Update of the BIPM comparison BIPM.RI(II)-K1.Co-60 of activity measurements of the radionuclide ^{60}Co to include the 2020 result of the PTB (Germany), the 2020 result of the NIST (United States), the 2020 result of the SMU (Slovakia), the 2021 result of the BARC (India), the 2021 result of the LNE-LNHB (France), the 2021 result of the POLATOM (Poland), the 2021 result of the ENEA-INMRI (Italy), the 2021 result of the NPL (United Kingdom), the 2021 result of the LNMRI-IRD (Brazil), the 2022 result of the NMISA (South Africa) and the 2022 result of the ANSTO (Australia)

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Abstract Since 1976, 30 laboratories have submitted 85 samples of ^{60}Co 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.Co-60. Recently, the PTB (Germany), the NIST (United States), the SMU (Slovakia), the BARC (India), the LNE-LNHB (France), the POLATOM (Poland), the ENEA-INMRI (Italy), the NPL (United Kingdom), the LNMRI-IRD (Brazil), the NMISA (South Africa) and the ANSTO (Australia) 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. For radioactive gases, a different standard ampoule is used. 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 2022, the SIR has been used to measure 1045 ampoules to give 799 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.Co-60 key comparison. The results of earlier participations in this key comparison were published previously [3–10].

2. Participants

Laboratory details are given in Table 1, with the earlier submissions being taken from [3–10]. 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.Co-60.

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	1980-04-11 1993-12-20
ANSTO	AAEC	Australian Nuclear Science and Technology Organisation	Australia	APMP	1992-05-13 2022-08-18
ASMW	-	Amt für Standardisierung, Meßwesen und Warenprüfung	former East Germany	-	1976-09-02
BARC	-	Bhabha Atomic Research Centre	India	APMP	1981-09-03 1994-06-20 2001-01-10 2012-01-09 2021-01-07
BEV	IRK	Bundesamt fur Eich- und Vermessungswesen	Austria	EURAMET	1998-10-14 2007-09-27
BIPM	-	Bureau International des Poids et Mesures			1976-07-22
BKFH	OMH, MKEH	Government Office of the Capital City Budapest	Hungary	EURAMET	1977-03-11 1979-12-13 1999-06-11

... Continuation of Table 1.

NMI or laboratory	**Previous acronyms or other institutes**	**Full name**	**Country**	**RMO**	**Date of SIR measurement** yyyy-mm-dd
CIEMAT	-	Centro de Investigaciones Energéticas, Medioambientales y Tecnologicas	Spain	EURAMET	1999-11-30
CMI	UVVVR, CMI-IIR	Czech Metrological Institute	Czechia	EURAMET	1977-03-25 1978-04-18
CNEA	-	Comision Nacional de Energia Atomica	Argentina	SIM	1992-01-28 2003-01-17 2011-10-24
ENEA-INMRI	-	Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile - Istituto Nazionale di Metrologia delle Radiazioni Ionizzanti	Italy	EURAMET	1991-01-22 2021-04-15
IAEA	-	International Atomic Energy Agency			1978-04-03 1978-05-25
IFIN-HH	-	Institutul National de Cercetare - Dezvoltare in Fizica si Inginerie Nucleara- "Horia Hulubei"	Romania	EURAMET	1983-12-15 2007-05-10
IRA	IER	Institut de Radiophysique	Switzerland	EURAMET	1979-05-17 2000-12-06
JRC	IRMM, CBNM	EC-JRC Institute for Reference Materials and Measurements	European Union	EURAMET	2005-01-27
KRISS	KSRI	Korea Research Institute of Standards and Science	Republic of Korea	APMP	1995-01-18
LNE-LNHB	LMRI, LPRI, BNM-LNHB	Université Paris-Saclay, CEA, List, Laboratoire National Henri Becquerel	France	EURAMET	1978-07-17 1986-12-19 1999-10-20 2021-03-04
LNMRI-IRD	IEA, IPEN[b]	Laboratorio Nacional de Metrologia das Radiações Ionizantes	Brazil	SIM	1976-10-07 1984-11-21 2021-09-01

... Continuation of Table 1.

NMI or laboratory	**Previous acronyms or other institutes**	**Full name**	**Country**	**RMO**	**Date of SIR measurement** yyyy-mm-dd
NIM	-	National Institute of Metrology	China	APMP	1978-10-12 2014-07-01
NIST	NBS	National Institute of Standards and Technology	United States	SIM	1980-09-03 1997-01-24 2007-08-07 2020-11-09
NMIJ	ETL	National Metrology Institute of Japan	Japan	APMP	1976-11-24 2004-03-17
NMISA	NAC, CSIR-NML[c]	National Metrology Institute of South Africa	South Africa	AFRIMETS	1981-07-15 1992-10-27 2002-05-30 2022-04-08
NPL	-	National Physical Laboratory	United Kingdom	EURAMET	1977-01-05 2000-06-30 2021-05-03
NRC	-	National Research Council	Canada	SIM	2012-08-29 2021-03-03 [d]
POLATOM	IBJ, RC	National Centre for Nuclear Research Radioisotope Centre POLATOM	Poland	EURAMET	2003-06-17 2021-03-03
PTB	-	Physikalisch-Technische Bundesanstalt	Germany	EURAMET	1977-09-16 1988-01-22 2001-07-02 2017-05-10 2020-07-30
PTKMR	PDS, PSPKR, P3KRBiN	Pusat Teknologi Keselamatan dan Metrologi Radiasi	Indonesia	APMP	1984-06-22
SMU	-	Slovensky Metrologicky Ustav	Slovakia	EURAMET	2020-11-09
TENMAK-NÜKEN	TAEK	Turkish Energy, Nuclear and Mineral Research Agency - Nuclear Energy Research Institute	Türkiye	EURAMET	2018-01-08
VNIIM	-	D.I. Mendeleyev Institute for Metrology	Russian Federation	COOMET	2019-06-28

... 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.
[c] NAC is another institute in the country now named iThemba LABS.
[d] participation in the frame of a pilot study

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 K1 reports [3–10]. The list of acronyms used to summarize the methods is given in Appendix E.

Since 2003, the half-life used by the BIPM is 1925.5(5) days as published in IAEA TECDOC-619 [11]. The half-life of 1924.8(10) days [12] was used for the earlier results.

Table 2: Standardization methods of the participants for ^{60}Co.

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	4$\pi\beta$(PC)-γ coincidence (4P-PC-BP-NA-GR-CO)	1183.4[j] 1189.3	0.02 0.02	0.02 0.02	1980-02-05 17:00 UTC	-
	4$\pi\beta$-γ coincidence (4P-PC-BP-NA-GR-CO)	2069.9	0.05	0.05	1993-10-01 19:00 UTC	
ANSTO	4$\pi\beta$-γ coincidence (4P-PC-BP-NA-GR-CO)	1676	0.1	0.08	1992-04-08 23:00 UTC	
	4$\pi\beta$(LS)-γ anticoincidence (4P-LS-BP-NA-GR-AC) 4$\pi\beta$(LS)-γ coincidence (4P-LS-BP-NA-GR-CO) 4$\pi\beta$(HPPC)-γ coincidence with DCC (4P-PP-BP-NA-GR-CO)	401.88 401.88 401.96	0.020 0.058 0.035	0.129 0.123 0.171	2022-05-02 02:00 UTC	1925.23(29) [16]
ASMW	4$\pi\beta$(PC)-γ coincidence (4P-PC-BP-NA-GR-CO)	1867.8[j] 1870.0	0.04 0.04	0.1 0.1	1976-06-15 12:00 UTC	-
BARC	4$\pi\beta$-γ coincidence (4P-PC-BP-NA-GR-CO)	584.4	0.03	0.25	1981-06-01 06:30 UTC	
	4$\pi\beta$-γ coincidence (4P-PC-BP-NA-GR-CO)	676.1	0.04	0.11	1994-05-01 06:30 UTC	
	4$\pi\beta$-γ coincidence (4P-PC-BP-NA-GR-CO)	1072	0.6	0.3	2000-12-01 06:30 UTC	1922
	4$\pi\beta$(LS)-γ coincidence (4P-LS-BP-NA-GR-CO)	1560	0.29	0.36	2011-03-15 06:30 UTC	1925
	4$\pi\beta$(PC)-γ coincidence (4P-PC-BP-NA-GR-CO) 4$\pi\beta$(SP)-γ coincidence (4P-SP-BP-NA-GR-CO) 4$\pi\beta$(LS)-γ coincidence (4P-LS-BP-NA-GR-CO)	281.94 282.08 283.20	0.44 0.64 0.38		2020-12-01 00:00 UTC	1925.23(29) [16]
BEV	Ionization chamber traceable to the NPL (4P-IC-GR-00-00-00)	2980	0.07	0.58	1998-10-01 12:00 UTC	1925.5
	Ionization chamber traceable to the NPL (4P-IC-GR-00-00-00)	3081	0.08	0.22	2007-10-01 00:00 UTC	1925.2 [16]
BIPM	4$\pi\beta$(PC)-γ coincidence (4P-PC-BP-NA-GR-CO)	2611.2	0.014	0.02	1973-06-06 12:00 UTC	-
BKFH	4$\pi\beta$-γ coincidence (4P-PC-BP-NA-GR-CO)	1345[j] 1345	0.02 0.02	0.32 0.32	1977-03-01 12:00 UTC	1926(3)

