno-Yamada mass formula.

A multi-dimensional Langevin model approach to calculating fission properties was further developed. We have found that this approach gives a good reproduction of the neutron-induced fission fragment mass distributions for ^{233}U, ^{235}U and ^{249}Pu targets, and also compares favorably with data obtained by the surrogate method. We are going to extend this method to include 1) capability to calculate isotopic yield rather than mass yield only, 2) different deformation of the two fragments, 3) transport coefficients from microscopic linear-response theory, and 4) emission of prompt neutrons to convert the primary fission yield to an independent one.

Summation calculations of delayed-neutron yields were performed, and the following results were obtained

- DN yield of ^{235}U from JENDL: overestimation at t<10 s
- best results obtained with GEF code (Jurado, KH Schmidt) and JEFF-3.1
- FY of ^{86}Ge too high in JENDL and ENDF. Possibly a simple mistake carried over from last version of ENDF.
- JEFF-3.1 uses GEF code (R. Mills)
- JEFF prototype based on CYFP code (by Wahl) overestimates the ^{235}U DN yield.
- ^{239}Pu DN yield: GEF does not give good agreement
- DN yield is a more sensitive probe than decay heat, better for testing the model.

4.2 Theoretical calculations of beta-delayed neutrons and sensitivity analyses, F. Minato (JAEA)

Theoretical calculations of delayed neutron (DN) branching ratios and half-lives were presented. To calculate the beta strength function and half-lives, the quasiparticle random phase approximation (QRPA) was adopted. We used the Skyrme-Hartree-Fock + BCS model for calculating ground states and assumed axial and reflection symmetric deformation of nuclei. Odd nuclei were treated within the independent particle model. The SkO effective interaction was adopted. Neutron emission probability from excited states populated by beta-decay was estimated by the Hauser-Feshbach statistical model. We calculated the half-lives of 233 nuclei ranging from Z=30 to 60 and obtained the rms deviation value of 5.09. We also presented DN branching ratios for Z=27-44 nuclei and DN spectra. Theoretical results roughly reproduce the experimental DN branching ratios. The results are expected to be improved if the first-forbidden transition is included, which is not taken into account in the present formalism.

The dependence of DN yields of actinide nuclei on the incident neutron energy was estimated with the aggregate calculation of DN precursors. We chose U-235, 238 and Pu-239 and adopted the code of Oyamatsu [2] for the aggregate calculation. Decay data of fission products was taken from JENDL/FPD-2011 [3]. The mass yield was calculated with a five-Gaussian model and the fractional independent yields (FIY), which give the charge distribution of a certain mass, were taken from England and Rider’s [4], and Nethaway’s evaluations [5]. The FIYs of England and Rider showed a weak sensitivity to incident neutron energy and deviated from evaluated data of JENDL-4.0, ENDF/B-VII.1, and JEFF-3.2 at high energies. On the other hand, Nathaway’s evaluation showed a reasonably good agreement with the evaluated data. We also tested other evaluations of FIYs and found that only Nathaway’s approach worked well.

Sensitivity studies producing a list of important precursors for DN yields of burst fission were also presented. Decay data and fission yield data were taken from JENDL/FPD-2011 and JENDL/FPY-2011[6], respectively. Thermal fission of U-235 and Pu-239, and fast fission of U-235, U-238, and Pu-239 were tested. It turned out that the sensitivity to fission yields and delayed neutron branching ratios was almost identical. Br isotopes and Rb-94, Y-98m and I-137 were the leading contributors to the DN yields. As, Nb, and Cesium isotopes also contributed to DN yields but their contributions were smaller. For thermal fission of U-235, we found a strong sensitivity to Ge-86, which however may be due to the incorrect Ge-86 fission yield data in JENDL/FPY-2011 as well as ENDF/B-VII. The results are to be published in Nuclear Data Kenkyukai proceedings.

We also listed the important DN precursors for r-process nucleosynthesis calculations with different entropy conditions. The list differed from the one found for actinide nuclei and varied with different entropy conditions. We also showed that light DN precursors could also emit neutrons after the freeze-out.

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[2] K.Oyamatsu, JAERI-Conf 99-002, pp.234-239 (1999).
[3] J. Katakura, JAERI-Research2003-004 (2003).
[4] T.F. England and B.F. Rider, LA-UR-94-3106, ENDF-349 (1994)
[5] D.R. Nethaway, Lawrence Livermore Laboratory Report No. UCRL-51538 (1974).

4.3 Delayed neutron emission near semi-shell closures, I.N. Borzov (Kurchatov Institute Moscow)

The β-decay half-lives and β-delayed neutron emission probabilities of very neutron-rich nuclei are of great value for nuclear structure theory. Often these are the only fingerprints of nuclear isospin response far from stability. Given an increasing amount of new β-decay data on fission and fragmentation products from the radioactive beam facilities, the combined analysis of total β-decay half-lives and multi-neutron emission probabilities provides a unique possibility to reconstruct the beta-strength functions. They provide important information on the nuclear density functional in the high isospin-asymmetry regime [1]. Reliable sets of masses and beta-rates of very neutron-rich nuclei are required for the r-process modeling. Accurate beta-decay data on fission products are important for safety studies of advanced nuclear reactors.

The IAEA CRP on a new database of beta-decay half-lives ($T_{1/2}$) and delayed neutron emission branching (P_{xn} values) [2] will compile not only experimental data but also theoretical predictions for nuclides beyond the reach of existing or planned facilities. In this respect, the fully microscopic models are of particular importance as they ensure more reliable extrapolation of nuclear data to extreme N/Z ratios.

Review. The continuum QRPA (CQRPA) approach to the allowed Gamow–Teller (GT) and first-forbidden (FF) beta decays based on the self-consistent description of the ground state properties within the local energy–density functional (DF) theory has been developed. A necessity to improve treatment of the T=0 proton-neutron effective interaction in all the available models is stressed.

Main results. It is shown that the DF+CQRPA model provides better description of the recent experimental beta-decay half-lives and delayed neutron emission rates [3-6] for the nuclei near the neutron closed shells N=28, 50, 82, 126 than the standard global approach [7]. Special attention is paid to the decisive role of the FF decays in accelerating the beta-decay and reducing the total delayed neutron emission probabilities in nuclides beyond the neutron closed shells. The impact of quasi-particle phonon coupling on the Gamow-Teller strength, half-lives [8] and delayed multi-neutron emission rates near the closed shells is emphasized in Ref. [9].

[1] http:// www.unedef.org
[2] D. Abriola, I. Dillmann, B. Singh, INDC(NDS)-0594;I. Dillmann, P. Dimitriou, B. Singh, INDC(NDS)-0643, 2014.
[3] I.N. Borzov, Phys.Rev. C67, 025802 , 2003; C71, 065801, 2005..
[4] J. Winger et al . Phys.Rev. Lett. 102, 142502, 2009.
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[6] I.N. Borzov, Phys.At. Nucl. 74, 1435, 2011;
[7] P. Moeller et al., Phys.Rev. C67, 055802 , 2003, Prog. Nucl. Energy 41,39, 2002.
[8] A.P. Severukhin et al., Phys.Rev. C90, 044320 , 2014.
[9] K. Miernik et al., Phys. Rev. Lett. 111,132502, 2013.

4.4 Large scale evaluations of beta-decay rates of r-process nuclei, T. Marketin (Univ. Zagreb)

One of the currently most active fields of nuclear astrophysics deals with the synthesis of elements heavier than iron by the r process. Apart from the complexities involved in astrophysical modeling, the r process presents a particularly difficult challenge due to the large amount of nuclear input involved. Crucial nuclear properties having a direct impact on the distribution of the elemental abundances are the beta-decay half-lives, together with the beta-delayed neutron emission probabilities.

The calculation of beta-decay rates and emission probabilities requires the evaluation of both the nuclear ground state of the parent nucleus and excited states of the daughter nucleus, together with the transitions between them. Because the calculation requires a good description of a wide range of physical properties, and because the goal is to obtain the decay rates for a very large number of nuclei, we employ a fully microscopic theoretical framework based on the relativistic nuclear energy density functional (RNEDF). In the calculation of the transition rates we include a full description of the first-forbidden transitions, calculated on an equal theoretical footing as the allowed transitions, that allows us to perform direct comparisons of the relative contributions of particular multipoles in the total decay rates.

Using a fully self-consistent theoretical framework, we obtain all the necessary properties from the same underlying interaction, and the results compare favourably to the measurements. By averaging the logarithm of the ratio of the calculated and measured half-lives of known nuclei, we obtain a very good average agreement with experiment, comparable to the FRDM results. However, we find that in the case of FRDM this average agreement is a consequence of cancellation of systematic overestimation of half-lives of even-even nuclei and underestimation of half-lives of odd-odd nuclei. The results of this study show much weaker discrepancies with respect to the type of nucleus, with the same good average agreement.

In the case of beta-delayed neutron emission, we have evaluated the probabilities as a ratio of the decay rate within a window between two neutron separation energies and the total decay rate. Essentially, we have used the approximation that a particular nucleus will emit as many nucleons as is energetically allowed. Using this approximation, we obtain reasonable results across the whole nuclear chart, up to the drip line, whereas the FRDM model has displayed unphysical behaviour close to the neutron drip line.

Finally, we have started to study correlations between the model parameters, nuclear half-lives and r-process abundances. With statistical tools we aim to test the sensitivity of calculated half-lives to specific parameters of the model with the goal of using beta-decay rates as an additional constraint in the process of adjusting the model parameters to measurements. Additionally, we shall obtain the correlations between the half-lives of neutron rich nuclei and the r-process abundances in an effort to determine regions of the nuclear chart, or even specific nuclei, which play an important role in the process of heavy element nucleosynthesis.

4.5 Update on relevant proposals on beta-delayed neutron emission, recent experiments and evaluated data, K. Rykaczewski (ORNL)

Status of the proposals to measure the decay properties of beta-delayed neutron emitters

A new program aiming to study beta-delayed neutron emission has started within an international collaboration at RIKEN laboratory, Wako (Japan). The collaboration of over 100 physicists from several countries is planning to measure beta-delayed 1n and 2n emission from nuclei produced by fragmentation of intense 238U beam at 345MeV per nucleon. This setup is nicknamed BRIKEN for Beta-delayed neutron studies at RIKEN.

The BRIKEN construction proposal (Domingo-Pardo et al) was approved at RIKEN in December 2013, and two subsequent proposals for experiments in mass region A~ 130-140 region (Lorusso et al.,) and A~ 75-90 region (Rykaczewski et al.,) were accepted with top priority in 2014. The proposal to study nuclei, mostly north-east from doubly-magic ^{78}Ni, aims at measuring new P1n and P2n branching ratios, which means an identification of new beta-delayed 2n emitters (only one β2n activity of 86Ga is known in this region). It includes the first direct measurement of 20 P1n branching ratios in the decay of ^{76}Co, for doubly-magic ^{78}Ni, for ^{79}Ni, ^{80}Cu, ^{81}Cu, ^{83}Zn, ^{84}Zn,^{85}Ga, ^{85}Zn, ^{87}Ge, ^{88}As, ^{87}Ga, ^{88}Ge, ^{89}As, ^{90}Se, ^{89}Ge, ^{90}As, ^{90}Ge, ^{91}As and ^{92}Se, as well as the first observation of β2n emission and P2n branching ratio measurement in the decay of 14 exotic nuclei ^{80}Cu, ^{81}Cu, ^{82}Cu, ^{83}Zn, ^{84}Zn, ^{84}Ga, ^{85}Ga, ^{87}Ga, ^{87}Ge, ^{88}Ge, ^{88}As, ^{89}As, ^{90}As and ^{91}As. This "beyond ^{78}Ni" project is aims at providing new data on β1n and β2n emission probabilities, which should yield better understanding of the 1n/2n competition and help verify the microscopic and empirical model calculations (Moeller et al; Borzov; Kawano et al; Miernik). A test experiment with full BRIKEN setup including over 80 3He Reuter-Stokes detectors from ORNL served by UTK's Mesytec preamplifiers is now planned for April 2016.

The previously accepted proposal to measure βn-values at ISAC-1/TRIUMF was deferred since the requested 3He tubes certification procedures were not performed at the time of detector production, and the permit to transport the equipment for about 14 km on Canadian soil was not granted.

Recent experiments on beta-strength function with ORNL's Modular Total Absorption Spectrometer.

