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Summary Report of Consultants' Meeting

Beta-delayed neutron emission evaluation

IAEA Headquarters, Vienna, Austria
10 – 12 October 2011

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Abstract

A summary is given of a Consultants' Meeting assembled to assess the viability of a new IAEA Co-ordinated Research Project (CRP) on *Beta-delayed neutron emission evaluation*. The current status of the field was reviewed, cases in which new measurements are needed were identified and the current theoretical models were examined. The best known cases were selected as standards and were assessed and preliminary best values of the emission probabilities were obtained. The need of such a CRP was strongly agreed. Both the technical discussions and the expected outcome of such a project are described, along with detailed recommendations for its implementation.

December 2011

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1. Introduction

1.1 Motivation

The creation of the proposed Evaluated Beta-delayed Neutron Database is timely for several reasons.

One is that due to the availability of much better mass measurements, mass-evaluations [1], and theoretical predictions more and more delayed-neutron precursors are “discovered” which have not yet been investigated.

Second, since the last evaluation in 1993 [2] and the last compilation in 2002 [3] quite some progress has been made in the production and identification of delayed-neutron precursors, and more than 60 papers have been published since then which are not yet included in any database.

Third, a new generation of radioactive beam facilities (RIB) in France (Spiral-2), Germany (FAIR), Japan (RIBF), and the USA (FRIB) are already or will come online in the next few years allowing experimental nuclear structure studies deep into the neutron-rich side of the chart of nuclides where β-delayed (multiple) neutron emission is very prevalent. For the execution of these experiments at the borders of the chart of nuclides an exact knowledge of the decay properties of other contributing, less neutron-rich nuclei is indispensable. Only then new, short-lived (few ms) neutron-rich isotopes can be unambiguously distinguished, identified and investigated despite the vast amount of “contaminating” by-products.

Fourth, theoreticians need a reliable basis of experimental data to set constraints on their models, and in turn help experimentalists to better plan new measurements.

And last but not least the human component should not be neglected. The “golden nuclear years” are over, many scientists who have been working in the field of β-delayed neutrons for decades are retired now, sometimes without the possibility of a knowledge transfer to younger scientists. The documentation and reports from some early experiments are still only available in paper form and not digital, and are in many places disappearing upon retirement of scientists or closure of labs and facilities, without any possibility to retrieve them.

The interest of the communities in such an Evaluated Beta-delayed Neutron Database is different. The main focus of the nuclear physics (astrophysics/ structure) community is on improvement of the accuracy of β-delayed neutron emission probabilities (P_n values), which will help theoreticians to improve their models and, in turn, make extrapolations to more neutron-rich isotopes more reliable. New measurements in the heavier mass region A>150 (the so-called “terra incognita”) are desired, and also more measurements of multiple neutron emitters will become possible in the next years.

For reactor physics and (since more than a decade ago now) also for homeland security in the United States, an accurate knowledge of decay properties of fissile nuclei is required, which goes hand in hand with a detailed knowledge of delayed neutron precursors and fission yields. Although the six-group-parameterization from Keepin 1957 [4] still satisfies the requirements of commercial organizations, a higher accuracy of the delayed neutron yields and a better energy resolution in the delayed neutron spectra is desired.

References

[1] http://amdc.in2p3.fr/masstables/Ame2011int/filel.html (Priv. Comm. by Georges Audi and Wang Meng, April 2011).

[2] G. Rudstam, K. Aleklett, L. Sihver, Delayed- Neutron Branching Ratios of Precursors in the Fission Product Region, At. Data Nucl. Data Tables **53** (1993) 1.

[3] B. Pfeiffer, K.-L. Kratz, P. Möller, Status of delayed-Neutron Precursor Data: Half-Lives and Neutron Emission Probabilities, Prog. Nucl. Energy **41** (2002) 39.

[4] G.R. Keepin, T.F. Wimett, R.K. Zeigler, Delayed Neutrons from Fissionable Isotopes of Uranium, Plutonium and Thorium, Phys. Rev. **107** (1957) 1044.

1.2 History of β-delayed neutrons

Very neutron-rich nuclei can emit neutrons after β^--decay when their reaction Q-value is larger than the (one/two/three…) neutron separation energy: $Q_\beta > S_{xn}$. This decay mode is called "β-delayed (one/two/three…)-neutron emission" (Fig. 1) and was discovered in 1939 by Roberts et al. [1], shortly after the discoveries of fission by Meitner, Hahn, and Strassmann in 1938, and the neutron by Chadwick in 1932. "Delayed" in this context means, that the neutron is emitted with the β-decay half-life of the precursor ^{A}Z, ranging from few milliseconds for the most neutron-rich isotopes up to 55.65 s for the longest-lived βn-precursor ^{87}Br. These delayed neutrons have to be distinguished from the prompt neutrons evaporated immediately (in the order of 10^{-14} s) after a fission event from a neutron-rich nucleus.

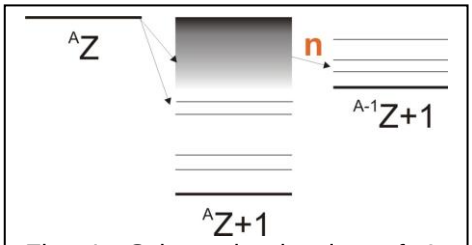

Fig. 1: Schematic drawing of β-delayed one-neutron emission.

Roberts and collaborators [1] used a boron-lined ionization chamber and bombarded a bottle with 100 g uranium nitrate with a beam of deuterium. They stated that *"neutrons were observed as long as 1.5 minutes after the bombardment of the uranium, the initial intensity being about one neutron per second".* The authors discussed two possibilities for this delayed emission: either the direct disintegration by emission of a neutron or the photodisintegration of fission fragments by high-energy photons. In a following publication [2] they confirmed their findings, excluded the photo-emission theory and coined the term "delayed neutron emission".

	6-group	8-group
Group	Half-life (s)	Half-life (s)
1	55.72	55.6
2	22.72	24.5
3	6.22	16.3
4	2.3	5.21
5	0.614	2.37
6	0.23	1.04
7		0.424
8		0.195

Fig. 2: Comparison of six-group and new eight-group parameters.

In the following months and years, several authors found additional delayed neutron groups [3-8].

In 1954 an extensive delayed neutron program was initiated at Los Alamos National Laboratory. One major outcome of this program was the six-group fitting parameters by Keepin and co-workers [9]. In a computerized least-squares curve fitting of the delayed neutron emission from ^{235}U, they found that a "six-group model" (Fig. 2) was sufficient to fit the experimental data.

In 1990, a NEA working group [10] was established with the following task:

"The following report has been prepared by Subgroup 6, which was set up in 1990 with the aim of reducing the discrepancies between calculated and measured values of the reactivity scale based on reactor kinetics. These discrepancies were resulting in undesirable conservatism in the design and operation of reactor control systems. A collaborative effort was initiated to reduce the uncertainties in the delayed neutron data used in these calculations. This effort included international benchmark measurements of the effective delayed neutron fraction, made on fast critical assemblies, which aimed to provide high-quality experimental information for ^{235}U, ^{238}U and ^{239}Pu. A study was also made of the representation of the time dependence of delayed neutron emission. Based on this work new recommendations have been made concerning the total delayed neutron yields for ^{235}U, ^{238}U and ^{239}Pu, and the time dependence and energy spectra for delayed neutron emission in the fission of a comprehensive set of isotopes."

One of the achievements of this working group was the further development of the Keepin parameters by the laboratories in Los Alamos and Obninsk from a six-group fit to an eight-group fit (Fig. 2). This was done by separating the three longest-lived delayed-neutron precursors (^{87}Br, ^{137}I, and ^{88}Br) into single groups.

References

[1] R.B. Roberts, R.C. Meyer, P. Wang, Further Observations on the Splitting of Thorium and Uranium, Phys. Rev. **55** (1939) 510.

[2] R.B. Roberts, L.R. Hafstad, R.C. Meyer, P. Wang, The Delayed Neutron Emission which Accompanies Fission of Uranium and Thorium**,** Phys. Rev. **55** (1939) 664.

[3] E.T. Booth, J.R. Dunning, F.G. Slack, Delayed Neutron Emission from Uranium*,* Phys. Rev. **55** (1939) 876.

[4] K.J. Brostrom, J. Koch, T. Lauritsen*,* Delayed Neutron Emission Accompanying Uranium Fission, Nature **144** (1939) 830.

[5] A.H. Snell, V.A. Nedzel, H.W. Ibsen, J.S. Levinger, R.G. Wilkinson, M.B. Sampson, Studies of the Delayed Neutrons I: The Decay Curve and the Intensity of the Delayed Neutrons, Phys. Rev. **72** (1947) 541.

[6] A.H. Snell, J.S. Levinger, E.P. Meiners, M.B. Sampson and R.G. Wilkinson*,* Studies of the Delayed Neutrons II: Chemical Isolation of the 56-Second and the 23-Second Activities*,* Phys. Rev. **72** (1947) 545.

[7] F. De Hoffmann, B.T. Feld, P.R. Stein, Delayed Neutrons from U235 after Short Irradiation*,* Phys. Rev. **74** (1948) 1330.

[8] D.J. Hughes, J. Dabbs, A. Cahn, D. Hall, Delayed Neutrons from Fission of U235, Phys. Rev. **73** (1948) 111.

[9] G.R. Keepin, T.F. Wimett, R.K. Zeigler, Delayed Neutrons from Fissionable Isotopes of Uranium, Plutonium and Thorium, Phys. Rev. **107** (1957) 1044.

[10] G. Rudstam, Ph. Finck, A. Filip, A. D'Angelo, R.D. McKnight, Delayed Neutron Data for the Major Actinides, Volume 6, NEA/WPEC-6, NEA/OECD, Paris, France, 2002.

1.3 Beta-delayed neutron emitters

Beta-delayed neutron emission occurs only on the neutron-rich side on the chart of nuclides (Fig. 3). For an exact prediction of the transition to βn-emitters an accurate knowledge of the masses is needed. Especially for masses there has been a giant leap forward concerning the accuracy of these measurements, which is reflected in the new Atomic Mass Evaluation [1].

Nowadays, about 200 βn-emitting isotopes are known between ^{8}He and ^{210}Tl, about 75 of them in the non-fission region (A<70). According to the new Atomic Mass

Evaluation about 80 more precursors were identified, but not yet measured. Most of the known βn-emitters are in the fission region between A=70-150, with ^{210}Tl being (up to now) the only exception in the heavy (non-fission) mass region [2]. This result, yielding an emission probability of P_n= 0.007 (+0.007 -0.004)%, has not been confirmed so far, but is energetically possible (Q_β=5482 keV, S_n= 3680 keV[1]).

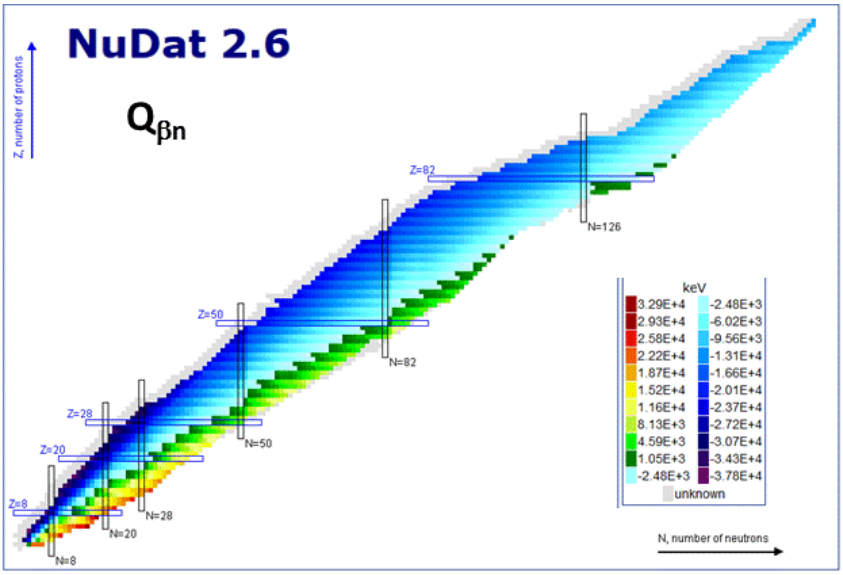

Fig. 3: Screenshot from the Interactive Chart of Nuclides (http://www.nndc.bnl.gov/nudat2) showing all known isotopes with their $Q_{\beta n}$ values. Positive $Q_{\beta n}$ values denote β-delayed neutron emitters [3].

Recently, an experimental campaign was started at the GSI Helmholtz Center for Heavy Ion Research in Darmstadt, Germany, aiming to measure very neutron-rich, heavy βn-emitters for astrophysical applications [4]. For these measurements in the "terra incognita", the heavy mass region is of special interest for experimentalists and theoreticians due to the missing experimental information and good accessibility by fragmentation reactions rather than by fission. First results for neutron-rich Tl, Hg, and Au isotopes will be available soon.

In 1979, the first β-delayed two neutron (β2n) emitter ^{11}Li was identified at CERN/ISOLDE [5]. Since then, only a few more were discovered, with ^{98}Rb [6] and ^{100}Rb being the only two examples in the fission region. It has to be assumed that much more β2n-emitters have been measured, but could not be separated from the one-neutron emission channel.
This misidentification can lead to wrong P_{1n} values and, in turn, also wrong half-lives if they are determined from the decay of the β-delayed neutron intensity. One possible candidate for the unclear transition between the one- and the two-neutron channel, which needs more careful investigations is ^{134}In (Fig. 4): Quasi Random Phase Approximation (QRPA) predictions for Gamow-Teller transitions including the first-forbidden decays (GT+ff) from Möller *et al.* [7] follow the experimental values for ^{128}In to ^{133}In quite nicely For the P_n value of ^{134}In two contradicting conference proceedings exists [8, 9]. One reports upper limits of P_{1n}<17%, and deduced P_{2n}< 4.4% [8]. Whereas the P_{1n} value is still in agreement with the QRPA calculations (Fig. 4), it predicts ^{134}In to be a strong β2n-emission precursor, with a sequential two-neutron decay into the doubly-magic ^{132}Sn. This is in clear contradiction to the value deduced by [8]. A more recent measurement by [9] revealed a preliminary result of P_{1n}~57%, which is in clear contradiction to the previous measurement and the QRPA predictions. However, both half-life measurements for ^{134}In carried out via time-

dependent counting of the β-delayed neutrons agree [10,11] and show no deviation to the general trend (underestimation by a factor of three) in comparison to the QRPA predictions (Fig. 4). Interestingly, the next isotope in the chain, ^{135}In, is predicted to be even a β3n emitter (again with ^{132}Sn as decay-product). This indicates that the QRPA calculations overestimate the P_{2n} channel, but to draw a definite conclusion, more experimental measurements have to be carried out in this interesting mass region.

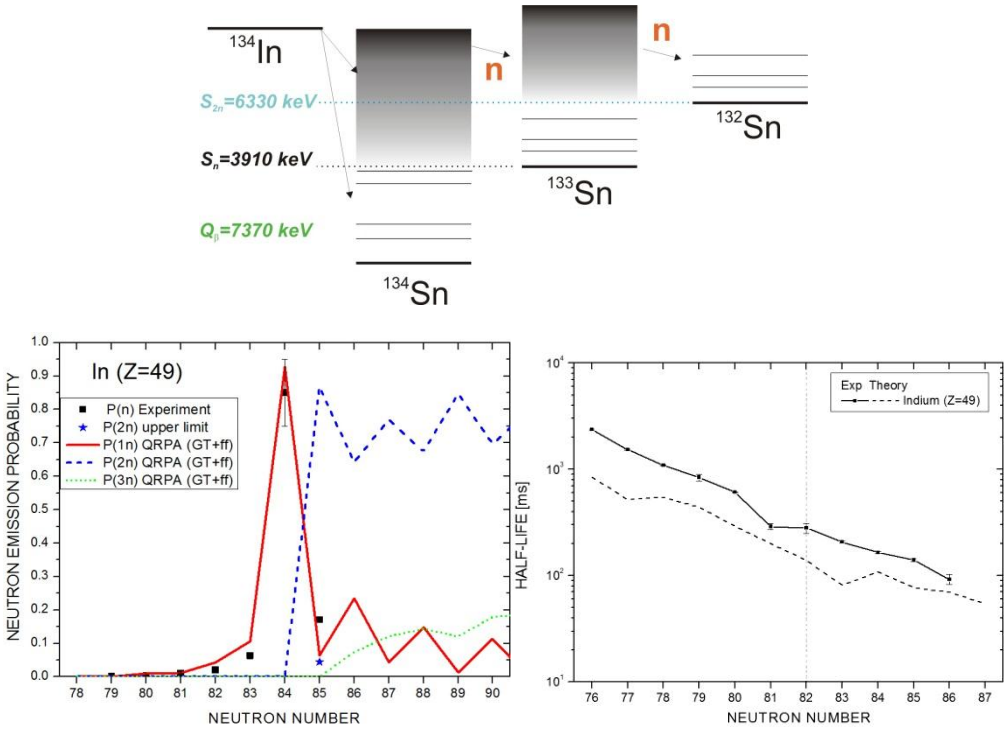

Fig. 4: (Top) Decay scheme for ^{134}In, a candidate for β2n-emission. (Bottom) QRPA predictions compared to measured values for the P_n value and half-lives [7].

These examples show the importance of new measurements with new data acquisition systems which allow to read-out each neutron counter separately and thus determine the multiplicity of the decays and avoid misidentifications. Fig. 5 shows a screenshot from the NuDat 2.6 database [3] with all possible cases for β2n-precursors. Most of the known cases are in the lighter mass region A<60.

According to the JEFF 3.1 database, 241 βn-emitter, 18 β2n-emitter, and only four β3n-emitters (^{11}Li, ^{14}Be, ^{17}B, ^{31}Na) exist up to now. These numbers, especially for the multiple neutron-emitters, will change drastically when all planned RIB facilities come online and become fully operational over the next years, shifting the experimental focus into the more neutron-rich region.

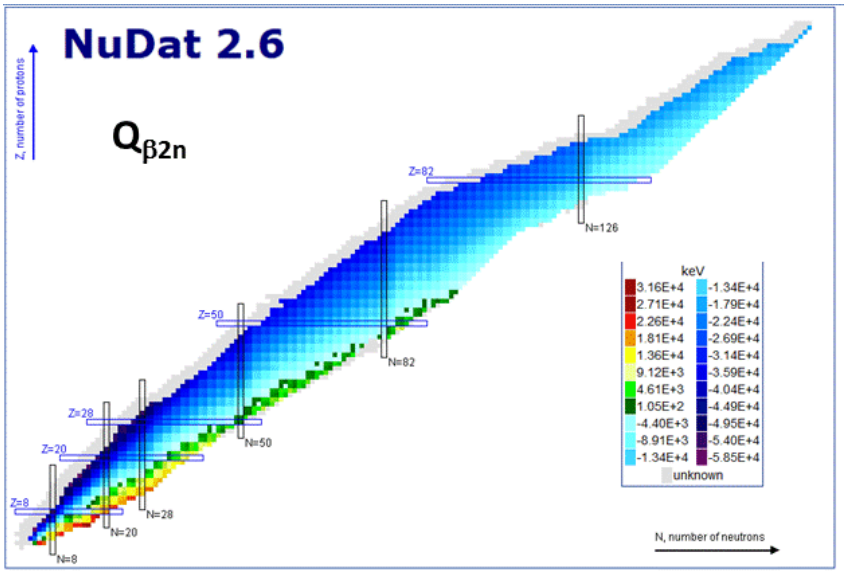

Fig. 5: Screenshot from the Interactive Chart of Nuclides (http://www.nndc.bnl.gov/nudat2) showing all known isotopes with their $Q_{\beta 2n}$ values. Positive $Q_{\beta 2n}$ values denote β-delayed two-neutron emitters.

References

[1] Atomic Mass Evaluation; http://amdc.in2p3.fr/masstables/Ame2011int/filel.html (Priv. Comm. by Georges Audi and Wang Meng, April 2011)

[2] G. Stetter, Nucl. Sci. Abstr. **16**, Abstr.10963 (1962) 1409.

[3] *http://www.nndc.bnl.gov/nudat2*

[4] C. Domingo-Pardo, I. Dillmann, M.B. Gomez-Hornillos, J.L. Tain, GSI-proposal S410, Measurement of beta-delayed neutrons around the third r-process peak, 2010.

[5] R. Azuma L.C. Carraz, P.G. Hansen *et al.*, First Observation of Beta-Delay Two Neutron Radioactivity: ^{11}Li, Phys. Rev. Lett. **43** (1979) 1652.

[6] P.L. Reeder, R.A. Warner, *et al.*, Beta-Delayed Two-Neutron Emission from ^{98}Rb,Phys. Rev. Lett. **47** (1981) 483.

[7] P. Möller, B. Pfeiffer, *et al.*, New calculations of gross β-decay properties for astrophysical applications: Speeding-up the classical r process, Phys. Rev. C **67** (2003) 055802.

[8] A. Jokinen, *et al.*, Int. Conf. on Exotic Nuclei and Atomic Masses ENAM95, Arles, June 19-23, 1995; p. 499.

[9] L. Mathieu, e*t al.*, AIP Conf. Proc. 1175 (2010) 285.

[10] P. Hoff, P. Baumann, A. Huck, *et al.*, Single-Neutron States in ^{133}Sn, Phys. Rev. Lett. 77, 1020 (1996).

[11] I. Dillmann, M. Hannawald, *et al.*, Selective laser ionization of N≥82 indium isotopes: The new r-process nuclide ^{135}In, Eur. Phys. J. A **13** (2002) 281.

1.4 Beta-delayed neutrons for reactor control and decay heat calculations

Some fission products emit β-delayed neutrons (βn), which then can contribute to the neutron economy and cause more neutron-induced fissions. Thus an accurate knowledge of the amount of neutrons released by neutron-rich fission products is indispensable for the control and kinetic behavior of fission reactors. For example, the fission of ^{235}U releases on average 2.47 prompt and 0.0065 β-delayed neutrons.

The number of delayed neutrons per fission neutron, designated as β or delayed neutron fraction, is quite small (typically below 1% considering the fission induced by thermal neutrons) and thus does not contribute significantly to the power generation of a nuclear reactor. The delayed neutrons are, however, essential from the point of view of reactor kinetics and safety: the delayed emission of neutrons at times ranging

from a fraction of a second up to minutes provides a long time constant that slows the dynamic time response of a nuclear reactor, making it controllable by mechanical systems such as the control rods containing neutron absorbing materials. For this reason, excessively large uncertainties in the delayed neutron data used in reactor calculations (for determining β_{eff}) lead to costly conservatism in the design and operation of reactor control systems.
Delayed neutron data are also necessary in summation calculations for determining the decay heat produced by the γ-rays and β-particles emitted by the β^--decaying fission products. The competition between the neutron and γ-ray emission processes needs to be quantified correctly for the proper determination of the intensity and energies of the γ-ray and β-particles [1].

Although the accuracy of the delayed neutron data for individual fission products has improved during the past decades, it is insufficient for performing reliable β_{eff} calculations. Therefore, the necessary data are taken from macroscopic measurements of the delayed neutron emission for the major isotopes and validated in reactor measurements or integral experiments. It is however expected that more accurate delayed neutron data calculated by summation techniques will be available in the future, thanks to more accurate experimental techniques applied at the radioactive ion beam facilities which deliver neutron-rich isotopes.

