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REPORT ON THE INTERNATIONAL COMPARISON OF GAMMA-RAY REFERENCE SOURCES

by

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Abstract

An international comparison of γ-ray reference sources was organised by Physikalisch-Technische Bundesanstalt on behalf of Bureau International des Poids et Mesures and took place during 1977 through 1979. Nearly one hundred sources of sixteen different radionuclides, prepared and calibrated by eight laboratories, have been measured at Physikalisch-Technische Bundesanstalt, using NaI(Tl) or Ge(Li) spectrometry, under well-defined and stable conditions. The results of these relative measurements are expressed as deviations from the mean values and checked against activity values based on the international reference system for activity measurements of γ-ray emitting nuclides. Some important experimental details are described, and the results are presented in tabular and graphical forms.

1. Introduction

During the past decade Ge(Li) detectors - and recently high purity germanium detectors - have become a powerful and indispensable tool in radiation research and applied γ-ray spectrometry. They allow an accurate measurement of γ-ray emission probabilities P_γ or, with the knowledge of the P_γ values, the activity determination of γ-ray emitting radionuclides, even if the source consists of a mixture of several radionuclides. This occurs e.g. in the field of activation analysis, non-destructive burn-up determinations, analysis of radioactive waste or environmental samples and in the measurement of radioactive impurities. All these measurements require a calibration of the full-energy peak efficiency of the spectrometer system as a function of the γ-ray energy. The most accurate efficiency calibration is obtained experimentally by means of γ-ray reference sources, prepared from various radionuclides with γ rays of different energies and well-known emission probabilities. To date sources of this kind are produced and distributed by several national laboratories.

Because of the increasing importance of such sources, Section II of Comité Consultatif pour les Etalons de Mesure des Rayonnements Ionisants (CCEMRI) decided at its third meeting, in 1975, to carry out an international comparison of γ-ray reference sources and charged PTB with its organization.

A circular letter explaining details of the organization and the planned measurements was distributed in September 1976 to several national laboratories which produce calibration sources. They were asked to furnish a set of such sources for a comparison to be carried out at PTB by means of a NaI(Tl) scintillation counter and/or a Ge(Li) spectrometer. In addition, participants were asked to supply BIPM with the corresponding solutions for an intercomparison within the scope of the international reference system for activity measurements of γ-ray emitting nuclides (SIR).

Eight laboratories followed the invitation and forwarded sources of different radionuclides together with the corresponding certificates to PTB; altogether 94 single-radionuclide sources of 16 different radionculides and one mixed-radionuclide γ-ray emission-rate source were included in this intercomparison. The last sources arrived at PTB at the beginning of 1979.

The list of the participating laboratories is reproduced in Table 1. The sources used in the comparison are listed in Table 2.

2. Sources

Gamma-ray point sources for calibration are normally prepared from standardized solutions. They consist of a dried deposit - 3 to 5 mm in diameter - of the radionuclide considered, sealed between two layers of plastic foil which are mounted in an annular source holder.
The dimensions of the sources from the different laboratories varied considerably. In order to guarantee equal counting conditions with respect to self-absorption, scattering and source-to-detector distance, the sources were carefully removed from their holders and repacked into identical PTB holders, if necessary by adding further plastic foils. Moreover, ^{22}Na sources were sandwiched between two brass disks of (0.301 ± 0.002) mm each, in order to ensure that the annihilation radiation be produced within the source. Six sources transmitted by AAEC were so-called "2π sources", with the radioactive substance deposited onto a 3 mm thick plastic support and covered by a polyethylene film of 2.4 mg/cm^2.

The data of the individual sources, as given in the accompanying certificates, are reproduced in Table 3. If in the certificate the γ-ray emission rate was stated together with the emission probability, for the sake of uniformity, the activity was calculated from both values. The total uncertainty in column 6 is the linear sum of the random uncertainty at the 99% confidence level and the estimated systematic uncertainty.

3. Measurements

For the intercomparison the sources of the same radionuclide were compared relatively under identical geometrical conditions by means of a NaI(Tl) scintillation counter, operated in the integral mode, or by a Ge(Li) spectrometer. If possible, scintillation counting was preferred, owing to the higher efficiency and better reproducibility. Moreover, this measuring device was provided with an automatic sample changer, allowing countings during the night or over the weekends without interference by other radiation sources.

3.1. Scintillation counting

The scintillation counter used was equipped with a NaI(Tl) crystal of 76 × 76 mm. It was shielded by 10 cm of lead reducing the background count rate to 12 s^{-1}. The storage position of the sample changer, situated at a distance of 120 cm from the NaI crystal, was additionally shielded by 10 cm of lead. As shown experimentally, the contribution to the background from the sources in the storage position amounted to less than 2 s^{-1}.

During the measurements the sources were located at a distance of 30 cm from the front face of the detector. To reduce the intensity of pulses near the discriminator level (normally 30 keV), a Pb foil of 1 mm thickness was placed over the crystal, except in the case of ^{241}Am or ^{57}Co.

Since the source material is generally not exactly in the middle plane of the source holder, each source was counted twice - once with each face towards the detector. Both readings were averaged. The deviations from the mean value were normally less than 0.2%. Each of these two measurements consisted of at least ten single readings with a counting period of 850 s, in each case.

For checking the stability of the measuring device, the standard deviation σ of the ten readings was compared with the expectation value $\sqrt{\bar{N}}$, where $\bar{N}$ is the mean value of the ten readings. In all cases the quotient $\sigma/\sqrt{\bar{N}}$ was between 0.8 and 1.2. In addition, some of the sources obtained at the beginning of the intercomparison were compared quarterly with corresponding PTB sources. Over the two years, the spread in the ratios of the corresponding count rates was up to 0.1% in the case of weak sources and less than 0.04% for stronger sources.

