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Comparison of 24.5 keV Neutron Fluence Measurements 1993 - 1996

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ABSTRACT

A comparison of measurements of 24.5 keV neutron fluence was organised by Section III (Neutron Measurements) of the Comite Consultatif pour Rayonnements Ionisantes (CCRI). The exercise involved the circulation to six laboratories of a set of three Bonner spheres for calibration in fields with energies around 25 keV. The fields were produced using a total of four different methods of neutron production.

The responses of the individual spheres, per unit of neutron fluence, were determined by the participating laboratories. To derive the 24.5 keV sensitivities, it was necessary to make corrections for spectral effects employing response functions produced using the code MCNP. The results were submitted to the author for analysis and comparison. The results demonstrate good consistency within the estimated uncertainties (between about 5% and 10% at 95% confidence level) between the results reported by all establishments.

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1 INTRODUCTION

One of the main activities of Section III, CCRI, is the sponsorship of comparisons of neutron metrology standards in order to achieve a consistent international measurement system, to improve neutron metrology worldwide and to evaluate the state-of-the-art in measurement. A series of comparisons of measurements of fast neutron fluences has been carried out under the auspices of Section III, starting in 1973 [1]. Up until 1992, the lowest neutron energy used for fluence measurement comparison was 144 keV [2,3]. In view of the importance of the measurement of lower energy neutron components, it was decided to extend the scope of these exercises to lower energies.

A Working Party was appointed by Section III to produce proposals for a comparison of neutron fluence measurements in the energy range from 20 to 50 keV. Six laboratories were interested in participating (see Section 2). Some indicated a preference for the measurements to be made at a neutron energy of 22.8 keV (as produced by an Sb-Be(γ, n) source), some preferred an energy of about 24.5 keV (obtained with iron-filtered reactor beams), whilst others preferred energies of around 27.4 keV produced using the ^{45}Sc(p,n)^{45}Ti reaction (see Section 3). The use of the ^{7}Li(p,n)^{7}Be reaction, producing a neutron energy of about 30 keV, was suggested later.

A single reference energy of 24.5 keV was chosen by Section III for this comparison.

This energy corresponds to that obtained using iron-filtered reactor beams and lies about midway between the energies produced using Sb-Be(γ,n) sources and the ^{45}Sc(p,n)^{45}Ti reaction.

Neither of the two techniques (indium foil activation [2] and a ^{235}U fission counter [3]) used before were considered to be sufficiently sensitive or convenient for the neutron fields that would be used. Alternatives, such as a ^{3}He spectrometer and a hydrogen-filled proportional counter were considered to be too sensitive to background neutrons or gamma rays. The Bonner sphere detector was advocated by the Working Party and chosen by Section III as the most suitable transfer detector in the chosen energy region. A set of three spheres with different diameters and employing a common central detector, used for a previous comparison, were available (see Section 4). The comparison involved the circulation of the Bonner spheres for participants to calibrate in neutron fields that were routinely in use at their laboratories.

The aim of the comparison was to measure the 24.5 keV neutron fluence sensitivities of all three Bonner spheres.

Values obtained from measurements made at energies other than 24.5 keV would be corrected to the reference energy using computed response functions for the Bonner spheres (Section 5).

The exercise started in March 1993 and the measurements of five of the participants ended in April 1996. The schedule of measurements is shown in Appendix 1. A protocol for the comparison was drafted by the Working Party and approved by the participants. This provided guidance on the operation of the instrumentation and specified the various items of information to be sent to the Evaluator. All measurements were reported [5] to the Chairman of Section III (V E Lewis, NPL), who carried out the analysis of the results and drafted this report (the Evaluator was not involved in the calibrations carried out at NPL.) An interim report covering the five sets of results reported here, but not disclosing absolute values, was presented at a meeting of Section III at the Bureau International des Poids et Mesures (BIPM) in April 1997.

The measurements of the sixth participant were delayed until late 1997 due to problems at other facilities and the refurbishment of that facility. Unfortunately it was then discovered that background neutron component was so large relative to the low intensity of the selected neutrons that accurate measurements were not possible. It was therefore decided to limit the exercise to the first five participating laboratories.

2 PARTICIPANTS

The establishments participating in the comparison were -

China Institute of Atomic Energy (CAEI), Beijing, People's Republic of China
Electro-Technical Laboratory (ETL), Japan
D I Mendeleyev Institute for Metrology (VNIIM), St Petersburg, Russia
National Institute of Standards and Technology(NIST), Gaithersberg, USA
National Physical Laboratory (NPL), Teddington, United Kingdom
Physikalisch Technische Bundesanstalt (PTB), Braunschweig, Germany

The neutron field(s) used by each participant are given in Appendix 1

3 RADIATION FIELDS

3.1 Antimony - beryllium source

The neutrons are produced by the reaction of 1691 and 2091 keV gamma rays from ^{124}Sb on beryllium. The ^{124}Sb is produced by irradiating a source containing natural antimony surrounded by a beryllium layer in a reactor. Since the half life is only 60 day this is usually done immediately prior to any measurements. The source has a very high gamma radiation activity. The main neutron group has an energy of 22.8 keV with a spread of ± 1.3 keV. The mean energy is lowered slightly by source scattering effects. There is also a higher energy group at 378 keV with an intensity of less than 3% that of the 22 keV group. The sensitivity values obtained must be corrected to give those at 24.5 keV. Two participants used Sb-Be sources.

3.2 Reactor beam with iron filter

The iron absorption cross section has a narrow window at an energy of about 24.5 keV. Higher and lower energy neutrons may be present in the transmission spectrum and measured responses must be corrected accordingly to give values for 24.5 keV. Three participants used iron-filtered reactor beams. The diameters of these collimated beams were less than those of the Bonner spheres and therefore scanning techniques were employed.

3.3 ^{45}Sc(p,n)^{45}Ti reaction

This reaction has a threshold energy of 2.908 MeV and has a resonance structure. The neutron energy therefore depends sensitively on the proton beam energy and also on the angle of neutron emission relative to the proton beam. A widely-used resonance yields neutrons with energies of 27.4 keV at 0° to the proton beam axis or 24.5 keV at 35°. To obtain neutrons from only one resonance it is necessary to use a target thickness corresponding to an energy loss of less than 2 keV. The resulting neutron field has a low intensity. Since the neutron field strength at 35° is so low, measurements were normally made at 0° and the sensitivity corrected to give that at 24.5 keV. Three participants used neutron fields produced using the ^{45}Sc(p, n)^{45}Ti reaction.

3.4 ^{7}Li(p,n)^{7}Be reaction

This reaction has a threshold energy of 1.88 MeV and is widely used to produce mono-energetic neutrons below 600 keV. With a proton beam energy of 1.942 MeV, 144 keV neutrons are emitted at zero degrees to the beam axis and 24 keV neutrons at 76.5°. A proton beam energy with a stability of about ± 0.1 keV is necessary. Only one participant used this reaction.

4 INSTRUMENTATION

4.1 Construction

The Bonner sphere detector system consisted of three spheres, designated *A*, *B* and *H*, made at NPL of high density polyethylene with diameters 63.5, 88.9 and 241.3 mm (2.5, 3.5 and 9.5 inch respectively). These are shown in Figures 1 and 2 along with the central detector, a spherical ^{3}He proportional counter type SP9, provided by BIPM. The two halves of sphere *A* are unscrewed and separated, the ^{3}He detector placed inside, and the two halves screwed together again. Sphere *B* is assembled in the same manner. To assemble sphere *H*, sphere *A*, containing the ^{3}He detector, was pushed into the central cavity and an end plug inserted to fill the remaining void.

The spheres were mounted on light-weight aluminium stands and oriented with the detector stem horizontal with connector diametrically opposite the sphere surface nearest to the neutron source.

4.2 Electronics and spectrum

A simple electronic system consisting of a pre-amplifier, main amplifier, single channel analyser (SCA) and scaler system could be used, along with a 850 V bias supply for the ^{3}He detector.

An example of a typical spectrum from the ^{3}He detector is shown in Figure 3. It has a main peak below which there is a plateau extending down to around 25% of the height of the peak. Below this the events fall to almost background level until the noise level is reached. The SCA lower level discriminator was set at a pulse height 20% that of the main peak, at the position shown in the flat valley region. The upper level discriminator was set at least 40% higher than the main peak position. The position of the peak could vary slightly with count rate necessitating a small adjustment of amplifier gain or a small correction to the total number of recorded events.

5 BONNER SPHERE RESPONSE FUNCTIONS

The three Bonner spheres respond to neutrons over about nine decades of neutron energy with varying sensitivity. The smaller spheres are most sensitive to neutrons with energies below about 10 keV whilst the large sphere is most sensitive to MeV neutrons. Since the fields used in this exercise were not mono-energetic and/or did not have a principal energy of 24.5 keV, it was necessary to calculate spectral corrections for each sphere in each field.

