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The determination of a neutron source position in an unknown homogeneous medium: The planar case

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Abstract

The possibility of localization of an unknown neutron source in various bulky homogeneous media (box) was studied. For the planar case, two ^{3}He detectors on the opposite faces of the box were used. A constant polypropylene shield around the box and detectors was used to eliminate the varying contribution from the environment to increase count rates of the detectors and to protect the experimentalist. It is shown that the location of a single small neutron emitting source in a large box can be found to a better than 7% by using two neutron detectors positioned on parallel faces of the box, coplanar with the source. The localization requires measurement of the count rate of both the unknown source and an extra source positioned on one of the faces of the box. The localization is based on the finding that the ratio of the count rates of the two detectors is an exponential function of the distance of the source from one of the detectors.

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Keywords: Neutron source; Location; Homogeneous medium

1. Introduction

The purpose of this research is to find the location of a point neutron source in an unknown homogeneous medium of a known large size sample. Possible applications of our results are for example measurement of radioactive wastes, finding small sources in glove boxes, the discovery of smuggled neutron emitting point sources as well as alpha sources due to (α,n) reactions, etc. The work was carried out both experimentally and by means of computational Monte-Carlo simulations.

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It was established in the past [1–4] that there is a possibility to determine the location of a gamma radiation sources (by measuring their characteristic peaks) in homogeneous medium by the use of several detectors. But the utilization of this method for the case of a neutron source is much more complicated. In the case of a γ source only the non-interacted photons can be measured due to the initial γ-rays being mono-energetic, and to the measurement of the full energy peak. In contrast, in the case of neutrons we cannot know if the detected neutrons went through scattering interaction prior to the detection. This is due to the continuous character of the spectrum of the emitted neutrons and the difficulty of the measurement of the spectrum of the detected neutrons. Due to the higher sensitivity for measurement of thermal neutrons, all the detected neutrons have already made one or several interactions. This work was done to find if we can use two detectors to locate the position of a point neutron source which is known to be on the plane connecting the two detectors.

It was found [5] that a number of neutrons in a narrow beam in a homogeneous medium falls off exponentially with absorber thickness, but in case of real source (isotropic emission) one should perform transport computation (Monte-Carlo) to find the neutron flux because of the interactions and scatterings of neutrons on their pass in the medium. In reality the reflections from the environment that contribute to the count rate in the detector should be taken into consideration.

To eliminate the varying contribution from the environment, a constant polypropylene shield was placed around the whole area of the sample (box) and the detectors. Another purpose of the polypropylene shield is to increase the neutron count rate in the detectors, due to reflections. It was found that the increase in the neutron net count rate due to the reflector is up to a factor of 10. This makes it possible to detect weaker sources in reasonable time.

Some studies on the localization of a neutron source were made in the past. Antonopoulos-Domis and Tambouratzis [6] determined the presence of even plutonium isotopes (EPI) within sealed tanks by oscillating the suspect tank in a well counter. The well counter consisted of a paraffin cylinder and 12 ^{3}He detectors. The tank was rotated with a known frequency and the problem of localization was solved by the least squares estimation.

Peurrung et al. [7] proposed the use of a moderator-free directional thermal neutron detector for identification and localization of neutrons sources even at distances up to 24 m. They placed neutron detector that is sensitive only to thermal neutrons inside a thermal neutron shield (cadmium box) and restricted the field of view using a collimator coated with a thermal neutron absorber. The experimental setup contained 23 ^{3}He proportional counter tubes placed in cadmium box with collimating array. This method works only when some amount of moderator is present near the source or between the source and the detector.

Linden et al. [8] used a small scintillation detector, attached to an optical fiber to localize neutron source in a homogeneous water medium, by measuring the flux and its gradient.

Later Avdic et al. [9] measured scalar neutron flux and neutron current by an optical fiber detector to localize a neutron source in a water tank.