The dead time of the counting equipment, which was of the non-extendable type, has been determined to (6.030 ± 0.003) μs using the two-oscillator as well as the two-source method. Its stability in time has been controlled by counting two ^{152}Eu sources of different activities in the course of each measurement.

3.2. Ge(Li) spectrometry

Ge(Li) spectrometry has been applied in the case of the following sources:

- mixed radionuclide γ-ray emission-rate source of NBS,
- the six 2π sources of AAEC, in order to avoid contributions from radiation scattered within the source support,
- ^{46}Sc, ^{51}Cr and ^{139}Ce sources of AAEC and LMRI respectively because, at the measuring date, no further sources of these radionuclides were available,
- ^{152}Eu sources from LMRI and PTB which contained different amounts of impurities.

The Ge(Li) crystal used had a volume of 40 cm^3. The resolution amounted to 2.9 keV at 1.33 MeV. The sources were located at a distance of 16.5 cm from the front face of the crystal. As in the case of scintillation counting, the sources were measured twice, with each face towards the detector. Normally five spectra were taken for each measurement. Peak areas were obtained both by fitting analytical functions and by summing up the counts in a well-defined region around the peak and subtracting the background obtained by extrapolation of the spectrum from above and below the peak. The total count rates were less than 1 000 s^{-1}. The pulse-generator method was applied for dead-time and pile-up corrections. The stability of the complete spectrometer set-up was ensured by regularly checking for efficiency constancy by a ^{152}Eu source.

4. Results

4.1. Scintillation counting

The results obtained from scintillation counting are reproduced in Table 4 and graphically represented at the end of the report. They are expressed for each source by the ratio Q = N/A, where

N = count rate recorded by the scintillation counter,
A = activity quoted in the certificate,

both calculated for the same reference date. The common reference date and the half-life value used for the decay correction are indicated in the heading for each radionuclide. The uncertainty of the Q values by counting statistics, dead-time and decay corrections is less than 0.1%.

For a comparison of the relative deviations in column 5, the ratios $Q/\overline{Q}$ are given, where $\overline{Q}$ is the unweighted mean value for the radionuclide concerned.

Column 6 contains the corresponding results of the solutions measured within the scope of SIR, expressed by the equivalent activity A_e. As Q is inversely proportional, and A_e proportional, to the activity quoted by the participant, $Q/\overline{Q}$ corresponds to $\overline{A}_e/A_e$. In the graphical representation the $Q/\overline{Q}$ values are indicated by circles and $\overline{A}_e/A_e$ by asterisks. It must be mentioned in this connection that the solutions measured in the framework of SIR are not in all cases identical with the solutions used to prepare the sources. Usually the sources are prepared from stronger solutions so that the deviations observed between the two comparisons may be caused partly by dilution errors.

4.2. Ge(Li) spectrometry

The results obtained by Ge(Li) spectrometry are reproduced in Tables 5 and 6. For the sources without a direct partner at the date of measurement (^{46}Sc, ^{51}Cr and ^{139}Ce in Table 5), the activities A have been determined by PTB according to the relation

$$A = \frac{N}{\varepsilon P} ,$$

where

N = count rate within the full-energy peak, corrected for losses by dead time, pile-up and summation,

ε = full-energy-peak efficiency,

P = γ-ray-emission probability.

The results reproduced in column 7 of Table 5 are compared with the activities quoted in the certificates. The ratios are represented in the last column. The uncertainties given in brackets include only the uncertainty of the PTB value, but not the uncertainty quoted by the laboratory in its certificate. In the case of ^{152}Eu, the efficiency at 1 408 keV had been determined by the measurement of a PTB source at the same time. The uncertainty of the activity of both sources is not included in the final result.

For the mixed radionuclide γ-ray emission-rate source (Table 6), the emission rates B stated in the certificates were compared with the corresponding emission rates measured by PTB according to the relation $B = N/\varepsilon$. The ratios are reproduced in the last column.

Table 1

List of the participants

1.	AAEC	Australian Atomic Energy Commission, Lucas Heights, Australia
2.	AECL	Atomic Energy of Canada Limited, Chalk River, Canada
3.	LMRI	Laboratoire de Métrologie des Rayonnements Ionisants, Saclay, France
4.	NBS	National Bureau of Standards, Washington, D.C., USA
5.	NPL	National Physical Laboratory, Teddington, United Kingdom
6.	OMH	Országos Mérésügyi Hivatal, Budapest, Hungary
7.	PTB	Physikalisch-Technische Bundesanstalt, Braunschweig, Federal Republic of Germany
8.	UVVVR	Ústav pro výzkum, výrobu a využití radioisotopů, Prague, ČSSR

Table 2

Radionuclides and number of sources included in the comparison

x: single-radionuclide source
o: mixed-radionuclide gamma-ray emission-rate source

	AAEC	AECL	LMRI	NBS	NPL	OMH	PTB	UVVVR
^{22}Na	xx		x	x	x	x	xx	xx
^{46}Sc	xx							
^{51}Cr	xx		x					
^{54}Mn	xx		x	x	x	x	xx	xx
^{57}Co	xx		x	o		x	xx	xx
^{60}Co			x	xo	x	x	xx	xx
^{65}Zn	xx		x				xx	
^{85}Sr				xo			xx	
^{88}Y	xx		x	xo	x		xx	xx
^{113}Sn				o				
^{133}Ba	x		x			x	xx	
^{134}Cs		xx					xx	
^{137}Cs	xx	xx		xo	x	x	xx	xx
^{139}Ce			x	xo			xx	
^{152}Eu			x				x	
^{203}Hg				xo			xx	
^{241}Am	xx					x	xx	xx

