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Total Absorption Gamma-ray Spectroscopy (TAGS), Current Status of Measurement Programmes for Decay Heat Calculations and Other Applications

Summary Report of Consultants' Meeting

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Abstract

A Consultants' Meeting on "Total Absorption Gamma-ray Spectroscopy (TAGS)" was held on 27-28 January 2009 at the IAEA Headquarters, Vienna, Austria. All presentations, discussions and recommendations of this meeting are contained within this report. The purpose of the meeting was to report and discuss progress and plans to measure total gamma-ray spectra in order to derive mean beta and gamma decay data for decay heat calculations and other applications. This form of review had been recommended by contributors to Subgroup 25 of the OECD-NEA Working Party on International Evaluation Cooperation of the Nuclear Science Committee, for implementation in 2008/09. Hence, relevant specialists were invited to discuss their recently performed and planned TAGS studies, along with experimentalists proposing to assemble and operate such dedicated facilities. Knowledge and quantification of antineutrino spectra is believed to be a significant asset in the non-invasive monitoring of reactor operations and possible application in safeguards, as well as fundamental in the study of neutrino oscillations – these data needs were also debated in terms of appropriate TAGS measurements. A re-assessment of the current request list for TAGS studies is merited and was undertaken in the context of decay heat calculations, and agreement was reached to extend these requirements to the derivation of antineutrino spectra.

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1. Introduction

Proceedings were opened by Alan Nichols, Head of the Nuclear Data Section and Scientific Secretary for the meeting. He welcomed participants and gave a few remarks concerning the evolution of the TAGS studies (Total Absorption Gamma-ray Spectroscopy), as strongly encouraged by the OECD-NEA, Working Party on International Evaluation Cooperation of the Nuclear Science Committee (WPEC), Subgroup 25, and the need to maintain an active programme of experimental work to ensure that the specified requirements are also satisfactorily addressed for the benefit of the nuclear physics and nuclear data communities. As noted in Section 2.1, this Consultants' Meeting will emphasize and explore the current status of specific TAGS experimental studies in order to assess progress, and review the outstanding requirements as defined previously in 2006 by WPEC Subgroup 25 [1]. Additional consideration would also be given to the emerging needs for antineutrino spectra as related directly to β^- decay and TAGS measurements.

Claes Nordborg agreed to chair the meeting, and Alan Nichols was nominated as Scientific secretary. The Agenda was adopted with some adjustments in timing (Appendix A), and a list of participants is given in Appendix B.

2. Opening Presentations

2.1. WPEC Subgroup 25 (A.L. Nichols (IAEA))

Alan Nichols reminded participants of the observations concerning decay heat calculations (see relevant Web link):

(a) contribution of TAGS to the derivation of mean β and γ energies of importance in decay heat calculations, particularly when considering inadequate and non-existent decay schemes;

(b) additional requirements for experimental measurements of ill-defined β^- and γ feeding;

(c) avoid adoption of theory-based data (such as Gross β^- theory) in decay databases by undertaking the types of measurement defined in (a) and (b), above.

WPEC Subgroup 25 focused attention on identifying the radionuclides that made important contributions to decay heat 10 to 10000 secs after the termination of fuel irradiation in the reactor core [1]. Modelling difficulties arise from inadequate decay data (sometimes described as "the Pandemonium effect" [2]) by which high-resolution Ge detectors are extremely inefficient for the detection of both high-energy and weak gamma-ray emissions, erroneously distorting our understanding of the high-energy nuclear level structure of the daughter nucleus and β^- transitions that populate such states. TAGS measurements can clarify such decay scheme inadequacies, and such data can be coupled with the determination of β^- decay directly to the ground state to generate reliable contributions to the overall decay heat. A list of requirements had been formulated by Subgroup participants, and some degree of priority defined, as shown in Table 1

TAGS specialists from IFIC-Valencia, Spain, began their well-focused measurement programme in 2006, and plans to develop TAGS facilities at Argonne National Laboratory, USA, and VECC, Kolkata, India, merit a review of the current situation. This Consultants' Meeting has also been organized on the basis of a recommendation to be found in the WPEC-25 report, pages 37-38 [1]: "…… progress made by experimentalists over 2006-2008 should be monitored by staff at the IAEA Nuclear Data Section, …….. hopefully in late 2008".

