Rapport BIPM-92/6

BIPM participation in an international comparison of neutron fluence measurements using two Bonner spheres as transfer instruments*

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Abstract

The comparison of neutron fluence measurements using two Bonner spheres for energies of 2,5 MeV and 14,7 MeV, undertaken by the BIPM, PTB, CBNM and NPL, left several problems unresolved. Section III of the CCEMRI, at its 1991 meeting, requested that further measurements be made at the BIPM to clarify the situation by checking the stability of the detector system and determining the effect on detector response of neutron interactions with the neutron-producing targets. This report summarizes the results of these investigations.

I. Introduction

A report on the international comparison of neutron fluence using two Bonner spheres as transfer instruments was presented by the coordinator [1] at the 1991 meeting of Section III (Neutron Measurements) of the Comité Consultatif pour les Etalons de Mesure des Rayonnements Ionisants (CCEMRI). To clarify several unresolved problems observed in this comparison, which took place from 1986 to 1990, Section III requested that further measurements be made at the Bureau International des Poids et Mesures (BIPM): i) to check the stability of the detector system, ii) to determine the effects on detector response of neutron interactions with the neutron-producing targets and iii) to assess the effects due to the presence of secondary neutron sources. This report describes the experimental conditions. The results of the measurements carried out in 1992 are compared with those of 1986 and with the results of the other participating laboratories (PTB, CBNM and NPL).

II. Theoretical background

The theoretical background is given in the protocol of measurements [1], which is based on published work by J.B. Hunt [2, 3]. According to the protocol, the dead-time corrected sphere response, $C_M(D_o)$, corresponding to one count in the fluence monitor, M, is given by the equation

$$C_M(D_0) = \frac{K}{D_0^2} F_1(D_0) F_2(D_0) , \quad (1)$$

* This report is dedicated to Denise Müller who has been the secretary of the Ionizing Radiation Section of the BIPM for more than thirty years. She did all her work with great competence, extreme care - and incredible speed. Working with her was a pleasure.

where
D_0 is the distance from neutron source to centre of the sphere,
K is the detection efficiency, ε, multiplied by the fluence per steradian corresponding to one count in the fluence monitor,
$F_1(D_0)$ is the geometrical correction factor,
$F_2(D_0)$ is the combined air and room scattering correction factors.

The distance D_0 is given by

$$D_0 = d + R, \tag{2}$$

where d is the distance between the target and sphere front face and R is the radius of the sphere.

The geometrical correction factor can be expressed by

$$F_1(D_0) = 1 + \delta F_3(D_0), \tag{3}$$

where

$$F_3(D_0) = 2\left(\frac{D_0^2}{R^2}\right)\left\{1 - \left[1 - \left(\frac{R^2}{D_0^2}\right)\right]^{1/2}\right\} - 1 \tag{4}$$

and δ is the so-called pseudo-effectiveness factor.
The second term of (3) accounts for the additional fraction of neutrons entering the detector volume on account of the non-parallel incidence of neutrons on the detector. For isotropic neutron fields, the constant δ, which represents the relative detector efficiency of the additional neutrons, has a value between 1/2 and 2/3. With non-isotropic fields, the constant δ depends on the angular distribution of the neutrons intercepted by the detector. For a forward-peaked distribution, its value can be negative.

The scattering correction factor may be expressed as

$$F_2(D_0) = 1 + A\,D_0 + S\,D_0^2. \tag{5}$$

The linear component, due to neutron interactions with air, has two terms, namely

$$A = L - N, \tag{6}$$

where L is due to the effect of inscatter by air throughout the room and N is due to the outscatter and absorption by the air between source and detector.

The component S is due to neutrons scattered from the walls, the floor, etc.; its value is considered to be constant over the range of distances used in the present work. Because the scattered neutrons have lower energies than the primary neutrons, the coefficients A and S are usually field-dependent.

