Comparison of the standards of air kerma of the BNM-LPRI and the BIPM for ^{137}Cs γ rays

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Abstract
Comparison of the standards of air kerma of the Bureau National de Métrologie - Laboratoire Primaire Rayonnements Ionisants (BNM-LPRI) and of the Bureau International des Poids et Mesures (BIPM) have been carried out in ^{137}Cs gamma radiation. They show that the BNM-LPRI and BIPM standards agree to within 0,2 %.

1. Introduction

A direct comparison of the standards of air kerma of the Bureau National de Métrologie - Laboratoire Primaire des Rayonnements Ionisants, Saclay, France and of the Bureau International des Poids et Mesures, has been carried out for the first time in ^{137}Cs gamma radiation. The standard of air kerma of the BNM-LPRI is an oblate spheroid graphite cavity ionization chamber constructed at the BNM-LPRI (type GCS10, serial number 1). The standard of air kerma at the BIPM is described in [1]. The comparison took place at the BIPM in December 1995.

In addition, an indirect comparison was attempted using a very small transfer chamber belonging to the BNM-LPRI. This transfer chamber is a secondary-standard thimble ionization chamber (type NE 2571, serial number 2343), of volume 0,6 cm^3, with a build-up cap of graphite made by the BNM-LPRI as an alternative to the one supplied by the manufacturer.

2. Conditions of measurement

The air kerma is determined under the following conditions [2]:
- the distance from source to reference plane is 1 m,
- the field size in air at the reference plane is 11 cm diameter, the photon fluence rate at 3 cm from the centre being 98 % of the photon fluence rate at the centre. (One comparison was made using a 20 cm diameter field, the air kerma rate on the beam axis being about 5 % higher),
- the electronic measuring equipment and voltage supply used for the BNM-LPRI standard was provided by the BNM-LPRI.

3. Determination of the air kerma

The air kerma rate is determined from

$$\dot{K} = \frac{I}{m}\frac{W}{e}\frac{1}{1-\bar{g}}\left(\frac{\mu_{en}}{\rho}\right)_{a,c} \bar{s}_{c,a} \Pi k_i \quad , \tag{1}$$

where

I/m	is the mass ionization current measured by the standard,
W	is the average energy spent by an electron of charge e to produce an ion pair in dry air,
$\bar{g}$	is the fraction of energy lost by bremsstrahlung,
$(\mu_{en}/\rho)_{a,c}$	is the ratio of the mean mass-energy absorption coefficients of air and graphite,
$\bar{s}_{c,a}$	is the ratio of the mean stopping powers of graphite and air,
Πk_i	is the product of the correction factors to be applied to the standard.

The main characteristics of the BNM-LPRI primary standard are given in Table 1. The cavity volume of the primary standard was determined mechanically by the BNM-LPRI.

Table 1. Characteristics of the BNM-LPRI standard of air kerma.

BNM-LPRI standard		GCS10-1
		Nominal values / mm
Chamber	Inner height	33
	Inner diameter	22
	Wall thickness	3
Electrode	Diameter	2,0
	Height	23
Volume	Air cavity	9,477 1cm^3
Wall	Materials	ultrapure graphite
	Density	1,80 g·cm^{-3}
	Impurity	< 1,5 x 10^{-4}
Insulator		reticulated polyethylene
Applied voltage	Both polarities	800 V

4. Correction factors

The correction factors for the BNM-LPRI standard were determined at the BNM-LPRI and some factors were redetermined in the BIPM beam.

4.1. Attenuation and scattering in the chamber wall (k_{at} and k_{sc})

The correction for attenuation and scattering in the wall is obtained at the BNM-LPRI by adding graphite caps to the chamber. The ionization current is measured for several values of total thickness, averaged over the cross-section of the cavity, and extrapolated to zero thickness. The value obtained for the correction factor (1,024 9) is less than 0,7 % from that which is derived by a classical extrapolation versus the cap thickness. However, the mean wall thickness is quite large (4,9 mm) and the extrapolation made does not take into account the non-linear variation of the scatter for smaller thicknesses. The uncertainty attributed to the correction factor takes this into account.

The experiment was repeated at the BIPM and gives results compatible with those obtained at the BNM-LPRI (see Table 2). For consistency the value derived at the BIPM was used in the comparison.

Table 2. Graphite wall attenuation and scatter determination (chamber GCS10-1)

Additional cap thickness / mm	2	4	6	Extrapolated value of $k_{at} \cdot k_{sc}$
I/I_0 (BNM-LPRI beam)	0,988 0	0,976 1	0,964 1	1,024 9
I/I_0 (BIPM beam)	0,987 8	0,975 8	0,964 0	1,025 7

4.2. Radial non-uniformity of the beam (k_{rn})

While the beam at the BNM-LPRI can be assumed to be radially uniform (as confirmed by their measurements), this is not the case at the BIPM and a correction factor derived for the BNM-LPRI standard is used for the comparison. From measurements described in [1] this factor is 1,003 0 and 1,000 5 for the standard located in the small and wide BIPM beams, respectively.