Table 1. Requested TAGS measurements to improve decay heat calculations [1].

Radionuclide	Priority	Q_β-value (keV)	Half-life	Comments
35-Br-86	1	7626(11)	55.1 s	-
35-Br-87	1	6852(18)	55.65 s	(β^-n) branch.
35-Br-88	1	8960(40)	16.36 s	-
36-Kr-89	1	4990(50)	3.15 min	-
36-Kr-90	1	4392(17)	32.32 s	-
41-Nb-98	1	4583(5)	2.86 s	-
41-Nb-99	1	3639(13)	15.0 s	-
41-Nb-100	1	6245(25)	1.5 s	-
41-Nb-101	1	4569(18)	7.1 s	-
42-Mo-103	1	3750(60)	67.5 s	-
42-Mo-105	1	4950(50)	35.6 s	-
43-Tc-102	1	4532(9)	5.28 s	-
43-Tc-103	1	2662(10)	54.2 s	-
43-Tc-104	1	5600(50)	18.3 min	-
43-Tc-105	1	3640(60)	7.6 min	-
43-Tc-106	1	6547(11)	35.6 s	-
51-Sb-132	1	5509(14)	2.79 min	-
53-I-136	1	6930(50)	83.4 s	-
53-I-136m	1	7580(120)	46.9 s	-
53-I-137	1	5877(27)	24.13 s	(β^-n) branch.
54-Xe-137	1	4166(7)	3.82 min	-
54-Xe-139	1	5057(21)	39.68 s	-
53-Xe-140	1	4060(60)	13.6 s	-
37-Rb-90m	2	6690(15)	258 s	Repeat of INL TAGS.
37-Rb-92	2	8096(6)	4.49 s	Small (β^-n) branch.
38-Sr-89	2	1493(3)	50.53 d	-
38-Sr-97	2	7470(16)	0.429 s	Possible (β^-n) branch.
39-Y-96	2	7096(23)	5.34 s	-
40-Zr-100	2	3335(25)	7.1 s	-
41-Nb-102	2	7210(40)	1.3 s	-
43-Tc-107	2	4820(90)	21.2 s	-
52-Te-135	2	5960(90)	19.0 s	-
56-Ba-145	2	5570(110)	4.31 s	Repeat of INL TAGS.
57-La-143	2	3425(15)	14.2 min	Repeat of INL TAGS.
57-La-145	2	4110(80)	24.8 s	Repeat of INL TAGS.
40-Zr-99	3	4558(15)	2.1 s	-
55-Cs-142	3	7308(11)	1.69 s	(β^-n) branch.

2.2. IFIC, CSIC – University of Valencia (see relevant Web links)

2.2.1. Analysis of ^{102,104,105,106,107}Tc, ^{105}Mo and ^{101}Nb measurements (M.D. Jordán)

Emphasis had been placed on the importance of the priority request list from WPEC-25 in formulating a TAGS measurement programme conducted at the Ion Guide Isotope Separator On-Line (IGISOL) facility, University of Jyväskylä, Finland (see Table 1, above). The Valencia team has also used the JYFL-TRAP as their high-resolution separator in conjunction with IGISOL. A natural uranium target tilted at seven degrees to the beam had been irradiated with 4 μA of 30-MeV protons. Details of the experimental arrangements were described, including the detector system (standard Ge detector, and TAGS detectors: NaI(Tl) well-detector containing a silicon detector), along with the spectral analysis techniques.

Fission products studied in 2006-2008 are listed in Table 2. Spectral details were provided for all seven radionuclides, including the specific assumptions made when conducting the analysis. Knowledge of the β^- intensity directly to the ground state of the daughter is particularly important for several radionuclides in this work (e.g. ^{101}Nb, ^{105}Mo, ^{102}Tc, ^{105}Tc and ^{107}Tc), and their values were taken from the literature. As the work progressed, the importance of possessing complete information that defined the nuclear level scheme at low excitation energies became clear in order to reduce systematic uncertainties in the analysis. Extremely large differences were observed between the mean beta and gamma energies adopted previously in the nuclear applications libraries (ENDF/B-VII.0 and JEFF3.1) and those derived from these new experiments (for ^{104,105,106,107}Tc and ^{105}Mo).