Two methods have been used to derive unknown constants related to the detection efficiency and various scattering and geometrical effects.

a) According to (1), a non-linear least-squares fitting of all input data, which consist of sphere counts per unit monitor count for all distances, makes it possible to determine the unknown parameters K, A, S and δ. This method is designated the "polynomial fitting" method.

b) Shadow-cone technique. The response of a detector shielded from the source by a well-positioned shadow cone may be expressed as

$$S_M(D_0) = K(L\,D_0^{-1} + S)\,. \qquad (7)$$

It should be noted that the geometrical factor, $F_1(D_0)$, may be assumed to be unity because D_0 is large, making $(R^2/D_0^{\,2})$ negligible. The gradient of a plot of $S_M(D_0)$ against D_0 yields a value for $(K\,L)$ and the intercept yields $(K\,S)$.

Combining expressions (6), (7) and (1) yields

$$[\,C_M(D_0) - S_M(D_0)\,]\,D_0^2 = K(1 - N\,D_0)\,. \qquad (8)$$

Because, however, N is less than 1 % per metre, the attenuation correction may be calculated with sufficient accuracy; the expression

$$\left[\frac{(1 - N\,D_0)}{C_M(D_0) - S_M(D_0)}\right]^{1/2} = D_0\,K^{-1/2} \qquad (9)$$

may thus be fitted linearly against D_0 and the gradient yields $K^{-1/2}$.

Since the input data consist of sphere counts per unit monitor count, the sphere efficiency, ε, which is the basis of the comparison, is obtained by dividing K by the neutron fluence per steradian corresponding to one count in the fluence monitor.

III. Measurements

1. *Neutron production and fluence measurements*

The experimental arrangement for neutron production and fluence measurements at the BIPM is shown in Figure 1. The 2,50 MeV and 14,61 MeV neutrons are produced by the $^2H(d,n)^3He$ and $^3H(d,n)^4He$ reactions, respectively. The associated-particle method was used to determine the fluence. The associated particles were measured in a defined solid angle using a silicon surface-barrier detector.

a) 2,50 MeV neutrons
In the comparison, the silicon detector was placed 20 cm from the target and at 78° with respect to the incident deuteron beam of 140 keV, with a corresponding neutron emission angle of 86°. The beam current was 50 µA. The associated-particle method was applied by measuring the uncorrelated proton fluence (monitor counts)

from the competing $^2H(d,p)^3H$ reaction. The ratio of the ^3He/proton count rates was separately determined using a small beam current (1 µA). The target, supplied by the Centre d'Etudes Nucléaires of Valduc (CENV), has a Ti-D layer of 771 µg cm^{-2} on a copper disc, of 49 mm diameter, with a backing of 1 mm in thickness.

b) 14,61 MeV neutrons

The number of ^4He particles (monitor counts) was measured by a silicon detector placed 1 m from the target at an angle of 150° with respect to the incident deuteron beam of 140 keV. The beam current was 20 µA. A small correction (< 0,5 %) was used to account for the contamination of the ^4He-particle count by the secondary $^2H(d,p)^3H$ source, and a correction of 1 % was made to account for the pulses originating from the (n,α) and (n,p) reactions in the silicon detector. The corresponding neutron emission angle was 26,7°. The target, supplied by the CENV, has a Ti-T layer of 1,06 mg cm^{-2} on a copper disc, of diameter 28 mm, with a backing of 0,5 mm in thickness.

