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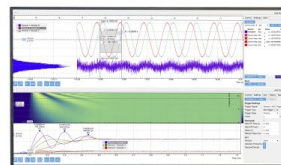## ARTICLES YOU MAY BE INTERESTED IN

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Improved calibration of DD neutron counters by activation of two indium disks in the Frascati 1-MJ plasma focus

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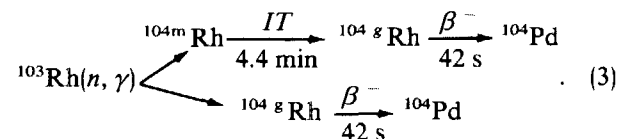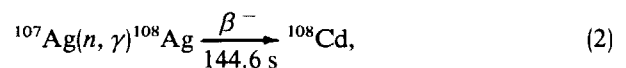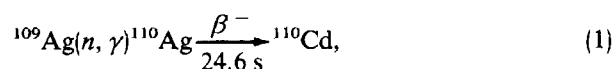(Presented on 19 September 1984)

Three Geiger counters made sensitive to DD neutrons by paraffin covers with interposed Ag, ^{109}Ag, and Rh foils were calibrated by exposing them to 50 PF (plasma focus) shots and by recording counts while simultaneously irradiating two indium disks placed on the PF vacuum vessel. The "polar" disk came out to be about three times more activated than the "equatorial" disk, which was interpreted by assuming an extended focus instead of a point-like one as used in a previous work. The utilized formalism is reported and some minor discrepancies with counters calibration by removal of an Am/B source are discussed. Further refinements of the activation method are suggested.

INTRODUCTION

In a previous work[1] we described the calibration of a silver-activated GM counter performed by exposing it to a series of plasma focus (PF) shots and recording counts while simultaneously irradiating one indium disk placed close to the focus in a side-on position. In that work, in which the counter was calibrated by other methods, a dispersion of about 15% was found among the various techniques. As a consequence, improvements were considered to further reduce the discrepancies. In this paper we describe an experiment which was carried out to calibrate three GM counters (activated with natural Ag, ^{109}Ag, and Rh foils) by activation of two indium disks located one in side-on position (equatorial disk) and the other in end-on position (polar disk). The experimental results, incompatible with a point-like focus, were interpreted in terms of a cylindrical focus and of extended disks by a formalism which is shortly outlined. In addition, we made the calibration of the three neutron counters by removal of an Am/B neutron source. Calibration constants determined by both methods are reported and discussed. Finally, possible further refinements of the activation technique are pointed out.

I. DESCRIPTION OF THE EXPERIMENT

The Frascati 1-MJ plasma focus machine has been fully described in Ref. 2. The Ag-activated neutron counter used for this work is the same counter shown in Fig. 2 of Ref. 1; the other two counters considered in this paper differ from the first one in the activating foil only, which was ^{109}Ag in the second counter and Rh in the third one. Fast neutrons coming from the PF, after having been thermalized in the paraffin cover, activate the metallic foils according to the reactions

$$^{109}\text{Ag}(n, \gamma)^{110}\text{Ag} \xrightarrow[24.6\text{ s}]{\beta^-} {}^{110}\text{Cd}, \tag{1}$$

$$^{107}\text{Ag}(n, \gamma)^{108}\text{Ag} \xrightarrow[144.6\text{ s}]{\beta^-} {}^{108}\text{Cd}, \tag{2}$$

$$^{103}\text{Rh}(n, \gamma) \begin{cases} {}^{104m}\text{Rh} \xrightarrow[4.4\text{ min}]{IT} {}^{104\,g}\text{Rh} \xrightarrow[42\text{ s}]{\beta^-} {}^{104}\text{Pd} \\ {}^{104\,g}\text{Rh} \xrightarrow[42\text{ s}]{\beta^-} {}^{104}\text{Pd} \end{cases} \tag{3}$$

Isotopic composition of the ^{109}Ag foil was determined by irradiating a sample in the Casaccia Triga fission reactor. The subsequent activation analysis gave the following composition: 98% of ^{109}Ag and 2% of ^{107}Ag with an accuracy better than 10%.[3]

The indium disks (2.8 cm diameter and 0.2 cm thickness) were positioned within stainless-steel penetrating cans, as shown schematically in Fig. 1, and kept in place by appropriate disk holders (for other details see Fig. 3 of Ref. 1). The equatorial disk and the polar disk were located at distances of 16 and 14.5 cm, respectively, from the geometrical center O. Temperature of the polar disk was monitored by a thermocouple inserted into the vertical can. The neutron counters were positioned on the equatorial plane at about
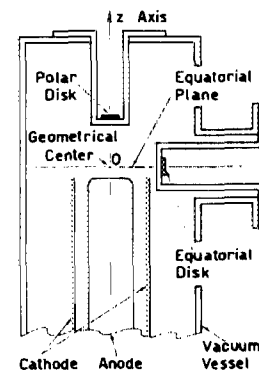

FIG. 1. Schematic arrangement of the irradiation equipment (not to scale).

