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Summary Report

Consultants' Meeting on

High-precision beta-intensity measurements and evaluations for specific PET radioisotopes

IAEA Headquarters
Vienna, Austria

3-5 September 2008

Prepared by

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Vienna, Austria

December 2008

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Abstract

A summary is given of a Consultants' Meeting on "High-precision beta-intensity measurements and evaluations for specific PET radioisotopes". Participants assessed and reviewed the decay data for close to 50 positron-emitting radionuclides. Technical discussions are described in this report, along with the detailed recommendations and a priority list for future work.

Direct positron and X-ray measurements are required to resolve a significant number of outstanding issues associated with the radionuclides reviewed. The following new measurements are recommended: gamma-ray emission probability for Cu-64, positron and X-ray emission probabilities for Ni-57, Cu-62, Ga-66, As-72, Se-73, Rb-81,82m, Sr-83, Y-86 and Tc-94m. The following immediate evaluations were also recommended: Br-76 and I-120g.

December 2008

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1. Introduction[1]

PET studies are finding increasing application in diagnostic nuclear medicine, which includes cardiology, oncology, neurology and neuro-psychology. A list of selected applications is given below:

Cardiology:

PET is becoming an increasingly important form of diagnostic testing in cardiology, for example myocardial viability and coronary heart disease. ^{13}N-ammonia is used in myocardial perfusion, and PET scans help to differentiate viable myocardium from infarcted tissue in patients suspected to have hibernating or stunned myocardium.

Oncology:

The onset of PET imaging has generated various investigative studies in oncology by means of ^{18}F-FDG. PET now has distinctive uses in clinical areas such as cancer, lymphoma, melanoma, strokes and benign tumors.

Neurology:

PET is used to distinguish recurrent brain tumors from radiation fibrosis or necrosis, which is essential to neurological studies. ^{15}O-oxygen measures the flow of blood to the upper or main portion of the brain, and ^{11}C-compounds are used as radiotracers in PET scans to study normal/abnormal brain functions. This method is also used to localize areas of the brain affected by epileptic seizures.

Neuropsychology and Cognitive Neuroscience Pharmacology:

PET is used in clinical applications to study psychiatric disorders. Studies link direct visualization of blunted regional brain responses to serotonin release with major depression. PET is also used to evaluate neurological activity in amnesiac patients.

Along with the commonly used short-lived organic positron emitters (^{11}C, ^{13}N, ^{15}O and ^{18}F), many useful or potentially useful longer-lived positron emitters have been identified for PET applications. The decay data of all these radionuclides are reasonably well defined, but there are remaining deficiencies, especially with regard to positron emission probabilities. Both the positron energy and emission probability have a direct impact on the resolution and quantification of any PET study. Therefore, the available decay data need to be critically reviewed, and new measurements and evaluations recommended if necessary. A Consultants' Meeting on "High-precision beta-intensity measurements and evaluations for specific PET radioisotopes" was held at IAEA Headquarters, Vienna, Austria, from 3 to 5 September 2008, in order to fulfil these requirements. Four external consultants attended (S.M. Qaim, G.F. Steyn, T. Nozaki and S.L. Waters) and the IAEA was represented by A.L. Nichols (Head, Nuclear Data Section), D. Abriola and R. Capote, who served as Scientific Secretary. S.M. Qaim was elected Chairman of the meeting. The approved Agenda is attached (Appendix 1), as well as a list of participants and their affiliations (Appendix 2).

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2. Presentations

Four presentations by the consultants are available on the IAEA/NDS web page http://www-nds.iaea.org/pet/

2.1. Positron Emission Tomography, S.M. Qaim

An introduction to Positron Emission Tomography (PET) was given by S.M. Qaim. Four short-lived positron-emitting radionuclides are most commonly used (C-11, N-13, O-15 and F-18), following their cyclotron production. Two additional short-lived positron emitters (Rb-82 and Ga-68) can also be obtained from longer-lived generator systems (Sr-82 and Ge-68, respectively). The production and decay data of all those radionuclides appear to be satisfactorily defined.

PET is finding increasing application in diagnostic nuclear medicine, especially in neurology, cardiology and oncology. More than 100 PET centres have been established in Germany, many of which operate both a cyclotron and imaging tomography; a large number have only an imaging device and purchase radiopharmaceuticals from commercial suppliers. At a few centres such as Jülich, Dresden, etc., research work is also pursued to develop methods of production for new positron emitters and radiopharmaceuticals abeled with these radioisotopes.

Over the years, production methods for about 25 useful or potentially useful longer-lived positron emitters have been developed. Extensive nuclear reaction cross-section measurements have been carried out in several laboratories, and evaluations of these data are recommended. The decay data of these radionuclides are reasonably well defined but there are deficiencies in the case of several radionuclides, especially with regard to positron emission probabilities. Some of these measurements were carried out more than 30 years ago by means of low-resolution techniques. Both the positron energy and emission probability have a direct impact on the resolution and quantification of any PET study. Furthermore, the associated gamma rays distort the image due to scattering effects. Therefore, the available data need to be critically reviewed, and new measurements and evaluations recommended if necessary.

