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CALIBRATION OF AN ANISOTROPIC NEUTRON DETECTOR

Alessandro Rindi, Silvia Miozzi and Francesco Celani
INFN, Laboratori Nazionali di Frascati, C.P.13, 00044 Frascati (Roma), Italy

ABSTRACT

We shall measure the neutron flux in the underground facilities of the Gran Sasso International Laboratory in Italy which is being built for experiments in high energy physics and other research fields.

Theoretical calculations show that the flux should range between some 10^{-7} and 10^{-6} n cm^{-2} s^{-1} and will be be isotropic.

The very sensitive large long counters which will be used for measuring the fast neutron component are very asymmetric and their calibration for operating in an isotropic neutron flux presents some peculiar problems.

We describe a semiempirical method for calculating the sensitivity of one or more asymmetric long counter to be used in an isotropic neutron field.

From an empirical equation which indicates the angular variation of the sensitivity of a single counter, we derive and experimentally verify the expression for the angular variation of several counters operated in parallel. This is used for finding the sensitivity constant for operation in an isotropic field.

1. - Introduction

We describe the calibration of a very large and anisotropic fast neutron detector to be used for measuring neutron fluxes in an isotropic neutron field.

We want to measure with high accuracy the very low neutron flux expected in the Gran Sasso underground Laboratory, which is located at a depth of 2.000 in the rock.

Neutrons underground are produced by the cosmic muons which penetrate the upper rock thickness and by the spontaneous fission elements present in the rock. Given the geometry of the laboratory, we can suppose, as a first approximation, that the neutron field is isotropic.

The expected flux in the fast neutron region ranges between some 10^{-6} and 10^{-7} n cm^{-2} s^{-1}.

For reaching a neutron sensitivity such as to detect this flux, one has to use very large volume neutron detectors. In particular, we chose to use the ^{3}He filled neutron detector model 100He3/228/50G manufactured by the Centronic in England.

The detector has a cylindrical shape, 100 cm length, 5 cm diameter and has a thermal neutron sensitivity, as stated by the manufacturer, of 433 c n^{-1} cm^2; it is filled with pure ^{3}He gas at a pressure of 3 atm.

For detecting fast neutrons, the detector is introduced into a cylindrical paraffin moderator 120 cm long and 30 cm diameter.

Such a detector can be assimilated to a long counter; given, however, its shape it is very far from being a symmetrical detector as it would be required for operating in an isotropic neutron field.

The calibration of this counter presents some peculiar problems which are described in the following.

2. - The calibration of the counter

The calibration of long counters is usually performed by exposing them at a given distance from a point-like neutron source. Attention is mainly given to find the "effective centre" of the counter i.e. the point in the detector from where to measure the distance to the source: from that distance the detector behaves as point-like and the count rate decreases with the inverse square of the distance. The sensitivity of the detector (expressed in count $n^{-1}cm^2$) is then inferred from the neutron flux at that distance. In addition, one strives to calculate the scattered component of the neutron flux which adds to the direct flux (see, f.i. ref. [1], [2], [3], [4] or, more recently, [5]).

When the dimensions of the cylindrical counter or of the moderator are such that the ratio length-to-diameter is not much higher than 1 and the required precision of the measurement is not very high (as for dosimetry measurements), one can neglect the angular dependence of the sensitivity and consider the detector as symmetrical.

Unfortunately, this is not our case.

Given the cylindrical shape of our counter with a length to diameter ratio of 4, its sensitivity is symmetrical for a rotation of the neutron direction around the X axis (see Fig. 1) but not for rotations around the Y and Z axes, even though these asymmetries are equivalent.