The total gamma absorption spectrometry is known to provide reliable data on beta-strength functions even for complex decay schemes. In a recent multi-week campaign at ORNL, we have measured over twenty decays of fission products using ORNL's Modular Total Absorption Spectrometer at the on-line mass separator (On-line Test Facility OLTF). Several of the measured activities were exhibiting beta-delayed neutron emission. MTAS consist of 19 hexagonal NaI(Tl) modules arranged in rings around the measuring point on the activity transport tape. In the recent experiment, neutron-rich nuclei were produced in fission of ^{238}U induced by 40 MeV protons (intensity up to 50 pnA). Nuclei in mass region A ~ 130-140 have been studied so far including nuclei having priority 1 for decay heat simulations in nuclear fuel as assessed by the WPEC Sub-group 25 Working Party of OEDC's Nuclear Energy Agency in 2007.

The results on beta-decay patterns obtained with MTAS point to previously undetected beta-feeding of highly excited states in daughter nuclei which changes dramatically the beta-strength function. It results in increasing the gamma decay heat and reducing beta- and antineutrino endpoint energies. Shifting anti-neutrino energy spectra to lower energies results in a reduced number of anti-neutrino interactions with matter. These results have important implications in reactor anti-neutrino applications.

New data on 86Ge decay.

The decay properties and yields of ^{86}Ge were used recently to evaluate the ‘ kinetic behavior’ of a nuclear fission reactor [Chiba et al., NDS 118, 401, 2014]. By using yields and decay data listed in ENDF and JENDL libraries, ^{86}Ge was found to be a beta-delayed neutron emitter important for estimating the time-dependent budget of neutrons in power reactors. In fact, this conclusion results from wrong data on ^{86}Ge yields and properties (and in general, of a part of Z=29 to 33 isotopes) in ENDF and following JENDL libraries. We have compared the production of ^{86}Ge and other nuclei in its neighborhood in proton-induced fission of ^{238}U [Mazzocchi 2015, to be published]. It is obvious that these high yields in ENDF and JENDL libraries must result from an error in the evaluation or in the incorporation of these values in the data files base (see ENSDF web page for comparison of ENDF/JENDL yields with the most-likely correct JEFF yield pattern). Moreover, the half-life and βn-branching ratio of 45(15)% for the quite exotic nucleus ^{86}Ge were determined for the first time in the course of our studies. Our experimental values do not match ENDF/JENDL data. This example illustrates the importance of nuclear structure studies of beta-delayed neutron emitters for a critical assessment of reactor sensitivity to particular isotopes.

4.6 Report on activities of the IFIC-Valencia group, J.L. Tain (IFIC/CSIC-Univ. Valencia)

Results from 2011 measurements: Two experiments were performed during 2011 at the GSI-Darmstadt Fragment Separator (FRS) to determine half-life and beta-delayed neutron emission probabilities of neutron-rich isotopes around A=130 and A=210. Both experiments were aiming to obtain information, which could help refining estimates of the nuclear physics input for r-process calculations. The experiments were performed using the BELEN-30 neutron counter, developed in the frame of the FAIR project by the Barcelona-Darmstadt-Madrid-Valencia collaboration. The high-energy ions were implanted inside BELEN, in the SIMBA multi-DSSSD detector developed by T.U. Munich. The analysis of experiment S410: “Measurement of β-delayed neutrons around the third r-process peak” (C.Domingo-IFIC, B.Gomez-UPC, I.Dillmann-GSI, et al.) constitutes the PhD Thesis of R. Caballero (UPC, May 2015). Implanted ions were identified using the measured ToF along the FRS and their energy loss in two ionization chambers. The number of identified ions with Z=79-83 varied between few tens and over one thousand. Time correlations between the implanted ion and the subsequent registration of a beta particle at the same location were used to determine the half-life for 20 isotopes from which 10 are new and 2 deviate considerably from previous values. The measurement of P_n values was more challenging because of statistics and the observed large secondary-beam induced neutron background. By using the information registered between the beam pulses it was possible to determine for the first time neutron emission probabilities for two isotopes (^{213}Tl and ^{214}Tl) and establish upper limits for another five. The measured $T_{1/2}$ and P_n were compared with QRPA theoretical values from Moeller et al. and I. Borzov (priv. com.). Further work is needed to understand the agreements and disagreements observed. Data will be published soon. Experiment S323: “Beta-decay of very neutron rich Rd, Pd, Ag isotopes including the waiting point 128Pd” (F. Montes-MSU, et al.) constitutes the PhD Thesis of K. Smith (U. Notre-Dame, 2014). The same setup described earlier was used in these measurements. The number of identified isotopes ranged between a hundred and more than ten thousand. The main difference comes from the fact that half-lives of the measured Ag and Pd isotopes were shorter and the analysis had to consider the data measured during beam spill. An additional difficulty was the existence of a spurious background due to light ions traversing the SIMBA detector that could not be distinguished from beta signals. A careful determination of the background using a Monte Carlo method to create wrong correlations from the registered data allowed us to determine the half-life for 11 isotopes, including 3 new values, and 6 new P_n values plus 5 additional upper limits. The measured values were compared with several QRPA calculated values (Moeller 2003, Borzov, 2003, Fang 2013, Niu 2013). The most striking result for Ag isotopes is the overall good agreement for $T_{1/2}$ while the P_n values are clearly too low. For Pd isotopes the experimental P_n value seems also much larger than calculation while there is good agreement for $T_{1/2}$ except for Moeller’s calculation, which is too large.

New 2014 measurements: Two experiments were performed at the University of Jyväskylä Cyclotron Laboratory (JYFL) in November 2014. The experiments measured the mono-isotopic beams extracted from the Penning trap located after the IGISOL mass separator for greater accuracy. The isotopes were implanted on a movable tape in front of a plastic β detector at the centre of BELEN-48 the upgraded version of the neutron counter. Experiment I162: “Delayed neutron measurements for advanced reactor technologies and astrophysics” (J.L.Tain-IFIC, B.Gomez-UPC, et al.) was devoted to the measurement of fission products, which were identified in a sensitivity study as having sizeable contribution to the delayed neutron fraction per fission $\bar{\nu}_d$ and a relatively large P_n uncertainty. Some of the isotopes are relatively close to the r-process path and the information can be used to verify different models calculations and assess their predictive power. Data with sufficient statistics were acquired for: ^{98,98m,99}Y, ^{135,137}Sb,^{138}Te, ^{138,139,140}I. The most challenging case was ^{137}Sb with an implantation rate of 0.5 ions/s. Experiment I181: “Measurement of the beta-delayed two neutron emitter ^{136}Sb with the BELEN detector” (I. Dillmann-TRIUMF, et al.) aimed to measure the P_{2n} emission probability of this isotope, which was predicted to be relatively large (Moeller, 2003). Up to now the heaviest fission product with known P_{2n} is ^{100}Rb. The measurement is very challenging, with an implantation rate of 1.5 ions/s. By modifying the BELEN-48 detector configuration we were able to increase the two-neutron registration efficiency up to 36%. Moreover we determined that the two-neutron background rate was 0.07 cps, possibly coming from cosmic muons capture and spallation reactions. However, the on-line beta-gated spectra show positive indications of delayed two-neutron emission. Analysis of the data is in progress.

Preparation of upcoming measurements at RIKEN: The proposal NP1412-RIBF127: “Measurements of new beta-delayed neutron emission properties around doubly magic 78Ni” (K. P. Rykaczewski-ORNL, J. L.Tain,-IFIC R. K. Grzywacz-U. Tennessee, I. Dillman-TRIUMF) aiming at the measurement of 20 new P_{1n} and 14 new P_{2n} values has been approved at the RIKEN Nishina Centre. Measurements will be performed on fragments produced in U beam reactions and separated with the BigRIBS spectrometer. The ions will be implanted in the AIDA detector array (Edinburg, Daresbury, Liverpool), which serves also to tag the beta decays. Neutrons will be registered with the BRIKEN neutron counter (Barcelona, Darmstadt, Oak Ridge, Tennessee, Valencia), which is the largest ever build moderated ^{3}He detector array. One of our tasks is to develop the BRIKEN data acquisition system, based on the BELEN digital triggerless DACQ and upgraded to 176 acquisition channels. The new control and online software, and the new digitizers and signal conversion cards were successfully tested in the November run at JYFL. Further upgrades and tests continue at IFIC. We have performed also the first synchronization test with the AIDA and BigRIBS DACQs at RIKEN in February. Another task has been the design an optimization of a hybrid detector geometry including two CLOVER HPGe γ-ray detectors. This configuration will allow a better control of the experiment and permit to obtain valuable physics relevant information. The next parasitic beam test at RIKEN is planed for the end of April.

Total absorption γ-ray spectroscopy measurements: The JYFL experiment “Decay properties of beta delayed neutron emitters” (A. Algora-IFIC, D. Cano-CIEMAT, B. Gomez-UPC, A. Jokinen-JYFL et al.) approved in 2009 introduced a new approach in the study of neutron-rich nuclei by aiming at a comprehensive study of the β-strength function combining γ-ray and neutron spectroscopy. In particular TAS studies were proposed to accurately study the complete β-intensity distribution including the γ-ray emission from neutron-unbound states. The experiment was carried out with the new Valencia-Surrey spectrometer which was specially designed for this purpose. BaF_2 was chosen as scintillation material instead of the usual NaI(Tl) because of the much smaller sensitivity to delayed neutrons (reduced background). It was also the first segmented TAS spectrometer dedicated to β-decay studies, which allowed the measurement of γ-ray cascade multiplicity and helped to improve the reliability of the analysis. The analysis of ^{87,88}Br and ^{94}Rb constitutes the PhD Thesis of E. Valencia (U. Valencia). The result shows a large *Pandemonium* effect for all three nuclei. With respect to gamma-neutron competition above S_n, we find that the γ emission intensity is comparable to the neutron emission intensity for bromine isotopes, while it is even larger in the case of ^{87}Br. This is the first observation of such high γ intensity from neutron-unbound states in β-decay. In both cases the phenomenon can be understood as a consequence of the spin and parities of the levels involved and the hindrance of neutron emission with large orbital angular momentum. Such nuclear structure effect can be of importance whenever the level density in the final nucleus is low and should be taken into account when estimating P_n values from β-strength calculations. In the case of ^{94}Rb, although the γ intensity is only 5% of the neutron intensity, the value is much larger than the one calculated with the Hauser-Feshbach model using standard statistical model parameters. For this comparison it was necessary to introduce statistical fluctuation corrections to the ratio $\langle \Gamma_\gamma / (\Gamma_\gamma + \Gamma_n) \rangle$ which we did using a Monte Carlo method. It seems that the difference between calculation and experiment can only be bridged by a large increase of the photon strength function. If proved correct this increase will have an impact on estimations of (n,γ) cross sections for very neutron-rich nuclei used in r-process abundance calculations. We have thus introduced a new method to obtain experimental constrains on neutron capture cross sections estimates for very unstable nuclei. The publication of these results is being finalized.

4.7 Progress on the βDN CRP by the Guelph/TRIUMF group, P. Garrett (Univ. of Guleph)

Instrumentation

DESCANT, one hemisphere of which is pictured in Fig. 1 below, was successfully coupled to the GRIFFIN spectrometer. DESCANT is comprised of 70 individual detector elements each of which contains approximately 2 litres of deuterated benzene. Deuterated benzene has the advantage over traditional scintillator materials since the neutron-deuteron scattering cross section is highly anisotropic resulting in a peak-like structure in the pulse height spectrum. Further, the scattering cross section possesses a minimum at 90º, thus also minimizing neutron multiple scattering into adjacent detectors – a problem that often plagues arrays of neutron detectors. DESCANT offers 15 cm deep scintillator cans, a 1.08π sr solid angle coverage, a 50 cm flight path, and pulse-shape discriminator for separating neutron and γ-ray interactions in the detector, DESCANT represents a powerful tool for nuclear structure and nuclear reaction investigations at both ISAC-I and ISAC-II at TRIUMF. Work continues on the development of the firmware for the on-board processing of the digitalized signals from the DESCANT detectors.