Each sphere was modelled using the detailed design drawings of the polyethylene components and of the ^{3}He proportional counter detector. Care was taken to establish the density of the moderator material and the dimensions of any cavities between its parts. A Monte Carlo code was used to track neutrons of any given energy entering a sphere and being moderated by the polyethylene before either entering the central detector and producing an event or being lost elsewhere. Incident neutron energies ranging from 10^{-3} eV to 20 MeV were selected for the simulations; there was special emphasis on calculating the response in the region from 20 to 30 keV. These extensive computations were made by PTB employing the code *MCNP*. The report from PTB describing this work more fully and giving calculated response values is attached as an Annex to this report.

The results are shown in Figure 4 as response relative to that at 24.5 keV. The response of the 2.5 inch sphere is five times more sensitive to eV neutrons than to 25 keV neutrons, but essentially insensitive to MeV neutrons. The situation for the 9.5 inch sphere is the opposite to this. Both spheres have response characteristics that vary more markedly in the 10 to 40 keV region than that for the 3.5 inch sphere which is almost energy-independent in this particular energy range.

6 MEASUREMENTS BY PARTICIPANTS

The Bonner sphere set was circulated to participating laboratories by BIPM. In between the periods spent at the participants' laboratories the Bonner spheres were returned to BIPM for checks of the response of the ^{3}He proportional counter detector using a ^{241}Am-Be source in a fixed geometry arrangement. The results are described in Section 7.

The participants measured the response of each sphere in each of the fields available for calibration in the 25 keV energy region. The choice of field and of the technique for the determination and monitoring of neutron fluence was left to participants.

Where necessary, the contributions to the sphere response due to air- and room-scattered neutrons were determined using an appropriate method such as the shadow cone technique.

Spectral corrections were required as appropriate for -

a) effects of lower energy neutrons produced by interactions of the primary neutrons with the neutron-producing target or the material of the source;
b) presence of lower and higher energy neutron groups due to competing reactions;
c) presence of contaminant neutrons from other sources;
d) difference between the energy of the principal neutron group and reference energy 24.5 keV.

These corrections were calculated by folding the sphere response functions with the measured or derived spectra. The experimental details are summarised in Appendix 3.

Reports were sent to the Evaluator for analysis at NPL. Participants were asked to provide the various items of information listed in Appendix 2. This included details of the neutron spectrum at the point of measurement, stating how it was measured or derived.

7 RESULTS OF INSTRUMENTATION CHECKS

7.1 Arrangement for checking stability of instrumentation

The BIPM designed and constructed a polyethylene sphere, 200 mm in diameter, into which a 3.7 GBq Am-Be source could be inserted. This provided a stable neutron field into which the ^{3}He proportional counter detector could be placed at a reference position and the count rate measured as a check on the detector's stability.

7.2 Use of detector SP9-BIPM1

The stability of the ^{3}He proportional counter detector chosen for the comparison, designated SP9-BIPM1, was checked several times in the test rig at BIPM in 1992. A mean count rate of $(979.9 \pm 1.0)\ s^{-1}$ was observed. Subsequent checks just before the instrumentation was sent to NIST and on its return from NIST yielded values of $(979.9 \pm 1.0)\ s^{-1}$ and $(980.1 \pm 1.0)\ s^{-1}$ respectively. It was concluded that the detector was stable over this period.

Use of detector SP9-BIPM2

When the instrumentation was received at CIAE the detector did not work satisfactorily. It was then replaced by a similar detector, SP9-BIPM2. This also had been checked for stability in 1992 and was again checked on its return from CIAE. The measured count rates were $(1009.6 \pm 0.7)\ s^{-1}$ and $(1007.3 \pm 1.5)\ s^{-1}$ respectively. It was concluded that the detector was stable over the period of the measurements at CIAE.

On the return of the instrumentation from PTB, a count rate of (981.4 ± 1.3) s^{-1} was observed. Because it could not be determined when and why this apparent decrease in sensitivity took place, a mean value of (995 ± 14) s^{-1} was assumed for the effective count rate.

On the return of the instrumentation from NPL, a count rate of (978.6 ± 1.0) s^{-1} was observed. Due to the transfer of the test rig to another room at BIPM, the count rate was re-measured in a new location before the instrumentation was sent to VNIIM. The observed count rate was higher at (1140.0 ± 0.4) s^{-1} due to increased background. On the return of the instrumentation from Russia, a count rate of (1140.5 ± 0.4) s^{-1} was observed and therefore it was concluded that the sensitivity had remained stable since the return of the instrumentation from PTB.

7.4 Normalisation

It was decided to normalise the measured responses to a count rate in the BIPM arrangement of 979 s^{-1}. The reported sensitivities would be multiplied by the correction factors below.

NIST	980 s^{-1}	Normalisation factor:	0.999
CIAE	1008.5 s^{-1}		0.970
PTB	995 ± 14 s^{-1}		0.985 ± 0.014
NPL	979 s^{-1}		1.000
CIAE	979 s^{-1}		1.000

8 ANALYSIS

The 24.5 keV sensitivity values reported initially to the Evaluator are shown in Table 1, denoted by *R(d)*, where *d* is the sphere diameter in inches. The units are cm^2 throughout. All corrections had been made by the participants, although not all had corrected the values to the reference energy. (The order of participants is not chronological, but has been arranged for easier comparison of results in similar neutron fields.) The uncertainties are those estimated by the participants. The values obtained from the MCNP computations are also given in Table 1.

These sensitivity values were multiplied by the factors given in Section 7 above to correct for changes in the sensitivity of the ^{3}He detector. The corrected values, denoted by *R'(d)*, are also shown in Table 1.

When the newly-calculated relative response functions became available from PTB, the spectral corrections discussed in Section 6 were re-calculated by the participants as necessary. The correction varied between -10% to about +1%, generally being less than 5% in magnitude. The values, also corrected by the Evaluator for the changes in the sensitivity of the ^{3}He detector, denoted by *R''(d)*, are shown in Table 2. The ratios of the sensitivities of pairs of spheres are also given. Table 2 is the definitive set of values for the blind comparison exercise.

In general the estimated uncertainties are better than 10% at 95% confidence level. However, due to observed inconsistencies in the beam calibration, NIST assigned a non-random uncertainty of 20% (at 1σ confidence level) to their values.

A year after these results were collated, and before it was decided that no further results would be included (due to the problems at ETL), PTB reported an error in the corrections for the measurements performed using the accelerator [6]. The values for the ^{45}Sc(p,n) and ^{7}Li(p,n) fields were revised by about 4% and 6% respectively, and the filtered beam results were also modified (by 1.3%) due to a change in the common fluence reference value. The revised values (shown in Table 3) represent the present state-of-the-art. The changes, which slightly worsen the general consensus, do not affect the overall conclusions (below) drawn from this exercise.

9 RESULTS

9.1 Results for 2.5 inch sphere

The measured results in Table 3 (Figure 5) consist of a band of seven values from four participants with upper and lower limits (both from CIAE) 11% apart, with an isolated value (NIST) about 17% lower than the unweighted mean of the others. The uncertainty for the NIST value is 33% of the mean and therefore this value is consistent within its uncertainty with the other values. The other values are consistent within the estimated uncertainties which are all less than 10% (at 95% confidence level). The calculated (MCNP) value is 8% lower than the unweighted mean of the values from the four groups.

9.2 Results for 3.5 inch sphere

Similar to the above results for the smallest sphere, these results consist of a band of seven values from four participants with upper and lower limits 9% apart, with an isolated value (NIST) about 25% lower than the unweighted mean of the others. The uncertainty for the NIST value is 30% of the mean and therefore this value is consistent within its uncertainty with the other values. The other values are consistent within the estimated uncertainties which are all less than about 9% (at 95% confidence level). The calculated (MCNP) value is 5.5% lower than the unweighted mean of the values from the four groups.

9.3 Results for 9.5 inch sphere

These results also consist of a band of seven values from four participants with upper and lower limits 9% apart, with an isolated value (NIST) about 16% lower than the unweighted mean of the others. The uncertainty for the NIST value is 33% of the mean and therefore this value is consistent within its uncertainty with the other values. The other values are consistent within the estimated uncertainties which are all less than 9% (at 95% confidence level). The calculated (MCNP) value is about 3% higher than the unweighted mean of the values from the four groups.

9.4 Overall trends

a) The NIST values are consistently around 30% lower than the mean of the other values.

b) The values obtained from the CIAE Sb-Be field are consistently higher than those for the VNIIM Sb-Be field. These differences are however within the estimated uncertainties and that for the 9.5 inch sphere values is not significant.

c) The PTB results for the filtered beam are about 8% higher than those for the CIAE filtered beam for all three spheres. These differences are also within the estimated uncertainties.

d) The NPL values are higher than those obtained using the PTB $^{45}Sc(p,n)$ field, but the differences, averaging about 2%, are not significant.

e) The values obtained from the CIAE Sb-Be field are consistently higher than those for the CIAE filtered beam. The difference is 11% for the 2.5 inch sphere values but is not significant for the 9.5 inch sphere values. These differences are however within the estimated uncertainties.

f) There are no marked internal trends for the results for the three fields used at PTB.