The time behaviour of the delayed neutron data used in reactor calculations (either deterministic or Monte Carlo) is empirically divided into a number of six (or more recently eight) groups [2,3], characterised with a decay constant, a half-life and a yield constant from the fission process. The energy of the neutrons for the isotopes in each time group is obtained from summation calculations [4-6].

The most recent extensive review concerning the status of delayed neutron data was carried out by the NEA WPEC Subgroup 6 in the nineties [7-9]. The general conclusions of the review are:

"The use of the recommended delayed neutron yields therein for ^{235}U, ^{238}U and ^{239}Pu lead to overall accuracies in the calculation of β_{eff} of 3% for thermal systems and 2% for fast systems. Possible additional sources of uncertainty due to inaccuracies in relative fission rate and fission rate distribution calculations, and calculations of the relative importance of delayed neutrons, could increase this figure.
Additional work on delayed neutron data is necessary for satisfying new requirements emerging from the trends in reactor technologies. This affects in particular the nuclear data necessary for isotopes of interest for transmutation applications (^{237}Np, Am, Cm) and for the Thorium fuel cycle (^{232}Th and ^{233}U).
The dependence of the delayed neutron yields on the incident neutron energy remains an open problem due to contradictory data. There exist discrepancies on the β_{eff} from different integral experiments. The analysis of more recent experiments would be helpful."

The roadmap for the future of nuclear energy has evolved since the preparation of the above review. The general trends for reaching more sustainable nuclear energy can be summarised as follows:

- Improve the safety of the actual reactors, considering the need of higher burn-ups and life extension.
- Design future reactors which are:

    - more sustainable (use the more abundant ^{238}U or ^{232}Th as fuel),
    - more efficient (work at higher temperatures and fuel burn-ups),
    - safer (incorporate more passive safety elements),
    - proliferation resistant and
    - cleaner (produce less high level waste).

  Such reactor concepts are grouped in the “Generation IV” initiative.
- Solve the nuclear waste problem by reducing the high level waste inventory and the necessary number of geological repositories for its storage. The strategies proposed for transmutation of high level nuclear waste are the use of fast critical reactors (if deployed early enough) or dedicated subcritical Accelerator Driven Systems, which can burn nuclear fuels with a high content of Minor Actinides at a higher rate than critical reactors.

Extensive R&D programs, also addressing the needs of more accurate nuclear data, have started in Europe. At present, three main demonstrator facilities for future reactor concepts are being considered:

- ASTRID, a demonstrator of a fast sodium cooled reactor.
- ELSY, a demonstrator of a fast lead cooled reactor.
- MYRRHA, a demonstrator of fast lead cooled subcritical assembly coupled to an accelerator which drives the external spallation neutron source. It is foreseen that MYRRHA will be also operated in a critical configuration.

The status of the data available for the design and construction of the future demonstrators and reactors needs to be reviewed and possible data needs should be addressed well in advance for optimising the construction costs. In this sense, the existing and planned radioactive ion beam facilities and the undergoing developments and improvements of the experimental techniques (detectors, data acquisition systems) can deliver part of the nuclear data requested, as well as boost the complementary developments in theory and modelling, necessary for upgrading the reactor design codes and evaluated libraries currently in use.

References

[1] A. Tobias, Decay Heat, Prog. Nucl. Ener. **5** (1980) 1.

[2] G.R. Keepin, *et al.*, Delayed Neutrons from Fissionable Isotopes of Uranium, Plutonium, and Thorium, Phys. Rev. **107** (1957) 1044.

[3] V.M. Piksaikin, *et al.*, Measurements of Periods, Relative Abundances and Absolute Total Yields of Delayed Neutrons from Fast Neutron Induced Fission of ^{235}U and ^{237}Np, Proc. Int. Conf. Nucl. Data for Sci. and Technol., Trieste, 19-24 May 1997, Conference Proceedings edited for the Italian Physical Society, 59, 485 (1998). (See also CD-ROM Document No. 5, Part 1.).

[4] M.C. Brady, T.R. England, Delayed neutron data and group parameters for 43 fissioning systems, Nucl Sci. Eng. **103** (1989) 129.

[5] J.M. Campbell, G.D. Spriggs, Los Alamos Technical Report 99-2988 (1999).

[6] J.M. Campbell, G.D. Spriggs, 8-Group Delayed Neutron Spectral Data for Hansen-Roach Energy Group Structure, Prog. Nucl. Energy **41** (2002) 253.

[7] NEA/WPEC-6 G. Rudstam, Ph. Finck, A. Filip, A. D'Angelo, R.D. McKnight, Delayed Neutron Data for the Major Actinides, Volume 6, NEA/WPEC-6, NEA/OECD, Paris, France, 2002.

[8] A. D’Angelo, Overview of the delayed neutron data activities and results monitored by the NEA/WPEC subgroup 6, Prog. Nucl. Energy **41** (2002) 5.

[9] A. D’Angelo, J.L. Rowlands, Conclusions Concerning the Delayed Neutron Data for the Major Actinides, Prog. Nucl. Energy **41** (2002) 391.

1.5 Beta-delayed neutrons for astrophysics and nuclear structure studies

For nuclear (astro)physics, single nuclear physics quantities are of higher interest than aggregate quantities. Measuring the neutrons from βn emitters offers a very simple way to determine several nuclear physics parameters at once. From the time-dependence of the neutron emission one can deduce the half-life of the precursor. Also other important nuclear structure information can be deduced: from the neutron emission probability (P_n value) the β-strength above the neutron separation energy (S_n) can be deduced, whereas the low-lying strength defines the half-life of the daughter isotope.

The synthesis of elements heavier than iron in stars is driven mainly by two neutron-capture processes, which occur on long time scales relative to β-decays (slow neutron capture (*s*) process), or on relative short time scales (rapid neutron capture (*r*) process) [1,2]. The *s* process proceeds at rather low neutron densities (10^6-10^{10} n/cm^3) with approx. 10-1000 years between two subsequent neutron captures. Thus, this process runs along the valley of stability (Fig. 6) until it has reached ^{209}Bi and is responsible for ~50% of the observed solar abundances. Due to this proximity to the stability the underlying nuclear physics parameters of the s-process are very well determined, and the astrophysical scenario is also very well understood. The "p process" is an umbrella term for a superposition of astrophysical processes which are responsible for the production of heavy, proton-rich stable isotopes between ^{74}Se and ^{196}Hg, which contribute only to less than 1% to the solar abundances of heavy isotopes. The largest fraction of these isotopes can be produced by a secondary mechanism ("γ process") using existing s-process seed nuclei in a high-temperature scenario called "Core Collapse Supernova", which is the explosive final stage of massive stars with more than eight solar masses.

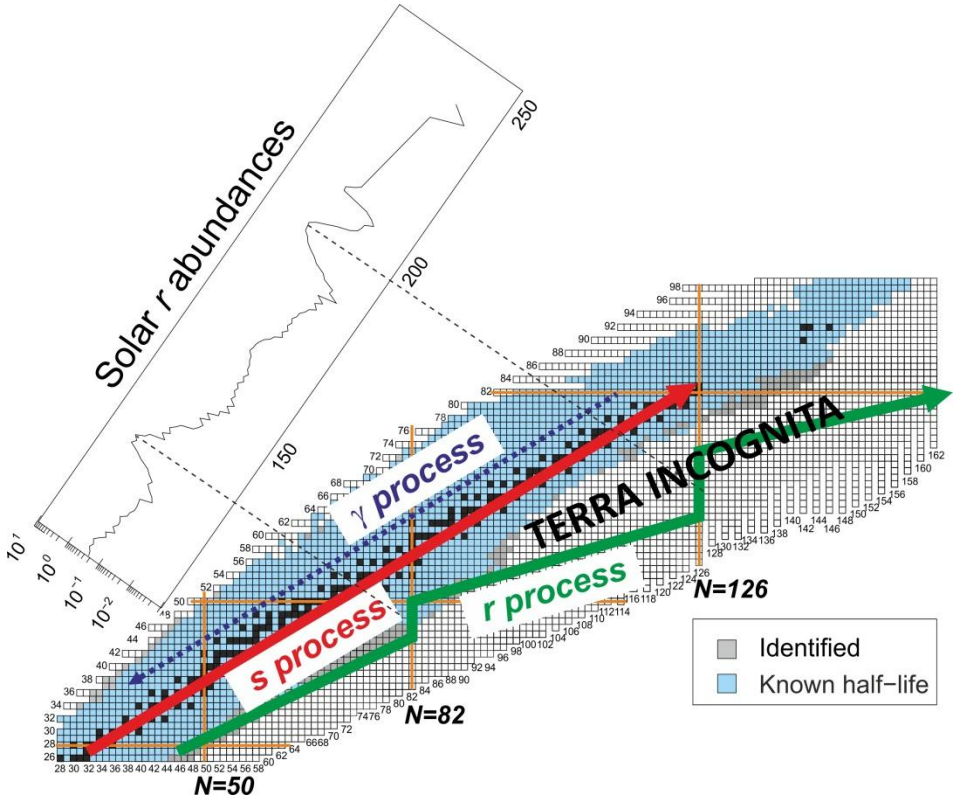

Fig. 6: Status of identified isotopes (grey boxes) and isotopes with measured half-lives (blue boxes). The three processes which are responsible for the nucleosynthesis of heavy elements in stars are shown.

The missing 50% of the solar abundances, among them also Uranium and Thorium, can also be produced during the core collapse in a different region of the star by a mechanism called “r process”. The conditions are very high neutron densities (10^{20} up to 10^{30} cm^{-3}) with moderate temperatures of 1-2 GK, which can be reached during the core collapse of a massive star close to the forming neutron star [3,4], or when two neutron stars merge [5]. Presently the supernova scenario is favored. The r process path due to these extreme conditions is located in the very neutron rich region (Fig. 6) and runs from iron through very short-lived nuclei up to the transactinide region within a few seconds. Here the assumed endpoint is in the region of plutonium isotopes with A~260 where fission reactions dominate further neutron captures, and material is cycled back into the A~130 region (“fission recycling”). However, the exact location of the endpoint is not known because it has to rely entirely on theoretical predictions of the fission parameters in this region.

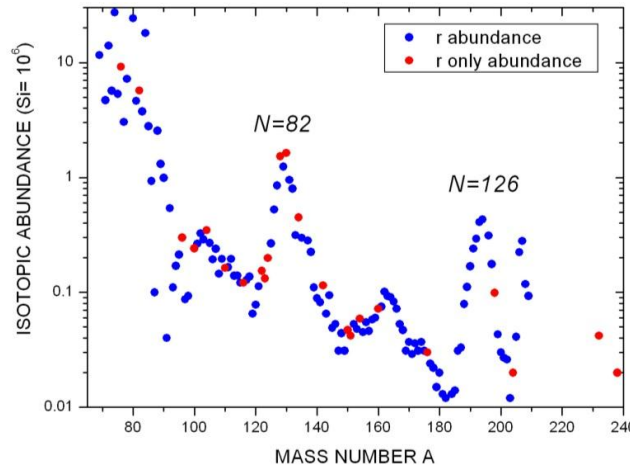

Fig. 7: Solar isotopic abundance

Fig. 6 also shows that only a small fraction of this reaction path has been examined experimentally up to now. Most of the experimental efforts in the last 25 years with respect to the r process focused on regions at or close to the neutron shell closures at N=50 and 82. The r-process isotopes around the other closed neutron shells (including N=126) are key nuclides for astrophysical investigations because they are responsible for the abundance maxima in the solar r-abundance curve (Fig. 7).

The mass region above A~150 and especially around the N=126 peak is today still a complete “terra incognita” for experiments, but will be to a large extent covered by the new generation of radioactive beam facilities which are or will come into operation within the next 10 years in France (Spiral-2), Germany (FAIR), and the USA (FRIB), or are already in operation since 2007 like RIBF at RIKEN/ Japan. For example, the maxima at A=195 is to a large extent caused by the r-process isotope ^{195}Tm and its neighbors. The most neutron-rich Tm isotope investigated so far is ^{177}Tm, still 18 mass units away from the r-process reaction path.

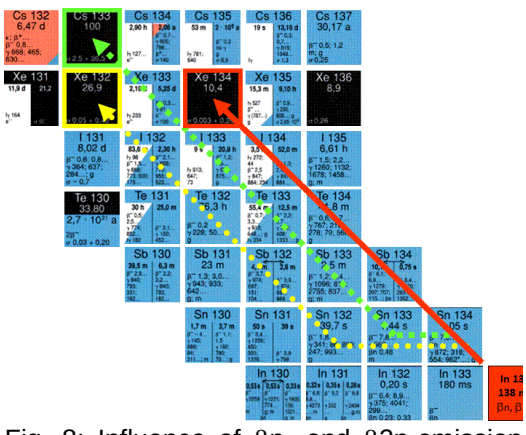

Fig. 8: Influence of βn- and β2n-emission during the freeze-out phase on the decay of r-process material back to stability.

Important nuclear physics parameters to understand the *r*-process nucleo-synthesis are primarily masses and half-lives. Whereas masses define the path (together with astrophysical parameters like temperature, neutron density, and neutron exposure time), the half-lives determine how much material is accumulated in a precursor. In the classical picture a “(n,γ)-(γ,n) equilibrium” is achieved within each isotopic chain, which means that most material is

stored in one “waiting point isotope” from where it can be transferred into the next isotopic chain by β-decay. β-delayed neutrons play an important role during the “freeze-out” phase when the temperature and the neutron density drop. The normal way of the r-process material back to stability would be via long β^--decay chains, so that all material stored e.g. in mass chain 134 (^{134}In) would show up in the observed solar *r* abundance curve (Fig. 7) also at A=134 (stable ^{134}Xe). However, β-delayed one- and two-neutron emission causes a detour of the material into neighboring mass chains (Fig. 8), A=133 (^{133}Cs) and A=132 (^{132}Xe). Thus an accurate understanding of βn-emitters is also important for a complete understanding of the r process nucleosynthesis.

[1] E.M. Burbidge, G.R. Burbidg, W.A. Fowler, F. Hoyle, Revs. Mod. Phys. **29** (1957) 547.
[2] A.G.W. Cameron, Pub. Astron. Soc. Pac. **69** (1957) 201.
[3] J. Witti, H.-T. Janka, K. Takahashi, Astron. Astrophys. **286** (1994) 841 and 857.
[4] S.E. Woosley, *et al*., Astrophys. J. **433** (1994) 229.
[5] C. Freiburghaus, S. Rosswog, and F.-K. Thielemann, Astrophys. J. Lett. **525** (1999) L121.

2. Goal of the meeting

The main goal of this meeting is to advise the IAEA-NDS on initiation of a Coordinated Research Project (CRP) on beta-delayed neutron emission evaluation and define the work to be carried out in the course of this project. To achieve that goal, the consultants will review the current state of affairs regarding beta-delayed neutron emission, the available compilations and new data from recent measurements.

The consultants should discuss if there is a need to coordinate efforts to achieve new measurements, possible ways to set up a dedicated database of evaluated data, and how to update the existing databases (ENSDF, EXFOR, ENDF/B, JEFF).

In case the initiation of a CRP is advised, a list of priorities for evaluations and new experiments should be proposed.

3. Past β-delayed neutron emission evaluations

The properties of β-delayed neutrons, emitted from fission products as aggregate or individual branching ratios P_n or energy spectra, are sensitive input data for nuclear reactor technology. Therefore, efforts to compile and evaluate these data have always been supported by the IAEA (see, e.g. [1, 2]).

Beta-delayed neutrons were studied intensively at all research reactors, as in Studsvik, Sweden [3]. Compilation and evaluation of the results was a task for national laboratories such as Los Alamos (see [4-9]). In 1986, these topics were discussed at the *Specialists' Meeting on Delayed Neutron Properties* in Birmingham, England (see [6,7]).

The evaluation of delayed-neutron branching ratios in the fission product region of Rudstam, *et al.* [10] was established as improved input data for the new versions of the European and American data bases JEF-2 and ENDF/B-VI, respectively. The authors not only compiled data from the literature but, in addition, performed a dedicated experiment covering the mass range 79 to 150 at the OSIRIS isotope separator on-line facility at Studsvik.

Certain published values from older experiments, determined via fission or normalized against another P_n value, were updated using new fission yields or branching ratios of the nuclides in the determination.

From 1990 to 2000, the Nuclear Energy Agency (NEA) of the Organisation for Economic Co-operation and Development (OECD) ran a Working Party on International Nuclear Data Evaluation Co-operation (WPEC). The Subgroup-6 Delayed Neutron Data published a summary report in 2002 [11].

Not all delayed-neutron precursors, the data of which are needed in applications such as reactor technology or astrophysical calculations of nucleosynthesis in explosive scenarios, can be measured in the laboratory. The missing data have to be obtained by theoretical calculations. In order to assess the calculated results, comparisons with evaluated experimental values have to be carried out.
In 2002, Pfeiffer, *et al.* [12] updated the 1993 evaluation of Rudstam, *et al.* [10] including about 40 branching ratios measured since 1990 and compared them with two model predictions:

(i) the empirical Kratz-Herrmann formula [13] and
(ii) the macroscopic-microscopic QRPA model [14].

Compilations have been continuously updated for a long time. At the IAEA and the National Nuclear Data Center [15], Brookhaven, nuclear structure and reaction databases including delayed-neutron emission information are maintained, such as the Evaluated Nuclear Structure Data File (ENSDF), the Experimental Unevaluated Data List (XUNDL), the Evaluated Nuclear Data File (ENDF), and the Experimental Nuclear Reaction Data (EXFOR) [16]. The Atomic Mass Data Center, Orsay, France, has complemented since 1997 the table of atomic masses by NUBASE, a compilation of decay data [17].

Only in recent years, have neutron-rich isotopes outside the range of fission products been produced at the new Radioactive Beam Facilities. Up till now, no evaluations for these precursors are available.

References

[1] G. Rudstam, in: Proc. 2nd IAEA Advisory Group Meeting on Fission Product Nuclear Data, Petten, The Netherlands (Sept. 5-9, 1977), Vol. II, p. 567.
[2] G. Rudstam, in: Proc. Consultants' Meeting on Delayed Neutron Properties, Vienna, Austria (Mar. 26-30, 1979), IAEA Report INDC NDS-107/G + Special (1979), p. 69.
[3] E. Lund, G. Rudstam, Studsvik Neutron Research Laboratory Report NFL-60 (1980).
[4] T.R. England, W.B. Wilson, R.E. Schenter, F.M. Mann, Aggregate Delayed Neutron Intensities and Spectra using Augumented ENDF/B-V Precursor Data, Nucl. Sci. Eng. **85** (1983) 139.
[5] F.M. Mann, M. Schreiber, R.E. Schenter, T.R. England, Evaluation of Delayed-Neutron Emission Probabilities, Nucl. Sci. Eng. **87** (1984) 418.
[6] T.R. England, M.C. Brady, E.D. Arthur, R.J. Labauve, F.M. Mann, in: Proc. Specialists' Meeting on Delayed Neutron Properties, Birmingham, England (Sept. 15-19, 1986), p. 117.
[7] F.M. Mann, in: Proc. Specialists' Meeting on Delayed Neutron Properties, Birmingham, England (Sept. 15-19, 1986), p. 21.
[8] M.C. Brady, Evaluation and Application of Delayed Neutron Precursor Data, Thesis, Texas A&M Univ. (1989); LA-11534-T (1989).
[9] M.C. Brady, T.R. England, Delayed Neutron Data and Group Parameters for 43 Fissioning Systems, Nucl. Sci. Eng. **103** (1989) 129.

[10] G. Rudstam, K. Aleklett, L. Sihver, Delayed- Neutron Branching Ratios of Precursors in the Fission Product Region, At. Data Nucl. Data Tables **53** (1993) 1.
[11] Report NEA/WPEC-6: http://www.oecd-nea.org/science/wpec/volume6/volume6.pdf and A. D'Angelo, Progr. Nucl. Energy **41** (2002) 5.
[12] B. Pfeiffer, K.-L. Kratz, P. Möller, Status of delayed-Neutron Precursor Data: Half-Lives and Neutron Emission Probabilities, Progr. Nucl. Energy **41** (2002) 39.
[13] K.-L. Kratz and G. Herrmann, Systematics of Neutron Emission Probabilities from Delayed Neutron Precursors, Z. Physik **263** (1973) 435.
[14] P. Möller and J. Randrup, New Developments in the Calculation of β-Strength Functions, Nucl. Phys. A**514** (1990) 1.
[15] National Nuclear Data Center NNDC, Brookhaven: http://www.nndc.bnl.gov
[16] IAEA Nuclear Data Services: http://www-nds.iaea.org/
[17] Atomic Mass Data Center, Orsay: http://amdc.in2p3.fr/nucleus/nucWxp2.exe

4. Summary of presentations

4.1. Need for Compilation and Evaluation of Beta-delayed Neutron Probabilities in Radioactive Decay, B. Singh

Introduction

Experimental studies of the β-delayed neutron decay mode have been carried out since the fifties. Until about 1980, most of the experiments involved neutron-rich nuclides produced in the fission process and were driven by the practical needs for reactor physics. Since then many neutron-rich nuclides in the lower mass region have also been studied for nuclear structure investigations. In recent years, with the advent of radioactive-ion beam facilities, mass separators, Penning-trap methods, etc. there is renewed interest in the measurement of β-delayed neutrons in different mass regions, for example beyond A=150, for which currently almost no experimental data are available. These studies are driven by interest in applications in nuclear astrophysics, fission process and nuclear structure of neutron-rich nuclei. To facilitate modern studies in this field, it is proposed that a dedicated database be established where one can find documentation of all the previous measurements together with recommended values of beta-delayed neutron probabilities (P_n values) for all the nuclides which have been studied, with a provision for frequent updates of this database.

Review of the previous compilations and evaluations in the literature

The Evaluated Nuclear Structure Data File (ENSDF) database maintained by the National Nuclear Data Center at Brookhaven National Laboratory, USA, and contributed by a network of data evaluators under the auspices of the IAEA contains the most information about β-delayed neutron decay mode as compared to the data contained in other compilations described below. However, the data for an individual nuclide date to when it was last evaluated, some quite outdated. Moreover, complete documentation about the methods employed in the measurements of β-delayed emission probabilities is often missing. In Appendix 3, recommended values of P_n from measurements for all the ~215 nuclides from ^{8}He to ^{150}La, as retrieved from the ENSDF database [1] are tabulated. Similar information, mainly taken from the ENSDF database can also be found in Nuclear Wallet Cards [2], NUBASE [3], NUDAT 2.6 (http://www.nndc.bnl.gov/nudat2/), and various wall charts of nuclides.

Since 1969, several compilations/evaluations have been published [4-10], the last three [8, 9, 10] being the most relevant at the present time:

- 1989 evaluation by M.C. Brady [8]: evaluation and simulation of neutron spectra and compilation of P_n values. Experimental neutron spectra obtained from Studsvik, Mainz and INEL-Tristan for 34 delayed-neutron emitters analyzed. Spectra for about 237 β-delayed neutron precursors were calculated based on statistical model. The values of P_n were compiled and evaluated for 89 fission fragments from ^{75}Cu to ^{149}La.