Table 2. Relevant data of radionuclides studied by means of TAGS (2006-2008).

Radionuclide	Half-life (s)	Q_β-value (keV)	Predicted number of levels	β intensity to ground state	Parent ground state (J^π)	Daughter ground state (J^π)
41-Nb-101	7.1(3)	4569(18)	4537	40 (13.5 keV)	$(5/2^+)$	$1/2^+$
42-Mo-105	35.6(16)	4950(50)	82058	< 4	$(5/2^-)$	$(3/2^-)$
43-Tc-102	5.28(15)	4532(9)	372	92.9	1^+	0^+
43-Tc-104	1098(18)	5516(6)	2030	-	(3^+)	0^+
43-Tc-105	456(6)	3746(6)	1769	< 9	$(3/2^-)$	$3/2^+$
43-Tc-106	35.6(6)	6547(11)	68358	-	(1, 2)	0^+
43-Tc-107	21.2(2)	4820(90)	44572	22	$(3/2^-)$	$(5/2)^+$

The spectral data and resulting mean energies were discussed in considerable detail, during which the importance of the JYFL-TRAP separator was emphasised. Fuller explanations were given for the spectral analyses – knowledge of the spins and parities of the populated nuclear levels are important, along with a sound quantification of the β^- intensity to the daughter ground state. This important work merits publication in a reputable scientific journal in the near future. Queries concerning the lower limit of the half-life for sound TAGS measurements furnished information on the speed of operation: msec extraction from the ion source and 1 to 2 secs to move the activity from the implanter to the detector permits measurements down to half-lives of 100 to 200 msecs.

The unavailability of the influential data of Greenwood *et al*. (INEL(INL)) in digitalised form was noted.

ACTION: Kellett to explore the possibility of digitizing INL spectra from available publications [3, 4]. If possible, provide Tain with one digitised set of spectra for the Valencia group to assess the feasibility of undertaking a comprehensive analysis from this data source.

2.2.2. Decay properties of beta-delayed neutron emitters (A. Algora)

A proposal has been prepared by a collaboration that includes the Valencia group, CIEMAT and UPC-Barcelona, and accepted by the University of Jyväskylä to undertake TAGS measurements of a number of specific β-delayed-neutron emitters. Some of these radionuclides were rated as priority 1 by participants of WPEC Subgroup 25 (^{87,88}Br and ^{137}I) and contribute significantly to the delayed-neutron spectra in reactors, while others are relevant for the r-process in astrophysics (see Table 3). Another feature of this particular measurement programme is the development and testing of instrumentation for the planned FAIR facility at GSI, Germany (DESPEC collaboration).

Table 3. Relevant data of radionuclides to undergo TAGS studies in 2009.

Radionuclide	Half-life (s)	Q_β-value (MeV)	S_n ‡ (MeV)	R # ($Q_\beta - S_n/Q_\beta$)	P_n †	Daughter
35-Br-87	55.65	6.85	5.5	0.195	0.0252	36-Kr-87
35-Br-88	16.36	8.96	7.05	0.213	0.0658	36-Kr-88
37-Rb-94	2.70	10.31	6.75	0.345	0.104	38-Sr-94
37-Rb-95	0.3775	9.29	4.4	0.527	0.0873	38-Sr-95
53-I-137	24.5	5.88	4.03	0.315	0.0697	54-Xe-137

‡ S_n – neutron separation energy.
# R – energy window.
† P_n - β^-n branching fraction.

Benefits include the preparation of high-purity sources by means of JYFL-TRAP and reasonable yields of material for spectral study. A segmented BaF_2 detector will be used for the TAGS measurements as developed by a specialist team from the universities of Surrey and Valencia, along with a mini-version of the planned 4π neutron detector for DESPEC that originates from UPC-Barcelona. Furthermore, a time-of-flight spectrometer is also proposed for these studies, based on a prototype under development at CIEMAT, Madrid (delivery expected later than the other two detectors).

Again much discussion ensued. Nichols stressed that a significant amount of measured decay data is available to define the decay scheme of ^{87}Br. However, there are serious disagreements concerning direct β^- decay to the ground state of ^{87}Kr – this problem results in significant uncertainties in the mean β and γ energies that need to be addressed by TAGS studies. ^{87,88}Br and ^{137}I are important contributors to the decay heat of U/Pu fuels, and remain high priority items for TAGS measurements in any assessment of decay heat.

