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BIPM.RI(II)-K1.Ba-133 (2026 update)

Activity of radionuclide Ba-133

KEY COMPARISON

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Update of the BIPM comparison BIPM.RI(II)-K1.Ba-133 of activity measurements of the radionuclide ^{133}Ba to include the 2024 result of the CMI (Czechia) and the 2024 result of the LNMRI-IRD (Brazil)

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Abstract Since 1977, 23 laboratories have submitted 47 samples of ^{133}Ba to the International Reference System (SIR) for activity comparison at the Bureau International des Poids et Mesures (BIPM), with comparison identifier BIPM.RI(II)-K1.Ba-133. Recently, the CMI (Czechia) and the LNMRI-IRD (Brazil) participated in the comparison and the key comparison reference value (KCRV) has been updated. The degrees of equivalence between each equivalent activity measured in the SIR or linked to the SIR from the APMP.RI(II)-K2.Ba-133 comparison and the updated KCRV have been calculated and the results are given in the form of a table. A graphical representation is also given.

1. Introduction

The SIR for activity measurements of γ-ray-emitting radionuclides was established in 1976. Each national metrology institute (NMI) may request a standard ampoule from the BIPM that is then filled with 3.6 g of the radioactive solution. Each NMI completes a submission form that details the standardization method used to determine the absolute activity of the radionuclide and the full uncertainty budget for the evaluation. The ampoules are sent to the BIPM where they are compared with standard sources of ^{226}Ra using pressurized ionization chambers. Details of the SIR method, experimental set-up and the determination of the equivalent activity A_e, are all given in [1].

From its inception until 31 December 2024, the SIR has been used to measure 1065 ampoules to give 818 independent results for 73 different radionuclides. The SIR makes it possible for national laboratories to check the reliability of their activity measurements at any time. This is achieved by the determination of the equivalent activity of the radionuclide and by comparison of the result with the key comparison reference value determined from the results of primary standardizations. These comparisons are described as BIPM continuous comparisons and the results form the basis of the BIPM key comparison database (KCDB) of the Comité International des Poids et Mesures Mutual Recognition Arrangement (CIPM MRA) [2]. The comparison described in this report is known as the BIPM.RI(II)-K1.Ba-133 key comparison.

The results of earlier participations in this key comparison were published previously [3–6].

Successful participation in this comparison by a laboratory may provide evidential support for Calibration and Measurement Capability (CMC) claims for ^{133}Ba measured using the laboratory's method(s) used in the comparison or methods calibrated by those used for the comparison. This comparison may also be used to support CMC claims for those radionuclides measured in the laboratory using the same method and having a degree of difficulty at or below that of the radionuclide measured in this comparison as indicated in the current Measurement Methods Matrix (MMM) [7].

2. Participants

Laboratory details are given in Table 1, with the earlier submissions being taken from [3–6]. The dates of measurement in the SIR given in Table 1 are used in the KCDB and all references in this report. The AECL (Atomic Energy of Canada Ltd) is not part of the NMI in Canada but was an invited participant in various SIR comparisons as, in the early years, J.G.V. Taylor of the AECL was a personal member of the predecessor to the Consultative Committee for Ionizing Radiation Section 2 (CCRI(II)).

Table 1: Details of the participants in the BIPM.RI(II)-K1.Ba-133.

NMI or laboratory	**Previous acronyms or other institutes**	**Full name**	**Country**	**Regional Metrology Organization (RMO)**	**Date of SIR measurement** yyyy-mm-dd
AECL[a]	-	Atomic Energy of Canada Ltd	Canada	SIM	1978-11-09

... Continuation of Table 1.

NMI or laboratory	**Previous acronyms or other institutes**	**Full name**	**Country**	**RMO**	**Date of SIR measurement** yyyy-mm-dd
ANSTO	AAEC	Australian Nuclear Science and Technology Organisation	Australia	APMP	1978-09-01
ASMW	-	Amt für Standardisierung, Meßwesen und Warenprüfung	former East Germany	-	1978-11-08
BEV	IRK	Bundesamt fur Eich- und Vermessungswesen	Austria	EURAMET	1998-06-25 2012-06-12
BIPM	-	Bureau International des Poids et Mesures			1983-11-16
BFKH	OMH, MKEH	Government Office of the Capital City Budapest	Hungary	EURAMET	1977-05-26 1978-10-26 1980-06-30 1991-04-10 1996-12-10
CMI	UVVVR, CMI-IIR	Czech Metrology Institute	Czechia	EURAMET	1978-11-06 1980-02-07 2024-07-15
CNEA	-	Comision Nacional de Energia Atomica	Argentina	SIM	1996-12-20
IAEA	-	International Atomic Energy Agency			1979-02-14
IFIN-HH	-	Institutul National de Cercetare - Dezvoltare pentru Fizica si Inginerie Nucleara "Horia Hulubei"	Romania	EURAMET	2005-12-08
IRA	IER	Institut de Radiophysique	Switzerland	EURAMET	2009-04-15
KRISS	KSRI	Korea Research Institute of Standards and Science	Republic of Korea	APMP	1995-01-19
LNE-LNHB	LMRI, LPRI, BNM-LNHB	Université Paris-Saclay, CEA, List, Laboratoire National Henri Becquerel	France	EURAMET	1979-11-07 2012-03-07
LNMRI-IRD	IEA, IPEN[b]	Laboratorio Nacional de Metrologia das Radiações Ionizantes	Brazil	SIM	1995-11-21 2024-11-05
NIST	NBS	National Institute of Standards and Technology	United States	SIM	1979-03-05 1986-07-24 1998-11-16

... Continuation of Table 1.