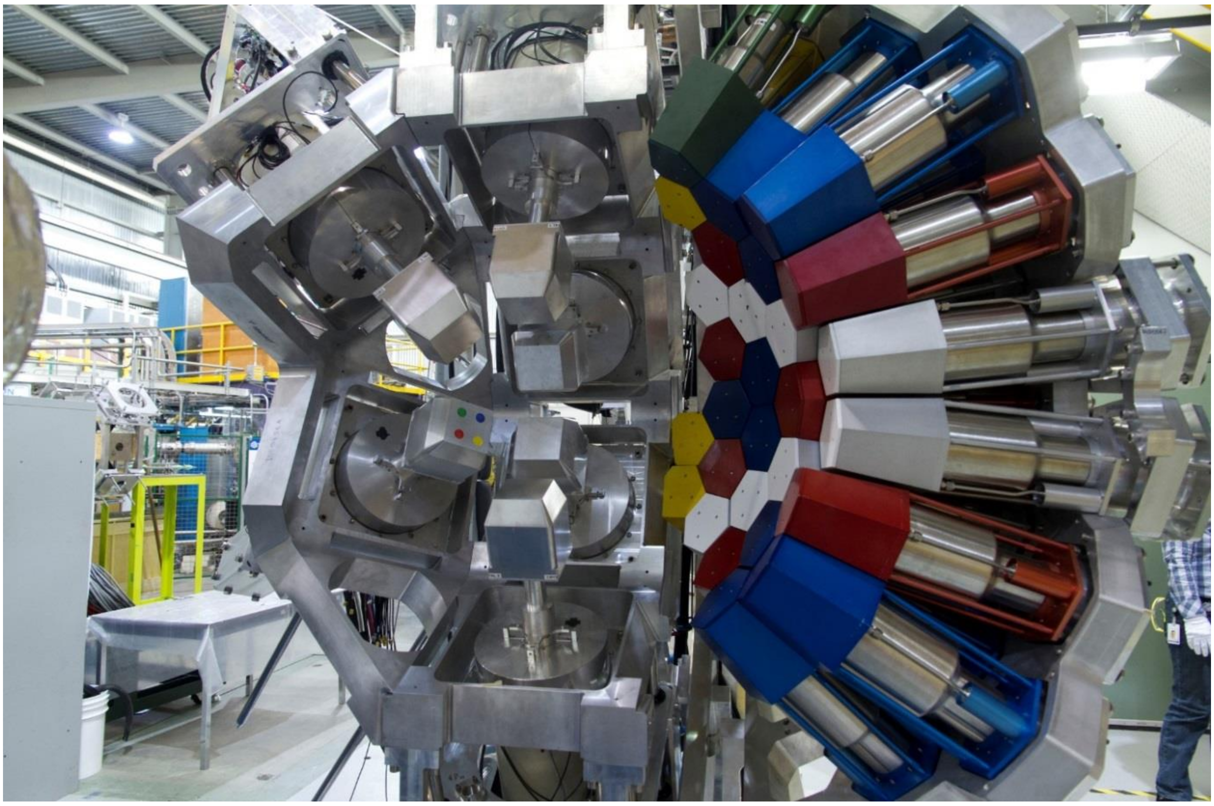


FIG. 1: One hemisphere of the DESCANT detector array coupled to the GRIFFIN spectrometer at the ISAC-I facility at TRIUMF. DESCANT represents a state-of-the-art array composed of 70 individual deuterated benzene liquid scintillators for the detection of neutrons, and can be used in conjunction with both the TIGRESS spectrometer for studies involving reactions with accelerated beams, and GRIFFIN for studies of β-delayed neutron emitters. The $2M GRIFFIN project was funded by CFI, the Ontario MRI, and TRIUMF.

Planned experiments and results

Data obtained from the 8π spectrometer on specific β-delayed neutron emitting isotopes continues. The first result that has been analyzed using the "gamma-and-gamma" method is ^{102}Rb. A new result, P_n=65±22%, has been extracted by comparing the yield of gamma rays from ^{101}Sr to those in ^{102}Sr. This is significantly greater than the previous result in ENSDF of 18±8%, and agrees much better with the expected systematics. Figure 2 displays the results for the neutron-rich Rb isotopes.

A DESCANT-GRIFFIN campaign of measurements is expected to take place during 2015. New data on ^{32}Na decay, $^{33–35}$Mg decay has been collected. Unfortunately, a combination of

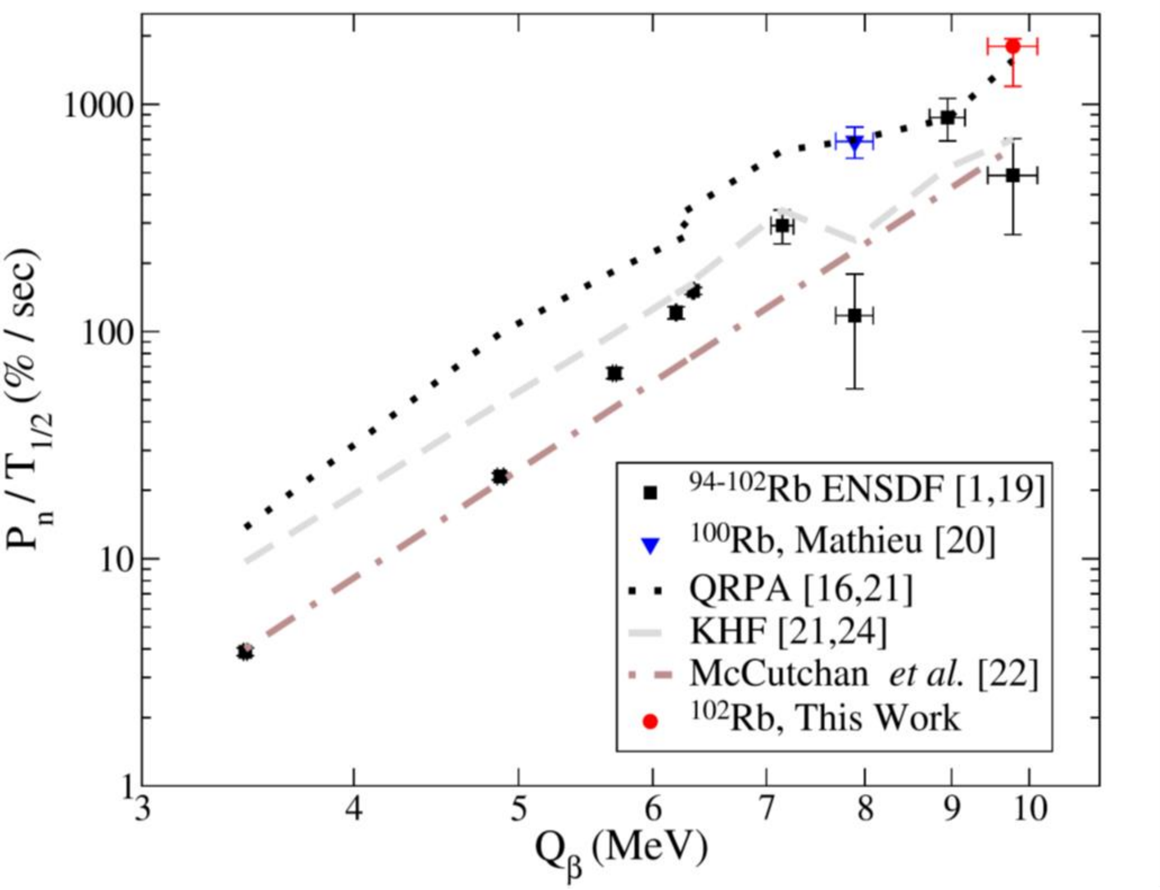


FIG. 2: the P_n value divided by the half life as a function of the Q value for the Rb isotopes. New measurements of ^{100}Rb and the result from the 8π for ^{102}Rb agree much better with the expected result from systematics.

problems with electronics and delivery of the main proton beam necessitated us to postpone the ^{145,146}Cs measurements. Upcoming measurements on $^{128–132}$Cd, and ^{132,133}In, are planned for a second phase of the campaign. A new proposal to measure the decay of ^{9}Li has been submitted and is awaiting a decision by the TRIUMF Experiment Evaluation Committee.

4.8 Nuclear structure insights from Pn measurements (in exotic nuclei): shape effects in the A=110 region, A. Algora (IFIC/CSIC-Univ. Valencia)

Nuclear shapes play an important role in our understanding of nuclear structure. Shapes and mixing are deduced commonly from spectroscopic measurements (B(E2), B(E0)) or from measurements of ground state properties using isotopic shifts (laser spectroscopy, muonic atoms) among other techniques.

In exotic nuclei, and from the perspective of beta decay, there is also another alternative. The idea was first proposed by I. Hamamoto and collaborators [1] and later further explored by P. Sarriguren and A. Petrovici. The point is that for particular cases there are different patterns of the distribution of the beta decay strength in the daughter, depending on the assumed shape of the parent nucleus. This method has been successfully applied to the study of strength functions obtained from total absorption measurements in the A~80 mass region [2] and more recently in the Pb mass region [3].

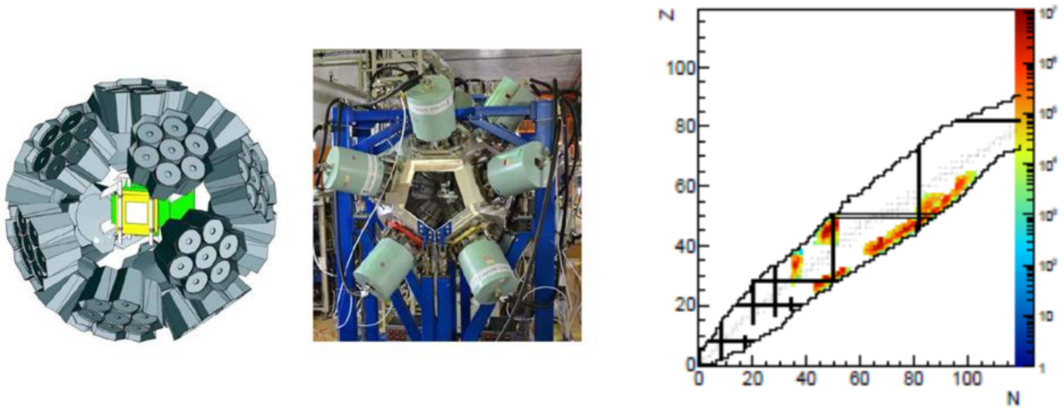
Beta-delayed neutron emission probabilities P_n and for neutron rich nuclei are "integral measurements" of the strength with particular sensitivity to the regions around the S_n and to low-lying excitated states in the daughter nucleus. This information can also provide insight on the shape of the parent nucleus for particular systems.

In this talk, recent theoretical calculations by Sarriguren et al. [4] are presented, that offer a possibility to explore shape effectsby combining measurements of beta decay half-lives and P_n values in the A~110 region. The new BRIKEN project, which aims to build the largest ever 3He counter array, combined with the intense radioactive beams provided by RIKEN, Japan, can provide opportunities to study shape effects from this perspective.

[1] I. Hamamoto Z. Phys. A353 (1995) 145.
[2] E. Nácher et al. PRL 92 (2004) 232501, E. Poirier et al. PRC 69, 034307 (2004).
[3] E. Estevez et al., PRC in preparation.
[4] P. Sarriguren et al., PRC 81 (2010) 064314; PRC 89 (2014) 034311.

4.9 Measurement of beta-delayed neutron emission probabilities with EURICA, G. Lorusso (Nuclear Physics Laboratory)

The Euroball RIKEN cluster array (EURICA) program [1, 2] is an experimental campaign aimed at studying isomer and beta-decay spectroscopy. The program takes advantage of the large beam intensities available at the Radioactive Isotope beam facility (RIBF, RIKEN), and the EURICA spectrometer consisting of twelve Euroball high-purity germanium cluster detectors (see Fig 1a). At the heart of EURICA is the active stopper WAS3ABi, a stack of eight DSSDs 1mm thick [2].
The program has been running since 2012 with more than 70 days of measurements. A large number of beta-decay schemes have been studied in different regions of the nuclear chart (Fig. 1b).



(a) (b)

FIG. 1: (a) The EURICA setup, (b) approximate distribution of nuclei studied so far by the EURICA program.

EURICA allows for the indirect determination of the beta-delayed neutron emission probability (P_n) by comparing the relative intensities of γ rays following the de-excitation of daughter nuclei. This technique is particularly suitable for measurements of P_n values of short lived nuclei ($T_{1/2}$ ~100 ms) where the parent decay can be correlated to the β-daughter nuclei as well as βn--daughter nuclei. By studying the correlations between parent and βn--daughter nuclei one can in principle bypass the problem of determining ground state feeding in daughter nuclei and the complexity of decay schemes. This is especially true when daughter nuclei are also transmitted with the beam. In this case however, one needs to pay special care to the β-decay efficiency when comparing γ intensities stemming from nuclei implanted in different pixels of the detector. Compared to direct neutron measurement techniques, this γ–γ correlation technique has the advantage of having a very well-known γ-ray efficiency, and sensitivity to isomers. The latter can in principle be used to disentangle the decay of the isomers from the decay of the ground state. The low γ-detector efficiency is possibly the main drawback of the technique, as it means that in general several thousands of nuclei have to be implanted in the detector to compensate for it. Also, since the technique requires extensive analysis of decay schemes, the data analysis can be rather time consuming. The first results of P_n measurents in the ^{78}Ni region will be published by the end of 2015.

[1] http://ribf.riken.jp/EURICA/
[2] P-A. Söderström, Proc. 12th Asia Pacific Physics Conference, JPS Conf. Proc., 013046 (2014).