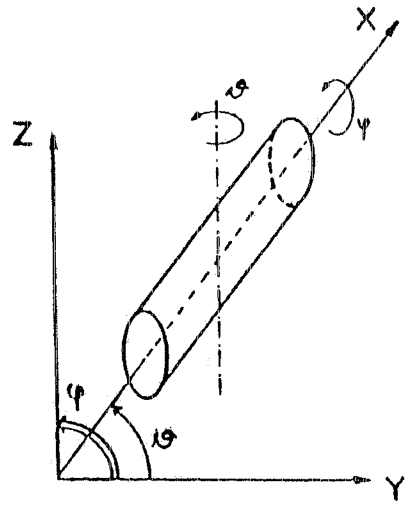

FIG. 1 - Rotation axis for I counter.

It would be very hard to generate a known isotropic neutron flux where to plunge the detector for finding an overall sensitivity: it would take several neutron sources of the same activity and a very large open space to perform the absolute calibration.

Quasi-isotropic fields of scattered neutrons may be generated using a neutron source inside a cubical or, better, a spherical concrete room [6], [7]. However, it is very difficult to perform an absolute measurement of the flux density of fast neutrons in the volume where to introduce the large detector to be calibrated. One cannot trust an absolute calibration based just on Monte Carlo calculations. Moreover, it is not easy to build such a facility with dimensions adequate to the dimensions of our detector.

We decided to use just one pointlike neutron source, keep it at a fixed distance from the counter along the Y axis and rotate the counter around the Z axis. If one can find a continuous mathematical function to fit the measured values at different angles, the average value of the function found by integration between 0° and 90° shall provide the correction factor to be applied to the sensitivity of the counter as measured at an angle $\theta = 0°$. The other asymmetry shall provide equivalent results.

However, as a first step, we have to find, for any angle, that distance source-detector at which the detector behaves as pointlike, i.e. the distance from the source to a given point of the detector (that we shall call symmetry center for that angle) from which an inverse square law is verified. Where all the symmetry centers at any angle coincide, from that distance we can measure the angular dependence of the sensitivity and find the mathematical expression that fits it.

3. - The measurements

The measurements reported in this and in the following paragraphs were performed at three different places:

a) inside a room at the first floor (7.5 x 5.5 x 3.3 m^3) with thin concrete walls and roof;

b) in a corridor 20 m long and 3 m wide;

c) in the open air.

We first used an AmB neutron source with an yield of 4.8 x 10^4 n s^{-1} for finding the right distance source-detector at which the detector behaves as pointlike.

The measurements should fit the equation:

$$Y = Aa/4\pi X^2 + b \qquad (1)$$

where

X = distance source-symmetry center of the counter (in cm)

Y = counting rate (in c s^{-1})

A = yield of the source (in n s^{-1})

a = sensitivity to neutrons from source at the given angle (in c n^{-1} cm^2)

b = total counting background (true background plus scattering component) (in c s^{-1}). It shall be constant starting from a source-to-detector distance which depends on the roof, ground and wall thickness of the room [1], [2], [3].

Fig. 2 and Fig. 3 show the results of measurements performed respectively for values of θ = 0° and θ = 45° and for various distances source to detector center.

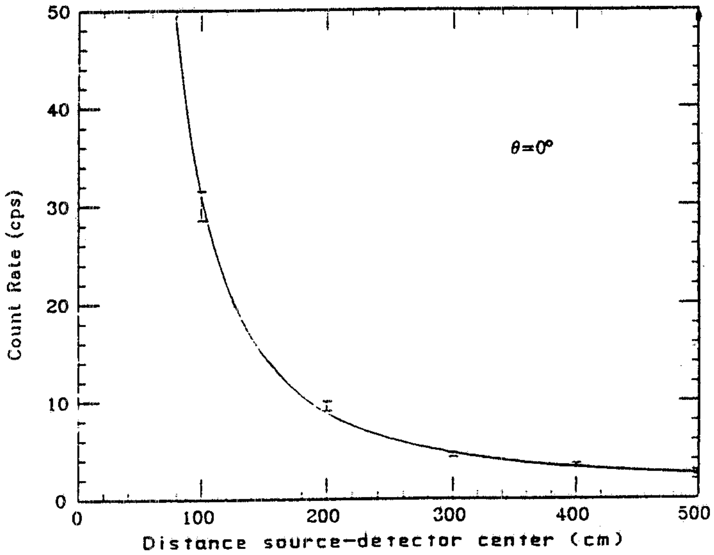

FIG. 2 - Count rate versus distance at θ = 0° for one counter. The line represents eq. (1) with overimposed the experimental data. The error bar indicates an "overall" error of 5%.