On the return of the instrumentation from PTB, a count rate of (981.4 ± 1.3) s^{-1} was observed. Because it could not be determined when and why this apparent decrease in sensitivity took place, a mean value of (995 ± 14) s^{-1} was assumed for the effective count rate.

On the return of the instrumentation from NPL, a count rate of (978.6 ± 1.0) s^{-1} was observed. Due to the transfer of the test rig to another room at BIPM, the count rate was re-measured in a new location before the instrumentation was sent to VNIIM. The observed count rate was higher at (1140.0 ± 0.4) s^{-1} due to increased background. On the return of the instrumentation from Russia, a count rate of (1140.5 ± 0.4) s^{-1} was observed and therefore it was concluded that the sensitivity had remained stable since the return of the instrumentation from PTB.

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It was decided to normalise the measured responses to a count rate in the BIPM arrangement of 979 s^{-1}. The reported sensitivities would be multiplied by the correction factors below.

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8 ANALYSIS

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A year after these results were collated, and before it was decided that no further results would be included (due to the problems at ETL), PTB reported an error in the corrections for the measurements performed using the accelerator [6]. The values for the ^{45}Sc(p,n) and ^{7}Li(p,n) fields were revised by about 4% and 6% respectively, and the filtered beam results were also modified (by 1.3%) due to a change in the common fluence reference value. The revised values (shown in Table 3) represent the present state-of-the-art. The changes, which slightly worsen the general consensus, do not affect the overall conclusions (below) drawn from this exercise.

9 RESULTS

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9.2 Results for 3.5 inch sphere

Similar to the above results for the smallest sphere, these results consist of a band of seven values from four participants with upper and lower limits 9% apart, with an isolated value (NIST) about 25% lower than the unweighted mean of the others. The uncertainty for the NIST value is 30% of the mean and therefore this value is consistent within its uncertainty with the other values. The other values are consistent within the estimated uncertainties which are all less than about 9% (at 95% confidence level). The calculated (MCNP) value is 5.5% lower than the unweighted mean of the values from the four groups.

9.3 Results for 9.5 inch sphere

These results also consist of a band of seven values from four participants with upper and lower limits 9% apart, with an isolated value (NIST) about 16% lower than the unweighted mean of the others. The uncertainty for the NIST value is 33% of the mean and therefore this value is consistent within its uncertainty with the other values. The other values are consistent within the estimated uncertainties which are all less than 9% (at 95% confidence level). The calculated (MCNP) value is about 3% higher than the unweighted mean of the values from the four groups.

9.4 Overall trends

a) The NIST values are consistently around 30% lower than the mean of the other values.

b) The values obtained from the CIAE Sb-Be field are consistently higher than those for the VNIIM Sb-Be field. These differences are however within the estimated uncertainties and that for the 9.5 inch sphere values is not significant.

c) The PTB results for the filtered beam are about 8% higher than those for the CIAE filtered beam for all three spheres. These differences are also within the estimated uncertainties.

d) The NPL values are higher than those obtained using the PTB ^{45}Sc(p,n) field, but the differences, averaging about 2%, are not significant.

e) The values obtained from the CIAE Sb-Be field are consistently higher than those for the CIAE filtered beam. The difference is 11% for the 2.5 inch sphere values but is not significant for the 9.5 inch sphere values. These differences are however within the estimated uncertainties.

f) There are no marked internal trends for the results for the three fields used at PTB.

9.5 Ratios of sensitivities for pairs of spheres

The three ratios of the results for the three spheres in each field for each participant were calculated in order to cancel out possible systematic errors, for example, in fluence monitoring. The values obtained in Table 3 show that the (2.5/3.5) ratio for the four participants excluding NIST fluctuates less than the corresponding (9.5/3.5) and (2.5/9.5) ratios. This is reflected in the standard deviations for the unweighted values which are 1.1%, 2.7% and 3.5% respectively. (The uncertainties are given for only the PTB values because participants had not been requested to supply this information.) This indicates that there is probably a closer correlation between the measurements using the smaller spheres than between either of them and the large sphere. The variation of the ratios is less than that for the sets of sensitivities of individual spheres in spite of the fact that the random uncertainty components for each pair of spheres are additive.

10 CONCLUSIONS

Although four fundamentally different types of neutron field were used in this comparison, consistent values were obtained by participants for the fluence responses of the Bonner spheres with three different diameters. The accuracies achieved here suggest that uncertainties in neutron fluence determination in this energy region of better than 9% (at 95% confidence level) are generally possible. However, there are practical difficulties with the production of neutron fields in this energy region (eg. low fluence rates with accelerator-produced fields, handling and half life problems with Sb-Be sources).

With the limited number of laboratories using each type of field it is not possible to draw any conclusion regarding trends between the different techniques for producing neutrons in this energy region.

The Bonner sphere detector has now been successfully used in comparisons of fluence measurements from 25 keV to 15 MeV [4]. This represents the range of neutron energy that has so far been covered by CCRI comparisons (excluding measurements of thermal neutron fluence rate). No spheres used in the present exercise had optimum response function for this neutron energy region and therefore the corrections for spectral effects were not minimised.

There are a few trends and discrepancies in the results which could usefully be investigated.

11 ACKNOWLEDGEMENTS

The extensive computing of the Bonner spheres sensitivity functions carried out by Dr Burkhard Wiegel (PTB) is much appreciated.

All participants are indebted to Dr V D Huynh (BIPM) and Dr Guy Ratel (BIPM) for their invaluable work of organising the transportation of the instrumentation between participating laboratories and BIPM, providing the test rig and performing the check source measurements.

The contribution made by the participating laboratories to this exercise is gratefully acknowledged.

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APPENDIX 1 SCHEDULE OF MEASUREMENTS

Participant	Field	Instrumentation sent from BIPM	Completion of measurements	Comments
NIST	Filtered beam	March 1993	August 1993	Detector SP9-BIPM1 used
CIAE	Sb-Be Filtered beam	October 1993	May 1994	Detector SP9-BIPM1 found to be defective; replaced by SP9-BIPM2.
PTB	Filtered beam $^{7}Li(p,n)$ $^{45}Sc(p,n)$	June 1994	November 1994	Calibration of SP9-BIPM2 changed between June and November
NPL	$^{45}Sc(p,n)$	December 1994	October 1995	Measurements in March 1995 stopped by failure of Van de Graaff beam deflection magnet. Six month delay to completion.
VNIIM	Sb-Be	December 1995	April 1996	No comments
ETL	$^{45}Sc(p,n)$	June 1996	March 1998	Measurements delayed by refurbishment of accelerator facility. Background due to contaminant neutrons too high. Measurements postponed indefinitely.

APPENDIX 2 EXPERIMENTAL DETAILS AND DATA

The following information was requested for the report to the Coordinator.

Neutron field

Antimony/beryllium source

- Construction/encapsulation
- Neutron emission energy for the principal reaction
- Mean neutron energy after escape from source
- Energy of contaminant group
- Mean neutron energy after escape from source
- Proportions of principal and higher energy group (%).

Filtered reactor beam

- Structure of filter
- Beam profile and/or description of scanning procedure
- Proportions of the principal and higher energy groups (%).

Scandium (p,n) reaction

- Thickness of scandium layer
- Backing material and thickness
- Proton beam energy
- Energy loss in scandium layer and mean reaction energy
- Angles used for measurements with set of spheres
- Corresponding neutron energies and spreads at those angles.

Lithium (p,n) reaction

- Thickness of lithium layer
- Backing material and thickness
- Proton beam energy
- Energy loss in lithium layer
- Mean neutron energy.

Spectra should be given for all fields used. State whether measured or derived by calculation.

Neutron monitoring system

- Device used to monitor neutron fluence
- Dead time
- Monitor counts and times
- Data relating to stability

Neutron fluence measurement

- Complete account of neutron fluence determination
- Corrections applied: their calculation or determination
- Values and associated uncertainties
- Spectrum obtained from detector used, if available
- Values for measured fluence per monitor unit

Measurements with spheres

Details of electronics
Example of pulse height spectrum with indication of bias used.
Effective overall dead time of electronics circuit
Detailed description of determination of corrections due to air- and room scattered neutrons, and to target interaction effects.

Analysis of data

Value of response of each sphere in field(s) used
(for a bias of 0.20 of peak height in the ^{3}He detector spectrum)
Corrections applied for scattered neutrons, etc
Spectral correction
Value of response of each sphere for 24.5 keV neutron energy
Ratios of responses of pairs of spheres (2.5"/3.5", 9.5"/3.5", 2.5"/9.5") and associated uncertainties

Uncertainties

A complete statement of uncertainties is required for all values
Random uncertainties
Non-random uncertainties
Combined uncertainties
Method used to combine components
Correlation coefficients
Confidence level, preferably 95%.

