https://doi.org/10.61092/iaea.h9j1-r5qm

INDC(NDS)-0676
Distr. EN, ND

International Atomic Energy Agency

INDC International Nuclear Data Committee

Total Absorption Gamma-ray Spectroscopy for Decay Heat Calculations and Other Applications

Summary Report of Consultants' Meeting

IAEA Headquarters
Vienna, Austria

15-17 December 2014

Prepared by

Paraskevi Dimitriou and Alan L. Nichols

IAEA Nuclear Data Section
Vienna, Austria

Departments of Physics
University of Surrey
Guildford, UK

February 2015

IAEA Nuclear Data Section
Vienna International Centre, P.O. Box 100, 1400 Vienna, Austria

Selected INDC documents may be downloaded in electronic form from
http://www-nds.iaea.org/publications
or sent as an e-mail attachment.
Requests for hardcopy or e-mail transmittal should be directed to
NDS.Contact-Point@iaea.org
or to:
Nuclear Data Section
International Atomic Energy Agency
Vienna International Centre
PO Box 100
1400 Vienna
Austria

Printed by the IAEA in Austria

February 2015

INDC(NDS)-0676
Distr. EN, ND

Total Absorption Gamma-ray Spectroscopy for Decay Heat Calculations and Other Applications

Summary Report of Consultants' Meeting

IAEA Headquarters
Vienna, Austria

15-17 December 2014

Prepared by

Paraskevi Dimitriou and Alan L. Nichols[*]

IAEA Nuclear Data Section
Vienna, Austria

[*] Departments of Physics
University of Surrey
Guildford, UK

Abstract

A summary is given of an IAEA consultants' meeting on "Total Absorption Gamma-ray Spectroscopy for Decay Heat Calculations and Other Applications". Participants assessed and reviewed plans and progress from 2005/06 and 2009 to identify and determine those radionuclides that merit measurement of their total absorption gamma-ray spectra (TAGS) in order to assist in the determination of the decay heat in and antineutrino spectral emissions from power reactor systems. This debate follows on from similar exercises undertaken by Subgroup 25 of the OECD-NEA Working Party on International Evaluation Cooperation of the Nuclear Science Committee in 2005/06 and a previous IAEA consultants' meeting in 2009. Various highly-relevant TAGS studies were undertaken from 2006/07 onwards based on the recommendations of WPEC-25. A further re-assessment of the request list formulated in 2005/06 and adjusted in 2009 is merited at this time. Debate focused on fission- and fusion-based decay-heat needs and the monitoring of antineutrino spectra to assist in non-invasive safeguards. Agreement was reached in re-defining and extending fission-reactor decay-heat and antineutrino spectral requirements for TAGS measurements as a tabulated list.

February 2015

Table of Contents

1. INTRODUCTION

A Consultants' Meeting on "Total Absorption Gamma-ray Spectroscopy (TAGS) measurements for decay heat and other applications" was held on 15-17 December 2014 at the IAEA Headquarters, Vienna, Austria. The purpose of this meeting was to review the current status of TAGS data, and to discuss progress and plans to measure complete gamma-ray spectra in order to derive total average beta and gamma decay data for decay heat calculations and other applications associated with the determination of antineutrino spectra and beta-delayed neutron emissions. Such a review is timely given the effort that has been expended to implement the recommendations for measurements as proposed by contributors to Subgroup 25 of the OECD-NEA Working Party on International Evaluation Cooperation of the Nuclear Science Committee in 2005/6 [1], particularly after a re-assessment of the original TAGS request list at an IAEA Consultants' Meeting in 2009 led to an agreement to extend the requirements to the determination of antineutrino spectra [2]. Therefore, relevant specialists were invited to discuss recently performed and planned TAGS studies for the above-mentioned applications, and produce a definitive re-defined list of priority radionuclides requiring TAGS measurements.

The meeting was opened by Robin Forrest, Head of the IAEA Nuclear Data Section, who welcomed the participants and emphasised the importance of the task that lay ahead of them in defining future TAGS research programmes for the nuclear science and data applications communities. Alan Nichols (University of Surrey) agreed to chair the meeting, and Paraskevi Dimitriou (IAEA, NDS) was nominated rapporteur. The adopted agenda can be found in Appendix 1, while the list of participants is given in Appendix 2. The meeting began with a short introduction of the history and goals of the meeting by the Chairman, Alan Nichols, followed by individual presentations by the participants (a group photograph and list of links to the presentations are provided in Appendices 3 and 4, respectively).

2. SUMMARIES OF PARTICIPANTS PRESENTATIONS

2.1. Recent results of the Valencia group from I153 and IS440 experiments within the DTAS collaboration, Alejandro Algora (IFIC-University of Valencia, Spain)

A discussion of the necessity of total absorption measurements for proper estimations of decay heat in reactors as well as for summation calculations for the antineutrino spectra in reactors was presented. Recently performed experiment I153 (spokespersons: Fallot, Tain, Algora) at the IGISOL IV facility were also described. The new DTAS total absorption spectrometer developed for the FAIR facility was used for the first time in this experiment, with the primary aim of measuring important contributors to the summation calculations of the antineutrino spectrum in nuclear reactors. Some examples of the measured spectra were shown.

Results were also presented from the IS440 experiment performed at ISOLDE (CERN). The goal of this experiment was to determine the shape of proton-rich Pb isotopes from a measurement of the distribution of the beta strength in the daughter. Details of the experiment and a comparison with theory were given.
[**Sec. note**: IFIC TAGS studies of relevance, from 2006 onwards: ^{86,87,88}Br, ^{91,92,93,94}Rb, ^{94,95}Sr, ^{96,96m,99}Y, ^{98,98m,101}Nb, ^{105}Mo, ^{102,104,105,106,107}Tc, ^{137,138}I and ^{142}Cs]

2.2. Modular Total Absorption Spectrometer measurements at ORNL, Marek Karny (University of Warsaw, Poland)

A Modular Total Absorption Spectrometer built at the Oak Ridge National Laboratory consists of 19 hexagonal modules, 23” in length and approximately 7” wide. The central module has a 2” diameter channel drilled through to allow source transport to the centre of the detector. Total efficiency of the detector reaches 98% at 300 keV and 96% at 4 MeV. Full peak absorption is 78%, and 71% at 0.3 and 4 MeV, respectively. Two 1-mm thick silicon strip detectors were placed in the centre of the detector to obtain beta-gamma coincidence data. During the first experiment, the following isotopes were measured: ^{85,86,87}Br, ^{87,89,90}Kr, ^{92}Rb, ^{137}I, ^{137,139}Xe, ^{142}La, ^{142}Ba, plus some daughter products.

The following isotopes are now under the evaluation:
^{86}Br, ^{89}Kr, ^{139}Xe: work of A. Fijałkowska, University of Warsaw,
^{137}I: work of Ch. Rasco, Luisiana State University,
^{142}La, ^{142}Ba: work of M. Wolińska-Cichocka, University of Warsaw,
^{85}Se, ^{85}Br: Ch. Goetz, University of Tennessee and ORNL.

^{142}La evaluation in terms of beta feeding does not show significant deviations from the data of Greenwood *et al*. [3]
^{86}Br: average gamma energy (EEM) derived from MTAS is 3710 keV
^{89}Kr: average gamma energy (EEM) derived from MTAS is 2280 keV
^{139}Xe: average gamma energy (EEM) derived from MTAS is 1370 keV.

^{139}Xe: contributions to the increased EEM (from 935 keV) come not only from “the Pandemonium effect” [4] but also from the lowering of the ground state to ground state feeding (from 16% to 2%). Final checks are being made and uncertainties are being evaluated for all three cases (^{86}Br, ^{89}Kr, ^{139}Xe).

^{137}I: work has involved the inclusion of beta-delayed neutrons into the GEANT4 simulation and experimental spectrum unfolding. Resulting P_n values in the 200-keV bin agree with the well-known β-n spectrum.

2.3. TAGS measurements for antineutrino spectra – Recent TAGS results from the Nantes group, Muriel Fallot (Subatech, Nantes, France)

The prediction of reactor antineutrino energy spectra is of interest in both fundamental and applied physics. More specifically, the reactor neutrino experiments entitled Daya Bay (China), RENO (Republic of Korea) and Double Chooz (France) involve quantification of the mixing angle θ_{13} for which calculations of reactor antineutrino energy spectra have also been revisited. Conversion of the integral beta energy spectra measured at the ILL high-flux reactor was re-assessed to produce new reference spectra; however, a re-analysis of the main short baseline reactor experiments has shown a deficit of measured antineutrinos with respect to this new reference.