Table 3: Data from the certificates of the participants

Radio-nuclide	Labora-tory	Source number	Activity kBq	Reference date	Total uncertainty	Recomm. half-life	γ-impurities
^{22}Na	AAEC 1	6572	67.340	78-10-01 0.00 UT	0.55 %		
	AAEC 2	6573	65.780	78-10-01 0.00 UT	0.55 %		< 0.1 %
	LMRI	3557	119.2	78-04-10 12.00 UT	1.0 %	2.602 a	< 0.1 %
	NBS	2 3/76	272.5	76-03-17 10.30 EST	1.6 %	2.609 a	
	NPL	no. 10	197.2	76-12-20 0.00 UT	2.1 %	2.60 a	< 0.03 %
	OMH	77-016	499.5	77-06-01	1.0 %	2.602 a	< 0.03 % for 0.1 < E < 2.5 MeV ∞
	PTB 1	18-72	116.2	77-01-01 16.00 CET	1.5 %	2.602 a	< 0.03 %
	PTB 2	22-72	166.2	77-01-01 16.00 CET	1.5 %		
	UVVVR 1	EFF 12	357.5	77-04-07	1.3 %	2.60 a	< 0.1 %
	UVVVR 2	EFF 13	323.1	77-04-07	1.3 %		
^{46}Sc	AAEC 1	6472	218.1	77-12-15 0.00 UT	0.44 %		
	AAEC 2	6473	213.6	77-12-15 0.00 UT	0.44 %		
^{51}Cr	AAEC 1	6550	1092.3	78-08-01 0.00 UT	0.6 %		< 0.1 %
	AAEC 2	6551	1031.9	78-08-01 0.00 UT			
	LMRI	4536	676	78-04-10 12.00 UT	1,2 %	27.70 d	< 0.1 %

Table 3 (cont'd)

Radio-nuclide	Labora-tory	Source number	Activity kBq	Reference date	Total uncertainty	Recomm. half-life	γ-impurities
^{54}Mn	AAEC 1	6343	121.19	77-03-01 0.00 UT	0.64 %	312.5 d	<0.2 %
	AAEC 2	6347	189.09	77-03-01 0.00 UT			
	LMRI	4151	33.3	78-04-10 12.00 UT	0.8 %	312.3 d	<0.1 %
	NBS	9	402.8	75-05-10 12.00 EST	2.2 %	312.2 d	
	NPL	no.15	190.2	76-12-20 0.00 UT	1.2 %	312.5 d	^{65}Zn 0.06 %
	OMH	77-031	531.0	77-03-15 12.00 UT	0.8 %	312.3 d	<0.02 % for 0.1 < E < 2.5 MeV
	PTB 1	272-76	776.4	76-01-01 16.00 CET	1.5 %	312.5 d	<0.03 %
	PTB 2	306-76	182.0				
	UVVVR 1	359-11	369.2	77-01-22 12.00 CET	1.6 %	312.2	<0.1 %
	UVVVR 2	359-13	408.7				
^{57}Co	AAEC 1	6498	110.18	78-01-15 0.00 UT	1.1 %		^{56}Co: 0.09%; ^{58}Co:0.010%
	AAEC 2	6499	113.76				
	LMRI	166	171.3	78-04-10 12.00 UT	1 %	271.4 d	^{56}Co: 0.06%; ^{58}Co:0.11 % ^{60}Co: 0.013 %
	OMH	77-045	425.5	77-06-01 12.00 UT	0.8 %	271.4 d	^{56}Co:0.015%; ^{58}Co:0.02 % ^{60}Co:0.025 %
	PTB 1	228-75	238.5	75-05-01 16.00 CET	1.5 %	272 d	^{56}Co:0.15%; ^{58}Co: 0.02 %
	PTB 2	422-78	357.9	78-01-01 16.00 CET	1.5 %	272 d	^{56}Co:0.08%; ^{58}Co:0.013 %

Table 3 (cont'd)

Radio-nuclide	Labora-tory	Source number	Activity kBq	Reference date	Total uncertainty	Recomm. half-life	γ-impurities
^{57}Co (cont'd)	UVVVR 1	355-07	407.3	77-01-20 12.00 CET	1.5 %	270 d	^{56}Co: < 0.1 %
	UVVVR 2	355-06	395.5				
^{60}Co	LMRI	417	17.620	78-10-13 12.00 UT		1925.5 d	<0.01 %
	NBS	4210-52	1081	69-04-15 12.00 EST	1.13 %	5.260 a	
	NPL	no. 5	178.5	76-12-20 0.00 UT	1.1 %	5.26 a	<0.05 %
	OMH	77-061	444.5	77-03-15 12.00 UT	0.8 %	5.272 a	<0.04 % for 0.1<E<2.5 MeV
	PTB 1	250-75	363.5	75-01-01 16.00 CET	1.0 %	5.272 a	<0.02 %
	PTB 2	79-70	836.1	73-01-01 16.00 CET			
	UVVVR 1	363-13	716.1	77-02-23	1 %	5.261 a	<0.01 %
	UVVVR 2	363-14	787.6				
^{65}Zn	AAEC 1	6435	100.33	77-10-03 0.00 UT	0.76 %		<0.22 %
	AAEC 2	6436	159.07				
	LMRI	4350	198	78-04-10 12.00 UT	1.5 %	243.75 d	^{60}Co: 0.09 %
	PTB 1	407-78	189.81	78-01-01 16.00 CET	1.5 %	243.97 d	<0.03 %
	PTB 2	408-78	194.36				
^{85}Sr	NBS	PSM6/2	109.5	76-07-18 12.00 EST	2.3 %	64.86 d	
	PTB 1	55-76	41.17	77-01-01 0.00 UT	2.0 %	64.85 d	
	PTB 2	57-76	67.48	77-01-01 0.00 UT	2.0 %		

Table 3 (cont'd)