NMI or laboratory	**Previous acronyms or other institutes**	**Full name**	**Country**	**RMO**	**Date of SIR measurement** yyyy-mm-dd
					2019-04-15
NMIJ	ETL	National Metrology Institute of Japan	Japan	APMP	1986-02-07 2006-07-07
NMISA	NAC, CSIR-NML[c]	National Metrology Institute of South Africa	South Africa	AFRIMETS	2019-03-12
NPL	-	National Physical Laboratory	United Kingdom	EURAMET	1982-05-04
NRC	-	National Research Council	Canada	SIM	2016-01-28
PTB	-	Physikalisch-Technische Bundesanstalt	Germany	EURAMET	1978-03-13 1981-10-13
PTKMR	PDS, PSPKR, P3KRBiN	Pusat Teknologi Keselamatan dan Metrologi Radiasi	Indonesia	APMP	1991-08-21
TENMAK-NÜKEN	TAEK	Turkish Energy, Nuclear and Mineral Research Agency - Nuclear Energy Research Institute	Türkiye	EURAMET	2018-01-10
VNIIM	-	D.I. Mendeleyev Institute for Metrology	Russian Federation	COOMET	1984-04-18

[a] Federal Crown corporation, not part of the NMI in Canada (see text)
[b] IEA, IPEN are other institutes of the country.
[c] NAC is another institute in the country now named iThemba LABS.

3. NMI standardization methods

Each NMI that submits ampoules to the SIR has measured the activity either by a primary standardization method or by using a secondary method, for example a calibrated ionization chamber. In the latter case, the traceability of the calibration needs to be clearly identified to ensure that appropriate correlations are taken into account.

A brief description of the standardization methods used by the laboratories, the activities submitted, the relative standard uncertainties and the half-life used by the participants are given in Table 2. The uncertainty budgets for the new submissions are given in Appendix D attached to this report; previous uncertainty budgets are given in the earlier reports [3–6]. The list of acronyms used to summarize the methods is given in Appendix E.

Since 2018, the half-life used by the BIPM is 3849.3(22) days as published in BIPM Monographie 5 vol. 8 [8]. The half-life of 3835(37) days [9] was used for the earlier results.

Table 2: Standardization methods of the participants for ^{133}Ba.

NMI or laboratory	**Method used and the acronym**	**Activity** A_i/**kBq**	**Relative standard uncertainty /10^{-2}**		**Reference date**	**Half-life /d**
			A	**B**	**yyyy-mm-dd**	
AECL	4π(PC)-γ coincidence (4P-PC-MX-NA-GR-CO)	3849[b] 4200	0.05 0.05	0.25 0.25	1978-02-28 17:00 UT	
ANSTO	4$\pi\beta$-γ coincidence (4P-00-BR-NA-GR-CO)	347.7	0.2	0.27	1978-07-01 00:00 UT	
ASMW	4π(PC)-γ coincidence (4P-PC-00-NA-GR-CO)	3235[b] 3365	0.1 0.1	0.2 0.2	1978-10-01 12:00 UT	
BEV	ionization chamber calibrated by the NPL (4P-IC-GR-00-00-00)	767	0.28	0.66	1998-06-01 00:00 UT	3848
	ionization chamber calibrated by the NPL (4P-IC-GR-00-00-00)	2698	0.02	0.67	2011-11-01 12:00 UT	3849.65
BIPM	4π(PC)-γ coincidence and selective sampling (4P-PC-00-NA-GR-CO & 4P-PC-00-NA-GR-SS)	4174.0[b] 4176.0 4175.6	0.03 0.03 0.03	0.11 0.11 0.11	1984-03-15 00:00 UT	3846(15)
BFKH	4π(e,x)-γ coincidence (4P-PP-MX-NA-GR-CO)	3535[b] 3534	0.1 0.1	0.8 0.8	1977-04-30 12:00 UT	3835(37)
	4π(e,x)-γ coincidence (4P-PP-MX-NA-GR-CO)	973.4[b] 973.8	0.07 0.07	0.6 0.6	1978-08-01 12:00 UT	3835(37)
	4π(e,x)-γ coincidence (4P-PP-MX-NA-GR-CO)	3578	0.02	0.8	1980-10-01 12:00 UT	3835(37)
	4π(e,x)-γ coincidence (4P-PP-MX-NA-GR-CO)	3476	0.02	0.17	1991-07-01 12:00 UT	3835(37)
	4π(e,x)-γ coincidence (4P-PP-MX-NA-GR-CO)	1585	0.02	0.2	1996-12-01 00:00 UT	3862(15)
CMI	x-γ coincidence (4P-00-XR-NA-GR-CO)	3637	0.12	0.62	1978-09-08 11:00 UT	3780
	4πx-γ coincidence (4P-00-XR-NA-GR-CO)	4303	0.12	0.62	1979-11-28 11:00 UT	3780
	4π (PC)e_A,x-γ coincidence (4P-PC-MX-NA-GR-CO)	465.6	0.1	0.42	2024-06-21 10:00 UTC	3849.4(22) [10]
CNEA	4π (PC)-γ coincidence (4P-PC-00-NA-GR-CO)	3275	0.2	0.8	1996-12-03 12:00 UT	

... Continuation of Table 2.

