Update of the BIPM comparison BIPM.RI(II)-K1.Mn-54 of activity measurements of the radionuclide ^{54}Mn to include the 2024 result of the POLATOM (Poland)

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Abstract Since 1976, 17 laboratories have submitted 43 samples of ^{54}Mn 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.Mn-54. Recently, the POLATOM (Poland) 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 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 2023, the SIR has been used to measure 1054 ampoules to give 807 independent results for 72 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.Mn-54 key comparison. The results of earlier participations in this key comparison were published previously [3–5].

Successful participation in this comparison by a laboratory may provide evidential support for Calibration and Measurement Capability (CMC) claims for ^{54}Mn 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) [6].

2. Participants

Laboratory details are given in Table 1, with the earlier submissions being taken from [3–5]. 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.Mn-54.

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	1980-11-27 1983-07-07
ANSTO	AAEC	Australian Nuclear Science and Technology Organisation	Australia	APMP	1977-03-15
ASMW	-	Amt für Standardisierung, Meßwesen und Warenprüfung	former East Germany	-	1976-09-01
BARC	-	Bhabha Atomic Research Centre	India	APMP	2002-05-16

... Continuation of Table 1.

NMI or laboratory	**Previous acronyms or other institutes**	**Full name**	**Country**	**RMO**	**Date of SIR measurement** yyyy-mm-dd
BEV	IRK	Bundesamt fur Eich- und Vermessungswesen	Austria	EURAMET	2001-09-27
BIPM	-	Bureau International des Poids et Mesures			1976-07-23 1976-12-01 2003-06-30
BKFH	OMH, MKEH	Government Office of the Capital City Budapest	Hungary	EURAMET	1977-03-10 1982-11-02 1998-10-28 2006-06-22
CMI	UVVVR, CMI-IIR	Czech Metrological Institute	Czechia	EURAMET	1977-02-24 1978-08-31 1979-09-07
IAEA	-	International Atomic Energy Agency			1979-02-13
IRA	IER	Institut de Radiophysique	Switzerland	EURAMET	1989-04-28
LNE-LNHB	LMRI, LPRI, BNM-LNHB	Université Paris-Saclay, CEA, List, Laboratoire National Henri Becquerel	France	EURAMET	1983-06-03 1992-12-18 1999-10-19 2006-07-19
LNMRI-IRD	IEA, IPEN[b]	Laboratorio Nacional de Metrologia das Radiações Ionizantes	Brazil	SIM	2000-11-07
NIST	NBS	National Institute of Standards and Technology	United States	SIM	1979-07-06 2002-06-19
NMIJ	ETL	National Metrology Institute of Japan	Japan	APMP	1976-11-22 1993-11-25
NPL	-	National Physical Laboratory	United Kingdom	EURAMET	1976-12-29 2006-03-09
POLATOM	IBJ, RC	National Centre for Nuclear Research Radioisotope Centre POLATOM	Poland	EURAMET	2023-10-06 2024-04-19
PTB	-	Physikalisch-Technische Bundesanstalt	Germany	EURAMET	1977-06-14 1979-03-02 2017-09-13

... Continuation of Table 1.

NMI or laboratory	Previous acronyms or other institutes	Full name	Country	RMO	Date of SIR measurement yyyy-mm-dd

[a] Federal Crown corporation, not part of the NMI in Canada (see text)
[b] IEA, IPEN are other institutes of the country.

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 budget for the new submission is given in Appendix D attached to this report; previous uncertainty budgets are given in the earlier reports [3–5]. The list of acronyms used to summarize the methods is given in Appendix E.

Since 2023, the half life used by the BIPM is 312.19(3) days as published in BIPM Monographie 5 vol. 1 [7]. The half life of 312.2(3) days was used for the earlier results.

Table 2: Standardization methods of the participants for ^{54}Mn.