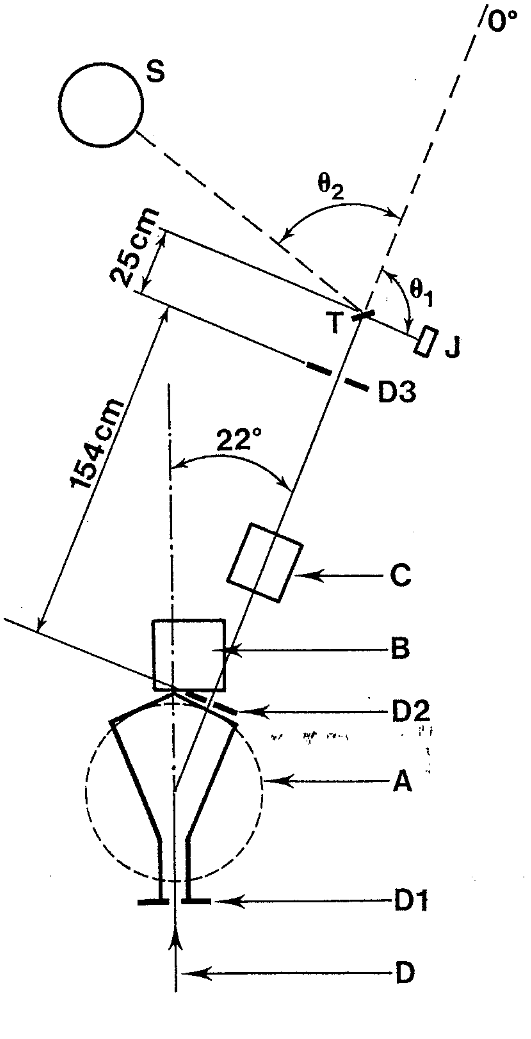

Figure 1. Experimental arrangement for neutron production and fluence measurements. D: deuteron beam; D1, D2, D3: diaphragms; A: magnetic field; B: polyethylene cubic slab shielded with 1 mm Cd; C: electrostatic lens; T: neutron producing target; J: silicon detector, θ_1 = 78° at 20 cm for (d+D) neutrons, or θ_1 = 150° at 1 m for (d+T) neutrons; S: Bonner sphere, θ_2 = 86° and 26,7° for (d+D) and (d+T) neutrons, respectively.

2. *Bonner-sphere measurements*

The two moderating spheres, designated sphere B and sphere H, were made at the NPL of high density polyethylene with diameters of 88,9 mm and 241,3 mm, respectively. Each has a central spherical cavity in which a spherical ^{3}He proportional counter, type SP90, provided by the BIPM, can be fitted. The protocol called for measurements at a large number of distances from 1,5 times the radius of the sphere up to 2,5 m.

Classical electronics were used. The SP90 counter was connected to a preamplifier (ORTEC 142 PC) followed by a main amplifier (Canberra 2022) and a pulse-height discriminator (made at BIPM). A voltage of 850 V was applied. A fixed non-extended dead time of (6,93 ± 0,02) µs was imposed on the electronics.

The spectrum was monitored using a pulse-height analyser. An example of a typical spectrum is shown in Figure 2. The discriminator bias was set at a pulse height of 20 % of the peak, at the position shown in the flat valley region, and all events above this were recorded by a scaler.