NMI or laboratory	**Method used and the acronym**	**Activity** A_i/**kBq**	**Relative standard uncertainty /10^{-2}**		**Reference date**	**Half-life /d**
			A	**B**	**yyyy-mm-dd**	
IAEA	-[a]	1618	0.1	0.7	1978-05-01 12:00 UT	3944
IFIN-HH	$4\pi\beta$-γ coincidence (4P-PC-MX-NA-GR-CO)	1431	0.1	0.27	2005-11-14 12:00 UT	3861
IRA	ionization chamber calibrated in 1984 by 4π(PC)β-γ coincidence (4P-IC-GR-00-00-00 & 4P-PC-BP-NA-GR-CO)	2178	0.02	0.2	2008-09-01 00:00 UT	3850(2)
KRISS	4π(e,x)-γ coincidence (4P-PP-MX-NA-GR-CO)	507	0.3	0.45	1994-10-01 00:00 UT	
LNE-LNHB	4π (NaI(Tl)) γ counting (4P-NA-GR-00-00-00)	4083[b] 4067	0.01 0.01	0.14 0.14	1979-04-11 00:00 UT	3835(37)
	4π (NaI(Tl)) γ counting (4P-NA-GR-00-00-HE)	2983	0.13	0.42	2011-10-01 12:00 UT	3850(2)
LNMRI-IRD	4π(e_A,x)-γ coincidence (4P-00-MX-NA-GR-CO)	820	0.06	0.29	1995-07-31 00:00 UT	
	Live Timed Anticoincidence Couting (4P-LS-MX-NA-GR-AC)	796.1	0.27	0.1	2024-09-01 12:00 UTC	3849.0(22)
NIST	4π(e,x)-γ coincidence (4P-00-MX-NA-GR-CO)	2004	0.13	0.29	1978-09-01 17:00 UT	3922
	ionization chamber calibrated by $4\pi\beta$(PPC)-γ coincidence (4P-IC-GR-00-00-00)	3585	0.07	0.21	1986-07-01 00:00 UT	
	ionization chamber calibrated by 4π(e,x)-γ coincidence in 1983 (4P-IC-GR-00-00-00)	1259	0.04	0.26	1998-11-16 12:00 UT	3842(47)
	4π(LS)-γ live-timed anti-coincidence confirmed by ionization chamber and γ spectrometry (4P-LS-MX-NA-GR-AC)	1375.79	0.58	0.11	2018-07-13 17:00 UT	3849.3(22)
NMIJ	4p(PC)x-γ coincidence (4P-PC-XR-NA-GR-CO)	2148[b] 2085	0.09 0.09	0.34 0.34	1986-02-04 12:00 UT	
	4π(e,x)-γ coincidence (4P-PC-MX-NA-GR-CO)	6629	0.21	0.03	2006-04-01 00:00 UT	3850(2) [10]
NMISA	4π(LS) (e,x)-γ coincidence (4P-LS-MX-NA-GR-CO)	1484.68	0.02	0.34	2019-02-07 10:00 UT	3849.3(22)

... Continuation of Table 2.

NMI or laboratory	**Method used and the acronym**	**Activity** A_i/**kBq**	**Relative standard uncertainty /10^{-2}** A	B	**Reference date** yyyy-mm-dd	**Half-life /d**
NPL	ionization chamber calibrated by primary method (4P-IC-GR-00-00-00)	2663	0.03	0.96	1982-04-28 00:00 UT	
NRC	4π (PPC)-γ anticoincidence (4P-AE-PP-GR-NA-AC)	3187.42	0.3	0.5	2015-10-21 12:00 UT	3849.6(22)
PTB	4π(PC)-γ coincidence and 4π(PPC)-γ coincidence (4P-PC-00-NA-GR-CO & 4P-PP-00-NA-GR-CO)	1924	0.03	0.2	1978-01-01 00:00 UT	
	ionization chamber (4P-IC-GR-00-00-00)	4531[b] 4506	0.08 0.08	2.01 0.2	1982-01-01 00:00 UT	
PTKMR	4π(PC)-γ coincidence (4P-PC-00-NA-GR-CO)	568.6	0.07		1991-05-23 00:00 UT	
TENMAK-NÜKEN	ionization chamber calibrated by the PTB (4P-IC-GR-00-00-00)	529.5	0.38	1.53	2016-04-01 12:00 UT	3849.7(23)
VNIIM	4π(e,x)-γ coincidence (4P-00-MX-NA-GR-CO)	6876[b] 6779	0.21 0.21	0.77 0.77	1983-11-28 12:00 UT	

[a] co-operation with The Radiochemical Centre, Amersham, UK
[b] several samples submitted

Details regarding the solutions submitted are shown in Table 3, including any impurities, when present, as identified by the laboratories. When given, the standard uncertainties on the evaluations are shown.

Table 3: Details of each solution of ^{133}Ba submitted.

NMI or laboratory / SIR year	**Chemical composition**	**Solvent conc.** /(mol dm^{-3})	**Carrier conc.** /(µg g^{-1})	**Density** /(g cm^{-3})	**Relative activity of any impurity**[d]
AECL 1978	$BaCl_2$ in HCl	0.6	$BaCl_2$: 10	1.02	-
ANSTO 1978	$BaCl_2$ in HCl	1	$BaCl_2$: 20	1	-
ASMW 1978	$BaCl_2$ in HNO_3	0.1	$BaCl_2$: 500	1.003	-
BEV 1998	$BaCl_2$ in HCl	0.1	$BaCl_2$: 30	1	-
2012	$BaCl_2$ in HCl	0.1	$BaCl_2$: 30	1	^{134}Cs: 4.36(15)x10^{-5}
BIPM 1983	$BaCl_2$ in HCl	1	$BaCl_2$: 60	1.016	^{134}Cs: 0.0011(5) %[a]
BFKH 1977	Ba in HCl	0.1	Ba: 25	-	^{65}Zn: 0.0022(5) % ^{134}Cs: 0.0007(2) %
1978	$BaCl_2$ in HCl	0.1	$BaCl_2$: 25	-	^{134}Cs: 0.0060(15) %

... Continuation of Table 3.