4.10 Completed compilation and evaluation of P_n and half-lives in Z=2-28 region, B. Singh (McMaster University)

Compilation and evaluation of P_n and half-lives of 219 potential beta-delayed neutron emitters in the Z=2-28 region has been carried out by a collaborative effort mentioned below, and a paper based on this work has been submitted for publication in Nuclear Data Sheets journal.

Collaboration and tasks:

McMaster University, Canada: Michael Birch and Balraj Singh
TRIUMF, Canada: Iris Dillmann
NNDC, BNL, USA: Alejandro Sonzogni, Elizabeth McCutchan, Timothy Johnson
CNEA, Argentina: Daniel Abriola

M. Birch and B. Singh: selection of relevant nuclides. Search and collection of literature. Compilation and evaluation. First draft of paper.
I. Dillmann, D. Abriola, T. Johnson, E. McCutchan, A. Sonzogni: Checking of data tables. Systematic plots, final draft of paper.

Half-lives of 219 potential beta-delayed neutron emitters were compiled and evaluated together with available experimental P_n values for 107 delayed one-neutron emitters, 20 two-neutron emitters, 5 three-neutron emitters, and one possible four-neutron emitter. Based on these evaluations, reference standards Li-9 and N-17 were re-examined and C-16 and K-49 were proposed as new standards with the caveat that K-49 should be re-measured to achieve better precision than the current 10%. In consideration of a recent publication PR-C 91, 024328 (Feb 27, 2015) on Li-9 and implied P_n value higher by about 20%, albeit with an uncertainty of 10% as compared to the earlier value of 1-2% accuracy, it was also proposed that a new measurement of P_n value for Li-9 should be made at TRIUMF facility.

Tables and Data Files of compiled and evaluated results for bDN database:

1. Table of recommended half-life and P_n data file with complete bibliography (list of references hyperlinked to NSR database)
2. Table of nuclides and Q-values for possible P_{1n}, P_{2n}, P_{3n} precursors (based on AME-12)
3. Table of compiled data for P_{1n}, P_{2n}, P_{3n} and half-lives with all the available references, including some secondary publications.
4. Supplementary Table of comments for P_n and half-life measurements. (This file will be made available, but not published)
5. Above data exist in three .excel files (Q values for relevant nuclides, recommended Pn and half-lives, compiled data for Pn and half-lives). These were sent to IAEA-NDS in February 2015 for setup of bDN database. Another updated version will be sent by April 15, 2015.

Future work

Compilation and evaluation of Z=29-57 region has started. This work will be shared by above collaboration, and with VECC group in India and CIAE group in China.

4.11 Progress report of IAEA project on beta-delayed neutron emission, K. Banerjee (Variable Energy Cyclotron Centre)

In the Coordination Research Project on beta-delayed neutron emission, we are actively engaged in the following: detector development for beta-delayed neutron emission measurements, compilation, evaluation of P_n and $T_{1/2}$ in A ~ 111 -136 mass region and digitization of neutron spectra found in the literature.

Detector development

We are involved in the development of the modular neutron spectrometer (MONSTER) for the beta-delayed neutron emission measurement in collaboration with the other institutes in Spain, Finland, Sweden and France. We have developed two prototype detectors for MONSTER at VECC and studied its detail characteristics. First experimental demonstration of MONSTER using 30 detectors from CIEMAT, Spain has been done in October 2014. The experiment was performed at ISOLDE, CERN to study the decay properties of ^{11}Li.

Compilation and evaluation work

We are also involved in the compilation and evaluation of P_n and $T_{1/2}$ for the beta-delayed neutron emitters in A ~ 111 -136 mass region. We have compiled roughly around 50 nuclei, but there may be some more papers to look through to complete the compilation in this mass region. Further work is in progress.

Digitization of the neutron spectra

We have digitized all the measured neutron energy spectra from the Rb, Cs isotopes from the papers Nuclear Science and Engineering 91, 305 (1985) (NSR key 1985Gr15) and Nuclear Science and Engineering 75, 140 (1980) (NSR key1980Re03).

4.12 Astrophysical sensitivity studies with β-delayed neutrons, I. Dillmann (TRIUMF)

The modern r-processes

The still open question until today is where and how exactly the rapid neutron capture takes place. The ν-driven wind during a Core Collapse Supernova Explosion (CCSN) was favored for many years for the one-scenario description. However, it has been realized that unphysically high entropies are required to reach the isotopes in the 3rd r-process peak at A≈195, and that due to ν-interactions with the neutron-rich matter the material turns proton-rich at later phases. New scenarios which can help filling the gaps are for example neutron star mergers or jet-like explosions of magnetically driven CCSN [1]. The connection of at least some of the r-process abundances with CCSN explosions is supported by the observation of a "robust" pattern of these isotopes in old metal-poor stars in our Galactic halo (see Fig. 11 of Ref. [2]) which could have only been produced by CCSN explosions. The CCSN are classified as "hot" scenario since the temperature is high enough to enable for some time a (n,γ)/(γ,n)-equilibrium like in the classical r-process description.

Neutron star merger scenarios [3] are also able to provide the required neutron densities for a r-process. However, from the point of the Galactical Chemical Evolution they cannot account for the early r-process abundances since the formation and merging implies a time delay. Mergers of two neutron stars or a neutron star and a Black Hole produce a very robust heavy r-process abundance pattern due to repeated fission recycling. The central part of these mergers collapses into a Black Hole and is "lost" but tidal waves expel very neutron-rich material. This scenario is classified as "cold" r-process since no (n,γ)/(γ,n)-equilibrium is established, only a (n,γ)/β-equilibrium which drives the reaction path very deep into the (yet unknown) neutron-rich region. Very neutron-rich material beyond the neutron-dripline is cooled by expansion, before the reaction path, shifted by about 10-15 mass units further neutron-rich than the hot process path, continues to heavier masses. Such a cold scenario can also occur when during a CCSN a rapid cooling sets in.

The most important nuclear physics parameters for both scenarios are nuclear masses (which define the reaction path), and decay half-lives, neutron capture cross sections, and β-delayed neutron branching ratios which define the final shape of the r-process abundance curve. The latter two are of special importance when the process drops out of equilibrium, e.g. during the freeze-out phase, since it sensitively influences the neutron-to-seed ratio at later phases. Recent sensitivity studies focused on the investigation of the influence of various nuclear physics input parameters like masses, β-decay half-lives, and β-delayed neutron emission probabilities on the final r-process abundances, see e.g. Ref. [4].

The group at the University of Notre Dame has carried out detailed sensitivity studies, e.g. investigating the influence of the astrophysical scenario [5], the neutron capture rates [6], β-decay rates [7], or nuclear masses [8]. The sensitivity study for β-delayed neutrons is in preparation but the results are similar to those of Ref. [4]: βn-emitters have less influence in hot r-process scenarios but are important for fine details of the abundance distribution, e.g. leveling out the even-odd staggering. This picture changes for cold scenarios, e.g. neutron star mergers or a cold ν-driven wind.

"r-Java 2.0": r-process simulations for everyone

r-Java 2.0 is a r-process nucleosynthesis code with a simple-to-use graphical user interface which has been developed by the University of Calgary [9]. It includes three possible r-process scenarios: the high-entropy ν-driven wind [10], neutron star mergers [11], and hypothetical Quark Novae [12]. The latest version of the code can be downloaded at www.quarknova.ca/rJava/index.html. However, it has to be noted that the astrophysical models used here, especially the high-entropy wind and the neutron star mergers, do not include the most recent developments in this field. This code is thought to help experimentalists to get an easy access to r-process simulations and carry out their own sensitivity studies to identify key nuclei for experimental investigations.

The ν-driven wind scenario in r-Java has been validated [13] and sensitivity studies in this hot r-process scenario have been carried out. One problem for r-process simulations is that the number of self-consistent models (half-lives calculated from the predicted masses) is limited. As default in r-Java, the half-lives and β-delayed neutron emission probabilities are taken from Möller 2003 [14] (which were calculated with FRDM masses), but masses are from the HFB-21 mass model [15] and the Atomic Mass Evaluation 2012 [16], and neutron cross sections from the TALYS [17] code. For the TRIUMF sensitivity studies in Ref. [13] the following procedure has been chosen to replace theoretical predictions with experimental data:

a) If the experimental values for the mass and half-life were both available for an individual isotope, then they were both used in place of the theoretical values.

b) If the experimental value for the half-life was available but not the mass, then only the experimental half-life would be used in place of the theoretical half-life. The theoretical mass remains unchanged.

c) If the experimental mass was available but not the half-life, then both properties for this isotope in the table would remain theoretical.

With this, the influence of yet unmeasured or uncertain β1n-emission probabilities (P_{1n}) of isotopes around doubly-magic ^{78}Ni and ^{132}Sn was investigated. A first comparison of available experimental and theoretical data [14] showed that in the ^{78}Ni region the P_{1n}-values seem to be underestimated by theory by a factor of 2.4, whereas in the ^{132}Sn region these values are overestimated by a factor of 2. The largest sensitivity factors in this study were found for the yet unmeasured or uncertain P_{1n}-values of ^{76}Co, ^{80}Ni, ^{81}Cu, and ^{131}Cd.

[1] N. Nishimura et al., http://arxiv.org/abs/1501.06567
[2] C. Sneden et al., Annu. Rev. Astron. Astrophys. 46 (2008) 241
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[4] A. Arcones and G. Martinez Pinedo, Phys. Rev. C83 (2011) 045804
[5] R. Surman et al., EPJ Web Conf. 66 (2014) 07024
[6]R. Surman et al., AIP Advances 4 (2014) 041008
[7] M. Mumpower et al., AIP Advances 4 (2014) 041009
[8] A. Aprahamian et al., AIP Advances 4 (2014) 041101
[9] M. Kostka et al., Astronomy & Astrophysics 568, A97 (2014); M. Kostka et al., arXiv:1402.3824
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[15] http://www-astro.ulb.ac.be/bruslib/nucdata/hfb21-dat
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[17] http://www.astro.ulb.ac.be/pmwiki/Brusslib/Talys

4.13 Visualizing beta-delayed neutron emission, S. Ciccone (TRIUMF/McMaster University)

Beta-delayed neutron emission (BDNE) plays a role in the r-process, contributing to detours of beta-decay chains during freeze-out and leading to abundance build-ups of neutron-rich isotopes that would not have been seen otherwise. Experimental and theoretical work continues to measure the neutron emission probabilities of various neutron-rich isotopes to better understand these processes and I have designed and programmed software that displays this information in a useful way.

The BDNE visualization software tool was written using Python 2.7 and displays information from ENSDF (2011) [1], Möller (2003) [2], Birch et al. (2015) [3], and others with planned updates to the database to ensure that the most current and verified experimental and theoretical BDNE information is being displayed. It is easy to quickly install and use with the provided instructions in the software package. Based on user prompts in a GUI window, it creates a chart of the desired region and highlights potential beta-delayed neutron emitters as well as those with measured P_{1n}, P_{2n}, P_{3n}, or P_{4n} values. Users can choose a variety of options in how they display the data such as: a color bar display, zooming in to a region to see the specific probability values for each isotope, or instead a ratio between the experimental value and the theoretical prediction for comparison purposes. Users can also upload their own data in column-divided file format to display where notably, user-uploaded data will supersede the database equivalent to ensure no inconsistencies. This software was designed to be a useful tool for researchers to see what is currently known about beta-delayed neutron emission in order to observe patterns in the data, confirm findings, or plan for future experiments.

Based on feedback from the meeting, it is planned to improve the GUI for better ease of use as well as add more to the database to display if need be. Any additional display options will also be considered. The software will be continuously updated to ensure that any new experimental or theoretical work has been accounted for and to maintain the usability of this software. A link for downloading the software can be found on the main IAEA CONNECT web page as well as in Ref. [4].

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[2] P. Möller et al, Phys.Rev.C 67, 055802 (2003).
[3] M. Birch et al, Nuclear Data Sheets, in review (2015).
[4] (Ciccone 2015) BDNE Visualization Software Tool

4.14 Verification of the evaluated fission product yields data from the neutron induced fission of ^{235}U, ^{238}U and ^{239}Pu based on the delayed neutron characteristics, V. Piksaikin (Institute of Physics and Power Engineering)

The summation method was used for the determination of the most reliable data sets of fission product yields, which are available in the latest version of ENDF/B, JEFF, JENDL, ROSFOND libraries. The criterion for the choice was the consistency of the calculated macroscopic (aggregate) characteristics of delayed neutrons (ν_d and $<T_{1/2}>$) with the corresponding evaluated experimental data.