Radio-nuclide	Labora-tory	Source number	Activity kBq	Reference date	Total uncertainty	Recomm. half-life	γ-impurities
^{88}Y	AAEC 1	6419	116.21	77-09-01 0.00 UT	0.9 %		<0.2 %
	AAEC 2	6420	119.38				
	LMRI	3544	42.88	78-04-10 12.00 UT	1 %	106.6 d	<0.1 %
	NBS	PSM 6-A1	128.33	76-07-18 12.00 EST	2.3 %	106.66 d	
	NPL	G 58/77	349.1	77-06-01 0.00 UT	0.8 %	107 d	<0.04 %
	PTB 1	299-77	199.16	77-04-01 16.00 CET	1.0 %	106.64 d	<0.03 %
	PTB 2	309-77	471.2	77-04-01 16.00 CET	1.0 %	106.64 d	<0.03 %
	UVVVR 1	365-11	564.6	77-03-04	1.2 %	106.6 d	<0.1 %
	UVVVR 2	365-12	565.8				
^{133}Ba	AAEC	6527	118.26	78-07-01 0.00 UT	1.45 %		
	LMRI	3597	119	78-04-10 12.00 UT	1.5 %	10.7 a	<0.1 %
	OMH	77-090	438.8	77-06-01	1.1 %	10.5 a	^{65}Zn:0.002%;^{134}Cs:0.0007 %
	PTB 1	293-75	354.3	75-01-01	1.5 %	10.74 a	<0.1 %
	PTB 2	357-77	257.2	77-01-01	1.5 %	10.74 a	<0.05 %

Table 3 (cont'd)

Radio-nuclide	Labora-tory	Source number	Activity kBq	Reference date	Total uncertainty	Recomm. half-life	γ-impurities
^{134}Cs	AECL 1	11	55.80	77-03-18 17.00 UT	0.55 %	2.062 a	< 0.02 %
	AECL 2	13	37.42	77-03-18 17.00 UT	0.55 %		< 0.02 %
	PTB 1	285-74	169.27	74-01-01 16.00 CET	1.0 %	2.062 a	< 0.03 %
	PTB 2	324-77	168.54	77-05-01 16.00 CET	1.0 %		< 0.03 %
^{137}Cs	AAEC 1	6381	110.8	77-05-01	2.2 %		^{134}Cs: 0.09 % other < 0.1%
	AAEC 2	6382	194.1	77-05-01	2.2 %		
	AECL 1	8	83.11	77-08-16	0.8 %	30.0 a	^{134}Cs: 0.03 %
	AECL 2	14	171.7	77-08-16	0.8 %		
	NBS	4207-167	369.6	68-12-02	1.34 %	29.83 a	
	NPL	G 39/77	434.9	77-06-01	3.8 %	30 a	^{134}Cs < 0.01 %
	OMH	77-105	434.4	77-06-01	1.2 %	29.90 a	^{60}Co: 0.003%; ^{134}Cs: 0.02%,
	PTB 1	333-73	663.3	74-01-01	2 %	30.0 a	< 0.02 %
	PTB 2	327-73	148.1	74-01-01	2 %		< 0.02 %
	UVVVR 1	EFF-02	364.6	76-12-15	1.5 %	30.1 a	< 0.3 %
	UVVVR 2	EFF-11	409.4	76-12-15	1.5 %		< 0.3 %

Table 3 (cont'd)

Radio-nuclide	Labora-tory	Source number	Activity kBq	Reference date	Total uncertainty	Recomm. half-life	γ-impurities
^{139}Ce	LMRI	4095	169.7	78-04-10 12.00 UT	1 %	137.65 d	< 0.1 %
	NBS	PS28-3	52.02	76-03-14 19.00 EST	1.25 %	137.65 d	
	PTB 1	23-76	8.458	77-01-01 16.00 CET	1.5 %	137.65 d	< 0.03 %
	PTB 2	24-76	8.825	77-01-01 16.00 CET	1.5 %		
^{152}Eu	LMRI	2378	162.0	78-04-10	1.2 %	13.1 a	^{154}Eu: 0.08 %
	PTB	285-73	373.0	78-01-01	1.5 %	13.33 a	^{154}Eu: 0.34 %
^{203}Hg	NBS	PSM6 2	103.26	76-07-18 12.00 EST	1.2 %	46.61 d	
	PTB 1	297-76	470.5	76-05-01 16.00 CET	2.0 %	46.59 d	< 0.03 %
	PTB 2	300-76	271.9	76-05-01 16.00 CET	2.0 %		
^{241}Am	AAEC 1	6358	114.5	77-04-01	0.4 %		< 0.1 %
	AAEC 2	6363	187.1				
	OMH	77-135	445.6	77-03-15	0.6 %	433 a	< 0.0005 %
	PTB 1	318-75	688.1	75-01-01	1.0 %	432 a	< 0.01 %
	PTB 2	340-75	111.07	75-01-01	1.0 %		
	UVVVR 1	EFF-5	377.4	77-03-24	0.9 %	433 a	< 0.1 %
		EFF-6	436.0	77-03-24	0.9 %		

Table 4: Results from NaI(Tl)-measurements

Laboratory	Activity A (kBq)	Pulse rate N (s^{-1})	Q = N/A (s^{-1} kBq^{-1})	$Q/\bar{Q}$	SIR(BIPM) $\bar{A_e}/A_e$
^{22}Na Reference date: 77-01-01 0.00 UT; adopted half-life: 950.4 d sandwiched between brass disks of (0.301 ± 0.002) mm					
AAEC 1	107.28	1821.7	16.981	0.984	
AAEC 2	104.79	1780.6	16.992	0.984	
LMRI	167.3	2907.8	17.381	1.007	
NBS	220.7	3807.7	17.253	0.999	
NPL	195.5	3369.5	17.235	0.998	1.000
OMH	557.9	9586.2	17.183	0.995	0.999
PTB 1	116.2	1996.6	17.182	0.995	
PTB 2	166.3	2859.2	17.193	0.996	
UVVVR 1	383.6	6658.2	17.357	1.005	1.001
UVVVR 2	346.6	6011.7	17.345	1.005	
^{54}Mn Reference date: 77-01-01 0.00 UT; adopted half-life: 312.5 d					
AAEC 1	138.13	*)	6.129	0.999	0.998
AAEC 2	215.53	*)	6.130	0.999	
LMRI	93.3	575.2	6.165	1.005	
NBS	106.14	645.1	6.078	0.991	
NPL	185.2	1141.6	6.164	1.005	1.001
OMH	625.0	3811.9	6.099	0.994	0.997
PTB 1	345.2	2117.6	6.134	1.000	0.998
PTB 2	80.93	496.3	6.132	1.000	
UVVVR 1	385.5	2382.4	6.180	1.008	1.007
UVVVR 2	426.7	2626.0	6.154	1.003	