NMI or laboratory / SIR year	**Chemical composition**	**Solvent conc. /(mol dm^{-3})**	**Carrier conc. /(µg g^{-1})**	**Density /(g cm^{-3})**	**Relative activity of any impurity[d]**
1980	Ba in HCl	0.1	Ba: 25	-	^{60}Co: 0.007(2) %
1991	$BaCl_2$ in HCl	0.1	$BaCl_2$: 25	-	^{60}Co: 0.0020(3) % ^{134}Cs: 0.020(5) %
1996	$BaCl_2$ in HCl	0.1	$BaCl_2$: 25	-	^{60}Co: 0.0010(3) % ^{134}Cs: 0.0040(5) %
CMI 1978	$BaCl_2$ in HCl	0.08	$BaCl_2$: 30	-	< 0.2 %
1980	$BaCl_2$ in HCl	0.08	$BaCl_2$: 30	-	^{131}Ba: 0.15(3) %
2024	$BaCl_2$ in HCl	0.16	$BaCl_2$: 30	1	-
CNEA 1996	$BaCl_2.2H_2O$ in HCl	0.1	$BaCl_2.2H_2O$: 36	0.9904	^{134}Cs: 0.30(1) % ^{137}Cs: 0.070(7) %
IAEA 1979	-	-	Ba: 100	-	< 0.05 %
IFIN-HH 2005	$BaCl_2$ in HCl	0.1	$BaCl_2$: 70	1	^{134}Cs: 0.020(7) %
IRA 2009	$BaCl_2$ in HCl	1	$BaCl_2$: 60	1.0163	^{134}Cs: 1.033(9)x10^{-3} ^{137}Cs: 3.168(47)x10^{-4}
KRISS 1995	$BaCl_2.2H_2O$ in HCl	0.5	$BaCl_2.2H_2O$: 1.9	1.0073	^{134}Cs: 0.29(1) %
LNE-LNHB 1979	$BaCl_2$ in HCl	1	$BaCl_2$: 15	1.02	< 10^{-4} %
2012	$BaCl_2.2H_2O$ in HCl	1	Ba: 22 or 73[b]	1.016	-
LNMRI-IRD 1995	$BaCl_2$ in HCl	1	$BaCl_2$: 50	1.013	-
2024	$BaCl_2$ in HCl	0.1	$BaCl_2$: 10	1	None detected
NIST 1979	$BaCl_2$ in HCl	1	$BaCl_2$: 118	1.014(2)	^{134}Cs: 0.0018(2) %
1986	$BaCl_2$ in HCl	1	$BaCl_2$: 62	1.015	< 0.01 %[a]
1998	$BaCl_2$ in HCl	1	$BaCl_2$:120	1.015	-
2019	Ba_2+ in HCl	0.98	$Ba2^+$: 88	1.015(2)	None detected
NMIJ 1986	$BaCl_2$ in HCl	1	$BaCl_2$: 50	1.015	-
2006	$BaCl_2$ in HCl	0.1	$BaCl_2$: 50	1.004	-[c]
NMISA 2019	$BaCl_2$ in HCl	0.1	$BaCl_2$: 2160	1.002	None detected
NPL 1982	$BaCl_2$ in HCl	1	Ba: 50	1.015	-
NRC 2016	HCl	0.1	-	1	None detected
PTB 1978	$BaCl_2$ in HCl	0.1	$BaCl_2$: 30	1	< 0.01 %
1981	$BaCl_2$ in HCl	1	$BaCl_2$: 23	1	-
PTKMR 1991	$BaCl_2$ in HCl	2.7	$BaCl_2$: 28	1	-
TENMAK-NÜKEN 2018	$BaCl_2$ in HCl	0.1	$BaCl_2$: 30	1	None detected

... Continuation of Table 3.

NMI or laboratory / SIR year	**Chemical composition**	**Solvent conc.** / $(\mathrm{mol\,dm^{-3}})$	**Carrier conc.** / $(\mathrm{\mu g\,g^{-1}})$	**Density** / $(\mathrm{g\,cm^{-3}})$	**Relative activity of any impurity**[d]
VNIIM 1984	$BaCl_2$ in HCl	0.1	Ba: 40	1.001	-

[a] Same solution as in the CCRI(II)-K2.Ba-133 comparison in 1984
[b] the Ba concentration measured by ICP-AES of 73 $\mathrm{\mu g\,g^{-1}}$, higher than the value given by the solution provider, was probably due to release of Ba from the glassware
[c] Same solution as in the APMP.RI(II)-K2.Ba-133 comparison in 2006
[d] The ratio of the activity of the impurity to the activity of ^{133}Ba at the reference date

4. Results

All the submissions to the SIR since its inception in 1976 are maintained in a dedicated database based on CSV formatted files controlled by the Git version control system [11]. A machine-readable version of this report (XML format) is attached to this document [12]. The latest submission has added 2 ampoules for the activity measurements of ^{133}Ba giving rise to 47 ampoules in total.

The SIR equivalent activity, $A_{\mathrm{e}i}$, for each ampoule received from each NMI, i, including both previous and new results, is given in Table 4. The relative standard uncertainties arising from the measurements in the SIR are also shown. This uncertainty is additional to that declared by the NMI ($u(A_i)$) for the activity measurement shown in Table 2. Although submitted activities are compared with any of five sources of ^{226}Ra, all the SIR results are normalized to the radium source number 5 [1]. Table 4 also shows the comparison results selected for the KCRV as explained in section 4.1.