APPENDIX 3 EXPERIMENTAL DETAILS

A3.1 Antimony - beryllium sources

The VNIIM source consisted of a 6.3 mm diameter antimony ball in a 25 mm diameter sphere of beryllium, encapsulated in iron. The neutron emission (up to 5×10^6 s^{-1} at the time of the measurements with the Bonner spheres) was determined using the manganese bath method. The CIAE source consisted of a 15 mm diameter antimony ball in a 25 mm diameter beryllium shell. This was put into an aluminium cylinder, 25 mm diameter by 25 mm length, with a 0.5 mm wall. The neutron emission (up to 1.7×10^6 s^{-1} at the time of the measurements) was determined using the manganese bath method.

Both laboratories calculated the fluence rate at a given distance from the source emission rate, source anisotropy and the distance between source and detector effective centres. Corrections were applied for air and room scatter using the shadow-cone technique. For both sources the neutron spectrum was calculated in order to calculate the spectral corrections to the sphere responses. This type of source has a very high gamma radiation activity that necessitated a correction for the gamma pile-up effect in the ^{3}He detector of the Bonner spheres.

A3.2 Reactor beams with iron filter

The diameters of the filtered beams depended on collimator size, beam divergence and distance from the collimators. The collimator diameters were about 25, 30 and 50 mm for NIST, CIAE and PTB respectively. The beam profile at the measurement positions depended on other geometrical parameters such as distance and beam divergence. Each laboratory employed a scanning technique to measure the effective uniform irradiation responses of the Bonner spheres.

NIST determined fluence using a cylindrical BF_3 proportional counter that had been calibrated using a thermal neutron beam to determine the number of ^{10}B atoms and an evaluated value for the n-^{10}B cross section at 24.5 keV, and applying various corrections. Proton recoil counter measurements showed 97.1% of the fluence to be at 24.5 keV with 1.6% at 135 keV and 1% at 280 keV. The large uncertainty was essentially due to the beam calibration, assigned on the basis of inconsistent results obtained in this and previous work.

CIAE used a long counter, calibrated at 144 keV, 565 keV and higher energies, and a set of four Bonner spheres, with calibrations calculated employing MCNP, to determine the neutron beam fluence. The beam profile was measured using a cadmium-covered ^{3}He proportional counter. Measurements of the spectrum using a high-pressure, cylindrical ^{3}He proportional counter indicated that the higher energy contamination was less than 1% and therefore no spectral corrections were applied.

The PTB filtered beam was monitored with a fission chamber which was calibrated using a proton recoil proportional counter (see below). The spectral distribution was obtained for two filter arrangements (iron filter and iron filter with difference filter) using a transmission calculation with ENDF/B-VI cross sections, taking into account the reactor spectrum at the filter entrance. The ratio of the higher energy lines to the 24 keV line of 0.14 for the iron filter was reduced to 0.017 for the 'difference' beam. Difference spectra calibrations of detectors were made by taking the difference in responses obtained using the iron filter and the iron filter with difference filter.

A3.3 Accelerator-based fields

At PTB, a cylindrical proton recoil proportional counter, sensitive length 193 mm and diameter 55 mm, was used to determine the fluence of neutrons produced using the $^{45}Sc(p, n)^{45}Ti$ and $^{7}Li(p,n)^{7}Be$ reactions. The gas filling was 57.9 kPa hydrogen and 2.1 kPa methane. The response function was calculated for mono-energetic neutrons and folded with the neutron spectrum for a specified neutron-producing target for a specified measurement position, taking account of the neutron interactions with the target and counter materials.
Special efforts were required to subtract the background due to the photon radiation in the accelerator-based neutron fields.

NPL measured the fluence of neutrons produced with the $^{45}Sc(p,n)^{45}Ti$ reaction using a precision long counter that had been calibrated using a range of radionuclide sources, including an Sb - Be source. From earlier time-of-flight measurements the spectrum was known to be mono-energetic. No corrections were applied for the effect of interactions in the neutron-producing target.

24.5 keV NEUTRON FLUENCE SENSITIVITIES (cm^2)

		R(2.5)	Corrected R′(2.5)	R(3.5)	Corrected R′(3.5)	R(9.5)	Corrected R′(9.5)
VNIIM:	Sb - Be	0.532 ± 0.021	0.532 ± 0.021	1.760 ± 0.067	1.760 ± 0.067	0.566 ± 0.020	0.566 ± 0.020
CIAE:	Sb - Be	0.548 ± 0.036	0.532 ± 0.036	1.882 ± 0.125	1.826 ± 0.125	0.600 ± 0.040	0.582 ± 0.040
	Filtered beam	0.493 ± 0.044	0.478 ± 0.044	1.738 ± 0.155	1.686 ± 0.155	0.587 ± 0.052	0.569 ± 0.052
NIST:	Filtered beam	0.422 ± 0.170	0.422 ± 0.170	1.342 ± 0.535	1.341 ± 0.535	0.493 ± 0.195	0.493 ± 0.195
PTB:	Filtered beam	0.520 ± 0.046	0.512 ± 0.046	1.824 ± 0.172	1.797 ± 0.172	0.621 ± 0.056	0.612 ± 0.056
	^{7}Li(p,n)	0.492 ± 0.042	0.485 ± 0.042	1.783 ± 0.150	1.756 ± 0.150	0.583 ± 0.048	0.574 ± 0.048
	^{45}Sc(p,n)	0.497 ± 0.046	0.490 ± 0.046	1.738 ± 0.145	1.712 ± 0.145	0.559 ± 0.050	0.551 ± 0.050
NPL:	^{45}Sc(p,n)	0.506 ± 0.050	0.506 ± 0.050	1.791 ± 0.165	1.791 ± 0.165	0.608 ± 0.053	0.608 ± 0.053
Calculated (MCNP)		0.468	0.468	1.684	1.684	0.610	0.610

Participants have applied their own corrections to adjust values to a mean energy of 24.5 keV

Uncertainties are for 95% confidence level.

Table 1 **Values initially submitted to Evaluator and corrected for variation of ^{3}He proportional counter sensitivity**

24.5 keV NEUTRON FLUENCE SENSITIVITIES (cm^2)

		R″(2.5)	R″(3.5)	R″(9.5)	2.5/3.5	9.5/3.5	2.5/9.5
VNIIM:	Sb - Be	0.500 ± 0.021	1.755 ± 0.067	0.567 ± 0.020	0.285	0.322	0.882
CIAE:	Sb - Be	0.534 ± 0.036	1.832 ± 0.125	0.583 ± 0.040	0.291	0.318	0.915
	Filtered beam	0.478 ± 0.044	1.686 ± 0.155	0.569 ± 0.052	0.284	0.338	0.840
NIST:	Filtered beam	0.422 ± 0.170	1.341 ± 0.535	0.493 ± 0.195	0.314	0.367	0.856
PTB:	Filtered beam	0.512 ± 0.046	1.797 ± 0.172	0.612 ± 0.056	0.285 ± 0.022	0.340 ± 0.024	0.837 ± 0.052
	$^{7}Li(p,n)$	0.485 ± 0.042	1.756 ± 0.150	0.574 ± 0.048	0.276 ± 0.032	0.327 ± 0.036	0.844 ± 0.100
	$^{45}Sc(p,n)$	0.490 ± 0.046	1.712 ± 0.145	0.551 ± 0.050	0.286 ± 0.036	0.322 ± 0.040	0.889 ± 0.110
NPL:	$^{45}Sc(p,n)$	0.513 ± 0.050	1.797 ± 0.165	0.600 ± 0.053	0.285	0.334	0.855
Calculated (MCNP)		0.468	1.684	0.610	0.278	0.362	0.767

Table 2 **Values corrected to reference energy of 24.5 keV using response functions calculated by PTB**

24.5 keV NEUTRON FLUENCE SENSITIVITIES (cm^2)

		R″(2.5)	R″(3.5)	R″(9.5)	2.5/3.5	9.5/3.5	2.5/9.5
VNIIM:	Sb - Be	0.500 ± 0.021	1.755 ± 0.067	0.567 ± 0.020	0.285	0.322	0.882
CIAE:	Sb - Be	0.534 ± 0.036	1.832 ± 0.125	0.583 ± 0.040	0.291	0.318	0.915
	Filtered beam	0.478 ± 0.044	1.686 ± 0.155	0.569 ± 0.052	0.284	0.338	0.840
NIST:	Filtered beam	0.422 ± 0.170	1.341 ± 0.535	0.493 ± 0.195	0.314	0.367	0.856
PTB:	Filtered beam	0.519 ± 0.046	1.820 ± 0.156	0.620 ± 0.048	0.285 ± 0.022	0.340 ± 0.025	0.837 ± 0.054
	$^{7}Li(p,n)$	0.516 ± 0.044	1.838 ± 0.156	0.614 ± 0.052	0.281 ± 0.032	0.334 ± 0.036	0.841 ± 0.100
	$^{45}Sc(p,n)$	0.511 ± 0.048	1.772 ± 0.150	0.574 ± 0.052	0.288 ± 0.036	0.324 ± 0.040	0.890 ± 0.110
NPL:	$^{45}Sc(p,n)$	0.513 ± 0.050	1.797 ± 0.165	0.600 ± 0.053	0.285	0.334	0.855
Calculated (MCNP)		0.468	1.684	0.610	0.278	0.362	0.767