NMI or laboratory	Method used and the acronym	Activity A_i/kBq	Relative standard uncertainty /10^{-2}		Reference date yyyy-mm-dd	Half life /d
			A	B		
AECL	4π(PC)-γ coincidence (4P-PC-MX-NA-GR-CO)	16 579[i] 17 336	0.03 0.03	0.35 0.35	1980-08-15 17:00 UT	312.21(10)
	4π(PC)-γ coincidence (4P-PC-MX-NA-GR-CO)	2262.9[i] 2254.6	0.05 0.05	0.33 0.33	1983-06-01 05:00 UT	312.21(10)
ANSTO	4π(e,x)-γ coincidence (4P-PC-MX-NA-GR-CO)	1387.7	0.08	0.41	1977-03-01 00:00 UT	
ASMW	4π(e_A,x)-γ coincidence (4P-PC-MX-NA-GR-CO)	1718.3[i] 1715.9	0.06 0.06	0.10 0.10	1976-06-09 12:00 UT	
BARC	4π(e,x)-γ coincidence (4P-PC-MX-NA-GR-CO)	1089	0.68	0.13	2002-02-06 06:30 UT	312.2

... 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	
BEV	ionization chamber (4P-IC-GR-00-00-00)[a]	532.9	0.07	0.68	2001-09-01 00:00 UT	312.15
BIPM	4π(PC)-γ coincidence (4P-PC-MX-NA-GR-CO)	3517.9	0.01	0.14	1975-06-04 00:00 UT	312.2(3)
	4π(PC)-γ coincidence (4P-PC-MX-NA-GR-CO)	3244.1	0.11	0.21	1977-01-01 00:00 UT	312.2(3)
	4π(LS) CIEMAT/NIST (4P-LS-MX-NA-GR-CO)[b]	1161.6	0.3	0.51	2003-10-01 00:00 UT	312.3(4) [8]
BKFH	4π(e,x)-γ coincidence (4P-PP-MX-NA-GR-CO)	2013.7[i] 2014.7	0.15 0.15	0.32 0.32	1977-03-01 12:00 UT	312.3(3) [9]
	4π(e,x)-γ coincidence (4P-PP-MX-NA-GR-CO)	3782	0.02	0.27	1982-11-01 12:00 UT	312.3(3) [9]
	4π(PPC)-γ coincidence (4P-PP-MX-NA-GR-CO)	3314	0.03	0.33	1998-10-27 00:00 UT	312.3(4) [8]
	4π(PPC)e,x-γ coincidence (4P-PP-MX-NA-GR-CO)	479.9	0.06	0.32	2006-07-01 00:00 UT	312.13(3) [10]
CMI	4π(e,x)-γ coincidence (4P-PP-XR-NA-GR-CO)	40 370	0.07	0.35[c]	1977-01-18 11:00 UT	312.2
	4π(e,x)-γ coincidence (4P-PP-XR-NA-GR-CO)	3601	0.1	0.37	1978-07-26 11:00 UT	312.2
	4π(e,x)-γ coincidence (4P-PP-XR-NA-GR-CO)	3112	0.1	0.37	1979-07-17 10:00 UT	312.2
IAEA	4π(e,x)-γ coincidence (4P-PC-MX-NA-GR-CO)	3515	0.1	0.37	1978-07-26 11:00 UT	312.2
IRA	4π(PC)e (4P-PC-MX-NA-GR-CO) x-γ coincidence (4P-NA-GR-00-00-00)	2037[j]	0.01	0.12	1989-04-01 00:00 UT	
LNE-LNHB	4π(PPC)-γ coincidence (4P-PP-XR-NA-GR-CO)	2881[i] 2923	0.1 0.1	0.09 0.09	1983-05-27 12:00 UT	
	4π(PPC)x-γ coincidence (4P-PP-XR-NA-GR-CO)	448	0.15	0.06	1992-11-19 12:00 UT	
	4π(e,x)-γ coincidence (4P-PP-MX-NA-GR-CO)	2119	0.1	0.24	1999-06-14 12:00 UT	312.16(5)
	4π(LS)β-γ coincidence (4P-LS-MX-NA-GR-AC)	1500[i] 1529	0.24 0.24	0.07 0.07	2005-09-15 12:00 UT	312.13(3) [10]
LNMRI-IRD	ionization chamber (4P-IC-GR-00-00-00)[d]	318.1	0.4	0.6	2000-09-15 12:00 UT	312.2(2)
NIST	4π(e (4P-PP-MX-NA-GR-CO)	2218.4[j]	0.06	0.28	1979-04-30 17:00 UT	312.07(5)