2.2. Position in the UK, S.L. Waters

There are an increasing number of PET facilities in the UK which are managed both by the National Health Service Trusts and privately funded clinics. Nearly all of these facilities are either producing or using commercially supplied F-18 FDG for clinical studies. There is nearly always a need within these operational PET facilities for commercial viability with special adherence to Health and Safety and Quality Assurance programmes that underpin cGMP standards. Not all of these units have their own cyclotrons, but there are a number with cyclotrons that are undertaking contract research for international pharmaceutical companies. These studies involve C-11, O-15 and F-18 labelled radiopharmaceuticals prepared to cGMP standard.

There are also a small number of universities and university hospitals that have both cyclotrons and PET imaging facilities, and are actively researching the use of more exotic radionuclides such as Cu-64, Ga-68, Rb-82, Tc-94m and I-124. However, the progress of these programmes in producing materials for clinical use is limited due to the regularity of supply of the radioisotope, the final quality of the abeled pharmaceuticals, and the important issue of the induced radiation dose to the subject.

2.3. Status of PET in Oriental Countries, T. Nozaki

The number of PET instruments and cyclotrons in Japan has increased by more than 20% year on year, now reaching about 2.35 and 0.85 machines per million inhabitants[2], respectively. PET facilities per person is likely to be overtaken soon by the Republic of Korea and Taiwan, while the PET age also appears to have begun in a significant number of other countries. China, with about eleven times the population of Japan, will have more facilities than Japan within the next few years.

Standard radionuclides are all being produced in facilities that have cyclotrons (C-11, N-13, O-15 and F-18), but a new trend in Japan is the increasing number of PET facilities (about 40%) that do not have their own cyclotrons and are using commercially supplied F-18 FDG.

As for PET staff, their numbers, ability and experience cannot be regarded as significant enough to undertake substantial developments in the field and measure fundamental data of increased reliability. Furthermore, there is a tendency only to support studies with potential immediate outcome, rather than longer-term studies of more fundamental importance. The quality of PET scientists needs to be evaluated in detail, as well as the development of new radionuclides.

2.4. Status of PET in South Africa, G.F. Steyn

The cyclotron at iThemba LABS is a multi-disciplinary facility operated by the National Research Foundation (NRF) of South Africa to provide accelerated ion beams for (1) research and training in the physical and biomedical sciences, (2) the treatment of cancer with energetic neutrons and protons, and (3) development and production of radionuclides and radiopharmaceuticals. This cyclotron is operated 24 hours a day, 7 days a week, with about 40% of the total beam time allocated to the production of radionuclides (mostly overnight). Radionuclides for PET include F-18, Cu-64, and the generator systems Ge-68/Ga-68 and Sr-82/Rb-82. Two smaller commercial cyclotrons, one privately owned and the other operated under the auspices of the Nuclear Energy Corporation of South Africa (Necsa), are dedicated to the supply of F-18 FDG. Presently, nine PET centres are operational in South Africa, and at least one further new facility is expected to become operational in 2009.

A number of positron-emitting radionuclides were selected for closer scrutiny, all produced and available at iThemba LABS. The following radionuclides have other gamma-ray emissions in addition to the 511-keV annihilation photon emission: Na-22, Fe-52, Mn-52m, Cu-61, Cu-64, Zn-65, Ga-66, Ga-68, Rb-82, Y-88 and Cs-132. Single gamma-ray spectra have been acquired by means of a calibrated HPGe detector to determine the ratio of measured activities from both the 511-keV and another gamma line for each radionuclide. These ratios should have a value of exactly one if the experimental methods are sound (perfect) and decay data are correct. Any large deviation from unity may be an indication of problems in the decay data. While not considered to be a conclusive test by any means, a ratio close to unity may give some re-assurance about the quality of the data. Adopting the decay data from the NuDat 2.4 compilation, values sufficiently close to one (within the respective combined standard uncertainties) were obtained in all cases, with the exception of Y-88. Furthermore, a discrepancy was also noted to exist in the case of Cu-64 concerning the weak 1345.77-keV gamma ray (0.475%, according to NuDat 2.4) for which a later study reports a 15% higher intensity.

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[2] Estimated population of 127 million in 2007.