Several explanations have been invoked: the existence of light sterile antineutrinos, or still persisting systematic errors in the reference spectra arising from nuclear uncertainties such as the large uncertainty associated with the weak magnetism term in the calculation of the antineutrino spectra, and the effect of forbidden non-unique decays. The measured integral beta spectra remain a unique reference, although a new measurement would be desirable in order to re-define the reference with greater confidence.

Daya Bay, RENO and Double Chooz reported new measurements of the antineutrino energy spectrum at power plants in 2014. All three experiments reported a distorted shape in their converted spectra, with a distinctive “bump” within the 4 to 6 MeV energy range. Distortions were also observed below 4 and above 6 MeV. These findings reinforce the need for alternative methods to compute reactor antineutrino spectra.

An alternative calculation method relies on nuclear data whereby fission yield distributions and beta-decay properties of the fission products can be used to derive reactor antineutrino spectra by means of a summation method. Recent TAGS measurements performed by the Valencia group on ^{102,104,105,106,107}Tc, ^{105}Mo, and ^{101}Nb have been incorporated into such summation calculations. The impact of only five of these fission products whose beta properties have been corrected for "the Pandemonium effect" is fairly large, reaching 8% for ^{239,241}Pu isotopes in the 3-4 MeV bins. Studies comparing summation method spectra combining several nuclear databases with integral beta spectra showed that the best agreement can be reached when using the maximum amount of data which do not suffer from the Pandemonium effect, including the βγ studies of Rudstam *et al.* [5] and the TAGS data of the Valencia group [6] and Greenwood *et al*. [3].

An experiment proposal prepared by members of the Valencia-Nantes collaboration was accepted in 2009 to perform TAGS measurements at Jyväskylä on a set of important contributors to the antineutrino emission from standard thermal power plants. Two nuclei from this list were measured in 2009, and preliminary calculations of the beta feeding were shown: ^{92}Rb and ^{93}Rb (results from the PhD thesis of A.-A. Zakari, University of Nantes, Spring 2015). The impact of these new measurements on the antineutrino energy spectra from $^{235,\ 238}$U and ^{239,241}Pu has been assessed, reaching 6% at 7 MeV in ^{235}U (4.5% for ^{92}Rb alone), 5% in ^{239}Pu, and 3% in ^{238}U and ^{241}Pu when the new TAGS data for these two Rb isotopes replace Rudstam data in the summation calculations. These new experimental results also alter the electromagnetic (EM) and light particle (LP) decay heat after thermal fission bursts of ^{235}U and ^{239}Pu. Thus, the new ^{92}Rb data decrease the EM decay heat in both nuclei when they replace the existing ENDF/B-VII.1 data.

As envisaged, the experimental programme has continued in 2014, with TAGS measurements at the new IGISOL-4 facility of twenty isotopes (plus daughters), a fraction from the Nantes-Valencia proposal of 2009. Spectral analyses has been shared among the Valencia and Nantes teams of which ^{95}Sr, ^{98,98m}Nb, ^{96,96m}Y, ^{99}Y, ^{138}I and ^{142}Cs are being analysed at Nantes.

The Nantes-Valencia collaboration also submitted a letter of intent to the ALTO facility in early 2014 for TAGS measurements on nuclei of interest for reactor antineutrino spectra and decay heat. As contemplated, these experiments could be performed on a 2 to 3 year timescale from now, depending on necessary laser ion source developments.

2.4. TAGS measurements by the Valencia-Surrey Group, Jose L. Tain (IFIC-University of Valencia, Spain)

The results of TAGS measurements performed in November 2009 at the IGISOL-JYFLTRAP installation of the Jyvaskyla University Accelerator were presented. These studies constitute parts of two PhD theses: ^{86}Br, ^{91}Rb and ^{94}Sr, S. Rice (University of Surrey, June 2014), and ^{87}Br, ^{88}Br and ^{94}Rb, E. Valencia (University of Valencia, early 2015). The data analyses have been completed, and journal publications are in preparation. All three Br isotopes were labelled as priority 1 in the WPEC-SG25 list of measurements for decay heat calculations [1]. The results of the TAGS measurements show that all of these particular isotopes suffer from sizeable Pandemonium effects that result in an increase of 16% (^{86}Br), 29% (^{87}Br) and 60% (^{88}Br) in the average γ-ray energy ($\bar{E}_g$) when compared with equivalent calculations based on high-resolution γ-ray spectroscopy data tabulated in ENSDF. Both ^{91}Rb and ^{94}Sr have been used as crosschecks with the equivalent Idaho National Laboratory TAGS data (Greenwood *et al.* [3]). Good agreement was observed between the two sets of data: within ±3.5% for the average γ-ray energy. The systematic uncertainty in $\bar{E}_g$ due to the Pandemonium effect was also found to be extremely large for ^{94}Rb, being a factor of 2.3 higher than the actual $\bar{E}_g$ value. Impacts of the new results on decay heat and reactor antineutrino summation calculations will be evaluated shortly.

There was an additional reason for the inclusion of delayed neutron emitters (^{87,88}Br, ^{94}Rb) in the experimental studies, namely to investigate the γ-ray emission from neutron unbound states populated in the decay. These measurements were experimentally very challenging (very weak intensity at very high excitation energy), and required careful analyses and control of the sources of systematic error. The intensities measured were surprisingly large at 3.5% (^{87}Br), 1.6% (^{88}Br) and 0.5% (^{94}Rb) in comparison with naive expectations. Results were compared with Hauser-Feshbach calculations: Br data can be understood as a nuclear structure effect, while Rb data point towards the need to increase the photon-strength functions of the statistical calculations. The findings will have an impact on comparisons of experimental neutron emission probabilities with theoretical estimates, and on the estimation of neutron capture cross-sections for very neutron-rich nuclei of interest in astrophysical r-process calculations.

The TAGS measurements were carried out with a newly developed spectrometer designed to be compact, with a low neutron sensitivity (hence the use of BaF_2) and the capability of measuring γ-cascade multiplicities for the very first time (through 12-fold segmentation). This new detector system provides an increased accuracy in analysis, as the response function should also reproduce multiplicity-dependent spectra, and opens a new application of TAGS decay measurements with the ability to provide a realistic distribution of delayed γ-rays in the whole decay window that could be useful, for example, in dosimetry.

Finally, a brief report was given concerning a recent workshop organized in Valencia by the Nantes-Valencia collaboration. The meeting gathered together 27 participants to discuss the data from recent studies and plans for approved experiments, as well as exploring new ideas for future measurements at existing facilities or new facilities under construction.

2.5. Analysis of reactor beta- and antineutrino energy spectra on the basis of Gross Theory, Tadashi Yoshida (Tokyo Institute of Technology, Tokyo, Japan)

An accurate determination of the antineutrino energy spectra is a key issue in the interpretation of reactor antineutrino experiments, such as Kamioka (KamLAND), Double-Chooz and RENO. There are two ways of realizing this aim: (a) convert the measured electron spectra into antineutrino spectra through energy conservation of the leptons in the beta-decay process; (b) summation calculation of the aggregate FP contributions. Both methods require a detailed definition of the FP decay, and the best way to obtain this information is by means of summation calculations.

One of the major obstacles encountered is the Pandemonium problem, which became well known with the aid of the Gross Theory of beta-decay (GTBD) in the early days of summation-calculation developments [7]. Total absorption gamma-ray spectroscopy (TAGS) is now recognised as a decisive experimental means of addressing and overcoming this problem. However, TAGS requires much significant experimental and analytical effort, which merits appropriate and critical selection of the FP nuclei to be studied by this technique. GTBD can play an important role even now in this process, and has been applied to clarify and identify which type of beta transition must be studied further along with FP nuclei possessing the potential to suffer from the Pandemonium effect.

The main conclusions are as follows.
a). A large number of FP nuclides contribute to the antineutrino spectra of a power reactor system. Extensive TAGS studies are proposed, especially to address the low-energy range which includes the neutrino-detection peak at 4 MeV.
b). Discrepancy is found above 8 MeV where odd-odd nuclei dominate, although the practical importance is small because of the very low antineutrino-detection efficiency at such energies. However, these particular conditions provide a very good opportunity to refine theory, especially for odd-odd nuclei.
c). Over the energy region up to 12 MeV, Gamow-Teller transitions occupy about 90% of the lepton number-spectra, followed by first forbidden transitions, while the contribution from the Fermi transition is minimal – this kind of information was readily obtained by the summation calculations of Gross Theory [7].