It is assumed that these results are insensitive to SIR rotation angle effect. See [13].

Table 4: Results of SIR measurement of ^{133}Ba.

NMI or laboratory / SIR year	Mass m_i **/g**	A_i **/kBq**	^{226}**Ra source**	$A_{\mathrm{e}i}$ **/kBq**	**Relative uncert. from SIR /10^{-4}**	$u_{\mathrm{c}i}$ **/kBq**	$A_{\mathrm{e}i}$ **for KCRV /kBq**
AECL 1978	0.301 524[a]	3849	3	43 788	9	118	43 780(120)[c]
	0.329 044	4200	3	43 773	9	118	-
ANSTO 1978	3.659 2	347.7	1	43 910	13	160	43 910(160)
ASMW 1978	3.554 39	3235	3	43 948	8	105	43 950(100)[c]
	3.697 75	3365	3	43 946	8	104	-
BEV 1998	3.633	767	1	43 670	13	320	-
2012	3.591 1	2698	3	44 060	9	300	-
BIPM 1983	3.601 39	4174.0	3	43 784	8	59	43 767(58)[c]
	3.603 12	4176.0	3	43 769	8	58	-

... Continuation of Table 4.

NMI or laboratory / SIR year	m_i /g	A_i /kBq	^{226}**Ra source**	A_{ei} /kBq	**Relative uncert. from SIR** /10^{-4}	$u_{c,i}$ /kBq	A_{ei} **for KCRV** /kBq
	3.602 75	4175.6	3	43 748		58	-
BFKH 1977	3.605 2	3535	3	44 360	7	360	-
	3.604 4	3534	3	44 340	8	360	-
1978	3.601 3	973.4	2	44 540	10	270	-
	3.602 8	973.8	2	44 520	10	270	-
1980	3.603 7	3578	3	43 990	8	350	-
1991	3.614 8	3476	3	43 636	8	80	-
1996	3.630 1	1585	2	43 772	10	97	43 772(97)
CMI 1978	3.630 06	3637	3	44 310	8	280	-
1980	3.554 93	4303	3	43 900	8	280	-
2024	3.606 7(2)	465.6	1	43 879	12	197	43 880(200)
CNEA 1996	3.593 04	3275	3	44 440	9	370	44 440(370)
IAEA 1979	3.601 4	1618	2	43 730	12	330	-
IFIN-HH 2005	3.641 33	1431	2	43 590	11	140	43 590(140)
IRA 2009	3.650 81(9)	2178	2	43 920	12	100	-
KRISS 1995	3.575 98	507	1	44 300	15	250	44 300(250)
LNE-LNHB 1979	3.688 61	4083	3	43 926	9	72	-
	3.673 46	4067	3	43 930	9	72	-
2012	3.770 9	2983	3	43 880	8	190	43 880(190)
LNMRI-IRD 1995	3.532 66	820	2	44 340	10	140	44 340(140)
2024	3.589 48(179)	796.1	1	44 610[d]	11	140	-
NIST 1979	3.664 17	2004	3	44 330	8	150	-
1986	3.602 23	3585	3	43 730	8	100	-
1998	3.626 02	1259	2	43 910	11	120	-
2019	3.596 26	1375.79	2	43 880	9.9	260	43 880(260)
NMIJ 1986	3.676 9	2148	3	44 189	8	160	-
	3.569 2	2085	3	44 164	8	160	-
2006	3.599 44	6629	3	44 030[b]	8	100	44 030(100)
NMISA 2019	3.535 59	1484.68	2	44 120	10	160	44 120(160)
NPL 1982	3.646 2	2663	3	43 990	9	420	43 990(420)
NRC 2016	3.655 3	3187.42	3	43 310	8.4	260	43 310(260)
PTB 1978	3.615 5(1)	1924	2	43 910	11	100	43 910(100)
1981	3.648 63	4531	3	43 930	8	890	-
	3.629 01	4506	3	43 930	8	890	-
PTKMR 1991	3.678 4	568.6	1	41 801[e]	14	66	-
TENMAK-NÜKEN 2018	3.663 1	529.5	1	43 920	14	700	-
VNIIM 1984	3.522 64	6876	3	43 430	8	350	43 400(350)[c]

... Continuation of Table 4.

NMI or laboratory / SIR year	m_i /g	A_i /kBq	^{226}**Ra source**	A_{ei} /kBq	**Relative uncert. from SIR** /10^{-4}	$u_{c,i}$ /kBq	A_{ei} **for KCRV** /kBq
	3.472 69	6779	3	43 360	8	350	-

[a] mass of active solution before dilution
[b] This result was used to link the APMP.RI(II)-K2.Ba-133 comparison.
[c] An average value and average uncertainty between all submitted samples is used for the KCDB [14].
[d] After being informed that the result was a possible outlier, the LNMRI-IRD re-measured the activity concentration of the solution with a gamma window corrected by a few keV, obtaining a result of 217.8 kBq/g and a corresponding equivalent activity of 43 810(320) kBq.
[e] result identified as an outlier

The results were linked to the 2006 BIPM.RI(II)-K1.Ba-133 comparison through the measurement in the SIR of at least one ampoule of the APMP comparison as explained in [15].