3. General discussion

- Standard positron-emitting radionuclides (such as C-11, O-15, F-18 and Rb-82) are commonly used to study fast metabolic and physiological processes; they are almost all 100% positron emitters.
- Non-standard positron-emitting radionuclides (such as Cu-64 and I-124) are needed for the study of slow metabolic and physiological processes.
- Some non-standard positron-emitting radionuclides (such as Y-86) are also used for internal radiotherapy, including planning, on-line monitoring and dosimetry.
- Production methods for many of the non-standard positron-emitting radionuclides in pure form have been developed [1], although the cross-section data needed for production have not been evaluated. Furthermore, the decay data often exhibit discrepancies, especially positron emission probabilities and half-lives.
- The bulk of the experimental data were obtained by means of γ-ray spectroscopy linked to new technical developments. However, beta spectroscopic measurements were limited.
- The PET technique is quantitative; therefore, precise half-lives and positron emission probabilities are required.
- The PET technique has high resolution when the positron end-point energy is low and the gamma rays are non-existent or are of very low intensity. Since non-standard positron-emitting radionuclides often have many gamma rays, precise end-point energies of beta particles, and gamma-ray energies and their emission probabilities are required for accurate scattering corrections.
- Some non-standard positron-emitting radionuclides (such as Cu-64) have very low intensity gamma rays, resulting in large uncertainties in the determination of radioactivity if these emission probabilities are not sufficiently well known.

4. Discussions

Three types of positron-emitting radionuclides have been considered:

- standard radionuclides,
- non-standard radionuclides,
- very short-lived radionuclides formed in hadron therapy.

The database of the Decay Data Evaluation Project (DDEP) [2] as well as the MIRD [3] and NuDat 2.4 [4] retrievals from the ENSDF database [5] were employed as sources of decay data.

4.1. Standard positron-emitting radionuclides

C-11, N-13, O-15 and F-18 are the four commonly used positron-emitting radionuclides produced by cyclotrons – their data were reviewed. Decay data from all three sources were consistent. Data in the DDEP database were adopted because they represent the most recent and comprehensive evaluation – relevant data are given in Table 1. Data are denoted as, for example: 960.5(*9*) and 99.750(*13*), which represent 960.5 ± 0.9 and 99.750 ± 0.013, respectively, whereby the uncertainty is expressed as one sigma (1σ) confidence level.

Table 1: Relevant decay data for standard positron-emitting radionuclides.

Radionuclide	Half-life	End-point energy (keV)	Positron emission probability (%)
C-11 [2]	20.370(*29*) min	960.5(*9*)	99.750(*13*)
N-13 [2]	9.9670(*37*) min	1198.45(*27*)	99.818(*13*)
O-15 [2]	2.041(*6*) min	1735.0(*13*)	99 885(*6*)
F-18 [2]	1.8288(*3*) h	633.5(*6*)	96.86(*19*)
Ge-68 (parent) [2]	270.95(*16*) d	-	-
Ga-68 [2]	67.71(*9*) min	243.2(*12*) 821.7(*12*) 1899.1(*12*)	0.00026(*3*) 1.20(*3*) 87.94(*12*) *Total*: 89.14 (*12*)
Sr-82 (parent) [5]	25.55(*15*) d	-	-
Rb-82 [5]	1.273(*2*) min	191(7) 434(*7*) 722(*7*) 816(*7*) 869(*7*) 898(*7*) 928(*7*) 1206(*7*) 1421(*7*) 1890(*7*) 1903(*7*) 2601(*7*) 3378(*7*)	0.000031(*5*) 0.00156(*12*) 0.0028(*3*) 0.00027(*16*) 0.00034(*22*) 0.0275(*8*) 0.0049(*4*) 0.319(*5*) 0.0138(*11*) 0.044(*3*) 0.121(*6*) 13.13(*14*) 81.76(*17*) *Total*: 95.43(*22*)

Of increasing importance are the positron-emitting radionuclides Ga-68 and Rb-82, obtained from generator systems (Ge-68 and Sr-82, respectively). The Ge-68/Ga-68 data in the DDEP database were adopted; however, DDEP entries for Sr-82/Rb-82 do not exist. Therefore, ENSDF data were adopted for Sr-82/Rb-82. Relevant data for Ge-68/Ga-68 and Sr-82/Rb-82 are given in Table 1.

4.2. Non-standard positron-emitting radionuclides

4.2.1. Directly produced

DDEP evaluations have been undertaken for the positron-emitting radionuclides Na-22, Ni-57, Cu-64 and Ga-66 produced by cyclotrons. Their decay data were reviewed to give the following recommendations:

- **Na-22:** adopt the DDEP evaluation.
- **Ni-57:** we recommend new measurements of the half-life, X-ray and positron emission probabilities to be subsequently re-evaluated, along with the existing more than 30-year old measurements.
- **Cu-64:** DDEP-evaluated positron emission probability of 17.86(14)% was found to be in good agreement with a recently measured value of 17.8(2)% [6]; however, the emission probability of the only useful gamma ray at 1346 keV in the DDEP evaluation (0.475(10)%) needs to be re-evaluated, being discrepant with respect to the Jülich-measured value of 0.54(3)% [6]. We also recommend new measurements of the gamma-ray probability for future evaluation.
- **Ga-66:** we recommend new measurements of the X-ray and positron emission probabilities, to be subsequently re-evaluated along with the existing more than 30-year old measurements.