... 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**
	$4\pi\beta$-γ coincidence (4P-PC-BP-NA-GR-CO)	1490	0.1	0.26	1979-12-01 12:00 UTC	
	$4\pi\beta$(PC)-γ coincidence (4P-PC-BP-NA-GR-CO)	1808	0.03	0.25	1999-06-01 12:00 UTC	1925.5(5) [11]
CIEMAT	$4\pi\beta$(PC)-γ coincidence (4P-PC-BP-NA-GR-CO) CIEMAT/NIST (4P-LS-BP-00-00-CN)[b]	364.8	0.11	0.1	1999-10-05 12:00 UTC	1925.2
CMI	$4\pi\beta$-γ coincidence (4P-PC-BP-NA-GR-CO)	37 680	0.05	0.8	1977-02-23 13:00 UTC	-
	$4\pi\beta$-γ coincidence (4P-PC-BP-NA-GR-CO)	4190	0.1	0.3	1978-02-09 11:00 UTC	1925(4)
CNEA	$4\pi\beta$(PC)-γ coincidence (4P-PC-BP-NA-GR-CO)	785.3	0.05	0.12	1992-01-01 12:00 UTC	-
	CIEMAT/NIST (4P-LS-BP-00-00-CN) PPC coincidence (4P-PP-BP-NA-GR-CO)	641.2[c]	0.21		2002-10-31 00:00 UTC	1925.3
	$4\pi\beta$(PC)-γ coincidence (4P-PC-BP-NA-GR-CO) TDCR (4P-LS-BP-00-00-TD)	175.5 174.1	0.38 0.32	0.37 0.33	2010-06-27 2010-07-12	1925.2(3) [16]
ENEA-INMRI	$4\pi\beta$(PC)-γ coincidence (4P-PC-BP-NA-GR-CO)	1053	0.2	0.3	1990-12-01 12:00 UTC	-
	4π integral γ counting (4P-NA-MX-00-00-HE) TDCR (4P-LS-BP-00-00-TD)	287.11 287.75	0.30 0.25	0.27 0.36	2021-02-16 12:00 UTC	1925.23(29) [16]
IAEA	$4\pi\beta$-γ coincidence and anticoincidence (4P-??-BP-??-GR-CO, 4P-??-BP-??-GR-AC)	1770	0.07	0.13	1977-04-01 12:00 UTC	1925(4)
	$4\pi\beta$-γ coincidence (4P-PC-BP-NA-GR-CO)	3600	0.1	0.3	1978-02-09 11:00 UTC	1925
IFIN-HH	$4\pi\beta$(PC)-γ coincidence (4P-PC-BP-NA-GR-CO)[d]	1444[j] 1424	0.05 0.05	0.09 0.09	1983-09-01 12:00 UTC	-
	$4\pi\beta$(PC)-γ coincidence (4P-PC-BP-NA-GR-CO)	2149	0.08	0.32	2006-10-06 00:00 UTC	1925.2(4)
IRA	$4\pi\beta$(PC)-γ coincidence (4P-PC-BP-NA-GR-CO)	3007[j] 2982	0.02 0.02	0.1 0.1	1979-05-01 12:00 UTC	-

... 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	
	Ionization chamber calibrated in 1979 by 4$\pi\beta$-γ coincidence (4P-IC-GR-00-00-00)	2518	0.014	0.1	2000-12-01 12:00 UTC	1925.3(2)
JRC	4π(PPC)-NaI well digital coincidence (4P-PP-BP-NA-GR-CO)	1412	0.17	0.16	2004-05-01 00:00 UTC	1925.2(4) [17]
KRISS	4$\pi\beta$-γ coincidence (4P-PP-BP-NA-GR-C0)	511.6	0.3		1994-10-01 12:00 UTC	-
LNE-LNHB	4$\pi\beta$-γ coincidence (4P-PC-BP-GL-GR-CO)	3303.3[j] 3296.3	0.02 0.02	0.04 0.04	1978-06-15 12:00 UTC	
	4$\pi\beta$-γ(Ge(Li) coincidence) (4P-PC-BP-GL-GR-CO)	1777.5[j] 1781.2	0.03 0.03	0.05 0.05	1986-07-11 12:00 UTC	
	4$\pi\beta$(PC)-γ coincidence (4P-PC-BP-NA-GR-CO)	2838.9	0.05		1999-06-01 12:00 UTC	1925.2(4)
	4$\pi\beta$(PC)-γ anticoincidence (4P-PC-BP-NA-GR-AC) 4$\pi\beta$(LS)-γ anticoincidence (4P-LS-BP-NA-GR-AC) TDCR (4P-LS-BP-00-00-TD)	373.12 372.75 373.09	0.10 0.19 0.10	0.10 0.10 0.22	2021-02-22 12:00 UTC	1925.23(29) [16]
LNMRI-IRD	4$\pi\beta$(PC)-γ coincidence (4P-PC-BP-NA-GR-CO)	189.4[j] 193.8	0.14 0.14	0.04 0.04	1976-06-28 12:00 UTC	-
	4$\pi\beta$(PC)-γ coincidence (4P-PC-BP-NA-GR-CO)	327.8[j] 334.5	0.04 0.04	0.08 0.08	1984-10-17 12:00 UTC	
	4$\pi\beta$(LS)-γ anticoincidence counting (4P-LS-BP-NA-GR-AC) 4$\pi\beta$(LS)-γ digital coincidence counting (4P-LS-BP-NA-GR-DC) Peak-sum counting (UA-GH-GR-00-00-SC) TDCR counting (4P-LS-MX-00-00-TD)	370.39 366.91 370.41 368.43	0.3 0.639 0.081 0.262	0.095 0.059 0.212 0.112	2020-08-20 12:00 UTC	1925.23(29) [16]
NIM	4$\pi\beta$(PC)-γ coincidence (4P-PC-BP-NA-GR-CO)	1746.2[j] 1746.4	0.05 0.05	0.2 0.2	1978-08-31 04:00 UTC	-
	4$\pi\beta$(PC)-γ coincidence (4P-PC-BP-NA-GR-CO)	1049.4	0.21	0.15	2014-06-07 00:00 UTC	1925.2(3) [16]

... 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**	
NIST	$4\pi\beta$-γ coincidence and anticoincidence (4P-PC-BP-NA-GR-CO, 4P-PC-BP-NA-GR-AC)	2038	0.06	0.15	1980-05-30 17:00 UTC	-
	Ionization chamber (4P-IC-GR-00-00-00)[e]	1402	0.03	0.23	1997-01-01 12:00 UTC	
	$4\pi\beta$-γ anticoincidence (4P-PC-BP-NA-GR-AC)	183	0.03	0.18	2007-01-01 17:00 UTC	1925.2(3) [16]
	$4\pi\beta$(LS)-γ anticoincidence (4P-LS-BP-NA-GR-AC)	312.41	0.19	0.12	2020-10-01 17:00 UTC	1925.23(29) [16]
NMIJ	$4\pi\beta$(PC)-γ coincidence (4P-PC-BP-NA-GR-CO)	1848[j] 1859	0.03 0.03	0.21 0.21	1976-11-01 12:00 UTC	-
	$4\pi\beta$(PC)-γ coincidence (4P-PC-BP-NA-GR-CO)	1435.7	0.05	0.09	2004-02-01 12:00 UTC	1925.2
NMISA	$4\pi\beta$(LS)-γ coincidence (4P-LS-BP-NA-GR-CO)	4659[j] 5329	0.05 0.05	0.18 0.18	1981-06-19 10:00 UTC	-
	$4\pi\beta$(LS)-γ coincidence (4P-LS-BP-NA-GR-CO)[f]	7066[j] 20 525	0.014 0.014	0.133 0.133	1992-09-10 12:00 UTC	1925.4(2) [17]
	$4\pi\beta$(LS)-γ coincidence (4P-LS-BP-NA-GR-CO)[f]	214	0.02	0.2[l]	2002-03-28 12:00 UTC	
	$4\pi\beta$-γ coincidence counting (4P-LS-BP-NA-GR-CO)	818.5	0.03	0.294	2022-02-21 10:00 UTC	1925.23(29) [16]
NPL	Ionization chamber calibrated by $4\pi\beta$(PC)-γ coincidence (4P-IC-GR-00-00-00)	667[j] 644	0.03 0.03	1.02 1.02	1976-12-20 12:00 UTC	-
	$4\pi\beta$(PPC)-γ digital coincidence counting (4P-PP-BP-NA-GR-CO)	2290	0.1	0.27	2000-02-01 12:00 UTC	
	$4\pi\beta$(LS)-γ Digital Coincidence Counting (4P-LS-BP-GH-CO)	355.8	0.04	0.11	2020-10-01 12:00 UTC	1925.23(29) [16]
NRC	$4\pi\beta$(PP)-γ anticoincidence (4P-PP-BP-NA-GR-AC)	298.15	0.03	0.1	2011-11-09 17:00 UTC	1925.2(3) [16]
	$4\pi\beta$(PP)-γ anticoincidence (4P-BP-PP-GR-NA-AC)	376.03	0.008	0.1	2020-08-01 07:00 UTC	1925.23(29) [16]
POLATOM	$4\pi\beta$(LS)-γ coincidence and anticoincidence (4P-LS-BP-NA-GR-CO, 4P-LS-BP-NA-GR-AC)	177.4[g]	0.27	0.5	2003-04-03 12:00 UTC	1925.3 [18]