4.3. Recombination loss (k_s)

The correction factor for losses due to recombination (1,000 4) was measured at the BNM-LPRI by extrapolating the straight line of the reciprocal of the ionization current versus the reciprocal of the collecting voltage to 1/V = 0: only the initial recombination is considered, the volume recombination being neglected. The experiment was repeated at the BIPM but the range of applied voltage (700 V to 900 V) was too narrow to allow effective extrapolation. This resulted in a value of k_s of 1,001 1 but with an uncertainty of about 0,1 %. As the air kerma rate at the BIPM is smaller than at the BNM-LPRI, the value of k_s estimated for the BNM-LPRI standard at the BIPM cannot be greater than at the BNM-LPRI. Consequently the value measured at the BNM-LPRI was used in the comparison.

4.4. Stem and polarity effects (k_{st} and k_{pol})

The scattering produced by the stem of the BNM-LPRI standard was measured in the BIPM beam, as was the polarity effect. Both effects agree with the measurements in the BNM-LPRI beam (see Table 3).

4.5. Mean centre of electron production (k_{CEP})

The calculation for the mean centre of electron production is based on the use of effective attenuation coefficients for photons and electrons [3].

4.6. Bragg-Gray cavity approximation (k_{BURLIN})

As the ionization chamber cavity is large, the Bragg-Gray theory is not strictly applicable. A correction based on the general cavity theory of Burlin is therefore used. The value applied is k_{BURLIN} = 0,999 8.

4.7. Axial non-uniformity of the beam (k_{an})

An estimation has been made by the BNM-LPRI for the effect of axial non-uniformity of the beam over the cross-section of the BNM-LPRI standard. The ratio of the ionization currents measured by the standard, which has a comparatively large cavity, and a small cavity chamber does not vary significantly along the beam axis. Consequently, the value of k_{an} is assumed to be unity. The uncertainty estimated for this correction is combined with that for the radial non-uniformity.

5. Results of the direct comparison

The physical constants [4] and the correction factors entering in (1), together with the uncertainties associated with the measurement of $\dot{K}$, are given in Table 3.

During the comparison, BNM-LPRI instruments were used to measure temperature, pressure and ionization current. A previous comparison of the BNM-LPRI and the BIPM measurement systems, made with the ^{60}Co beam, shows agreement to within 0,01 % [5].

The results of the direct comparison, $R_K = \dot{K}_{\text{BNM-LPRI}} / \dot{K}_{\text{BIPM}}$, are given in Table 4. The values of $\dot{K}$ refer, by convention, to an evacuated path length between source and standard. They are given at the reference date of 1995-01-01, 0h UT (the half life of ^{137}Cs is taken as (11 050 d, σ = 40 d) by the BIPM [6] and (11 020 d, σ = 60 d) by the BNM-LPRI [7]. The BIPM values are the means of measurements which were performed over a period of two months before and after the comparison at the BIPM.

Table 3. Physical constants and correction factors entering in the determination of the air kerma rates, $\dot{K}_{BIPM}$ and $\dot{K}_{BNM-LPRI}$, and their estimated relative uncertainties in the BIPM ^{137}Cs beam.

	BIPM values	BNM-LPRI values at BIPM	BNM-LPRI values at BNM-LPRI	BNM-LPRI relative uncertainty[1]		$R_{\dot{K}}$ relative uncertainty[1]	
Physical constants				100 s_i	100 u_i	100 s_i	100 u_i
dry air density / kg·m^{-3}	1,293 0	1,293 0	1,293 0	-	0,01	-	-
$(\mu_{en}/\rho)_{a,c}$	0,999 0	0,999 0	0,999 5	-	0,05	-	-
$\bar{s}_{c,a}$	1,010 4	1,010 4	1,011	-	0,30	-	-
W/e / (J·C^{-1})	33,97	33,97	33,97	-	0,15	-	-
$\bar{g}$ fraction of energy lost by bremsstrahlung	0,001 2	0,001 2	0,001 6	-	0,02	-	-
Correction factors							
k_s recombination losses	1,001 4	1,001 1[2]	1,000 4	0,01	0,03	0,01	0,03
k_h humidity	0,997 0	0,997 0	0,997 0	-	0,03	-	-
k_{st} stem scattering	0,999 8	0,997 6	0,997 4	-	0,04	0,01	0,04
k_{at} wall attenuation	1,054 0	1,025 7	1,024 9	0,03	0,20	0,03	0,20
k_{sc} wall scattering	0,953 5					0,01	0,15
k_{CEP} mean origin of electrons	0,997 2	0,997 5	0,997 5	-	0,07	-	0,07
k_{BURLIN} electron attenuation	-	0,999 8	0,999 8	-	0,02	-	0,02
k_{an} axial non-uniformity	0,998 1	1	1,000	-		-	0,07
k_{rn} radial non-uniformity	1,007 0	1,003 0	1,000	-	0,05	0,01	0,06
V volume / cm^3	6,834 4	9,477 1	9,477 1	-	0,03	0,01	0,10
I_- ionization current / pA		6,907 8[3]		0,01	0,07	0,03	0,07
I_+ / I_- polarity correction factor	-	1,000 4	1,000 5	0,01	-	0,01	-
Uncertainties							
quadratic summation				0,03	0,42	0,05	0,31
combined uncertainty				0,42		0,31	

[1] Expressed as a standard deviation
s_i represents the relative uncertainty estimated by statistical methods, type A,
u_i represents the relative uncertainty estimated by other means, type B.