... 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
	x)-γ coincidence (4P-PP-MX-NA-GR-AC)					
	ionization chamber (4P-IC-GR-00-00-00)[e]	1474	0.06	0.25	2002-06-01 17:00 UT	312.12(6)
NMIJ	4π(e,x)-γ coincidence (4P-PC-XR-NA-GR-CO)	2569.3[i] 2561.0	0.03 0.03	0.35 0.35	1976-11-01 12:00 UT	
	4π(e,x)-γ coincidence (4P-PC-MX-NA-GR-CO)	1057	0.4	0.5	1993-11-01 00:00 UT	
NPL	ionization chamber (4P-IC-GR-00-00-00)[f]	691.3[i] 668.4	0.03 0.03	0.96 0.96	1976-12-20 00:00 UT	
	4π(PC)e,x-γ coincidence (4P-PC-MX-NA-GR-CO)	1459	0.08	0.27	2006-03-01 12:00 UT	312.13(3) [10]
POLATOM	4π(LS)-γ coincidence (4P-LS-AE-NA-GR-CO) 4π(LS)-γ anticoincidence (4P-LS-AE-NA-GR-AC) 4π(LS)-γ coincidence (4P-LS-AE-NA-GR-CO)	415.0 416.4 416.7	0.44 0.31 0.26	0.42 0.38 0.47	2023-08-01 10:00 UT	312.19(3) [7]
	4π(LS)-γ coincidence (4P-LS-AE-NA-GR-CO)[g1] 4π(LS)-γ anticoincidence (4P-LS-AE-NA-GR-AC)[g2] 4π(LS)-γ coincidence (4P-LS-AE-NA-GR-CO)[g3]	1700.3 1706.9 1703.1	0.43 0.53 0.24	0.61 0.72 0.54	2024-05-15 12:00 UT	312.19(3) [7]
PTB	4π(PC)-γ coincidence and 4π(PPC)-γ coincidence (4P-PC-MX-NA-GR-CO & 4P-PP-MX-NA-GR-CO)	4431.9[i] 4431.4	0.03 0.03	0.11 0.11	1977-05-01 00:00 UT	
	ionization chamber (4P-IC-GR-00-00-00)[h]	6689	0.01	0.2	1979-03-01 00:00 UT	
	4π(PC)-γ coincidence (4P-PC-MX-NA-GR-CO)	6068.6	0.19	0.25	2017-07-01 00:00 UT	312.15(8)

[a] traceable to NPL
[b] The uncertainty budget is available in the CCRI(II)-K2.Mn-54 Final report.
[c] maximum likely error (99 % level) of 1.3×10^{-2}
[d] calibrated by $4\pi\beta$-γ coincidence in 2000
[e] calibrated in 1979 by the primary methods
[f] calibrated by a primary measurement of the same radionuclide
[g1] measurement system (called 4π) using the 4π(LS)-γ coincidence method
[g2] measurement system (called 4π) using the 4π(LS)-γ anticoincidence method
[g3] measurement system (called TDKG) using the 4π(LS)-γ coincidence method
[h] calibrated in 1977 by the primary methods above
[i] several samples submitted
[j] The result is the mean of the different methods.

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 ^{54}Mn 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**[a]
AECL 1980	$MnCl_2$ in HCl	0.3	Mn^{++}:10	1	< 0.2 %
1983	$MnCl_2$ in HCl	0.1	$MnCl_2$:8	1	< 0.2 %
ANSTO 1977	$MnCl_2$ in HCl	0.1	-	-	< 0.2 %
ASMW 1976	$MnCl_2$ in HCl	0.1	$MnCl_2$:20	-	-
BARC 2002	Mn in HCl	0.1	-	1	-
BEV 2001	$MnCl_2$ in HCl	0.1	$MnCl_2$:30	1	^{65}Zn: 9(1)x10^{-5} % ^{134}Cs: 0.0011(1) %
BIPM 1976	$MnCl_2$ in HCl	0.1	$MnCl_2$:5	0.999	< 0.1 %
1976	Mn in HCl	0.1	-	-	-
2003	$MnCl_2$ in HCl	0.1	-	-	^{55}Fe: < 0.12 %
BKFH 1977	Mn in HCl	0.1	Mn^{++}:25	-	-
1982	$MnCl_2$ in HCl	0.1	$MnCl_2$:25	-	^{60}Co: 0.07(2) % ^{65}Zn: 0.08(2) %
1998	$MnCl_2$ in HCl	0.1	$MnCl_2$:25	-	^{60}Co: 0.009(1) %
2006	$MnCl_2$ in HCl	0.1	$MnCl_2$:17	-	^{60}Co: 0.033(4) %
CMI 1977	$MnCl_2$ in HCl	0.01	$MnCl_2$:20	-	< 0.1 %
1978	$MnSO_4$ in HCl	0.08	$MnSO_4$:50	-	^{51}Cr: 0.2(2) %
1979	$MnSO_4$ in HCl	0.08	$MnSO_4$:50	-	< 0.01 %
IAEA 1979	$MnSO_4$ in HCl	0.08	$MnSO_4$:50	-	^{51}Cr: 0.2(2) %
IRA 1989	$MnCl_2$ in HCl	0.1	$MnCl_2$:10	1	^{51}Cr: < 0.008 % ^{59}Fe: < 0.002 %
LNE-LNHB 1983	$MnCl_2$ in HCl	0.1	$MnCl_2$:10	0.999	^{46}Sc: 0.032(3) %