2.6. Contribution of Valencia and Idaho TAGS to FP decay-heat calculations: their complementarity and problems remaining, Tadashi Yoshida (Tokyo Institute of Technology, Tokyo, Japan)

Total absorption gamma-ray spectroscopy (TAGS) is now recognised as the source of decay data of decisive importance in overcoming the well-known Pandemonium problem in FP decay heat calculations. The role of the Idaho and Valencia TAGS data [3, 6] has been assessed by means of summation calculations over a wide range of fissile nuclei from ^{233}U to ^{241}Pu, based on JEFF3.1 decay data assumed to be equivalent to the original ENSDF data without theoretical corrections. E_β and E_γ, were replaced by the equivalent total average data from the TAGS studies of Valencia- and Idaho to see their contributions to the decay heat. Idaho data dominate such calculations over the whole cooling-time range of the lightest fissile fuel (^{233}U). The impact of the Valencia data increases gradually with increase in fissile atomic number, culminating at ^{239}Pu. FP nuclides that remain to be measured were ranked on the basis of a new parameter for each nuclide, the Pandemonium-index P. TAGS data for bromine, niobium, antimony and xenon were judged to be of a higher priority than others. A clearly negative correlation between P and $t_{1/2}$ was also found.

2.7. TAGS data in ENDF/B-VII.1 and ENDF/B-VII.1.1, Alejandro A. Sonzogni (National Nuclear Data Centre, Brookhaven National Laboratory, USA)

Work was presented concerning the inclusion of TAGS data in the ENDF/B-VII.1 decay data sub-library, as well as in the development of the new sub-library referred to as ENDF/B-VII.1.1. Mean electromagnetic (EEM) and light-particle (ELP) energies for nuclides studied by Algora *et al.* [6] and Greenwood *et al.* [3] for which the Pandemonium effect was substantial were introduced into the VII.1 sub-library, while beta intensity distributions from these TAGS experiments were also included in VII.1.1.

Summation calculations have been performed to generate antineutrino spectra for ^{235,238}U and ^{239,241}Pu, decomposing the total in terms of contributions from each level populated in fission that undergoes β^- decay. Surprisingly, at energies larger than 4.5 MeV, there are fewer nuclides contributing significantly than one might expect. These nuclides decay with a large Q-value and substantial beta intensity to the ground state or low-lying levels.

Calculations of the integral of the cross-section averaged antineutrino spectra have been undertaken. These data are similar in behaviour to the averaged delayed-neutron multiplicity in that a dependence with (3Z-A) of the fissioning nucleus was observed.

2.8. TAGS, Pandemonium effects, verification and validation: EASY-II & TENDL-2014, ENDF/B-VII.1, JENDL-4.0u and JEFF-3.2, Jean-Christophe Sublet (UKAEA, UK)

The calculation of fuel and activation inventories is a key input to every aspect of the safe operation, safeguards and environmental assessment of all nuclear plants. An important aspect of fission and activation-transmutation products is decay heat power which arises after shutdown from the energy released in α, β and γ decay of the products of neutron interaction. Computation of the decay power is performed by sophisticated computer codes, which solve the large number of coupled differential equations governing the generation and decay chains for the many radionuclides involved. Such programs rely on a large volume of nuclear data that includes both activation-transmutation cross-sections and radioactive decay data.

Validation of decay power computational predictions by means of direct comparison with integral data and measurement of sample structural materials under relevant high-energy neutron spectra generates confidence in the values calculated. Such successful procedures also permit assessments of the adequacies of the methods and nuclear data adopted, and indicate any inaccuracies or omissions that may have led to erroneous results.

The FISPACT-II inventory code solves the Bateman equations in EASY-II when coupled with the ENDF/B-VII.1, JEFF-3.2, JENDL-4.0 and TENDL-2014 nuclear data libraries, to predict time-dependent decay heat and source terms characteristics of irradiated fuels. Particular attention will be paid in future to the isotopes susceptible to the Pandemonium effect and their impact as major antineutrino precursors.

2.9. Total absorption measurements as a benchmark for nuclear models, Alejandro Algora (IFIC-University of Valencia, Spain)

A theoretical description of the nuclei measured in the first trap assisted in the total absorption measurements of important contributors to fissile ^{239}Pu decay heat in reactors (^{101}Nb, ^{105}Mo, ^{102,104,105,106,107}Tc). These studies were performed using the FRDM-QRPA model of Möller *et al.* [8]. The optimization procedure of the calculations was outlined, and the results were compared with the experimental beta-decay probability distributions and deduced strength distributions. Both the effect of deformation and the impact of introducing the first forbidden component in the model were discussed, along with comparisons with other models such as the Gross Theory of beta decay [7], and the excited Vampir code [9]. Predictive powers of the models were also debated with respect to the derived half-lives of these nuclei.

3. DECAY HEAT

3.1. U/Pu fuel cycle

A review was undertaken of the list of radionuclides that make important contributions to decay heat from 10 to 10000 sec for the U/Pu fuel cycle, and may possibly benefit from TAGS measurements to address inadequate decay-heat calculations. Possible beneficial TAGS measurements were identified and tabulated by considering several sensitivity studies performed on decay-heat calculations with respect to different decay-data libraries (JEFF 3.1, ENSDF/B VII, JENDL-FPDD) by participants of WPEC Subgroup 25 (WPEC-25). Since this table was proposed by WPEC-25 in 2006/2007, several TAGS measurements have been performed and published [6], some of which have already resulted in new mean β and γ energies being included in ENDF/B-VII.1 and JENDL (^{101}Nb, ^{105}Mo, ^{102,104,105,106,107}Tc). The impact of these new TAGS data on decay-heat calculations was demonstrated and discussed. Although their implementation in such calculations improved predictions of the decay-heat data for ^{239}Pu against benchmark measurements, they had less impact on the corresponding decay-heat calculations for ^{235}U. The latter are more sensitive to the TAGS data of Greenwood et al [3] which when included in the calculations led to an improvement between 10 and 1000 sec cooling times. Furthermore, the Tobias decay-heat data at lower cooling times still cannot be reproduced [10] which may also warrant a need for all decay-heat measurements to be reviewed and critically assessed. A first step towards that goal would be the creation of an online inventory of measurements, evaluations and sensitivity studies on decay heat for major and minor fuels.

No definite conclusions can be drawn at present since, out of the seven nuclei of the WPEC-25 list that have been measured and published [6], only five (^{105}Mo, ^{104,105,106,107}Tc) have resulted in significantly modified mean beta and gamma energies being incorporated in the nuclear data libraries for implementation in summation calculations. A further five (^{86}Br, ^{87}Br, ^{88}Br, ^{92}Rb ^{94}Rb) have been measured and are about to be published. Twelve (^{89,90}Kr, ^{96}Y, ^{99}Zr, ^{98,100}Nb, ^{103}Mo, ^{103}Tc, ^{137}I, ^{137,139}Xe, ^{142}Cs) have been measured, but are in the early stages of analysis. Since additional TAGS measurements are needed to address the remaining nuclei in the original table of fission products as assembled by WPEC Subgroup 25 [1], this work needs to be pursued and fully completed.

3.2. Th/U fuel cycle

A detailed assessment of fission product decay data requirements for decay-heat calculations of irradiated Th/U fuel was performed by Gupta *et al.* [11], based on inventory calculations at different time intervals followed by decay-heat calculations as a function of these time intervals. The radionuclides with the major contributions to the decay heat were identified as a function of the cooling time, and were subsequently analyzed with respect to their known nuclear structure and Q-value. Tables of radionuclides common to both U/Pu and Th/U fuels, and unique to Th/U fuel were formulated and re-assessed in terms of their Q_β-values and highest known energy of nuclear levels populated by β^- decay (Table 1). Such an oversimplified approach contains some questionable features, and the resulting identification of individual radionuclides possessing significant Pandemonium should be treated with some caution along with the resulting priority ratings for TAGS studies.