4.1. The key comparison reference value

In May 2013, the CCRI(II) decided to calculate the key comparison reference value (KCRV) by using the power-moderated weighted mean [16] rather than an unweighted mean, as had been the policy. This type of weighted mean is similar to a Mandel-Paule mean in that the NMIs' uncertainties may be increased until the reduced chi-squared value is one. In addition, it allows for a power α smaller than two in the weighting factor. As proposed in [16], α is taken as $2 - 3/N$ where N is the number of results selected for the KCRV. Therefore, all SIR key comparison results can be selected for the KCRV with the following provisions:

(a) results for solutions standardized by only primary techniques are accepted, with the exception of radioactive gas standards (for which results from transfer instrument measurements that are directly traceable to a primary measurement in the laboratory may be included);

(b) each NMI or other laboratory may use only one result (normally the most recent result or the mean if more than one ampoule is submitted);

(c) results more than 20 years old are included in the calculation of the KCRV but are not included in data shown in the KCDB or in the plots in this report, as they have expired;

(d) possible outliers can be identified on a mathematical basis and excluded from the KCRV using the normalized error test with a test value of 2.5 and using the modified uncertainties;

(e) results can also be excluded for technical reasons; and

(f) the CCRI(II) is always the final arbiter regarding excluding any data from the calculation of the KCRV.

Although the KCRV may be modified when other NMIs participate, on the advice of the Key Comparison Working Group of the CCRI(II), such modifications are made only by the CCRI(II) during one of its biennial meetings, or by consensus through electronic means (e.g., email) as discussed at the CCRI(II) meeting in 2013.

Consequently, using the recent result produces an updated KCRV for ^{133}Ba in 2024 of **43 898(59) kBq** with the power α =1.833 that has been calculated using the previously published results, selected as shown in Table 4, for the AECL (1978), ANSTO (1978), ASMW (1978), PTB (1978), NPL (1982), BIPM (1983), VNIIM (1984), LNMRI-IRD (1995), KRISS (1995), BFKH (1996), CNEA (1996), IFIN-HH (2005), NMIJ (2006), LNE-LNHB (2012), NRC (2016), NIST (2019), NMISA (2019), and the CMI (2024) result. This can be compared with the previous KCRV value of 43 899(59) kBq published in 2022 [6].

4.2. Degrees of equivalence

Every participant in a comparison is entitled to have one result included in the KCDB as long as the NMI is a signatory or designated institute listed in the CIPM MRA and the result is valid (i.e., not older than 20 years). No recent submission has been identified as a pilot study so the most recent result of each NMI is normally eligible for inclusion on the KCDB platform of the CIPM MRA [2]. An NMI may withdraw its result only if all other participants agree.

The degree of equivalence of a given measurement standard is the degree to which this standard is consistent with the KCRV [2]. The degree of equivalence is expressed quantitatively in terms of the deviation from the key comparison reference value and the expanded uncertainty of this deviation ($k = 2$). The degree of equivalence between any pair of national measurement standards is expressed in terms of their difference and the expanded uncertainty of this difference and is independent of the choice of key comparison reference value.

4.2.1. Comparison of a given NMI result with the KCRV

The degree of equivalence of the result of a particular NMI, i, with the key comparison reference value is expressed as the difference D_i between the values

$$D_i = A_{\mathrm{e}i} - \mathrm{KCRV} \tag{1}$$

and the expanded uncertainty ($k = 2$) of this difference, U_i, known as the equivalence uncertainty; hence

$$U_i = 2u(D_i) \tag{2}$$

When the result of the NMI i is included in the KCRV with a weight w_i, then

$$u^2(D_i) = (1 - 2w_i)u_i^2 + u^2(\mathrm{KCRV}) \tag{3}$$

However, when the result of the NMI i is not included in the KCRV, then

$$u^2(D_i) = u_i^2 + u^2(\mathrm{KCRV}) \tag{4}$$

The introductory text in Appendix A is the one agreed by the CCRI(II) for all the K1 comparisons.

4.2.2. Comparison between pairs of NMI results

The degree of equivalence between the results of any pair of NMIs, i and j, is expressed as the difference D_{ij} in the values

$$D_{ij} = D_i - D_j = A_{\mathrm{e}i} - A_{\mathrm{e}j} \tag{5}$$

and the expanded uncertainty ($k = 2$) of this difference, $U_{ij} = 2u(D_{ij})$, where

$$u^2(D_{ij}) = u_i^2 + u_j^2 - 2u(A_{\mathrm{e}i}, A_{\mathrm{e}j}) \tag{6}$$

where any obvious correlations between the NMIs (such as a traceable calibration, correlations normally coming from the SIR, or from the linking factor in the case of linked comparison) are subtracted using the covariance $u(A_{\mathrm{e}i}, A_{\mathrm{e}j})$ (see [17] for more detail). However, the CCRI decided in 2011 that these pair-wise degrees of equivalence no longer need to be published as long as the methodology is explained.

Appendix B shows the matrix of all the degrees of equivalence as they will appear in the KCDB. It should be noted that for consistency within the KCDB, a simplified level of nomenclature is used with $A_{\mathrm{e}i}$ replaced by x_i. The introductory text is that agreed for the comparison. The graph of the results in Appendix B, corresponding to the degrees of equivalence with respect to the KCRV (identified as x_R in the KCDB), is shown in Figure C1. This graphical representation indicates in part the degree of equivalence between the NMIs but obviously does not take into account the correlations between different NMIs. It should be noted that the final data in this paper, while correct at the time of publication, will become out-of-date as NMIs make new comparisons. The formal results under the CIPM MRA [2] are those available in the KCDB.