... 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**[a]
1992	$MnCl_2$ in HCl	0.1	$MnCl_2$:5	1	^{57}Co: 0.0023(5) %
1999	Mn^{++} in HCl	0.1	Mn^{++}:10	1.001	^{154}Eu: 0.008(1) %
2006	$MnCl_2$ in HCl	0.1	$MnCl_2$:41	1	^{154}Eu: 0.010(5) %
LNMRI-IRD 2000	$MnCl_2$ in HCl	0.1	$MnCl_2$:30	0.9996	-
NIST 1979	$MnCl_2$ in HCl	1	$MnCl_2$:64	1.016(2)	-
2002	$MnCl_2$ in HCl	0.4	$MnCl_2$:80	1.006(1)	-
NMIJ 1976	$MnCl_2$ in HCl	0.1	$MnCl_2$:50	-	-
1993	$MnCl_2$ in HCl	0.1	$MnCl_2$:50	1	^{55}Fe: 0.3(1) %
NPL 1976	$MnCl_2$ in HCl	0.1	$MnCl_2$:100	-	^{65}Zn: 0.06 %
2006	$MnCl_2$ in HCl	0.5	$MnCl_2$:50	1	-
POLATOM 2023	$MnCl_2$ in HCl	0.5	$MnCl_2$:25	1	^{58}Co: 0.0060(30) % ^{51}Cr: 0.030(15) % ^{59}Fe: 0.0025(13) % ^{65}Zn: 0.0030(15) %
2024	$MnCl_2$ in HCl	0.1	$MnCl_2$:25	1	^{106}Ru/^{106}Rh: 0.215(26) % ^{133}Ba: 0.0354(22) %
PTB 1977	$MnCl_2$ in HCl	0.1	$MnCl_2$:15	-	^{65}Zn: 0.05(1) % ^{55}Fe: $<$ 0.08 %
1979	$MnCl_2$ in HCl	0.1	$MnCl_2$:20	1	^{51}Cr: 1.2(1) % ^{65}Zn: 0.02(1) % ^{55}Fe: $<$ 0.1 %
2017	$MnCl_2$ in HCl	0.1	$MnCl_2$:30	1	^{55}Fe: $<$0.029(12) %

[a] The ratio of the activity of the impurity to the activity of ^{54}Mn 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 1 ampoule for the activity measurements of ^{54}Mn giving rise to 43 ampoules in total.

The SIR equivalent activity, A_{ei}, 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.

POLATOM's 2023 A_{ei} results proved to be outliers, exceeding the KCRV by around 2 %, and so identified as outlier by the PMM [13]. The ampoule was re-measured at a one-month interval, with results increasing from 19 664(16) kBq to 19 702(20) kBq. POLATOM suspected a problem with the ampoule preparation and the mass value reported. The laboratory has resubmitted a ^{54}Mn solution to the SIR in 2024. The ampoule was re-measured at three-month intervals, showing compatible results to within one standard uncertainty (19 520(11) kBq and 19 502(12) kBq).

Table 4: Results of SIR measurement of ^{54}Mn.