ENSDF evaluations are available for the cyclotron-produced, positron-emitting radionuclides P-30, Cl-34m, K-38, Ti-45, V-48, Cr-49, Mn-51,52g,m, Fe-52, Co-55, Cu-61, As-72, Se-73, Br-75,76, Kr-77, Rb-81,82m, Sr-83, Y-86, Nb-90, Tc-94m, In-110m, I-120g,124 and Tb-152. Their decay data were reviewed, and resulted in the following recommendations:

- **P-30, Cl-34m, K-38, Ti-45, V-48, Cr-49, Mn-51,52g,m, Fe-52, Co-55, Cu-61, Nb-90, In-110m** and **Tb-152:** adopt ENSDF data.
- **As-72, Se-73, Y-86, Tc-94m:** we recommend new measurements of the X-ray and positron emission probabilities, to be subsequently re-evaluated, along with the existing more than 30-year old measurements.
- **Br-75** and **Kr-77:** more experimental studies are needed – however, because of their short half-lives and relatively minor importance in current medical applications, we suggest adopting ENSDF values.
- **Br-76:** ENSDF data for the total positron emission probability of 55(3)% is in good agreement with a recently measured value of 58.2(19)% [6]; we recommend a new evaluation.
- **Rb-81,82m** and **Sr-83:** the accuracies of the available data are poor; new measurements are recommended.
- **I-120g:** new measurements have recently been published; a new evaluation is recommended.
- **I-124:** 2008 ENSDF evaluation includes recent measurements, and should be adopted.

All relevant data are given in Table 2.

Table 2: Relevant decay data for non-standard positron-emitting radionuclides produced in cyclotrons (data are taken from Ref. [4] if not indicated otherwise).

Radionuclide	Half-life	End-point energy (keV) taken from [5]	Positron emission probability (%)
Na-22 [2]	2.6027(*10*) y	545.6(*4*) 1820.2(*4*)	89.836(*10*) 0.056(*14*) *Total:* 89.892(*17*)
Ni-57 [2]	35.9(*3*) h	320.6(*3*) 482.6(*3*) 735.4(*3*) 862.6(*3*)	0.45(*3*) 0.85*(6)* 6.8(*3*) 35.3(*5*) *Total:* 43.4(*6*)
Cu-64 [2]	12.701(*2*) h	653.1(*2*)	17.86(*14*)
Ga-66 [2]	9.49(*7*) h	362(*3*) 415(3) 721(*3*) 726(*3*) 772(*3*) 924*(3)* 1326(*3*) 1781(*3*) 4153(*3*)	0.94(*8*) 0.0009(*3*) 0.16(*2*) 0.0020(*5*) 0.70(*6*) 3.7(*3*) 0.0053(*8*) 0.30(*3*) 50(*4*) *Total:* 56(*4*)
P-30	2.498(*4*) min	975.0(*4*) 3210.3(*4*)	0.052(*3*) 99.803(*4*) *Total*: 99.855(*5*)
Cl-34m	32.00(*4*) min	500.83(*8*) 1311.43(*8*) 2488.08(*8*)	0.264(*6*) 25.6(*3*) 28.4(*5*) *Total:* 54.3(*6*)
K-38	7.636(*18*) min	955.9(*6*) 2724.4(*4*)	0.133(*11*) 99.333(*13*) *Total:* 99.466(*17*)
Ti-45	184.8(*5*) min	320.0(*5*) 1040.1(*5*)	0.0135(*12*) 84.80(*13*) *Total:* 84.81(*13*)
V-48	15.9735(*25*) d	694.6(*24*)	49.9(*4*)
Cr-49	42.3(*1*) min	1452(*3*) 1514(*3*) 1605(*3*)	46.4(*17*) 34.7(*13*) 11.7(*16*) *Total:* 92.8(*27*)
Mn-51	46.2(*1*) min	184.1(*4*) 286.1(*5*) 628.1(*4*) 832.3(*6*) 1436.4(*4*) 2185.5(*4*)	0.000262(*15*) 0.00023(*3*) 0.0079(*4*) 0.015(*1*) 0.200(*3*) 96.86(*7*) *Total:* 97.08(*7*)