5. Conclusion

The BIPM continuous key comparison for ^{133}Ba, BIPM.RI(II)-K1.Ba-133, currently comprises 11 valid results, incorporating the new degrees of equivalence from CMI

(Czechia) and LNMRI-IRD (Brazil). The KCRV has been recalculated to include the latest result from the CMI (Czechia). The SIR results, together with the previously published APMP.RI(II)-K2.Ba-133 results, have been analyzed with respect to the updated KCRV, providing degrees of equivalence for 18 national metrology institutes. Other results may be added when other NMIs contribute ^{133}Ba activity measurements to this comparison or take part in other linked comparisons.

6. References

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Appendix A. Introductory text for ^{133}Ba degrees of equivalence

Key comparison BIPM.RI(II)-K1.Ba-133

MEASURAND: Equivalent activity of ^{133}Ba

Key comparison reference value: the SIR reference value x_{R} for this radionuclide is 43 898 kBq , with a standard uncertainty, u_{R} equal to 59 kBq (see Section 4.1 of the Final Report). The value x_i is taken as the equivalent activity for a laboratory i.

The degree of equivalence of each laboratory with respect to the reference value is given by a pair of terms: $D_i = (x_i - x_{\mathrm{R}})$ and U_i, its expanded uncertainty ($k = 2$), both expressed in MBq, and $U_i = 2((1 - 2w_i)u_i^2 + u_{\mathrm{R}}^2)^{1/2}$, where w_i is the weight of laboratory i contributing to the calculation of x_{R}.

Appendix B. Table of degrees of equivalence for BIPM.RI(II)-K1.Ba-133

Table B1: The table of degrees of equivalence for BIPM.RI(II)-K1.Ba-133

NMI i	D_i **/MBq**	U_i **/MBq**
IFIN-HH	-0.31	0.29
NMIJ	0.13	0.22
IRA	0.02	0.23
LNE-LNHB	-0.02	0.38
BEV	0.16	0.61
NRC	-0.59	0.52
TENMAK-NUKEN	0.0	1.4
NMISA	0.22	0.32
NIST	-0.02	0.52
CMI	-0.02	0.39
LNMRI-IRD	0.71	0.30

Table B2: The table of degrees of equivalence for the APMP.RI(II)-K2.Ba-133(2006) comparison

NMI i	D_i **/MBq**	U_i **/MBq**
ANSTO	-0.01	0.38
BARC	-1.5	1.2
INER	0.12	0.30
KRISS	0.20	0.32
NIM	0.35	0.59
OAP	-0.1	1.5
PTKMR	1.3	1.4

Appendix C. Graph of degrees of equivalence with the KCRV for ^{133}Ba (as it appears in Appendix B of the CIPM MRA)

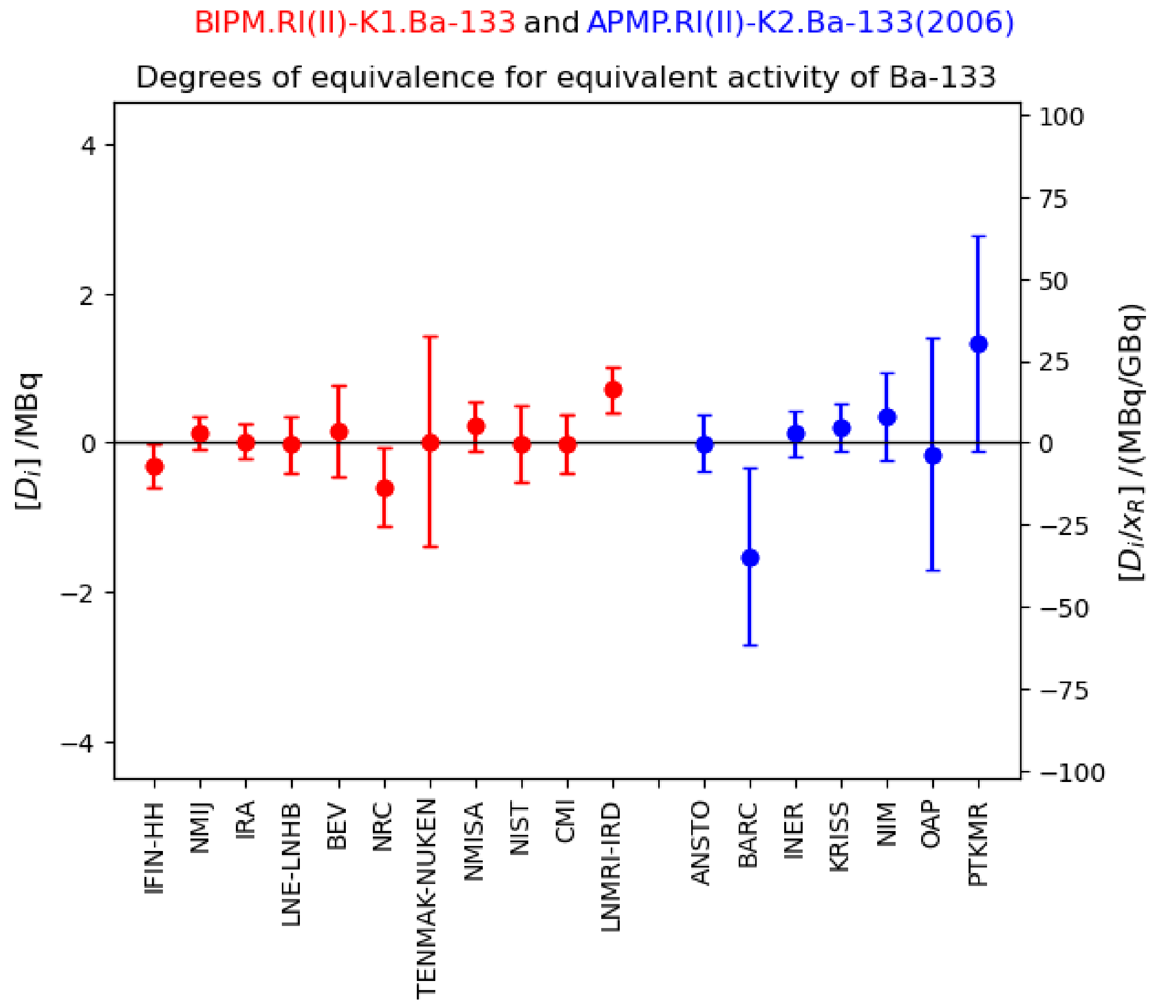

Figure C1. Degrees of equivalence for equivalent activity of ^{133}Ba.