2. Experimental setup

The experimental setup consists of a rectangular box $460 \times 200 \times 200\,\mathrm{mm}^3$ made of 5 mm thick Perspex with two ^{3}He detectors on opposite sides of the box (i.e. at 180° one to another), at a distance of 485 mm (center to center). A point source (^{252}Cf or AmBe) was positioned at different locations on the plane connecting the two detectors at a constant height, which is at about the center of the two detectors. Plates made of different materials were inserted into the box. The source holder was made of polypropylene 2.5 cm thick, 30 cm height and 20 cm length (the source placed in the middle of the holder in height of 10 cm).

A schematic diagram of the experimental system is shown in Fig. 1. The two detectors were operated simultaneously, each connected to a separate multi-channel analyzer (MCA) via con-

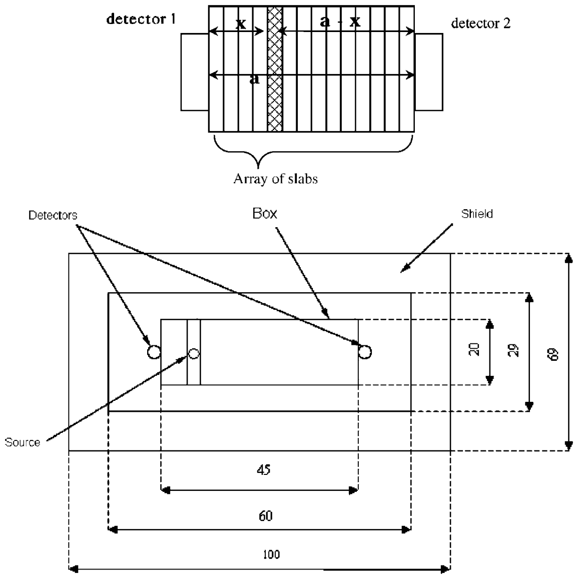

Fig. 1. Diagram of the experimental system: (a) side-view, and (b) top-view.

ventional electronic setup. The processing of the results was made by computing the sum over the spectrum due to the neutrons. γ-rays have much smaller voltage in a ^{3}He detector than neutrons and are rejected by the bias voltage of the MCA.

Neutron calculations were performed with the Monte-Carlo code MCNP-4C (Breiesmeister 2000) [10], utilizing the cell flux tally (F4). The F4 tally is an estimator of the expected flux value in the cell. This tally, when weighted by the material atomic density and absorption cross-section (F4 and FM4 combination), scores the number of neutrons absorbed in a real ^{3}He detector placed at the same flux [10].

The energy spectrum of the neutrons emitted by the AmBe source was taken from the literature [11]. ^{252}Cf spontaneous fission spectrum was taken directly from MCNP-4C libraries, according to Watt fission spectrum [10].

$$f(E) = C \exp\left(-\frac{E}{a}\right) \sinh(bE)^{1/2}$$

with the constants $a = 1.025\,\text{MeV}$ and $b = 2.926\,\text{MeV}^{-1}$.

3. Results

3.1. Measurement with a Single detector

Experimental results and Monte-Carlo simulations show that for a single detector and AmBe or ^{252}Cf sources, in different moderating medium, the dependence of the count rate due to neutrons on the source-to-detector distance can be described reasonably, but not too well, by an exponential function, as can be seen in Figs. 2(a) and 3(a). In Fig. 3(a) the value of the last point is lower than the value of the next-to-last point. This is due to absence of moderator between detector 2 and source in this point and hence the count rate drops. The detector is sensitive only to thermal neutrons, so without the slowdown of neutrons the detector will count only slow neutrons originating from the source and neutrons reflected from the shield but not neutrons coming directly from the source.