- 1993 Evaluation by G. Rudstam, *et al.* [9]: contains evaluation and measurements for fission produced precursors. Data for 93 nuclides from ^{75}Cu to ^{150}La, including P_n values measured for 64 nuclides in this work. A significant number of new measurements have since then become available, thus the evaluation by Rudstam, *et al.* [9] is out-of-date. Nevertheless, it remains a most comprehensive compilation and evaluation of beta-delayed neutron data as of the present date. This paper also gives details about the methods employed in the measurement of P_n.

- 2002 Compilation by B. Pfeiffer, *et al.* [10]: 338 fission produced nuclides listed in this paper with experimental (compiled) values for 129 nuclides. This paper gives theoretical values from QRPA models and systematic values from Kratz-Herrmann formula for all the 338 nuclides. Although no documentation of input experimental values is provided in the paper, such a list has been kindly made available as a private communication by B. Pfeiffer.

New Data

A scan of the Nuclear Science References (NSR) database at http://www.nndc.bnl.gov/nsr/ shows about 60 new papers dealing with β-delayed neutron measurements since 2000. Most of these data have not yet been incorporated in ENSDF or other databases. Currently there is also renewed interest in the measurements of P_n for nuclei relevant to the r-process in nucleosynthesis. Using radioactive ion-beam facilities (at GSI, GANIL, JYFL, RIKEN, TRIUMF, etc.), studies in the region of A>150 have become possible, for which there are currently no data available.

At TRIUMF facility at the University of British Columbia in Canada, a decay spectroscopy system called GRIFFIN is planned for completion in 2014. This system will comprise an array of 16 Clover HPGe detectors, array of fragmented Si detectors, possibly combined with a fixed-magnet magnetic spectrometer, array of scintillation detectors for β rays, arrays of $LaBr_3$ and BaF_2 detectors for level lifetime determination, and a 70-element set of deuterated scintillators for neutron detection and n-n correlations, the latter called the DESCANT array shown in Fig. 9.

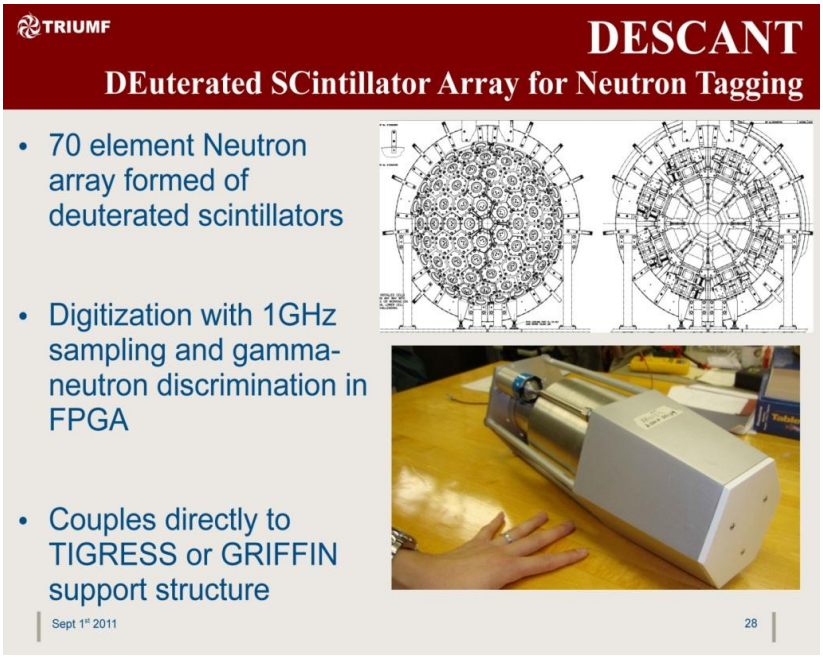

Fig. 9: DESCANT array (planned for completion in 2014, courtesy of Adam Garnsworthy, TRIUMF).

The need for a new compilation and evaluation of beta-delayed neutron data and creation of a dedicated database for this activity seems well justified in view of the above discussion.

Samples of original (compiled) data

Below are samples of compiled data for Na isotopes (in the low-mass region) and ^{98}Rb in the fission region. From the spread of measured values in these examples, it is obvious that it is not quite straightforward to deduce recommended values. Policies and procedures are needed for evaluation of such data, which will often form a discrepant dataset.

Table 1. Sample of compiled data for P_n values (in %) for Na isotopes (low-mass region)

Nuclide	[1984Gu19]: γ	[1984La03]/ [1980De26]: n	[1991Re02]: n	Others
Na-27	0.13(4)		1.0(6)	
Na-28			0.4(4)	0.8(2): [1974Ro31]
Na-29	21(4)	21.5(30)	27.1(16)	
Na-30	30(4), P(2n)=1.15(25)	33(5), P(2n)=1.30(25)	47.9(65)	
Na-31	40(12), P(2n)<1.5	36(6), P(2n)=0.87(24)	40(14)	
Na-32	32(13), P(2n)=8(3)	21(8), P(2n)=9.4(25)		
Na-33	52(20), P(2n)=12(5)	77(15), P(2n)=17(5)		47(6): [2002Ra16] P(2n)=13(3)
Na-34		115(20)		

Comments:

1974Ro31: E. Roeckl *et al.*, Phys. Rev. C**10**, 1181 (1974): neutron counting, data normalized to P_n = 35.0% for Li-9.

1981Bj01: T. Bjornstad *et al.*, Nucl. Phys. A**359**, 1 (1981) measured P_n = 50(4)% for Li-9 and

1991Re02: P.L. Reeder *et al.*, Phys. Rev. C **44**, 1435 (1991) measured P_n = 50.0(18)%, revised to 50.8(2)% priv. comm. P.L. Reeder (1995) and

1992Te03: O. Tengblad *et al.*, Z. Physik A**342**, 303 (1992) measured P_n = 51(1)%. Thus all P_n values in [1974Ro31] need re-normalization.

1984Gu19: D. Guillemaud-Mueller *et al.*, Nucl. Phys. A**426**, 37 (1984): gamma counting.
1980De26: C. Detraz *et al.*, Phys. Lett. B**94**, 307 (1980).
1984La03: M. Langevin *et al.*, Nucl. Phys. A**414**, 151 (1984): neutron counting.
1991Re02: P.L. Reeder *et al.*, Phys. Rev. C **44**, 1435 (1991): neutron counting.
2002Ra16: Z. Radivojevic *et al.*, Nucl. Instrum. Methods A**481**, 464 (2002): neutron counting.
For some of the recommended values, see ENSDF database.

Table 2: Sample of compiled data for P_n values (in %) of ^{98}Rb (fission region).

[1986Wa17]	[1987PfZX]	[1981En05]	[1980ReAA]	[1979Ri09]	[1974Ro15]
13.6(5); also 13.6(9) in a 1985 conf. rep.	13.0(10)	16.7(16)	12.8(20)	18.4(29)	13.3(21); renorm. to 19(3) by [1981Bj01]

Comments:
1981Bj01: T. Bjornstad *et al.*, Nucl. Phys. A**359**, 1 (1981).
1981Re05: P.L. Reeder *et al.,* Phys. Rev. Lett. **47**, 483 (1981): P(2n)=0.051(7) %.
1986Wa17: A. Warner, P.L. Reeder, Radiat. Effects **94**, 27 (1986).
1987PfZX: B. Pfeiffer *et al.*, Proc. Conf. Delayed Neutron Properties, Birmingham, p75 (1987).
1981En05: G. Engler, E. Neeman, Nucl. Phys. A**367**, 29 (1981).
1980ReAA: P.L. Reeder, R.A. Warner, Res. Report PNL-SA-8766 (1980).
1979Ri09: C. Ristori *et al.*, Z. Physik A**290**, 311 (1979).
1974Ro15: E. Roeckl *et al.*, Nucl. Phys. A**212**, 621 (1974).

Conclusions

Based on literature survey, a complete and comprehensive topical evaluation of β-delayed neutron probabilities is non-existent. Such an evaluation will prove useful to address the data needs of reactor physics, nuclear astrophysics, and nuclear structure communities. Ultimately, a database is required which can be regularly updated for new experimental results.

References

[1] ENSDF database: available at http://www.nndc.bnl.gov
[2] J.K. Tuli, Nuclear Wallet Cards (2005); also on http://www.nndc.bnl.gov
[3] G. Audi, O. Bersillon, *et al.*, The NUBASE evaluation of nuclear and decay properties, Nucl. Phys. A **729** (2003) 3.
[4] P. del Marmol, Nuclear Data Tables A6, 141 (1969): data for 30 nuclides from ^{8}He to ^{144}Cs.
[5] L. Tomlinson, At. Data Nucl. Data Tables **12** (1973) 179: data for 41 nuclides.
[6] T. Izak-Biran, S. Amiel, Nucl. Sci. Eng. **57** (1975) 117: data for 42 nuclides.
[7] F.M. Mann, *et al.*, Nucl. Sci. Eng. **87** (1984) 418: data for about 80 nuclides.
[8] M.C. Brady, Ph.D. thesis (Texas A&M, 1989), LA-11534-T.
[9] G. Rudstam, K. Aleklett, L. Sihver, At. Data Nucl. Data Tables **53** (1993) 1.
[10] B. Pfeiffer, K.L. Kratz, P. Moller, Status of delayed-Neutron Precursor Data: Half-Lives and Neutron Emission Probabilities, Prog., Nucl. Energy **41** (2002) 39.

4.2. Beta-delayed neutrons in the new ENDF/B-VII.1 library, A. Sonzogni

The ENDF/B-VII.1 library will be released in December 2011. It contains an updated decay data sub-library. The goal of the sub-library is to give full radiation data for all known ground states and isomers. The data included are half-life, decay modes as well as energy and intensity for all radiation types.

This sub-library includes a large number of nuclei that undergo β-delayed neutron emission. Most of them are nuclides that are produced in the fission of actinides

nuclei. For these nuclides the source of data is:

a) Half-lives and P_n values are obtained from the most recent evaluated experimental values in ENSDF or [1]. If they are not available, the systematic values of [1] were used.
b) Q-values were obtained from the 2011 update of the Atomic Mass evaluation by Audi, *et al.* [2].
c) Neutron energy spectra were obtained from the evaluated experimental data in the ENDF/B-VII.8 library in combination with Coordinate Generator Method (CGM) calculations [3]. When partial or no experimental data was available, CGM results were used.

An example of a neutron spectrum is seen in Fig. 10 for ^{140}I, where CGM values were used for energies larger than 1.7 MeV.

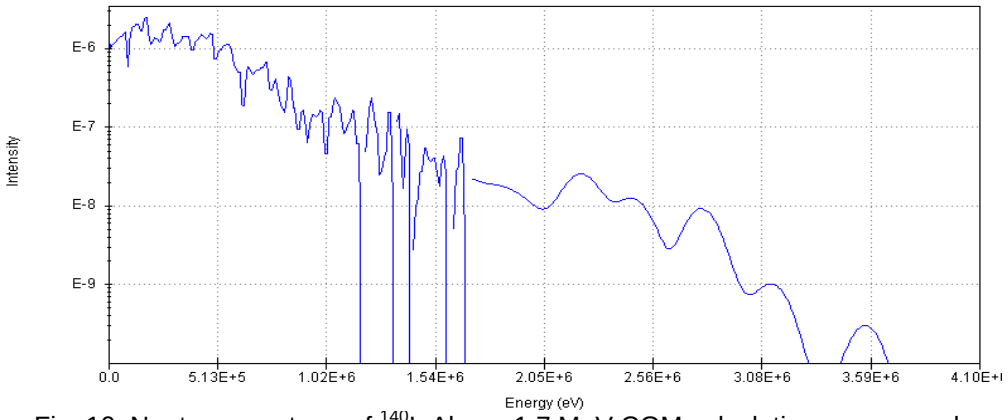

Fig. 10: Neutron spectrum of ^{140}I. Above 1.7 MeV CGM calculations were used.

As part of this work, we have studied the systematic behavior of P_n. For this, we followed the method described in [4] to obtain the average β-strength function ($<S_\beta>$) in the excitation energy range where neutron emission is allowed. The results are plotted in Fig. 11 as a function of the dimension-less parameter $(Q_\beta - S_n)/(Q_\beta + S_n)$. As could be expected, the points align fairly well. This alignment can be used to calculate P_n for cases where there are no experimental results.

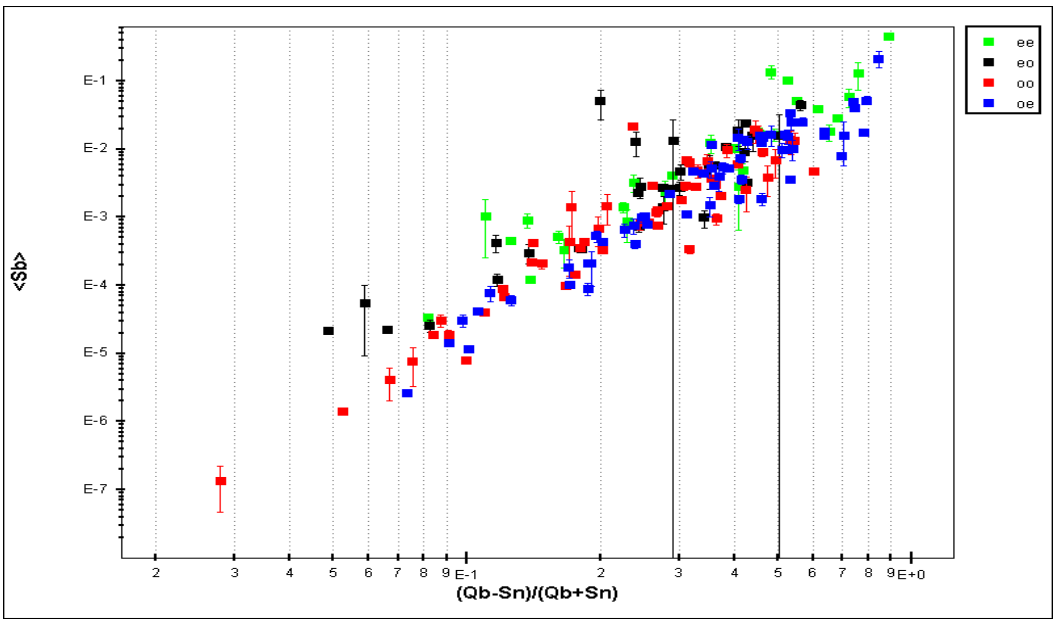

Fig. 11: Plot of the β-strength function vs. dimension-less parameter $(Q_\beta - S_n)/(Q_\beta + S_n)$

In terms of benchmarking the sub-library, we have calculated the thermal nu-bars for ^{235}U and ^{239}Pu using the JEFF-3.1 fission yields. We obtained 0.01604 and 0.006543 respectively, which means these values are within 2% of the evaluated nu-bars.

References

[1] B. Pfeiffer, K. Kratz, P. Moller, Status of delayed-Neutron Precursor Data: Half-Lives and Neutron Emission Probabilities Prog. Nucl. Energy **41** (2002) 39.

[2] Atomic Mass Evaluation; http://amdc.in2p3.fr/masstables/Ame2011int/filel.html (Priv. Comm. by Georges Audi and Wang Meng, April 2011).

[3] T. Kawano, P. Moller, W.B. Wilson, Calculation of delayed-neutron energy spectra in a quasiparticle random-phase approximation-Hauser-Feshbach model, Phys.Rev. C **78** (2008) 054601.

[4] J.C. Hardy, I.S. Towner, Gamow-Teller Strength Distribution in the β-Decay of Exotic Nuclei, J. Phys. (Paris), Colloq.C-4 (1984) 417.

4.3. Delayed Neutron Data in the JEFF library, M.A. Kellett

A brief overview was given on the type of delayed neutron data available in the evaluated data files using the ENDF format, such as JEFF, ENDF/B and JENDL. Different types of delayed neutron data are stored in a variety of sections and/or sub-libraries of these evaluated libraries.

The macroscopic delayed nu-bar values for neutron-induced fission are given in the cross-section sub-library, along with group parameters (decay constants and relative abundance, referred to as MF=1, MT=455) and an aggregate delayed neutron emission spectrum (in MF=5, MT=455). These are the parameters which are used in reactor kinetics calculations and are thus the most important for the nuclear power industry. Typically either the classic six (“Keepin”) or eight groups are used.

For spontaneous fissioning nuclei, the macroscopic delayed nu-bar value is stored in the relevant file in the radioactive decay data sub-library (in MF=1, MT=455 as above).

For individual precursors, (β^-,n) branching fractions (P_n values) and emission spectra are given in the relevant part of the file, again in the radioactive decay data sub-

library (MF=8, MT=457). These emission spectra are stored as simple X-Y value pairs, which may also include uncertainties on both (or either) quantity. The amount and quality of these data are very limited in the major libraries. In the JEFF library there are 263 nuclei denoted as decaying via delayed neutron decay (241 (β^-,n); 18 (β^-,2n) and 4 (β^-,3n)) and a very limited number of emission spectra, most of which are given as individual neutron emission lines which have been identified through the underlying nuclear structure information, i.e. specific high-energy nuclear levels which are assumed to decay to the ground state of the daughter as no accompanying gamma rays are observed.

One way to make an assessment of the individual P_n values, and at the same time test the fission yields, is to make a summation calculation over all delayed neutron precursors, and compare this with the evaluated delayed nu-bar. Examples were presented for a variety of fissioning systems using data from the JEFF-3.1 library (calculations originally made by Robert W. Mills, NNL, UK, but corrected to the evaluated delayed nu-bar, rather than an experimental value). Generally the agreement is within 10%, but with some fissioning systems showing a difference of up to 40%. Again this suggests there are problems with individual precursor data as the associated fission yield data are generally thought to be of better quality.

Examples of delayed neutron spectra from the JEFF-3.1 (also adopted in JEFF-3.1.1) radioactive decay data sub-library were shown for ^{87}Br, $^{93, 94, 95}$Rb, and ^{152}La and compared to ENDF/B-VII.0 (where available). The differences in the data are striking, owing both to the underlying poor quality data, but also related to the evaluation method. Although both libraries must store these data in the same format, i.e. as individual discrete neutron emission lines, the evaluator's comments in the JEFF library indicate that they should be treated as discrete neutron emissions, whereas in the ENDF/B-VII library they seem to be treated as a continuous spectrum, with additional emission values included. It is quite clear from these limited comparisons that further measurements of delayed neutron spectra (and P_n values) are merited.

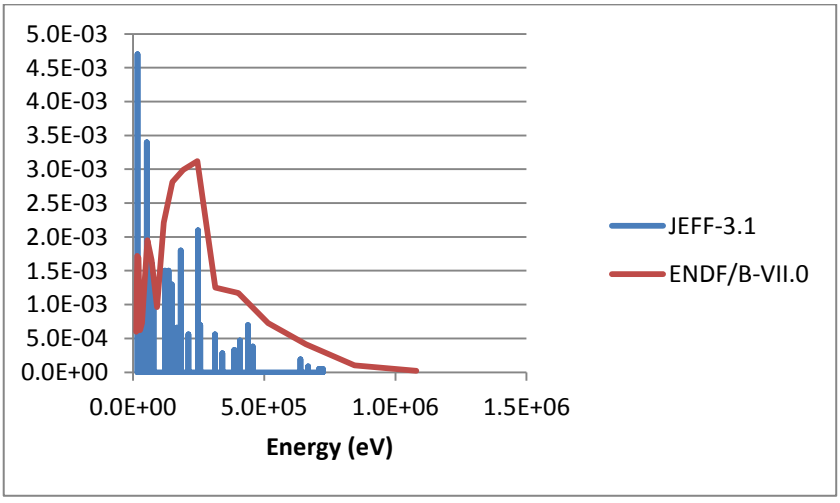

Fig. 12: ^{87}Br delayed neutron emission data stored in the JEFF-3.1 and ENDF/B-VII libraries. (All data are actually stored as discrete neutron emission lines.)

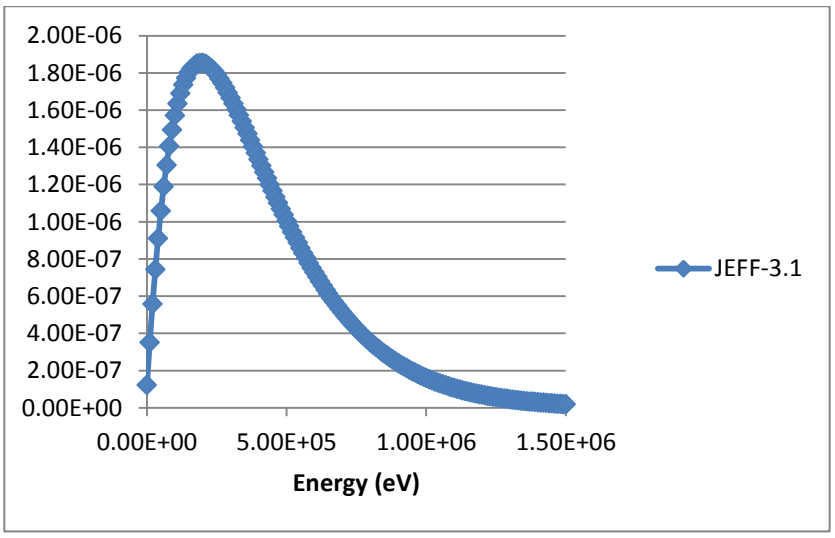

Fig. 13: ^{152}La delayed neutron emission data from JEFF-3.1, showing in this case a calculated spectrum.

4.4. Ongoing and planned β-delayed neutron measurements with BELEN for astrophysics, nuclear structure and reactor technology, J.L. Tain

The BELEN detector

A new neutron counter BELEN (BEta deLayEd Neutron) is being developed within the DESPEC-NUSTAR collaboration [1] for experiments at the future FAIR facility. Meanwhile the detector has been employed at several installations for the study of beta-delayed neutron emitters and in particular the determination of the neutron emission probability P_n. The detector uses ^{3}He proportional counters embedded in a polyethylene neutron moderator matrix to detect neutrons by means of the $n+^3He \rightarrow p+t$ reaction which provides a very clean neutron signature. The detector concept is a modular one, which allows an easy adaptation to different experimental environments and the optimization of the detector efficiency by incrementing the number of counters and their redistribution. An essential feature is the novel data acquisition system developed at IFIC-Valencia [2]. The signals conveniently shaped are fed to independent channels of a 100 MHz 16 bit digitizer working in self-triggered mode. The firmware trapezoidal filter provides independent time-amplitude pairs for each tube allowing unambiguous noise discrimination and the free choice of time correlation conditions in the off-line analysis. The use of two alternating memory banks for data fill-in/read-out provides a virtually dead time free system. In this way we avoid the usual complications associated to the long moderation + capture time (~200 microseconds) of the neutrons when employing a conventional ADC/TDC triggered DACQ.