Table 2 cont'd

Radionuclide	Half-life	End-point energy (keV) taken from [5]	Positron emission probability (%)
Mn-52m	21.1(*2*) min	116.1(*21*) 295.6(*19*) 595.2(*19*) 905.5(*19*) 1102.5(*19*) 2633.2(*19*)	0.0000008(*3*) 0.00035(*5*) 0.013(*3*) 0.161(*8*) 0.0373(*20*) 94.8(*20*) *Total:* 95.0(*20*)
Mn-52g	5.591(*3*) d	575.6(*19*)	29.6(*4*)
Fe-52	8.275(*8*) h	806(*6*)	55.49(*??*)
Co-55	17.53(*3*) h	128.5(*5*) 217.6(*5*) 285.8(*5*) 1021.3(*4*) 1113.2(*4*) 1498.5(*4*)	0.0039(*5*) 0.0178(*13*) 0.0149(*19*) 25.6(*15*) 4.26(*20*) 46(*3*) *Total:* 76(*3*)
Cu-61	3.333(*5*) h	306.6(*12*) 559.2(*12*) 932.2(*12*) 1147.8(*12*) 1215.2(*12*)	0.035(*6*) 2.6(*5*) 5.5(*10*) 2.3(*4*) 51(*5*) *Total:* 61(*5*)
As-72	26.0(*1*) h	240(*4*) 298(*4*) 391(*4*) 394(*4*) 819(*4*) 932(*4*) 1269(*4*) 1606(*4*) 1870(*4*) 2500(*4*) 2643(*4*) 3334(*4*)	0.00126(*15*) 0.0066(*5*) 0.0203(*10*) 0.063(*3*) 0.466(*18*) 0.166(*9*) 0.032(*11*) 0.056(*14*) 5.82(*18*) 64.2(*15*) 0.7(*4*) 16.3(*17*) *Total:* 87.8(*23*)

Table 2 cont'd

Radionuclide	Half-life	End-point energy (keV) taken from [5]	Positron emission probability (%)
Se-73	7.15(*8*) h	390(*10*) 425(*10*)[3] 425(*10*)[4] 540(*10*) 725(*10*) 1290(*10*) 1651(*10*)	0.0040(*4*) 0.019(*2*) 0.019(*2*) 0.0183(*12*) 0.0007(*4*) 64.7(*9*) 0.64(*6*) *Total:* 65.4(*9*)
Br-75	96.7(*13*) min	447(*14*) 628(*14*) 633(*14*) 763(*14*) 809(*14*) 824(*14*) 863(*14*) 934(*14*) 988(*14*) 1005(*14*) 1045(*14*) 1113(*14*) 1149(*14*) 1231(*14*) 1344(*14*) 1422(*14*) 1580(*14*) 1721(*14*) 2008(*14*)	0.031(*5*) 0.015(*3*) 0.046(*6*) 0.64(*7*) 0.43(*5*) 0.26(*3*) 0.057(*10*) 0.42(*4*) 0.65(*9*) 0.11(*1*) 0.062(*10*) 0.98(*11*) 3.4(*4*) 0.47(*5*) 3.3(*2*) 1.21(*13*) 4.9(*8*) 52(*3*) 4(*4*) *Total:* 73(*5*)
Br-76	16.2(*2*) h	337(*9*) 385(*9*) 482(*9*) 589(*9*) 781(*9*) 871(*9*) 990(*9*) 1271(*9*) 1285(*9*) 1310(*9*) 1426(*9*) 1512(*9*) 2153(*9*) 2725(*9*) 2819(*9*) 3382(*9*) 3941(*9*)	0.03(*1*) 0.04(*1*) 0.13(*3*) 0.92(*11*) 1.44(*13*) 6.3(*6*) 5.2(*4*) 1.24(*13*) 0.20(*9*) 0.30(*17*) 0.35(*14*) < 1 1.0(*4*) 2.8(*13*) 2.1(*7*) 25.8(*19*) 6(*1*) *Total:* 55(*3*)

[3] Populates 1292.75-keV nuclear level of As-73.
[4] Populates 1292.81-keV nuclear level of As-73.

Table 2 cont'd

Radionuclide	Half-life	End-point energy (keV) taken from [5]	Positron emission probability (%)
Kr-77	74.4(*6*) min	465(*9*)	0.026(*3*)
		943(*9*)	0.021(*5*)
		1017(*9*)	0.19(*2*)
		1074(*9*)	0.17(*1*)
		1176(*9*)	0.33(*3*)
		1623(*9*)	2.7(*4*)
		1765(*9*)	33.8(*17*)
		1874(*9*)	0.11(*3*)
		1879(*9*)	0.19(*3*)
		1911(*9*)	41.5(*19*)
		2041(*9*)	< 5
			Total: 84(*4*)
Rb-81	4.572(*4*) h	191(*6*)[5]	0.0028(*4*)
		223(*6*)[5]	0.0090(*11*)
		297(*6*)[5]	0.00194(*20*)
		516(*6*)[5]	0.28(*6*)
		580(*6*)[5]	1.82(*10*)
		609(*6*)[5]	0.018(*6*)
		1026(*6*)[5]	25(*1*)
			Total: 27(*1*)
Rb-82m	6.472(*6*) h	409(*7*)	0.002(*2*)
		436(*7*)	0.17(*4*)
		527(*7*)	0.029(*6*)
		597(*7*)	0.042(*7*)
		619(*7*)	0.61(*8*)
		798(*7*)	19.7(*16*)
		899(*7*)	0.18(*3*)
			Total: 20.8(*16*)
Sr-83	32.41(*3*) h	449(*6*)	0.9(*4*)
		494(*6*)	0.012(*6*)
		517(*6*)	0.0021(*11*)
		689(*6*)	0.023(*12*)
		830(*6*)	3.1(*16*)
		865(*6*)	0.014(*9*)
		1212(*6*)	9(*6*)
		1254(*6*)	13(*19*)
			Total: 26(*20*)

[5] End-point energy calculated directly from ENSDF nuclear levels and Q-value.