Table 3 **Values corrected to reference energy of 24.5 keV using response functions calculated by PTB and with further revisions**

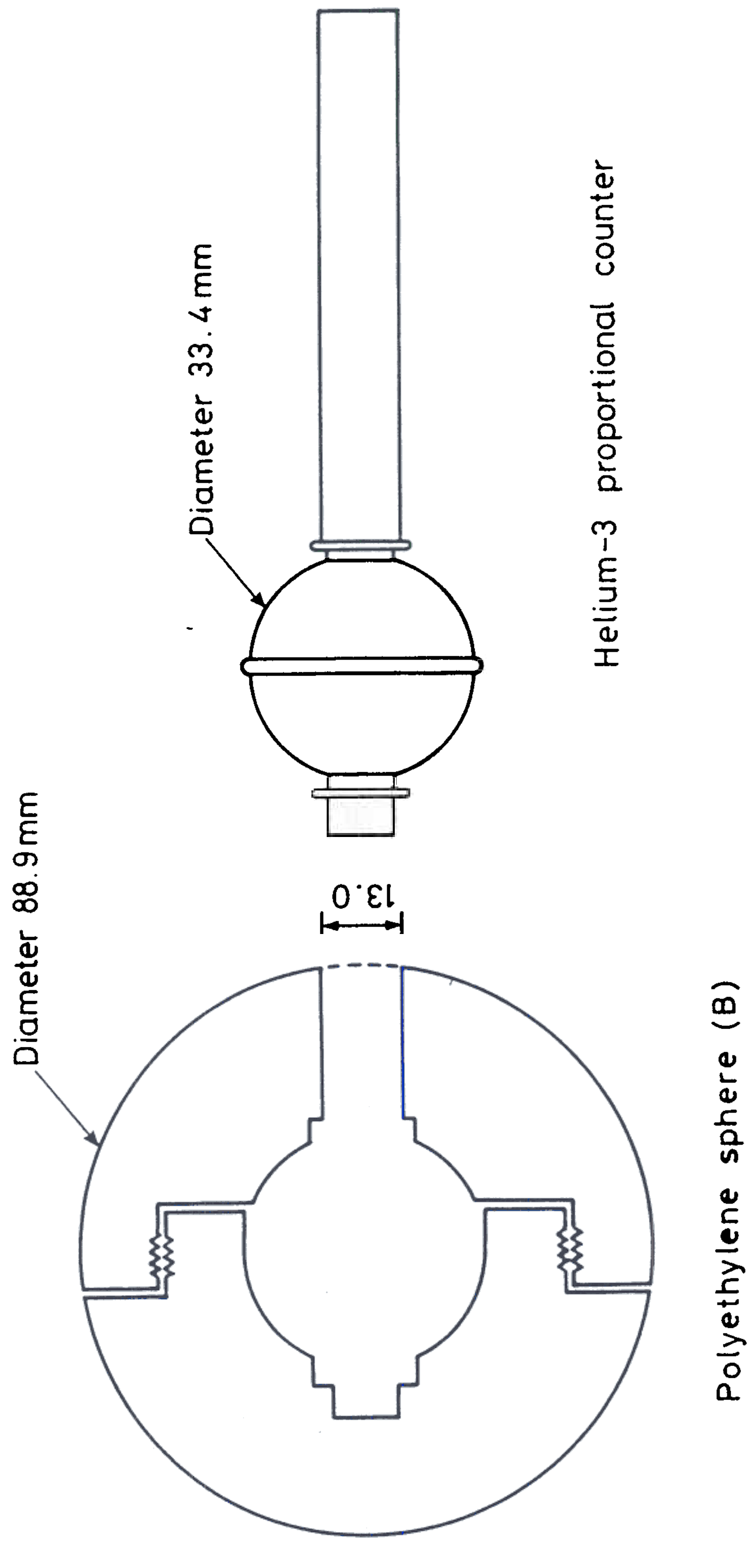


Figure 1 Bonner sphere *B* and central ^{3}He proportional counter detector

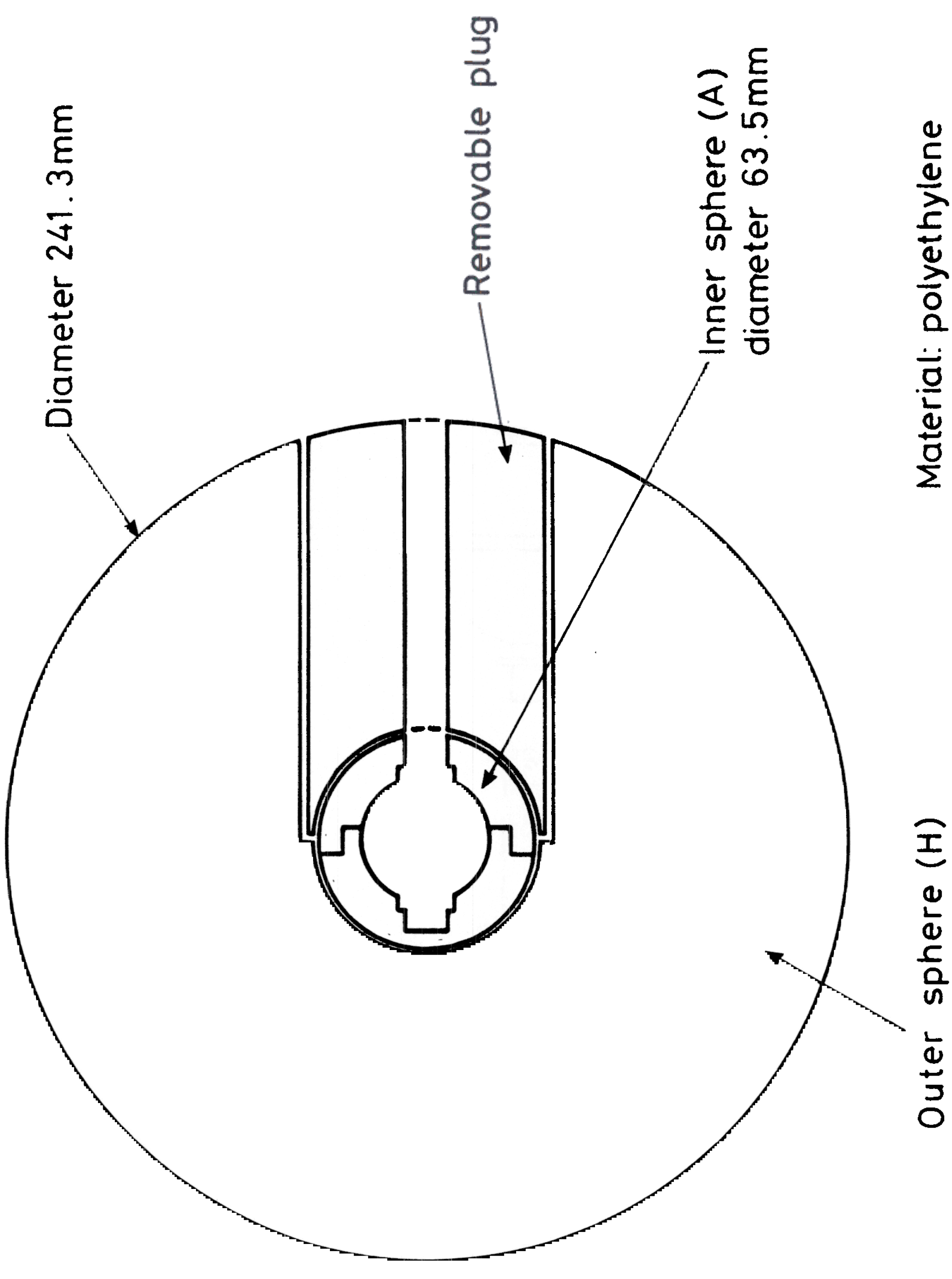
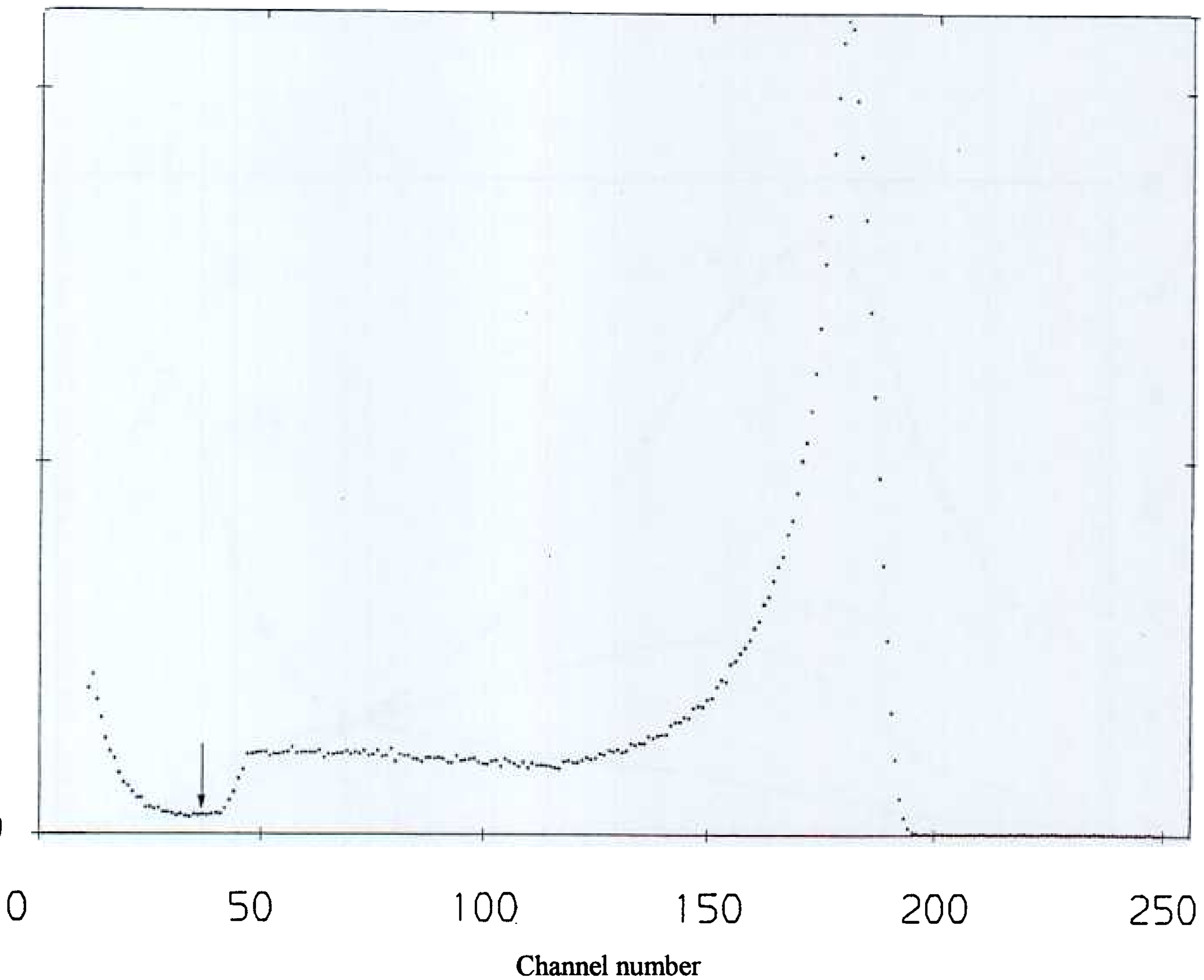