Experiments at JYFL

The initial version of BELEN with 20 counters of 2.5cm diameter and 60 cm length at 20 atm was used in a commissioning experiment at the JYFL Accelerator Laboratory during 2009 [3]. This facility offers unique characteristics for accurate measurements of P_n values. On one hand the combination of the IGISOL [4] mass-separator with the proton/deuteron induced U fission ion-guide source allows the measurement of refractory fission products, not available at other mass separators. On the other hand the possibility to couple at the exit of the separator the JYFLTRAP Penning trap acting as a very high resolution mass separator allows the production of pure isotopic beams (eventually isomer beams) for implantation and measurement. This eliminates the ambiguities in the decomposition of source activities from isobaric contaminants, and permits the measurement of even weakly produced species. In order to handle the inevitable contamination of the descendants the purified beam was implanted at the centre of BELEN onto a movable tape. The implant-wait-move time of the measurement cycle is optimized for the selected isotope. The decomposition of the growth and decay curves for both β and neutron counts using the Bateman equations provides the right fraction attributable to the implanted ion. These together with the number of registered β-neutron delayed time coincidences give the neutron emission probability. The neutron efficiency calibration was done using ^{88}Br and ^{95}Rb which we took as suitable standards. In the measurement new accurate P_n values were obtained for ^{94}Rb and ^{138}I which will have an impact in the data evaluation for these isotopes.

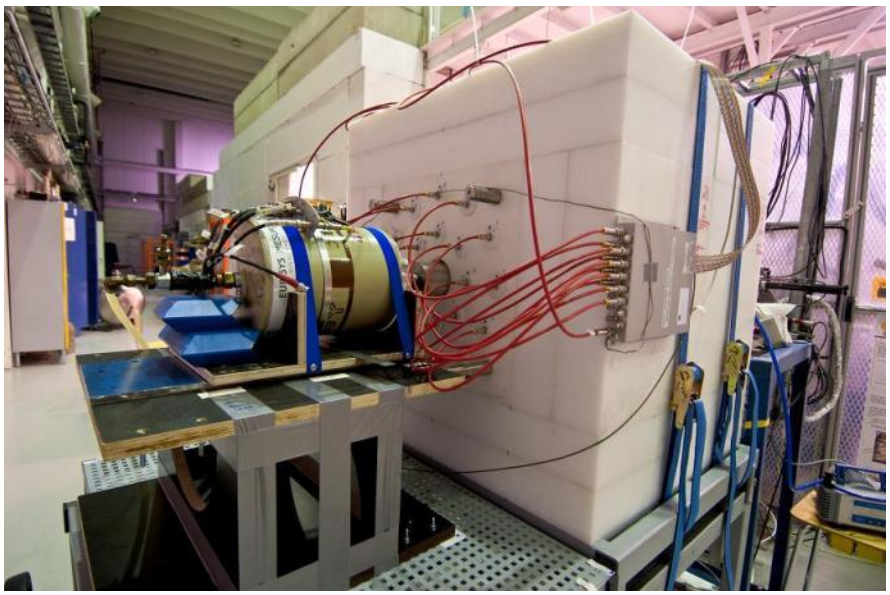

Fig. 14. View of the BELEN neutron detector at the IGISOL-JFLTRAP facility

In a second experiment during 2010 [5], a new ^{3}He counter arrangement with improved efficiency was used in detriment of the flatness of the efficiency versus neutron energy response. In this experiment several light fission products (Ge, As, Br) were investigated. The isotopes were selected after an investigation of data bases [6] with the aim to improve delayed neutron fraction summation calculations. Additional criteria based on nuclear structure and astrophysics considerations shaped the final list of proposed isotopes. The analysis of this data is in progress. The measurements will be continued during 2012 with an upgraded version of BELEN.

Experiments at GSI

The initial 20 counters at 20 atm were purchased (by UPC-Barcelona) before the worldwide shortage of ^{3}He supply. The new market prices make the upgrade of BELEN with the same type of counters economically unviable. Moreover there is little efficiency gain using 20 atm tubes when compared to 10 atm or even 5 atm tubes. Therefore the next version of BELEN which has been put into use in very recent experiments at GSI has supplemented the original 20 counters with 10 additional counters at 10 atm (from GSI-Darmstadt). Two measurements were performed in September 2011 at the FRagmet Separator (FRS) [7] to investigate very neutron-rich isotopes in the vicinity of the r-process nucleo-synthesis path. The measurements concentrate respectively on nuclei close to the 2nd [8] and 3rd [9] peaks of the r-process element abundance distribution. The isotopes were produced by fission /fragmentation of ~1 AGeV ^{238}U beam on a thin Be target. By a combination of magnetic fields and matter distribution the FRS selects only a fraction of the ions produced. These are implanted into a stack of Double-Sided Silicon Strip Detector (DSSSD) located at the centre of BELEN, which allows the spatial and time correlation of the implanted ion with its subsequent decay (β emission detection) and the time correlation between the decay and the neutron registration in BELEN. The implantation detector (called SIMBA) was developed at the TU Munich/ Germany. A series of detectors (scintillators, ionization chambers, TPCs) at the final and intermediate focal planes of the spectrometer allow the identification of the isotopes from the measurement of their velocity (time of flight) and energy loss in transmission detectors. The high counting rates and the large number of parameters render

impossible the use of a totally trigger-less DACQ. Therefore we opted to combine the BELEN self-triggered system with the traditional triggered DACQ for the remaining parameters. A particular problem encountered in these experiments is the production of background neutrons by the ions exiting the FRS into the experimental area, when going through the different material elements. Many of these ions do not reach the end of the detection system which defines the trigger of the DACQ but still produce neutrons. The self-triggered system has proved very useful to solve this problem since we were able to readout independently the signals from the first detector element in the experimental area which essentially registers all the incoming ions and can be used to veto background signals.

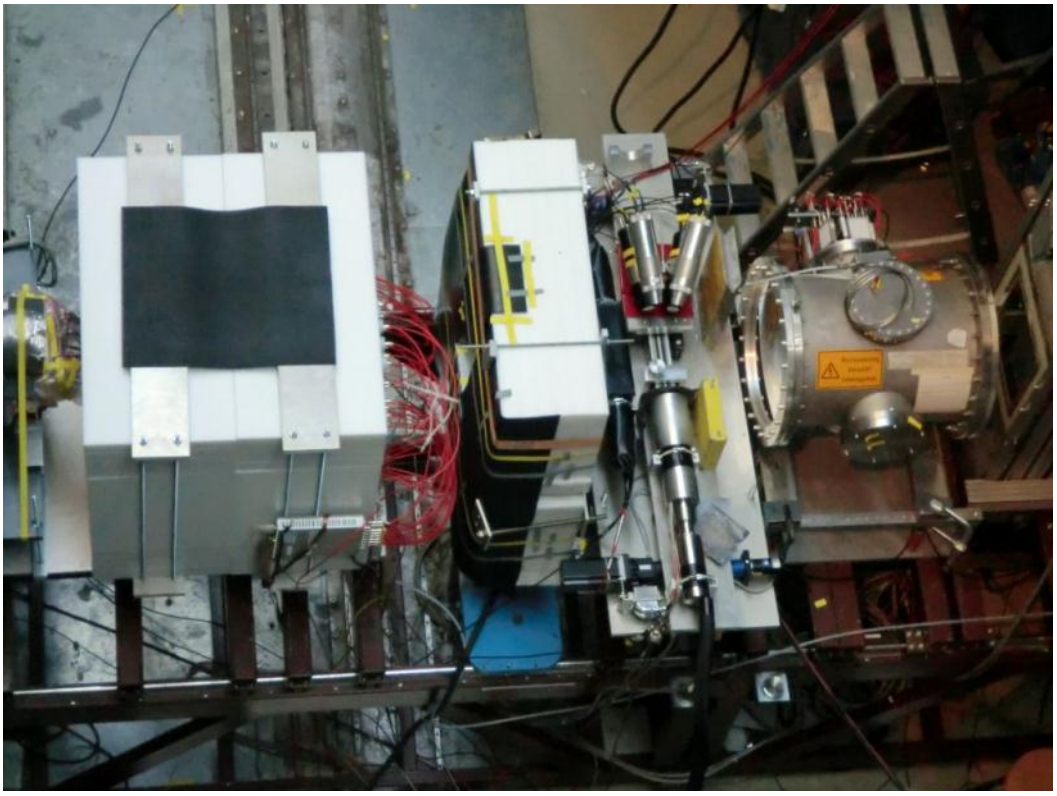

Fig. 15: Setup at the focal plane S4 at the Fragment Separator FRS at GSI in Darmstadt.

Future plans

The continuation of the last measurement at JYFL will take place during 2012 after the ongoing upgrading of the facility is completed. In the new experiment we will use an upgraded version of BELEN with higher efficiency using 50 counters. For this the 20×20atm ^{3}He tubes will be converted into 40×10atm. A further upgrade of the detector for the future experiments at FAIR with an additional 40 counters at 4 atm coming from JINR-Dubna is envisaged. A proposal for further measurements (2013…) of beta-delayed neutron emitters with BELEN at JYFL is under preparation. At GSI-FRS a stopped-beam campaign is under discussion to perform decay experiments with different detectors including BELEN before the shutdown for FAIR construction (2015).

We are also planning for β-delayed neutron measurements at other facilities in Europe. At ALTO-Orsay [10] the JINR group is building a new ^{3}He based neutron counter TETRA for measurement of β-delayed neutron emitters. Once the facility is commissioned (2012) there will be the opportunity to extend the measurements to more neutron-rich nuclei. Furthermore we have presented two Letters of Intent for measurements at SPIRAL2 once the DESIR facility [11] is built (2015). The proposals

address very neutron rich nuclei around the doubly magic ^{78}Ni and ^{132}Sn. The measurements could be performed with BELEN or TETRA or even a combination of the two.

References:

[1] http://personal.ph.surrey.ac.uk/~phs1zp/Home.html
[2] J. Agramunt, *et al.*, A trigger-less data acquisition system for nuclear decay experiments, to be published.
[3] A. Algora, D. Cano, B. Gomez, *et al.*, JYFL Proposal: Decay properties of β-delayed neutron emitters, 2008.
[4] https://www.jyu.fi/fysiikka/en/research/accelerator/igisol
[5] B. Gomez, J.L. Tain, *et al.*, JYFL Proposal: Delayed neutron measurements for advanced reactor technologies and astrophysics.
[6] J.L. Tain, Investigation of candidates for new delayed neutron measurements based on reactor technology motivations, IFIC Preprint, 2010.
[7] http://www-wnt.gsi.de/frs/index.asp
[8] F. Montes, *et al.*, GSI-FRS Proposal S323: Beta-decay of very neutron rich Rh, Pd, Ag isotopes including the waiting point ^{128}Pd, 2006.
[9] C. Domingo, B. Gomez, I. Dillmann, *et al.*, GSI-FRS Proposal S410: Measurement of β-delayed neutrons around the third r-process peak, 2010.
[10] http://ipnweb.in2p3.fr/tandem-alto/alto/index.html
[11] http://www.cenbg.in2p3.fr/desir/

4.5. Status and progress in neutron detector research, D. Cano-Ott

4.5.1. Introduction

Neutron detectors are used extensively at almost every nuclear research facility. Their range of application covers nearly all the topics in basic and applied nuclear research: in nuclear structure, for decay studies and as ancillary detectors for powerful in-beam spectroscopy arrays; in nuclear reactions, for the identification of the reaction channels and reconstruction of the complete kinematics; in nuclear astrophysics, for determining the neutron emission probabilities; in nuclear technology, for nuclear data measurements and in-core/off-core monitors; in nuclear medicine, as radiation monitors and dosimeters and in material science, for neutron imaging techniques.

Paradoxically, the improvements during the last decades in neutron detection techniques have been modest in comparison to other fields of nuclear instrumentation. Materials, techniques and electronics developed 40 years ago are still the state of the art in neutron detection.

Most of the neutron detectors in use are:

- Gaseous detectors. These are mainly based on the ^{3}He(n,p), ^{10}B (n,a), ^{1}H(n,p) and (n,fission) reactions. Due to its gaseous nature, they have low intrinsic efficiencies, limited time resolution and require special safety measures in their use (due to toxicity, flammability or other aspects). Furthermore, the recent price increase for ^{3}He of about a factor of 10 has shown the need to develop neutron detectors covering the range from thermal up to several hundreds of keV with reasonable efficiencies and cost.
- Liquid organic scintillators. These are based on the ^{1}H(n,p) reaction and are still one of the preferred options for building large neutron spectrometers when pulse

shape discrimination is required. They are however difficult to handle (due to the toxicity and flammability) and depending on the size, the lowest neutron energy that can be detected is 50 - 100 keV.
- Solid organic scintillators. These are based on the ^{1}H(n,p) reaction and are one of the preferred option for building large neutron spectrometers when pulse shape discrimination is not required, i.e. for favourable neutron signal to γ-ray background ratios. Their neutron energy detection threshold is 50 - 100 keV.
- Organic scintillators loaded with neutron converters. These rely on the ^{1}H(n,p) reaction which moderates the neutron energy after a few collisions and trigger a different (n, charged particle) or (n,γ) reaction in the doping material.
- Solid inorganic scintillators. Some solid inorganic scintillators doped with neutron converters are being used in neutron spectroscopy. However, due to the limited presence of dopant and the small neutron reaction cross sections involved (typically charged particle production), their efficiency drops rapidly at energies above a few tens of keV.

4.5.2. R&D on neutron detectors

Existing and future Radioactive Ion Beam facilities like GANIL/SPIRAL2 [1, 2], GSI/FAIR [3-5], INFN LNL-Legnaro/SPES [6], IGISOL/JFLTRAP-Jÿväskÿla [7], ALTO-Orsay [8] and HIE-ISOLDE [9] in Europe, FRIB [10] in the USA and RIKEN [11] in Japan do or will offer a wide range of experimental conditions for extending our knowledge on the structure of nuclei far from the β-stability line.

In the short and mid-term future, it will be possible to continue decay studies of neutron rich nuclei at existing facilities like IGISOL/JFLTRAP, ALTO-Orsay, FRS at GSI, ISOLDE at CERN and RIKEN. Some of them have been upgraded recently (IGISOL) or are expected to increase their intensity in the near future (ALTO, ISOLDE). A major breakthrough will come however in the longer term perspective, as soon as the DESPEC experiment at FAIR (Germany), S3 and DESIR at SPIRAL2 (France), SPES at LNL (Italy) and FRIB at MSU (USA) become available. Such new facilities will produce ion beams of very neutron rich isotopic species with unprecedented intensities, as high as several orders of magnitude larger than is possible nowadays.

New detector concepts are needed for the optimal exploitation of experiments at present and future radioactive ion beam facilities. In particular, more efficient and sensitive neutron detectors are necessary, with lower detection thresholds and better background rejection mechanisms. Such detectors will allow low yield βn and β2n experiments or identifying high multiplicity neutron emission channels in in-beam experiments to be carried out.

The actual efforts in neutron detector R&D are focussed towards:

- The design and construction of neutron spectrometers for determining the neutron emission probabilities and energy spectra of neutrons with energies above 100 keV.
- The construction of high efficiency long counters for the accurate measurement of neutron emission probabilities of neutrons in the entire energy range.
- The design and construction of high performance data acquisition systems.
- The improvements in Monte Carlo simulation codes.
- Networking, dissemination and training activities at an international level.

4.5.3. Neutron spectrometers

Several neutron spectrometers are being constructed as equipment that will be used in future radioactive ion beam facilities for β-delayed neutron measurements and/or neutron detection:

- The MOdular Neutron SpectromeTER (MONSTER) detector for the DESPEC experiment at FAIR. It will consist of an array of up to 200 modules filled with the NE213/BC501A/EJ301 liquid scintillator. Despite its existence for several decades, NE213 does still offer the best neutron/γ-ray pulse shape discrimination capabilities among all the organic scintillators for neutron energies above a few hundred keV. A 30 cell demonstrator of MONSTER has been built recently by CIEMAT using modules manufactured by St. Gobain Crystals and will be used for test experiments at IGISOL/JFLTRAP (β-decays of ^{94,95}Br and ^{88}Br), ISOLDE (β-decay of ^{11}Li) and the FRS/GSI (commissioning for FAIR).
- An upgraded version of the EDEN [12] neutron detector array, also based on the NE213 liquid scintillators, that will installed at the future DESIR facility at SPIRAL2.
- The DESCANT [13] detector at TRIUMF, consisting in 70 hexagonal cells filled with the deuterated liquid scintillator BC537.
- The NEDA [14] neutron detector, to be operated as an ancillary detector of the AGATA [15] Germanium detector array. The design of the detector is still on-going and several options for the liquid scintillators are being considered.
- The TONNERRE [16] detector array is composed of 32 plastic scintillator (BC400) modules each of which provide for time-of-flight (energy) and position measurements. The intrinsic detection efficiency is 30% at E_n=2 MeV and the resolution ΔE/E~10% (FWHM).
- The VANDLE [17] neutron detector. It will consist of a modular array of BC408 scintillator bars for detecting neutrons by means of the time of flight technique. The large neutron energy dynamic range, from 100 keV to 20 MeV, and its modular design will give the flexibility necessary to use the detector in experiments with requirements as different as beta decay of neutron rich elements and (d,n) reaction experiments.
- Interesting neutron spectrometers have also been also built for other applications. For example, the proton-recoil detectors for time-of-flight measurements of neutrons with kinetic energies from some tens of keV up to a few MeV at the nELBE [18] facitily. The nELBE neutron detector array is based on EJ200 plastic scintillator bars. Special electronics has been developed for operating the detectors at a gain that allows to detect the single photoelectron peak in the photomultiplier tubes. In this way, it is possible to set a threshold as low as a few keV on the recoil energy of the protons produced in the ^{1}H(n,p) reactions.

All of these spectrometer concepts do have limitations in the lowest neutron energy that can be detected. For this reason, alternative neutron detector concepts based on new inorganic materials doped with ^{6}Li/^{10}B or coupled to neutron converters and new organic scintillators with or without doping materials are being investigated. There is however a consensus that neutron spectroscopy at energies below 100 keV will remain a challenging task for the future and will depend largely on the funding available.

4.5.4. High efficiency long-counters

The neutron long-counter constructed over 20 years ago by the group of K.-L. Kratz [19] at Mainz (Germany) has been used successfully at European laboratories like CERN-ISOLDE (Switzerland), GANIL (France) and GSI (Germany). It is able to detect β-delayed neutrons with a nearly constant efficiency of about 40% in the neutron energy range between eV and 2 MeV. By construction, such a detector concept does not provide any information on the detected neutron energy and thus can only be used for determining neutron emission probability P_n values. Several versions of the Kratz counter are being used or built:

- The NERO [20] neutron long-counter. It was built at the National Superconducting Cyclotron Laboratory (NSCL) and reaches an efficiency of 40% up to 1 MeV by combining 16 ^{3}He and 44 BF_3 counters.
- The ^{3}Hen [21] detector, built at ORNL and that uses 74 ^{3}He tubes for reaching an efficiency close to 80% for neutron energies up to 2 MeV.
- The BELEN [22] detector. A new neutron counter BELEN (BEta deLayEd Neutron) is being developed within the DESPEC-NUSTAR collaboration for the measurement of neutron emission probabilities P_n. A demonstrator version of the detector with 40 ^{3}He proportional counters embedded in a polyethylene neutron moderator matrix is already operative. Efficiencies as high as 40% can be achieved with an inner hole adequate for holding the DSSSD based implantation setups required at fragmentation facilities such as the FRS at GSI or the future Super FRS at FAIR. The final version of BELEN will have an efficiency similar to that of the ^{3}Hen detector.
- The TETRA detector. It has been developed by JINR-Dubna and tested at the ALTO facility. It consists of a modular assembly of ^{3}He tubes embedded in hexagonal shaped polyethylene blocks. It is possible to vary its geometric configuration for different types of measurements. For an adequate geometric arrangement, it can reach neutron detection efficiencies close to 60% for neutron energies up to 1.5 MeV.
- The long counter at LOHENGRIN. It is a low efficiency (20%) version of Kratz's neutron long-counter that has however a more constant efficiency in the range of eV up to several MeVs.

4.5.5. Data acquisition systems

New developments are becoming available for digital data acquisition systems (DAQ). The R&D efforts on DAQ used for the data taking of neutron detectors are classified in the following groups:

- Development of high performance digitizers with high resolution (12 or 14 bits), fast sampling rate (up to 1 GHz), on board pulse shape analysis capabilities for data reduction and large memory (a few Gbytes). Examples of those technologies are the digitisers being developed at CIEMAT in Spain and at LPC-Caen in France.
- Evolution of DAQ systems based on standard electronic modules that minimise the dead time. The triggerless DAQ developed by IFIC-Valencia [22] for the BELEN detector is the state of the art of such a concept, since it allows to deal with long neutron moderation times (typically of several hundred microseconds) without adding any significant dead time.

4.5.6. Improvements in Monte Carlo simulation codes

Monte Carlo simulation tools are essential for determining the characteristics of radiation detectors. The standard codes used in neutron transport problems are MCNP(X) [24] and GEANT4 [25], the last one being better suited for the simulation of complex detection systems.

Important efforts have been made recently for improving the performance of the GEANT4 high precision neutron transport model. The neutron transport in GEANT4 relies on the G4NDL cross section libraries, prepared by the GEANT4 collaboration from evaluated cross section files and distributed freely together with the code. Even though the performance of the G4NDL library has been improved over time, users running complex simulations which involve the transport of neutrons need more flexibility, in particular when assessing the uncertainties in the simulation results due to the neutron data library used. For this reason, CIEMAT has translated [26] eight different releases of ENDF, JEFF, JENDL, CENDL, BROND and ROSFOND libraries into the G4NDL format and released the available files to IAEA's nuclear data service for its distribution.

4.5.7. Networking

A first international initiative on neutron detector R&D has been funded recently through the NUPNET program: the NEutron DEtector developments for Nuclear Structure, Astrophysics and Applications (NEDENSAA) NUPNET project. NEDENSAA is an effort to pool available resources and ongoing R&D by the various partners throughout Europe with the aim of providing significant improvements in neutron detection. It is structured in seven work packages: Development of new materials, characterisation of scintillator materials for neutron detection, innovative detector concepts, photosensors, data processing technologies, optimal design of neutron detectors and gamma-ray detectors, training and networking.

NEDENSAA is formed by nearly all the groups/collaborations in Europe working in neutron detector research: INFN – Legnaro (Italy), CNRS – IN2P3 and CEA (France), University of Jÿväskÿla (Finland), CIEMAT – Madrid and IFIC – Valencia (Spain), TU Dresden (Germany), INRNE (Bulgaria), TÜBITAK (Turkey) and University of Uppsala (Sweden).