3.3. Decay heat - Remarks/recommendations

3.3.1. Outstanding issues regarding decay-heat calculations

There is a need to create a definitive list of measured decay-heat data for comparison with summation calculations that would allow for clear conclusions to be drawn. Most of the existing data for fission systems are relatively old and the relevant publications are difficult to find, which hampers efforts to adopt a global set of measured data even for the U/Pu fuel cycle. The recommended decay-heat data of Tobias [10] need to be revisited to clarify their origin (measured, compiled, evaluated), and produce a unique set of accepted and updated values for use in various studies.

Recommendation: NDS-IAEA should explore the possibility of creating an inventory of data, publications and reports for decay-heat measurements.

Recommendation: Encourage/propose new measurements of decay heat for ^{235}U and certain minor actinides such as ^{237}Np in order to assist in the resolution of discrepancies between existing data sets.

3.3.2. Fission product yields and decay heat

The role of fission product yields (FPY) and their uncertainties in summation calculations should not be underestimated or neglected. Extensive comparisons of the cumulative FPYs implemented in the most important nuclear data libraries reveal discrepancies that need to be addressed. On the other hand, it is not clear how calculations based on energy-dependent FPYs that have evolved as a function of time can be compared. Therefore, care should be taken to compare the results of summation calculations for decay heat, antineutrino spectra or delayed neutrons, based on the same cumulative FPY data.

Fission product yields recommendation: carry out detailed decay-heat calculations for both fuels, U/Pu and Th/U, adopting the same set of FPYs, namely those included in the JEFF-3.2 database.

ACTION: J-Ch. Sublet agreed to perform inventory calculations of irradiated ^{235}U, ^{239}Pu, ^{232}Th and ^{233}U fissile materials vs cooling time (at intervals of 10, 100, 1000, 5000 and 10000 sec), and to identify in order the major contributors to decay heat for each fissile material as a function of time (complete over a period of 6-9 months).

ACTION: An action was placed on A. Algora, J.-L. Tain and M. Karny to analyze the above lists of nuclides provided by J.-Ch. Sublet in terms of Q values and maximum excitation energy for potential Pandemonium effects, and to compare their resulting list with the summary findings and possible TAGS requirements proposed by meeting participants (see Section 6, below).

4. ANTINEUTRINO SPECTRA

Considerable effort has been expended on the accurate determination of antineutrino spectra since the previous CM on TAGS measurements [2]. Sensitivity studies based on the summation method have provided lists of nuclides that contribute significantly to the antineutrino spectra at different energy intervals, suffer from Pandemonium, and therefore need to be measured by the TAGS technique.

A priority list of nuclei for TAGS measurements has been produced by the Nantes group, with the emphasis on radionuclides calculated to contribute over 1% to antineutrino spectra in the energy range from 3 to 8 MeV. As well as discrepancies occurring in the spectral shape of measured and calculated antineutrino spectra, this particular range of energies is important in ensuring non-proliferation of reactor operations and investigating previously observed reactor anomalies. The origins of and explanations for the differences between equivalent calculated and measured beta spectra are being investigated, and potential candidates to explain this behavior include the shape of the beta spectra for non-unique forbidden transitions, weak magnetism, and problems related to the original spectral measurements of Schreckenbach *et al.* [12].

Some of the nuclei are in common with those in the priority lists for improved decay-heat calculations of the two main fuel cycles (U/Pu and Th/U). Their potential for Pandemonium effects can be found in the WPEC-25 table [1] and Table 1 of Section 3.2. The additional remaining radionuclides have also been studied with respect to their Q_{β}-value and the highest known energy of nuclear level populated by β^{-} decay, along with other supportive features such as the existence of unplaced high-energy gamma-ray emissions and uncertainties in level placements in the decay scheme. High-resolution data have also been compared with the TAGS measurements of Greenwood *et al.* [3], whenever possible. Subjective conclusions are presented in Table 2. Taking into account the percentage contribution of the radionuclides in the two energy intervals and the potential for Pandemonium, priority ratings of 1 and 2 were assigned in a similar manner to the studies of the two reactor fuel cycles.

Fifteen of these important nuclides have been measured at Jÿvaskÿla (IGISOL), and the data are under analysis (^{92,93,95}Rb, ^{95}Sr, ^{96,99}Y, ^{98,98m,100,100m}Nb, ^{137,138}I, ^{137}Xe, ^{140,142}Cs), with the ^{92,93}Rb data due for publication shortly. A letter of intent has also been submitted to the PAC for measurements at the ALTO facility to commence within the next 2-3 years, while a proposal to measure several In and Sn isotopes relevant to astrophysics has been approved and will be undertaken at the ALTO facility in 2015.

Several recommendations were made to address various outstanding issues regarding the determination of antineutrino spectra for non-invasive monitoring of reactors and basic sciences:

Recommendation: Precision measurements (with accuracies < 1%) of the beta-shape for radionuclides that are major contributors to antineutrino spectra are required to help resolve the discrepancies observed in the shapes of measured and calculated beta spectra.

Recommendation: In line with the above recommendation, there is a need for new integral measurements of the beta spectra for ^{235}U, ^{239}Pu, ^{233}U, ^{241}Pu thermal fission, ^{232}Th, ^{238}U fast fission, and ^{252}Cf spontaneous fission. All comparisons are currently made with only a single set of reference data for ^{235}U and ^{239}Pu as measured by Schreckenbach *et al.* [12].

Recommendation: A thorough investigation is required of the impact of decay data, fission product yields and their uncertainties on summation calculations producing antineutrino spectra.

5. BETA-DELAYED NEUTRONS

5.1. IAEA coordinated research project on beta-delayed neutrons

One of the primary aims of an on-going CRP dedicated to beta-delayed neutrons is the assembly of a comprehensive delayed-neutron emission database which will include delayed-neutron emission probabilities, delayed-neutron spectra and integral delayed-neutron data [13]. Resulting recommended delayed-neutron emission probabilities will also be benchmarked against integral measurements by means of the summation method.

Short-term decay heat up to 200 s after shutdown is primarily identified with continued fission multiplication driven by delayed-neutron precursors, with radionuclide decay becoming of significance after ~ 100 s. Thus, beyond 200 s after reactor shutdown, α-, β- and γ-decay processes play the much more dominant role [14]. Some of the outstanding issues regarding beta-delayed neutron data for reactor kinetics will be addressed in the existing CRP, as related to decay heat and antineutrino spectra. Thus, as agreed at the first research coordination meeting on beta-delayed neutrons, Pandemonium nuclei that undergo delayed-neutron emission will be identified and labelled in the new reference database, and possible TAGS measurements assessed with respect to any existing inadequacies in the related decay data [13]. Furthermore, the competition between delayed-neutron and gamma emissions in the daughter nucleus requires study in conjunction with measured delayed-neutron emission spectra and theoretical models.

5.2. CONNECT Sharepoint collaboration site

An online collaboration tool has been made available to participants of the CRP on beta-delayed neutrons and the current consultants' meeting on TAGS. A Sharepoint work site has been established to serve as an easily accessible location for an appropriate and comprehensive inventory of documents published in peer-reviewed journals, laboratory reports, conference proceedings and theses. Such a dedicated site also allows for collaboration on the preparation/editing of reports and data tables, keeping track of timelines and ensuring that only one person is working on a given document at a particular time. This site is available on the IAEA CONNECT Platform, which is designed to be a link between different IAEA networks, enhances the sharing of information, and promotes 'good practices'. Access to this site is open only to registered participants of the bDN (beta-Delayed Neutron) coordinated research project and the TAGS consultants' meeting. A wealth of information has already been uploaded on to this site, including useful links to TAGS-related data and documents. Sharepoint is envisaged as the focus for an accessible assembly of all documents and data related to beta-delayed neutron emission, decay heat and antineutrino applications, to be continuously updated.

6. TAGS MEASUREMENTS AND FACILITIES

Proposed requirements for TAGS measurements to improve
(a) decay-heat calculations for irradiated Th/U fuel,
(b) antineutrino spectra
have been merged with an equivalent WPEC-25 table for decay-heat calculations of irradiated U/Pu fuel [1] to produce a single list that contains the most likely candidates for TAGS studies to assist in the resolution of important issues in decay-heat and antineutrino applications (Table 3). As noted above in Section 4, priority ratings of 1 and 2 were assigned to the antineutrino requirements on the basis of the percentage contribution to the total antineutrino spectra of individual radionuclides within the two energy intervals (3-5 and 4-6 MeV) and the potential for Pandemonium, and judgements have been included in Table 3. Radionuclide priorities in this particular table are only absolute within each

of the three separate sets of needs, and do NOT strictly apply across the table in a fully consistent manner to cover both fuel types and antineutrino applications.