Table 4 (cont'd)

Laboratory	Activity A (kBq)	Pulse rate N (s^{-1})	Q = N/A (s^{-1} kBq^{-1})	$Q/\overline{Q}$	SIR(BIPM) $\overline{A_e}/A_e$
^{57}Co Reference date: 77-01-01 0.00 UT; adopted half-life: 272 d					
AAEC 1	289.44	1981.5	6.846	0.999	0.996
AAEC 2	298.84	2045.3	6.844	0.998	
LMRI	559.5	3835.9	6.856	1.000	
OMH	626.0	4289.0	6.851	0.999	0.995
PTB 1	50.35	345.6	6.864	1.001	
PTB 2	908.7	6235.3	6.862	1.001	
UVVVR 1	428.0	2939.6	6.868	1.002	1.009
UVVVR 2	415.6	2848.8	6.855	1.000	
^{60}Co Reference date: 77-01-01; adopted half-life: 5.272 a					
LMRI	22.27	254.64	11.434	0.998	1.000
NBS	392.1	4484.8	11.438	0.999	
NPL	177.7	2041.1	11.486	1.003	0.999
OMH	456.4	5219.2	11.436	0.998	1.001
PTB 1	279.5	3203.4	11.461	1.001	0.999
PTB 2	494.2	5665.8	11.465	1.001	
UVVVR 1	730.0	8378.0	11.477	1.002	1.000
UVVVR 2	802.9	9208.2	11.469	1.001	
^{85}Sr Reference date: 77-01-01 0.00 UT; adopted half-life: 64.85 d					
NBS	18.52	542.7	29.303	1.000	0.999
PTB 1	41.17	1205.9	29.291	1.000	1.001
PTB 2	67.48	1977.8	29.309	1.000	

Table 4 (cont'd)

Laboratory	Activity A (kBq)	Pulse rate N (s^{-1})	Q = N/A (s^{-1} kBq^{-1})	$Q/\overline{Q}$	SIR (BIPM) $\overline{A_e}/A_e$
^{88}Y Reference date: 77-01-01 0.00 UT; adopted half-life: 106.64 d					
AAEC 1	563.9	6279.2	11.135	0.991	0.996
AAEC 2	579.3	6454.9	11.143	0.992	
LMRI	878.0	9923.6	11.303	1.006	
NBS	43.54	491.8	11.295	1.005	
NPL	931.5	10429.0	11.196	0.997	0.999
PTB 1	358.9	4035.6	11.244	1.001	1.005
PTB 2	849.2	9536.3	11.230	1.000	
UVVVR 1	847.3	9155.6	10.806	0.962	0.965
UVVVR 2	849.1	9181.8	10.814	0.963	
^{133}Ba Reference date: 77-01-01; adopted half-life: 10.74 a					
AAEC	130.24	744.7	5.718	1.006	1.005
LMRI	129.19	730.6	5.655	0.995	
OMH	450.7	2556.6	5.673	0.999	0.991
PTB 1	311.4	1766.7	5.673	0.999	1.005
PTB 2	257.2	1462.8	5.687	1.001	
^{134}Cs Reference date: 77-01-01 0.00 UT; adopted half-life: 753.1 d					
AECL 1	59.88	831.1	13.879	1.001	
AECL 2	40.16	557.0	13.870	1.000	
PTB 1	61.76	856.2	13.863	1.000	
PTB 2	188.33	2610.9	13.863	1.000	

Table 4 (cont'd)

Laboratory	Activity A (kBq)	Pulse rate N (s^{-1})	Q = N/A (s^{-1} kBq^{-1})	$Q/\overline{Q}$	SIR (BIPM) $\overline{A_e}/A_e$
^{137}Cs Reference date 77-01-01; adopted half-life: 30.0 a					
AAEC 1	111.6	*)	5.353	1.001	0.999
AAEC 2	195.6	*)	5.342	0.999	
AECL 1	84.32	449.9	5.336	0.998	0.994
AECL 2	174.19	929.8	5.338	0.998	
NBS	306.7	1626.3	5.303	0.991	
NPL	439.1	2352.4	5.357	1.001	1.005
OMH	438.6	2347.9	5.353	1.001	1.001
PTB 1	618.9	3338.8	5.395	1.009	1.005
PTB 2	138.16	744.1	5.386	1.007	
UVVVR 1	364.2	1951.1	5.357	1.001	0.997
UVVVR 2	409.0	2191.2	5.357	1.001	
^{139}Ce Reference date: 77-01-01 0.00 UT; adopted half-life: 137.65 d					
NBS	11.96	61.52	5.144	1.001	
PTB 1	8.485	43.53	5.130	0.998	
PTB 2	8.853	45.46	5.135	0.999	
^{203}Hg Reference date: 77-01-01 0.00 UT; adopted half-life: 46.59 d					
NBS	8.708	93.73	10.764	0.996	0.995
PTB 1	12.424	134.73	10.844	1.004	1.005
PTB 2	7.180	77.91	10.851	1.004	