2.2.3. Overview of on-going/planned TAGS measurements (J.L. Tain)

Total Absorption Spectroscopy is judged to be the best method to measure the intensities/strengths in complex decay schemes. Problems of "Pandemonium" are experienced when undertaking such studies by means of standard singles and coincidence gamma spectroscopy, despite the high-resolution of HPGe detectors. Beta intensities are a basic property of a nucleus, and are very sensitive to the nuclear wave function – their data can be readily used to deduce γ-ray, β-particle and antineutrino (ν) distributions, and assist greatly in the understanding of nuclear structure. Examples were given involving studies of the Fermi/Gamow-Teller transitions, and revelation of trends from TAGS measurements that can be compared with theoretical calculations.

Mono-energetic neutrino beams based on β^+ and β^- emitters contained within storage rings have been proposed for advanced nuclear physics research. The region around ^{146}Gd is being studied to identify suitable EC-beam candidates with appropriate half-lives, single state population, and large EC/β+ ratios. Tain singled out ^{152}Yb, although other possibilities will be investigated at ISOLDE. Neutrino spectra represent a separate issue of possible importance to safeguards and non-proliferation – there is a need to define the reactor antineutrino spectrum with greater accuracy, and this aim could be achieved by means of TAGS measurements. TAGS studies would also be valuable in assessing nuclear shape competition (oblate-prolate) and shape co-existence. Work is underway on the Lucrecia facility at ISOLDE, including oblate-prolate competition of ^{76}Sr and shape co-existence for neutron-deficient Pb, Hg and Pt nuclides.

Tain reconsidered the TAGS measurements on IGISOL at the University of Jyväskylä (see Section 2.2.1), which had presented the opportunity to improve theoretical models in the A ~ 100 region. He had also assessed the studies of Greenwood *et al*. [3, 4] and Rudstam *et al*. [5]. Both sets of measurements are subject to several sources of systematic error, and there appeared to be no reason to believe that the Rudstam *et al*. data were superior.

Other facilities under development and of interest to TAGS specialists were noted:

ALTO, IPN-Orsay, France;

FAIR, GSI, Germany (includes DESPEC experiments – NUSTAR collaboration);

SPIRAL 1 and 2, GANIL, Caen, France.

TAGS can also assist greatly in the benchmarking of existing theoretical models (e.g. Quasiparticle Random Phase Approximation (QRPA) of Möller, Nix and Kratz [6]), states with extreme iso-spin values, the r-process for elements heavier than iron to clarify specific features of astrophysics, and resolution of queries concerning anomalous quenching of the GT operator or erroneous S_β distributions.

2.3. CARIBU at ATLAS – opportunities for improving decay data for neutron-rich fission products (F.G. Kondev (ANL, USA))

A brief description was given of the Argonne Tandem Linac Accelerator System (ATLAS), which is capable of accelerating all stable nuclei from ^{1}H to ^{238}U with great flexibility and high time-energy resolution (see relevant Web link). Appropriate studies of neutron-rich nuclei have been proposed, based on the CAlifornium Rare Ion Breeder Upgrade (CARIBU) of ATLAS (1-Ci ^{252}Cf spontaneous fission source with gas catcher and isobar separator). Various important nuclear physics topics will be addressed by CARIBU:

shell-structure quenching;

single-particle structure near neutron-rich magic number nuclei;

pairing interaction in weakly-bound systems;

collective behaviour in neutron-rich systems;

r-process path for astrophysics, including ground-state information, neutron capture rate, and fissionability of very heavy neutron-rich nuclides.

Both the CARIBU gas catcher and isobar mass separator were described in some detail.