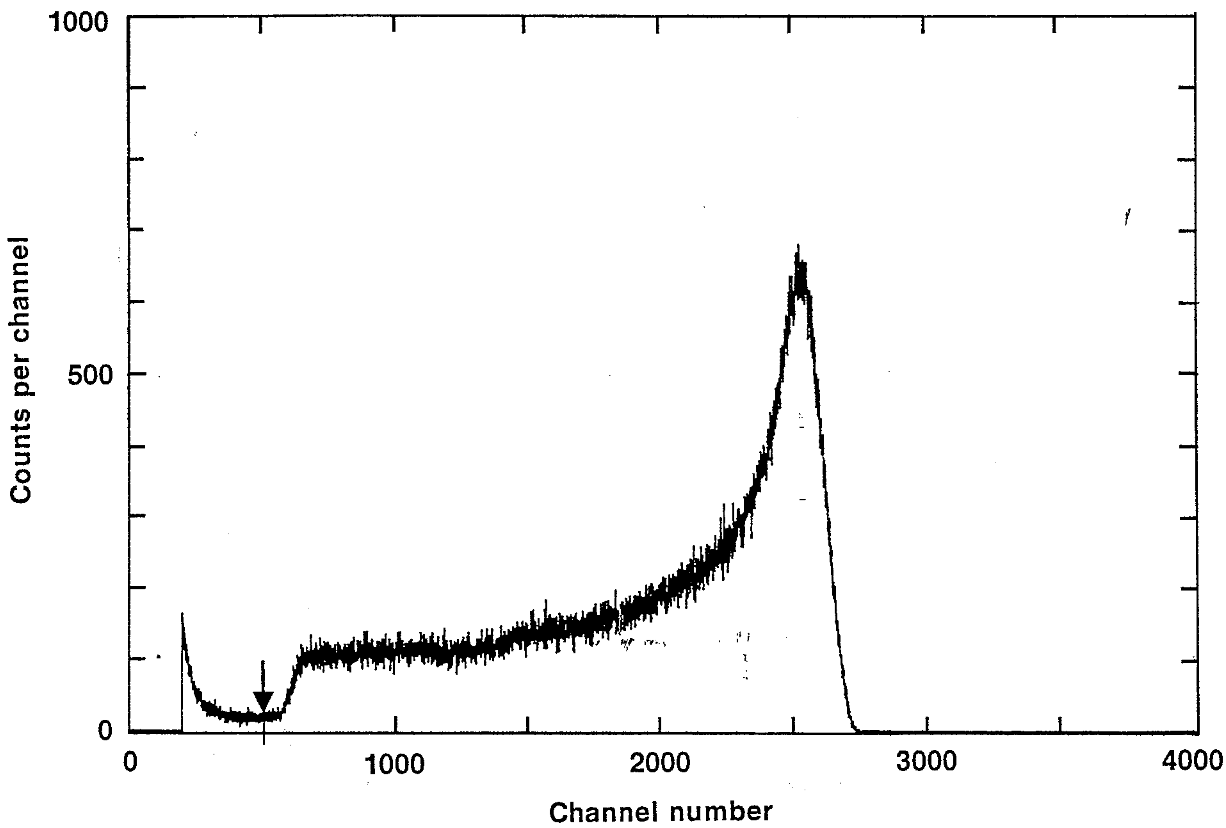

Figure 2. Typical pulse-height spectrum for a Bonner-sphere detector. The discriminator bias at 20 % of the peak is shown by an arrow.

For each distance of the sphere, measurements were carried out with two target configurations in succession, in order to determine the target-scattering effect. The configurations used were a 'thin' target of normal type and a target with a double thickness of backing material, called a 'thick' target.

The full programme involved 16 experimental conditions: two spheres, two target configurations, energies 2,50 MeV and 14,61 MeV, and measurements with or without a shadow cone.

IV. Results and discussion

For each target configuration, energy/sphere combination and source-sphere distance, the following data were obtained: measuring time (t), distance from the source to the centre of the sphere (D_0), monitor or associated particle counts (N_a), sphere counts (N_s) and normalized sphere counts (C_M). (Note: normalized sphere counts are the dead-time corrected sphere counts divided by the fluence per steradian). In the case of shadow-cone measurements, the normalized sphere counts, S_M, similar to C_M, were obtained. By using these normalized sphere counts (C_M and S_M) as input data, the quantity K given in (1) is simply equal to the detection efficiency, $\underline{\varepsilon}$, and is taken to be the sensitivity of the detector (sphere count rate per unit of fluence rate).

1. *Sphere B measurements at* 2,50 MeV

Measurements were performed at 22 distances (D_0 ranging from 0,136 m to 2,542 m) and, in addition, seven of them were also carried out using a shadow cone ($D_0 \geq$ 1,048 m). The results of these measurements are summarized in Table 1. One can see that the values of $\underline{\varepsilon}$ obtained by the shadow-cone and the polynomial-fitting techniques agree well. The mean values measured by these two methods, for the thin and thick target configurations respectively, are $\underline{\varepsilon}$ = 0,361 cm^2 and $\underline{\varepsilon}$ = 0,378 cm^2, giving a value for the target-scattering effect of 4,7 %. Finally, the corrected efficiency is $\underline{\varepsilon}$ = (0,344 ± 0,009) cm^2.