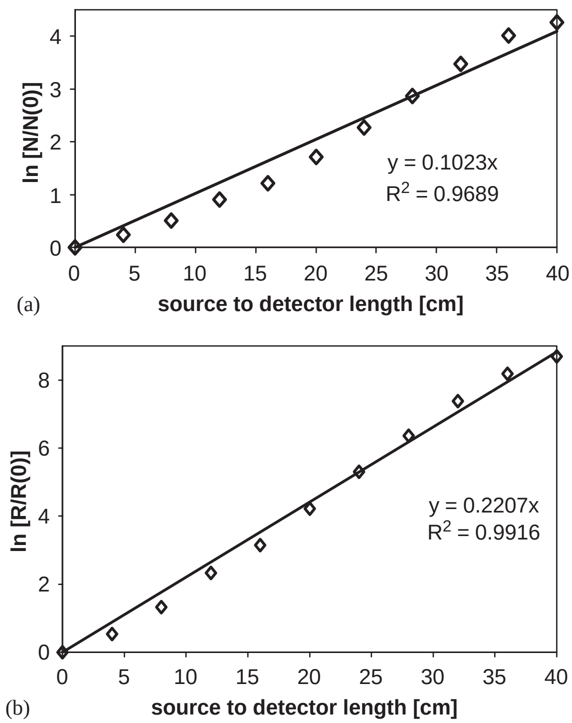

Fig. 2. Ln normalized (a) count rate of a single detector and (b) ratio of the count rate of two detectors as a function of source-to-detector distance for an AmBe source.

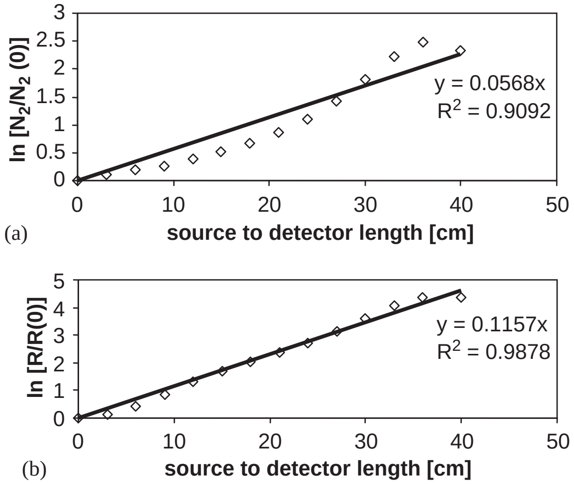

Fig. 3. Ln normalized (a) count rate of a single detector and (b) ratio of the count rate of two detectors as a function of source-to-detector distance for an Cf source.

Assuming exponential dependence it can be expressed mathematically

$$N_1(x) = N_{10}\mathrm{e}^{-\mu x} \tag{1}$$

$$N_2(x) = N_{20}\mathrm{e}^{-\mu(a-x)} = N_{20}\mathrm{e}^{-\mu a}\,\mathrm{e}^{\mu x} \tag{2}$$

where N_1 and N_2 are the count rates of detectors 1 and 2, respectively, when the source is at a distance x from detector 1 and a is the distance between the two detectors (box length minus source holder thickness).

Another way to test the exponential dependence of the count rates of single detector is to look on the geometric mean of the counts measured by the two detectors. In a case of perfect exponential dependence, the geometric mean should be constant independent of the distance x.

$$M_\mathrm{g} = \sqrt{N_1 N_2} = \sqrt{N_{10} N_{20}}\,\mathrm{e}^{-\mu a/2} \tag{3}$$

where N_1 and N_2 are the count rates of detectors 1 and 2, as given in Eqs. (1) and (2), respectively.

However, it was observed experimentally (results are given in Fig. 4(a,b), normalized to $N_{10}N_{20}$ equal to (1)) that M_g is not constant and decreases to 67% and 29% for AmBe and ^{252}Cf sources, respectively, toward the center of the box for some materials. It means that in this case, the exponential dependence is not always a good approximation.