NMI or laboratory / SIR year	Mass m_i /g	A_i /kBq	^{226}**Ra source**	A_{ei} /kBq	**Relative uncert. from SIR /10^{-4}**	u_{ci} /kBq	A_{ei} **for KCRV /kBq**
AECL 1980	0.973 89[a]	16 579	3	19 260	6	68	-
	1.018 36	17 336	3	19 270	6	68	-
1983	0.145 047[a]	2262.9	3	19 268	6	64	19 264(64)[h]
	0.144 518	2254.6	3	19 260	5	64	-
ANSTO 1977	3.596 5	1387.7	3	19 221	4	81	19 221(81)
ASMW 1976	3.602 4(5)	1718.3	3	19 263	8	28	19 256(28)[h]
	3.597 3(5)	1715.9	3	19 248	7	28	-
BARC 2002	3.637 6	1089	3	19 470	8	140	19 470(140)
BEV 2001	3.596	532.9	2	19 060	10	130	-
BIPM 1976	3.741 67	3517.9	3	19 231	10	33	-
1976	3.741 78[b]	3244.1	3	19 258	7	46	-
2003	3.663 14	1161.6	3	19 470[c]	7	120	19 470(120)
BKFH 1977	3.601 6	2013.7	3	19 232	5	69	-
	3.603 4	2014.7	3	19 244	6	69	-
1982	3.602 2	3782	4	19 145	7	54	-
1998	3.612 6	3314	3	19 212	5	64	-
2006	3.611 7	479.9	2	19 139	10	66	19 139(66)
CMI 1977	1.129 84[d]	40 370	5	19 048	4	68	-
1978	3.603 03	3601	3	19 331	6	74	-
1979	3.470 22	3112	3	19 222	6	72	19 222(72)
IAEA 1979	3.576 85	3515	3	19 334	7	75	-
IRA 1989	3.594 5	2037	3	19 229	6	25	19 229(25)
LNE-LNHB 1983	3.562 4	2881	4	19 173	5	27	-
	3.615 3	2923	4	19 175	5	28	-
1992	3.609 7	448	2	19 125	7	34	-
1999	3.574 29	2119	3	19 308	7	51	-
2006	3.553 7	1500	2	19 187	12	53	19 199(54)[h]
	3.623 1	1529	2	19 211	12	54	-
LNMRI-IRD 2000	3.467 14	318.1	1	-[e]	15	-	-
NIST 1979	3.661 9	2218.4	3	19 219	6	56	19 219(56)

... 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
2002	3.629 8(2)	1474	3	19 268	6	51	-
NMIJ 1976	3.644 94	2569.3	3	19 271	5	69	-
	3.633 16	2561.0	3	19 275	5	69	-
1993	3.610 5	1057	3	19 230	7	130	19 230(130)
NPL 1976	3.690 8	691.3	2	19 179	9	190	-
	3.568 7	668.4	2	19 153	8	190	-
2006	3.610 46	1459	3	19 268	6	55	19 268(55)
POLATOM 2023	3.592 75	415.0	2	19 611[f]	8	120	-
		416.4		19 677		98	-
		416.7		19 689		107	-
2024	3.631 73(60)	1700.3	3	19 490	6	145	19 520(140)[g]
		1706.9		19 566		175	-
		1703.1		19 522		115	-
PTB 1977	3.660 9(1)	4431.9	4	19 217	5	23	-
	3.660 5(1)	4431.4	4	19 217	5	23	-
1979	3.625 6	6689	4	19 209	5	39	-
2017	3.641 43	6068.6	4	19 250	5	61	19 250(61)

[a] mass before dilution
[b] mass before dilution: 0.62774g
[c] measurement used to link the CCRI(II)-K2.Mn-54 comparison
[d] mass after transfer at the BIPM to an NBS-type ampoule
[e] pilot study
[f] The weighted average of the three methods evaluated by POLATOM, 416.2(22) kBq, was used to calculate an equivalent activity equal to 19 660(110) kBq. This result deviates from the KCRV by around 2 %.
[g] The weighted average of the three methods evaluated by POLATOM, 1702.3(126) kBq, was used to calculate the equivalent activity for the KCDB. The final measurement uncertainty of 12.6 kBq was determined as the systematic uncertainty of the mean.
[h] An average value and average uncertainty between all submitted samples is used for the KCDB [14].

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 [13] 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 [13], 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 ^{54}Mn in 2024 of **19 246(19) kBq** with the power α =1.786 that has been calculated using the previously published results, selected as shown in Table 4, for the ASMW (1976), ANSTO (1977), CMI (1979), NIST (1979), AECL (1983), IRA (1989), NMIJ (1993), BARC (2002), BIPM (2003), BKFH (2006), LNE-LNHB (2006), NPL (2006), PTB (2017), and the present POLATOM (2024) result. This can be compared with the previous KCRV values of 19 252(20) kBq published in 2003 [3] and 19 240(15) kBq published in 2020 [5].