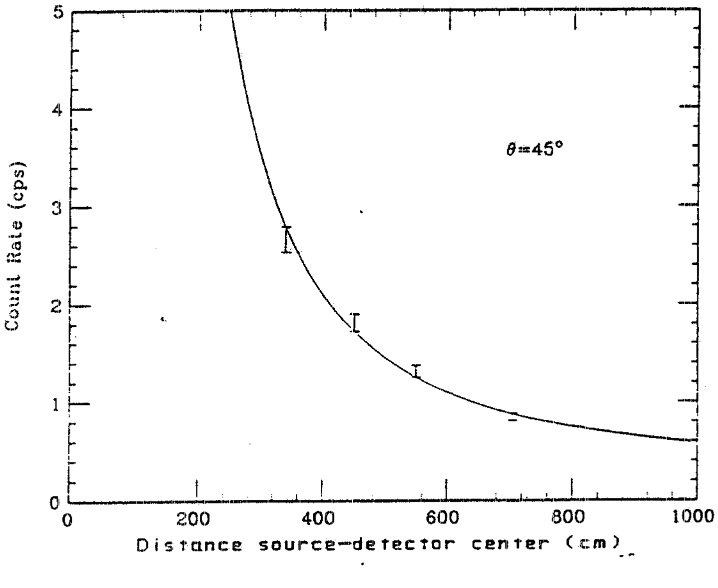

FIG. 3 - Count rate versus distance at θ = 45° for one counter. The line represents eq. (1) with overimposed the experimental data. The error bar indicates an "overall" error of 5%.

The experimental points follow rather well equation (1), at least for distances larger than 3 m, with values for a and b of 77.8 and 1.39 for the 0° case and of 75.4 and 0.3 for the 45° case. The rather high difference between the values of b is justified by the fact that we were forced by the dimensions of the room to change the experimental conditions and rotate the source around the detector.

Then, we performed the second series of measurements at a distance source-detector of 3 m and for values of $\theta = 0°, 22°, 45°, 70°$ and $90°$.

The measured values fitted (see Fig. 4) an equation of the type:

$$R_1(\theta) = S_1(\theta)/S_1(0°) = c_1 + d_1 \cos^2\theta \qquad (2)$$

where:

$R_1(\theta)$ = ratio between the count rate at an angle θ [$S_1(\theta)$]and that at 0° [$S_1(0°)$].

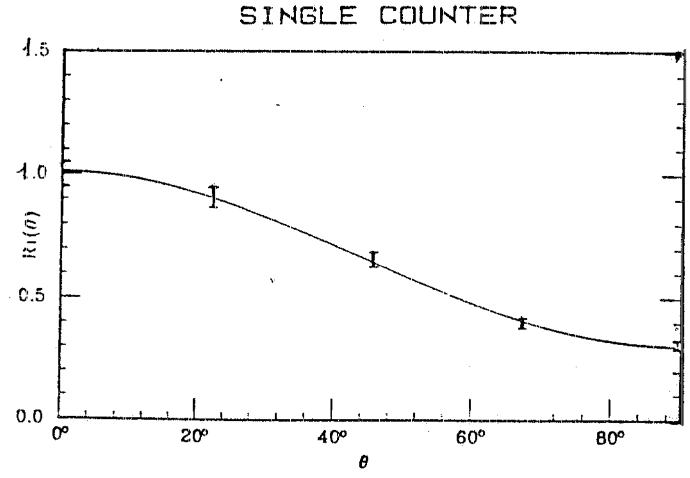

FIG. 4 - Fitting of experimental measurements of count rate for one counter for different angles θ. The line represents eq.(2) with overimposed the experimental data. The error bar indicates an "overall" error of 5%. /9

We did not find any intuitive explanation to this angular dependence.