The macroscopic characteristics of delayed neutrons have been calculated for the thermal and fast neutron-induced fission of ^{235}U, ^{238}U and ^{239}Pu by the summation method. The cumulative yields (CY) of 368 fission products taken from the latest version of JEFF, ENDF/B, JENDL, ROSFOND libraries, and the Wahl data were used as the basic input data. The emission probabilities of delayed neutrons P_n and the half-lives of their precursors $T_{1/2}$ were represented by four data sets obtained on the basis of the systematics and the evaluated experimental data. As a result, for each database of fission products CYs, four values of the absolute total delayed neutrons yields ν_d and four values of the average half-life of delayed neutron precursors $<T_{1/2}>$ were obtained. For each combination of data sets 'CY – (P_n,$T_{1/2}$)', a model curve of delayed neutron activity was calculated for the $^{235}U(n_{th},f)$ reaction. The analysis of the results based on the comparison of the obtained ν_d and $<T_{1/2}>$ values with the appropriate evaluated data allowed us to study the sensitivity of the macroscopic delayed neutron parameters (ν_d, $T_{1/2}$) to the microscopic delayed neutron data sets (P_n,$T_{1/2}$) for each of the considered fission reactions. In addition, this analysis can be used to choose the fission product database that is consistent with the most accurate aggregate delayed neutron data.

It was found that the sensitivity of the ν_d and $<T_{1/2}>$ data to the individual sets of (P_n,$T_{1/2}$) data used in the calculation depends on the fissioning system. Specifically, this sensitivity ranged from low (1.1-1.2%), middle (2.7-3.1%) to high (7.9-9.9%) values for the fissioning systems $^{235}U(n,f)$, $^{239}Pu(n,f)$ and $^{238}U(n,f)$, respectively. It was proposed that the high sensitivity to the (P_n,$T_{1/2}$) data observed for $^{238}U(n,f)$ was connected with the appearance of another group of DN precursors with significant yields as compared to the $^{235}U(n,f)$ and $^{239}Pu(n,f)$ reactions. This group consists of mainly short-lived DN precursors because the average half-life for ^{238}U is essentially less than for ^{235}U and ^{239}Pu (5.3 s against 9.03 and 10.09 s). In general, the P_n and $T^i_{1/2}$ data for these precursors were obtained from different models and systematics and as a result they have large uncertainties and the different data sets (P_n,$T_{1/2}$) are discrepant.

It turns out that the CY database which is the most consistent with the macroscopic DN data (ν_d and $<T_{1/2}>$) for the considered reactions is JEFF-3.1.1, with the exception of the fission product yields for the $^{239}Pu(n_f,f)$ reaction and $^{235}U(n_f,f)$ reaction in case of the ν_d calculation. In this last case, the most appropriate CY data are provided by the ENDF/B-VII.1 library. The most reliable (P_n,$T_{1/2}$) data are from the compilation of Rudstam (Rudstam et.al., 1993). In case of the $^{235}U(n_f,f)$ reaction, the ν_d data are not that sensitive to the (P_n,$T_{1/2}$) data and good agreement is obtained for all CY data sets. This indicates that ν_d has a more pronounced energy dependence than that presented in the last recommendation (D'Angelo and Rowlands, 2002).

The simulation of the DN decay curves for the case of thermal neutron-induced fission of ^{235}U showed that the saturation DN activity varies strongly with different combinations of these

CY-(P_n,$T_{1/2}$) data. These variations are correlated with the average half-lives of the delayed neutron precursors. The decay curve calculated on the basis of the P-K-M (P_n,$T_{1/2}$) data set and the JEFF CY database reproduces Keepin's experimental data (Keepin et. al., 1957).

On the one hand the obtained results show that the proposed approach to choosing the most reliable data on the fission product yields is effective. On the other hand, a comparative analysis of the data revealed a number of issues that need to be resolved in order to validate and recommend fission product yield data.

4.15 High resolution measurements of aggregate delayed neutron spectra in different time intervals from thermal neutron induced fission of ^{235}U (comparison with data obtained by summation calculation), V. Piksaikin (Institute of Physics and Power Engineering)

In order to estimate the consistency of different approaches in developing a delayed neutron spectra database for individual precursors one should have information on aggregate delayed neutron spectra that include contributions from a variety of individual precursors. The purpose of this work is to measure composite delayed energy spectra in different time intervals after the end of irradiation of ^{235}U sample by epithermal neutrons. The measurements of the energy spectra of delayed neutrons in the fission of ^{235}U nuclei by epithermal neutrons were carried out at the IPPE electrostatic accelerator CG-2.5 facility.

Measurements have been performed by cyclic irradiation of ^{235}U sample by epithermal neutrons followed by delayed neutron counting with a ^{3}He-spectrometer. The neutron source was produced by the $T(p,n)^{3}He$ reaction on the solid tritium target of the IPPE electrostatic accelerator CG-2.5. For production of epithermal neutron flux the accelerator target was surrounded by a polyethylene cube of 27 cm. The ^{235}U metallic sample was placed in the horizontal hole of the cube. During irradiation the sample was located about 3.2 cm from the neutron target. Transport of the sample from the irradiation position to the ^{3}He-spectrometer was accomplished by a fast pneumatic system.

A high resolution ^{3}He-spectrometer of FNS-1 type was employed for the measurements of delayed neutron spectra. The ^{3}He-spectrometer is a cylindrical gridded ion chamber with active volume dimensions of 5 cm diameter and 15 cm length. It is filled with ^{3}He at a partial pressure of 6 atm, Ar of 3 atm, and CH_4 of 0.5 atm. This value of gas pressure was enough to enable full ranges of tritons and protons from the $^{3}He(n,p)^{3}H$ reaction in the active volume of the spectrometer for the production of primary neutrons with energy up to 2.5 MeV. The lead shielding of 6.1 cm thick placed between the ^{235}U sample and ^{3}He-specrometer was used to suppress gamma-background from the irradiated sample and to decrease the pile-up effects.

Measurements were made with different irradiation and counting time intervals to probe particular delayed neutron precursors. Two sets of measurements have been performed. The first one was made with irradiation time of 120 s which was followed by measurements of delayed neutron spectra in the following sequence of time intervals after the end of irradiation: 0-2, 2-12, 12-22, 22-32, and 32-152 s. The second set of measurements was made with irradiation time of 20 s and measurements of delayed neutron spectra in the following time intervals: 0-1, 1-2, 2-3, 3-4, and 4-44 s. The neutron background was measured in the same conditions as during experiments but instead of uranium samples we used an empty container.

These data provide a comprehensive set of composite spectra with enhanced sensitivity to neutrons emitted in less than 1 s following fission. These are the first composite delayed neutron measurements that show good overall agreement with appropriate composite spectra obtained by summation calculations using the most up-to-date individual precursor database especially for the relatively long delay-time intervals. The observed agreement can be considered as a proof of the consistency of the microscopic and macroscopic approach in developing a database of delayed neutron energy spectra. Nevertheless the calculated composite spectra have worse resolved peak structure compared to the present measured data. This can be explained partly by the fact that the evaluated individual precursor spectra are based on models that do not predict any peak structure.

Appendix 4

The near-equilibrium spectrum we obtained has definitely a peak structure in contrast with early experiments but in agreement with results obtained from summation of individual precursor data. However, the present equilibrium spectrum displays less structure and intensity of delayed neutrons in the energy range below 200 keV. Besides that, some of the energy peaks in the equilibrium spectra cannot be reproduced by summation of the individual precursor data.

It was found that both the equilibrium spectrum and composite spectra at different time windows, calculated on the basis of experimental precursor data only, are closer to our measured spectra in the energy region below 200 keV than spectra calculated with both experimental and theory- based precursor data.

The obtained composite spectra of delayed neutrons for ^{235}U can be used as benchmark data for testing the spectral delayed neutron precursor database. As a by-product of this work, we found close similarity between the composite spectra calculated on the basis of group data and individual precursor data. The unfolding procedure will be applied to the present set of composite spectra with the purpose of improving the delayed neutron 8-group model spectra.

4.16 Delayed Neutron Calculations using available evaluated files and study of the components to identify important delayed neutron emitters for reactor applications, R. Mills (National Nuclear Laboratory)

A description of the JEFF fission yield evaluation and then a preliminary document looking to identify the important precursors of delayed neutrons a study of the important delayed neutron emitters for νd using decay data and cumulative yields from standard ENDF formatted files was presented. The files considered were ENDFB66, ENDFB71, JEF22, JEFF311 and JENDL2011. The presentation then considered future work for the CRP. The presentation and draft paper was distributed via the bDN Connect workspace for other participants to comment upon.

The first section of the report compares the νd for important systems (thermal neutron 233,235U, 239,241Pu, 245Cm, and fast neutron induced fission of 232Th, 233,235,238U, 239,241Pu and 14 MeV fission of 232Th, 233,235,238U, 239Pu) in a matrix of the results using different neutron fission yields (NFY) and radioactive decay data (RDD) datasets. The $\bar{\nu}_d$ was calculated from the cumulative yields, half-life and P_{xn} branches for all combinations of the data (i.e NFY from one source and RDD from another). It was noted that the JEF-2.2 values given agreed with that reported by Piksaikin.

The $\bar{\nu}_d$ is given by

$$\overline{\nu_d} = \sum_{i=1}^{N_{FP}} P_{n_i} CY_i$$

The uncertainty on this being given by

$$\sigma_{\overline{\nu_d}} = \sqrt{\sum_{i=1}^{N_{FP}} \left[(\sigma_{P_{n_i}} CY_i)^2 + (\sigma_{CY_i} P_{n_i})^2 \right]}$$

The uncertainties are quoted both using this equation and the uncertainty data in the files and in brackets the uncertainity, if values with no uncertainty are assumed to have the value data to show the effect of this missing uncertainty data. In the tables to gauge the relative effect on the uncertainty of $\bar{\nu}_d$ the square root of the summation of the first term is quoted to estimate the effect of P_n uncertainty and the square root of the summation of the second term is quoted to estimate the effect of fission yield uncertainty.

Table 2: Comparison of $\bar{\nu}_d$ calculated with different fission yields and decay data for 92-U -235 Thermal

NFY RDD	ENDFB66	ENDFB71	JEF22	JEFF311	JENDL2011
ENDFB66	1.898 ± 0.111 (0.184) dPn=0.031 dCum=0.107	1.906 ± 0.104 (0.161) dPn=0.019 dCum=0.102	2.669 ± 0.204 (0.204) dPn=0.136 dCum=0.152	1.732 ± 0.058 (0.199) dPn=0.022 dCum=0.054	1.971 ± 0.119 (0.128) dPn=0.071 dCum=0.095
ENDFB71	1.898 ± 0.111 (0.184) dPn=0.031 dCum=0.107	1.906 ± 0.104 (0.161) dPn=0.019 dCum=0.102	2.669 ± 0.204 (0.204) dPn=0.136 dCum=0.152	1.732 ± 0.058 (0.199) dPn=0.022 dCum=0.054	1.971 ± 0.119 (0.128) dPn=0.071 dCum=0.095
JEF22	1.661 ± 0.111 (0.115) dPn=0.036 dCum=0.106	1.643 ± 0.109 (0.111) dPn=0.019 dCum=0.107	1.708 ± 0.116 (0.116) dPn=0.045 dCum=0.107	1.560 ± 0.106 (0.114) dPn=0.030 dCum=0.101	1.726 ± 0.122 (0.122) dPn=0.055 dCum=0.108
JEFF311	1.571 ± 0.084 (0.088) dPn=0.033 dCum=0.078	1.568 ± 0.081 (0.083) dPn=0.018 dCum=0.079	1.618 ± 0.089 (0.089) dPn=0.042 dCum=0.079	1.477 ± 0.079 (0.088) dPn=0.027 dCum=0.074	1.637 ± 0.094 (0.094) dPn=0.049 dCum=0.080
JENDL2011	1.871 ± 0.090 (0.172) dPn=0.033 dCum=0.084	1.859 ± 0.087 (0.154) dPn=0.019 dCum=0.085	2.658 ± 0.198 (0.198) dPn=0.137 dCum=0.143	1.747 ± 0.061 (0.217) dPn=0.026 dCum=0.055	1.983 ± 0.101 (0.114) dPn=0.059 dCum=0.082

In the case of thermal n-induced fission of 235U, the experimental results are evaluated as 1.62 ± 0.05 (from D'Angelo and Rowlands, 2002) and 1.66 ± 0.05 (by Blachot, Brady, Filip, Mills and Weaver, 1990). It is noted that in all cases considered the fission yield uncertainties dominate the Pn uncertainties.

The second section of the report shows the $\bar{\nu}_d$ from JEFF-3.1.1 for all systems and then shows all delayed neutron precursors that represent the top 25 most important in any of the JEFF-

3.1.1 NFY data; to help clarify the precursors are split into 6 time group by half-life (>30, 10-30, 3-10, 3-1, 0.3-1 and <0.3 seconds). This time dependant grouping is designed to help inform discussion on the most important nuclides and as an initial step into looking at the time dependence of delayed neutron emission.