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 [15] 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_{ei} replaced by x_i. The introductory text is that agreed for the comparison. The graph of the results in Table 5, 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 ^{54}Mn, BIPM.RI(II)-K1.Mn-54, currently comprises 5 valid results. The KCRV has been recalculated to include the latest result from the POLATOM (Poland). The results have been analyzed with respect to the updated KCRV, providing degrees of equivalence for 5 national metrology institutes. The degrees of equivalence have been approved by the CCRI(II) and are published in the BIPM key comparison database. Other results may be added when other NMIs contribute ^{54}Mn activity measurements to this comparison or take part in other linked comparisons.

6. References

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Appendix A. Introductory text for ^{54}Mn degrees of equivalence

Key comparison BIPM.RI(II)-K1.Mn-54

MEASURAND: Equivalent activity of ^{54}Mn

Key comparison reference value: the SIR reference value x_{R} for this radionuclide is 19 246 kBq , with a standard uncertainty, u_{R} equal to 19 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.Mn-54

Table B1: The table of degrees of equivalence for BIPM.RI(II)-K1.Mn-54

NMI i	D_i /**MBq**	U_i /**MBq**
NPL	0.02	0.11
BKFH	-0.11	0.13
LNE-LNHB	-0.05	0.10
PTB	0.00	0.12
POLATOM	0.27	0.29

Appendix C. Graph of degrees of equivalence with the KCRV for ^{54}Mn (as it appears in Appendix B of the CIPM MRA)