TAGS measurements need to continue in the foreseeable future in order to cover the data needs discussed in the above sections, and presented together in Table 3. Developments in detector technology and data analysis are expected to result in the extraction of additional information such as the distribution of absolute intensities in both the discrete and continuum regions, which may be prove of importance in decay-heat calculations and beyond. Further thought needs to be given as where to locate such data, and what format to adopt.

Recommendation: The possibility of storing more advanced TAGS data in existing databases (e.g. EXFOR, ENSDF), or in a dedicated database should be explored.

The status of possible TAGS measurements at the CARIBU-ATLAS facility of the Argonne National Laboratory was briefly discussed. An ambitious experimental programme was presented at the IAEA consultants' meeting on TAGS in 2009 [2] to study complex decay schemes suffering from Pandemonium by means of a combination of high-resolution gamma-ray spectroscopy (Gammasphere – spherical shell of 110 large-volume HPGe detectors, each enclosed within a BGO Compton-suppression shield) and TAGS measurements with the NaI(Tl) detector system developed at INL by Greenwood *et al*. [3]. [**Sec. note**: Based on up-to-date information provided by C.J. Lister (University of Massachusetts Lowell), the TAGS programme at ANL-CARIBU has suffered some delay due mainly to the time and effort expended to set-up the desired infrastructure for CARIBU. Staff at Lowell have started working on re-shaping and improving the NaI(Tl) crystal detector and support structures. The plan is to start mapping the response of the detector in February 2015, and undertake calibration runs in late spring 2015. The group expects to start contributing to the TAGS experimental programme soon afterwards.]

With regards to the TAGS measurement programme in India as proposed in 2009 [2], progress has been limited to testing the performance of a set-up of 50 BaF_2 detectors (25 on each side) of compact 4π geometry with different sources. Large granularity has been demonstrated with sources possessing different numbers of coincidence gamma rays such that the "sum" peaks can be clearly separated from the "single" peak by multiplicity-gated off-line summing. Mention was also made of a new activity at Michigan State University, USA, to measure beta spectra in a fragmentation facility. Contact should be established with this particular research team.

7. EVALUATIONS, VALIDATION AND VERIFICATION

Recommended ordering of proposed procedures to be adopted when evaluating decay schemes and their decay data for inclusion in nuclear applications libraries:

1) Evaluation of discrete decay data to derive a proposed decay scheme (singles γ and γ–γ coincidence, etc.) – if TAGS data available but no evidence of Pandemonium do not overlay specific entries with the TAGS data, and so avoid unnecessary inconsistencies in the recommended decay data.

2) If TAGS data available along with good evidence for the existence of Pandemonium within the discrete decay-data evaluation, adopt and place the highly-specific TAGS data within the decay-data file established in (1) above (mean β^- and γ, total average LP, EM energies).

3) If steps (1) and (2) are not feasible, adopt the crude one-third shared hypothesis: total average LP energy = total average EM energy = total average $\bar{\nu}$ energy = $Q_\beta/3$.

All new TAGS data in the public domain should be considered for adoption in the nuclear applications libraries at the earliest convenience with respect to their release schedules.

8. CONCLUSIONS

The meeting reviewed the contents and priorities of the original request table produced by WPEC Subgroup 25 [1], discussed the status of ongoing measurements and future perspectives, and broadened the content of the table to cover the decay heat of irradiated Th/U fuel and antineutrino spectral applications (Table 3).

Participants recommended strongly that previously highlighted TAGS measurements for the U/Pu fuel cycle should continue towards completion. These data needs were re-assessed and expanded somewhat. TAGS studies towards the generation of decay data that ensure more reliable decay-heat calculations for other fuel cycles also need to be pursued. Despite the significant efforts made so far, further work remains to be done regarding both decay heat and the antineutrino, and every effort should be made with respect to data analysis and development to ensure that all of these TAGS requirements are satisfied.

Developments of the TAGS technique and the evolution of extensive measurement campaigns for antineutrino applications are to be applauded. The noteworthy use of TAGS data as a means of testing nuclear models and their predictions was demonstrated, particularly with respect to beta-decay strengths, nuclear deformation and first-forbidden transitions. These studies are potentially of importance in astrophysics.

A regular review of progress in these TAGS measurements is recommended. Given the complex technical issues that were raised at this meeting, participants acknowledged the need for concerted and coordinated efforts to focus on these issues with the aim of resolving them over a well-defined timescale.

REFERENCES

1. M.A. Kellett, A.L. Nichols, O. Bersillon, H. Henriksson, R. Jacqmin, B. Roque, J. Katakura, K. Oyamatsu, T. Tachibana, T. Yoshida, A. Algora, B. Rubio, J.L. Tain, C.J. Dean, W. Gelletly, R.W. Mills, I.C. Gauld, P. Möller, A. Sonzogni, Assessment of Fission Product Decay Data for Decay Heat Calculations, A Report by the Working Party on International Evaluation Co-operation of the NEA Nuclear Science Committee, Vol. 25, NEA/WPEC-25, 2007, OECD/NEA, Paris, France, ISBN 978-92-64-99034-0.
2. A.L. Nichols, C. Nordborg, Summary Report of a Consultant's Meeting on Total Absorption Gamma-ray Spectroscopy (TAGS), Current Status of Measurement Programmes for Decay Heat Calculations and Other Applications, 27-28 January 2009, IAEA report INDC(NDS)-0551, February 2009, IAEA, Vienna, Austria https://www-nds.iaea.org/publications/indc/indc-nds-0551.pdf
3. R.C. Greenwood, M.H. Putnam, K.D. Watts, Ground-state β^--branching Intensities of Several Fission-product Isotopes Measured Using a Total Absorption γ-ray Spectrometer, *Nucl. Instrum. Methods Phys. Res.* **A378** (1996) 312-320;
   R.C. Greenwood, R.G. Helmer, M.H. Putnam, K.D. Watts, Measurement of β^--decay Intensity Distributions of Several Fission-product Isotopes Using a Total Absorption γ-ray Spectrometer, *Nucl. Instrum. Methods Phys. Res.* **A390** (1997) 95-154.
4. J.C. Hardy, L.C. Carrez, B. Jonson, P.G. Hansen, The Essential Decay of Pandemonium: A Demonstration of Errors in Complex Beta-decay Schemes, Phys. Lett. **71B** (1977) 307-310.
5. G. Rudstam, P.I. Johansson, O. Tengblad, P. Aagaard, J. Eriksen, Beta and Gamma Spectra of Short-lived Fission Products, *At. Data Nucl. Data Tables* **45** (1990) 239-320.
6. A. Algora, *et al.*, Reactor Decay Heat in ^{239}Pu: Solving the γ Discrepancy in the 4-3000 s Cooling Period, *Phys. Rev. Lett.* **105** (2010) 202501, 1-4;
   D. Jordan, *et al.*, Total Absorption Study of the β Decay of ^{102,104,105}Tc, *Phys. Rev.* **C87** (2013) 044318, 1-14.
7. K. Takahashi, M. Yamada, T. Kondoh, Beta-decay Half-lives Calculated on the Gross Theory, *At. Data Nucl. Data Tables* **12** (1973) 101-142.
8. S.T. Holloway, T. Kawano, P. Möller, Time Dependent Particle Emission from Fission Products, *J. Korean Phys. Soc.* **59** (2011) 875-878.
9. A. Petrovici, Self-consistent Description of Exotic Structure and Decay Near the N = Z Line, *Int. J. Mod. Phys.* **E17**, Supplement 1 (2008) 219-232;
   A. Petrovici, K.W. Schmid, A. Faessler, Beyond Mean Field Approach to the Beta Decay of Medium Mass Nuclei Relevant for Nuclear Astrophysics, *Prog. Part. Nucl. Phys.* **66** (2011) 287-292.
10. A. Tobias, Decay Heat, *Prog. Nucl. Energy* **5** (1980) 1-93;
    A. Tobias, Derivation of Decay Heat Benchmarks for U-235 and Pu-239 by a Least Squares Fit to Measured Data, Central Electricity Generating Board report RD/B/6210/R89, May 1989, CEGB, London, UK.
11. M. Gupta, M.A. Kellett, A.L. Nichols, O. Bersillon, Decay Heat Calculations: Assessment of Fission Product Decay Data Requirements for Th/U Fuel, IAEA report INDC(NDS)-0577, May 2010, IAEA, Vienna, Austria https://www-nds.iaea.org/publications/indc/indc-nds-0577.pdf
12. K. Schreckenbach, H.R. Faust, F. von Feilitzsch, A.A. Hahn, K. Hawerkamp, J.L. Vuilleumier, Absolute Measurement of the Beta Spectrum from ^{235}U Fission as a Basis for Reactor Antineutrino Experiments, *Phys. Lett.* **99B** (1981) 252-256;
    F. von Feilitzsch, A.A. Hahn, K. Schreckenbach, Experimental Beta-spectra from ^{239}Pu and ^{235}U Thermal Neutron Fission Products and their Correlated Antineutrino Spectra, *Phys. Lett.* **118B** (1982) 162-166.
13. I. Dillmann, P. Dimitriou, B. Singh, Summary Report of the First Research Coordination Meeting on Reference Database of Beta-delayed Neutron Emissions,