... 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**	
	$4\pi\beta$(LS)-γ coincidence (4P-LS-BP-NA-GR-CO)	2155.5	0.253	0.047	2021-02-15 11:00 UTC	1925.23(29) [16]
	$4\pi\beta$(LS)-γ anticoincidence (4P-LS-BP-NA-GR-AC)	2157.3	0.250	0.052		
PTB	$4\pi\beta$(PC)-γ coincidence (4P-PC-BP-NA-GR-CO)	3222.6[j]	0.02	0.07	1977-01-01 12:00 UTC	-
		3176.0	0.02	0.07		
	Ionization chamber calibrated by $4\pi\beta$(PC)-γ coincidence (4P-IC-GR-00-00-00)	100 020[j]	0.02	0.07	1987-09-01 12:00 UTC	
		18 272	0.02	0.06		
		2036	0.03	0.09		
	Ionization chamber calibrated by $4\pi\beta$-γ coincidence (4P-IC-GR-00-00-00)	13 760	0.03	0.22	2001-01-01 12:00 UTC	1925.3(4)
	$4\pi\beta$(PC)-γ coincidence (4P-PC-BP-NA-GR-CO) $4\pi\beta$(LS)-γ coincidence (4P-LS-BP-NA-GR-CO) CIEMAT/NIST (4P-LS-MX-00-00-CN) TDCR (4P-LS-MX-00-00-TD)	2068.7[h]	0.05	0.2	2016-01-01 00:00 UTC	1925.3(4)
	$4\pi\beta$(PC)-γ coincidence counting (4P-PC-BP-NA-GR-CO)	365.659[i]	0.166	0.158	2020-06-30 23:00 UTC	1925.3(4) [18]
	$4\pi\beta$(LS)-γ coincidence counting (4P-LS-BP-CB-GR-CO)	367.473	0.069	0.149		
	CIEMAT/NIST efficiency tracing (4P-LS-MX-00-00-CN)	367.400	0.050	0.221		
	TDCR (4P-LS-MX-00-00-TD)	367.473	0.042	0.174		
PTKMR	$4\pi\beta$(PC)-γ coincidence (4P-PC-BP-NA-GR-CO)	1014[j]	0.4		1984-06-01 08:00 UTC	-
		1019	0.4			
SMU	TDCR (4P-LS-BP-00-00-TD)	375.27	0.224	0.301	2020-09-15 12:00 UTC	1925.23(29) [16]
	$4\pi\beta$(LS)-γ coincidence counting (4P-LS-BP-NA-GR-CO)	376.32	0.451	0.284		

... 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**	
TENMAK-NÜKEN	Ionisation chamber calibrated at the PTB in 2012 (4P-IC-GR-00-00-00)	888.7	0.49	1.16	2016-04-01 12:00 UTC	1925.3(3)
VNIIM	$4\pi\beta$(PC)-γ coincidence (4P-PC-BP-NA-GR-CO)	1521.4	0.065	0.052	2018-04-01 00:00 UTC	1925.23(29)

[b] For the CIEMAT/NIST method, a ^{3}H tracer from LNE-LNHB was used.

[c] The activity concentrations measured by the CIEMAT/NIST and coincidence methods are 641.0(19) kBq and 641.4(19) kBq, respectively.

[d] see details in [13]

[e] calibrated in 1980 by $4\pi\beta$-γ coincidence and anticoincidence

[f] see details in [14]

[g] see details in [15]

[h] The final result is the weighted mean of the results of four methods. The relative combined uncertainty (0.20 %) of the TDCR result is adopted for the final result. This is larger than the internal and external relative uncertainties of the weigthed mean. Correlations and anti-correlations between the results were not considered

[i] The LSC based results are about 0.4% to 0.5% higher. It is rather likely that the solution submitted in 2020 contains an impurity that cannot be identified by γ spectrometry

[j] Several samples submitted

[k] The result is the mean of the different methods.

[l] The uncertainty of 0.08 % submitted originally has been increased to include the uncertainty of an additional correction (see section 4 of [4]).

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 ^{60}Co 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 1980	$CoCl_2$ in HCl	0.3	Co^{++}: 10	1	-
1993	$CoCl_2.6H_2O$ in HCl	0.1	$CoCl_2.6H_2O$: 100	1	-
ANSTO 1992	$CoCl_2$ in HCl	0.1	Co: 47	1	-
2022	HCl	0.1	$CoCl_2$: 324(3)	1.002(2)	none detected
ASMW 1976	$CoCl_2$ in HCl	0.1	$CoCl_2$: 20	-	-
BARC 1981	$CoCl_2$ in HCl	0.1	$CoCl_2$: 55	-	-
1994	$Co(NO_3)_2$ in HNO_3	0.1	$Co(NO_3)_2$: 50	1	-
2001	$CoCl_2$ in HCl	0.1	$CoCl_2$: 25	1	-
2012	$CoCl_2$ in HCl	0.1	$CoCl_2$: 20	1	-

... 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]
2021	$CoCl_2$ in HCl	0.1	$CoCl_2$: 50	1	-
BEV 1998	$CoCl_2$ in HCl	0.1	$CoCl_2$: 50	1	-
2007	$CoCl_2$ in HCl	0.1	$CoCl_2$: 50	1	-
BIPM 1976	$CoCl_2$ in HCl	0.1	$CoCl_2$: 5	1	-
BKFH 1977	Co in HCl	0.1	Co: 25	-	-
1979	Co in HCl	0.1	Co: 25	-	-
1999	$CoCl_2$ in HCl	0.1	$CoCl_2$: 25	-	-
CIEMAT 1999	$CoCl_2$ in HCl	1	$CoCl_2$: 413	1.019	^{63}Ni: 0.012 %
CMI 1977	$CoCl_2$ in HCl	0.1	$CoCl_2$: 20	1	<0.1 %
1978	$CoCl_2$ in HCl	0.08	$CoCl_2$: 20	-	<0.1 %
CNEA 1992	$CoCl_2.6H_2O$ in HCl	0.1	$CoCl_2$: 10	0.999	<0.1 %
2003	$CoCl_2.6H_2O$ in HCl	1	$CoCl_2.6H_2O$: 150	1.015	<0.01 %
2011	$CoCl_2.6H_2O$ in HCl	0.1	$CoCl_2.6H_2O$: 90	1	-
ENEA-INMRI 1991	$CoCl_2.6H_2O$ in HCl	0.1	Co^{++}: 100	0.999	^{137}Cs: 0.003(1) % ^{63}Ni: 0.026(5) %
2021	HCl	1	N/A	1.02	none detected[a]
IAEA 1978	Co in HCl	0.1	Co: 100	-	-
1978	$CoCl_2$ in HCl	0.08	$CoCl_2$: 10	-	<0.1 %
IFIN-HH 1983	$CoCl_2$ in HCl	0.1	Co: 50	1	-
2007	$CoCl_2$ in HCl	0.1	$CoCl_2$: 100	1	<0.01 %
IRA 1979	Co^{++} in HCl	0.1	Co^{++}: 30	-	-
2000	Co^{++} in HCl	0.1	Co^{++}: 25	1.000(7)	-
JRC 2005	$CoCl_2$ in HCl	0.1	Co: 50	-	none detected[b]
KRISS 1995	$CoCl_2.6H_2O$ in HCl	0.5	$CoCl_2.6H_2O$: 46	1.0061	-
LNE-LNHB 1978	$CoCl_2$ in HCl	0.1	$CoCl_2$: 10	0.999	<0.02 %
1986	$CoCl_2$ in HCl	0.1	$CoCl_2$: 10	0.999	<0.01 %
1999	Co in HCl	0.1	Co^{++}: 10	1.001	-
2021	$CoCl_2.6H_2O$ in HCl	0.1	Co: 45	1	none detected
LNMRI-IRD 1976	$CoCl_2$ in HCl	0.1	$CoCl_2$: 17.1	-	-
1984	Co in HCl	0.2	Co: 0.02	1.003	-
2021	$CoCl_2$ in HCl	0.1	$CoCl_2$: 1000	1	none detected
NIM 1978	$CoCl_2$ in HCl	0.1	$CoCl_2$: 100	1.0004	-
2014	Co^{++} in HCl	0.1	Co^{++}: 10	1.006	-
NIST 1980	Co in HCl	1	Co: 50	1.015(2)	-
1997	$CoCl_2$ in HCl	0.1	$CoCl_2$: 100	1	-
2007	$CoCl_2$ in HCl	1.1	$CoCl_2$: 130	1.017	^{57}Co: 1.5(2)x10^{-5}