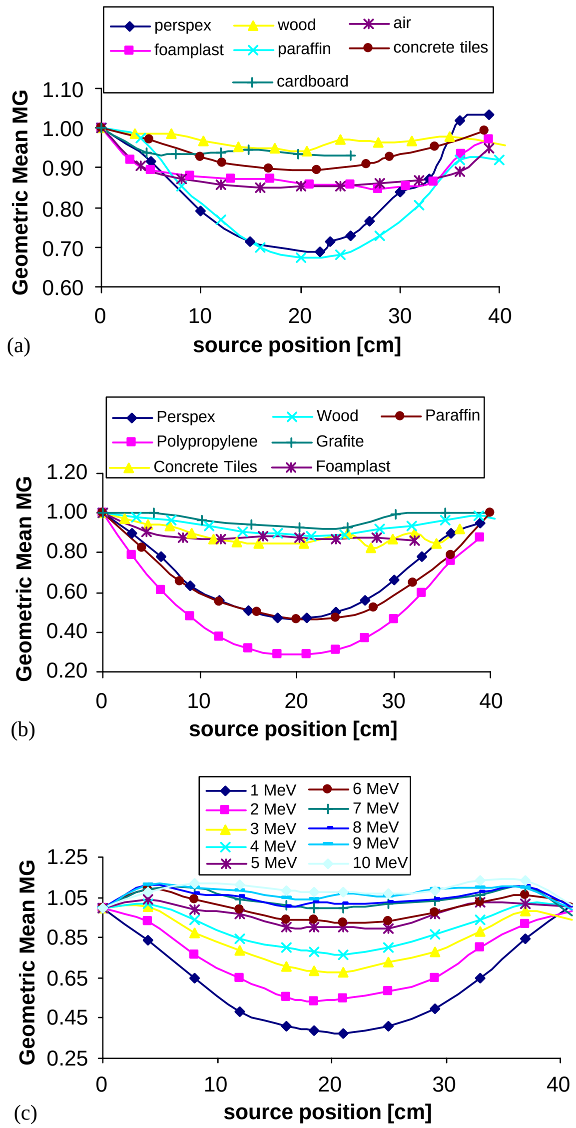

Fig. 4. The experimental geometric mean (M_g) for: (a) an AmBe source and (b) a Cf source, inside a box filled with different scattering media, as a function of the source distance from detector 1 (x). (M_g is normalized for distance = 0). (c) Geometric mean of the two detectors count rate, as calculated from MCNP simulations with paraffin medium, for various energies of monoenergetic neutrons.

Fig. 4(c) presents the geometric mean when N_1 and N_2 are calculated by MCNP rather than those measured experimentally. It shows clearly that M_g

is not constant and that the decrease of geometric mean toward the center of the box is more pronounced for lower energies of neutrons. This explains why the experimental results showed less constant geometric mean for ^{252}Cf source than AmBe. Fig. 4(c) also shows that the geometric mean drops sharply (to 0.7 for a AmBe source and to 0.4 for a Cf source) toward the center of the box for materials with high hydrogen concentration.

If Eq. (3) was valid, i.e. M_g is constant over various locations along the two detectors plane, the geometric mean can be used to calculate the activity of the point source as it is independent of the source location. Since the measurement shows that the geometric mean is not constant, it cannot be used for quantitative determination without prior determination of the location of the source.

3.2. Simultaneous measurement with two detectors

As we mentioned before, the exponential dependence for a single detector though reasonable is not too good. A better exponential dependence was found for the ratio of the count rates of the two detectors $R(x) = (N_1/N_2)$ (where in this case N_2 is the count rate of the detector positioned at the distance a and N_1 is the count rate at the detector positioned at distance 0), as can be seen in Figs. 2 and 3 and Table 1, which gives the correlation coefficient for exponential dependence for a single detector N_2 and for the ratio of the two detectors $R(x)$. A linear fit correlation coefficient equals 1 means a perfect fit and the closer is R^2 to 1 means a better correlation. The difference of the agreement with exponential dependence between a single detector and the ratio of two detectors is more prominent for ^{252}Cf source than for AmBe source, probably due to the lower energy of neutrons and/or to the different width of energy spectra (Figs. 2 and 3). We can clearly show that the difference is larger for lower energy by MCNP calculation (Fig. 5). In case of media with lower concentration of hydrogen, the difference in R^2 of the single detector and the ratio of two detectors are negligible, but for high concentration hydrogenous media, a much better exponential agreement of the ratio than for a single detector was found also by the Monte-Carlo calculations. Hence we will use only the exponential dependence of ratio of count rates of two detectors rather than the counts of one detector.