Figure 2 Bonner sphere *H* with small sphere *A* at centre



The arrow indicates the discriminator setting

Figure 3 **Pulse height distribution for ^{3}He proportional counter detector**

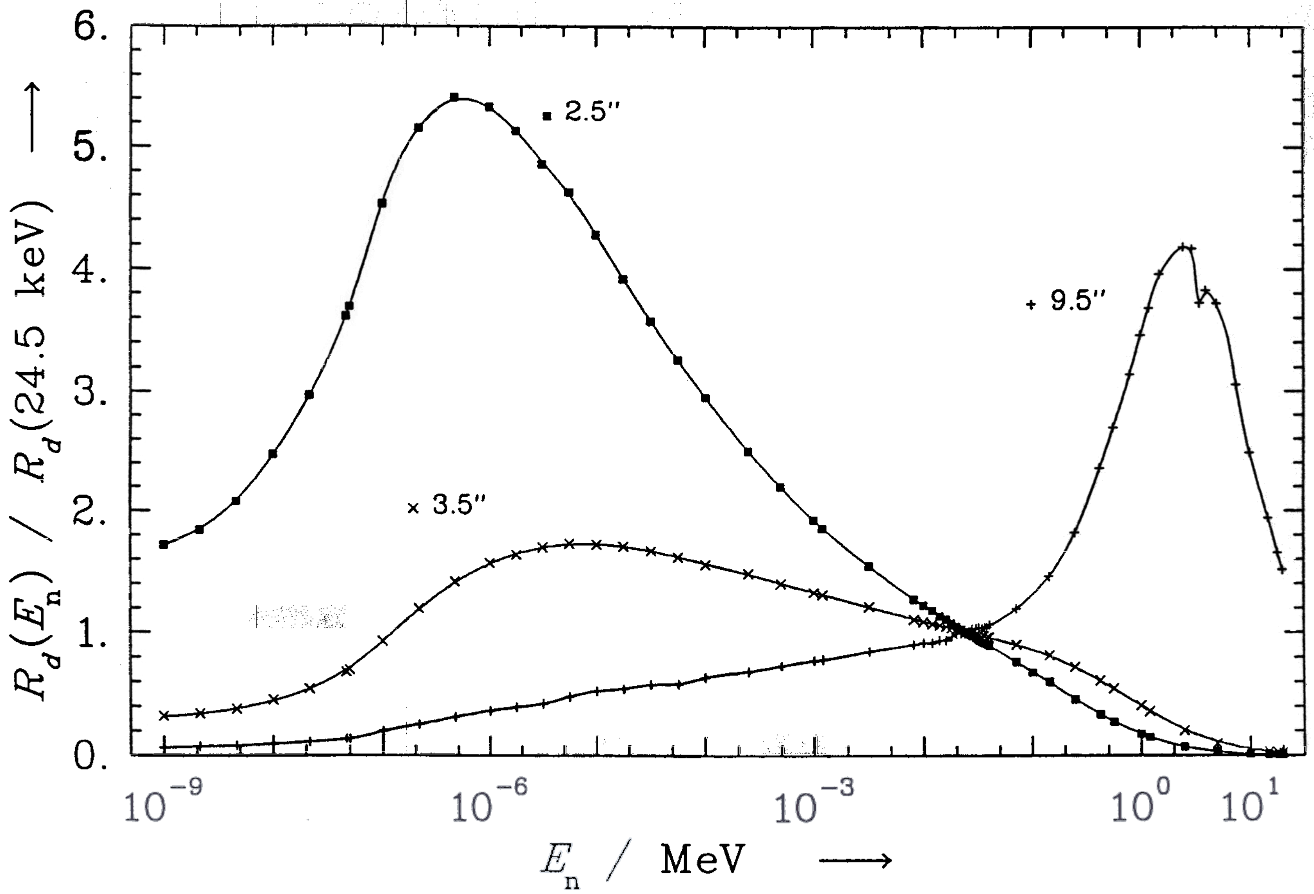


Figure 4 **Calculated Bonner sphere response function**

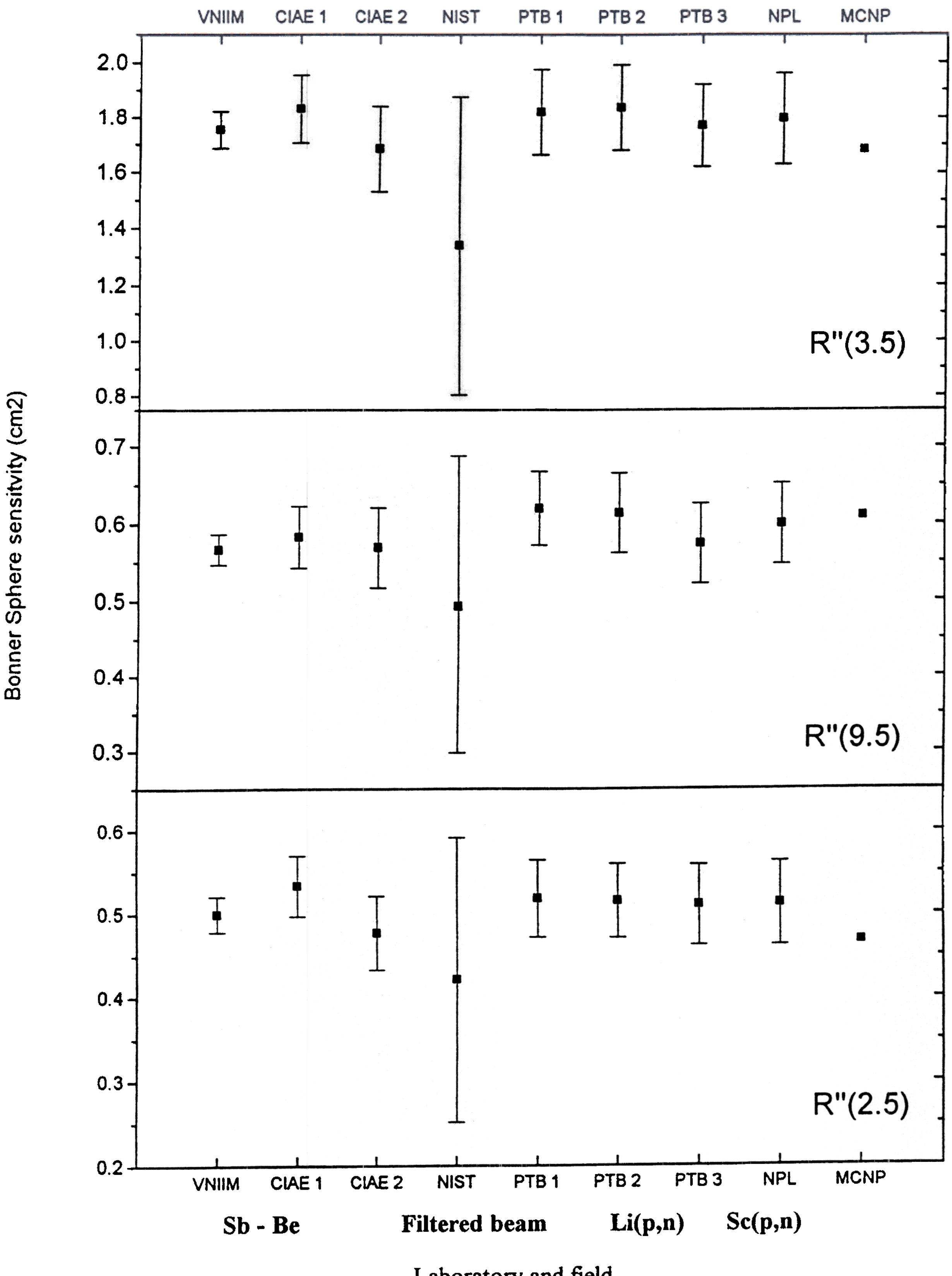


Figure 5 **Measured and calculated Bonner sphere 24.5 keV sensitivities**

ANNEX BONNER SPHERE RESPONSE FUNCTIONS, DETAILED DATA

(B. Wiegel, PTB Braunschweig)

The response $R_d(E_n)$ for neutron energy E_n was calculated with the Monte Carlo code MCNP4A [1]. In order to get consistent results between calculations and calibration measurements at different energies for a set of Bonner Spheres, e.g. the one used at PTB (called PTB-C), the geometry model used as input to MCNP needs to include a detailed description of the central ^{3}He-filled counter (Centronic Ltd., Model SP9). For details of the calculations for the PTB-C set see reference [2].

For the special set of Bonner Spheres used in this comparison (2.5", 3.5" and 9.5") the above mentioned model was used with some modifications. Figure A1 shows as an example the MCNP geometry plot of the NPL 2.5" sphere as a cross section along the symmetry axis (the stem on the right side of the counter is not shown completely). The technical drawing of the moderator sphere, as given in Figure 1, shows an extra gap between the counter and the polyethylene (PE) sphere - compared to the PTB hardware, labeled "air gap