350 cm from the geometrical center O.

The PF machine was operated with electrode geometry of the Mather-type and in a working regime optimized for neutron production (25 kV, 390 kJ, 6 torr). The experiment consisted of the performance of 50 shots distributed over a 5 h interval, as shown by Fig. 2 in which vertical bars represent beta counts G_{12j} taken by the above specified three counters from $T_1 = 100$ to $T_2 = 200$ s after each shot ($j = 1, 2, ..., 50$), according to the procedure described in Ref. 1. Deuterium gas was changed after each shot; the above-mentioned thermocouple showed that polar disk temperature never exceeded 90 °C (indium melting point: 156 °C). Activities of the indium disks right after 50 shots were measured by the equipment and by the procedure described in Ref. 1. The results came out to be $A_{EQ} = (963 \pm 96)$ dis/s for the equatorial disk, and $A_{POL} = (3173 \pm 317)$ dis/s for the polar disk.

II. DETERMINATION OF CALIBRATION CONSTANTS

In Ref. 1 it was shown that the calibration constant K, which relates the beta counts G_{12j} to the neutron yield Y_j of the jth shot through the formula

$$Y_j = KG_{12j}, \quad (\text{with } j = 1, 2, ..., N), \tag{4}$$

can be expressed, in the case of the single equatorial disk, as

$$K = (4\pi r_0^2 A) \Big/ \Big(N_T \bar{\sigma} \lambda C \sum_{j=1}^{N} G_{12j} \exp(-\lambda T_j) \Big), \tag{5}$$

where r_0 represents the distance of the indium disk from the focus and C is a factor which is equal to 1 when the focus and the disk are assumed to be point-like.

Now, with three counters and two indium disks one has to do with six calibration constants which should lead to the same neutron yield for any PF shot. In addition, for a given neutron counter the two calibration constants K_{EQ} and K_{POL}, obtained from the equatorial and polar indium disks, should be the same, i.e., one should have

$$K_{EQ}/K_{POL} = 1. \tag{6}$$

Contrary to this requirement, it was found that by assuming point-like focus and disks (with the focus located on
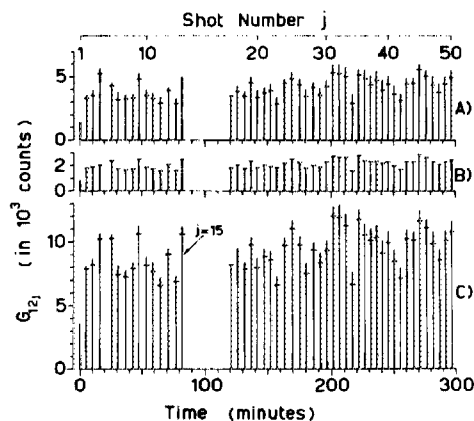

Shot Number j

FIG. 2. Beta counts G_{12j} vs time after the first shot. Upper ends of vertical bars represent uncorrected counts; cross marks near upper ends represent counts corrected for residual foil activity due to previous shots. (a) Ag-activated counter; (b) ^{109}Ag-activated counter; (c) Rh-activated counter.

the geometrical center O), this ratio comes out to be about 0.382, which is approximately equal to the ratio of the activities A_{EQ} and A_{POL}.

To overcome this inconsistency and to take into account experimental evidence on the extended localization of the neutron source,[4] we have abandoned the simplified assumption of a point-like focus. Furthermore, we have also considered extended indium disks.

The geometry used for this new approach is shown in Fig. 3, in which $dV = rd\phi\, dr\, dz$ is the generic volume element of the focus and $da = \rho d\delta\, d\rho$ is the generic surface element of the indium disk. With this arrangement it can be shown that the coefficient C appearing in Eq. (5) is expressed by

$$C = r_0^2 \int_V dV \int_a [\beta(\gamma)/X^2] da/(Va), \tag{7}$$

where X is the distance of da from dV, γ is the incidence angle for the neutrons reaching da from dV, and $\beta(\gamma)$ is a reduction factor taking into account removal of neutrons in the structural materials existing between focus and indium disk. Expressions for X and γ can be derived from the geometry of Fig. 3.