The experimental values for c_1 and for d_1 were 0.3 and 0.7 respectively.

The R_1 mean value is found by integrating (2) between 0° and 90° and is

$$|R_1| = c_1 + d_1/2 \qquad (3)$$

The sought sensitivity constant to be used for the measurements in the isotropic neutron field will be given by the product of a at 0° and the correction factors for the asymmetries around the Y and Z axes which, being equivalent, have the same mean values. Then, the calibration factor is given by $a_{0°} |R_1|^2$. For our particular case it has the value of 32.9 c n^{-1} cm^2.

4. - Further measurements

Preliminary measurements of the neutron flux inside the underground Gran Sasso laboratories showed that the sensitivity of a single counter is not enough for reaching the sought statistical accuracy [8] [9].

We, then, decided to build a detector composed by 3 separate moderated counters of the type described in §1 electronically connected in parallel [10].

Practical reasons forced us to arrange the 3 counters as shown in Fig. 5.

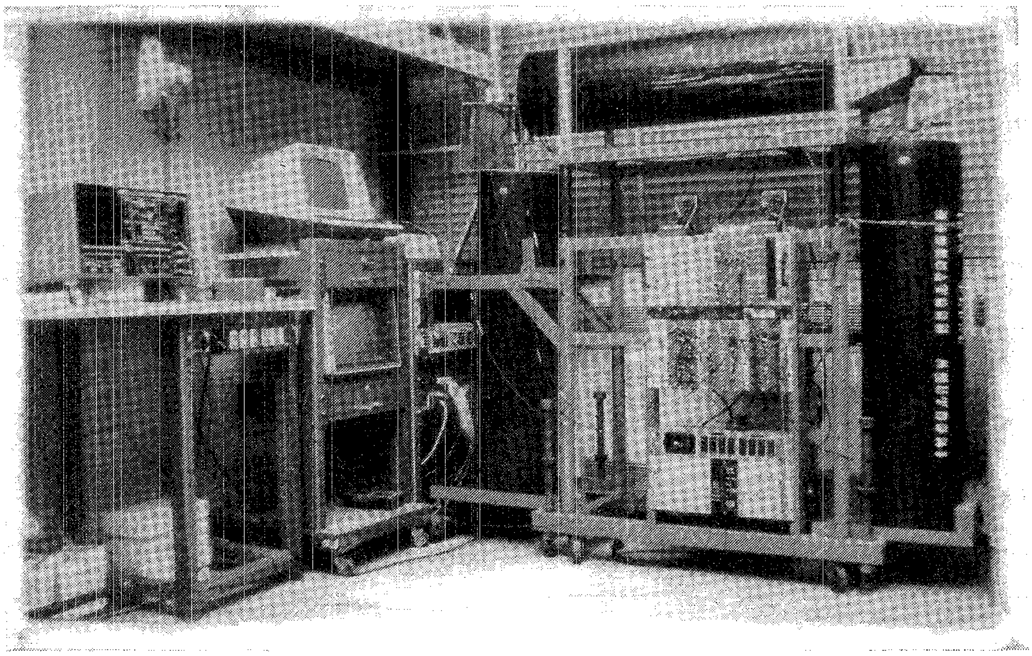

FIG. 5 - A view of the set of three counters.

Such a geometry is, of course, not symmetrical for an isotropic neutron field and, then, the calibration of such a detector presents the same kind of problems as for a single counter.

In this case, the detector is asymmetric for rotations around any of the three axes. We have, then, to find 3 different correction factors, one for each rotation axis.

However, the asymmetry of the system of three counters around each axis should be deduced from the asymmetry of a single counter around the same axis.