Gamma-ray spectroscopy is a fundamental building block in developing a sound and valid understanding of nuclear structure, and the work undertaken by Gammasphere has proved to be extremely significant in such studies. Gammasphere consists of a spherical shell of 110 large-volume HPGe detectors, each enclosed within a BGO Compton-suppression shield that with modest upgrade could be used as a calorimeter to assist in TAGS measurements, as well as providing good quality, high-resolution data. The NaI(Tl) detector used originally at INL by Greenwood *et al*. has also been acquired, and will be used in the proposed studies. Thus, a combination of high-resolution gamma-ray spectroscopy and TAGS will be coupled together to reduce decay scheme uncertainties that engender “Pandemonium”. Commissioning is planned for the second half of 2009, and ANL would welcome multinational collaboration. While measurement campaigns will be relatively short with two or three experimental time slots of up to two weeks each, a large number of nuclei can be studied (including all nuclei on the priority list prepared by WPEC Subgroup 25 (Table1)), given the available low-energy beam intensities and the significant flexibility in beam-changing procedures. However, data analyses will be considerably more time consuming and would benefit from such collaboration.

2.4. TAGS and related measurements in India (G. Mukherjee (VECC, Kolkata, India))

A nuclear data committee was formed in 2006/07 to assess the feasibility and scope of an Indian Nuclear Data Centre. Agreement has been reached that one of the envisaged data centre activities would be the benchmarking of decay heat calculations for the Th/U fuel cycle (see relevant Web link). This focused technical area of work would involve TAGS measurements, preferably within India. Nuclear physicists from Manipal University, BARC/Mumbai and VECC/Kolkata have expressed interest in such studies, with the need to engage in strong collaboration with laboratories elsewhere (i.e. IFIC-Valencia and ANL).

Comparisons have been made of evaluated fission yield data for ^{233}U, ^{235}U and ^{239}Pu, and the differences now need to be assessed with respect to the known decay schemes of the individual radionuclides and the possible existence of "Pandemonium" arising from the Q_β-values and lack of knowledge of daughter nuclear levels. A suitable point at which to collaborate with others would be to participate in on-going TAGS measurements elsewhere in order to gain experience prior to undertaking equivalent studies in India.

Mukherjee described the cyclotron facilities at VECC, Kolkata that are capable of delivering proton and alpha-particle beams up to 20 and 60 MeV, respectively. High-resolution gamma-ray spectrometers are available, including LEPS detectors, and plans are being formulated to procure a large NaI(Tl) detector for TAGS measurements. Various other new and proposed facilities were also mentioned:

low-energy Rare Ion Beam (RIB) facility;

superconducting cyclotron capable of delivering heavy-ion beams up to 60 MeV/A;

BaF_2 detector arrays;

neutron detector array (for Time-of-Flight (ToF) and multiplicity studies);

charged-particle detector arrays.

A short-term aim will be to identify the major nuclei of interest in decay heat calculations for irradiated Th/U fuel that are inadequately characterized on the basis of their known decay schemes. Early measurements will be conducted in collaboration with laboratories that possess the necessary irradiation facilities and TAGS detector systems. A TAGS measurement system will be established in India over a longer time span, preferably at the VECC, Kolkata.

2.5. Nuclear reactor and β/ν spectral simulations for reactor antineutrino applied physics (M. Fallot (Subatech, France))

Antineutrinos are emitted as part of the β^--decay process of fission products generated in the core of nuclear power reactors:

$$^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + e^- + \bar{\nu}$$

Such antineutrino emissions undergo virtually no attenuation in their flux over long distances. Their spectral signature could be used to monitor the efficacy of reactor operations based on the precise nature of the fuel under irradiation and the detection of clandestine procedures and movements (see relevant Web link). Multinational collaborations have aided in the development of antineutrino detection techniques to probe reactor operations non-invasively.

The detection of reactor antineutrinos can be performed by means of the inverse decay process on a quasi-free proton:

$$\bar{\nu} + p \rightarrow e^{+} + n,$$

with a reaction threshold of 1.8 MeV and a cross section of ~ 10^{-43} cm^2. Several reactor antineutrino experiments in the past (e.g. Rovno, Bugey and Chooz) have experimentally established the relationship between the antineutrino flux and energy spectrum emitted by the core and the thermal power of the reactor and the fuel burn-up. The Double Chooz experiment is devoted to a better determination of the θ_{13} mixing angle, one of the parameters that characterises neutrino oscillations. Thus, this study will use two identical, complex detectors placed at 400 m (near detector) and 1050 m (far detector) from the Chooz reactor cores, filled with 10.3 m^3 of Gd-loaded liquid scintillator monitored by means of a well-defined array of photomultiplier tubes.