Table 1

Results for sphere B measurements at 2,50 MeV

a) *Thin target configuration*

Method	$\underline{\varepsilon}$/cm^2	100 A/m^{-1}	100 S/m^{-2}	δ
Shadow cone	0,361	14,2	30,8	
Polynomial fitting	0,362	11,6	31,9	1,10

Mean value: $\underline{\varepsilon}$ = 0,361

b) *Thick target configuration*

Method	$\underline{\varepsilon}$/cm^2	100 A/m^{-1}	100 S/m^{-2}	δ
Shadow cone	0,378	11,1	31,5	
Polynomial fitting	0,379	8,5	33,2	0,84

Mean value: $\underline{\varepsilon}$ = 0,378

From the difference, the value obtained for the target-scattering correction is 4,7 %.

2. *Sphere H measurements at* 2,50 MeV

Measurements were made at 16 distances (D_0 ranging from 0,332 m to 2,626 m) and, in addition, five of them ($D_0 \geq$ 1,552 m) were carried out using a shadow cone. The results are summarized in Table 2. The values of $\underline{\varepsilon}$ obtained by the shadow cone technique and by polynomial fitting can be considered to be in agreement within the measurement uncertainties. The mean values measured by these two methods, for the thin and thick target configurations respectively, are $\underline{\varepsilon}$ = 2,604 cm^2 and $\underline{\varepsilon}$ = 2,650 cm^2, giving a value for the target-scattering effect of 1,8 %. Finally, the corrected efficiency is $\underline{\varepsilon}$ = (2,557 ± 0,061) cm^2.

Table 2

Results for sphere H measurements at 2,50 MeV

a) *Thin target configuration*

Method	$\underline{\varepsilon}$/cm^2	100 A/m^{-1}	100 S/m^{-2}	δ
Shadow cone	2,581	9,3	2,5	
Polynomial fitting	2,627	6,5	2,9	1,00
Mean value:	$\underline{\varepsilon}$ = 2,604			

b) *Thick target configuration*

Method	$\underline{\varepsilon}$/cm^2	100 A/m^{-1}	100 S/m^{-2}	δ
Shadow cone	2,606	8,9	2,5	
Polynomial fitting	2,694	3,9	3,7	0,74
Mean value:	$\underline{\varepsilon}$ = 2,650			

From the difference, the value obtained for the target-scattering correction is 1,8 %.

3. *Sphere B measurements at* 14,61 MeV

The measurements were made at 21 distances (D_0 ranging from 0,135 m to 2,549 m) and, in addition, seven of them ($D_0 \geq$ 1,046 m) were carried out using a shadow cone. The results are summarized in Table 3. Corrections for sphere counting due to events from the (d+D) neutrons produced in the target have been taken into account. One can see that there is a difference of about 6 % between the values of $\underline{\varepsilon}$ obtained by the shadow-cone technique and by polynomial fitting. The latter method, which uses data from both long and short distances, seems to be inadequate in the case of 14,61 MeV neutrons. This is caused by the complexity of the scattering and interaction effects which result from the small size of the experimental room. It is due also, in part, to the secondary neutron sources created in the experimental set-up for neutron production (see Figure 1), especially the sources produced in the beam analyzing magnet and the different diaphragms. On the other hand, the sensitivity of sphere B to 14,61 MeV neutrons is very low relative to that of scattered and secondary-source neutrons of lower energy. For all these considerations, the assumption in (5) that the scattering parameter S has a constant value is probably not realistic. From Table 3, one can also see that the value of the pseudo-effectiveness factor, δ, is negative (δ = -1,06); this seems inconsistent with the relatively isotropic nature of the (d+T) neutron source. For these reasons, only the results obtained with the shadow-cone technique are considered reliable. The value of $\underline{\varepsilon}$, obtained for the thin target configuration, is $\underline{\varepsilon}$ = 0,068 8 cm^2 and a correction for the target-scattering effect of 9,6 % has been determined. Finally, the corrected efficiency is $\underline{\varepsilon}$ = (0,062 2 ± 0,001 8) cm^2.