References

[1] S. Gales, Nucl. Physics A **834** (2010) 717c–723c. http://www.ganil-spiral2.eu

[2] http://www.cenbg.in2p3.fr/desir/

[3] H.H. Gutbrod, I. Augustin, H. Eickhoff, *et al.,* (Eds.), FAIR Baseline Technical Report, ISBN 3-9811298-0-6, Nov. 2006. http://www.fair-center.de/

[4] H. Geissel, P. Armbruster, K.H. Behr, A. Bruenle, K. Burkard, M. Chun, H. Folger, B. Franczak, H. Keller, *et al.,* Nucl. Instr. Methods Phys. Res. B **70** (1992) 286-297. http://www-wnt.gsi.de/frs/index.asp

[5] Z. Podolyák, for the HISPEC/DESPEC collaboration, Nucl. Instr. Methods Phys. Res. B **266** (2008) 4589-4594. http://personal.ph.surrey.ac.uk/~phs1zp/Home.html

[6] A. Andrighetto, L. Biasetto, M. Manzolaro, D. Scarpa, J. Montano, J. Stanescu, P. Benetti, *et al.*, Nucl. Physics A **834** (2010) 754c-757c. http://www.lnl.infn.it/~spes/

[7] P. Karvonen, H. Penttilä, J. Äystö, J. Billowes, P. Campbell, V.-V. Elomaa, U. Hager, J. Hakala, A. Jokinen, T. Kessler, *et al.*, Nucl. Instr. Methods Phys. Res. B **266** (2008) 4454-4459. https://www.jyu.fi/fysiikka/en/research/accelerator/igisol

[8] F. Ibrahim, D. Verney, M. Lebois, B. Roussière, S. Essabaa, S. Franchoo, S. Gales, D. Guillemaud Mueller, C. Lau, *et al.*, the ALTO collaboration, Nuclear Physics A **787** (2007) 110-117.
[9] M. Lindroos, P.A. Butler, M. Huyse, K. Riisager, Nucl. Instr. Methods Phys. Res. B **266** (2008) 4687-4691.
http://hie-isolde.web.cern.ch/hie-isolde/
[10] M. Thoennessen, Nucl. Physics A **834** (2010) 688c-693c.
http://frib.msu.edu/
[11] T. Kubo, Nucl. Instr. Methods Phys. Res. B **204** (2003) 97- 113.
[12] H. Laurent, *et al.*, Nucl. Instr. Methods Phys. Res. A **326** (1993) 517-525.
[13] J. Wong, PhD Thesis with P.E. Garret as advisor, University of Guelph (2008).
https://gamma.triumf.ca/descant
http://www.physics.uoguelph.ca/Nucweb/theses/JWongMScThesis.pdf
[14] http://es-es.facebook.com/pages/NEDA-NEutron-Detector-Array/185824731465460
[15] S. Akkoyun, A. Algora, B. Alikhani, F. Ameil, G. de Angelis, L. Arnold, A. Astier, A. Ataç, Y. Aubert, *et al.*, Nucl. Instr. Methods Phys. Res. A **668** (2012), 26-58.
[16] A. Buta, T. Martin, C. Timiş, N. Achouri, J.C. Angélique, C. Borcea, I. Cruceruet, *et al.*, Nucl. Instr. Methods Phys. Res. A **455** (2000) 412-423.
[17] C. Matei, D. Bardayan, J. Blackmon, J. Cizewski, *et al.*, The Versatile Array of Neutron Detectors at Low Energy (VANDLE), in: Proceedings of Science (NiC) 138, 2008.
[18] R. Beyer, E. Grosse, K. Heidel, J. Hutsch, A.R. Junghans, J. Klug, D. Légrády, R. Nolte, S. Röttger, M. Sobiella, A. Wagner, Nucl. Instr. Methods Phys. Res. A **575** (2007) 449-455.
[19] K. Hannawald, PhD Thesis, with K.-L. Kratz as advisor, Mainz, Germany (2000).
http://ubm.opus.hbz-nrw.de/volltexte/2000/33/
[20] J. Pereira, P. Hosmer, G. Lorusso, P. Santi, A. Couture, J. Daly, M. Del Santo, T. Elliot, J. Görres, *et al.*, Nucl. Instr. Methods Phys. Res. A **618** (2010) 275–283.
[21] http://www.phy.ornl.gov/hribf/equipment/leribss/3hen-prop.pdf
[22] M.B. Gomez-Hornillos, J. Rissanen, J.L. Taín, A. Algora, D. Cano-Ott, J. Agramunt, V. Gorlychev, R. Caballero, T. Martínez, *et al.*, J. Phys: Conf. Ser. **312** (2011) 052008.
[23] J. Agramunt, *et al.*, "A trigger-less data acquisition system for nuclear decay experiments", to be published.
[24] Denise B. Pelowitz (Ed.), MCNPX User's Manual Version 2.5.0. LA-CP-050369, April (2005).
[25] S. Agostinelli, J. Allison, K. Amako, J. Apostolakis, H. Araujo, P. Arce, M. Asai, D. Axen, S. Banerjee, *et al.*, Nucl. Instr. Methods Phys. Res. A **506** (2003) 250-303.
[26] E. Mendoza, D. Cano-Ott, C. Guerrero, R. Capote, New evaluated neutron cross section libraries for the GEANT4 code, IAEA Report INDC(NDS)-0612, in preparation.

5. Proposed programme

Several items have been discussed:

5.1. Standards

In the course of this meeting, the following beta-delayed neutron precursors were selected as "standards" for the purpose of data evaluation and measurements: Li-9, N-17, Br-87, Br-88, Rb-94, Rb-95, I-137 and I-138. Relevant compiled data are shown below.

Table 3: Q values (from [1]), and decay parameters from ENSDF database. In the cases listed here, S(2n) of beta-daughter nuclides is larger than Q(β-) of the precursors. The S(n) value is for the beta-daughter nuclide (^: J^{π} proposed in [2]: 3/2- in ENSDF database)).

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

SY – systematic value

References:

[1] G. Audi, W. Meng, Interim mass adjustment file, Private Communication, 2011.

[2] M.-G. Porquet, Ts. Venkova, *et al.,* Eur. Phys. Jour. A**28**, 153 (2006).

Table 4: Compiled data for Li-9

(Notes: there are additional, less precise, half-life data using beta detection. Li-9 was the second beta-delayed neutron emitter identified outside the fission-produced precursors).

Reference	Half-life (ms)	%P(n)	Method	Comments
1992Te03	178(1)	51(1)	n-counting	
1991Re02 2008ReZZ+1995ReZZ	175.5(76) 178.1(6)	50.0(18) 50.8(2), 50.1(5)	Recoil-tagging delayed n coin.	
1990Ny01	-	-	Neutron spectra	Decay branches
1981Bj01	-	50(4)	n-β coin	
1981La11	-	49.5(50)	β-delayed α	
1976Al02	178.3(4)	-	n-counting	
1974Ro31	175(1)	-	n-counting	Used %P(n)=35(4)
1970Ch07	177(3)	35(4)	(Li-9)α corr., n	
1965Do13	176(1)	-	n-counting	
1965Sc17	172(25)	-	n-counting	
1963Al18	-	75(15)	β, β-n coin	P(n) from β spectra
1951Ga30	168(4)	-	n-counting	Identified as βn emitter

Comments:

1992Te03: O. Tengblad, *et al.*, Z. Physik A**342**, 303 (1992).
1991Re02: P.L. Reeder, *et al.*, Phys. Rev. C**44**, 1435 (1991): see also 1995ReZZ and 2008ReZZ.
1995ReZZ: P.L. Reeder, *et al.*, Proc. Int. Conf. ENAM, Arles, France, June 1995, p.587 (1995).
2008ReZZ: P.L. Reeder, priv. comm. to B. Singh (2008): data related to 1995ReZZ report.
1990Ny01: G. Nyman, *et al.*, Nucl. Phys. A**510**, 189 (1990).
1981Bj01: T. Bjornstad, *et al.*, Nucl. Phys. A**359**, 1 (1981).
1981La11: M. Langevin, *et al.*, Nucl. Phys. A**366**, 449 (1981).
1976Al02: D.E. Alburger, D.H. Wilkinson, Phys. Rev. C**13**, 835 (1976).
1974Ro31: E. Roeckl, *et al.*, Phys. Rev. C**10**, 1181 (1974); also 1974Ro15: Nucl. Phys. A**222**, 621 (1974).
1970Ch07: Y.S. Chen, *et al.*, Nucl. Phys. A**146**, 136 (1970).
1969Ma11: B.E.F. Macefield, *et al.*, Nucl. Phys. A**131**, 250 (1969): neutron spectrum.
1966Ch20: P.R. Christensen, C.L. Cocke, Nucl. Phys. A**89**, 656 (1966): neutron spectrum.
1965Do13: I. Dostrovsky, *et al.*, Phys. Rev. **139**, B1513 (1965).
1965Sc17: R. Schoneberg, *et al.*, Z. Physik **188**, 38 (1965): neutron spectrum, half-life=172(25) ms.
1963Al18: D.E. Alburger, Phys. Rev. **132**, 328 (1963).
1952Ho25: R.B. Holt, *et al.*, Phys. Rev. **87**, 378 (1952): Half-life=170(5) ms by beta-detection.
1951Ga30: W.L. Gardner, *et al.*, Phys. Rev. **83**, 1054 (1951).

Note: In 2005Mu26 (I. Mukha, *et al.*, Nucl. Phys. A**758**, 647c (2005)), significant beta feeding to the first excited state in Be-9 was implied/proposed from a gamma-ray peak at 1689(10) keV extracted from a large bremsstrahlung continuum. However, in 2006Ba47 (F.C. Barker and H.O.U. Fynbo, Nucl. Phys. A**776**, 52 (2006)), claim of a large intensity of this gamma ray (in 2005Mu26) and subsequent feeding of the first excited 1/2+ state in Be-9 was evaluated and found to be inconsistent with previous measurements.

Table 5: Compiled data for N-17

(N-17 was the first beta-delayed neutron emitter identified outside the fission-produced precursors).

Reference	Half-life (s)	%P(n)	Method	Comments
1991Re02 1995ReZZ+2008ReZZ	4.23(49)	102(6)	Recoil-tagging delayed n coin.	
1976Al02	-	95.1(7)	n-counting	
1976Oh05	4.174(4)	-	n-counting	n-spectrum
1972Al42	4.169(8)	-	n-counting	
1970MeAA	4.17(2)			
1965Do13	4.16(1)	-	n-counting	
1964Si06	-	95(1)	n-counting	
1961Hi01	4.20(8)		n-counting	
1948KnAA	4.14(4)	-	n-counting	

Comments:

1991Re02: P.L. Reeder, *et al.*, Phys. Rev. C**44**, 1435 (1991): see also 1995ReZZ and 2008ReZZ.
1995ReZZ: P.L. Reeder, *et al.*, Proc. Int. Conf. ENAM, Arles, France, June 1995, p.587 (1995).
2008ReZZ: P.L. Reeder, priv. comm. to B. Singh (2008): data related to 1995ReZZ report.
1977Fr19: H. Franz, W. Rudolph, *et al.,* Nucl. Instrum. Meth. **144**, 253 (1977): neutron spectrum.
1976Al02: D.E. Alburger, D.H. Wilkinson, Phys. Rev. C**13**, 835 (1976).
1976Oh05: H. Ohm, *et al.*, Nucl. Phys. A**274**, 45 (1976).
1973De32: De Meijer, *et al.,* Nucl. Phys. A**209**, 424 (1973): neutron spectrum.
1973Po11: A.R. Poletti, J.G. Pronkyo: Phys. Rev. C**8**, 1285 (1973): neutron spectrum.
1972Al42: D.E. Alburger, D.H. Wilkinson, Phys. Rev. C**6**, 2019 (1972).
1970MeAA: H.O. Menlove, *et al.*, Nucl. Sci. Eng. **40**, 136 (1970).
1967AmAA: S. Amiel, *et al.*, Trans. Am. Nucl. Soc. **10**, 181 (1967): neutron spectrum.
1965Do13: I. Dostrovsky, *et al.*, Phys. Rev. **139**, B1513 (1965).
1964Si06: M.G. Silbert, J.C. Hopkins, Phys. Rev. **134**, B16 (1964).
1963Gi04: J. Gilat, *et al.*, Bull. Am. Phys. Soc. **8,** 320 (1963): neutron spectrum.
1961Hi01: S. Hinds, *et al.*, Phys. Rev. Lett. **6**, 113 (1961).
1961PeAA: G.J. Perlow, *et al.*, Phys. Rev. **122**, 899 (1961); also 1961Pe01: neutron spectrum.
1949HaAA: E. Hayward, Phys. Rev. **75**, 917 (1949): neutron spectrum.
1949Al04: L.W. Alvarez, Phys. Rev. **75**, 1127 (1949).
1948KnAA: N. Knable, *et al.*, Phys. Rev. **74**, 1217 (1948).

Table 6: Compiled data for Br-87

Reference	Half-life (s)	%P(n)	Method	Comments
1993Ru01*	**55.6(3)**	**2.56(10)**	**n, β-**	
1980Lu04	55.5(3)	2.57(15)	n, β-	Same lab as 1993Ru01
1980ReZQ*		**2.1(3)**	**ion counting**	**Also 1977Re05**
1978Kr15	55.9(6)	2.6(4)	fission	Also 1974Kr21
1974Gr29	55.96(34)		n	Same group as 1993Ru01
1972Sc48	-	2.3(4)	fission	
1971De35*	**55.6(3)**	**2.3(3)**	**Kr-87, γ**	
1967Pa26		2.63(5)	fission	
1967Ga19		3(1)	Fission, time groups	
1966Si09	55.8(3)			
1964Ar24*	**56**	**3.1(6)**	**n, β-**	
1957Ke67	54.5(9)			

*: value used to calculate the weighted average

Weighted Average = 2.43 (14) %, reduced χ^2=1.0. Uncertainty of 0.10 in 1993Ru01 increased to 0.20 to limit weight to 50%.

1993Ru01, 2002Pf04: recommended value= 2.52 (7) %

Comments:

2002Pb04: B. Pfeiffer, *et al.*, Prog. Nucl. Energy **41**, 39 (2002).
1997Gr20: R.C. Greenwood, K.D. Watts, Nucl. Sci. Eng. **126**, 324 (1997): neutron spectrum.
1993Ru01: G. Rudstam, *et al.*, At. Data Nucl. Data Tables **53**, 1 (1993).
1980ReZQ: P.L. Reeder, R.A. Warner, PNL-SA-8766 (1980); also 1977Re05: Phys. Rev. C **15**, 2108 (1977).
1980Lu04: E. Lund, *et al.*, Z. Physik A**294**, 233 (1980).
1978Kr15: K.L. Kratz, Radiochim. Acta **25**, 1 (1978).
1977Nu04: F.M. Nuh, *et al.*, Nucl. Phys. A**293**, 410 (1977); neutron spectrum.
1977Re06: P.L. Reeder, *et al.*, Phys. Rev. C**15**, 2098 (1977): neutron spectrum.
1977Re05: P.L. Reeder, *et al.*, Phys. Rev. C**15**, 2108 (1977).
1974Kr21: K.L. Kratz, G. Herrmann, Nucl. Phys. A**229**, 179 (1974).
1974Gr29: Grapengiesser, *et al.*, J. Inorg. Nucl. Chem. **36**, 2409 (1974): half-life.
1974Sh18: S. Shalev, G. Rudstam, Nucl. Phys. A**230**, 153 (1974): neutron spectrum.
1972Sc48: H.D. Schussler, G. Herrmann, Radiochim. Acta **18**, 123 (1978).
1971De35: P. del Marmol, *et al.*, Radiochim. Acta **16**, 4 (1971).
1967Pa26: P. Patzelt, *et al.*, Ark. Fys. **36**, 453 (1967).
1967Ga19: H. Gauvin, L. Sauvage, J. Inorg. Nucl. Chem **29**, 2839 (1967).
1966Si09: M.D. Silbert, R.H. Tomlinson, Radiochim. Acta **5**, 223 (1966).
1964Ar24: P.M. Aron, *et al.*, At. Energ. USSR **16**, 368 (1964); Soviet J. At. Energy **16**, 447 (1965).
1957Ke67: G.R. Keepin, *et al.*, Phys. Rev. **107**, 1044 (1957).

Table 7: Compiled data for Br-88

Reference	Half-life (s)	%P(n)	Method	Comments
1993Ru01*	**16.34(8)**	**6.72(27)**	**n, β-**	
1987PfZX*	**16.20(10)**	**7.3(6)**	**n, β-**	
1980ReZQ*	**16.7**	**6.1(7)**	**ion counting**	**Also 1977Re05, P(n)=7.4(5)**
1980Lu04	16.7	6.6(4)	n, β-	Same group as 1993Ru01
1981Ho07*		**6.8(3)**	**gamma**	**Also 1980Ho03**
1978Kr15		6.5(7)	fission	Also 1974Kr21
1974Gr29	16.10(12)		n	Same group as 1993Ru01
1972Sc48	16.4(6)	6.4(7)	fission	Original P(n)=4.3(5) adjusted by 1993Ru01; also 1969ScZY
1971De35		5.2(8)	fission	
1967Ga19		~7	fission	
1966Si09		4.6(6)	fission	Adjusted in 1969De35 comp
1964Ar24*	**16**	**6.0(16)**	**n, β-**	
1959Pe28		4.0(8)	fission	Adjusted in 1969De35 comp

*: value used to calculate the weighted average

Weighted Average = 6.75(18) %, reduced χ^2=0.49.

Recommended values in 1993Ru01: 6.58 (18) %; 2002Pf04: 6.55 (18) %

Comments:

2002Pf04: B. Pfeiffer, K. Kratz, P. Moller, Prog. Nucl. Energy **41**, 39 (2002).
1997Gr20: R.C. Greenwood, K.D. Watts, Nucl. Sci. Eng. **126**, 324 (1997): neutron spectrum.
1993Ru01: G. Rudstam, *et al.*, At. Data Nucl. Data Tables **53**, 1 (1993).
1987PfZX: B. Pfeiffer, *et al.*, Proc. Int. Conf. Delayed Neutron Properties, Birmingham, D.R. Weaver, Ed., p.75 (1987).
1980ReZQ: P.L. Reeder, R.A. Warner, PNL-SA-8766 (1980); also 1977Re05: Phys. Rev. C **15**, 2108 (1977).
1980Lu04: E. Lund, *et al.*, Z. Physik A**294**, 233 (1980).
1980Ho03 P. Hoff, Phys. Scr. **21**, 129 (1980).
1981Ho07: P. Hoff, Nucl. Phys. A**359**, 9 (1981); also 1980Ho03: Phys. Scr. **21**, 129 (1980).
1978Kr15: K.L. Kratz, Radiochim. Acta **25**, 1 (1978); also 1974Kr21.
1977Sh01: S. Shalev, G. Rudstam., Nucl. Phys. A **275**, 76 (1977); neutron spectrum.
1977Re05: P.L. Reeder, *et al.*, Phys. Rev. C**15**, 2108 (1977).
1977Re06: P.L. Reeder, *et al.*, Phys. Rev. C**15**, 2098 (1977): neutron spectrum.
1974Kr21: K.L. Kratz, G. Herrmann, Nucl. Phys. A**229**, 179 (1974).
1974Gr29: Grapengiesser, *et al.*, J. Inorg. Nucl. Chem. **36**, 2409 (1974): half-life.
1974NoZR: J.H. Norman, Thesis Iowa State (1974): neutron spectrum.
1972Sc48: H.D. Schussler, G. Herrmann, Radiochim. Acta **18**, 123 (1978).
1971De35: P. del Marmol, *et al.*, Radiochim. Acta **16**, 4 (1971).
1969De35: P. del Marmol, Nucl. Data Tables A**6**, 141 (1969).
1969ScZY: H.D. Schussler, H. Ahrens, *et al.*, 2nd Symp. Phys. Chem. of Fission, Vienna, At. Energy Agency, Vienna, p.591 (1969); IAEA/SM-122/22.
1967Ga19: H. Gauvin, L. Sauvage, J. Inorg. Nucl. Chem. **29**, 2839 (1967).
1966Si09: M.D. Silbert, R.H. Tomlinson, Radiochim. Acta **5**, 223 (1966).
1964Ar24: P.M. Aron, *et al.*, Sovt. J. At. Energy **16**, 447 (1964).
1959Pe28: G.J. Perlow, A.F. Stehney, Phys. Rev. **113**, 1269 (1959); also 1957Pe19, 1958Pe18.
1957PE19: G.J. Perlow, A.F. Stehney, Phys. Rev. **107**, 776 (1957).
1958PE18: G.J. Perlow, A.F. Stehney, Bull. Am. Phys. Soc. **3**, No.1, 6, A4 (1958).

Table 8: Compiled data for Rb-94

Reference	Half-life (s)	%P(n)	Method	Comments
2011GO37*		**10.28(31)***	**n- β**	Penning Trap beam separator
1993Ru01*	**2.711(14)**	**10.9(7)***	**n- β**	
1986Ok07*	**-**	**9.73(62)***	**n- γ**	
1985Gr15				n-spectra
1981En05*	**2.76(6)**	**11.1(9)***	**n- β**	
1980Re03				n-spectra
1980Lu04	2.69(2)	10.1(6)	n- β	Same group as 1993Ru01
1980ReZQ*	**2.83(3)**	**10.1(10)***	**ion**	11.5(12) from beta counting
1979Ri09*	**2.73(2)**	**9.7(5)***	**n- β**	
1977Ru09				n-spectra
1977RE05	2.73(1)	13.7(10)	Ion,n	1993Ru01 list 10.0(1). 1984Ma39 list 10.1(2)
1974Ro15	2.755(80)	8.46(92)	n- β	Original value 8.46(92) Updated by 1981Bj01 for Li-9 new P(n). 1984Ma39 update to 11.8(13). 1993Ru01 do not adjust
1974Gr29	2.78(5)			B counting
1972Sc48	-	10.3(16)	fiss	Original value 11.0(20) updated by 1993Ru01 (previously updated to 9.8(16) by 1984Ma39)
1972Am01	2.8(1)			B counting
1969Am01*	**-**	**11.1(11)***	**ion**	**Source from fission followed by mass separation**
1967Am01	2.67(4)			Weighted ave. of b and n counting
1961Fr03	2.9(3)			From 1974Gr29

*: value used to calculate the weighted average

Weighted Average = 10.24 (21) %, reduced χ^2=0.72.

1993Ru01: recommended value= 10.01 (23) %. 2002Pf04: 9.1 (11) %

Comments:

2011GO37: M.B. Gomez Hornillos, J. Rissanen, J.L. Tain, *et al.*, J. Phys. Conf. Ser. **312**, 052008 (2011).

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

1993Ru01: G. Rudstam, *et al.*, At. Data Nucl. Data Tables **53**, 1 (1993) Compilation.

1986OK07: K. Okano, *et al.,* Ann. Nucl. Energy **13**, 467 (1986).

1985GR15: R.C. Greenwood, A.J. Caffrey, Nucl. Sci. Eng. **91**, 305 (1985) Neutron spectra.

1984MA39: F.M. Mann, *et al.*, Nucl. Sci. Eng. **87**, 418 (1984) Compilation.

1981En05: G. Engler, E. Neeman, Nucl. Phys. A**367**, 29 (1981).

1981Bj01: T. Bjornstad, H.A. Gustafsson, *et al.*, Nucl. Phys. A**359**, 1 (1981).

1980Re03: P.L. Reeder, *et al.*, Nucl. Sci. Eng. **75**, 140 (1980) Neutron spectra.
1980Lu04: E. Lund, *et al.*, Z. Phys. A**294**, 233 (1980).
1980ReZQ: P.L. Reeder, *et al.*, PNL-SA-8766 (1980).
1979Ri09: C. Ristori, *et al.*, Z. Phys. A**290**, 311 (1979).
1977RE05: P.L. Reeder, *et al*, Phys. Rev. C**15**, 2108 (1977).
1977RU09: G. Rudstam, E. Lund, Nucl. Sci. Eng. **64**, 749 (1977) Neutron spectra.
1977RE06: P.L. Reeder, *et al.*, Phys. Rev. C**15**, 2098 (1977) Average neutron energy.
1975As04: M. Asghar, *et al.*, Nucl. Phys. A**247**, 359 (1975).
1974Ro15: E. Roeckl, *et al.*, Nucl.Phys. A**222**, 621 (1974).
1974GR29: B. Grapengiesser, *et al.*, J. Inorg. Nucl. Chem. **36**, 2409 (1974) Half-life.
1972Sc48: H.-D. Schussler, G. Herrmann, Radiochim. Acta **18**, 123 (1972).
1972Am01: S. Amiel, *et al.*, Phys. Rev. C**5**, 270 (1972) Half-life.
1969Am01: I. Amarel, *et al.*, J. Inorg. Nucl. Chem. **31**, 577 (1969) Half-life.
1967Am01: I. Amarel, *et al.*, Phys. Letters **24**B, 402 (1967) Half-life.
1961Fr03: K. Fritze, *et al.*, Can. J. Chem. 39, 675 (1961) Half-life.