Table 1
A comparison between the linear fit correlation coefficient of the natural logarithm of the detector 1 (N_1) and the counts rate ratio ($R(x)$), for different scattering medias within the measured bulky sample

Source type	Exponential fit correlation coefficient R^2		
	Scatering media	N_2	$R(x)$
AmBe	Air	0.9765	0.9968
	Paper	0.9948	0.9933
	Concrete tiles	0.9976	0.9991
	Kardboard	0.9985	0.9971
	Foamplast + perspex	0.995	0.9973
	Wood	0.9837	0.995
	Foamplast + wood	0.9987	0.9989
	Paraffin	0.9689	0.9916
Cf	Polypropylene	0.8084	0.9921
	Perspex + foamplast	0.9898	0.992
	Grafite	0.9991	0.9991
	Paraffin	0.929	0.9878
	Perspex	0.9161	0.9889
	Wood	0.9939	0.9954

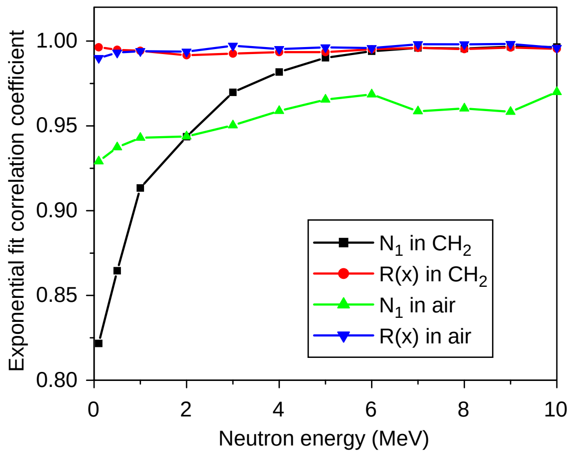

Fig. 5. A comparison between the exponential fit correlation coefficient of the count rate of detector 1 (N_1) and the counts rate ratio ($R(x)$), calculated from MCNP simulations in the media of paraffin or air for various energies of monoenergetic neutrons.

3.3. Source localization

We found that although the exponential dependence of a single detector involves relatively large deviation, the dependence of the ratio of the counts of the two detectors is quite accurate. Thus it can be written as

$$R(x) = R(0)\,e^{\mu x}. \tag{4}$$

Let us develop an equation for the calculation of the location x starting from Eq. (4). If a is the length of the box, then from Eq. (4)

$$R(a) = R(0)\,e^{\mu a}.$$

However the connection between $R(a)$ and $R(0)$ is the change in the naming of the detectors, detector 1 is now detector 2 and vice versa:

$$R(a) = R(0)\,e^{\mu a} = \frac{1}{R(0)}. \tag{5}$$

Hence

$$R(0) = e^{-(\mu a/2)} \tag{6}$$

$$\mu = -\frac{2\ln[R(0)]}{a}. \tag{7}$$

This equation can be developed not only for positions 0 and a but also for a general case. It can be written as

$$\frac{N_2}{N_1} = R(x)$$

$$\frac{N_1}{N_2} = R(a-x).$$

Since

$$R(x) = \frac{1}{R(a-x)}.$$

Then

$$R(0)\,e^{\mu x} = \frac{1}{R(0)\,e^{\mu(a-x)}}$$

$$R(0) = e^{-(\mu a/2)}$$

$$R(x) = R_0\,e^{\mu x} = e^{-(\mu a/2)+\mu x} = e^{\mu(x-(a/2))}. \tag{8}$$

Eq. (8) shows that $R(x)$ is independent of source activity, and can be used in order to calculate x.

To find the experimental μ we can measure $R(0)$, as Eq. (7) shows the correlation between them, with a source which will be located on the surface of the box.