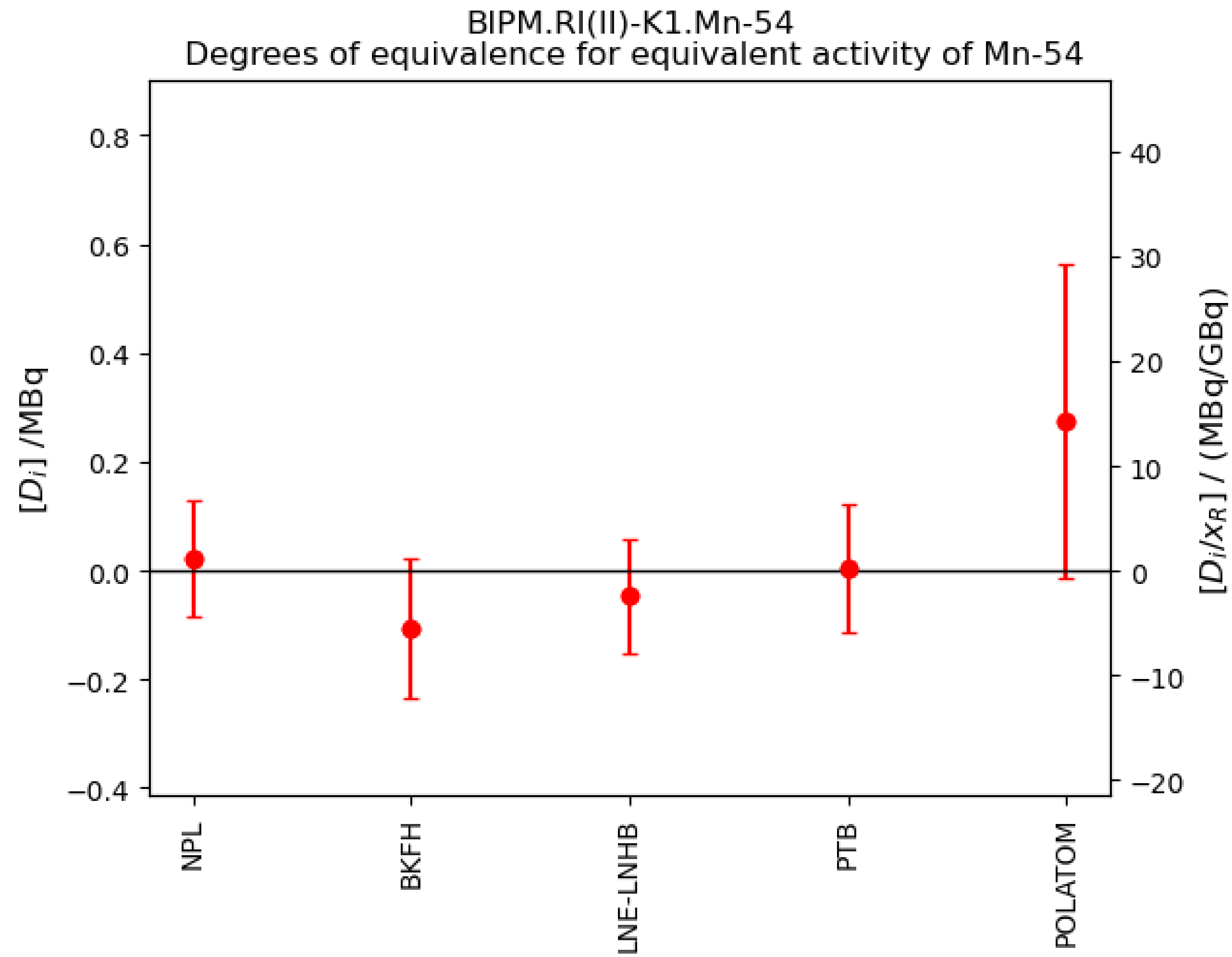

Figure C1. Degrees of equivalence for equivalent activity of ^{54}Mn.

Appendix D. Uncertainty budgets for the activity of ^{54}Mn submitted to the SIR

Detailed uncertainty budget from the POLATOM (method 1)

SIR/SIRTI reporting form - radioactive solution

V2.2 page 3a

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

Measurement method	4π(LS)-γ coincidence	
ACRONYM	4P-LS-AE-NA-GR-CO	**Comments:**
Activity concentration at reference date / kBq g^{-1}	468.18	The result from the measurement system called 4π.
Relative standard uncertainty / 10^{-2}	0.74	
Date of measurement at the NMI (YYYY-MM-DD)	2024-02-12 and 2024-03-05	

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	0.299	A	
Background	0.306	A	
Weighing	0.138	B	
Dilution			no dilution
Dead time	0.01	B	
Resolving time	0.049	B	
Pile-up, afterpulse			
Adsorption	0.04	B	
Impurities	0.25	B	
Decay correction	0.002	B	
Decay data			
Extra-/Inter-polation of efficiency curve	0.362	B	
Quenching, kB value			
Tracer			
Reproducibility			
Measurement method	0.388	B	the relative difference between the measurement results
Combined standard uncertainty	**0.74**		

Detailed uncertainty budget from the POLATOM (method 2)

SIR/SIRTI reporting form - radioactive solution V2.2 page 3b

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

Measurement method	4π(LS)-γ anticoincidence	
ACRONYM	4P-LS-AE-NA-GR-AC	**Comments:**
Activity concentration at reference date / kBq g^{-1}	470.01	The result from the measurement system called 4π.
Relative standard uncertainty / 10^{-2}	0.89	
Date of measurement at the NMI (YYYY-MM-DD)	2024-02-12 and 2024-03-05	

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	0.503	A	
Background	0.171	A	
Weighing	0.138	B	
Dilution			no dilution
Dead time	0.010	B	
Resolving time			
Pile-up, afterpulse			
Adsorption	0.040	B	
Impurities	0.250	B	
Decay correction	0.002	B	
Decay data			
Extra-/Inter-polation of efficiency curve	0.532	B	
Quenching, kB value			
Tracer			
Reproducibility			
Anticoincidence window time	0.012	B	
Measurement method	0.388	B	the relative difference between the measurement results

Detailed uncertainty budget from the POLATOM (method 3)

SIR/SIRTI reporting form - radioactive solution V2.2 page 3c

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

Measurement method	4π(LS)-γ coincidence	
ACRONYM	4P-LS-AE-NA-GR-CO	**Comments:**
Activity concentration at reference date / kBq g^{-1}	468.95	The result from the measurement system called TDKG.
Relative standard uncertainty / 10^{-2}	0.59	
Date of measurement at the NMI (YYYY-MM-DD)	2024-02-16 and 2024-02-28	

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	0.2	A	
Background	0.126	A	
Weighing	0.138	B	
Dilution			no dilution
Dead time	0.01		
Resolving time			
Pile-up, afterpulse			
Adsorption	0.04	B	
Impurities	0.25	B	
Decay correction	0.002		negligible
Decay data			
Extra-/Inter-polation of efficiency curve	0.236	B	
Quenching, kB value			
Tracer			
Reproducibility			
Measurement method	0.388	B	half of the relative difference between the measurement results
Combined standard uncertainty	0.59		

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