26-30 August 2013, IAEA report INDC(NDS)-0643, March 2014, IAEA, Vienna, Austria
https://www-nds.iaea.org/publications/indc/indc-nds-0643.pdf
https://www-nds.iaea.org/beta-delayed-neutrons/

14. R.N. Hill, Role of Decay Heat in Advanced Fuel Cycles, in Report on the Workshop "Decay Spectroscopy at CARIBU: Advanced Fuel Cycle Applications, Nuclear Structure and Astrophysics", 14-16 April 2011, Argonne National Laboratory, USA, Editors: M.P. Carpenter, P. Chowdhury, J.A. Clark, F.G. Kondev, C.J. Lister, A.L. Nichols, D. Seweryniak, ANL report ANL/NDM-168, Nuclear Data and Measurements Series, July 2011.

Table 1. Assessment and recommendations for TAGS measurements of radionuclides judged to be lacking average energy data of importance in decay-heat calculations for irradiated Th/U fuel.

Nuclide	Half-life	Q_β-value (keV)	(β^-,n) branch in β^- decay (%)	Highest daughter level and energy gap (keV)	Highest reaction level (keV)	Possible Pandemonium ?	% decay heat contribution at different cooling times (sec)					Priority
							10	100	1000	5000	10000	
34-Se-85	31.7 s	6161(4)	–	35-Br-85/4511 → Δ1650	5391	yes	0.99	1.24				1
34-Se-86	14.3 s	5129(4)	–	35-Br-86/2665 → Δ2464	3814	yes/significant	1.12					2
35-Br-84	31.76 min	4656(26)	–	36-Kr-84/4190 → Δ466	numerous up to 7653	borderline			1.48	2.13	0.83	2
35-Br-86	55.1 s	7633(3)	–	36-Kr-86/6769 → Δ864	numerous up to 7877	yes	1.15	5.15				1
35-Br-87	55.65 s	6818(3)	2.6	36-Kr-87/6192 → Δ626	6192	yes/borderline?	1.24	3.90				1
35-Br-88	16.29 s	8975(4)	6.58	36-Kr-88/7000 → Δ1975	7970	yes	2.54					1
35-Br-89	4.40 s	8262(4)	13.8	36-Kr-89/4707 → Δ3555	4707	yes/significant	1.16					1
36-Kr-87	76.3 min	3888.27(25)	–	37-Rb-87/3308 → Δ580	numerous up to 6989	yes/borderline?			1.26	4.13	4.63	1
36-Kr-89	3.15 min	5176(6)	–	37-Rb-89/4686 → Δ490	–	borderline		3.95	1.71			1
36-Kr-90	32.32 s	4405(7)	–	37-Rb-90/3881 → Δ524	–	yes/borderline?	2.34	3.06				1
36-Kr-91	8.57 s	6771(8)	–	37-Rb-91/4698 → Δ2073	6239	yes/significant	3.18					1
37-Rb-88	17.773 min	5312.4(11)	–	38-Sr-88/4853 → Δ459	numerous up to 20500	borderline			0.79	5.07	8.90	2
37-Rb-92	4.492 s	8095(6)	0.01	38-Sr-92/7363 → Δ732	7363	yes/borderline?	6.47					2
37-Rb-94	2.702 s	10283.0(26)	10.5	38-Sr-94/6064 → Δ4219	6064	yes/significant	0.96					1
38-Sr-92	2.66 h	1950(9)	–	39-Y-92/1384 → Δ566	ill-defined, and > 4048	yes/borderline?			0.79	3.52	5.87	2
39-Y-96	5.34 s	7103(6)	–	40-Zr-96/6232 → Δ871	6821	yes	4.29					2
39-Y-96m	9.6 s	8643(7)	–	40-Zr-96/5900 → Δ2743	6821	yes/significant	4.29					1
39-Y-97	3.75 s	6821(7)	0.06	40-Zr-97/3550 → Δ3271	up to 7296	yes/significant	1.43					1
40-Zr-98	30.7 s	2238(10)	–	41-Nb-98/0 → Δ2238	2023	yes/significant, but no γ observed		1.06				?
40-Zr-99	2.1 s	4707(16)	–	41-Nb-99/2336 → Δ2371	2336	yes/significant	1.69					1
40-Zr-100	7.1 s	3421(11)	–	41-Nb-100/704 → Δ2717	ill-defined, and > 1300	yes/significant	1.85					1

41-Nb-98	2.86 s	4584(5)	–	42-Mo-98/2608 → Δ1976	up to 7434	yes	2.14	2.94				1
41-Nb-99	15.0 s	3637(12)	–	42-Mo-99/2175 → Δ1462	up to 8118	yes	2.10					2
41-Nb-99m	2.5 min	4002(12)	>96.2% β^-, <3.8% IT	42-Mo-99/2944 → Δ1058	up to 8118	yes		0.80				2
41-Nb-100	1.5 s	6386(8)	–	42-Mo-100/3130 → Δ3256	up to 8114	yes/significant	4.76					1
41-Nb-100m	2.99 s	6699(3)	–	42-Mo-100/3647 → Δ3052	up to 8114	yes/significant	1.10					1
41-Nb-101	7.1 s	4628(4)	–	42-Mo-101/1099 → Δ3529	up to 5031	yes/significant	2.71					–
41-Nb-102	4.3 s	7260(9)	–	42-Mo-102/2480 → Δ4780	6201	yes/highly significant	0.96					2
41-Nb-102m	1.3 s	7354(11)	–	42-Mo-102/1245 → Δ6109	6201	yes/highly significant	0.93					1
42-Mo-101	14.61 min	2825(24)	–	43-Tc-101/2574 → Δ251	up to 4231	borderline			2.63	0.67		1
42-Mo-103	67.5 s	3635(14)	–	43-Tc-103/1621→ Δ2014	up to 4069	yes		0.99				2
43-Tc-102	5.28 s	4532(9)	–	44-Ru-102/2909 → Δ1623	numerous up to 12222	yes			2.09			–
43-Tc-103	54.2 s	2662(10)	–	44-Ru-103/1066 → Δ1596	up to 5127	yes		0.73				2
43-Tc-104	18.3 min	5587(25)	–	44-Ru-104/4268 → Δ1319	5357	yes			1.38	0.66		1
51-Sb-128m	10.4 min	4374(18)	96.4% β^-, 3.6%IT	52-Te-128/2852 → Δ1522	up to 7724	yes				0.66	0.59	2
51-Sb-129m	17.7 min	4227(21)	85% β^-, 15% IT	52-Te-129/1957 → Δ2270	numerous up to 6104	yes			0.54	0.31		2
51-Sb-130m	6.3 min	5072(14)	–	52-Te-130/3413 → Δ1659	7637	yes			1.69			1
51-Sb-132	2.79 min	5553(4)	–	52-Te-132/3562 or 4890[*] → Δ1991/663	4890	yes		0.79				2
51-Sb-133	2.34 min	4010(4)	–	52-Te-133/2756 → Δ1254	up to 6164	yes		0.59				2
52-Te-135	19.0 s	6061(6)	–	53-I-135/4773 → Δ1288	5849	yes	1.05					2
53-I-136	83.4 s	6884(14)	–	54-Xe-136/6624 → Δ260	6624	borderline		2.74				3
53-I-136m	46.9 s	7090(5)	–	54-Xe-136/6091 or 6412[†] → Δ999/678	6624	yes	1.55	3.69				2
53-I-137	24.13 s	6027(8)	7.14	54-Xe-137/5170 → Δ857	5408	yes	1.08	0.74				2
54-Xe-137	3.818 min	4162.4(3)	–	55-Cs-137/3976 → Δ186	numerous up to 12788	unlikely		2.37	1.87			3
54-Xe-138	14.08 min	2915(10)	–	55-Cs-138/2508 → Δ407	2508	borderline		0.63	3.53	0.79		1
54-Xe-139	39.68 s	5057(4)	–	55-Cs-139/4228 → Δ829	4228	yes	1.53	2.88				2
54-Xe-140	13.60 s	4064(9)	–	55-Cs-140/2324 → Δ1740	2930	yes	1.58					2