From Eq. (4):

$$x = \frac{1}{\mu}\ln\left[\frac{R(x)}{R(0)}\right]. \tag{9}$$

Because the exponential parameter μ is a characteristic of medium and does not depend on the source activity substituting Eq. (7) in Eq. (9) yields

$$x = -\frac{a}{2}\,\frac{\ln[R(x)/R(0)]}{\ln[R(0)]} = \frac{a}{2}\left(1 - \frac{\ln[R(x)]}{\ln[R(0)]}\right). \tag{10}$$

The value of $R(0)$ with a known source cannot be measured unless we previously measure the contribution from the source in the box. Consequently, to find the location, a first measurement by the two detectors of the count rate of the unknown source positioned in an unknown place in the medium must be made. In the next step, an additional source is placed in position $x = 0$ (the source close to detector 1) and the count rate of the two sources together are measured by the two detectors. The count rate of the external source is calculated by subtraction of the counts of the unknown source from the counts of the two sources together.

The position x of the unknown source could be calculated by Eq. (10):

Table 2 compared the measured x from the actual position of the source with the calculated x from Eq. (10) for the AmBe source (Table 2). For the ^{252}Cf source similar results were received.

It can be seen that the relative deviation in the source position between the calculated value and the measured one, relative to the size of the medium, is lower than 6.5% for every medium in the experiment. This is the linear error. The volume error will be $(2*0.065)^3 = 0.0022$. Thus, it means that if we want to search for the source we have to search at most only 0.22% of the volume of the box. The same effect will be on the accuracy of the calculation of the activity of the source. The linear deviation in the source position in the box in absolute value is in all cases less than 2.11 cm. From Table 2 it can be seen that the deviation in the source position is larger when the source is

Table 2
The measured (x_{mea}) and calculated (x_{cal}) source-to-detector distance (cm) for an AmBe source

Wood			Paraffin			Air		
x_{mea}	x_{cal}	$\Delta x/a$	x_{mea}	x_{cal}	$\Delta x/a$	x_{mea}	x_{cal}	$\Delta x/a$
0.0	0.0	0.000	0.0	0.0	0.000	0.0	0.0	0.000
3.3	2.8	0.012	4.0	2.4	0.040	4.0	4.8	0.020
7.0	5.9	0.026	8.0	6.0	0.050	8.0	8.8	0.020
10.3	9.2	0.027	12.0	10.5	0.037	12.0	12.4	0.009
13.8	13.0	0.019	16.0	14.3	0.044	16.0	16.2	0.004
17.5	17.0	0.013	20.0	19.1	0.023	20.0	19.7	0.007
20.7	20.6	0.002	24.0	24.0	0.000	24.0	23.3	0.018
24.0	21.7	0.058	28.0	28.7	0.018	28.0	26.8	0.030
27.8	28.2	0.011	32.0	33.4	0.034	32.0	30.2	0.044
31.2	32.0	0.019	36.0	37.0	0.025	36.0	33.8	0.054
35.0	35.4	0.010	40.0	39.3	0.018	39.0	38.0	0.024
40.6	39.8	0.020						
Foamplast			Paper			Concrete tiles		
0.0	0.0	0.000	0.0	0.0	0.000	0.0	0.0	0.000
3.0	4.1	0.028	2.4	1.5	0.022	4.8	4.8	0.001
5.0	6.7	0.041	5.2	3.3	0.047	10.0	9.8	0.006
9.0	10.3	0.031	7.8	6.0	0.046	12.1	12.2	0.001
13.0	14.0	0.025	12.0	10.6	0.036	16.8	17.4	0.015
17.0	17.6	0.015	16.0	15.5	0.012	21.7	22.5	0.019
21.0	20.8	0.004	21.5	20.9	0.016	26.6	27.4	0.021
25.0	24.2	0.020	25.0	25.0	0.000	29.0	29.8	0.019
27.8	27.0	0.020	29.0	29.3	0.007	33.6	34.3	0.017
30.6	29.9	0.018	31.5	32.4	0.022	38.5	38.3	0.005
33.4	33.1	0.007	34.0	36.4	0.061			
36.2	34.6	0.041	36.5	38.0	0.039			
39.0	38.3	0.016	39.0	39.9	0.023			

Table 3
MCNP's calculated distance of source from detector 1 cm within scattering shield and for various media