Table 18: Important components to delayed neutron time groups

Group No.	1	2	3	4	5	6
Half-life ranges	30-60s	30-10s	10-3s	3-1s	1-0.3s	0.3-0s
Top 5	Br87 55.65s (13)	I137 24.50s (20) Br88 16.34s (8)	I138 6.23s (3) Br89 4.36s (2)	Rb94 2.70s (0.5) I139 2.28s (1.1) Y98m 2.00s (20) Br90 1.91s (1)		Rb95 0.38s (0.08)
Top 6 to 10			Rb93 5.82s (2)	Nb105 2.95s (6) As85 2.02s (1.2) Sb135 1.68s (1.5) Y99 1.48s (0.7)	As86 0.95s (0.8) Br91 0.54s (0.4)	
Top 11 to 15				Te137 2.49s (5) Cs143 1.79s (0.7)	Nb106 0.93s (4) I140 0.86s (4) Cs145 0.59s (0.5) Br92 0.31s (2)	Rb96 0.20s (0.3) Rb97 0.17s (0.06)
Top 16 to 20				Se88 1.53s (6) Ga81 1.22s (0.5) Y97m 1.17s (3)	Cs144 0.99s (0.6) Ge84 0.95s (1.4) Y100 0.74s (0.7) Y98 0.55s (0.2) Se89 0.43s (5) I141 0.43s (2) Nb107 0.30s (0.9)	
Top 21 to 25			Nb104 4.90s (30) Y97 3.75s (3)	Te138 1.40s (40)	Sb136 0.92s (1.4) As87 0.56s (8)	

The third section of the report shows the ordered components of $\bar{\nu}_d$ calculated for all NFY datasets in JEFF-3.1.1, ENDF/B-VII.1 and JENDL2011 (calculated with the respective RDD).

In discussion, it was decided that the work would be updated to include a) in sections 1 and 2 calculations using a "complete dataset" such as Pfeiffer, Kratz and Moller (2002) or a more recent file, b) the average activity weighted half-life of the delayed neutron precursors (as calculated by Piksaikin) and c) full time-dependent calculations of "long" irradiation and "pulse" irradiation for systems with experimental data. When the CRP produces recommendations of P_n values, the work would be repeated to include these (it was noted that this may be after the third RCM).

4.17 Progress report of the CIEMAT activities in the CRP on Beta-delayed neutron emission data, D. Cano-Ott (CIEMAT)

The activities carried out by the CIEMAT group have covered three main areas: evaluated nuclear data, reactor calculations and experiments on delayed neutron data.

Evaluated nuclear data

The goal of this activity is to determine the differences in the delayed neutron emission rates and energy distributions obtained from delayed neutron data groups and from summation calculations:

- The group representation in the ENDF-6 format files used in reactor calculations, which depend on the incident neutron energy E_n and on the fissioning system.
- The decay data and fission fragment data libraries used in summation calculations, which are currently not used in reactor physics calculations. They contain a much larger amount of data and also uncertainties on some of the magnitudes.

A systematic comparison of several quantities calculated with the ENDF/B-VII.1, JENDL 4.0 and JEFF 3.1.2 libraries have been performed:

- $\nu_{delayed}$ obtained from the libraries and from summation calculations at different energies. The uncertainties in the P_n and fission yields have been included (no covariances are available).
- $\nu_{delayed}$ emission rates as a function of the time at thermal energies. The uncertainties in the P_n and fission yields have been included.
- Delayed neutron energy spectra as a function of the time.

The conclusion of the study is that there are important differences between the libraries and between the evaluated $\nu_{delayed}$ and the summation calculations. The time dependence of the delayed neutron emission rates has been calculated as well. A Monte Carlo based code has been programmed for generating the complete decay chain of the fission fragments: sampling of the fission yield distribution (either JEFF.3.1.2 or ENDF/B.VII.1), generation of the decay chain, and production of all the decay particles along the chain and the variation of the decay data according to their uncertainties. The delayed neutron emission rates have been calculated as a function of the time for all the fissioning systems and three libraries (JEFF 3.1.2, ENDF/B-VII.1 and JENDL-4.0). The results have been compared with the corresponding evaluated rates defined in the 6 or 8 group representation.

The delayed neutron emission rates as a function of the time have been calculated by the Monte Carlo method taking into account the uncertainties in the decay data (half-lives and branching ratios) and fission yields. From the uncertainties in the $\nu_{delayed}(t)$ obtained with the ENDF/B-VII.1 and JEFF 3.1.2 libraries it is evident that they are not compatible. As a general conclusion, JEFF predicts that the uncertainties are dominated by the uncertainties in the fission yields while ENDF predicts that the uncertainties in the nuclear data and fission yields are comparable at times above 10 s. The interpretation of these results is that the uncertainties in the fission yields in ENDF/B-VII.1 might be underestimated at release times larger than 1 s.

To conclude, the $\nu_{delayed}(E_n)$ and delayed neutron energy spectra $p(E_n,E_{n'})$ obtained from the 6 or 8 group representation and from summation calculations have been compared. The values of $p(E_n,E_{n'})$ obtained with JEFF, JENDL and ENDF libraries are similar however there are important differences in the $\nu_{delayed}(E_n)$. The neutron energy spectra provided by ENDF/B-VII.1 are much better described than in JEFF 3.2, which contains (sometimes discrete) data for a more limited set of fission fragments. Finally there seems to be an inconsistency between the evaluated data and decay data in ENDF/B-VII.1 which is attributed to the fission yields.

Reactor Calculations

The effective delayed neutron fraction β_{eff} is a crucial parameter in reactor safety since it corresponds to the maximum reactivity that can be inserted in a critical system without becoming prompt-critical. It is also fundamental to describe the kinetic and dynamic response of both critical and subcritical nuclear systems to internal or external perturbations.

A study of the systematic uncertainties in the β_{eff} with respect to the methodologies used (deterministic and Monte Carlo) has been performed. The systems investigated are representative of the advanced reactor demonstrators under design: the European Sodium Fast Reactor (ESFR, which stands for the ASTRID demonstrator) and the lead cooled critical and subcritical MYRRHA reactor. The details of the study are given in V. Bécares et al. Annals of Nuclear Energy 65 (2014) 402–410. The results have shown that the Monte Carlo calculated values of β_{eff} depend on the methodology applied. The variations can be very large for systems with reflector. However, for the systems without reflector the variations are small, at the level +/- 20 pcms.

In a second study, the most relevant beta-delayed neutron emitters have been identified for the ESFR reactor (cooled with sodium) and the European Facility for Industrial Transmutation (EFIT), which is a lead cooled subcritical system. First, the variation of the isotopic composition of the fuel has been calculated as a function of the burnup with the EVOLCODE 2.0 system developed at CIEMAT, allowing the identification of the the most important fissioning systems. Second, the isotopes with the largest contributions to the total delayed neutron yield (as a function of the time) were identified. The calculation has repeated for all the fissioning systems (thermal and fast energies) and for the 3 libraries JEFF3.1.2, ENDF/B-VII.1 and JENDL-4.

In a different study the impact of the nuclear data libraries and the delayed neutron energy spectra in the k_{eff} and β_{eff} was estimated for the case of the ASTRID fast sodium cooled reactor. The impact of using ENDF/B-VII.1 or JEFF-3.2 on the k_{eff} amounts to 100 pcm and the differences in the β_{eff} amount to 10 pcm and are compatible with the uncertainties.

In order to investigate the effect of the energy spectra the main fissioning systems contributing to the neutron balance in the reactor were identified. The calculations performed with MCNP and the two main isotopes which are responsible for ~80% of both the fission and delayed neutrons, namely ^{239}Pu and ^{238}Pu. Then, the delayed neutrons corresponding to the ^{239}Pu and ^{238}U fissions were generated with an unrealistic Watt fission spectrum. Such an extreme change allows estimating the magnitude of dependence of the k_{eff} and β_{eff} on the delayed neutron energy. The effect of replacing the evaluated delayed neutron spectra in one isotope is of ~25 pcm in the k_{eff} and of ~35 pcm in the β_{eff} and twice as much when the two isotopes are modified.

Appendix 4

Experiments on delayed neutron data

CIEMAT has participated in two experiments carried out with other collaborations:

- **Measurement of the beta delayed neutron emission probability of ^{85}As and ^{91}Br.** The experiment has been analysed by A. R. García and is part of his PhD thesis. It was carried out in 2010 at the IGISOL facility at the Cyclotron Laboratory of the University of Jyväskylä by an international collaboration formed by CIEMAT, IFIC-Valencia, Universidad Politécnica de Cataluña, University of Jyväskylä, University of Surrey and University of Istambul.

  The work consisted in the analysis of the data, the optimisation of the GEANT4 code for the simulation of neutron detectors based on the moderation principle and a careful investigation of the systematic uncertainties associated with the experimental technique.

- **Study of multi-neutron emission in the β-decay of ^{11}Li**. The experiment was carried out in 2014 at the ISOLDE facility (CERN) by an international collaboration formed by LPC Caen, CIEMAT, Universidad Complutense de Madrid, Aarhus University, CERN, IEM – CSIC Madrid, VECC Kolkata, CEA/SPhN Saclay, Universidad de Santiago de Compostela, IPN Orsay and IFIC –Valencia. The experiment has also served for the commissioning of the MOdular Nuetron SpectromeTER (MONSTER) in a β-decay experiment. The preliminary analysis of the data has shown that the neutron gamma pulse shape discrimination is crucial for P_{2n} measurements and very important for background rejection. The analysis is in progress and is expected to finish at the end of the CRP.

4.18 Synergy between reactor antineutrinos and b-delayed n emission: Progress report from the NANTES Group, M. Fallot (Subatech-Nantes)

The prediction of reactor antineutrino energy spectra is of interest for both fundamental physics and applied physics.

Two methods are currently employed for the computation of reactor antineutrino spectra. One consists in converting the integral beta energy spectra measured at the high flux reactor ILL by Schreckenbach et al. [1] to anti-neutrino sepctra. This method was revisited in 2011 by [2] using evaluated decay data [3] to reproduce 90% of the integral beta spectrum and only 5 fictive beta branches to fit the remaining part. The newly converted spectra exhibit a 3% upward shift after application of the detection threshold. After updating the neutron lifetime and taking into account off-equilibrium effects (time evolution of the fission product concentrations in a reactor core) the discrepancy with respect to previous converted antineutrino spectra further increased leading to the so-called reactor anomaly. Several explanations are being explored (existence of light sterile neutrinos, nuclear uncertainties due to the weak magnetism term [4], influence of first forbidden non-unique transitions [5]). Eventually a new measurement of the integral beta spectra would be desirable in order to confirm the unique reference measurement of [1]. In addition, the new measurements reported by Daya Bay, Reno and Double Chooz revealed a distinctive "bump" in the 4 to 6 MeV range in the measured spectra. Distortions are observed also below 4 MeV and above 6 MeV. These new results reinforce the need for developing alternative methods to compute reactor antineutrino spectra.

At present, the only alternative calculation method relies on nuclear data. Using fission yield distributions and beta decay properties of fission products, one can build reactor antineutrino spectra using the summation method. First comparisons between summation method spectra and integral beta spectra measured at ILL showed an overestimation of summation method spectra in the high energy range (above 6 MeV) and distortions, compatible with the pandemonium effect similar to what has been observed in reactor decay heat calculations [6]. Recent TAGS measurements on $^{102;104–107}$Tc, ^{105}Mo, and ^{101}Nb have been incorporated in these summation calculations [6]. The impact of only 5 fission products whose beta properties have been corrected from the pandemonium effect is fairly large, reaching 8% in ^{239,241}Pu isotopes in the 3-4 MeV bins. Studies comparing summation method spectra combining several nuclear databases with integral beta spectra showed that the best agreement can be reached when using the maximal amount of data which don't suffer from the pandemonium effect, like the TAGS data (Valencia [7], Greenwood [8]), but also the data from Rudstam [9]. A joint experiment proposal of the Nantes-Valencia collaboration was accepted in 2009 in Jyväskylä to perform TAGS measurements on a set of nuclides considered to be important contributors to the antineutrino emission at standard thermal power plants. Two nuclei from this list, ^{92}Rb and ^{93}Rb, were measured already in 2009. Preliminary results of the beta feeding extracted from the TAGS measurements were shown. The results for the decay of ^{93}Rb are compatible with the results obtained by Greenwood et al. with a ground-state feeding of about 35.7% [10]. The impact of these new measurements on antineutrino energy spectra from $^{235,\ 238}$U and ^{239,241}Pu has been assessed and displayed. It reaches 6% at 7 MeV in ^{235}U (4.5% for ^{92}Rb alone!), 5% in ^{239}Pu, 3% in ^{238}U and in ^{241}Pu, when the new TAGS data replace the Rudstam data for these two Rb isotopes in the summation calculations.