Table 2 cont'd

Radionuclide	Half-life	End-point energy (keV) taken from [5]	Positron emission probability (%)
Y-86	14.74(*2*) h	249(*14*) 275(*14*) 292(*14*) 346(*14*) 387(*14*) 443(*14*) 452(*14*) 531(*14*) 573(*14*) 856(*14*) 900(*14*) 927(*14*) 1033(*14*) 1162(*14*) 1221(*14*) 1340(*14*) 1430(*14*) 1545(*14*) 1576(*14*) 1736(*14*) 1988(*14*) 2364(*14*) 3141(*14*)	0.0038(*10*) 0.0029(*7*) 0.035(*7*) 0.0035(*6*) 0.22(*4*) 0.011(*2*) 0.26(*3*) 0.057(*7*) 0.31(*3*) 0.18(*2*) 1.1(*2*) 0.043(*16*) 1.9(*4*) 1.33(*11*) 11.9(*5*) 0.69(*12*) 0.05(*3*) 5.6(*5*) 0.05(*3*) 1.7(*10*) 3.6(*9*) 0.9(*9*) 2.0(*11*) *Total*: 31.9(*21*)
Nb-90	14.60(*5*) h	448(*4*) 714(*4*) 857(*4*) 1500(*4*)	0.0047(*3*) 0.0104(*11*) 0.031(*5*) 51.1(*18*) *Total:* 51.2(*18*)
Tc-94m	52.0(*10*) min	345(*5*) 440(*5*) 570(*5*) 917(*5*) 1243(*5*) 1446(*5*) 2439(*5*)	0.00026(*9*) 0.0024(*13*) 0.38(*2*) 0.92(*6*) 0.32(*4*) 0.93(*9*) 67.6(*4*) *Total:* 70.2(*4*)
In-110m	69.1(*5*) min	285(*12*) 441(*12*) 485(*12*) 562(*12*) 631(*12*) 755(*12*) 839(*12*) 1135(*12*) 1187(*12*) 1376(*12*) 1442(*12*) 1445(*12*) 2260(*12*)	0.00045(*8*) 0.0014(*2*) 0.00080(*13*) 0.0057(*10*) 0.0029(*4*) 0.0127(*12*) 0.023(*6*) 0.266(*20*) 0.011(*2*) 0.04(*3*) 0.28(*5*) 0.050(*6*) 62(*4*) *Total*: 63(*4*)

Table 2 cont'd

Radionuclide	Half-life	End-point energy (keV) taken from [5]	Positron emission probability (%)
I-120g	81.6(*2*) min	305(*16*) 310(*15*) 405(*15*) 445(*16*) 463(*15*) 475(*15*) 563(*15*) 591(*15*) 696(*15*) 706(*15*) 827(*15*) 921(*15*) 927(*15*) 1099(*15*) 1222(*15*) 1226(*15*) 1251(*15*) 1307(*15*) 1337(*15*) 1430(*15*) 1457(*15*) 1541(*15*) 1557(*15*) 1629(*15*) 1656(*15*) 1845(*15*) 1903(*15*) 1980(*15*) 2137(*15*) 2510(*15*) 2656(*15*) 2668(*15*) 2980(*15*) 3058(*15*) 3392(*15*) 3431(*15*) 3490(*15*) 4033(*15*) 4593(*15*)	0.00026(*6*) 0.00073(*16*) 0.0027(*4*) 0.00158(*23*) 0.0056(*7*) 0.0046(*6*) 0.0029(*3*) 0.0082(*8*) 0.044(*3*) 0.0037(*3*) 0.14(*2*) 0.0024(*3*) 0.069(*9*) 0.25(*3*) 0.15(*2*) 0.12(*2*) 0.0657(*23*) 0.162(*5*) 0.069(*12*) 0.131(*5*) 0.155(*4*) 0.43(*4*) 0.068(*8*) 0.53(*3*) 0.94(*8*) 0.65(*4*) 0.264(*4*) 0.422(*12*) 2.13(*14*) 6.2(*5*) 0.235(*15*) 0.664(*12*) 0.190(*2*) 1.93(*18*) 2.7(*5*) 0.93(*8*) 0.20(*5*) 29.3(*7*) 19.0 (*7*) *Total:* 68.2(*12*)[6]
I-124	4.1760(*3*) d	480.3(*19*) 812.1(*19*) 889.0(*19*) 1534.9(*19*) 2137.6(*19*)	0.000129(*11*)[7] 0.293(*24*)[7] 0.00065(*17*)[7] 11.7(*10*)[7] 10.7(*9*)[7] *Total:* 22.7(*13*)

[6] A recent measurement by means of beta counting and X-ray spectroscopy gave a value of 56(3)% [7].
[7] Positron emission probabilities calculated from ENSDF data – emission probabilities incorporate a normalization factor and uncertainty of 1.00(*8*).