Table 3

Results for sphere B measurements at 14,61 MeV

a) *Thin target configuration*

Method	$\underline{\varepsilon}/cm^2$	$100\,A/m^{-1}$	$100\,S/m^{-2}$	δ
Shadow cone	0,068 8	3,6	91,6	
Polynomial fitting	0,072 9	-4,6	88,0	-1,06

Mean value: $\underline{\varepsilon}$ = 0,070 8

b) *Thick target configuration*

Method	$\underline{\varepsilon}/cm^2$	$100\,A/m^{-1}$	$100\,S/m^{-2}$	δ
Shadow cone	0,076 0	2,3	85,4	
Polynomial fitting	0,079 2	-3,4	82,7	-1,23

Mean value: $\underline{\varepsilon}$ = 0,077 6

From the difference, the value obtained for the target-scattering correction is 9,6 %.

4. *Sphere H measurements at* 14,61 MeV

Measurements were made at 18 distances (D_0 ranging from 0,331 m to 2,621 m) and, in addition, five of them (D_0 ≥ 1,570 m) were carried out using a shadow cone. The results are summarized in Table 4. Although, superficially, there is agreement between the values of $\underline{\varepsilon}$, obtained by the shadow-cone technique and by polynomial fitting, the high negative value of δ (δ = -3,70) leaves some doubt about the results by the polynomial-fitting method. Only the results of the shadow-cone technique are considered reliable. The value of $\underline{\varepsilon}$, obtained for the thin target configuration, is $\underline{\varepsilon}$ = 1,328 cm^2 and a correction for the target-scattering effect of 2,2 % has been determined. Finally, the corrected efficiency is $\underline{\varepsilon}$ = (1,299 ± 0,032) cm^2.

Table 4

Results for sphere H measurements at 14,61 MeV

a) *Thin target configuration*

Method	$\underline{\varepsilon}$/cm^2	100 A/m^{-1}	100 S/m^{-2}	δ
Shadow cone	1,328	2,9	5,6	
Polynomial fitting	1,308	6,6	4,2	-3,70

Mean value: $\underline{\varepsilon}$ = 1,318

b) *Thick target configuration*

Method	$\underline{\varepsilon}$/cm^2	100 A/m^{-1}	100 S/m^{-2}	δ
Shadow cone	1,346	2,9	5,5	
Polynomial fitting	1,348	4,0	4,9	-4,04

Mean value: $\underline{\varepsilon}$ = 1,347

From the difference, the value obtained for the target-scattering correction is 2,2 %.

5. *Uncertainties*

The estimated uncertainties applicable to the determination of the sphere detection efficiency, $\underline{\varepsilon}$, are listed in Tables 5 and 6, for the measurements at 2,50 MeV and at 14,61 MeV, respectively. All uncertainties are estimated for a 68 % confidence level (one standard deviation).

Table 5

Estimated uncertainties, expressed as a fraction, for sphere-efficiency determinations at 2,50 MeV

Quantity	Uncertainty x 100* Sphere B	Sphere H
Fluence determination	1,6	1,6
Sphere response data fitting	1,2	1,4
Correction for target scattering	1,3	1,0
Correction for secondary source	1,0	0,5
Efficiency, $\underline{\varepsilon}$ (overall)	2,6	2,4

* Note: All uncertainties are estimated for a 68 % confidence level.

Table 6

Estimated uncertainties, expressed as a fraction, for sphere-efficiency determinations at 14,61 MeV

Quantity	Uncertainty x 100* Sphere B	Sphere H
Fluence determination	1,5	1,5
Sphere response data fitting	1,1	1,5
Correction for target scattering	2,0	1,0
Correction for secondary source	1,0	1,0
Efficiency, ε (overall)	2,9	2,5

* Note: All uncertainties are estimated for a 68 % confidence level.

V. Conclusion

In conclusion, we can make the following observations concerning the measurements performed at the BIPM.

1. The results of the efficiency measurements, carried out at the BIPM in 1986 and 1992 for the normal thin target configurations, and summarized in Table 7, indicate that the sphere efficiency has remained constant.