Only the far detector will accumulate data during the first phase of the Double Chooz experiment, and the resulting antineutrino spectrum will be compared with a simulation spectrum of reactor antineutrinos. This collaborative programme began with simulations of the antineutrino and beta spectra emitted by reactors that will also be useful for future neutrino experiments in which reactor antineutrinos may constitute an important background requiring precise determination (e.g. experiments devoted to relic neutrinos emitted by supernova such as LENA). The far detector of Double Chooz will start collecting data in the fall of 2009, while the near detector will perform the best ever measurement of a reactor antineutrino energy spectrum.

The potential use of antineutrinos for reactor monitoring is being explored in several experiments around the world. Reactor antineutrinos could constitute a new safeguards tool, and small detectors are being designed for such applications. The Nucifer experiment will consist of a target filled with 1 to 1.5 m^3 of Gd-loaded liquid scintillator contained in a stainless-steel vessel monitored by photomultiplier tubes and a muon-veto detector, with layers of shielding. This detector system will be installed 6 m from the OSIRIS research reactor in Saclay by early 2010. Both Double Chooz and Nucifer will allow comparisons of the antineutrino energy spectrum and flux simulations with their measurements, and place stringent limits on the sensitivity of the reactor antineutrino probe for reactor monitoring.

The spectral simulations require reliable fission product decay databases. Obviously, the antineutrino flux is rigidly linked to the overall β^{-}-particle emission spectrum of the fission products, and therefore improved β^{-} spectral data that did not contain uncertainties arising from "Pandemonium" would aid considerably in reducing uncertainties in the global shape of the antineutrino spectrum (currently 1.3% at 3 MeV to 9% at 8 MeV [7, 8]). Fallot reported that β^{-} spectral summations of the measured data for 111 nuclei by Rudstam *et al.* [5] do not agree with integral experimental studies (5%, 11% and 20% differences at 4, 5 and 8 MeV, respectively). The problems of completely uncharacterized/unknown nuclei and partially characterized nuclei ("Pandemonium effect") need to be addressed. Gross β theory has been adopted in the past (e.g. in JENDL 3.3), although this approach is now not advocated without extreme care. Other suitable models are being explored such as QRPA for uncharacterized nuclei, and TAGS measurements have been proposed to study the most important radionuclides lacking well-characterized decay schemes.

ACTION: Giot/Fallot to provide a priority list of radionuclides that merit TAGS measurements for antineutrino application to compare with the list of radionuclides requested to improve decay heat calculations.

3. Discussions

The emergence of new facilities in the intermediate term was debated in some detail with respect to the approval and emphasis of resulting work programmes, in particular, ISOLDE at CERN, ALTO at IPN-Orsay, and a new facility under construction at the University of Jyväskylä. Tain stressed that none of these facilities will favour work for nuclear application programmes, such as the improvement of decay-data files for decay heat calculations that assist in the adoption of safe and regular reactor shutdown procedures and subsequent preparations for re-fuelling. All participants appreciated that the next round of substantial funding by the European Union would fall within Framework Programme 7.

Contact with ALTO, IPN-Orsay, had been maintained by the Valencia group, and possible opportunities to undertake TAGS measurements on this facility would continue to be explored by Tain *et al*. However, Algora noted that ALTO will not include a Penning trap – rather, a laser system will be used to select each nuclide through a tuning process specific for each element which will require lengthy development. Studies will continue with the highly effective Penning trap system at the University of Jyväskylä. Tain stated that any new proposals for TAGS measurements need to include a much stronger case for basic nuclear structure studies and their immediate value to the astrophysics community. Nuclear theoreticians could provide suitable input to the re-definition of the list of measurement requirements. Such an appraisal might be beneficial and achieve a more sympathetic hearing when research proposals are under assessment and review.

The creation of stronger links between Spain/EU and India needs to be explored – collaboration may be possible through the FAIR project which includes the development of detector systems by means of experimental tests involving TAGS. However, there are significant problems in achieving the desired form of collaboration between the USA and Cuban-born TAGS specialists from Valencia – this unsatisfactory situation can only be monitored for signs of improvement.