Table 4 (cont'd)

Laboratory	Activity A (kBq)	Pulse rate N (s^{-1})	Q = N/A (s^{-1} kBq^{-1})	$Q/\overline{Q}$	SIR(BIPM) $\overline{A_e}/A_e$
^{241}Am Reference date: 77-01-01; adopted half-life: 432.0 a					
AAEC 1	114.55	*)	2.185	1.001	1.004
AAEC 2	187.17	*)	2.184	1.001	
OMH	445.7	972.2	2.181	0.999	0.992
PTB 1	685.9	1499.7	2.186	1.001	0.996
PTB 2	110.7	242.5	2.190	1.003	
UVVVR 1	377.5	823.5	2.181	0.999	1.008
UVVVR 2	436.2	948.7	2.175	0.996	
^{65}Zn Reference date: 78-01-01 0.00 UT; adopted half-life: 243.97 d					
AAEC 1	77.69	242.7	3.124	1.001	1.001
AAEC 2	123.18	385.5	3.130	1.003	
LMRI	262.69	818.2	3.115	0.998	
PTB 1	190.15	592.8	3.118	0.999	0.999
PTB 2	194.71	607.3	3.119	1.000	

*) "2π-sources" with the radioactive source deposited on a 3 mm thick polyethylene disk. Because of the higher contribution of scattered radiation, these sources were compared by means of a Ge(Li) spectrometer with two "foil sources" of the same radionuclide.

Table 5: Results from Ge(Li) measurements

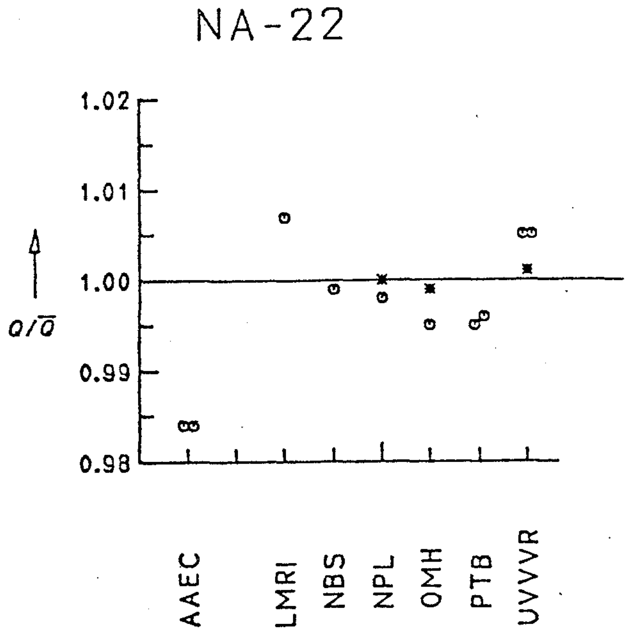
Radio-nuclide	Labora-tory	a) Reference date b) Date of measurement	Half-life used	E (keV)	p (%)	Activity A PTB (kBq)	Activity A Laboratory (kBq)	$\frac{A\ (Laboratory)}{A\ (PTB)}$
^{46}Sc	AAEC 1	a.) 77-12-15 0.00 UT	83.80 d	889	100	218.6 ± 1.1	218.1	0.998 (5)
	AAEC 2	b.) 78-01-06		1120.5	100	214.3 ± 1.1	213.6	0.997 (5)
^{51}Cr	AAEC 1	a.) 78-08-01 0.00 UT	27.705d	320	9.80	1104 ± 9	1092.3	0.989 (8)
	AAEC 2	b.) 78-09-12		320	9.80	1040 ± 8	1031.9	0.992 (8)
	LMRI	a.) 78-04-10 12.00 UT b.) 78-08-02		320	9.80	677.1 ± 3.4	676	0.998 (5)
^{139}Ce	LMRI	a.) 78-04-10 12.00 UT b.) 78-08-09	137.65 d	166	80.0	168.8 ± 0.7	169.7	1.005 (4)
^{152}Eu	LMRI	a.) 78-04-10 b.) 78-07-28	13.33 a	1408	20.85	161.3 ± 0.5	162.0	1.004 (3)

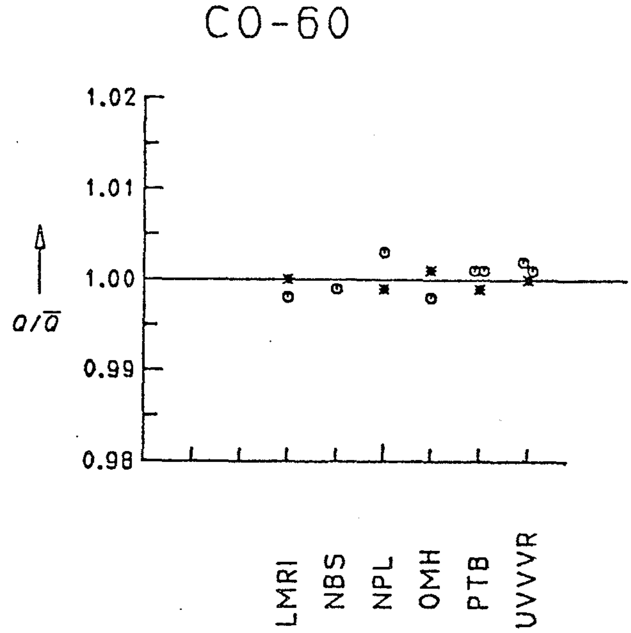
Table 6: NBS Mixed-Radionuclide Gamma-Ray Emission-Rate Source