C-S" in Figure A1. The way the two PE half spheres are connected (see Figure 1) implies an additional volume which is not filled with PE. This complicated looking gap was approximated by a ring of rectangular cross section which is labeled "air gap S-S" in Figure A1. All shaded areas in Figure A1 are additional air gaps compared to the PTB design.

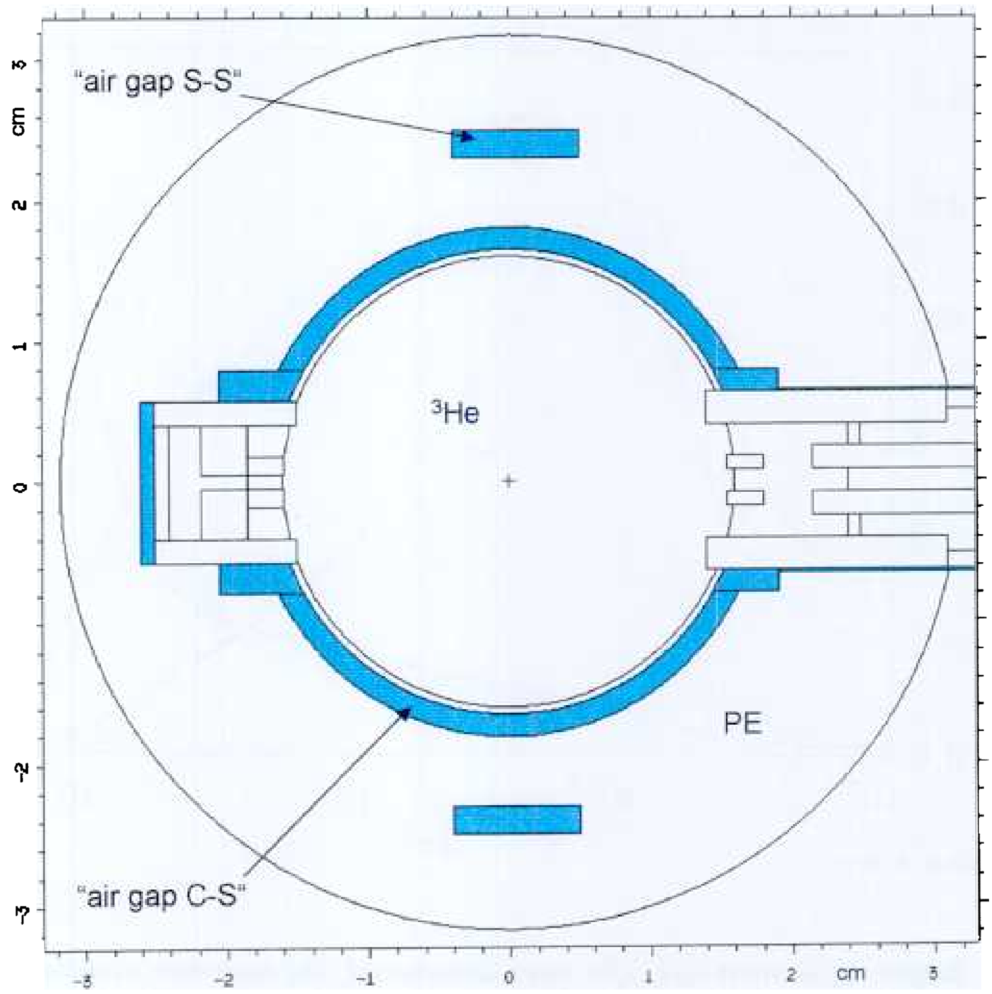


Figure A1: MCNP geometry plot of the NPL 2.5" sphere with additional air gaps.

Table A1: Calculated volumes and densities of the polyethylene (PE) shells. The numbers in parentheses are the results without "air gap S-S".

d (inch)	m (g)	V_{MCNP} (cm^3)	ρ_{PE} ($g\ cm^{-3}$)
2.5	98	103.3 (106.0)	0.9487 (0.9245)
3.5	315	333.3 (338.1)	0.9451 (0.9317)
9.5	6988	7313.9 (7316.6)	0.9554 (0.9551)

The polyethylene density ρ_{PE} is determined from the volumes of the PE shells calculated by MCNP and their measured masses (measurements were performed at NPL and at NIST). Since the three spheres were made from the same batch of polyethylene it is assumed that the densities are the same for all three spheres. With these constraints the dimensions of "air gap S-S" has been varied until the three calculated PE densities were comparable. Since the 2.5" sphere (A) is embedded in sphere shell H to become the 9.5" sphere (see Figure 2) the variation was always the same for those two spheres. Table A1 gives the final values for the MCNP-calculated volumes of the polyethylene shells and the corresponding PE densities.