It is then possible to calculate the angular variation of the sensitivity of the three counter system from a combination of one or more equation of the type (2) obtained for a single counter.

We first found the distance source-detector at which the detector behaves as pointlike by fitting the "inverse square law" of eq. (1) with the count rates at different distances. For these measurements we used an AmBe neutron source with an yield of 2.18 x 10^6 n s^{-1}. From Fig. 6 one can see that starting from about 5 m the fitting is acceptable. We than choose the distance of 6 m for the angular rotations. We found for a a value of 236.6 c $n^{-1}cm^2$.

Referring to Fig. 7, the angular variation of the sensitivity for a rotation around the X axis (angle ϕ) for neutrons coming along the Y axis, will be given by

$$R'_3(\phi) = S'_3(\phi)/S'_3(0°) = \frac{S_1(0°) + 2S_1(\phi)}{3S_1(0°)} \tag{4}$$

where:

$R'_3(\phi)$ = ratio between the count rate of the three counter at an angle ϕ [$S'_3(\phi)$] and that for ϕ = O° [$S'_3(0°) = 3S_1(0°)$] for rotation around the X axis

$S_1(\phi)$ and $S_1(O°)$ have the same meaning as in (2) where we replace ϕ by θ.

We then have:

$$R'_3(\phi) = 1/3 + 2R_1(\phi)/3 = (1/3+2c_1/3)+2(d_1\cos^2\phi)/3 \tag{5}$$

Replacing c_1 and d_1 with the experimental values for a single counter, we have

$$R'_3(\phi) = 0.53 + 0.47 \cos^2\phi \tag{6}$$

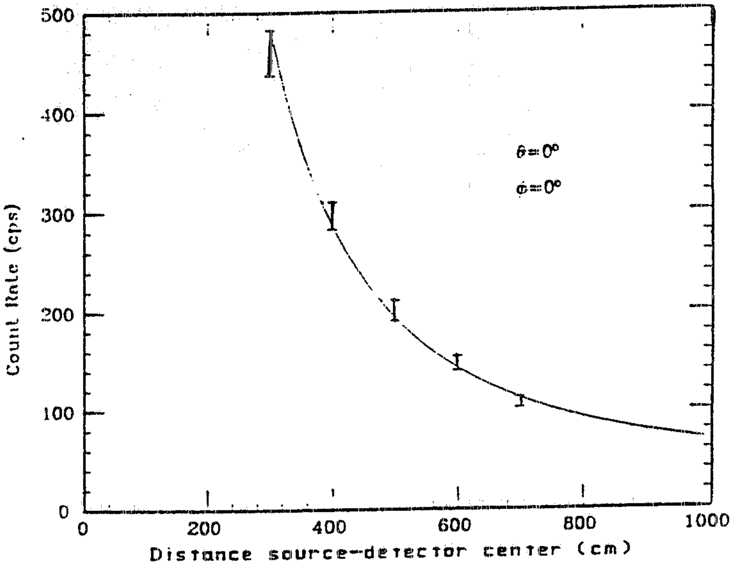

FIG. 6 - Count rate as a function of distance at θ = O° and ϕ = 0° for the set of three counters. The line represents eq.(1) with overimposed the experimental data. The error bar indicates an "overall" error of 5%.

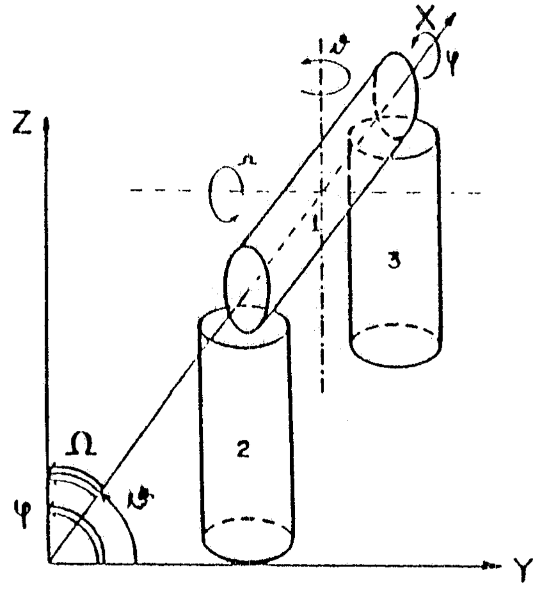

FIG.7 - Rotation angles for the set of three counters.