56-Ba-139	83.25 min	2314.6(23)	–	57-La-139/2060 → Δ255	numerous up to 18630	borderline			0.56	2.84	3.40	2
57-La-141	3.92 h	2501(4)	–	58-Ce-141/2329 → Δ172	numerous up to 3704	unlikely				1.67	3.30	–
57-La-146m	10.0 s	6715(130)	–	58-Ce-146/4522 → Δ2193	4690	yes	1.10					2

* highest ^{132}Te level populated by ^{132}Sb equilibrium mixture of ground and metastable states (half-lives of 2.79 + 4.10 minutes).
† highest ^{136}Xe level populated by ^{136}I equilibrium mixture of ground and metastable states (half-lives of 83.4 + 46.9 seconds).

Table 2. Assessment and recommendation for TAGS measurements of radionuclides that lack average energy data of importance in determining antineutrino spectra for nuclear reactor applications and are not included in the tables for decay-heat calculations (Table 1 in this work, and WPEC-25 table [1]).

Radionuclide	Half-life	Q_β-value	Last known daughter level and energy gap	Possible Pandemonium?	% Contribution	
					3-5 MeV	4-6 MeV
37-Rb-90	158 s	6584(7)	38-Sr-90/5827 -> Δ 757	possible	1.3	2.08
37-Rb-93	5.84 s	7466(9)	38-Sr-93/ 6707.4 -> Δ 758.6	possible	1.68	2.83
38-Sr-95	23.9 s	6089(7)	39-Y-95/4563.4 -> Δ 1526	possible	1.93	2.73
38-Sr-96	1.07 s	5412(10)	39-Y-96/1923 -> Δ 3489	possible/strong	1.86	1.86
39-Y-94	18.7 min	4918(6)	40-Zr-94/4098 -> Δ 820	possible	2.47	1.15
39-Y-95	10.3 min	4450(7)	40-Zr-95/4070 -> Δ 380	possible	1.96	0.66
39-Y-97m	1.17 s	7489(7)	40-Zr-97/4117.8 -> Δ 3371.2	strong	1.73	1.25
39-Y-98m	2.0 s	8992(32)	40-Zr-98/4292.3 -> Δ 4699.7	strong	1.63	2.62
39-Y-99	1.484 s	6969(12)	40-Zr-99/2484.2 -> Δ 4484.8	strong	1.57	1.99
40-Zr-101	2.3 s	5717(9)	41-Nb-101/2118.7 -> Δ 3598.3	possible	2.22	2.18
41-Nb-104m	0.94 s	8746(15)	42-Mo-104/0 -> Δ 8746	yes, but no γ observed	0.4	1.01
53-I-138	6.23 s	7992(7)	54-Xe-138/ 5814 -> Δ 2178	possible	1.02	1.39
54-Xe-141	1.73 s	6280(10)	55-Cs-141/1556 -> Δ 4724	strong	1.11	1.34
55-Cs-139	9.27 min	4213(3)	56-Ba-139/3950.84 -> Δ 262.16	borderline	2.52	0.46
55-Cs-140	63.7 s	6220(10)	56-Ba-140/ 5765.3 -> Δ 455	possible	2.84	2.94
55-Cs-141	24.84 s	5256(10)	56-Ba-141/4671 -> Δ 585	possible	1.61	1.4
57-La-146	6.27 s	6588(34)	58-Cs-146/4690.04 -> Δ 1897.96	possible	0.66	1

Table 3. Summary of priorities for TAGS measurements of importance in decay-heat calculations for U/Pu and Th/U fuel cycles and for determining the antineutrino spectra produced by standard nuclear power plants. Radionuclides that have already been studied by means of TAGS are ticked in the 5th column, where the initials stand for the experimental groups responsible for measurements: V for IFIC-Univ. Valencia group, N for Subatech-Univ. Nantes group, O for Oak Ridge National Laboratory group.

Radionuclide	Q_β-value (keV)	Half-life	Comments	TAGS measurements	Priority		
					U/Pu fuel	Th/U fuel	Antineutrinos Total [3-8] MeV
34-Se-85	6161(4)	31.7 s	-			1	
34-Se-86	5129(4)	14.3 s	-			2	
35-Br-84	4656(26)	31.76 min	-			2	
35-Br-86	7633(3)	55.1 s	-	√ V, O	1	1	
35-Br-87	6818(3)	55.65 s	(β^-,n) branch	√ V, O	1	1	
35-Br-88	8975(4)	16.29 s	(β^-,n) branch	√ V	1	1	
35-Br-89	8262(4)	4.40 s	(β^-,n) branch			1	
36-Kr-87	3888.27(25)	76.3 min	-	√ O		1	
36-Kr-89	5176(6)	3.15 min	-	√ O	1	1	
36-Kr-90	4405(7)	32.32 s	-	√ O	1	1	
36-Kr-91	6771(8)	8.57 s	-			1	2
37-Rb-88	5312.4(11)	17.773 min	-			2	1
37-Rb-90	6584(7)	158 s	-				1
37-Rb-90m	6691(7)	258 s	repeat of INL TAGS		2		
37-Rb-92	8095(6)	4.492 s	small (β^-,n) branch	√ V-N, O	2	2	1
37-Rb-93	7466(9)	5.84 s	(β^-,n) branch	√ V-N			1
37-Rb-94	10283.0(26)	2.702 s	(β^-,n) branch	√ V-N		1	2

38-Sr-89	1500.4(23)	50.53 d	-		2		
38-Sr-92	1950(9)	2.66 h	-			2	
38-Sr-95	6089(7)	23.9 s	-	√ V-N			1
38-Sr-96	5412(10)	1.07 s	-				1
38-Sr-97	7545(8)	0.429 s	possible small (β^-,n) branch		2		2
39-Y-94	4918(6)	18.7 min	-				1
39-Y-95	4450(7)	10.3 min	-				1
39-Y-96	7103(6)	5.34 s	-	√ V-N, O	2	2	1
39-Y-96m	8643(7)	9.6 s	-			1	
39-Y-97	6821(7)	3.75 s	small (β^-,n) branch			1	2
39-Y-97m	7489(7)	1.17 s	possible small (β^-,n) branch -				1
39-Y-98m	8992(32)	2.0 s	(β^-,n) branch				1
39-Y-99	6969(12)	1.484 s	(β^-,n) branch				1
40-Zr-99	4707(16)	2.1 s	-	√ V	3	1	
40-Zr-100	3421(11)	7.1 s	-		2	1	
40-Zr-101	5717(9)	2.3 s	-				1
41-Nb-98	4584(5)	2.86 s	-	√ V-N, O	1	1	1
41-Nb-99	3637(12)	15.0 s	-		1	2	
41-Nb-99m	4002(12)	2.5 min	-			2	
41-Nb-100	6386(8)	1.5 s	-	√ V	1	1	1
41-Nb-100m	6699(3)	2.99 s	-			1	
41-Nb-101	4628(4)	7.1 s	-	√ V	1		1
41-Nb-102	7260(9)	4.3 s	-		2	2	1
41-Nb-102m	7354(11)	1.3 s	-			1	
41-Nb-104m	8746(15)	0.94 s	small (β^-,n) branch				2
42-Mo-101	2825(24)	14.61 min	-			1	