Media	Perspex		Concrete tiles		Air		Fe	
x_{mea}	x_{cal}	$\Delta x/a$	x_{cal}	$\Delta x/a$	x_{cal}	$\Delta x/a$	x_{cal}	$\Delta x/a$
I. For AmBe source (R0 Cf source)								
4	4.6	0.014	5.2	0.029	5.7	0.040	7.5	0.085
8	7.9	0.001	8.9	0.022	9.5	0.037	10.9	0.070
12	11.6	0.009	12.4	0.011	13.2	0.030	13.5	0.038
16	15.7	0.006	16.0	0.001	16.4	0.010	16.6	0.014
18.5	18.0	0.013	18.2	0.008	18.2	0.008	18.6	0.003
21	20.4	0.015	20.4	0.015	20.2	0.019	20.4	0.014
25	24.4	0.015	23.9	0.027	23.6	0.034	23.3	0.041
29	28.1	0.021	27.5	0.035	26.9	0.051	26.0	0.074
33	32.0	0.025	31.1	0.046	30.6	0.060	29.1	0.094
37	35.7	0.031	34.8	0.053	34.0	0.073	32.7	0.106
41	38.1	0.072	38.8	0.052	39.0	0.049	38.5	0.062
II. For Cf source (R0 AmBe source)								
4	1.4	0.063	3.7	0.008	4.8	0.018	5.6	0.039
8	5.6	0.060	7.8	0.004	8.8	0.020	9.5	0.036
12	10.0	0.049	11.9	0.002	12.4	0.010	13.0	0.024
16	14.7	0.033	15.7	0.007	15.9	0.003	16.4	0.010
18.5	17.5	0.024	17.9	0.014	18.4	0.002	18.5	0.001
21	20.5	0.013	20.5	0.012	20.6	0.010	20.2	0.019
25	25.2	0.004	24.1	0.021	24.0	0.024	23.7	0.031
29	30.0	0.023	28.3	0.017	27.6	0.035	27.0	0.048
33	34.6	0.039	32.3	0.017	31.3	0.040	30.3	0.066
37	38.6	0.040	36.4	0.014	35.4	0.039	34.6	0.058
41	41.6	0.015	40.8	0.006	40.9	0.002	41.6	0.014

positioned in the edges of the box. This is due to less scattering and slowing down of neutrons when the source is situated very close to the detector, and hence the accuracy in the measurement drops. Similarly for MCNP calculation the measured x (as given in the input data) was compared with the x calculated from Eq. (10). The calculated source–detector distance is normalized to position 0 of the source. The results obtained from MCNP simulation and from experiments are in a good agreement with each other.

This method is accurate as long we know the type of the neutron source. For a completely unknown source in a box we have four unknowns: the location, the matrix, the type of the source which affects the neutron spectrum and the activity of the source. In our method, we ignore the activity of the source since we use the ratio of two detectors. The first two unknowns are determined by the two measurements of the unknown source in the unknown location and the known source on the surface. However, this assumes that both the neutron sources have a similar spectrum. This is the case for example when we look for a source of a known type in a glove box or for example in a measurement of nuclear waste, although nuclear waste can have both sources of neutrons, both spontaneous fission and (α,n) reaction with ^{18}O and ^{19}F. However, for a completely unknown source, larger errors in the calculated location will be caused because of the error in $\ln R(0)$.

Table 3 gives the error generated by a wrong assumption of the type of the neutron source comparing the actual position of the source, as it was given in MCNP input with the calculated x from Eq. (10) for the AmBe source by taking $\ln R(0)$ of the ^{252}Cf source, and for the ^{252}Cf source by taking $\ln R(0)$ of the Am–Be source. The error caused by the unknown energy of the source depends on the position of the source. The larger errors were obtained for sources close to one of the detectors up to 4 cm (10% in the case of $\ln R(0)$ of incompatible source and 8% for $\ln R(0)$ of the same source), and were about the same as for the known source type in other points. In conclusion, even in case of unknown source type Eq. (10) may be applied to determine the location of the source quite accurately.