... 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]
2020	$CoCl_2$ in HCl	0.1	$CoCl_2$: 103	0.999	-
NMIJ 1976	$CoCl_2$ in HCl	0.1	$CoCl_2$:50	-	-
2004	$CoCl_2$ in HCl	0.1	$CoCl_2$: 100	1.002	-
NMISA 1981	$CoCl_2$ in HCl	1	$CoCl_2$: 540	1.037	-
1992	$CoCl_2.6H_2O$ in HCl	1	Co^{++}: 110	1.0183	-
2002	$CoCl_2.6H_2O$ in HCl	-	Co^{++}: 110	1.0183	-
2022	$CoCl_2.6H_2O$ in HCl	0.89	Co^{++}: 99.291	1.018	none detected
NPL 1977	$CoCl_2$ in HCl	0.1	$CoCl_2$: 50	-	-
2000	$CoCl_2$ in HCl	0.1	$CoCl_2$: 25	1	-
2021	HCl	0.1	Co: 100	1	none detected
NRC 2012	$CoCl_2$ in HCl	0.1	$CoCl_2$: 230	1.000(3)	none detected
2021	$CoCl_2$ in HCl	0.1	$CoCl_2$: 30	1.001(3)	-
POLATOM 2003	$CoCl_2$ in HCl	0.1	Co: 25	1	<0.1 %
2021	$CoCl_2$ in HCl	0.1	$CoCl_2$: 25	1	^{56}Co $< 5.08 \times 10^{-4}$ [c] ^{57}Co $< 9.22 \times 10^{-5}$ ^{58}Co $< 6.38 \times 10^{-4}$ ^{59}Fe $< 6.05 \times 10^{-4}$
PTB 1977	$CoCl_2$ in HCl	0.1	$CoCl_2$: 50	-	-
1988	$CoCl_2$ in HCl	0.1	$CoCl_2$: 50	1	-
2001	$CoCl_2$ in HCl	0.1	$CoCl_2$: 50	1	-
2017	$CoCl_2$ in HCl	0.1	$CoCl_2$: 50	1	-
2020	$CoCl_2$ in HCl	0.1	$CoCl_2$: 50	1	none detected
PTKMR 1984	$CoCl_2.6H_2O$ in HCl	1	$CoCl_2.6H_2O$: 50.5	0.990(1)	-
SMU 2020	$CoCl_2$ in HCl	0.1	$CoCl_2$: 160	-	-
TENMAK-NÜKEN 2018	$CoCl_2$ in HCl	0.1	$CoCl_2$: 50	1	-
VNIIM 2019	HNO_3	2	-	1.065	< 0.01 %

[a] No relevant impurities were detected in the solution after measuring it by the ENEA high-energy resolution HPGe detector. The continuum Compton spectrum due to the 1173 keV emission of Co-60 does not allow to see gamma emissions of very weak intensity with energy lower than 1173 keV.
[b] Confirmed by measurements carried out at the BIPM
[c] Minimum detectable activity values
[d] The ratio of the activity of the impurity to the activity of ^{60}Co at the reference date

4. Results

All the submissions to the SIR since its inception in 1976 are maintained in a dedicated database [19]. The latest submission has added 11 ampoules for the activity measurements for ^{60}Co giving rise to 85 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 a given source 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.

Table 4: Results of SIR measurement of ^{60}Co.

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	0.941 77[a]	1183.4	3	7050	5	4	-
	0.946 42	1189.3	3	7051	5	4	-
1993	0.233 2[a]	2069.9	4	7064	4	6	7064(6)
ANSTO 1992	3.557 1	1676	4	7056	4	10	-
2022	3.603 69(71)	401.88[n]	3	7061	6	10	7062(9)[m]
		401.88		7061		11	-
		401.96		7063		13	-
ASMW 1976	3.601 0	1867.8	4	7063	4	8	7062(8)[l]
	3.605 2	1870.0	4	7061	4	8	-
BARC 1981	3.599 8	584.4	3	7078	6	19	-
1994	3.605 8	676.1	3	7076	5	9	-
2001	3.614 5	1072	3	7099	5	46	-
2012	3.603 23	1560	4	7184	5	33	-
2021	3.600 7(14)	281.94[b]	2	7037	9	32	7049(21)[m]
		282.08		7041		46	-
		283.20		7069		28	-
BEV 1998	3.618	2980	4	7049	4	42	-
2007	3.606 9	3081	4	7057	4	17	-
BIPM 1976	3.757 9	2611.2	4	7066	4	4	7066(4)
BKFH 1977	3.600 7	1345	4	7048	5	23	-
	3.600 6	1345	4	7043	5	23	-
1979	3.602 1	1490	4	7045	4	20	-
1999	3.612 2	1808	4	7051	5	18	7051(18)
CIEMAT 1999	3.682 16	364.8	2	7090	7	11	7090(11)
CMI 1977	3.568 43	37 680	5	7051	4	56	-
1978	3.615 29	4190	4	7054	4	20	7054(20)
CNEA 1992	2.075 43	785.3	3	7126	5	10	-
2003	3.650 37	641.2	3	7050[c]	5	15	-
2011	3.606 43	175.5	2	7079	9	38	7070(26)[d]
		174.1		7060		33	-
ENEA-INMRI 1991	3.57	1053	3	7065	6	26	-
2021	3.585 69(2)	287.11	2	7096	10	30	7096(30)[e]

... Continuation of Table 4.

NMI or laboratory / SIR year	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_{e} **for KCRV /kBq**
		287.75		7112		32	-
IAEA 1978	3.699 3	1770	4	7052	5	11	-
1978	3.584 18	3600	4	7053	4	20	-
IFIN-HH 1983	3.533 9	1444	4	7066	4	8	-
	3.485 4	1424	4	7068	4	8	-
2007	3.617 39	2149	4	7101	4	24	7101(24)
IRA 1979	3.629 93	3007	4	7039	4	8	7041(8)[l]
	3.599 67	2982	4	7042	4	8	-
2000	3.598	2518	4	7037	4	8	-
JRC 2005	3.497 98	1412	4	7039	4	17	7039(17)
KRISS 1995	3.585 26	511.6	3	7047	7	22	7047(22)
LNE-LNHB 1978	3.626 37	3303.3	4	7053	4	4	-
	3.618 76	3296.3	4	7052	4	4	-
1986	3.592 43	1777.5	4	7065	4	5	-
	3.599 83	1781.2	4	7063	4	5	-
1999	3.583 06	2838.9	4	7060	4	4	-
2021	3.709 7(6)	373.12	2	7070	11	12	7070(12)[f]
		372.75		7063		17	-
		373.09		7070		19	-
LNMRI-IRD 1976	3.459 33	189.4	2	7062	9	12	-
	3.539 01	193.8	2	7065	8	12	-
1984	3.468 94	327.8	2	7081	6	8	-
	3.540 29	334.5	2	7073	6	8	-
2021	3.603 55(180)	370.39	2	7058	8	23	7058(23)[g]
		366.91		6991		45	-
		370.41		7058		17	-
		368.43		7020		21	-
NIM 1978	3.605 25	1746.2	4	7046	4	15	-
	3.605 67	1746.4	4	7042	4	15	-
2014	3.611 28	1049.4	3	7052	5	19	7052(19)
NIST 1980	3.666 88	2038	4	7069	4	12	-
1997	3.608 47	1402	4	7085	4	17	-
2007	3.659 57	183	2	7083	8	14	-
2020	3.594 24(40)	312.41	2	7062	11	18	7062(18)
NMIJ 1976	3.607 86	1848	4	7044	4	16	-
	3.628 78	1859	4	7044	4	16	-
2004	3.633 75	1435.7	4	7050	4	8	7050(8)
NMISA 1981	3.600	4659	5	7064	3	13	-
	3.613	5329	5	7067	3	13	-
1992	3.612	7066	5	7066	3	10	-
	3.610	20 525	5	7065	3	10	-
2002	3.596	214	2	7098	10	16	-
2022	3.628 96(112)	818.5	3	7068	6	21	7068(21)

... Continuation of Table 4.

NMI or laboratory / SIR year	m_i /g	A_i /kBq	^{226}**Ra source**	$A_{\mathbf{e}i}$ /kBq	**Relative uncert. from SIR** /10^{-4}	$u_{\mathbf{c},i}$ /kBq	$A_\mathbf{e}$ **for KCRV** /kBq
NPL 1977	3.770 4	667	3	7059	5	72	-
	3.640 7	644	3	7057	5	72	-
2000	3.567 15	2290	4	7053	4	21	-
2021	3.619 19	355.8	2	7058	8	10	7058(10)
NRC 2012	3.605 6	298.15	2	7065	8	9	7065(9)
2021	3.612 190 (9)	376.03	2	7068[h]	13	11	-
POLATOM 2003	3.699 87	177.4	2	7040	8	40	-
2021	3.600 63	2155.5[i]	4	7073	4	18	7076(26)[m]
		2157.3		7079		18	-
PTB 1977	3.670 0	3222.6	4	7062	5	6	-
	3.616 9	3176.0	4	7060		6	-
1988	3.599 2	100 020	5	7068	3	6	-
	3.603 3	18 272	5	7056	3	5	-
	3.644 5	2036	4	7056	4	7	-
2001	3.600 7(9)	13 760	5	7057	3	16	-
2017	3.600 56	2068.7	4	7057	4	15	-
2020	3.619 35(13)	365.659	2	7069	10	18	7069(18)[j]
		367.473		7104		14	-
		367.400		7102		18	-
		367.473		7104		15	-
PTKMR 1984	3.550	1014	3	7103	5	27	7104(27)[l]
	3.567	1019	3	7105	6	27	-
SMU 2020	3.720 0(19)	375.27	2	7047	8	27	7047(27)[k]
		376.32		7066		38	-
TENMAK-NÜKEN 2018	3.584	888.7	3	7048	5	89	-
VNIIM 2019	3.597 67	1521.4	4	7062	4	7	7062(7)

[a] mass of solution before dilution

[b] The average calculated by the BARC of activity measured by the 3 methods and equal to 282.41(82) kBq.