Table 7

Summary of the results of efficiency measurements at the BIPM (normal thin target configuration)

Neutron energy/MeV	Sphere	Method	Efficiency/cm^2 1986	1992	1992/1986
2,50	B	Shadow cone	0,365	0,361	0,989
		Polynomial fitting	0,351	0,362	1,031
	H	Shadow cone	2,596	2,581	0,994
		Polynomial fitting	2,516	2,627	1,044
14,61	B	Shadow cone	0,068 3	0,068 8	1,007
		Polynomial fitting	0,073 3	0,072 9	0,995
	H	Shadow cone	1,294	1,328	1,026
		Polynomial fitting	1,325	1,308	0,987

Ratio of ε (1992/1986), mean value: 1,009

2. The results of efficiency measurements, performed at the BIPM (1992) and at the other participating laboratories, and summarized in Table 8, indicate that good agreement exists between the BIPM and the NPL results. The PTB and the CBNM values are generally higher, but the latter laboratory has not corrected for target-scattering effects and no measurements were made with a shadow cone. These results are summarized in Figure 3. As regards the BIPM results, the mean values obtained by the two methods at 2,50 MeV are given, but for 14,61 MeV only those based on the shadow-cone technique.

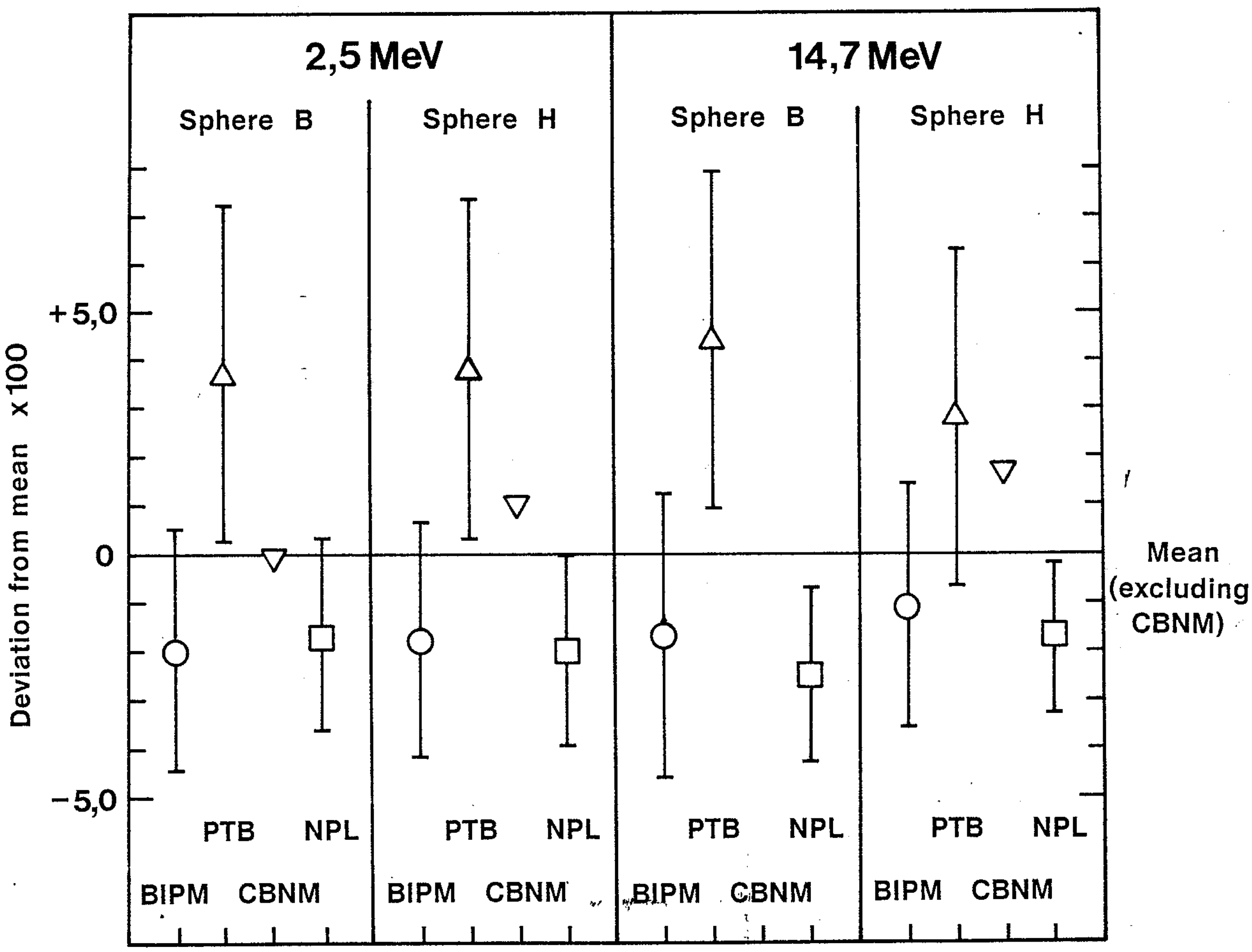

Figure 3. Results of efficiency measurements at all participating laboratories.

Table 8

Summary of the results of measurements at all participating laboratories

Laboratory	Sphere	Neutron energy/MeV	100 Target-scattering correction	Efficiency* $\underline{\varepsilon}$/cm^2		$\underline{\varepsilon}_{14,7}/\underline{\varepsilon}_{2,5}$
BIPM	B	2,50	4,7	0,344 5	(90)	0,180 6
		14,61	9,6	0,062 2	(18)	
	H	2,50	1,8	2,557	(61)	0,508
		14,61	2,2	1,299	(32)	
	B/H	2,50		0,134 5		
		14,61		0,047 1		
PTB	B	2,5	3,4	0,363	(14)	0,184 8
		14,7	4,4	0,067 1	(25)	
	H	2,5	1,4	2,71	(10)	0,502
		14,7	1,5	1,36	(5)	
	B/H	2,5		0,134		
		14,7		0,049 3		
CBNM	B	2,5		0,351	(9)	
		14,8				
	H	2,5		2,632	(73)	0,507
		14,8		1,335	(37)	