TAGS measurement priorities need to be better defined for antineutrino studies, as agreed by an action placed on Giot and Fallot (see Section 2.5). Refinements to the list of decay heat radionuclides are also required based on:

(a) Q_{β}-value in relation to the highest known nuclear level of the daughter;

(b) measured gamma-ray spectra;

(c) spins and parities of the decaying nuclide and daughter nuclear levels;

(d) quantification of β^- decay directly to the daughter ground state.

ACTION: Algora will undertake an assessment of the remaining radionuclides within the WPEC-25 decay-heat tabulation, and provide a list of those nuclides requiring high-resolution measurements.

4. Agreed Comments and Recommendations

TAGS studies by Valencia group from 2006 onwards were described in some detail, and this work is warmly applauded. This work included the production, purification and collection of isotopically-pure ^{101}Nb, ^{105}Mo and ^{102,104,105,106,107}Tc for TAGS, involving the facilities at the University of Jyväskylä, Finland. All data have been processed, and their appropriate β and γ mean energies have been derived for decay heat calculations – their impact is suspected to be significant for U/Pu fuel cycle decay heat benchmark studies (see Report by the Working Party on International Evaluation Co-operation of the NEA Nuclear Science Committee, NEA/WPEC-25, OECD/NEA, Paris, 2007 [1]).

Work undertaken by the Valencia group will continue to centre on facilities available and operational at the University of Jyväskylä, Finland. A new proposal has been formulated and accepted for implementation at the University of Jyväskylä to study a number of important β^- n emitters: ^{87,88}Br, ^{94,95}Rb and ^{137}I (of which ^{87,88}Br and ^{137}I have been requested by WPEC Subgroup 25). This work is also strongly encouraged as part of the current efforts to improve the existing fission product decay databases.

The β^- decay process includes the emission of antineutrinos, and their spectral signal has been proposed to assess and monitor reactor operations, particularly with respect to a non-invasive method of detecting the clandestine production of fissile materials. Relevant decay scheme data are lacking for a number of fission products of importance in such studies, and recommendations were made to implement TAGS measurements. These studies are also of importance for fundamental neutrino physics.

New TAGS facilities have been proposed and TAGS studies are in preparation:

(a) assembly is underway at the CARIBU facility, Argonne National Laboratory, USA (includes adoption of INL NaI(Tl) detector of Greenwood *et al*. [3, 4]);

(b) initiation of an appropriate programme of work at VECC, Kolkata, India.

Indian interest will include requirements for decay heat calculations involving the Th/U fuel cycle. All of the new studies and developments are strongly endorsed, and participants were encouraged to ensure that their experimental work integrates in a fully complementary manner.

<u>Nuclear theory</u>:
Suggestions should be solicited for TAGS studies to assist in the development of nuclear theory and structure, and thus obtain a suitable list of neutron-rich fission products. This approach might prove more beneficial, and achieve a more sympathetic hearing when defending proposals and seeking financial support for experimental studies at international facilities.

<u>High resolution gamma-ray spectroscopy</u>:
Needs for high resolution gamma-ray spectroscopy have been demonstrated in the work emanating from the Valencia group, and such studies are highly recommended. The current table of required TAGS measurements (Table 3 of WPEC-25 [1]) should be further developed by assessing the spectral information, spins and parities of nuclear levels, and quantification of and uncertainty in direct decay to the ground state. This latter exercise will provide guidance on additional needs for high resolution gamma-ray spectroscopy – Algora will undertake this task (see Action in Section 3).

<u>Intermediate- and longer-term possibilities</u>:
A collaborative proposal should be prepared in 2009 and submitted to the PAC of the University of Jyväskylä to cover further data needs for key radionuclides of importance in the determination of reactor antineutrino spectra and decay heat. A collaborative letter of intent should also be submitted to the PAC of the ATLAS facility, Argonne National Laboratory, by relevant parties within Europe.

Collaboration with the ALTO facility, IPN-Orsay, France, is encouraged, and meeting participants look forward to future developments with interest. A formal agreement between the ALTO facility and relevant parties in Europe is strongly encouraged.

One possible route for cooperation between the Valencia group and India would be through their common interest in the FAIR project.