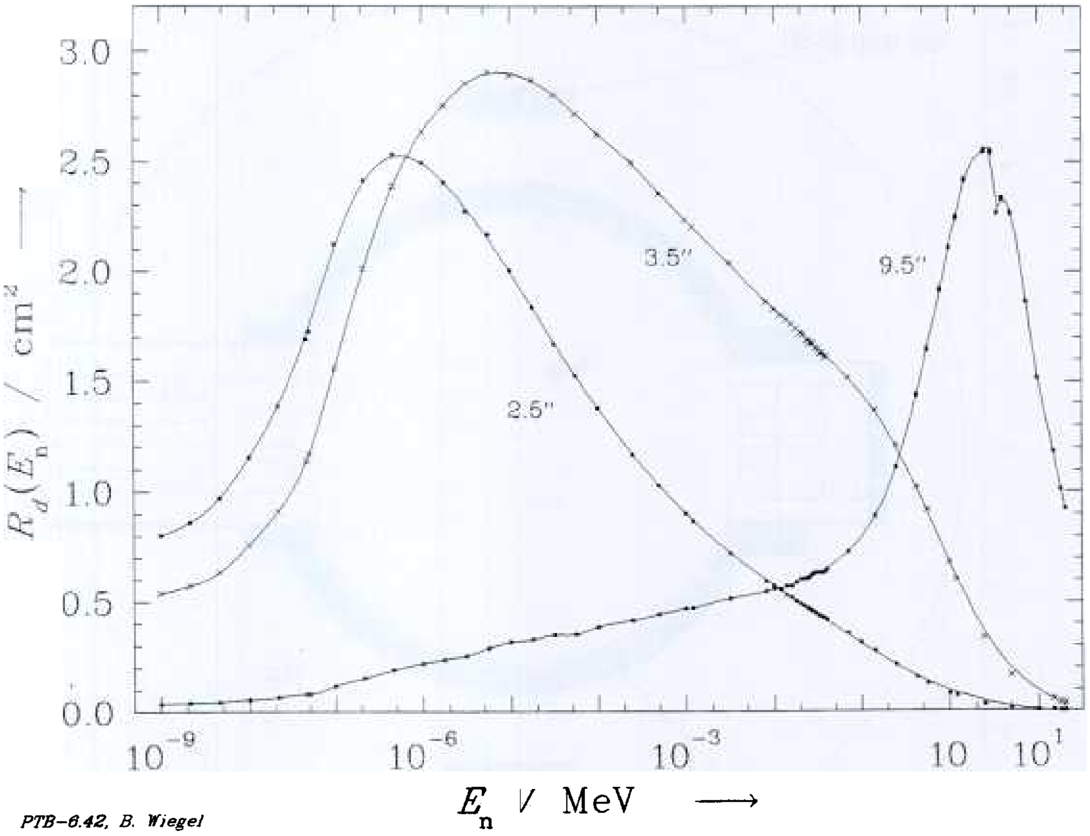


Figure A2: Response functions $R_d(E_n)$ for three diameters d. The responses were calculated at the energies marked by the symbols (uncertainties smaller than the symbol sizes), the lines are spline fits. Responses are valid only for the specified parameter values of ρ_{PE} and n_{He}.

The response functions $R_d(E_n)$ of the Bonner Sphere including the SP9 detector provided by NPL were calculated with the following parameters:

- $\rho_{PE} = 0.95$ g/cm^3 (average of three values of polyethylene density listed in Table A1)
- $n_{He} = 4.9418 \cdot 10^{19}$ cm^{-3} (^{3}He number density as determined for PTB detector "A")

It is important to note that the absolute responses shown in Figure A2 and listed in Table A2 are valid only for the parameter values given above. The energy grid is that used for the PTB set with special emphasis on energies between 10 keV and 40 keV.

Table A2: Absolute response values $R_d(E_n)$ and their relative statistical uncertainties u_d for three diameters d. Responses are valid only for the specified values of ρ_{PE} and n_{He}.

E_n MeV	$R_{2.5}(E_n)$ cm^2	$u_{2.5}$ %	$R_{3.5}(E_n)$ cm^2	$u_{3.5}$ %	$R_{9.5}(E_n)$ cm^2	$u_{2.5}$ %
1.000E-09	0.80400	0.32	0.53791	0.51	0.03640	3.27
2.150E-09	0.86258	0.32	0.57346	0.51	0.04280	3.09
4.640E-09	0.97201	0.32	0.63500	0.51	0.04720	2.95
1.000E-08	1.15600	0.33	0.75962	0.47	0.05582	3.16
2.150E-08	1.38670	0.31	0.91086	0.44	0.06616	2.84
4.640E-08	1.68880	0.30	1.13700	0.42	0.08072	2.58
5.000E-08	1.72490	0.30	1.16750	0.42	0.08070	2.54
1.000E-07	2.12020	0.29	1.55820	0.36	0.11819	2.15
2.150E-07	2.41160	0.27	2.01060	0.33	0.15289	1.95
4.640E-07	2.53210	0.26	2.38440	0.32	0.19001	2.01
1.000E-06	2.49370	0.26	2.63440	0.31	0.21973	1.87
1.780E-06	2.40130	0.25	2.75230	0.31	0.23759	1.82
3.160E-06	2.27340	0.25	2.85420	0.32	0.25510	1.76
5.620E-06	2.16620	0.25	2.90380	0.34	0.28944	1.64
1.000E-05	2.00450	0.26	2.89320	0.33	0.31742	1.68
1.780E-05	1.83440	0.27	2.87040	0.33	0.32862	1.66
3.160E-05	1.67020	0.28	2.80360	0.34	0.34990	1.59
5.620E-05	1.52400	0.29	2.71850	0.34	0.35340	1.56
1.000E-04	1.37870	0.31	2.62120	0.35	0.38555	1.52
2.500E-04	1.16850	0.32	2.49410	0.34	0.41400	1.46
5.000E-04	1.02820	0.31	2.35410	0.32	0.44252	1.40
1.000E-03	0.90015	0.33	2.23470	0.33	0.46873	1.37
1.200E-03	0.86747	0.34	2.20140	0.33	0.47326	1.37
3.160E-03	0.72156	0.37	2.03820	0.34	0.51431	1.31
8.150E-03	0.59413	0.38	1.85850	0.36	0.54860	1.27
1.000E-02	0.57130	0.37	1.82690	0.36	0.55867	1.26
1.200E-02	0.55212	0.38	1.79750	0.37	0.55720	1.24
1.400E-02	0.52966	0.39	1.77950	0.37	0.57034	1.24
1.600E-02	0.51743	0.39	1.75940	0.37	0.57046	1.23
1.800E-02	0.50185	0.40	1.73740	0.37	0.58881	1.21
2.000E-02	0.49020	0.41	1.71820	0.37	0.60138	1.21
2.200E-02	0.47962	0.41	1.71340	0.37	0.60365	1.21
2.400E-02	0.47051	0.19	1.68960	0.17	0.60411	0.54
2.450E-02	0.46777	0.19	1.68410	0.17	0.60966	0.54
2.600E-02	0.45998	0.42	1.67330	0.38	0.61783	1.20
2.740E-02	0.45537	0.42	1.67360	0.38	0.62328	1.19
2.800E-02	0.45550	0.42	1.66960	0.38	0.62761	1.17

Table A2 continued

E_n MeV	$R_{2.5}(E_n)$ cm^2	$u_{2.5}$ %	$R_{3.5}(E_n)$ cm^2	$u_{3.5}$ %	$R_{9.5}(E_n)$ cm^2	$u_{2.5}$ %
3.000E-02	0.44611	0.43	1.65180	0.38	0.63150	1.19
3.200E-02	0.43752	0.43	1.64640	0.38	0.63351	1.18
3.400E-02	0.43055	0.43	1.62640	0.38	0.63049	1.18
3.600E-02	0.42640	0.44	1.63210	0.38	0.63388	1.17
3.800E-02	0.42259	0.44	1.61120	0.39	0.63577	1.17
4.000E-02	0.41769	0.44	1.61480	0.39	0.64766	1.17
7.100E-02	0.35530	0.46	1.51490	0.38	0.72852	1.10
1.000E-01	0.31456	0.47				
1.440E-01	0.27878	0.49	1.36910	0.37	0.88973	0.99
2.500E-01	0.21357	0.54	1.21200	0.39	1.11130	0.89
4.250E-01	0.15686	0.60	1.02160	0.40	1.43660	0.78
5.650E-01	0.12777	0.63	0.91741	0.42	1.64400	0.71
8.000E-01					1.91540	0.60
1.000E+00	0.08120	0.71	0.68085	0.44	2.10880	0.54
1.200E+00	0.06880	0.76	0.60003	0.46	2.24450	0.53
1.500E+00					2.41460	0.51
2.500E+00	0.03180	0.98	0.33780	0.56	2.55060	0.50
3.000E+00					2.54300	0.50
3.500E+00					2.26830	0.52
4.000E+00					2.33180	0.52
5.000E+00	0.01400	1.27	0.16493	0.69	2.26700	0.52
7.500E+00					1.86210	0.55
1.000E+01	0.00563	1.89			1.51560	0.57
1.480E+01	0.00431	1.92	0.05352	1.09	1.18390	0.62
1.800E+01	0.00340	2.03	0.04243	1.22	1.00960	0.66
2.000E+01	0.00291	2.08	0.03774	1.31	0.92338	0.68

REFERENCES

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[2] Wiegel B., Alevra A., Siebert B.R.L., *Calculations of the Response Functions of Bonner Spheres with a Spherical ^{3}He Proportional Counter Using a Realistic Detector Model*, PTB report PTB-N-21, Braunschweig 1994.