Table 9: Compiled data for Rb-95

Reference	Half-life (s)	%P(n)	Method	Comments
1993Ru01*	**0.379(2)**	**9.7(4) ***	**n- β**	
1986Ok07*		**8.60(57) ***	**n- γ**	
1986ReZR*	**0.377(1)**	**9.0(11) ***	**n- β coin**	Supercedes REE-85
1985Gr15				n-spectra
1981En05*	**0.40(1)**	**8.2(8) ***	**n- β**	
1980Re03				n-spectra
1980Lu04	0.38(1)	8.9(6)	n- β	Same group as 1993Ru01
1980ReZQ	0.377(4)	8.7(9)	ion	9.5(10) from beta counting
1979Ri09*	**0.377(6)**	**8.6(5) ***	**n- β**	
1977Ru09				n-spectra
1977RE05	0.369(5)	11.0(8)	Ion, n	1993Ru01 list 8.2(6), 8.7(9). 1984Ma39 list 8.2(6), 8.71(9)
1974Ro15		12.2(13)	n- β	Original value 8.54(91) Updated by 1981Bj01 for Li-9 new P(n). 1984Ma39 update to 12.0(13). 1993Ru01 do not adjust
1969Am01*		**7.10(93) ***	**ion**	
1967Am01	0.36(2)			Weighted ave. of b and n counting

*: value used to calculate the weighted average

Weighted Average = 8.87 (29) %, reduced χ^2=1.5.

1993Ru01: recommended value= 8.73 (20) %. 2002Pf04: 8.73 (31) %

Comments:

2002Pf04: B. Pfeiffer, K. Kratz, P. Moller, Prog. Nucl. Energy **41**, 39 (2002).
1993Ru01: G. Rudstam, *et al.*, At. Data Nucl.Data Tables **53**, 1 (1993) Compilation.
1986OK07: K. Okano, *et al.,* Ann. Nucl. Energy **13**, 467 (1986).
1986ReZR: P.L. Reeder, *et al.*, PNL-SA-14026 (1986).
REE85: P.L. Reeder, *et al.*, Proc. Am. Soc. Nucl. Chem. Meeting, Chicago, 1985, p. 171 (1985).
1985GR15: R.C. Greenwood, A.J. Caffrey, Nucl. Sci. Eng. **91**, 305 (1985) Neutron spectra.
1984MA39: F.M. Mann, *et al.*, Nucl. Sci. Eng. **87**, 418 (1984) Compilation.
1981EN05: G. Engler, E. Neeman, Nucl. Phys. A**367**, 29 (1981).
1981Bj01: T. Bjornstad *et al.*, Nucl. Phys. A**359**, 1 (1981).
1980Re03: P.L. Reeder, *et al.*, Nucl. Sci. Eng. **75**, 140 (1980) Neutron spectra.
1980Lu04: E. Lund, *et al.*, Z. Phys. A**294**, 233 (1980).
1980ReZQ: P.L. Reeder, *et al.*, PNL-SA-8766 (1980).
1979Ri09: C. Ristori, *et al.*, Z. Phys. A**290**, 311 (1979).
1977RU09: G. Rudstam, E. Lund, Nucl. Sci. Eng. **64**, 749 (1977) Neutron spectra.
1977RE05: P.L. Reeder, *et al.*, Phys. Rev. C**15**, 2108 (1977).
1977RE06: P.L. Reeder, *et al.*, Phys. Rev. C**15**, 2098 (1977) Average neutron energy.
1975As04: M. Asghar, *et al.*, Nucl. Phys. A**247**, 359 (1975).
1974Ro15: E. Roeckl, *et al.*, Nucl. Phys. A**222**, 621 (1974).
1972Am01: S. Amiel, *et al.*, Phys. Rev. C**5**, 270 (1972) Half-life.
1969Am01: I. Amarel, *et al.*, J. Inorg. Nucl. Chem. **31**, 577 (1969).
1967Am01: I. Amarel, *et al.*, Phys. Letters **24**B, 402 (1967) Half-life.
1961Fr03: K. Fritze, *et al.*, Can. J. Chem. **39**, 675 (1961) Half-life Upper limit (2.5 s)

Miscellaneous:

1982KR07: K.-L. Kratz, *et al.*, Z. Phys. A**305**, 93 (1982) n/g 0+ states.
1983KR11: K.-L. Kratz, *et al*, Z. Phys. A**312**, 43 (1983) b/g neutron spectra, partial Pn.
1982KR11: K.-L. Kratz, *et al*, Z. Phys. A**306**, 239 (1982) n/g neutron spectra, partial Pn.
1991LEZT: B. Leist-Horner, Thesis, University of Mainz (1991).

Table 10: Compiled data for I-137

Reference	Half-life (s)	%P(n)	Method	Comments
2010MaZS		~6.9	n	Preliminary result
1993Ru01*	**24.13(12)**	**7.46(30)**	**n, β-**	
1980ReZQ*		**7.6(8)**	**ion counting**	**Also 1977Re05, P(n)=8.5(9)**
1980Lu04	24.3	6.7(4)	n, β-	Same group as 1993Ru01
1978Kr15		6.1(5)	fission	Also 1974Kr21
1975As03*	**24.8(2)**	**6.1(8)**	**n, β-**	
1974Gr29	23.99(22, 24.57(11)		n	Same group as 1993Ru01
1972Sc48	24.3(8)	6.6(8)	fission	Adjusted in 1993Ru01 from 5.2(7). Also 1969ScZY
1971De35*	**24.7(2)**	**8.6(12)**	**gamma,Xe-137**	
1964Ar24	24	3.0(5)	n, β-	Outlier: Chauvenet`s criterion
1959Pe28	24.4(4)		fission	

*: value used to calculate the weighted average

Weighted Average = 7.33 (38) %, reduced χ^2=1.2. Uncertainty of 0.30 in 1993Ru01 increased to 0.45 to limit weight to 56%.

Recommended values in 1993Ru01: 7.14 (23) %; 2002Pf04: 7.02 (54) %

Comments:

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

2010MaZS: L. Mathieu, *et al.*, Proc. 4th. Int. Workshop Nucl. Fission and Fission-Product Spectrosc., Cadarache, France, 13-16 October 2009, p.285 (2010); AIP Conf. Proc. 1175 (2010).

1997Gr20: R.C. Greenwood, K.D. Watts, Nucl. Sci. Eng. **126**, 324 (1997): neutron spectrum.

1993Ru01: G. Rudstam, *et al.*, At. Data Nucl. Data Tables **53**, 1 (1993).

1991AlZZ: G.D. Alkhazov, *et al.*, Program and Thesis, Proc. 41st Ann. Conf. Nucl. Spectrosc. Struct. At. Nuclei, Minsk, p.212 (1991).

1980ReZQ: P.L. Reeder and R.A. Warner, PNL-SA-8766 (1980); also 1977Re05: Phys. Rev. C**15**, 2108 (1977).

1980Lu04: E. Lund, *et al.*, Z. Physik A**294**, 233 (1980).

1980Oh04: H. Ohm, *et al.*, Z. Physik A**296**, 23 (1980): neutron spectrum.

1979Kr03: K.L. Kratz, *et al.*, Nucl. Phys. A**317**, 335 (1979): neutron spectrum.

1978Kr15: K.L. Kratz, Radiochim. Acta **25**, 1 (1978); also 1974Kr21.

1977Sh01: S. Shalev, G. Rudstam, Nucl. Phys. A **275**, 76 (1977); neutron spectrum.

1977Fr19: H. Franz, W. Rudolph, H. Ohm, Nucl. Instrum. Methods **144**, 253 (1977): neutron spectrum.

1977Re05: P.L. Reeder, *et al.*, Phys. Rev. C**15**, 2108 (1977).

1976Lu02: E. Lund, G. Rudstam, Phys. Rev. C**13**, 1544 (1976).

1975As03: M. Asghar, *et al*, Nucl. Phys. A **247**, 359 (1975).

1974Kr21: K.L. Kratz and G. Herrmann, Nucl. Phys. A**229**, 179 (1974).

1974Gr29: Grapengiesser, *et al.*, J. Inorg. Nucl. Chem. **36**, 2409 (1974): half-life.

1974Sh18: S. Shalev, G. Rudstam, Nucl. Phys. A**230**, 153 (1974): neutron spectrum.

1974NoZR: J.H. Norman, Thesis Iowa State (1974): neutron spectrum.
1972Sc48: H.D. Schussler, G. Herrmann, Radiochim. Acta **18**, 123 (1978).
1971De35: P. del Marmol, P. Fettweis, D.C. Perricos, Radiochim. Acta **16**, 4 (1971).
1969ScZY: H.D. Schussler, H. Ahrens, *et al.*, 2nd Symp. Phys. Chem. of Fission, Vienna, At. Energy Agency, Vienna, p.591 (1969); IAEA/SM-122/22.
1964Ar24: P.M. Aron, *et al.*, Sovt. J. At. Energy **16**, 447 (1964).
1959Pe28: G.J. Perlow, A.F. Stehney, Phys. Rev. **113**, 1269 (1959).

Table 11: Compiled data for I-138

Reference	Half-life (s)	%P(n)	Method	Comments
2011GO37*		**5.32(20)***		Penning Trap beam separator
2010MaZS		~5.4	n	Preliminary result
1993Ru01*	**6.233(31)**	**5.56(22)***	**n, β-**	**Also 1976Lu02**
1980ReZQ		5.1(30)	ion counting	Also 1977Re05, P(n)=6.0(35)
1980Lu04	6.5	5.5(4)	n, β-	Same group as 1993Ru01
1978Kr15	6.21(20)	4.5(9)	fission	Also 1974Kr21
1975As03	6.5(2)	2.58(22)	n, β-	
1974Gr29	6.44(26), 7.03(26)		n	Same group as 1993Ru01
1972Sc48		4.5(10)	fission	Adjusted in 1993Ru01 from 3.0(8). Also 1969ScZY
1964Ar24	6.3	2.0(5)	n, β-	
1959Pe28	6.3(7)	2.0(5)	fission	Adjusted in 1969De35

*: value used to calculate the weighted average

The discrepant data: 2.58 (22) % in 1975As03 and 2.0(5) % in 1964Ar24 were not included in averaging.

LWM weighted average= 5.43 (20) % where the uncertainty of 0.15 given by the LWM was increased to the lowest value of the dataset: 0.20, reduced χ^2=0.65

CAUTION IF USED AS STANDARD: ONLY TWO INDEPENDENT MEASUREMENTS

Comments:

2011GO37: M.B. Gomez Hornillos, J. Rissanen, J.L. Tain, *et al.*, J. Phys. Conf. Ser. **312**, 052008 (2011).

2010MaZS: L. Mathieu, *et al.*, Proc. 4th. Int. Workshop Nuclear Fission and Fission-Product Spectr., Cadarache, France, 13-16 October 2009, p.285 (2010); AIP Conf. Proc. 1175 (2010).

1997Gr20: R.C. Greenwood, K.D. Watts, Nucl. Sci. Eng. **126**, 324 (1997): neutron spectrum.

1993Ru01: G. Rudstam, *et al.*, At. Data Nucl. Data Tables **53**, 1 (1993).

1980ReZQ: P.L. Reeder, R.A. Warner, PNL-SA-8766 (1980); also 1977Re05: Phys. Rev. C**15**, 2108 (1977).

1980Lu04: E. Lund, *et al.*, Z. Physik A**294**, 233 (1980).

1978Kr15: K.L. Kratz, Radiochim. Acta **25**, 1 (1978); also 1974Kr21.

1977Sh01: S. Shalev, G. Rudstam., Nucl. Phys. A**275**, 76 (1977); neutron spectrum; also 1972Sh03.

1977Re05: P.L. Reeder, *et al.*, Phys. Rev. C**15**, 2108 (1977).

1976Lu02: E. Lund, G. Rudstam, Phys. Rev. C**13**, 1544 (1976).

1975As03: M. Asghar, *et al*, Nucl. Phys. A **247**, 359 (1975).

1974Kr21: K.L. Kratz, G. Herrmann, Nucl. Phys. A**229**, 179 (1974).

1974Gr29: Grapengiesser, *et al.*, J. Inorg. Nucl. Chem. **36**, 2409 (1974): half-life.

1974NoZR: J.H. Norman, Thesis Iowa State (1974): neutron spectrum.

1972Sc48: H.D. Schussler, G. Herrmann, Radiochim. Acta **18**, 123 (1978).

1969ScZY: H.D. Schussler, H. Ahrens, *et al.*, 2nd Symp. Phys. Chem. of Fission, Vienna, At. Energy Agency, Vienna, p.591 (1969); IAEA/SM-122/22.

1969De35: P. del Marmol, Nucl. Data Tables A6, 141 (1969).

1964Ar24: P.M. Aron, *et al.*, Sovt. J. At. Energy **16**, 447 (1964).

1959Pe28: G.J. Perlow, A.F. Stehney, Phys. Rev. **113**, 1269 (1959).

5.2. Methods for beta-delayed neutron measurements

Notation

Precursor (^{A}Z): **M**, mother

β-decay daughter ($^{A}Z+1$): **I**, intermediate

β-delayed neutron-daughter ($^{A-1}Z+1$): **F**, final nucleus (**F1** for β1n, **F2** for β2n)

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

There are several ways to determine the amount of mother nuclei (starting activity) and then the β-delayed neutron branch of the final nucleus. Note that the correction for background or contaminations is not considered here, and the number of decays counted has to be corrected properly.

In the compilation of Rudstam [1] the following methods to determine β-delayed neutron emission probabilities were distinguished:

1. "n/β": Neutron-beta coincidences. Beta efficiency not required. Neutron efficiency is determined in absolute terms:

   $$P_n = 1/\varepsilon_n * N_{\beta n}/N_\beta$$

2. "n-β": Neutrons and betas counted separately (no coincidences) but simultaneously.

   $$P_n = \varepsilon_\beta/\varepsilon_n * N_n/N_\beta$$

3. "γ $^{A}Z+n$": Abundance of precursor determined via gamma-counting of any β-decay daughter.

   Absolute γ-intensities needed. The neutron fraction is first determined with a neutron detector, then the γ-activity of the longer-lived daughter is measured in a dedicated separated γ-decay station. This method is only applicable if the half-life of the respective measured β-decay daughter $^{A}Z+n$ is sufficiently long compared to the half-life of the mother ^{A}Z to avoid too much decay corrections: $t_{1/2}(^{A}Z+n) \sim 10 * t_{1/2}(M)$

   $$P_n = (\varepsilon_\gamma * I_{abs,\gamma}(^{A}Z+n)/ N_\gamma(^{A}Z+n)) * (N_n/\varepsilon_n)$$

4. "P_n ^{A}Z": Normalization of the ratio $\varepsilon_\beta/\varepsilon_n$ with known P_n value from precursor ^{A}Z Ratio $\varepsilon_\beta/\varepsilon_n$ is obtained from known precursor/ standard (see 2., n-β method) and used to normalized to the unknown isotope. Spectral shapes of neutrons and betas are in this method assumed to be the similar for efficiency considerations.

   $$P_n = P_n(\text{standard}) * (N_\beta(\text{standard})/N_n(\text{standard})) * N_n/N_\beta$$

5. "ion": Ion counting

   Counting of number of precursor M (N_{ion}). The amount of neutron decays is determined with any suitable method, and the P_n value deduced from this.

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

6. "fiss": Fission yields

   Updated yields from Wahl 1988 (Y_A) [2] and using the charge fraction P_Z. Newer fission yields $Y_{A,Z}$ available (ENDF/B-VII.0 and JEFF 3.1) which do not

need any charge fraction. This method used chemical separation methods and is probably the least reliable method.

$$P_n = 1/\varepsilon_n * N_n/(Y_A * P_Z) \text{ or } P_n = 1/\varepsilon_n * N_n/Y_{A,Z}$$

7. The method labeled wrongly by Rudstam with "n-γ" seems to be a pure γ-counting technique, which we would label as "γ–γ". It relies on measuring gammas to determine both, the number of mother nuclei and the number of neutron decays.
8. "γ-γ": Number of neutron decays determined only via γ-counting. Total counting of all γ-rays emitted by daughter and/or βn-daughter, but no counting of neutrons is carried out. Absolute γ-intensities are required, that means a complete knowledge the decay scheme including β's going to the ground state or eventually competing γ-decays from levels above the neutron separation energy.

$$P_n = (\varepsilon_{\gamma,daughter} * I_{abs,daughter,\gamma}/N_{daughter,\gamma}) / (\varepsilon_{\gamma,final} * I_{abs,final,\gamma}/N_{final,\gamma})$$

All experimental methods can be improved nowadays with:

- better production methods (pure isotopic beams using either Penning traps or laser-ionization sources),
- identification of implanted species which allow a better separation of contaminants (as with Fragment Separator FRS at GSI Helmholtzzentrum für Schwerionenforschung in Darmstadt or the Holifield Radioactive Beam Facility HRIBF at Oak Ridge National Laboratory or the ISAC facilities at TRIUMF in Vancouver),
- the use of modern digital data acquisition systems that allow event-by-event signal discrimination, flexible time correlations and minimum dead times.

References

[1] G. Rudstam, K. Aleklett, L. Sihver, Delayed Neutron Branching Ratios of Precursors in the Fission Product Region, At. Data Nucl. Data Tables **53** (1993) 1.
[2] A.C. Wahl, At. Data Nucl. Data Tables **39** (1988) 1.

5.3. Evaluators Guidelines

The evaluators will have to consider the following:

a) Compilation of existing data

The existing data should be compiled in a suitable database. XUNDL is one clear possibility.

b) Assessment of the measurement method

Each of the methods mentioned in section 2 should be assessed to determine strengths and weaknesses and, in particular, potential sources of systematic errors and uncertainties:

- The "n/β" method seems to be the best method. Only one absolute efficiency is needed, namely for the neutron detector. This efficiency is dependent on the neutron energy and it has to be determined with the help of a Monte Carlo code like MCNP. It would be the major source of systematic uncertainty. Still, the true signal has to be separated from contaminants using the decay curves, for which the proper knowledge of the different half-lives ($T_{1/2}$) is needed.

- The "n-β" method needs two efficiencies, one for neutron detection to which all the comments in 5.2.1 apply, and the other for the detection of β–particles. The detection of these particles has its own problems like potential sources of background as conversion electrons. However, this method could be advantageous in cases were the detectors cover a solid angle close to 4π.
- The "γ ^{A}Z+n" method uses neutron and gamma-ray detection, all comments in 5.2.1. apply to the neutron part. The gamma efficiency is usually known with sufficient accuracy, but the absolute gamma intensity (from ENSDF, DDEP or another library) is needed, there could be an extra uncertainty associated with this.
- The "P_n ^{A}Z" method is similar to 5.2.2, but the Ratio $\varepsilon_\beta/\varepsilon_n$ is obtained from comparison with a known precursor/standard to be measured in the same experiment that is $\varepsilon_\beta/\varepsilon_n = P_n(\text{standard})^* (N_\beta(\text{standard})/N_n(\text{standard})$ where P_n(standard) is already known and N_β(standard) and N_n(standard) are measured. Sometimes this is better than the individual determination of ε_β and ε_n but as the efficiencies are energy-dependent the method relies on the assumption that the β and the neutron spectra are similar for the unknown nuclei and for the standard.
- The "ion" method relies on direct ion-counting. It seems a very good method for the new experiments where new equipment and better identification and counting techniques are applied. In the older experiments perhaps only the ion current was measured and the number and identity of ions derived through a series of assumptions.
- The "fiss" method presents the same problems and comments as 5.2.5. For the older experimental data, the lack of separation of the different isotopes and the presence of contaminants makes it less reliable. The older data were normalized to older fission yields (mass number) and the charge-fraction was calculated. Nowadays the new fission yields are mass and charge dependent and more precise. If the only available data were taken by means of this method, the renormalization to the new fission yield standards would be advisable.

c) Recommended (evaluated) data

After a careful consideration of the experimental data the evaluator should:

- Evaluate the uncertainty of the data. Is the author's estimation realistic? Are there systematic errors or uncertainties that were not considered? There are very few cases where a P_n can be determined with accuracy better than 5%.
- Evaluated value. The evaluator has to consider the different options to produce an evaluated value. To recommend the newest values is not necessarily a good option. Different statistical methods of varying degrees of complexity (ranging from weighted averages to bootstrap techniques) have to be considered. For a full review and application of those methods see [1].
- Correlation of P_n and $T_{1/2}$. According to the method used, the value of P_n may be dependent on the adopted value for $T_{1/2}$ their correlation or covariance has to be considered.

d) Compilation of recommended data

When the evaluation is completed, the results have to be documented and compiled, preferably in an ENSDF file. It is recommended that this is done first for the proposed Standards of Table 1.

References

[1] J. Chen, *et al.*, App. Rad. Isot. **69** (2011) 1064.

5.4. Availability of Experimental Data (including Neutron Spectra)

The available experimental data should be compiled into a database.

5.5. Format of database

A possible format for the database is the ENSDF format. The inclusion of neutron spectra in the format will be explored.

5.6. Inclusion of delayed neutron data – EXFOR, JEFF, ENDF/B, ENSDF

5.6.1. EXFOR

Delayed Neutron Data in the EXFOR Database

Regarding the characteristics of the delayed neutrons emitted from the fission products, a survey in EXFOR database shows that total average delayed fission neutron yields (nu-bar) are extensively compiled. Several energy spectra for specific delayed neutron groups are available in EXFOR as well. However, data for delayed-neutron emission probabilities (P_n values) and delayed neutron spectra for individual fission product precursors are rather scarce. This is to a certain extent due to the fact that those data are on the border between reaction data and decay data, and were not considered for the EXFOR compilation with a high priority in the past.

Presently, the (β^-,n) branching fractions (P_n values) and emission spectra for delayed fission neutrons are considered within the scope of EXFOR database, and corresponding compilation formats are provided in the EXFOR manuals. In order to respond to the need to include delayed neutron data in a database, the current situation will be assessed at IAEA NDS (number of articles, other available resources, e.g. XUNDL), and a Memo prepared in order to inform the NRDC community (i.e. EXFOR compilers) about this request and the results of the assessment for discussion. A list of relevant articles (17 for the delayed-neutron energy spectra and 34 for the P_n values, see Tables 12 and 13 below) identified in relation with the Consultants' Meeting will be included in this NRDC Memo. The references have been selected from M.C. Brady, Ph.D. thesis (Texas A&M, 1989), LA-11534-T, B. Pfeiffer, K.L. Kratz and P. Moller, Prog. Nucl. Energy 41, 39 (2002), and from the presentations of the meeting. The existing entries will be revised in order to ensure consistency in coding in the EXFOR database.