[c] solution contained in a CNEA-type ampoule (see section 4 of [4])

[d] The weighted mean of the comparison results based on two methods is used for the KCDB.

[e] The result 7096(30) kBq from 4π integral gamma counting is used in the KCDB.

[f] The result 7070(12) kBq from 4π beta(PC)-gamma anticoincidence is used in the KCDB.

[g] The result 7058(23) kBq from 4π beta(LS)-gamma anticoincidence counting is used in the KCDB.

[h] Result obtained in the frame of a SIR/ESIR pilot study, not included in the KCDB

[i] The weighted mean calculated by POLATOM of activity measured by two methods is equal to 2156.2(78) kBq.

[j] The result 7069(18) kBq from 4π beta(PC)-gamma coincidence counting is used in the KCDB.

[k] The result 7047(27) kBq from TDCR is used in the KCDB.

[l] An average value and average uncertainty between all submitted samples is used for the KCDB [20].

[m] The result was obtained using an average between methods.

[n] The average calculated by the ANSTO of activity measured by average of two methods (4P-LS-BP-NA-GR-AC and 4P-PP-BP-NA-GR-CO) is equal to 401.9(5) kBq.

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 [21] 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 [21], 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 ^{60}Co in 2022 of **7062.0(23) kBq** with the power α =1.889 that has been calculated using the previously published results, selected as shown in Table 4, for the ASMW (1976), BIPM (1976), CMI (1978), IRA (1979), PTKMR (1984), AECL (1993), KRISS (1995), BKFH (1999), CIEMAT (1999), NMIJ (2004), JRC (2005), IFIN-HH (2007), CNEA (2011), NRC (2012), NIM (2014), VNIIM (2019), SMU (2020), NIST (2020), PTB (2020), LNMRI-IRD (2021), BARC (2021), NPL (2021), ENEA-INMRI (2021), POLATOM (2021), LNE-LNHB (2021), NMISA (2022), and the ANSTO (2022) result. This can be compared with the previous KCRV values of 7064.6(38) kBq published in 2003 [3] , 7061.3(35) kBq published in 2006 [6] , 7063.3(40) kBq published in 2010 [7] , 7062.7(27) kBq published in 2017 [8] , 7062.7(27) kBq published in 2020 [9] and 7062.6(25) kBq published in 2021 [10].

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

$$D_{ij} = D_i - D_j = A_{ei} - A_{ej} \tag{5}$$

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

$$u^2(D_{ij}) = u_i^2 + u_j^2 - 2u(A_{ei}, A_{ej}) \tag{6}$$

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 $u(A_{ei}, A_{ej})$ (see [22] 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.

Table B1 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 the 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 ^{60}Co, BIPM.RI(II)-K1.Co-60, currently comprises 20 results. The KCRV has been recalculated to include the latest result from the SMU (Slovakia) , ANSTO (Australia) , LNE-LNHB (France) , LNMRI-IRD (Brazil) , BARC (India) , NIST (United States) , NMISA (South Africa) , NPL (United Kingdom) , ENEA-INMRI (Italy) , POLATOM (Poland) , and the PTB (Germany). The results have been analyzed with respect to the updated KCRV, providing degrees of equivalence for 20 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 ^{60}Co activity measurements to this comparison or take part in other linked comparisons.

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Appendix A. Introductory text for ^{60}Co degrees of equivalence

Key comparison BIPM.RI(II)-K1.Co-60

MEASURAND: Equivalent activity of ^{60}Co

Key comparison reference value: the SIR reference value x_{R} for this radionuclide is 7062.0 kBq , with a standard uncertainty, u_{R} equal to 2.3 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 kBq, 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.Co-60

Table B1: The table of degrees of equivalence for BIPM.RI(II)-K1.Co-60

NMI i	$A_{\mathrm{e}i}$ **/kBq**	u_i **/kBq**	D_i **/kBq**	U_i **/kBq**
NMIJ	7050	8	-12	16
JRC	7039	17	-23	34
IFIN-HH	7101	24	39	48
BEV	7057	17	-5	34
CNEA	7070	26	8	52
NRC	7065	9	3	18
NIM	7052	19	-10	38
TENMAK-NUKEN	7048	89	-14	178
VNIIM	7062	7	0	14
PTB	7069	18	7	36
NIST	7062	18	0	36
SMU	7047	27	-15	54
BARC	7049	21	-13	42
POLATOM	7076	26	14	52
LNE-LNHB	7070	12	8	24
ENEA-INMRI	7096	30	34	60
NPL	7058	10	-4	20
LNMRI-IRD	7058	23	-4	46
NMISA	7068	21	6	42
ANSTO	7062	9	0	18

Appendix C. Graph of degrees of equivalence with the KCRV for ^{60}Co (as it appears in Appendix B of the MRA)

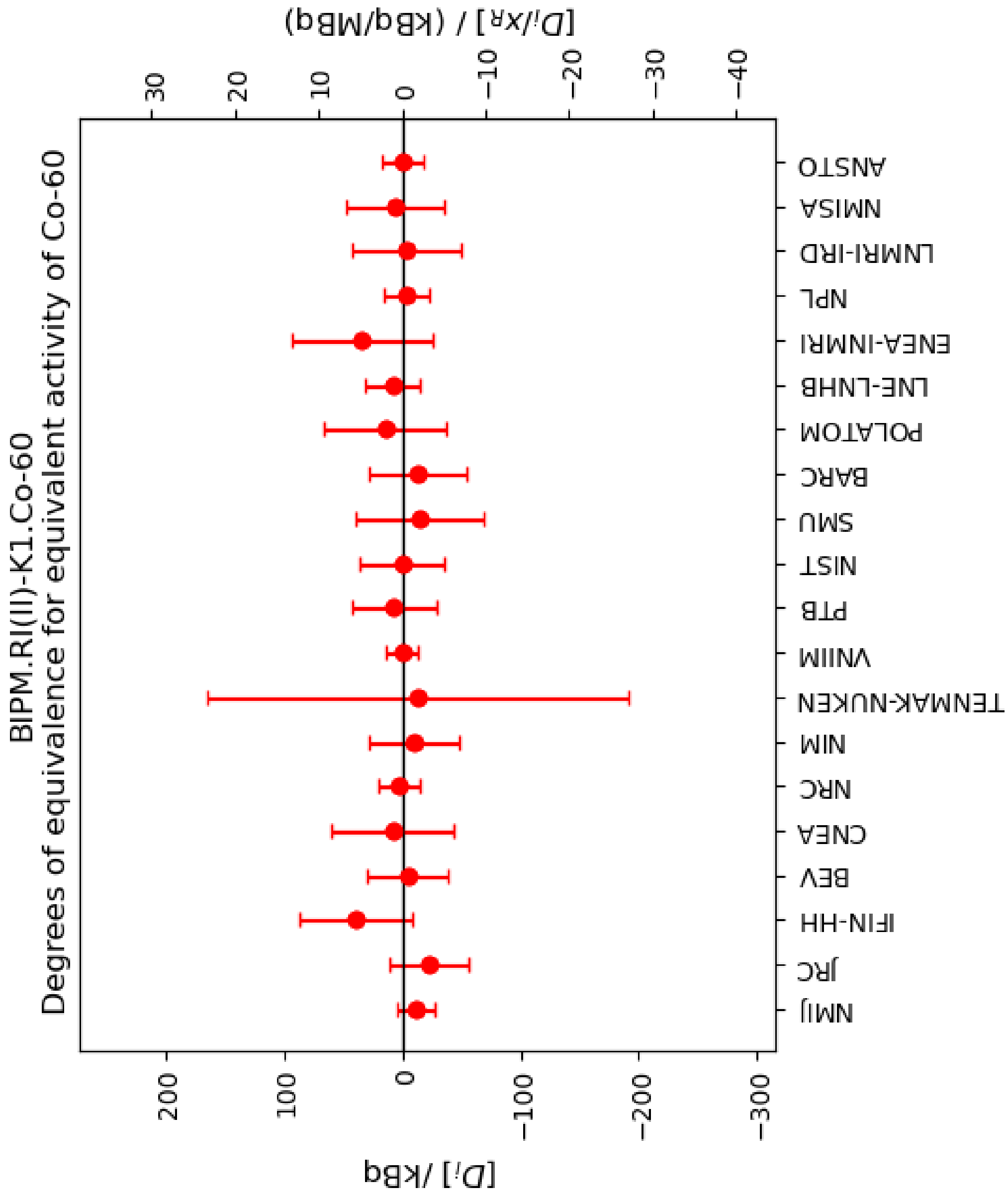

Figure C1. Degrees of equivalence for equivalent activity of ^{60}Co.