The preliminary impact of these new experimental results on electromagnetic (EM) and light particle (LP) decay heat after thermal fission bursts of ^{235}U and ^{239}Pu has been computed by A. Sonzogni [11]. The new ^{92}Rb data decrease the EM decay heat in both nuclei when replacing ENDF7.1 data.

Twenty isotopes (plus daughters), a large part of it from the Nantes-Valencia proposal of 2009, were measured at the new IGISOL-4 facility in 2014. The analysis has been shared among the Valencia and Nantes teams. Currently ^{95}Sr, $^{98,98m}Nb$, $^{96,96m}Y$, ^{99}Y, ^{138}I and ^{142}Cs are being analyzed in Nantes.

Among the measured nuclides, ^{93}Rb, ^{99}Y, ^{138}I exhibit a small delayed neutron branch and are relevant to this CRP. The analysis of ^{93}Rb data is nearly final, while the analysis of ^{99}Y and ^{138}I is on-going. Another task of the Nantes group was to propose a new TAGS experiment at the ALTO facility, in collaboration with the Valencia group. The proposal, focussed on nuclear structure and astrophysics motivations, was accepted by the ALTO PAC in early 2014. Among the proposed nuclei, 8 beta-delayed neutron emitters will be measured in the region of the doubly magic nucleus ^{132}Sn with the TAGS technique. Some of them exhibit very large β-delayed neutron branches. The experiment should be performed in Orsay in early 2016.

The Nantes-Valencia collaboration has also submitted a letter of intent to the ALTO facility, focussed on nuclei of interest for reactor antineutrino spectra and decay heat and the experiments could be performed in a 2 to 3 year scale from now provided the required laser ion source developments are completed in time.
Reactor simulations developed originally to assess the antineutrino emission of various reactor designs for non-proliferation purposes could be relevant for studying beta-delayed neutrons emission for reactor kinetics and equilibrium. If the time scale of the CRP allows it, some of these simulations could be used to help prepare high-priority list of beta-delayed emitters important for these applications.

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4.19 Delayed neutron activity and correlations, A. Sonzogni (NNDC-BNL)

We discussed some aspects of delayed neutrons following the fission of an actinide nuclide, such as:

a) Summation calculation of nubars.
b) Calculation of delayed neutron activity.
c) Calculation of delayed neutron spectra.
d) Delayed neutron activity correlations, including correlation between group parameters.
e) Database formats to archive these data.

For the calculation of nubars using the summation method, we'll use the ENDF/B and the JEFF fission yields in conjunction with the Pn data from ENDF/B, JEFF and JENDL decay data as well as those from the Pfeiffer-Kratz-Moller evaluation and the upcoming evaluation led by McMaster.

We'll use the same combination to calculate the delayed neutron activity, which will be fitted with 6 or 8 group parameters. These activities will be compared with different measurements, for instance Keepin's, as well as with the results from the different libraries. The fitting procedure will also produce a correlation matrix. Alternatively, a correlation matrix can be obtained using a Monte Carlo method. A comparison of both methods will be performed.

Using the calculated activity and neutron spectrum for each precursor from ENDF/B, the total spectrum can be calculated for different experimental conditions, which will be compared to measured values. Preliminary results show very good agreement for longer measurements, and somewhat poorer for shorter times.

4.20 Gamow-Teller decays of nuclei beyond N>50, R. Grzywacz (University of Tennessee-ORNL)

Beta delayed neutron spectroscopy on nearly 30 isotopes was performed using Versatile Array for Neutrons at Low-Energies (VANDLE). The experiment was performed at the Holifield Radioactive Ion Beam Facility on isotopes, fission fragments, which were produced in the UCx target irradiated by the high intensity 50 MeV proton beam at the IRIS1 facility. The mass separated products were transported to the LeRIBSS facility where the implantation setup and detector system was installed. VANDLE is a hybrid array for measurement of neutron energies using the time of flight and is also capable to measure gamma rays associated with the decay. Neutrons are detected in the plastic scintillators bars. The light is recorded by photomultiplier attached to both ends of each bar. Gamma rays were measured using two clover detectors. Start for the time of flight measurement was provided by the high-efficiency thin plastic scintillators, wrapped around the implantation spot. VANDLE is using fully digital electronics that performs real-time analysis of the signals and provides energy and timing. The distributed triggering scheme is implemented using onboard FPGA's. New data analysis code was developed using C/C++ programming language. The response of the detectors to neutrons and gammas was simulated using GEANT 4 code.

The measurements were focused on isotopes near doubly magic 78Ni and 132Sn and very deformed Rb isotopes. Data analysis process includes several steps. The first step is a decomposition of the neutron time-of-flight measurement into neutron energy spectrum. This uses modeled detector response function validated in measurements with mono-energetic neutrons. The neutron energy spectra are constructed in coincidence with gamma rays detected in clovers. The efficiency corrected neutron energy spectra are combined in the final stage of the analysis, which is used to reconstruct the feeding intensity spectrum, to the neutron unbound states in the daughter nucleus. The analysis led to the construction of the beta strength function. This analysis was demonstrated for the decays of 83Ga and 84Ga, where the intense neutron structures at high energies exceeding 3 MeV were observed.

Data interpretation was based on the shell model calculation of the decay strength. New beta strength calculations were developed which used truncations applicable for the Gamow-Teller type transitions. The model, when applied for the N>50 83,84Ga decays demonstrated that the main part of the observed decay strength is due to the fpg neutrons of the 78Ni core. The model was also validated by the observation of the decays of the neutron bound states, in decays of 82Zn and 82,83Ga. Here, high energy gamma-rays were identified, which were attributed to the feeding of states at 4-6 MeV. Most recently VANDLE was utilized in an experiment at CARIBU at Argonne National Laboratory where the decays of 135,136Sb, 137I and 85As were identified. This included a new design of the detector, which aimed to improve its time-of-flight measurement resolution and minimize the neutron scattering. Future measurements at ISOL and fragmentation facilities are planned.

4.21 Status of beta-delayed neutron spectra for reference isotopes: ^{87}Br, ^{88}Br, ^{94}Rb, ^{95}Rb, ^{137}I, and ^{138}I, J.L. Tain (IFIC/CSIC-Univ. Valencia)

An assessment of the status of experimental information on β-delayed neutron spectra for fission products has been done. The assessment was restricted to isotopes which have been regarded as reference (calibration) isotopes for P_n measurements during the October 2011 IAEA Consultants Meeting (Report INDC(NDS)-0599).
The study was limited to review documents where a comparison of spectra for the given isotopes has been already performed. After the completion of the digitization of the original publications, one of the tasks of this CRP, a direct evaluation should be performed. The sources of information that were considered are the following:

[BRA89] M.C. Brady, PhD Thesis, LA-11534-T/UC-413, 1989
[REE80] P.L. Reeder et al. Nucl. Sci. Eng. 75, 140 (1980)
[GRE85] R.C. Greenwood et al. Nucl. Sci. Eng. 91, 305 (1985)
[GRE97] R.C. Greenwood et al. Nucl. Sci. Eng. 126, 324 (1997)

M.C. Brady PhD Thesis: Evaluation and Application of Delayed Neutron Precursor Data (1989)

This represents a rather comprehensive compilation and evaluation work of data (existing at that moment) on yields and spectral shapes both for individual precursors and fission systems. A summary of the experimental data used in her evaluation can be found in the figure:

Summary of Experimental Spectra

Studsvik measurements:

^{3}He spectrometers
On-line isotope separator
Measurements for ~25 precursor nuclides
Energy range ~ 100 keV – 2 MeV

Mainz measurements:

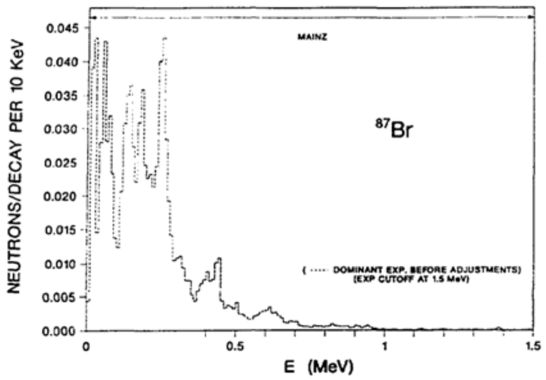
^{3}He spectrometers
One-line isotope separator
Measurements for ~23 precursor nuclides
Energy range ~40 keV – 3 MeV

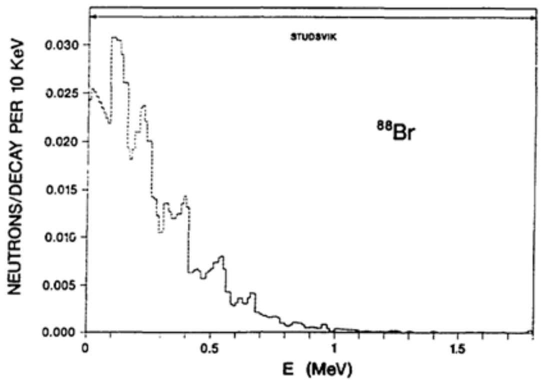
INEL measurements:

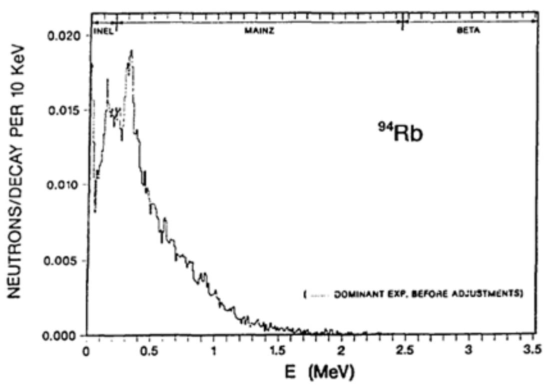
Proton-recoil spectrometer
On-line isotope separator (TRISTAN-ISOL)
Measurements for 8 precursor nuclide
Energy range ~10 keV – 1300 keV

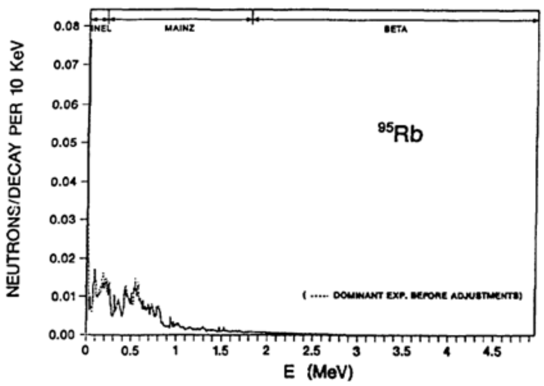
The data was measured at OSIRIS and ISOLDE with ^{3}He spectrometers, and at TRISTAN-ISOLDE with proton-recoil spectrometers respectively. Data available at the time coming from Brookhaven (SOLAR facility, Reeder et al.) was dismissed as it was considered of inferior quality.
Studsvik data was provided by G. Rudstam in electronic form. Experimental data contained error information and was augmented with calculated (model) data below and above the experimental range. Mainz data was partially provided by K.L. Kratz as a table with no errors, and digitized from publications for the remaining cases. Brady added uncertainties based on a generic estimation of errors, associated with the technique, made by Weaver et al. and cited by Kratz in his 1979 review paper (INDC (NDS)-107/G+SP). 1985 Idaho data was digitized from publication. Error was provided in tables for rebinned data and converted back into an

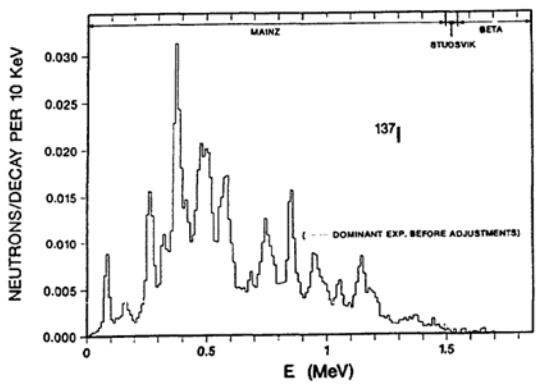
error for each bin. Idaho data for bromine and iodine came in a later paper [GRE97] and was therefore not considered.
In the process of evaluation the following criteria were applied. Preference was given to one set of data in a given energy region, i.e. there was no attempt to combine data (by averaging) in a given region. As a rule preference was given to Mainz data over Studsvik data because of the superior energy resolution and smaller statistical error (which was assigned from generic considerations as it was mentioned above). Data at low energy was replaced by Idaho data whenever available, otherwise it was replaced with statistical model calculations (with the BETA code). Calculated data was also used to augment experimental data at high energies. The augmentation process leads also to a renormalization. In the Thesis there are no comparisons of the different data sets for each isotope. The final result is given as a graph without errors and with 10 keV binning.
The plots for the relevant isotopes, indicating the source of data in each energy range are shown below:

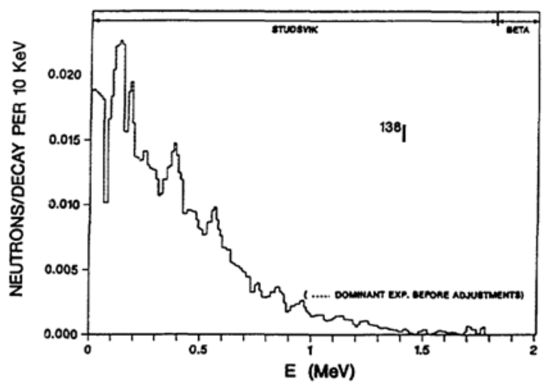












It is not clear why the rule of preference for Mainz data was broken for the ^{138}I case, since the data was available (H. Ohm, PhD Thesis, U. Mainz).
It can be verified that this data is identical to the data in ENDF/B-VII.1 database except that the model data at high energies is replaced with T. Kawano and P. Moeller CGM calculations. According to A. Sonzogni (priv. com.) this is also true for the remaining isotopes, except for few cases where minor modifications were introduced in the data.