Appendix D. Uncertainty budgets for the activity of ^{133}Ba submitted to the SIR

Detailed uncertainty budget from CMI

SIR/SIRTI reporting form - radioactive solution

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BIPM.RI(II)-K1 or BIPM.RI(II)-K4

Measurement method	4π (PPC) β-γ coincidence	
ACRONYM	4P-PC-BP-NA-GR-CO	**Comments:**
Activity concentration at reference date / kBq g^{-1}	129,0900	
Relative standard uncertainty / 10^{-2}	0,42	
Date of measurement at the NMI (YYYY-MM-DD)	2024-06-21	

For relative methods:

Primary methods or standards used for calibration	
Date of calibration	
Date of primary measurement	

Uncertainty budget

Uncertainty component	**Relative uncertainty / 10^{-2}**	**Evaluation type (A or B)**	**Comment**
Counting statistics	0,100	A	
Background	0,100	B	
Weighing	0,010	B	
Dilution	0,050	B	
Dead time	0,010	B	
Resolving time	0,020	B	
Pile-up, afterpulse			
Adsorption			
Impurities	0,030	B	
Decay correction			
Decay data			
Extra-/Inter-polation of efficiency curve	0,400	B	
Quenching, kB value			
Tracer			
Reproducibility			
Combined standard uncertainty	**0,420**		

Detailed uncertainty budget from LNMRI/IRD

SIR/SIRTI reporting form - radioactive solution

V2.3 page 3a

BIPM.RI(II)-K1 or BIPM.RI(II)-K4

Measurement method	Live Timed Anticoincidence Couting	
ACRONYM	4P-LS-MX-NA-GR-AC	**Comments:**
Activity concentration at reference date / kBq g^{-1}	222	The activity concentration is : 221.8 kBq/g and the total activity is 796237 Bq.
Relative standard uncertainty / 10^{-2}	0.29	
Date of measurement at the NMI (YYYY-MM-DD)	2023 05 28	

For relative methods:

Primary methods or standards used for calibration	
Date of calibration	
Date of primary measurement	

Uncertainty budget

Uncertainty component	Relative uncertainty / 10^{-2}	Evaluation type (A or B)	Comment
Counting statistics	0,15	A	
Background	0,1	B	
Weighing	0,05	B	
Dilution			
Dead time	0,01	B	Live Time
Resolving time			
Pile-up, afterpulse			
Adsorption			
Impurities			
Decay correction	0,01	B	
Decay data			
Extra-/Inter-polation of efficiency curve	0,22	A	
Quenching, kB value			
Tracer			
Reproducibility			
Combined standard uncertainty	**0.29**		

Appendix E. Acronyms used to identify different measurement methods

Each acronym has six components, geometry-detector (1)-radiation (1)-detector (2)-radiation (2)-mode. When a component is unknown, ?? is used and when it is not applicable 00 is used.

Geometry	**acronym**	**Detector**	**acronym**
4 π	4P	proportional counter	PC
defined solid angle	SA	press. Prop. Counter	PP
2 π	2P	liquid scintillation counting	LS
undefined solid angle	UA	NaI(Tl)	NA
		Ge(HP)	GH
		Ge(Li)	GL
		Si(Li)	SL
		CsI(Tl)	CS
		ionization chamber	IC
		grid ionization chamber	GC
		Cerenkov detector	CD
		calorimeter	CA
		solid plastic scintillator	SP
		PIPS detector	PS
		CeBr3	CB

Radiation	**acronym**	**Mode**	**acronym**
positron	PO	efficiency tracing	ET
beta particle	BP	internal gas counting	IG
Auger electron	AE	CIEMAT/NIST	CN
conversion electron	CE	sum counting	SC
mixed electrons	ME	coincidence	CO
bremsstrahlung	BS	anticoincidence	AC
gamma rays	GR	coincidence counting with efficiency tracing	CT
x-rays	XR	anticoincidence counting with efficiency tracing	AT
photons $(x+\gamma)$	PH	triple-to-double coincidence ratio counting	TD
photons + electrons	PE	selective sampling	SS

Radiation	**acronym**	**Mode**	**acronym**
alpha particle	AP	high efficiency	HE
mixture of various radiation	MX	digital coincidence counting	DC

Examples of methods	**acronym**
4π(PC)β-γ coincidence counting	4P-PC-BP-NA-GR-CO
4π(PPC)β-γ coincidence counting eff. trac	4P-PP-MX-NA-GR-CT
defined solid angle α-particle counting with a PIPS detector	SA-PS-AP-00-00-00
4π(PPC)AX-γ(GeHP)-anticoincidence counting	4P-PP-MX-GH-GR-AC
4πCsI-β,AX,γ counting	4P-CS-MX-00-00-HE
calibrated IC	4P-IC-GR-00-00-00
internal gas counting	4P-PC-BP-00-00-IG