42-Mo-103	3635(14)	67.5 s	-	√ V	1	2	
42-Mo-105	4950(40)	35.6 s	-	√ V	1		
43-Tc-102	4532(9)	5.28 s	-	√ V	1		
43-Tc-103	2662(10)	54.2 s	-	√ V	1	2	
43-Tc-104	5587(25)	18.3 min	-	√ V	1	1	
43-Tc-105	3640(40)	7.6 min	-	√ V	1		
43-Tc-106	6547(11)	35.6 s	-	√ V	1		
43-Tc-107	5113(12)	21.2 s	-	√ V	2		
51-Sb-128m	4374(18)	10.4 min	-			2	
51-Sb-129m	4227(21)	17.7 min	-			2	
51-Sb-130m	5072(14)	6.3 min	-			1	
51-Sb-132	5553(4)	2.79 min	-		1	2	
51-Sb-133	4010(4)	2.34 min	-			2	
52-Te-135	6061(6)	19.0 s	-		2	2	1
53-I-136	6884(14)	83.4 s	-		1	3	2
53-I-136m	7090(5)	46.9 s	-		1	2	1
53-I-137	6027(8)	24.13 s	(β^-,n) branch	√ V, O	1	2	1
53-I-138	7992(7)	6.23 s	(β^-,n) branch	√ V-N			2
54-Xe-137	4162.4(3)	3.818 min	-	√ V, O	1	3	
54-Xe-138	2915(10)	14.08 min	-			1	
54-Xe-139	5057(4)	39.68 s	-	√ O	1	2	1
54-Xe-140	4064(9)	13.60 s	-		1	2	
54-Xe-141	6280(10)	1.73 s	small (β^-,n) branch				2
55-Cs-139	4213(3)	9.27 min	-				1
55-Cs-140	6220(10)	63.7 s	-	√ V-N			1
55-Cs-141	5256(10)	24.84 s	small (β^-,n) branch				2
55-Cs-142	7325(9)	1.684 s	small (β^-,n) branch	√ V-N, O	3		1

56-Ba-139	2314.6(23)	83.25 min	-			2	
56-Ba-142	2181(8)	10.6 min	-	√ O			
56-Ba-145	5319(15)	4.31 s	repeat of INL TAGS		2		
57-La-142	4509(6)	91.1 min	-	√ O			
57-La-143	3435(8)	14.2 min	repeat of INL TAGS		2		
57-La-145	4230(40)	24.8 s	repeat of INL TAGS		2		
57-La-146	6588(34)	6.27 s	-				2
57-La-146m	6715(130)	10.0 s	-			2	

Consultants' Meeting on
Total Absorption Gamma-ray Spectroscopy for Decay Heat Calculations
and Other Applications

IAEA Headquarters, Vienna, Austria
15 – 17 December 2014
Room A2311

APPENDIX 1

ADOPTED AGENDA

Monday, 15 December

08:30 – 09:30 **Registration (IAEA Registration Desk, Gate 1)**

09:30 – 10:00 **Opening Session**

Welcoming address
Administrative matters
Election of Chairman and Rapporteur
Adoption of the Agenda
Goals of meeting

10:00 – 12:30 **Presentations by participants (45 min. each)**

1) TAGS measurements by Valencia group (I), A. Algora (IFIC – Univ. Valencia)
2) TAGS measurements by ORNL-Warsaw group, M. Karny (Univ. Warsaw)
3) TAGS measurements for anti-neutrino spectra-recent anti-neutrino measurements, M. Fallot (SUBATECH – Univ. Nantes)

12:30 – 14:00 ***LUNCH***

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

4) TAGS measurements by Valencia group (II), J.-L. Tain (IFIC – Univ. Valencia)
5) Part I: Analysis of reactor beta- and anti-neutrino energy spectra on the basis of the gross theory, T. Yoshida (Tokyo Tech. University)
6) Part II: Contributions of Jyvaskyla and Idaho TAGS to FP Decay-Heat Calculations: Their Complementarity and Problems Left, T. Yoshida (Tokyo Tech. University)
7) TAGS data in ENDF/B VII.1, A. Sonzogni (NNDC-BNL)
9) Verification and Validation: EASY=II & TENDL-2013, ENDF/B-VII.1, JENDL-4.0u or JEFF-3.2, J.-Ch. Sublet (AEA UK)

Coffee break as needed

19:00 ***Dinner at a restaurant (see separate information)***

<u>Tuesday, 16 December</u>

09:00 – 12:30 **Presentations cont'd – Round Table Discussions**

10) bDN collaboration site on IAEA NUCLEUS, M. Verpelli (NDS-IAEA)
11) Connection with IAEA Database on beta-delayed neutrons, P. Dimitriou (NDS-IAEA)
12) Testing Nuclear Models with TAGS Data, A. Algora (IFIC-Univ. Valencia)

Discussions

Coffee break as needed

12:30 – 14:00 ***LUNCH***

14:00 – 18:00 **Round Table Discussions (cont'd)**

Formulation of Requirements/Recommendations

Coffee break as needed

<u>Wednesday, 17 December</u>

09:00 – 12:30 **Drafting of the Summary Report**

12:30 – 13:00 **Closing of the meeting**

Consultants' Meeting on Total Absorption Gamma-ray Spectroscopy for Decay Heat Calculations and Other Applications
15-17 December 2014
Vienna, Austria

APPENDIX 2

LIST OF PARTICIPANTS

FRANCE
Muriel FALLOT
Laboratoire Subatech
École des Mines de Nantes
4, rue Alfred Kastler - B.P. 20722
44307 Nantes Cedex 3
Tel: +33 2 51 85 84 15
E-mail: muriel.fallot@subatech.in2p3.fr

JAPAN
Tadashi YOSHIDA
Tokyo Institute of Technology
Research Laboratory for Nuclear Reactors
152-8550 Ookayama 2-12-1, Meguro-ku, Tokyo
Tel: +81 03 5734 3329
E-mail: tyoshida@nr.titech.ac.jp

POLAND
Marek KARNY
Institute of Experimental Physics
Faculty of Physics
Warsaw University
ul. Pasteura 5
02-093 Warsaw
Tel: + 48 22 55 32 000
E-mail: karny@mimuw.edu.pl

SPAIN
Alejandro ALGORA
Instituto de Fisica Corpuscular
Univ. Valencia - C.S.I.C.
46071 Valencia
Tel: +34 96 3543498
E-mail: algora@ific.uv.es

José TAIN
Instituto de Fisica Corpuscular
Univ. Valencia - C.S.I.C.
46071 Valencia
Tel: + 34 96 3543497
E-mail: tain@ific.uv.es

UNITED KINGDOM
Alan L. NICHOLS
38 Mattock Way
Abingdon, Oxfordshire OX14 2PQ
Tel. +44 1235 524077
E-mail: alanl.nichols@btinternet.com

UNITED KINGDOM
Jean-Christophe SUBLET
UK Atomic Energy Authority
Culham Centre for Fusion Energy
Abingdon, Oxfordshire OX14 3DB
Tel: +44 1235 466400
E-mail: jean-christophe.sublet@ccfe.ac.uk

UNITED STATES
Alejandro SONZOGNI
Brookhaven National Laboratory
National Nuclear Data Center
Building 817, PO Box 5000
Upton, New York 11973-5000
Tel: +1 631 344 5334
E-mail: sonzogni@bnl.gov

IAEA
Paraskevi DIMITRIOU
Nuclear Data Section
Division of Physical and Chemical Sciences
Tel.: +43 1 2600 21708
E-mail: p.dimitriou@iaea.org

APPENDIX 3: Group Photo

APPENDIX 4

Links to Presentations

#	Author	Title	Link
1	A. Algora	TAGS measurements by Valencia group (I)	PDF
2	M. Karny	TAGS measurements by ORNL-Warsaw group	PDF
3	M. Fallot	TAGS measurements for anti-neutrino spectra-recent anti-neutrino measurements	PDF
4	J.-L. Tain	TAGS measurements by Valencia group (II)	PPT
5	T. Yoshida	Part I: Analysis of reactor beta- and anti-neutrino energy spectra on the basis of the gross theory	PPT
6	T. Yoshida	Part II: Contributions of Jyvaskyla and Idaho TAGS to FP Decay-Heat Calculations: Their Complementarity and Problems Left	PPT
7	A. Sonzogni	TAGS data in ENDF/B VII.1	PPT
8	J.-Ch. Sublet	Verification and Validation: EASY=II & TENDL-2013, ENDF/B-VII.1, JENDL-4.0u or JEFF-3.2	PDF
9	A. Algora	Testing Nuclear Models with TAGS Data	PDF
10	P. Dimitriou	Connection with IAEA Database on beta-delayed neutrons	PDF

Nuclear Data Section
International Atomic Energy Agency
Vienna International Centre, P.O. box 100
A-1400 Vienna, Austria

E-mail: nds.contact-point@iaea.org
Fax: (43-1) 26007
Telephone: (43-1) 2600 21725
Web: http://www-nds.iaea.org