Experimental measurements for rotation around the X axis (Fig. 7) confirmed very well the expression (6) and gave for the constants c and d the values of 0.51 and 0.49 respectively.

For the variation due to a rotation around the Z axis (angle θ) for neutrons coming along the Y axis, we can write:

$$R''_3(\theta) = S''_3(\theta)/S''_3(0°) = \frac{2S_1(0°)+S_1(\theta)}{3S_1(0°)} = \qquad (7)$$

$$=2/3 + R_1(\theta)/3 = (2/3 + c_1/3) + d_1(\cos^2\theta)/3$$

where, as previously:

$R''_3(\theta)$ = ratio between the count rate of the three counters at an angle θ $[S''_3(\theta)]$ and that for $\theta = 0°$ $[S''_3(0°) = 3S_1(0°)]$ for rotation around the Z axis.

Replacing for c_1 and d_1 we have

$$R''_3(\theta) = 0.77 + 0.23\cos^2\theta \qquad (8)$$

Measurements for this rotation (Fig. 8) confirmed the expression (8) and gave for the constants c and d the values of 0.80 and 0.20 respectively, in very good agreement with the theory.

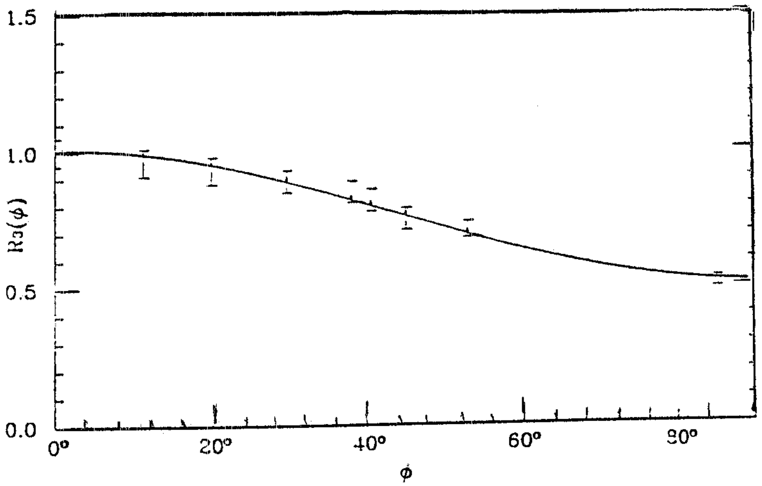

FIG. 8 - Fitting of experimental measurements of count rate for the set of three counters at different angles ϕ (rotation around X axis). The line represents eq. (6).

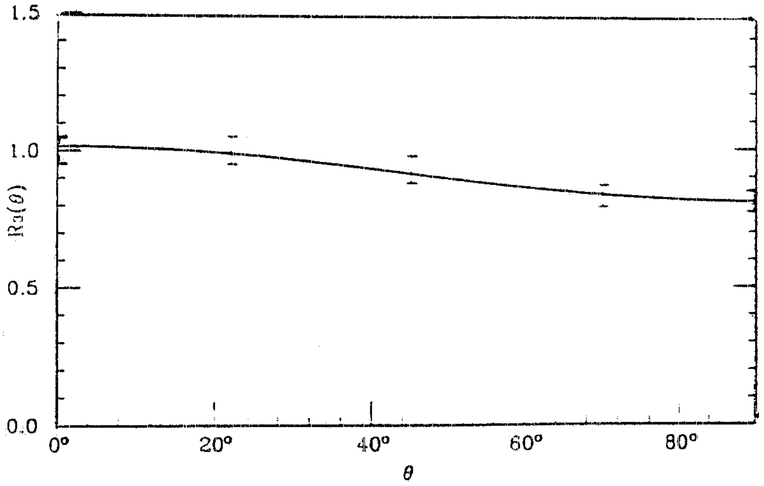

FIG. 9 - Fitting of experimental measurements of count rate for the set of three counters at different angles θ (rotation around the Z axis). The line represents eq. (8)