Reference date: 76-09-01 12.00 EST

Date of measurements: 77-01-04

Data from the certificate							
Radio-nuclide	Energy (keV)	Gamma rays per decay	Half-life	Emission rate B (s^{-1})	Total uncertainty	Half-life used	$\frac{B(NBS)}{B(PTB)}$
^{109}Cd	88	-	464.2 d	1317	2.9 %	not measured	
^{57}Co	122	0.8559(19)	272.4 d	1634	2.5 %	272.0 d	0.988(3)
^{139}Ce	166	0.8006(13)	137.5 d	1316	1.1 %	137.65 d	1.010(4)
^{203}Hg	279	0.815(8)	46.61 d	3884	1.2 %	46.59 d	1.013(5)
^{113}Sn	392	-	115.2 d	4464	2.9 %	115.2 d	0.997(3)
^{85}Sr	514	0.98(1)	64.86 d	6610	2.3 %	64.85 d	0.983(6)
^{137}Cs	662	-	30.0 a	3674	2.1 %	30.0 a	1.016(4)
^{60}Co	1173	0.9990(2)	5.271a	10460	1.4 %	5.272a	1.000(3)
^{60}Co	1332	1.00		10470	1.4 %		0.996(4)
^{88}Y	898	0.950(5)	106.66 d	24480	2.9 %	106.64 d	0.996(3)
^{88}Y	1836	0.9935(3)		25600	2.3 %		0.994(5)


NA-22
1.02
1.01
1.00
0.99
0.98
Q/Q̄
AAEC
LMRI
NBS
NPL
OMH
PTB
UVVVR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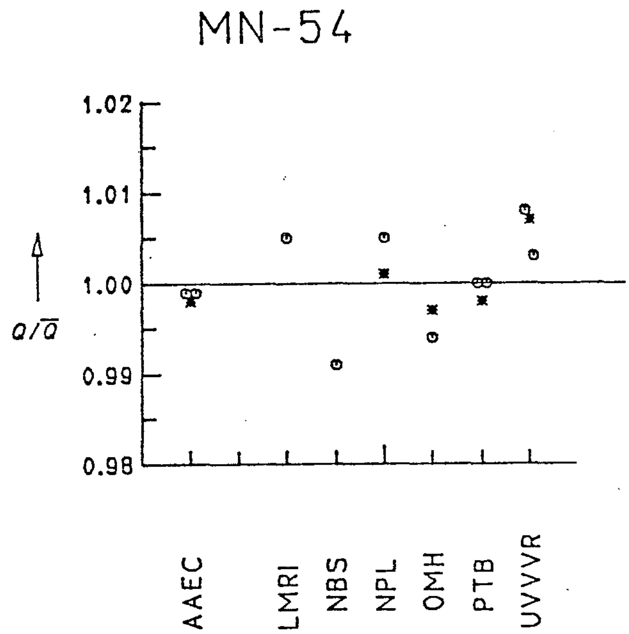
1.00
0.99
0.98
Q/Q̄
LMRI
NBS
NPL
OMH
PTB
UVVVR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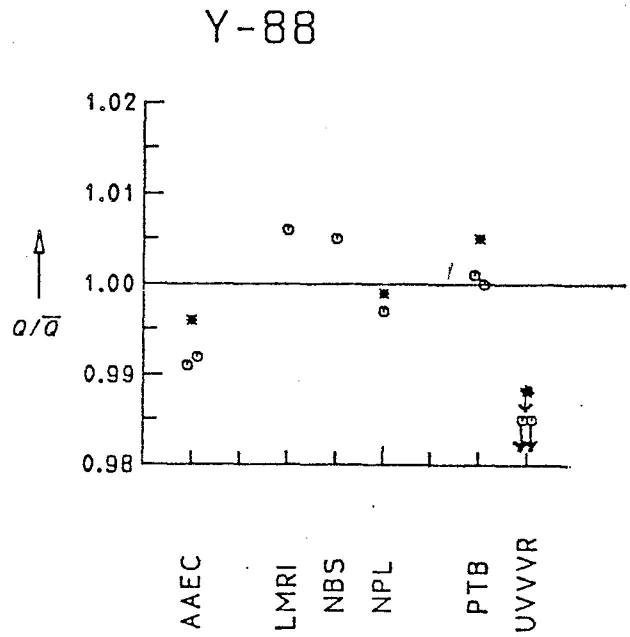
1.01
1.00
0.99
0.98
Q/Q̄
AAEC
LMRI
NBS
NPL
OMH
PTB
UVVVR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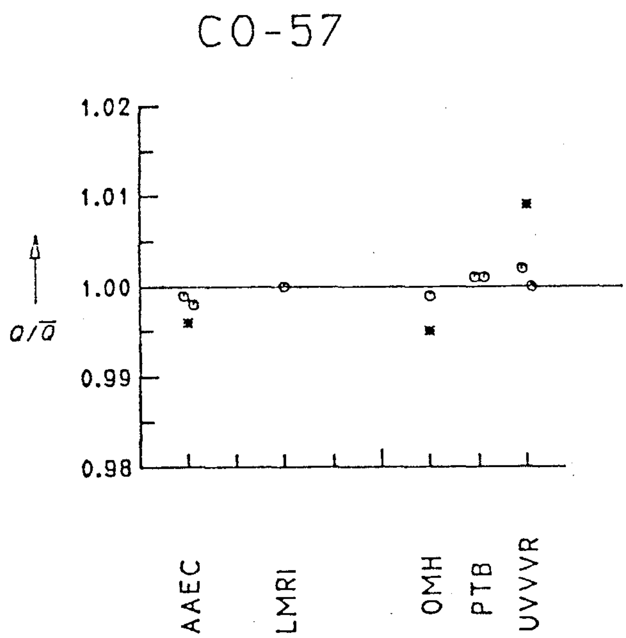
1.00
0.99
0.98
Q/Q̄
AAEC
LMRI
NBS
NPL
PTB
UVVVR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1.00
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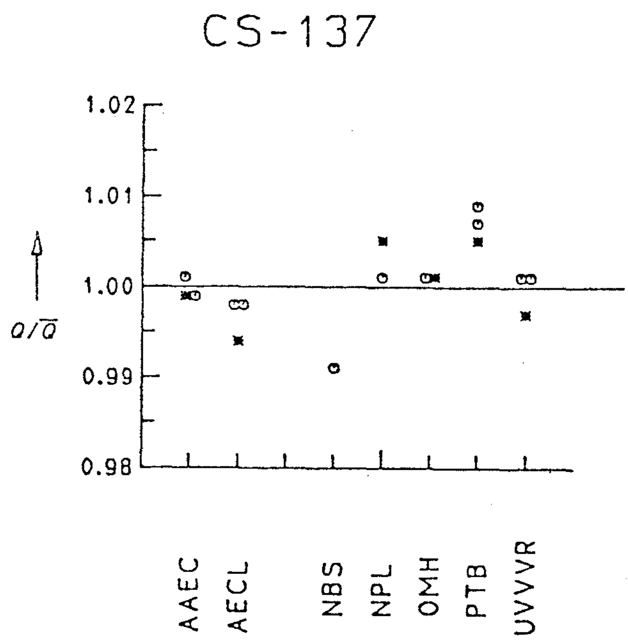
0.98
Q/Q̄
AAEC
LMRI
OMH
PTB
UVVVR