Table 2 cont'd

Radionuclide	Half-life	End-point energy (keV) taken from [5]	Positron emission probability (%)
Tb-152	17.5(*1*) h	528(*15*)	0.0039(*6*)
		563(*15*)	0.0020(*3*)
		581(*15*)	0.019(*3*)
		626(*15*)	0.0018(*3*)
		816(*15*)	0.016(*2*)
		852(*15*)	0.0058(*11*)
		887(*15*)	0.11(*1*)
		913(*15*)	0.0092(*17*)
		966(*15*)	0.068(*6*)
		988(*15*)	0.011(*2*)
		1020(*15*)	0.0049(*9*)
		1056(*15*)	0.015(*2*)
		1136(*15*)	0.046(*5*)
		1185(*15*)	0.14(*2*)
		1222(*15*)	0.190(*16*)
		1278(*15*)	0.0074(*10*)
		1394(*15*)	0.082(*11*)
		1510(*15*)	0.40(*5*)
		1513(*15*)	0.16(*3*)
		1546(*15*)	0.013(*3*)
		1705(*15*)	0.43(*9*)
		1719(*15*)	0.61(*8*)
		1780(*15*)	0.08(*3*)
		1897(*15*)	1.9(*2*)
		2073(*15*)	0.12(*4*)
		2213(*15*)	0.87(*12*)
		2484(*15*)	5.5(*6*)
		2828(*15*)	6.2(*18*)
			Total: 17(*2*)

4.2.2. Produced by generator systems

Positron-emitting radionuclides Sc-44, Cu-62 and Pr-140 are produced by generator systems (Ti-44, Zn-62 and Nd-140, respectively):

- **Ti-44/Sc-44:** adopt DDEP data.
- **Zn-62/Cu-62:** adopt ENSDF evaluation, updated in August 2008.
- **Nd-140/Pr-140:** adopt ENSDF data.

Relevant data are given in Table 3.

Table 3: Relevant decay data for non-standard positron-emitting radionuclides in generator systems (data are taken from Ref. [4] if not indicated otherwise).

Radionuclide	Half-life	End-point energy (keV) taken from [5]	Positron emission probability (%)
Ti-44 (parent)	60.0(*11*) y	-	-
Sc-44	3.97(*4*) h [2]	1474.3 (*19*) [2]	94.27(*5*) [2]
Zn-62 (parent)	9.186(*13*) h	-	-
Cu-62	9.67(*3*) min	624(*4*) 877(*4*) 1753(*4*) 2926(*4*)	0.018(*1*) 0.077(*5*) 0.135(*9*) 97.200(*20*) *Total:* 97.43(*2*)
Nd-140 (parent)	3.37(*2*) d	-	-
Pr-140	3.39(*1*) min	463(*6*) 770(*6*) 2366(*6*)	0.00096(*16*) 0.0067(*8*) 51.0(*3*) *Total:* 51.0(*3*)

4.3. Very short-lived radionuclides formed in hadron therapy

Along with C-11, N-13, O-15 and F-18, very short-lived positron-emitting radionuclides C-10, O-14, F-17 and Ne-18,19 are also formed in hadron therapy. The data for the first four radionuclides were discussed in Section 4.1. – decay data for C-10, O-14, F-17 and Ne-18,19 were reviewed, and ENSDF data should be adopted. Relevant data are given in Table 4.

Table 4: Relevant decay data for very short-lived positron-emitting radionuclides produced in hadron therapy (data are taken from Ref. [4] if not indicated otherwise).

Radionuclide	Half-life (s)	End-point energy (keV) taken from [5]	Positron emission probability (%)
C-10	19.290*(12)*	886.0*(6)* 1907.6*(6)*	1.4601*(19)* 98.500*(20)* Total: 99.960*(20)*
O-14	70.606*(18)*	172.94*(21)* 1808.24*(7)* 4121.04*(7)*	0.019*(1)* 99.249*(10)* 0.610*(10)* Total: 99.878(*14*)
F-17	64.49*(16)*	1738.8*(5)*	99.854*(2)*
Ne-18	1.672*(8)*	1723*(5)* 2343(*5*) 2382*(5)* 3424*(5)*	0.188*(6)* 0.0021(*3*) 7.69*(21)* 92.08*(21)* Total: 100.0(*3*)
Ne-19	17.22*(2)*	662.4(6) 2106.5*(6)* 2216.4*(6)*	0.00213(*20*) 0.012*(2)* 99.888*(2)* Total: 99.902(*3*)