	B/H	2,5		0,133 4		
		14,8				
NPL	B	2,5	4,2	0,345 5	(60)	0,178 6
		14,7	8,6	0,061 7	(7)	
	H	2,5	1,8	2,552	(45)	0,506
		14,7	2,0	1,291	(11)	
	B/H	2,5		0,135 4		
		14,7		0,047 8		

* The uncertainties (in parentheses) are for a 68 % confidence level.

3. For the 14,61 MeV neutrons, the sensitivity of the spheres is relatively low compared to that for scattered neutrons of lower energy and for neutrons from secondary sources. The assumption of a constant value for the scattering parameter S in (5) is probably not justified because of the complexity of the scattering and interaction effects produced by the primary and secondary-source neutrons in a small experimental room.

4. In Table 8, the values of the target-scattering correction are given. These corrections were measured at the BIPM and at the NPL by doubling the thickness of the target backing material and were computed at the PTB using a Monte-Carlo code. It would be useful, for purposes of comparison, to calculate these corrections using the PTB code for the BIPM and the NPL measurements.

Acknowledgments

The authors are pleased to thank Dr. V.E. Lewis (NPL, chairman of CCEMRI Section III) for his participation in some of the measurements carried out at the BIPM in the course of this comparison. Special thanks are due to Mrs. M. Boutillon (BIPM) who supplied the calculation code for analyzing the results by the polynomial-fitting method.

References

[1] Axton, E.J., Report on the intercomparison of neutron fluence using two Bonner spheres as transfer instruments, *BIPM Com. Cons. Etalons Mes. Ray. Ionisants,* 1991, Document CCEMRI(III)/91-4

[2] Hunt, J.B., The calibration of neutron sensitive spherical devices, *Radiat. Prot. Dosim.* 1984, 8, 239-251

[3] Hunt, J.B., The calibration of neutron sensitive spherical devices in non-isotropic neutron fields, *Radiat. Prot. Dosim.* 1984, 9, 105-112

(October 1992)