P.L. Reeder et al., Nucl. Sci. Eng. 75, 140 (1980)

In this publication one can find a graphical comparison of SOLAR data with Mainz and Studsvik data as well as with other data sets.
The plots for the relevant isotopes are included below.

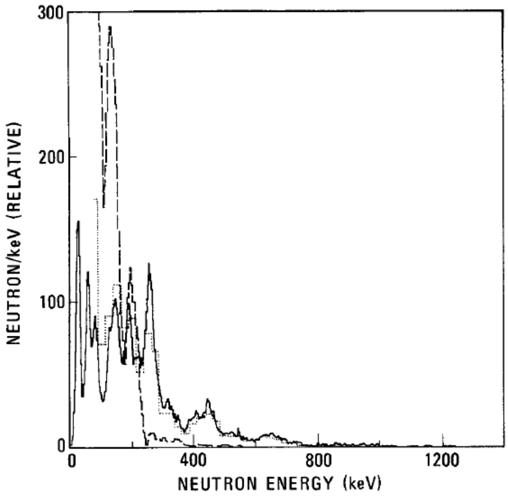


Fig. 11. Delayed-neutron spectrum of ^{87}Br; solid curve = data from Mainz, dashed curve = data from Pennsylvania State University, dotted curve = data from Studsvik.

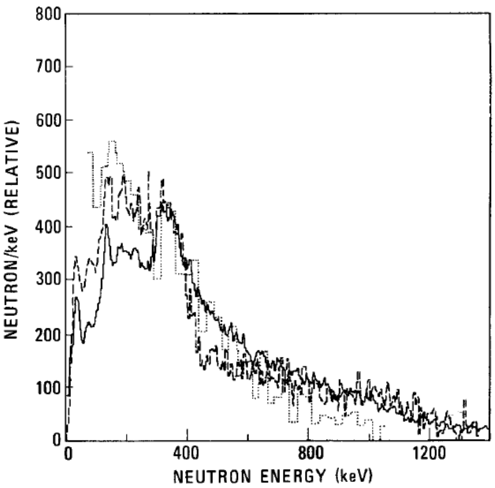


Fig. 13. Delayed-neutron spectrum of ^{94}Rb; solid curve = data from Mainz, dashed curve = present data, dotted curve = data from Studsvik.

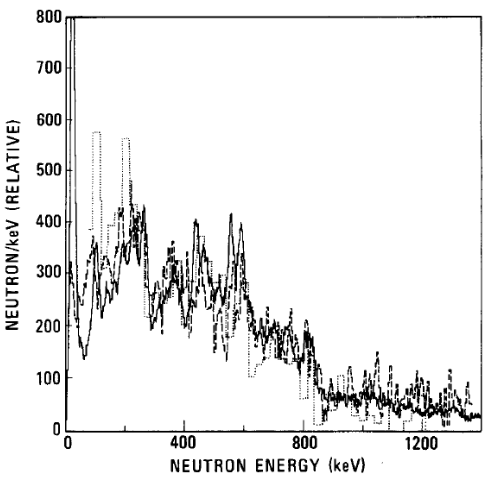
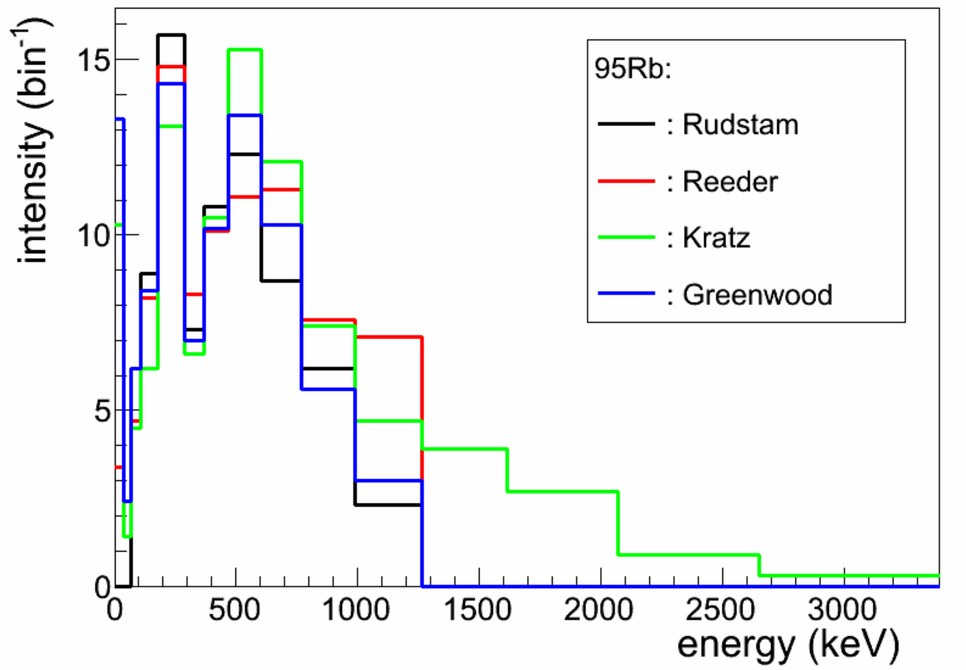


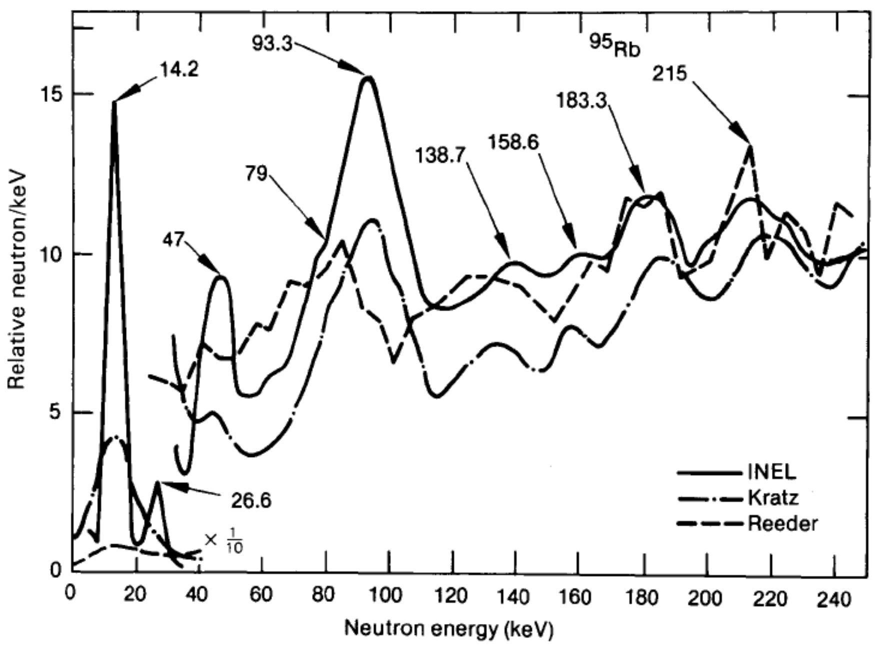
Fig. 14. Delayed-neutron spectrum of ^{95}Rb; solid curve = data from Mainz, dashed curve = present data, dotted curve = data from Studsvik.

R.C. Greenwood et al., Nucl. Sci. Eng. 91, 305 (1985)

In the publication one can find statements in verbal form comparing their data with previous data (Studsvik, Mainz and Brookhaven). Only for ^{95}Rb there is a more detailed comparison. For the whole energy range it is made trough a table where the different data (Rudstam, Reeder, Kratz, Greenwood) was grouped using wide energy bins. All data sets are normalized to Mainz data (63.8%) in the region 106.8 keV to 770.2 keV (bins 4-9). A plot of the table content is shown below:



A comparison with high resolution was made for the low energy range in graphical form (Studsvik data was excluded) as it is shown below:



R.C. Greenwood et al., Nucl. Sci. Eng.126, 324 (1997):

In the new publication there is proton recoil-data for 8 new isotopes including both bromine and iodine isotopes. This data was not included in Brady's evaluation.
There are no graphical comparisons to previous data. The comparison is made only in the form of comments:
^{87}Br: "good agreement" with Kratz
^{88}Br: "reasonably consistent" with Rudstam
^{137}I: "in good overall agreement" with Rudstam and Kratz
^{138}I: "closer agreement" with Rudstam than with Kratz

Conclusion

It is clear that a more detailed comparison must wait for the digitization of all published information.
Nevertheless in the case of ^{95}Rb one can observe very large differences, between 20% and 50%, in energy regions where one would expect a closer agreement between the different groups and methods. If this is the general case it will be quite difficult to establish standard reference spectra. It will be important in any case to quantify the differences, as this will allow estimating systematic errors in various quantities that depend on spectral shapes.

Appendix 5

Group Photo

Appendix 6

2nd Research Coordination Meeting on
Reference Database for Beta-delayed Neutron Emission
IAEA, Vienna, Austria
23 – 27 March 2015

Links to Presentations

#	Participant	Title	Link
1	S. Chiba	A comprehensive approach to determine delayed-neutron data-mass yield measurements, calculations of independent yield, decay heat and dealyed neutrons	PDF
2	F. Minato	Theoretical calculations of beta-delayed neutrons and sensitivity analyses	PPT
3	I. Borzov	Beta-delayed neutron emission near the shell closures	PPT
4	T. Marketin	Large-scale evaluation of beta-decay rates of r-process nuclei	PDF
5	K. Rykaczewski	Update on bdn-relevant proposals and experiments (ORNL, RIKEN, TRIUMF) and recently evaluated data	PPT
6	J. Tain	Progress report on Valencia group activities	PDF
7	A. Algora	Nuclear structure insights from Pn measurements	PDF
8	P. Garrett	Update on GRIFFIN and DESCANT and bDN measurements via gamma-ray spectroscopy	PPT
9	G. Lorusso	Pn value Measurements with EURICA	PDF
10	B. Singh	Completed compilation and evaluation of Pn and half-lives for Z=2-28 region nuclei	PPT
11	K. Banerjee	Progress report of IAEA project on beta-delayed tron emission	PPT
12	I. Dillmann	Nuclear Astrophysics and beta-delayed neutrons	PDF
13	S. Ciccone	Visualizing Beta-delayed neutron emission	PDF
14	P. Dimitriou	bDN database+CONNECT Platform	PDF
15	V. Piksaikin	Verification of evaluated fission product yields data based on the beta-delayed neutron characteristics	PDF
16	V. Piksaikin	High-resolution measurements of aggregate delayed-neutron spectra in different time intervals from neutron-induced fission of 235U	PDF
17	D. Cano-Ott	Beta-delayed Neutron Data and Reactor Calculations	PDF

Appendix 6

#	Participant	Title	Link
18	R. Mills	Delayed neutroncalculations using available evaluated files and study of the components to identify important delayed neutron emitters for reactor applications	PPT
19	M. Fallot	Synergy btw reactor antineutrinos and beta-delayed neutron emission-Progress report from Nantes group	PDF
20	A. Sonzogni	Beta-delayed neutron covariances	PPT
21	R. Grzywacz	Gamow-Teller decays of nuclei beyond N>50	PDF
22	X. Huang	Progress Report of CNDC group	PDF

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