The ZVView retrieval system will be improved to facilitate the search, and visualization of the delayed neutron spectra and emission probabilities will be provided.

Table 12. Measurements of Delayed Neutron Spectra

Author	Reference	Laboratory
Rudstam+	J,NSE,80,238,1982	2SWDSWR
Rudstam+	J,NSE,64,749,1977	2SWDSWR
Kratz+	J,NP,317,335,1979	2GERMNZ
Franz+	J,PRL,333,859,1974	2GERMNZ
Shalev+	J,NP/A,230,153,`974	2SWDSWR
Kratz+	R,INDC(NDS)-107/G,103,1979	2GERMNZ
Batchelor+	J,JNE,3,7,1956	2SWDSWR

Table 12. Measurements of Delayed Neutron Spectra

Rudstam+	J,NIM,120,333,1974	2SWDSWR
Rudstam+	J,NP/A,235,397,1974	2SWDSWR
Shalev+	J,NP/A, 275,76,1977	2SWDSWR

Table 12. cont'd

Greenwood+	J,NSE,91,305,1985	1USABNL
Greenwood+	J,NSE,126,324,1997	1USABNL
Kratz+	J,ZPA,312,33,1983	2GERMNZ
Reeder+	J,NSE,75,140,1980	1USABNW
Franz+	J,NIM,144,253,1977	2GERMNZ
Shalev+	J,PRL,28,697,1972	2SWDSWR
Ohm+	J,NP/A,274,45,1976	2GERMNZ

Table 13. Measurements of Delayed Neutron Emission Probabilities

Author	**Reference**	**Laboratory**
Asghar+	J,JIN,37,1563,1975	2FR GRE
Tomlinson+	J,JIN,30,1649,1968	2UK HAR
Tomlinson+	J,JIN,30,1125,1968	2UK HAR
Tomlinson+	J,JIN,33,3609,1971	2UK HAR
Asghar+	J,NP/A,247,359,1975	2FR GRE
Crancon+	J,ZP/A,287,45,1978	2FR GRE
Kratz+	J,JIN,32,3713,1970	2GERMNZ
Schussler+	J,RCA,18,13,1972	
Kratz+	J,JIN,35,1407,1973	2GERMNZ
Kratz+	J,NP/A,229,179,1974	2GERMNZ
Peuser+	J,ZP/A,289,219,1979	2GERMNZ
del Marmol+	J,JIN,32,705,1970	2BLGMOL
del Marmol+	J,RA,16,4,1971	2BLGMOL
Amarel+	J,JIN,31,577,1969	2FR PAR
Roeckl+	J,NP/A,222,621,1974	2ZZZCER
Lund+	J,ZP/A,294,233,1980	2SWDSWR
Aleklett+	J,ZP./A,295,331,1980	2SWDSWR
Ristori+	J,ZP/A,290,311,1979	
Gabelmann+	J,ZPA,308,359,1982	2GERMNZ
Aron+	J,SNP,16,447,1964	
Engler+	J,NP/A,367,29,1981	3ISLSOR
Reeder+	J,PR/C,15,2108,1977	1USABNW
Reeder+	PNL report PNL-SA-8766 (1980)	1USABNW
Reeder+	PNL report PNL-SA-11,100,1983	1USABNW
Reeder+	J,PR/C,31,1029,1985	1USABNW
Reeder+	Proc. Specialists Mtg. on Delay Neutrons, Birmingham, England (1986)	1USABNW
Talbert+	J,PR,177,1805,1969	1USASUI
Ameil+	J,EPJ/A,1,275,1998	2GERGSI
Bernas+	J,NP/A,630,41c,1998	2GERGSI
Doerfler+	J,PR/C,54,2894,1996	2FR GAN
Fedoseyev+	J,Z. PHYS./A,353,9,1995	2ZZZCER
Franchoo+	J,PRL,81,3100,1998	2BLGLVN
Hannawald+	J,PR/C,62,054301,2000	2ZZZCER
Korgul+	J,EPJ/A,3,167,200	2SWDSWR
Kratz+	AIP Conf. Proc., 529,295,2000	2GERMNZ
Mehren+	J,PRL,77,458,1996	2SF JUV

Author	Reference	Laboratory
Mueller+	J,PR/C,61,054308,2000	2BLGLVN
Shergur+	J,NP/A,…..2000	2ZZZCER
Solin+	J,PR/C,47,2941,1993	2FR GAN
Wang+	J,PL/B,454,1,1999	2SF JYV
Weissmann	J, PR/C,59,2004,1999	2BLGLVN

Laboratory codes:

1USABNL – USA, Brookhaven National Laboratory, Upton, NY
1USABNW – USA, Pacific Northwest Laboratories, Richland, WA
1USASUI – USA, Iowa State University, Ames, IA
2BLGLVN – Belgium, Catholic Univ. of Louvain, Louvain-la-Neuve
2BLGMOL – Belgium SCK-C.E.N., Mol
2FR GAN – France, Grand Accelerateur National d'Ions Lourds, Caen
2FR GRE – France, Universite Joseph Fourier, Grenoble
2GERMNZ - Germany, Univ. of Mainz
2SF JYV - Finland - Jyvaeskylae, University
2SWDSWR - Sweden, Studsvik Science Research Laboratory
2UK HAR – UK AERE, Harwell, Berks
2ZZZCER – Switzerland, CERN, Geneva

Journal codes:

J,EPJ/A – European Physical Journal
J,JIN - Journal of Inorganic and Nuclear Chemistry
J,JNE - Journal of Nuclear Energy
J,NIM Nuclear Instruments and Methods
J,NP- Nuclear Physics
J,NP/A - Nuclear Physics, Section A
J,NSE – Nuclear Science and Engineering
J,PL/B - Physics Letters, Section B
J,PR – Physical Review
J,PR/C - Physical Review, Part C
J,PRL – Physical Review Letters
J,RCA – Radiochimica Acta
J,SNP– Soviet Journal of Nuclear Physics
J,ZP/ A – Zeitschrift fuer Physik A, Hadrons and Nuclei
R,INDC(NDS)-International Nuclear Data Reports (Nuclear Data Section)
R,PNL report - Pacific Northwest Laboratory report

Examples of Delayed Neutron Data in the EXFOR Database

Examples of delayed neutron data (see below) which are currently included in the EXFOR database were shown. It appears that some data exist, but the coding of these data needs to be verified; in particular the units specified in the DATA tables.

Earlier entries have been coded in a rather non-standard way, probably prior to the addition of specific delayed neutron coding capabilities, e.g. EXFOR entry 21058, see below under c) P_n values (2nd example).

Currently no individual precursor spectral data are included in the EXFOR database

as this was seen as outside the scope of the database; however the database has the capability to store such data. If the community considers it appropriate, these data could be added over time. The correction of exiting entries will also be undertaken.

An example was also given of how spectral data can be plotted through the online tool at the IAEA. For details see the presentation at http://www-nds.iaea.org/beta-delayed-neutron/.
A draft entry (from the work of Greenwood and Caffrey, Nucl. Sci. Eng. **91** (1985) 305) was prepared in order to demonstrate how such data would be stored in the EXFOR database. This entry (labelled as 77777.txt) is available from the meeting webpage http://www-nds.iaea.org/beta-delayed-neutron/.

Examples of delayed neutron REACTION coding in EXFOR:

a) Nubar (total delayed neutron yield)

```
REACTION (92-U-235(N,F),DL,NU)

ENTRY       12856
SUBENT      12856001
INSTITUTE   (1USABNW)
REFERENCE   (J,PR/C,28,1740,8310)
AUTHOR      P.L.REEDER,R.A.WARNER)
TITLE       DELAYED NEUTRON PRECURSORS AT MASSES
            97-99 AND 146-148
```

b) Nubar (delayed neutron yield) for individual precursors

```
REACTION (92-U-235(N,F)ELEM/MASS,DL,NU,,MXW)

ENTRY       20879
SUBENT      20879001
INSTITUTE   (2GERMNZ)
REFERENCE   (J,JIN,39,753,77)
AUTHOR      (W.RUDOLPH,K.L.KRATZ,G.HERRMANN)
TITLE       HALF-LIVES, FISSION YIELDS AND NEUTRON EMISSION
            PROBABILITIES OF NEUTRON RICH ANTIMONY ISOTOPES
```

with the individual precursors specified in the DATA table by their charge (ELEM) and mass (MASS) numbers.

c) P_n values (delayed neutron emission probability, i.e. branching fraction)

```
REACTION (ELEM/MASS(0,B-),,PN)[Note proposal below to include DL]

ENTRY       12946
SUBENT      12946001
INSTITUTE   (1USABNW)
REFERENCE   (C,85SANTA,,(DB01),8505)
AUTHOR      (R.A.WARNER,P.L.REEDER)
TITLE       DELAYED NEUTRON DATA FROM TRISTAN
```

with the individual precursors specified in the DATA table by their charge (ELEM) and mass (MASS) numbers as in the previous example.

PROPOSAL: In order to help users find delayed neutron data more easily and consistently, it is proposed that the DL code will be added into the REACTION string above, to give:

```
REACTION (ELEM/MASS(0,B-),DL,PN)
```

The example below also refers to P_n values, but with a different REACTION coding. Possibly this ENTRY was entered into the EXFOR database prior to the introduction of specific delayed neutron coding capabilities.

```
REACTION((92-U-235(N,F)ELEM/MASS,DL,NU,,MXW)/
         (92-U-235(N,F)ELEM/MASS,IND,FY,,MXW))

ENTRY       21058
SUBENT      21058001
INSTITUTE   (2GERMNZ)
REFERENCE   (J,RCA,25,1,78)
AUTHOR      (K.L.KRATZ)
TITLE       INDEPENDENT FISSION YIELDS AND NEUTRON EMISSION
            PROBABILITIES OF SHORT-LIVED HALOGEN ISOTOPES
```

d) Aggregate delayed neutron energy spectra

```
REACTION (90-TH-232(N,F),DL,DE,N,FST)  INCORRECT CODING!

ENTRY       10640
SUBENT      10640001
INSTITUTE   (1USAWAU)
REFERENCE   (J,NSE,62,636,1977)(J,ANS,23,492,197606)
AUTHOR      (G.W.ECCLESTON,G.L.WOODRUFF)
TITLE       Measured Near-Equilibrium Delayed Neutron Spectra
            Produced by Fast-Neutron-Induced Fission of 232Th,
            233U, 235U, 238U, and 239Pu
```

Should be coded as: `(90-TH-232(N,F),DL,NU/DE,,FST)`

e) Aggregate group delayed neutron energy spectra

```
REACTION (90-TH-232(N,F),DL/GRP,NU/DE,,REL,EVAL)

ENTRY       V0017
SUBENT      V0017001
INSTITUTE   (3ISLSOR)
REFERENCE   (J,NSE,62,660,197704)
AUTHOR      (D.Saphir, D.Ilberg, S.Shalev, S.Yiftah)
TITLE       Evaluated delayed neutron spectra in reactor calculations
```

f) Individual precursor delayed neutron energy spectra

Currently there are no such data in EXFOR, but they would be coded as:

```
REACTION (92-U-235(N,F)37-RB-93,DL,NU/DE,,FIS)
```

when identified as coming from a fission reaction, or as:

```
REACTION (37-RB-93(0,B-),DL,NU/DE)
```

when no information concerning the formation of the precursor is available, or it is not from a fission event.

5.6.2. JEFF
See Section 4.3.

5.6.3. ENDF/B
See Section 4.2.

5.6.4. ENSDF
See Section 5.5.

5.7. List of priorities for evaluation and new experiments

Based on the needs of the two communities (reactor physics and nuclear structure/ astrophysics), the priority lists are different. Reactor physics needs aggregate parameters as six-group (Keepin) or eight-group parameters and nu-bar, whereas nuclear astrophysics requires microscopic quantities like half-lives and P_n for individual isotopes. For the astrophysics community, the importance of the priorities will be shifted towards extreme neutron-rich isotopes due to the upcoming radioactive beam facilities. The priorities are likely to be shifted from P_{1n} to P_{2n} (or even P_{3n}).

5.8. Derivation of aggregate quantities

(Six group Keepin parameters and nu-bar) using P_n and $T_{1/2}$ from the proposed library and the fission yields from an existing library (ENDF and JEFF)

5.9. Systematics for precursors with no experimental data based on properties of known isotopes

In M.C. Brady's 1989 thesis, a list of more than 100 isotopes is given for which β-n data were based on statistical model calculations since there were no experimental values available. This situation has not changed much. Discovery of more neutron-rich nuclides at the extremities of the stability line in the last few years adds to this list more isotopes for which experimental β-n data are lacking. Perusal of the ENSDF/NUBASE databases suggests that there are at least 300 isotopes for which no experimental data exist. For these nuclides, at current time, only theoretical values are globally available from Moller-Nix-Kratz theory.

5.10. Improve Theoretical Predictions with help of recommended values

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

In the past, empirical formulas have been proposed to describe the dependence of the P_n values from the total decay energies Q_β and the neutron separation energies S_n. Quite successful in predicting unknown P_n-values is the “Kratz-Herrmann formula” [1], which is still applied today. More sophisticated calculations based on the shell model have been performed by several groups.

a) Möller et al. [2] have calculated ground state decay properties for all particle-stable nuclides with the macroscopic-microscopic QRPA model [3]. This tabulation is applied in many different fields, as, e.g. nuclear astrophysics. A drawback of these calculations is the fact that only the Gamow-Teller (GT) β-decay mode is included. Near magic numbers, e.g., the first-forbidden decay branches can dominate the gross decay properties half-lives and delayed-neutron branching ratios. In Pfeiffer et al. [4], first-forbidden β-strength from the Gross-theory of β-decay [5] was added heuristically to the calculated GT-strength.

b) Borzov [6] calculated β-decay $T_{1/2}$, β-delayed neutron emission probabilities P_n applying the finite range droplet mass model and a continuum QRPA approach based on the self-consistent ground state description in the framework of the nuclear-energy density functional theory. Up till now, the algorithms are restricted to spherical nuclei. They might be applied to isotopes near magic numbers which have only small ground-state deformations.

c) The Neutron and Gamma Decay Code "CGM" (Cascading Gamma and Multiplicity) developed by Kawano [7] is based on the combination of a quasiparticle random-phase approximation for the β-decay (as mentioned in Section a)) and a Hauser-Feshbach statistical model for the γ-decay. This method allows the calculation of not only the gross decay properties $T_{1/2}$ and P_n, but also delayed-neutron energy spectra. In Kawano et al. [8] energy spectra for 271 precursors are calculated and compared with the 36 measured spectra contained in the ENDF decay library. New efforts to measure delayed-neutron energy spectra should be undertaken.

References

[1] K.-L. Kratz, G. Herrmann, Z. Phys. **263** (1973) 435.
[2] P. Möller, J.R. Nix, K.-L. Kratz, At. Data Nucl. Data Tables **66** (1997) 131.
[3] P. Möller, J. Randrup, Nucl. Phys. A **514** (1990) 1.
[4] B. Pfeiffer, K.-L. Kratz, P. Möller, Prog. Nucl. Energy **41** (2002) 39.
[5] K. Takahashi, Prog. Theoret. Physics **47** (1972) 1500.
[6] I.N. Borzov, Nucl. Phys. A **777** (2006) 645.
[7] T. Kawano, S. Holloway, LANL Report LA-CC-11-018.
[8] T. Kawano, P. Möller, W.B. Wilson, Phys. Rev. C **78** (2008) 054601.

5.11. Outcome

Once the CRP is concluded, the resulting document should be published in the Nuclear Data Sheets.

6. Recommendations from this meeting

The CM participants strongly recommend that the IAEA starts a CRP on the subject no later than 2013.

Suggested Objectives:

- To create a reference database of evaluated data for beta-delayed neutron emission.
- The database should contain evaluated half-lives, emission probabilities and neutron spectra for individual precursors.
- The evaluation methodology should be described.
- Aggregate quantities like group values should be derived and stored in the database.
- The CRP should produce a priority list for evaluations and new experiments and well as improvements in the theoretical predictions.

7. List of possible countries and institutions participating in CRP

USA – BNL, LANL, MSU/NSCL, ORNL
CANADA – McMaster U., Triumf, Univ. Guelph
GERMANY – GSI Darmstadt/ Univ. Giessen
SPAIN – IFIC Valencia, CIEMAT Madrid, UPC Barcelona
FRANCE – Orsay, GANIL, LPC Caen, ILL Grenoble
CHINA – Chinese Acad of Sci, Lanzhou
FINLAND – Jyvaskyla (JYFL)
JAPAN – JAEA, RIKEN
RUSSIA – JINR Dubna, IPPE Obninsk
SOUTH KOREA - KAERI
ARGENTINA – CNEA
BRAZIL – U. Sao Paulo
INDIA – VECC, Kolkata

International Atomic Energy Agency

Consultants' Meeting on
"Beta-delayed neutron evaluation"

IAEA Headquarters, Vienna, Austria
10 – 12 October 2011
Meeting Room A2313

Adopted AGENDA

Monday, 10 October

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

09:30 - 10:15 **Opening Session**

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

10:15 - 12:30 **Presentations by participants (about 45 min each)**

1. The importance of beta-delayed neutrons for astrophysics and reactor physics (Dillmann)
2. Need for compilation and evaluation of Beta-delayed neutron probabilities in radioactive decay (Singh)
3. Remarks on problems in the determination of P_n values and compilation/evaluation (Pfeiffer)

Coffee break as needed

12:30 – 14:00 ***Lunch***

14:00 – 17:30 **Presentations by participants (cont'd)**

4. Release of ENDF/B-VII.1 decay data sub-library (Sonzogni)
5. Beta-delayed neutrons in JEFF 3.1.1 (Kellett)
6. On-going and planned beta-delayed neutron measurements with BELEN for astrophysics, nuclear structure and reactor technology (Tain)
7. Overview of the different neutron detectors in use and planned (Cano)
8. Delayed neutron data in EXFOR (Kellett)

Coffee break as needed

Tuesday, 11 October

09:00 - 12:30 Round Table Discussion

- Assessment of need for compilation and evaluation of beta-delayed neutron probabilities over the whole nuclear chart.
- Assessment of need for measurements of beta-delayed neutron probabilities by mass regions.
- Setting up priorities by nuclides/mass region.
- Neutron spectra, neutron/gamma/beta coincidences, impact of P_n values on $\bar{\nu}$.

Coffee break as needed

12:30 – 14:00 Lunch

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

- Scope of the evaluation/measurement project. Evaluation procedures. Timeline of the project.
- Theoretical (model) calculations.
- Responsibilities by data centres and labs.

Coffee break as needed

Wednesday, 12 October

09:00 - 17:00 Round table discussions (cont'd)

Drafting of the summary report

Coffee and lunch break(s) in between

17:00 Closing of the meeting

Consultants' Meeting
"Beta-delayed neutron evaluation"
IAEA Headquarters, Vienna, Austria
10 – 12 October 2011

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Table of P_n values from ENSDF database of June 2011

Retrieved by M. Verpelli (IAEA), June 2011

A Z	Nuclide	N	Energy (keV)	J^{π}	$T_{1/2}$	Decays	
8	He		0	0+	119.1 ms *12*	β-	100
2		6				β- n	16 *1*
9	Li		0	3/2-	178.3 ms *4*	β-	100
3		6				β- n	50.8 *2*
12	Be		0	0+	21.3 ms *1*	β-	100
4		8				β- n	≤ 1
14	Be		0		4.35 ms *17*	β- 2n	5 *2*
4		10				β-	100
						β- n	81 *4*
17	B		0	(3/2-)	5.08 ms *5*	β-	100
5		12				β- n	63 *1*
						β- 2n	11 *7*
						β- 3n	3.5 *7*
						β- 4n	0.4 *3*
16	C		0	0+	0.747 s *8*	β-	100
6		10				β- n	99.0 *3*
17	C		0		193 ms *13*	β-	100
6		11				β- n	32 *3*
18	C		0	(0+)	92 ms *2*	β-	100
6		12				β- n	31.5 *15*
20	C		0		14 ms *+6-5*	β-	100
6		14				β- n	72 *14*
22	C		0	0+	6.1 ms *+14-12*	β-	100
6		16				β- n	61 *+14-13*
						β- 2n	< 37
17	N		0	1/2-	4.173 s *4*	β-	100
7		10				β- n	95.1 *7*
18	N		0	1-	624 ms *12*	β-	100
7		11				β- α	12.2 *6*
						β- n	14.3 *20*
19	N		0		271 ms *8*	β-	100
7		12				β- n	54.6 *14*
20	N		0		130 ms *7*	β-	100
7		13				β- n	57 *3*
21	N		0	(1/2-)	85 ms *7*	β-	100
7		14				β- n	81 *7*
21	N		0	(1/2-) *2*	83 ms *8*	β-	100
7		14				β- n	90.5 *42*

A Z	Nuclide	N	Energy (keV)	J^{π}	$T_{1/2}$	Decays	
22	N		0		24 ms *5*	β-	100
7		15				β- n	36 *5*
						β- 2n	< 13
22	O		0	0+	2.25 s *9*	β-	100
8		14				β- n	< 22
23	O		0	1/2+	82 ms *+45-28*	β-	100
8		15				β- n	31 *7*
24	O		0	0+	65 ms *5*	β-	100
8		16				β- n	58 *12*
22	F		0	(4+)	4.23 s *4*	β-	100
9		13				β- n	< 11
24	F		0	(1,2,3)+	390 ms *70*	β-	100
9		15				β- n	< 5.9
25	F		0	5/2+	80 ms *9*	β-	100
9		16				β- n	23.1 *45*
26	F		0	1+	9.6 ms *8*	β-	100
9		17				β- n	11 *4*
26	F		0	(1+)	9.7 ms *7*	β-	100
9		17				β- n	11 *4*
27	F		0	(5/2+)	5.0 ms *2*	β-	100
9		18				β- n	77 *21*
27	F		0	(5/2+) *2*	5.0 ms *2*	β-	100
9		18				β- n	77 *21*
29	F		0	(5/2+)	2.5 ms *3*	β-	100
9		20				β- n	100 *80*
26	Ne		0	0+	197 ms *1*	β-	100
10		16				β- n	0.13 *3*
27	Ne		0	(3/2+)	32 ms *2*	β-	100
10		17				β- n	2.0 *5*
27	Ne		0	(3/2+) *2*	31.5 ms *13*	β-	100
10		17				β- n	2.0 *5*
28	Ne		0	0+	18.9 ms *4*	β-	100
10		18				β- n	11.9 *7*
						β- 2n	3.6 *5*
29	Ne		0	(3/2+)	14.8 ms *3*	β-	100
10		19				β- n	28 *5*
						β- 2n	4 *1*