Appendix D. Uncertainty budgets for the activity of ^{60}Co submitted to the SIR

Uncertainty budget from the ANSTO (method 1)

SIR/SIRTI reporting form - radioactive solution page 3a

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

Measurement method	4π(LS)β-γ live-timed anti-coincidence	
ACRONYM	4P-LS-BP-NA-GR-AC	**Comments:**
Activity concentration at reference date / kBq g^{-1}	111.52	Three sources from the master soln. M, and five sources from dilution D1 (DF=19.3109 (15)), were counted for 5 repeats of 300 seconds at each of 13 LS efficiency points (one source from D1 was measured twice). Beta efficiency was varied between 95-84% by threshold discrimination. All measurements were undertaken with a window over the two full-energy peaks. The unweighted mean of nine measurement results provides the activity concentration of Dilution D1.
Relative standard uncertainty / 10^{-2}	0.13	
Date of measurement at the NMI (YYYY-MM-DD)	2022-05-24 to 2022-06-07	

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	0.02	A	Standard deviation of the mean for 9 measurements of 8 sources
Background	0.04	B	Data analysis using two separate background acquisitions, mainly due to gamma background
Weighing	0.05	B	Weighing, dilution and solution handling
Dilution			
Dead time	0.05	B	Uncertainty of live time from count rate
Resolving time			
Pile-up, afterpulse			
Adsorption			
Impurities			No gamma-emitting impurities detected by HPGe detector
Decay correction	0.0002	B	Uncertainty in decay correction due to uncertainty in half-life = 5.2711 (8) years
Decay data			
Extra-/Inter-polation of efficiency curve	0.1	B	Largest difference between individual results, rectangular distribution
Quenching, kB value			
Tracer			
Reproducibility			
Combined standard uncertainty	**0.13**		

Uncertainty budget from the ANSTO (method 2)

SIR/SIRTI reporting form - radioactive solution page 3b

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

Measurement method	4π(LS)β-γ coincidence	
ACRONYM	4P-LS-BP-NA-GR-CO	**Comments:**
Activity concentration at reference date / kBq g^{-1}	111.52	Two sources from the master soln. M, and five sources from dilution D1 (DF=19.3109 (15)), were counted for 5 repeats of 300 seconds at each of 13 LS efficiency points (one source from D1 was measured twice). Beta efficiency was varied between 97-88% by threshold discrimination. All measurements were undertaken with a window over the two full-energy peaks. The unweighted mean of eight measurement results provides the activity concentration of Dilution D1.
Relative standard uncertainty / 10^{-2}	0.14	
Date of measurement at the NMI (YYYY-MM-DD)	2022-05-24 to 2022-06-07	

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	0.03	A	Standard deviation of the mean for 8 measurements of 7 sources
Background	0.05	B	Data analysis using two separate background acquisitions, mainly due to gamma background
Weighing	0.05	B	Weighing, dilution and solution handling
Dilution			
Dead time	0.05	A	Uncertainty of live time from count rate
Resolving time	0.01	B	Data analysis using τR=120 ± 30 ns
Pile-up, afterpulse			
Adsorption			
Impurities			No gamma-emitting impurities detected by HPGe detector
Decay correction	0.0002	B	Uncertainty in decay correction due to uncertainty in half-life = 5.2711 (8) years
Decay data			
Extra-/Inter-polation of efficiency curve	0.1	B	Largest difference between individual results, rectangular distribution
Quenching, kB value			
Tracer			
Reproducibility			
Combined standard uncertainty	0.136		

Uncertainty budget from the ANSTO (method 3)

SIR/SIRTI reporting form - radioactive solution page 3c

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

Measurement method	4π(HPPC)β-4πγ coincidence with DCC	
ACRONYM	4P-PP-BP-4P-NA-GR-CO	**Comments:**
Activity concentration at reference date / kBq g^{-1}	111.54	Eight sources were prepared using dilution D1 (DF= 19.3109 (15)) on VYNS substrates coated on both sides with conductive Au/Pd. Data was acquired using the ANSTO/NPL DCC system. Sources were counted for repeats of 600 seconds (three sources counted for 5 repeats, five sources counted for 3 repeats). Offline digital discrimination provided beta efficiencies between 94% to 80%. Linear regression provided the activity concentration.
Relative standard uncertainty / 10^{-2}	0.18	
Date of measurement at the NMI (YYYY-MM-DD)	2022-05-09 to 2022-06-15	

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	0.035	A	Standard deviation of the mean for 8 results
Background			
Weighing	0.06	B	Weighing and solution handling
Dilution			
Dead time			
Resolving time			
Pile-up, afterpulse			
Adsorption			
Impurities			
Decay correction	0.0002	B	Uncertainty in decay correction due to uncertainty in half-life = 5.2711 (8) years
Decay data			
Extra-/Inter-polation of efficiency curve	0.16	B	Largest uncertainty of the DCC produced fit uncertaity (reduction of a matrix), taking into accoutn the correlated and non-correlated components. Application of the Cox-Isham/Smith correction
Quenching, kB value			
Tracer			
Reproducibility			
Width of gamma window setting	0.014	B	Comparison of results obtained by applying narrow or wide setting of gamma window over full energy peaks (1173-1332 keV)
Combined standard uncertainty	0.175		

Detailed uncertainty budget from the BARC (method 1)

Measurement method	4P-PC-BP-NA-GR-CO	
ACRONYM	4p(PC)β-γ	**Comments:**
Activity concentration at reference date / kBq g^{-1}	78.3000	
Relative standard uncertainty / 10^{-2}	0.44	
Date of measurement at the NMI (YYYY-MM-DD)	2019-03-13	Efficiency variation by source self absorption.

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	0.230		
Background	0.040		
Weighing	0.040		
Dilution	0.001		
Dead time	0.220		
Resolving time	0.200		
Pile-up, afterpulse			
Adsorption			
Impurities			
Decay correction	0.001		
Decay data			
Extra-/Inter-polation of efficiency curve	0.230		
Quenching, kB value			
Tracer			
Reproducibility			
Combined standard uncertainty	**0.440**		

Detailed uncertainty budget from the BARC (method 2)

Measurement method	4P-SP-BP-NA-GR-CO	
ACRONYM	4pi(SP)β-γ	**Comments:**
Activity concentration at reference date / kBq g^{-1}	78.3400	Efficiency variation was achevied by HV variation and optical filtering. Activity concentration is the average of both methods
Relative standard uncertainty / 10^{-2}	0.64	
Date of measurement at the NMI (YYYY-MM-DD)	2019-07-15	

For relative methods:

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

Uncertainty budget

Uncertainty component	Relative uncertainty / 10^{-2}	Evaluation type (A or B)	Comment
Counting statistics	0.310		
Background	0.030		
Weighing	0.040		
Dilution	0.001		
Dead time	0.370		
Resolving time	0.200		
Pile-up, afterpulse			
Adsorption			
Impurities			
Decay correction	0.001		
Decay data			
Extra-/Inter-polation of efficiency curve	0.360		
Quenching, kB value			
Tracer			
Reproducibility			
Combined standard uncertainty	**0.640**		Uncertainty quoted is for the efficiency variation by Optical filtering and it is the highest among the two efficiency variation methods.

Detailed uncertainty budget form the BARC (method 3)

Measurement method	4P-LS-BP-NA-GR-CO	
ACRONYM	4pi(LS)β-γ	**Comments:**
Activity concentration at reference date / kBq g^{-1}	78.6500	Efficiency variation was achieved by chemical quenching. Combined data fit using all the sources
Relative standard uncertainty / 10^{-2}	0.38	
Date of measurement at the NMI (YYYY-MM-DD)	2019-03-13	

For relative methods:

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

Uncertainty budget

Uncertainty component	Relative uncertainty / 10^{-2}	Evaluation type (A or B)	Comment
Counting statistics	0.180		
Background	0.050		
Weighing	0.040		
Dilution	0.001		
Dead time	0.120		
Resolving time	0.100		
Pile-up, afterpulse			
Adsorption			
Impurities			
Decay correction	0.001		
Decay data			
Extra-/Inter-polation of efficiency curve	0.290		
Quenching, kB value			
Tracer			
Reproducibility			
Combined standard uncertainty	**0.380**		

Detailed uncertainty budget from the ENEA-INMRI (method 1)

Measurement method	4PI INTEGRAL GAMMA COUNTING	
ACRONYM	4P-NA-MX-00-00-HE	**Comments:**
Activity concentration at reference date / kBq g^{-1}	80.07	instrument used: NaI(Tl) 5''x5'' well-type + CAEN Digitizer DT5724 (4 CH; 100 MS/s, 14 bit ADC); 2 point-sources were measured with a mass of about 15 mg; tipical count rate 1000 cps; typical time of measurements 1200 s; number of independent measurememts for each source: 6; total efficiency of the well-type detector for Co-60: 0,8652 estimated by GEANT Monte Carlo code.
Relative standard uncertainty / 10^{-2}	0.41	
Date of measurement at the NMI (YYYY-MM-DD)	2021-02-25	

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	0.3	A	
Background	0.05	A	
Weighing	0.1	B	
Dilution			
Dead time	0.1	B	
Resolving time			
Pile-up, afterpulse			
Adsorption			
Impurities			
Decay correction	0.01	B	
Decay data	0.15	B	
Extra-/Inter-polation of efficiency curve			
Quenching, kB value			
Tracer			
Reproducibility			
	0.15	B	Extrapolation to zero threshhold
	0.1	B	Efficiency calculation by Monte Carlo method
Combined standard uncertainty	**0.41**		

Detailed uncertainty budget from the ENEA-INMRI (methode 2)

Measurement method	Triple-to-Double-Coincidence-Ratio	
ACRONYM	4P-LS-BP-00-00-TD	**Comments:**
Activity concentration at reference date / kBq g^{-1}	80.25	Instrument used: Hidex 300 SL "Metro" version; two 20 ml high-performance glass vial containing 10 ml UG as liquid scintillator and about 15 mg of radioactive solution; typical cout rate 1200 cps; typical efficiency 0.96%; number of measurements 10; typical time of measurement 1200 s
Relative standard uncertainty / 10^{-2}	0.44	
Date of measurement at the NMI (YYYY-MM-DD)	2021-02-25	