CS-137
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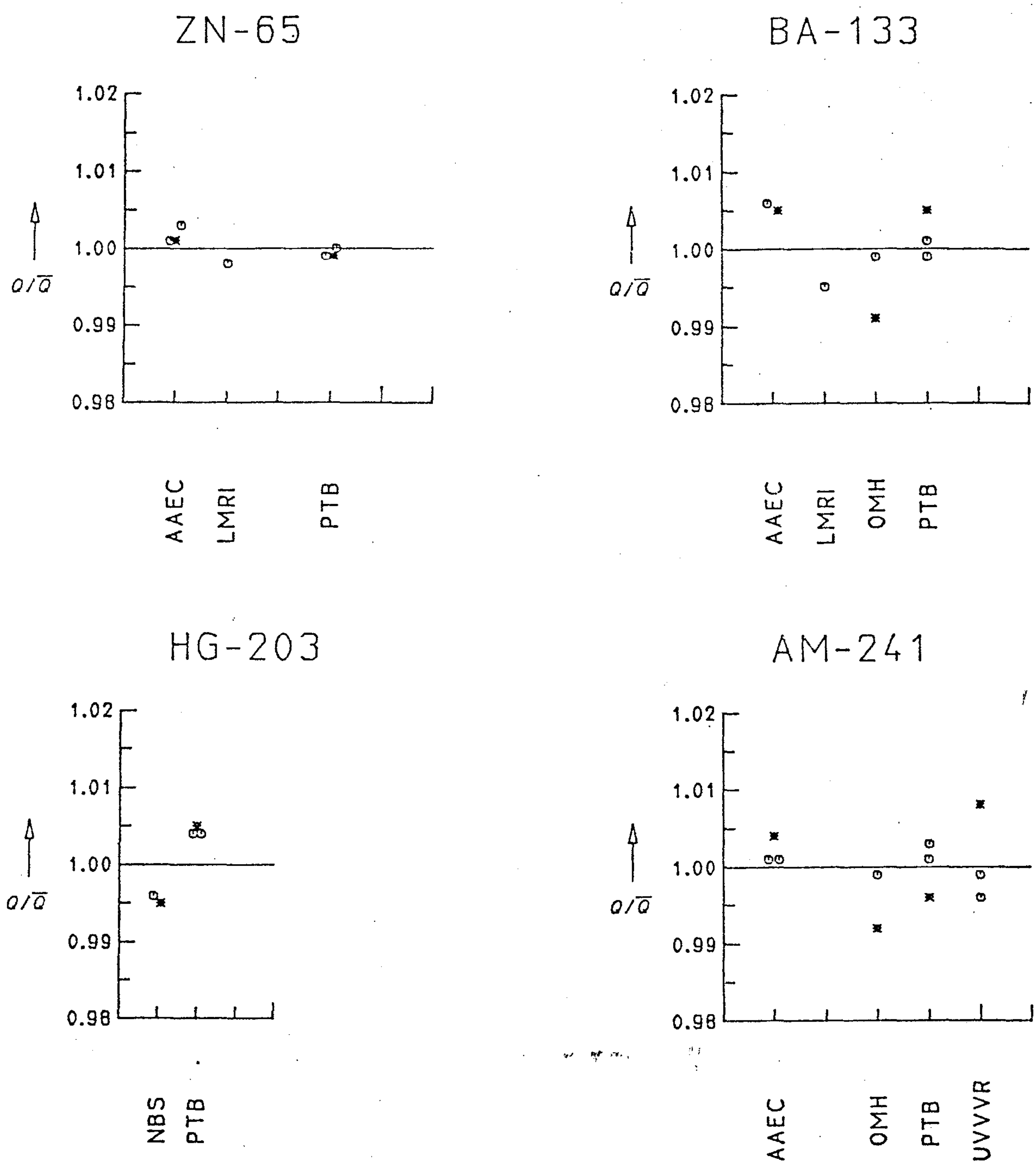
1.01
1.00
0.99
0.98
Q/Q̄
AAEC
AECL
NBS
NPL
OMH
PTB
UVVVR



ZN-65
1.02
1.01
1.00
0.99
0.98
Q/Q̄
AAEC
LMRI
PTB
BA-133
1.02
1.01
1.00
0.99
0.98
Q/Q̄
AAEC
LMRI
OMH
PTB
HG-203
1.02
1.01
1.00
0.99
0.98
Q/Q̄
NBS
PTB
AM-241
1.02
1.01
1.00
0.99
0.98
Q/Q̄
AAEC
OMH
PTB
UVVVR