[2] The value measured at the BNM-LPRI was used in the comparison.

[3] Measured at 20 °C with an air path between the source and chamber

Table 4. Results of the direct comparison of the BNM-LPRI and the BIPM standards

Beam diameter / cm	$\dot{K}_{BNM-LPRI}$ / µGy·s^{-1}	$\dot{K}_{BIPM}$ / µGy·s^{-1}	$R_{\dot{K}}$
11	21,214	21,165	1,002 3 σ = 0,003 1
20	22,216	22,181	1,001 6 σ = 0,003 1

Some of the uncertainties which appear in the BIPM and BNM-LPRI determinations of the air kerma rate (such as air density, W/e, μ_{en}/ρ, $\bar{g}$, $\bar{s}_{c,a}$ and k_h,) cancel when evaluating the ratio $R_{\dot{K}}$. The uncertainty in the position of each chamber is 0,01 %. The overall uncertainty of $R_{\dot{K}}$ is estimated to be 0,31 %.

As can be seen in Table 4, the results are in good agreement with the assumed uncertainties. The results of the comparisons are not significantly different between the small and wide beams since the statistical uncertainty of this ratio is 0,11 %.

6. Results of the indirect comparison

An indirect comparison has been attempted using a very small transfer chamber (type NE2571, serial number 2343) belonging to the BNM-LPRI. Calibrations of this chamber were made at the BIPM using both the special cap (2,98 mm graphite) manufactured at the BNM-LPRI and the normal cap (3,87 mm Delrin) provided by the manufacturer. In each case, both the small and wide BIPM beams were used, with radial non-uniformity corrections of 0,07 % and 0,02 % applied to the NE chamber reading, respectively.

The ionization current was measured with a positive voltage of 300 V applied to the chamber. The ionization current was normalized to 20 °C and 101,325 kPa. No corrections were made for polarity, humidity or any other factors, apart from k_m. The statistical uncertainty of a series of measurements with the NE chamber (0,6 cm^3) is about 0,1 %. In view of this value, there is no significant difference in the calibration factors obtained at the BIPM, with one or the other cap nor with one or the other beam. It seems reasonable then to take for the result of the indirect comparison the mean value 0,998 3 of the calibration factors, $\sigma =$ 0,003 3 (see Table 5).

There is a discrepancy of about 0,4 % between the results of the direct and the indirect comparisons, which is larger than the statistical uncertainties of their ratio (0,15 %). The discrepancy could be due to the statistical uncertainty of the BNM-LPRI calibration which is not taken into account in the above estimation. It seems evident that the NE 2571 chamber has too small a volume to be measured accurately in the BIPM beam.

Table 5. Results of the indirect comparison

Calibration factor of the NE 2571-2343 for beam diameter φ	$N_{\dot{K}\text{BNM-LPRI}}$ /10^6 Gy·C^{-1}	$N_{\dot{K}\text{BIPM}}$ /10^6 Gy·C^{-1}		$R_N = N_{\dot{K}\text{BNM-LPRI}} / N_{\dot{K}\text{BIPM}}$
		φ = 11 cm	φ = 20 cm	
with the graphite cap	41,55	41,64	41,57	0,998 3 $\sigma =$ 0,003 3
with the NE plastic cap		41,65	41,63	

6. Conclusion

It is interesting to compare the present results with those obtained for other laboratories and in other ionizing radiation fields. The results of other comparisons with the BIPM, using ^{137}Cs, are shown in Table 6 together with the corresponding result for ^{60}Co. Each laboratory used the same standards for both comparisons, with the exception of the NIST for which a large spherical transfer chamber was used for the comparison in ^{137}Cs and a small spherical transfer chamber was used for the comparison in ^{60}Co.

Table 6. Comparison of national laboratory results, $\dot{K}_{\text{Lab}}$ with $\dot{K}_{\text{BIPM}}$

Laboratory	$\dot{K}_{\text{Lab}}$ / $\dot{K}_{\text{BIPM}}$	
	^{137}Cs	^{60}Co
BNM-LPRI, direct (present work and [5])	1,001 9	1,002 5
BEV [8], direct	0,994 5	1,002 9
OMH [9], direct	0,995 4	1,002 5
NIST [10,11], indirect	1,002 5*	0,998 9*

* Values not yet final

The values obtained for $\dot{K}_{\text{Lab}}$ for ^{137}Cs are less consistent than for ^{60}Co. This is an indication that some correction factors related to air kerma measurements or their uncertainties in a ^{137}Cs beam could need revision. Of particular importance is the determination of the correction for attenuation and scattering in the chamber wall. This correction, for the BNM-LPRI, OMH and BEV standards, may be incorrectly estimated since it is obtained by extrapolation from measurements made with wall thicknesses far in excess of the maximum range of the electrons. As noted by Rogers and Bielajew [12], such an extrapolation can lead to substantial error.

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