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	0.25	A	
Background	0.01	A	
Weighing	0.1	B	
Dilution			
Dead time	0.1	B	
Resolving time	0.15	B	
Pile-up, afterpulse			
Adsorption			
Impurities			
Decay correction	0.01	B	
Decay data	0.2	B	
Extra-/Inter-polation of efficiency curve	0.2	B	efficiency computed by Micelle 2 code, provided by PTB, taking into account the experimental TDCR value (0,9643 typically)
Quenching, kB value	0.1	B	
Tracer			
Reproducibility			
Combined standard uncertainty	0.44		

Uncertainty budget from the LNE-LNHB (method 1)

Measurement method	4pi beta-gamma Anticoincidence counting	
ACRONYM	4P-PC-BP-NA-GR-AC	**Comments:**
Activity concentration at reference date / kBq g^{-1}	100.5800	Activity measurements with solid Vyns sources
Relative standard uncertainty / 10^{-2}	0.14	
Date of measurement at the NMI (YYYY-MM-DD)	March 2021	

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
Statistics	0.060	A	6 solid sources
Background	0.020	A	
Weighing	0.100	B	
Dilution			
Live time technique	0.020	B	MTR2 module
Resolving time			
Pile-up, afterpulse			
Adsorption			
Impurities			
Decay correction			negligible
Decay data			
Efficiency extrapolation technique	0.080	A	Efficiency variation obtained by adding gold-coated VYNS foils
Quenching, kB value			
Tracer			
Reproducibility			
Combined standard uncertainty	**0.140**		

Uncertainty budget from the LNE-LNHB (method 2)

Measurement method	4pibeta-gamma anticoincidence counting LS	
ACRONYM	4P-LS-BP-NA-GR-AC	**Comments:**
Activity concentration at reference date / kBq g^{-1}	100.4800	Activity measurements on SL source (10mL UG scintillator, HP glass vial)
Relative standard uncertainty / 10^{-2}	0.21	
Date of measurement at the NMI (YYYY-MM-DD)	March 2021	

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
Statistics	0.040	A	5 liquid scintillation sources
Background	0.100	A	
Weighing	0.100	B	
Dilution			
Live time technique	0.020	B	MTR2 module
Resolving time			
Pile-up, afterpulse			
Adsorption			
Impurities			
Decay correction			negligible
Decay data			
Efficiency extrapolation technique	0.150	A	Efficiency variation applied by defocusing the photomultipliers and using grey filter
Quenching, kB value			
Tracer			
Reproducibility			
Combined standard uncertainty	**0.210**		

Uncertainty budget from the LNE-LNHB (method 3)

Measurement method	TDCR LS	
ACRONYM	4P-LS-BP-00-00-TD	**Comments:**
Activity concentration at reference date / kBq g^{-1}	100.5700	Activity measurements on SL source (10mL UG scintillator, HP glass vial)
Relative standard uncertainty / 10^{-2}	0.24	
Date of measurement at the NMI (YYYY-MM-DD)	March 2021	

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**
Statistics	0.090	A	5 liquid scintillation sources
Background	0.030	A	
Weighing	0.100	B	
Dilution			
Live time technique	0.020	B	MAC3 module - resolving time 40 ns
Resolving time			
Pile-up, afterpulse			
Adsorption			
Impurities			
Decay correction			negligible
Decay data			
Extra-/Inter-polation of efficiency curve			
TDCR model (beta spectra, kB value	0.200	B	Main beta spectrum calculated with BetaShape code including atomic effects
Tracer			
Reproducibility			
Combined standard uncertainty	**0.240**		

Uncertainty budget from the LNMRI-IRD (method 1)

Measurement method	Anticoincidence counting	
ACRONYM	4P-LS-BP-NA-GR-AC	**Comments:**
Activity concentration at reference date / kBq g^{-1}	102.784 2020-08-20 12:00:00 UTC	
Relative standard uncertainty / 10^{-2}	0.31	
Date of measurement at the NMI (YYYY-MM-DD)	2020-09-18	

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	0.260	A	
Background	0.080	B	
Weighing	0.050	B	
Dilution			
Counting time	0.010	B	
Resolving time			
Pile-up, afterpulse			
Adsorption			
Impurities			
Decay correction	< 0.01	B	
Decay data			
Extra-/Inter-polation of efficiency curve	0.150	A	
Quenching, kB value			
Tracer			
Reproducibility			
Combined standard uncertainty	**0.310**		

Uncertainty budget from the LNMRI-IRD (method 2)

Measurement method	Digital Coincidence counting	
ACRONYM	4P-LS-BP-NA-GR-DC	**Comments:**
Activity concentration at reference date / kBq g^{-1}	101.818 2020-08-20 12:00:00 UTC	
Relative standard uncertainty / 10^{-2}	0.24	
Date of measurement at the NMI (YYYY-MM-DD)	2020-09-15	

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	0.220	A	
Background	0.020	A	
Weighing	0.050	B	
Dilution			
Dead time	0.030	B	
Resolving time	<0.01	B	
Pile-up, afterpulse			
Adsorption			
Impurities			
Decay correction	0.010	B	
Decay data			
Extra-/Inter-polation of efficiency curve	0.600	A	
Quenching, kB value			
Tracer			
Reproducibility			
Combined standard uncertainty	**0.240**		

Uncertainty budget from the LNMRI-IRD (method 3)

Measurement method	Peak-sum counting	
ACRONYM	UA-GH-GR-00-00-SC	**Comments:**
Activity concentration at reference date / kBq g^{-1}	102.791 2020-08-20 12:00:00 UTC	
Relative standard uncertainty / 10^{-2}	0.23	
Date of measurement at the NMI (YYYY-MM-DD)	2020-09-11	

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	0.010	A	
Background	0.010	A	
Weighing and dispersion	0.200	B	
Dilution			
Live time	< 0.01	B	
Resolving time			
Pile-up, afterpulse	0.070	B	
Adsorption			
Impurities			
Decay correction	0.010	B	
Decay data			
Extra-/Inter-polation of efficiency curve	0.080	A	
Quenching, kB value			
Tracer			
Reproducibility			
Combined standard uncertainty	**0.230**		

Uncertainty budget from the LNMRI-IRD (method 4)

Measurement method	TDCR counting	
ACRONYM	4P-LS-MX-00-00-TD	**Comments:**
Activity concentration at reference date / kBq g^{-1}	102.240 2020-08-20 12:00:00 UTC	
Relative standard uncertainty / 10^{-2}	0.28	
Date of measurement at the NMI (YYYY-MM-DD)	2020-08-25	

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	0.220	A	
Background	0.100	A	
Weighing	0.050	B	
Dilution			
Dead time			
Resolving time			
Pile-up, afterpulse			
Adsorption			
Impurities			
Decay-scheme and data model	0.100	B	
Decay data			
Extra-/Inter-polation of efficiency curve			
Quenching, kB value	0.100	A	
Tracer			
Reproducibility			
Combined standard uncertainty	**0.280**		

Uncertainty budget from the NIST

Measurement method	live-timed 4pi LS beta - NaI gamma anticoincidence	
ACRONYM	4P-LS-BP-NA-GR-AC	**Comments:**
Activity concentration at reference date / kBq g^{-1}	86.9200	
Relative standard uncertainty / 10^{-2}	0.23	
Date of measurement at the NMI (YYYY-MM-DD)	2020-10-06	

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
sample-to-sample var.	0.020	A	Standard deviation of the distribution N = 3
Background	0.040	B	
Weighing	0.050	B	Typical
Dilution			
Dead time	0.100	B	Systematic tests
Resolving time			
Pile-up, afterpulse			
Adsorption			
Impurities	0.020	B	None found. From HPGe limits
Decay correction	0.000	B	
Decay data			
Extra-/Inter-polation of efficiency curve	0.190	A	Standard deviation of the distribution for N=3 sets of gates, averaged over 8 measurements on 3 sources
Quenching, kB value			
Tracer			
Reproducibility			
Combined standard uncertainty	**0.230**		

Uncertainty budget from the NMISA

Measurement method	4pi-beta-gamma coincidence counting	
ACRONYM	4P-LS-BP-NA-GR-CO	**Comments:**
Activity concentration at reference date / kBq g^{-1}	225.56	
Relative standard uncertainty / 10^{-2}	0.30	
Date of measurement at the NMI (YYYY-MM-DD)	22-23 February 2022	

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	0.03	A	Standard deviation of the mean of 16 values
Background	0.12	B	BG square root statistics
Weighing	0.05	B	Mass from primary and ampoule preparation
Dilution			Added in weighing component
Dead time	0.15	B	From dead time uncertainty
Resolving time	0.15	B	From coincidence resolving time uncertainty
Pile-up, afterpulse	0.04	B	From afterpulse uncertainty
Adsorption	0.01	B	Count rates after multiple rinsings
Impurities	0		HPGe GS measurement
Decay correction	0.000005	B	From half-life uncertainty
Decay data			
Extra-/Inter-polation of efficiency curve	0.15	B	Difference between 1st and 2nd order fits
Quenching, kB value			
Tracer			
Reproducibility			
Counting time	0.001	B	From timer calibration
Combined standard uncertainty	**0.3**		