5. Prioritisation

1. Cu-64, Y-86 and I-124 are considered the three most important non-standard radionuclides for PET applications.
   I-124 has suitable physical and chemical properties, and various types of labelled compound are prepared for PET applications. Cu-64 has a shorter half-life, lower positron energy and insignificant gamma-ray emissions. Several compounds have been labelled by chelation, and there is great potential for further developments. Both are good candidates for clinical applications in therapy and diagnosis for a limited range of subjects.
   Y-86 is gaining significance in the clinical dosimetry of Y-90 internal radiotherapy.
2. Br-76, As-72, Se-73 and I-120g are becoming increasingly important for PET applications. Several organic compounds have been labelled with these radionuclides, and further developments can be expected. Tc-94m is gaining significance in the clinical quantification of the most widely used Tc-99m radiopharmaceuticals.
3. Cl-34m, Ni-57, Cu-62, Ga-66, Rb-81,82m and Sr-83 merit further work for potential applications.

6. Recommendations

The bulk of experimental data quantifying positron emission probabilities is obtained by γ-ray spectroscopy linked to new technical developments. Both beta-particle and X-ray measurements have not received much attention.

Direct positron and X-ray measurements are required to resolve a significant number of outstanding issues associated with the radionuclides highlighted above. The following new measurements are recommended:

gamma-ray emission probabilities for Cu-64;
positrons and X-rays in order of priority

1. Y-86,
2. As-72, Se-73 and Tc-94m,
3. Ni-57, Cu-62, Ga-66, Rb-81,82m and Sr-83.

The following immediate evaluations are recommended:

Br-76,
I-120g.

We recommend that BIPM, ICRM and DDEP be contacted. The IAEA should request their assistance in resolving the difficulties and needs regarding the measurements and evaluations outlined above.

Clear quantifications of the total individual EC and positron branching fractions would be beneficial to the Summary table of NuDat 2.4.

The total positron emission probability should be listed in the MIRD table.

Inconsistencies in MIRD and NuDat data were also noted:

MIRD - Cu-62,
NuDat - Sr-83.

(Sec. Note, 1 November 2008: some of these inconsistencies have been eliminated after contacting staff at the NNDC, Brookhaven National Laboratory, USA).

References

[1] Quarterly Journal of Nuclear Medicine and Molecular Imaging **52/2**, June 2008.
[2] DDEP webpage http://www.nucleide.org/DDEP_WG/DDEPdata.htm, October 2008.
[3] Medical Internal Radiation Dose (MIRD) database *http://www.nndc.bnl.gov/mird*, September 2008.
[4] ENSDF webpages *http://www-nds.iaea.org/ensdf/* and *http://www.nndc.bnl.gov/ensdf/*, October 2008.
[5] NuDat 2.4 webpage *http://www-nds.iaea.org/nudat2*, October 2008.
[6] QAIM, S.M., BISINGER, T., HILGERS, K., NAYAK, D., COENEN, H.H., Positron emission intensities in the decay of ^{64}Cu, ^{76}Br and ^{124}I, Radiochim. Acta **95** (2007) 67-73.
[7] HOHN, A., COENEN, H.H., QAIM, S.M., Positron emission intensity in the decay of ^{120g}I, Radiochim. Acta **88** (2000) 139-141.

Consultants' Meeting on

"High-precision beta-intensity measurements/evaluations for Specific PET radioisotopes"

IAEA Headquarters, Vienna, Austria
3 – 5 September 2008

Meeting Room B0404

Provisional AGENDA

Wednesday, 3 September

09:00 - 09:30	**Registration** (IAEA Registration desk, Gate 1)
09:45 - 10:00	**Opening Session**
	Welcoming address – Alan L. Nichols Introductory Remarks – Roberto Capote Noy Election of Chairman and Rapporteur Adoption of Agenda
10:00 - 12:30	**Session 1: Presentations by participants**
	A.L. Nichols, R. Capote Noy (IAEA activities on medical data) S.M. Qaim
	Coffee break
	S.L. Waters T. Nozaki G.F. Steyn
12:30 – 14:00	***Lunch***
14:00 – 17:30	**Session 2: General discussion and definition of nuclear data problems related to PET radionuclides**
	Coffee break
	Session 3: Detailed discussion on positron emission intensities of non-standard PET radionuclides

Thursday, 4 September

09:00 - 15:30	**Session 3 cont'd**
	Coffee break and lunch break in between
15:30 – 17:00	**Session 4: Start preparation of report and recommendations**

Friday, 5 September

09:00 - 15:30	**Session 5: Finalisation of report and recommendations**
	Coffee break and lunch break in between
15:30 – 17:00	**Session 5 cont'd**
17:00	**Closing of the meeting**

Consultants Meeting on
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