3.4. Error calculations

In the previous paragraphs we demonstrated that the deviation between the actual position and the one calculated by Eq. (10) is quite small. In the following way calculation of the theoretical error due to the measurement is done. The position is calculated according to Eq. (10).

The standard deviation from this equation can be calculated according to the rules given by Bevington [12]

$$\sigma[\ln R(x)] = \frac{\sigma[R(x)]}{R(x)}$$

$$\sigma_x = \frac{a}{2}\,\sigma\left[\frac{\sigma \ln R(x)}{\ln R(0)}\right].$$

From the definition of $R(x)$:

$$\sigma[\ln R(x)] = \frac{\sigma[R(x)]}{R(x)} = \left[\left(\frac{\sigma N_1}{N_1}\right)^2 + \left(\frac{\sigma N_2}{N_2}\right)^2\right]^{1/2} = \sqrt{\frac{1}{N_1} + \frac{1}{N_2}}.$$

$$\sigma_x = \frac{a}{2}\frac{\ln R(x)}{\ln R(0)}\left[\left(\frac{\sqrt{1/N_1 + 1/N_2}}{\ln R(x)}\right)^2 + \left[\left(\frac{\sqrt{1/N_{10} + 1/N_{20}}}{\ln R(0)}\right)^2\right]^{1/2}\right].$$

The maximal error, calculated at $x = 38$, 39 cm with AmBe source in Perspex media, is $(\sigma_x/x) = 0.004$.

The maximal errors, calculated at $x = 30$ and 39 cm with ^{252}Cf source in Polypropylene media, are $(\sigma_x/x) = 0.009$ and $(\sigma_x/x) = 0.03$, respectively.

The maximal error, calculated at $x = 39$ cm with ^{252}Cf source in mixed wood and foamplast media, yields is $(\sigma_x/x) = 0.00061$.

3.5. The accuracy of the localization determination vs. the energy of the neutrons

As it was mentioned above, the decrease of the geometric mean toward the middle(center) of the box is larger for lower energies of neutrons.

MCNP simulation, where the source–detector distances were calculated for different energies of neutrons, indicates that the accuracy of the localization is almost independent of the neutron energy. This is due to the fact that Eq. (10), used for calculating the distance, involves the ratio of count rates of the two detectors and not the count rate of one detector.

3.6. The shield contribution

The polypropylene shield (see Fig. 1(b)) serves several purposes:

(1) Safety of the workers
(2) Constant environment
(3) Increase of the number of thermal neutrons reaching the detector.

In order to study the increase in the count rates due to the shield, a thermal neutron absorber made of a Cd sheet was used in a series of experiments to prevent thermal neutrons reflected from the shield to reach the detector. A Cd foil 5 mm thick covered the box together with the ^{3}He detectors. However, fast neutrons still may return, pass through the cadmium, thermalized in the box and counted in the detector.

Similar MCNP simulations were also performed. For the simulation the box was kept in vacuum, so there were no returned neutrons.

Table 4
A comparison of the counts of the detector 1 with MCNP for AmBe source inside (a) water medium (b) paraffin medium, within and without scattering shield. Count rates normalized for source in position $x = 0$

MCNP—Water medium			Experimental—Paraffin medium		
Cm	With shield	Without shield (air)	Cm	With shield	Without shield (Cd)
0	1	0.08	0	1	0.12
4	1.43	0.11	4	1.27	0.16
8	1.87	0.19	8	1.66	0.22
12	2.84	0.38	12	2.46	0.35
16	4.25	0.65	16	3.38	0.56
18.5	5.76	0.98	20	5.57	1.04
21	7.47	1.46	24	9.67	2.15
25	11.89	3.02	28	17.53	4.15
29	20.68	6.32	32	32.27	8.73
33	36.10	13.05	36	55.12	16.92
37	60.62	24.71	40	70.82	19.94
41	81.80	31.28			

It was found that Eqs. (4)–(10) can still be applied to these results, but the number of counts drops dramatically up to a factor of 10 (Table 4).

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