For the rotation around the Y axis, we have a slightly different situation. All the three counters "rotate". Referring to Fig. 9, for neutrons coming along the X axis, the counters 2 and 3 start the rotation at 0° while counter 1 starts at 90°. The variation of the sensitivity of counter 1 with the angle will be expressed by

$$S_1(90° - \theta) / S_1(90°) \tag{9}$$

From (2) we can see that

$$S_1(90°)/S_1(0°) = c_1 \tag{10}$$

then

$$\begin{aligned} &S_1(90° - \theta) / S_1(90°) = S_1(90°-\theta)/c_1 S_1(0°) = \\ &(c_1+d_1\cos^2(90°-\theta))/c_1 = (c_1+d_1\sin^2\theta)/c_1 \end{aligned} \tag{11}$$

We, then, can write for the rotation of the three counters around the Y axis (angle Ω)

$$R'''_3(\Omega) = S'''_3(\Omega)/S'''_3(0°) = \frac{2S_1(\Omega)+S_1(90°-\Omega)}{2S_1(0°)+S_1(90°)} \tag{12}$$

where, as previously:
$R'''_3(\Omega)$ = ratio between the count rate of the three counters at an angle Ω [$S'''_3(\Omega)$] and that for $\Omega = 0°$ [$S'''_3(0°)$] for rotation around the Y axis, and $S_1(\Omega)$ have the same meaning as in (2), (9), (10) and (11) where, for convenience, we replace θ with Ω.
Using (9), (10) and (11) we have

$$R'''_3(\Omega) = \frac{3c_1+d_1}{2+c_1} + \frac{d_1}{2+c_1}\cos^2\Omega \tag{13}$$

Substituting for c_1 and d_1 the values found, we have:

$$R'''_3(\Omega) = 0.7 + 0.3\cos^2\Omega \tag{14}$$

For the 3 equations (6), (8) and (14) we calculate the average value for a rotation of 90° by integrating between 0° and 90°. As can be expected, the angular variation of the sensitivity of a system of three counters is equivalent to that found empirically for a single counter, (2), with the only variation of the values of the constants c and d.

As for the case of a single counter, the sensitivity of the system is given by the product of the sensitivity at 0° and the correction factors for the different rotations.

If the sensitivities at 0° are the same for all rotations, one has:

$$C = a\,|R'_3|\,|R''_3|\,|R'''_3| \qquad (15)$$

We can, however see that $a_1 = a_2 = a$ but $a_3 \neq a$ (where a_1, a_2 and a_3 are the sensitivities to neutrons for $\phi = 0°$, $\theta = 0°$ and $\Omega = 0°$).

We experimentally found for our case $a_3 = 0.77\ a$

We can, then, write

$$a_3|R'''_3| = a|0.77R'''_3|$$

The sensitivity is given by

$$C = a|R'_3|\,|R''_3|\,|0.77\ R'''_3|$$

For our set we found $C = 106\ c\ n^{-1}cm^2$.

5. - Conclusion

We described a semiempirical method for calibrating one or more asymmetrical detectors to be used for measuring the particle flux density in an isotropic field. In particular, we study the case of large neutron detectors of the type classified as "long counter".

From an empirical equation (2) which expresses the angular variation of the sensitivity of a single long counter, we derive and verify experimentally the equations for the angular variation of the sensitivity of a three counter system.

The method is applied to the measurement of the neutron flux at the underground Gran Sasso Laboratory.

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