5. Conclusions

The IAEA Consultants' Meeting proved extremely beneficial in ensuring that all interested parties were brought up to date with current and proposed TAGS measurement programmes, and further meetings of a similar type should be held on a two or three-year cycle. Much work remains to be done. Decay data needs embrace decay heat calculations, anti-neutrino spectral signatures, and basic nuclear physics. Good progress is being made, and TAGS measurements and high-resolution gamma-ray spectroscopy studies need to continue in order to assemble new and improved data files for specific applications, and also to contribute to important research on nuclear structure.

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ANNEX A

International Atomic Energy Agency

Consultants' Meeting (CM) on

"Total Absorption Gamma-ray Spectroscopy (TAGS)"

held in collaboration with NEA/OECD
IAEA Headquarters, Vienna, Austria
27 – 28 January 2009
Meeting Room B0485

AGENDA

Tuesday, 27 January

08:00 – 08:30 Registration (IAEA registration desk, Gate 1)

1. **Introduction**

08:30 – 08:50 Welcome and administrative matters — Chairman/Scientific Secretary

08:50 – 09:00 Approval of the Agenda

2. **Background**

WPEC Subgroup 25, and NEA/WPEC-25 report — A.L. Nichols/C. Nordborg

09:00 – 12:15 ** 3. **Presentations**

3.1 TAGS measurements at Jyvaskyla

3.1.1 Analysis of Tc-102,104,105,106,107, Mo-105 and Nb-101 measurements — D. Jordan

3.1.2 New proposal – Br-87,88, Rb-94,95 and I-137, including measurements of delayed neutrons — A. Algora

12:15 – 13:30 *Lunch break*

13:30 – 17:00 3. **Presentations** (cont'd).

3.1.3 Overall view of TAGS measurements with emphasis on future installations — J.L. Tain

See also "Applications of the Total Absorption Technique to Reactor Decay Heat Calculations: Study of the Beta Decay of ^{102,104,105}Tc" by A. Algora, et al., presented at 13th Int. Symp. Capture Gamma-ray Spectroscopy and Related Topics (CGS-13), 25 – 29 August 2008, Cologne, Germany.

3.2 TAGS facilities at Argonne National Laboratory Immediate- and longer-term plans — F.G. Kondev

See also "Decay Studies of Minor Actinide Nuclides, and Future Opportunities for Improving the Decay Data of Neutron-rich Fission Products" by F.G. Kondev, et al., presented at Int. Conf. Reactor Physics, Nuclear Power: a Sustainable Resource, PHYSOR-2008, 14 – 19 September 2008, Interlaken, Switzerland.

3.3 TAGS and related measurements in India — G. Mukherjee
Immediate- and longer-term plans

3.4 Antineutrino and safeguards – applied reactor physics — L. Giot/
Decay heat of different reactor types — M. Fallot

4. **Discussions**

4.1 Additional discussion concerning all of item 3 above

19:00 *Social Event*

Wednesday, 28 January

09:00** 4. **Discussions** (cont'd).

4.2 Future issues:

Any other radionuclides need to be TAGged (apart from those listed in Table 3 of NEA/WPEC-25)?

Decay heat and other applications requiring such highly specific measurements?

ALTO IPN-Orsay – current plans and status?

One active group, and two developing groups - consideration of the following:

- problems/difficulties?
- proposals for measurements?
- timetables?
- how is everyone's work best integrated and made complementary?
- short- and long-term thoughts,
- other issues?

5. **Recommendations and Actions**

6. **Any other business**

** *Break for Coffee and Administrative matters as appropriate*

ANNEX B

International Atomic Energy Agency

Consultants' Meeting

"Total Absorption Gamma-ray Spectroscopy (TAGS)"

IAEA Headquarters, Vienna, Austria

27 – 28 January 2009

Meeting Room B0485

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Specific Presentations

Working Links:

1. WPEC Subgroup 25: Assessment of fission product decay data and decay heat calculations
2. Analysis of ^{102}Tc, ^{104}Tc, ^{105}Tc, ^{106}Tc, ^{107}Tc, ^{105}Mo and ^{101}Nb measurements
3. Decay properties of beta delayed-neutron emitters
4. Overview of ongoing/planned TAS measurements
5. CARIBU at ATLAS: Opportunities for improving decay data for neutron-rich fission products
6. TAGS and related measurements in India: Immediate- and longer-term plans
7. Nuclear reactor and β/ν spectra simulations for reactor antineutrino applied physics - links with TAGS measurements

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