A Z	Nuclide	N	Energy (keV)	J^{π}	$T_{1/2}$	Decays	
30	**Ne**		0	0+	7.3 ms *3*	β-	100
10		**20**				β- n	13 *4*
						β- 2n	8.9 *23*
31	**Ne**		0		3.4 ms *8*	β-	100
10		**21**				β- n	?
32	**Ne**		0	0+	3.5 ms *9*	β-	100
10		**22**				β- n	?
27	**Na**		0	5/2+	301 ms *6*	β-	100
11		**16**				β- n	0.13 *4*
27	**Na**		0	5/2+ *2*	301 ms *6*	β-	100
11		**16**				β- n	0.13 *4*
28	**Na**		0	1+	30.5 ms *4*	β-	100
11		**17**				β- n	0.58 *12*
29	**Na**		0	3/2+	44.9 ms *12*	β-	100
11		**18**				β- n	21.5 *30*
30	**Na**		0	2+	48 ms *2*	β- 2n	1.15 *25*
11		**19**				β-	100
						β- α	5.5×10^{-5} *2*
						β- n	30 *4*
31	**Na**		0	3/2(+)	17.0 ms *4*	β-	100
11		**20**				β- n	37 *5*
						β- 2n	0.87 *24*
						β- 3n	< 0.05
32	**Na**		0	(3-,4-)	13.2 ms *4*	β-	100
11		**21**				β- n	24 *7*
						β- 2n	8 *2*
33	**Na**		0	(3/2+)	8.0 ms *3*	β-	100
11		**22**				β- n	47 *6*
						β- 2n	13 *3*
34	**Na**		0		5.5 ms *10*	β-	100
11		**23**				β- n	≈ 15
						β- 2n	≈ 50
31	**Mg**		0	1/2(+)	232 ms *15*	β-	100
12		**19**				β- n	1.7 *3*
32	**Mg**		0	0+	95 ms *16*	β-	100
12		**20**				β- n	2.4 *5*
33	**Mg**		0	(3/2+)	90.5 ms *16*	β-	100
12		**21**				β- n	17 *5*

A Z	Nuclide	N	Energy (keV)	J^{π}	$T_{1/2}$	Decays	
35 **12**	**Mg**	**23**	0	(7/2-)	70 ms *40*	β- β- n	100 52 *46*
32 **13**	**Al**	**19**	0	1+	33.0 ms *2*	β- β- n	100 0.7 *5*
33 **13**	**Al**	**20**	0	(5/2+)	41.7 ms *2*	β- β- n	100 8.5 *7*
34 **13**	**Al**	**21**	0		42 ms *6*	β- β- n	100 27 *5*
35 **13**	**Al**	**22**	0		150 ms *50*	β- β- n	100 65 *35*
36 **13**	**Al**	**23**	0		90 ms *40*	β- β- n	100 < 31
36 **14**	**Si**	**22**	0	0+	0.45 s *6*	β- β- n	100 < 10
37 **14**	**Si**	**23**	0	(7/2-)	90 ms *60*	β- β- n	100 17 *13*
38 **15**	**P**	**23**	0	(0-:4-)	0.64 s *14*	β- β- n	100 12 *5*
39 **15**	**P**	**24**	0	(1/2+)	0.28 s *4*	β- β- n	100 26 *8*
40 **15**	**P**	**25**	0	(2-,3-)	150 ms *8*	β- β- n	100 15.8 *21*
41 **15**	**P**	**26**	0	(1/2+)	100 ms *5*	β- β- n	100 30 *10*
42 **15**	**P**	**27**	0		110 ms *30*	β- β- n	100 50 *20*
43 **15**	**P**	**28**	0	(1/2+)	36.5 ms *15*	β- β- n	100 100
43 **16**	**S**	**27**	0		220 ms *65*	β- β- n	100 40 *10*
44 **16**	**S**	**28**	0	0+	100 ms *1*	β- β- n	100 18 *3*
45 **16**	**S**	**29**	0		68 ms *2*	β- β- n	100 54
44 **17**	**Cl**	**27**	0	(2-)	0.56 s *11*	β- β- n	100 < 8
45 **17**	**Cl**	**28**	0	(1/2+)	413 ms *25*	β- β- n	100 24 *4*

A Z	Nuclide	N	Energy (keV)	J^{π}	$T_{1/2}$	Decays	
46 **17**	**Cl**	**29**	0		223 ms *37*	β- β- n	100 60 *9*
47 **17**	**Cl**	**30**	0		101 ms *6*	β- β- n	100 > 0
47 **18**	**Ar**	**29**	0	(3/2)-	1.23 s *3*	β- β- n	100 < 0.2
49 **18**	**Ar**	**31**	0		170 ms *50*	β- β- n	100 65 *20*
48 **19**	**K**	**29**	0	(2-)	6.8 s *2*	β- β- n	100 1.14 *15*
49 **19**	**K**	**30**	0	(3/2+)	1.26 s *5*	β- β- n	100 86 *9*
50 **19**	**K**	**31**	0	(0-,1,2-)	472 ms *4*	β- β- n	100 29 *3*
51 **19**	**K**	**32**	0	(1/2+,3/2+)	365 ms *5*	β- β- n	100 47 *5*
52 **19**	**K**	**33**	0	(2-)	105 ms *5*	β- β- n β- 2n	100 ≈ 64 ≈ 21
53 **19**	**K**	**34**	0	(3/2+)	30 ms *5*	β- β- n β- 2n	100 ≈ 67 ≈ 17
54 **19**	**K**	**35**	0		10 ms *5*	β- β- n	100 > 0
52 **20**	**Ca**	**32**	0	0+	4.6 s *3*	β- β- n	100 ≤ 2
53 **20**	**Ca**	**33**	0	(3/2-,5/2-)	90 ms *15*	β- β- n	100 > 30
61 **23**	**V**	**38**	0	(3/2-)	47.0 ms *12*	β- β- n	100 ≥ 6
63 **23**	**V**	**40**	0	7/2-	17 ms *3*	β- β- n	100 ≈ 35
64 **25**	**Mn**	**39**	0	(1+)	90 ms *4*	β- β- n	100 33 *2*
68 **25**	**Mn**	**43**	0.0+X		28 ms *4*	β- β- n	> 0 > 0

A Z	Nuclide	N	Energy (keV)	J^{π}	$T_{1/2}$	Decays	
72	**Co**		0	[6-,7-]	59.9 ms *17*	β-	100
27		**45**				β- n	≥ 6
74	**Co**		0		30 ms *3*	β-	100
27		**47**				β- n	> 0
74	**Cu**		0	(1+,3+)	1.63 s *5*	β-	100
29		**45**				β- n	> 0
75	**Cu**		0	(3/2-)	1.224 s *3*	β-	100
29		**46**				β- n	3.5 *6*
76	**Cu**		0.0+X		0.641 s *6*	β-	100
29		**47**				β- n	3 *2*
78	**Cu**		0	(4-,5-,6-)	335 ms *11*	β-	100
29		**49**				β- n	65 *8*
79	**Cu**		0		188 ms *25*	β-	100
29		**50**				β- n	55 *17*
79	**Zn**		0	(9/2+)	0.995 s *19*	β-	100
30		**49**				β- n	1.3 *4*
80	**Zn**		0	0+	0.54 s *2*	β-	100
30		**50**				β- n	1.0 *5*
81	**Zn**		0	(5/2+)	0.32 s *5*	β-	100
30		**51**				β- n	7.5 *30*
79	**Ga**		0	(3/2-)	2.847 s *3*	β-	100
31		**48**				β- n	0.089 *19*
80	**Ga**		0	-3	1.676 s *14*	β-	100
31		**49**				β- n	0.86 *7*
81	**Ga**		0	(5/2-)	1.217 s *5*	β-	100
31		**50**				β- n	11.9 *7*
82	**Ga**		0	(1,2,3)	0.599 s *2*	β-	100
31		**51**				β- n	19.8 *10*
83	**Ga**		0		308.1 ms *10*	β-	100
31		**52**				β- n	62.8 *25*
84	**Ga**		0	(0-)	0.085 s *10*	β-	100
31		**53**				β- n	70 *15*
84	**Ge**		0	0+	0.954 s *14*	β-	100
32		**52**				β- n	10.2 *9*
85	**Ge**		0		535 ms *47*	β-	100
32		**53**				β- n	14 *3*

A Z	Nuclide	N	Energy (keV)	J^{π}	$T_{1/2}$	Decays	
84	**As**		0	(3-)	4.2 s *5*	β-	100
33		**51**				β- n	0.18 *10*
85	**As**		0	(3/2-)	2.021 s *10*	β-	100
33		**52**				β- n	59.4 *24*
86	**As**		0		0.945 s *8*	β-	100
33		**53**				β- n	33 *4*
87	**As**		0	(3/2-)	0.56 s *8*	β-	100
33		**54**				β- n	15.4 *22*
87	**Se**		0	(5/2+)	5.50 s *12*	β-	100
34		**53**				β- n	0.20 *4*
88	**Se**		0	0+	1.53 s *6*	β-	100
34		**54**				β- n	0.67 *30*
88	**Se**		0	0+ *2*	1.53 s *6*	β-	100
y		**54**				β- n	0.67 *30*
89	**Se**		0	(5/2+)	0.41 s *4*	β-	100
34		**55**				β- n	7.8 *25*
91	**Se**		0		0.27 s *5*	β-	100
34		**57**				β- n	21 *10*
87	**Br**		0	3/2-	55.65 s *13*	β-	100
35		**52**				β- n	2.60 *4*
88	**Br**		0	(2-)	16.29 s *6*	β-	100
35		**53**				β- n	6.58 *18*
89	**Br**		0	(3/2-,5/2-)	4.40 s *3*	β-	100
35		**54**				β- n	13.8 *4*
90	**Br**		0		1.91 s *1*	β-	100
35		**55**				β- n	25.2 *9*
91	**Br**		0		0.541 s *5*	β-	100
35		**56**				β- n	20 *3*
92	**Br**		0	(2-)	0.343 s *15*	β-	100
35		**57**				β- n	33.1 *25*
93	**Br**		0	(5/2-)	102 ms *10*	β-	100
35		**58**				β- n	68 *7*
94	**Br**		0		70 ms *20*	β-	100
35		**59**				β- n	68 *16*
95	**Br**		0		≥ 150 ns	β-	100
35		**60**				β- n	34

A Z	Nuclide	N	Energy (keV)	J^{π}	$T_{1/2}$	Decays	
92 **36**	**Kr**	**56**	0	0+	1.840 s *8*	β- β- n	100 0.0332 *25*
93 **36**	**Kr**	**57**	0	1/2+	1.286 s *10*	β- β- n	100 1.95 *11*
94 **36**	**Kr**	**58**	0	0+	212 ms *5*	β- β- n	100 1.11 *7*
95 **36**	**Kr**	**59**	0	1/2(+)	0.114 s *3*	β- β- n	100 2.87 *18*
96 **36**	**Kr**	**60**	0	0+	80 ms *6*	β- β- n	100 3.7 *4*
98 **36**	**Kr**	**62**	0	0+	46 ms *8*	β- β- n	100 7.0 *10*
92 **y**	**Rb**	**55**	0	0-	4.492 s *20*	β- β- n	100 0.0107 *5*
93 **37**	**Rb**	**56**	0	5/2-	5.84 s *2*	β- β- n	100 1.39 *7*
94 **37**	**Rb**	**57**	0	3(-)	2.702 s *5*	β- β- n	100 10.5 *4*
95 **37**	**Rb**	**58**	0	5/2-	377.7 ms *8*	β- β- n	100 8.7 *3*
96 **37**	**Rb**	**59**	0	2(-)	203 ms *3*	β- β- n	100 13.3 *7*
97 **37**	**Rb**	**60**	0	3/2+	169.1 ms *6*	β- β- n	100 25.5 *9*
98 **37**	**Rb**	**61**	0	(0,1)	114 ms *5*	β- β- n β- 2n	100 13.8 *6* 0.051 *7*
99 **37**	**Rb**	**62**	0	(5/2+)	50.3 ms *7*	β- β- n	100 15.9 *20*
100 **37**	**Rb**	**63**	0	(3+,4-)	51 ms *8*	β- β- n β- 2n	100 6 *3* 0.16 *8*
101 **37**	**Rb**	**64**	0	(3/2+)	32 ms *5*	β- β- n	100 28 *4*
102 **37**	**Rb**	**65**	0		37 ms *3*	β- β- n	100 18 *8*

A Z	Nuclide	N	Energy (keV)	J^{π}	$T_{1/2}$	Decays	
97 **38**	**Sr**	**59**	0	1/2+	429 ms *5*	β- β- n	100 ≤ 0.05
98 **38**	**Sr**	**60**	0	0+	0.653 s *2*	β- β- n	100 0.25 *5*
99 **38**	**Sr**	**61**	0	3/2+	0.269 s *1*	β- β- n	100 0.100 *19*
100 **38**	**Sr**	**62**	0	0+	202 ms *3*	β- β- n	100 0.78 *13*
101 **38**	**Sr**	**63**	0	(5/2-)	118 ms *3*	β- β- n	100 2.37 *14*
102 **38**	**Sr**	**64**	0	0+	69 ms *6*	β- β- n	100 5.5 *15*
97 **39**	**Y**	**58**	0	(1/2-)	3.75 s *3*	β- β- n	100 0.055 *4*
97 **39**	**Y**	**58**	667.52 *23* m1	(9/2)+	1.17 s *3*	β- IT β- n	> 99.3 < 0.7 < 0.08
98 **39**	**Y**	**59**	0	(0)-	0.548 s *2*	β- β- n	100 0.331 *24*
98 **39**	**Y**	**59**	410 *30* m	(4,5)	2.0 s *2*	β- IT β- n	> 80 < 20 3.4 *10*
99 **39**	**Y**	**60**	0	(5/2+)	1.470 s *7*	β- β- n	100 1.9 *4*
100 **39**	**Y**	**61**	0	1-,2-	735 ms *7*	β- β- n	100 0.92 *8*
101 **39**	**Y**	**62**	0	(5/2+)	0.45 s *2*	β- β- n	100 1.94 *18*
102 **39**	**Y**	**63**	0.0+X	HIGH J	0.36 s *4*	β- β- n	100 4.9 *12*
102 **39**	**Y**	**63**	0.0+Y	LOW J	0.298 s *9*	β- β- n	100 4.9 *12*
103 **39**	**Y**	**64**	0	(5/2+)	0.23 s *2*	β- β- n	100 8 *3*
104 **41**	**Nb**	**63**	0	(1+)	4.9 s *3*	β- β- n	100 0.06 *3*

A Z	Nuclide	N	Energy (keV)	J^{π}	$T_{1/2}$	Decays	
104 **41**	**Nb**	**63**	2.15 x 10^2 *12* m		0.94 s *4*	β- β- n	100 0.05 *3*
105 **41**	**Nb**	**64**	0	(5/2+)	2.95 s *6*	β- β- n	100 1.7 *9*
106 **41**	**Nb**	**65**	0		0.93 s *4*	β- β- n	100 4.5 *3*
108 **41**	**Nb**	**67**	0	(2+)	0.193 s *17*	β- β- n	100 6.2 *5*
109 **41**	**Nb**	**68**	0	(5/2)	0.19 s *3*	β- β- n	100 31 *5*
110 **41**	**Nb**	**69**	0		0.17 s *2*	β- β- n	100 40 *8*
109 **43**	**Tc**	**66**	0	(5/2+)	0.86 s *4*	β- β- n	100 0.08 *2*
110 **43**	**Tc**	**67**	0	(2+)	0.92 s *3*	β- β- n	99.96 0.04
111 **43**	**Tc**	**68**	0	(5/2+)	290 ms *20*	β- β- n	100 0.85 *20*
113 **43**	**Tc**	**70**	0	GT 5/2	160 ms *+50-40*	β- n	2.1 *3*
118 **45**	**Rh**	**73**	0		266 ms *+22-21*	β- β- n	100 3.1 *14*
119 **45**	**Rh**	**74**	0	(7/2+)	171 ms *18*	β- β- n	100 6.4 *16*
120 **45**	**Rh**	**75**	0		136 ms *+14-13*	β- β- n	100 < 5.4
121 **46**	**PD**	**75**	0		285 ms *24*	β- β- n	100 ≤ 0.8
122 **46**	**Pd**	**76**	0	0+	175 ms *16*	β- β- n	≥ 97.5 ≤ 2.5
120 **47**	**Ag**	**73**	0	3(+)	1.23 s *4*	β- β- n	100 < 0.003
121 **47**	**Ag**	**74**	0	(7/2+)	0.78 s *2*	β- β- n	100 0.080 *13*
122 **47**	**Ag**	**75**	0	(3+)	0.529 s *13*	β- β- n	99.8 0.186 *10*
123 **47**	**Ag**	**76**	0	(7/2+)	0.300 s *5*	β- β- n	100 0.55 *7*

A Z	Nuclide	N	Energy (keV)	J^{π}	$T_{1/2}$	Decays	
124	**Ag**		0	|>2	0.172 s *5*	β-	100
47		**77**				β- n	1.3 *9*
130	**Cd**		0	0+	162 ms *7*	β-	100
48		**82**				β- n	3.5 *10*
131	**Cd**		0	(7/2-)	68 ms *3*	β-	100
48		**83**				β- n	3.5 *10*
132	**Cd**		0	0+	97 ms *10*	β-	100
48		**84**				β- n	60 *15*
127	**In**		0	(9/2+)	1.09 s *1*	β-	100
49		**78**				β- n	≤ 0.03
127	**In**		462 *71* m	(1/2-)	3.67 s *4*	β-	100
49		**78**				β- n	0.69 *4*
128	**In**		0	(3)+	0.84 s *6*	β-	100
49		**79**				β- n	< 0.046
128	**In**		3.4×10^{2} *6* m	(8-)	0.72 s *10*	β-	100
49		**79**				β- n	< 0.046
129	**In**		0	(9/2+)	0.61 s *1*	β-	100
49		**80**				β- n	0.25 *5*
129	**In**		38×10^{1} *7* m	(1/2-)	1.23 s *3*	β-	> 99.7
49		**80**				β- n	2.5 *5*
						IT	< 0.3
130	**In**		0	1(-)	0.29 s *2*	β-	100
49		**81**				β- n	0.93 *13*
130	**In**		50 *50* m1	(10-)	0.54 s *1*	β-	100
49		**81**				β- n	1.65 *15*
130	**In**		400 *60* m3	(5+)	0.54 s *1*	β-	100
49		**81**				β- n	1.65 *15*
131	**In**		0	(9/2+)	0.28 s *3*	β-	100
49		**82**				β- n	≤ 2.0 *3*
131	**In**		302 *32* m1	(1/2-)	0.35 s *5*	β-	≥ 99.982
49		**82**				β- n	≤ 2.0 *3*
						IT	≤ 0.018
131	**In**		3764 *88* m2	(21/2+)	0.32 s *6*	β-	> 99
49		**82**				IT	< 1
						β- n	≈ 0.03
132	**In**		0	(7-)	0.207 s *6*	β-	100
49		**83**				β- n	6.3 *9*

A Z	Nuclide	N	Energy (keV)	J^{π}	$T_{1/2}$	Decays	
133 **49**	**In**	**84**	0	(9/2+)	165 ms *3*	β- β- n	100 85 *10*
134 **49**	**In**	**85**	0	(4- TO 7-)	140 ms *4*	β- β- n	100 65
135 **49**	**In**	**86**	0 ?		92 ms *10*	β- β- n	100 > 0
133 **50**	**Sn**	**83**	0	(7/2-)	1.45 s *3*	β- β- n	100 0.08
134 **50**	**Sn**	**84**	0	0+	1.050 s *11*	β- β- n	100 17 *13*
135 **50**	**Sn**	**85**	0	(7/2-)	530 ms *20*	β- β- n	100 21 *3*
136 **50**	**Sn**	**86**	0	0+	0.25 s *3*	β- β- n	100 30 *5*
137 **50**	**Sn**	**87**	0		190 ms *60*	β- β- n	100 58 *15*
134 **51**	**Sb**	**83**	0.0+X m1	(7-)	10.07 s *5*	β- β- n	100 0.088 *4*
135 **51**	**Sb**	**84**	0	(7/2+)	1.679 s *15*	β- β- n	100 22 *3*
136 **51**	**Sb**	**85**	0	1-	0.923 s *14*	β- β- n	100 16.3 *32*
137 **51**	**Sb**	**86**	0	(7/2+)	450 ms *50*	β- β- n	100 49 *10*
136 **52**	**Te**	**84**	0	0+	17.63 s *8*	β- β- n	100 1.31 *5*
137 **52**	**Te**	**85**	0	(7/2-)	2.49 s *5*	β- β- n	100 2.99 *16*
138 **52**	**Te**	**86**	0	0+	1.4 s *4*	β- β- n	100 6.3 *21*
137 **53**	**I**	**84**	0	(7/2+)	24.5 s *2*	β- β- n	100 7.14 *23*
138 **53**	**I**	**85**	0	(2-)	6.23 s *3*	β- β- n	100 5.56 *22*
139 **53**	**I**	**86**	0	(7/2+)	2.280 s *11*	β- β- n	100 10.0 *3*
140 **53**	**I**	**87**	0	(4-)	0.86 s *4*	β- β- n	100 9.3 *10*

A Z	Nuclide	N	Energy (keV)	J^{π}	$T_{1/2}$	Decays	
141 **53**	**I**	**88**	0		0.43 s *2*	β- β- n	100 21.2 *30*
141 **54**	**Xe**	**87**	0	5/2(-)	1.73 s *1*	β- β- n	100 0.044 *5*
142 **54**	**Xe**	**88**	0	0+	1.22 s *2*	β- β- n	100 0.406 *34*
145 **54**	**Xe**	**91**	0		188 ms *4*	β- β- n	100 5.0 *6*
147 **54**	**Xe**	**93**	0	(3/2-)	0.10 s *+10-5*	β- β- n	? < 8
141 **55**	**Cs**	**86**	0	7/2+	24.84 s *16*	β- β- n	100 0.035 *3*
142 **55**	**Cs**	**87**	0	0-	1.684 s *14*	β- β- n	100 0.090 *4*
143 **55**	**Cs**	**88**	0	3/2+	1.791 s *7*	β- β- n	100 1.64 *7*
144 **55**	**Cs**	**89**	0	1(-)	0.994 s *6*	β- β- n	100 3.03 *13*
145 **55**	**Cs**	**90**	0	3/2+	0.587 s *5*	β- β- n	100 14.7 *9*
146 **55**	**Cs**	**91**	0	1-	0.321 s *2*	β- β- n	100 14.2 *5*
147 **55**	**Cs**	**92**	0	(3/2+)	0.230 s *1*	β- β- n	100 28.5 *17*
148 **55**	**Cs**	**93**	0		146 ms *6*	β- β- n	100 25.1 *25*
147 **56**	**Ba**	**91**	0	(3/2-)	0.894 s *10*	β- β- n	100 0.06 *5*
148 **56**	**Ba**	**92**	0	0+	0.612 s *17*	β- β- n	100 0.4 *3*
149 **56**	**Ba**	**93**	0		0.344 s *7*	β- β- n	100 0.43 *12*
147 **57**	**La**	**90**	0	(3/2+)	4.06 s *4*	β- β- n	100 0.041 *4*
148 **57**	**La**	**91**	0	(2-)	1.26 s *8*	β- β- n	100 0.15 *3*
149 **57**	**La**	**92**	0	(3/2-)	1.05 s *3*	β- β- n	100 1.43 *28*
150 **57**	**La**	**93**	0		0.86 s *5*	β- β- n	100 2.7 *3*
210 **81**	**Tl**	**129**	0	(5+)	1.30 min *3*	β- β- n	100 0.007 *+7-4*

Colour scheme:

β- 2n

β- 3n

β- 4n

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