Detailed uncertainty budget from the NPL

SIR/SIRTI reporting form - radioactive solution

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

Measurement method	4pi(LS)-gamma Digital Coincidence Counting	
ACRONYM	4P-LS-BP-GH-GR-CO	**Comments:**
Activity concentration at reference date / kBq g^{-1}	98.32	
Relative standard uncertainty / 10^{-2}	0.12	
Date of measurement at the NMI (YYYY-MM-DD)	18-08-2020 12:00:00	

For relative methods:

Primary methods or standards used for calibration	N/A
Date of calibration	N/A
Date of primary measurement	N/A

Uncertainty budget

Uncertainty component	Relative uncertainty / 10^{-2}	Evaluation type (A or B)	Comment
Counting statistics	0.04	A	
Background	0.01	B	
Weighing	0.03	B	
Dilution	0.0025	B	
Dead time	0.02	B	
Resolving time	0.05	B	
Pile-up, afterpulse	0.001	B	
Gandy Effect	0.0001	B	
Impurities	0.01	B	
Decay correction	0.00026	B	
Decay data	0.015	B	
Extra-/Inter-polation of efficiency curve	0.05	B	
Order of Polynomial	0.01	B	
Choice of Gate	0.073	B	
Combined standard uncertainty	**0.12**		

Uncertainty budget from the POLATOM (method 1)

Measurement method	4π(LS)-γ coincidence	
ACRONYM	4P-LS-BP-NA-GR-CO	**Comments:**
Activity concentration at reference date / kBq g^{-1}	598.6400	
Relative standard uncertainty / 10^{-2}	0.26	
Date of measurement at the NMI (YYYY-MM-DD)	2021-02-15	

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	0.032	A	Counting statisctics and background in %
Background			
Weighing	0.151	A	in %
Dilution			
Dead time	0.001	B	in %
Resolving time	0.023	B	in %
Pile-up, afterpulse			
Adsorption	0.040	B	in %
Impurities	0.010	B	in %
Decay correction			
Decay data			
Extra-/Inter-polation of efficiency curve	0.201	A	in %
Quenching, kB value			
Tracer			
Reproducibility			
Combined standard uncertainty	**0.258**		

Uncertainty budget from the POLATOM (method 2)

Measurement method	4π(LS)-γ anticoincidence	
ACRONYM	4P-LS-BP-NA-GR-AC	**Comments:**
Activity concentration at reference date / kBq g^{-1}	599.1500	
Relative standard uncertainty / 10^{-2}	0.26	
Date of measurement at the NMI (YYYY-MM-DD)	2021-02-15	

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	0.051	A	Counting statisctics and background in %
Background			
Weighing	0.151	A	in %
Dilution			
Dead time	0.001	B	in %
Resolving time			
Pile-up, afterpulse			
Adsorption	0.040	B	in %
Impurities	0.010	B	in %
Decay correction			
Decay data			
Extra-/Inter-polation of efficiency curve	0.192	A	in %
Quenching, kB value			
Tracer			
Reproducibility			
Anticoincidence window	0.031	B	in %
Combined standard uncertainty	**0.255**		

Uncertainty budget from the PTB (method 1)

Measurement method	Beta-Gamma-coincidence counting	
ACRONYM	4P-PC-BP-NA-GR-CO	**Comments:**
Activity concentration at reference date / kBq g^{-1}	101.0290	Measurements carried out by: Dr. Ole Nähle
Relative standard uncertainty / 10^{-2}	0.23	
Date of measurement at the NMI (YYYY-MM-DD)	2020-08-21 to 2020-10-27	

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	0.165	A	
Background	0.014	A	
Weighing	0.050	B	
Dilution			
Dead time	0.000	B	<0.0002
Resolving time	0.002	B	
Pile-up, afterpulse			
Adsorption			
Impurities			
Decay correction	0.000	B	<0.0004
Decay data			
Extra-/Inter-polation of efficiency curve	0.008	B	
Quenching, kB value			
Tracer			
Sample variation	0.150	B	sample variation was larger than expected from weighing uncertainty
Counting time	0.000	B	<0.0002
Combined standard uncertainty	**0.229**		correlations were taken into account

Uncertainty budget from the PTB (method 2)

Measurement method	Beta-Gamma-coincidence counting	
ACRONYM	4P-LS-BP-NA*-GR-CO	**Comments:**
Activity concentration at reference date / kBq g^{-1}	101.5300	Measurements carried out by: Dr. Marcell Takács *gamma detector was a CeBr-detector
Relative standard uncertainty / 10^{-2}	0.16	
Date of measurement at the NMI (YYYY-MM-DD)	2020-07-28 to 2020-07-31	

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	0.055	A	measurement with typical best statistics
Background	0.042	A	measurement with typical best statistics
Weighing	0.020	B	
Dilution			
Dead time	0.100	B	
Resolving time	0.100	B	
Pile-up, afterpulse			
Adsorption			
Impurities			
Decay correction			
Decay data			
Extra-/Inter-polation of efficiency curve	0.028	B	
Quenching, kB value			
event definition	0.020	B	estimated from difference considering D or T events
Fit model function	0.020	B	estimated from difference between linear and quadratic fit
gamma setting	0.013	B	estimated from different gamma thesholds
Combined standard uncertainty	**0.164**		correlations were taken into account

Uncertainty budget from the PTB (method 3)

Measurement method	CIEMAT/NIST efficiency tracing	
ACRONYM	4P-LS-MX-00-00-CN	**Comments:**
Activity concentration at reference date / kBq g^{-1}	101.5100	Measurements carried out by: Dr. Karsten Kossert
Relative standard uncertainty / 10^{-2}	0.23	
Date of measurement at the NMI (YYYY-MM-DD)	2020-07-24 to 2020-09-09	

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	0.040	A	standard deviation of one sample series (glass)
Background	0.030	A	no crosstalk, only one sample in counter
Weighing	0.020	B	
Dilution			
Dead time	0.100	B	
Resolving time			
Pile-up, afterpulse			
Adsorption	0.050	B	
Impurities	0.030	B	none detected
Decay correction	0.010	B	also includes difference of half-life used to DDEP value
Decay data			
SQP(E) shift at high count rates	0.050	B	SQP(E) corrected
Quenching, kB value	0.070	B	
Tracer	0.050	B	includes interpolation
Model and decay data	0.150	B	e.g. beta spectra
PMT asymmetry	0.050	B	corrected
Counting time	0.010	B	
Combined standard uncertainty	**0.227**		correlations were taken into account

Uncertainty budget from the PTB (method 4)

Measurement method	TDCR	
ACRONYM	4P-LS-MX-00-00-TD	**Comments:**
Activity concentration at reference date / kBq g^{-1}	101.5300	
Relative standard uncertainty / 10^{-2}	0.18	
Date of measurement at the NMI (YYYY-MM-DD)	2020-07-21 to 2020-08-18	Measurements carried out by: Dr. Karsten Kossert

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	0.030	A	standard deviation of one sample series
Background	0.030	A	
Weighing	0.020	B	
Dilution			
Dead time	0.030	B	
Resolving time			
Pile-up, afterpulse			
Adsorption	0.050	B	
Impurities	0.030	B	none detected
Decay correction	0.010	B	also includes difference of half-life used to DDEP value
Decay data			
TDCR and numerical procedures	0.100	B	
Quenching, kB value	0.070	B	
Tracer			
Model and decay data	0.100	B	e.g. beta spectra
PMT asymmetry	0.025	B	corrected
Counting time	0.010	B	
Combined standard uncertainty	**0.180**		correlations were taken into account

Uncertainty budget from the SMU (method 1)

Measurement method	TDCR	
ACRONYM	4P-LS-BP-00-00-TD	**Comments:**
Activity concentration at reference date / kBq g^{-1}	100.8800	
Relative standard uncertainty / 10^{-2}	0.37	
Date of measurement at the NMI (YYYY-MM-DD)	March-April 2021	n:

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	0.200	A	
Background	0.200	B	
Weighing	0.050	B	
Dilution	-		
Dead time	0.100	B	
Resolving time	0.100	B	
Pile-up, afterpulse	-		
Adsorption	0.050	B	
Impurities	0.010	B	
Decay correction	0.050	B	
Decay data	0.020	B	
Extra-/Inter-polation of efficiency curve	-		
Quenching, kB value	0.150	B	
Tracer	-		
Reproducibility	0.100	A	
Combined standard uncertainty	**0.375**		

Uncertainty budget from the SMU (method 2)

Measurement method	4πβγ-coincidence counting	
ACRONYM	4P-LS-BP-NA-GR-CO	**Comments:**
Activity concentration at reference date / kBq g^{-1}	101.1600	
Relative standard uncertainty / 10^{-2}	0.53	
Date of measurement at the NMI (YYYY-MM-DD)	August-September 2021	

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	0.440	A	
Background	0.200	B	
Weighing	0.050	B	
Dilution	-		
Dead time	0.170	B	
Resolving time	0.060	B	
Pile-up, afterpulse	-		
Adsorption	0.050	B	
Impurities	0.010	B	
Decay correction	0.050	B	
Decay data	0.020	B	
Extra-/Inter-polation of efficiency curve	-		
Quenching, kB value	-		
Tracer	-		
Reproducibility	0.100	A	
Extrapolation	0.020	B	
Combined standard uncertainty	**0.533**		

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
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