Obviously, with the geometry of Fig. 3 one calculates the coefficient C_{EQ} for the equatorial disk. With a similar geometry one can calculate the coefficient C_{POL} for the polar disk. Entering Eq. (6) with K_{EQ} and K_{POL}, as derived from Eq. (5), one obtains that the coefficients must fulfill the condition

$$C_{POL}/C_{EQ} = (A_{POL} N_{T,EQ} r_{0,POL}^2 \bar{\sigma}_{EQ})/$$
$$(A_{EQ} N_{T,POL} r_{0,EQ}^2 \bar{\sigma}_{POL}). \tag{8}$$

Concerning the indium cross sections we have used neutron spectra measured by nuclear emulsion plates located end-on and side-on,[5] to obtain $\bar{\sigma}_{EQ} = (0.275 \pm 0.028)b$ and $\bar{\sigma}_{POL} = (0.303 \pm 0.031)b$. The masses of our two indium disks were found to be equal within 0.1%; as a consequence the numbers of target nuclei are also equal and can be dropped. Entering Eq. (8) with the remaining known values gives

$$C_{POL}/C_{EQ} \simeq 2.455. \tag{9}$$

As a preliminary representation of the extended focus we have assumed a cylindrical volume coaxial with the z axis and having radius R and height $H_1 + H_2$ as shown by the dashed contour in Fig. 3. From the experimental data on the localization of the neutron source,[4] we have put as a first
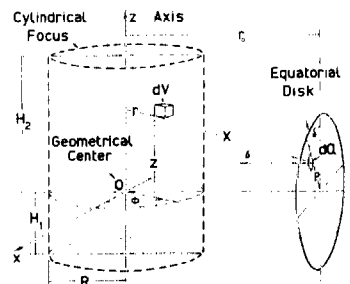

FIG. 3. Geometry used for extended focus and equatorial indium disk.

Table I. Calibration constants K of neutron counters.

	$K \left(\text{in } 10^7 \ \dfrac{\text{neut}}{\text{count shot}} \right)$		
Neutron counter	Indium activation		Source removal
	Equator. disk	Polar disk	
Ag	4.19 ± 0.83	4.17 ± 0.83	4.6 ± 1.7
[109]Ag	7.89 ± 1.57	7.85 ± 1.57	10.6 ± 3.6
Rh	1.85 ± 0.37	1.84 ± 0.37	2.2 ± 0.7

hypothesis $R = H_1 = 1$ cm. Since the maximum incidence angle is about 33° (in the case of the equatorial disk) we have used, as a first approximation, the assumption $\beta(\gamma) = \cos \gamma$. The integral appearing in Eq. (7) was determined numerically by the Simpson method. The free parameter H_2 was looked for by a trial and error procedure aimed at satisfying condition (9). The results were $H_2 = 8.4$ cm, $C_{EQ} = 0.8937$, and $C_{POL} = 2.201$. Then, from Eq. (5) we obtained the six calibration constants reported in Table I, which also includes three calibration constants determined by the removal of a 10-Ci Am/B neutron source. The formalism to be used when applying the source removal method to a Ag-activated counter was derived in Ref. 1; for [109]Ag- and Rh-activated counters the pertinent formalisms, derived from reactions (2) and (3), respectively, are reported in Ref. 6.

III. DISCUSSION AND CONCLUSIONS

Before the experiment described in Sec. I, we had carried out a preliminary test consisting of 41 shots, in which distribution of beta counts and activities of indium disks had characteristics quite similar to those reported in Sec. I. This similarity of experimental results allows us to be confident of their reproducibility.

Concerning the calibration constants shown in Table I, we note that they agree within experimental errors and that the calibration constants determined by indium activation appear to be systematically somewhat smaller and to have less dispersion than those obtained by source removal. This difference may be attributed to various causes, the most important of which seems to reside in the Am/B neutron source whose intensity $(5 \times 10^6 \pm 20\%$ neut/s) is not very well known (besides being too low for the source removal method[1]) and whose angular neutron emission, not measured, may appreciably differ from that of the focus. Another cause may be the difference between the neutron spectra existing in the indium disks locations and the neutron spectra measured by end-on and side-on nuclear plates, whose positions were somewhat farther away with respect to the indium disks locations. And finally, a systematic error of the indium activation method is certainly represented by the

coarse assumption of a cylindrical focus and of a uniform neutron emission, which implies flat profiles of ion density and ion temperature. In this connection it appears possible to refine the approach by using more elaborate models of the extended focus, such as the one considered in Ref. 7.

As far as the details of the adopted model are concerned it may be interesting to observe that Eq. (7) can be improved by the insertion of two factors, $g(r)$ and $f(\Omega)$ (possibly based on experimental evidence), describing the dependence of neutron emission on the position r of the focus element dV and on the direction Ω along which neutrons are emitted from dV. Another small improvement can be obtained by using a reduction factor $\beta(\gamma)$ determined experimentally.

In the end, it may be worthwhile to notice that Eq. (5) implies constancy of volume and shape of the extended focus during N shots, a condition that certainly does not occur. This inconvenience, which can cause a minor inaccuracy, can be eliminated if the indium activity is high enough to be measured on a single-shot basis $(N = 1)$ by using a Ge(Li) detector instead of a NaI crystal, an improvement which would also simplify the overall procedure.

As concluding remarks it seems reasonable to state that the accurate determination of the neutron yield is still an issue which offers room for improvements and that the indium activation method looks promising especially because it makes use of the neutrons produced by the plasma itself, without need of an external neutron source. The main difficulty of the indium activation method appears to be the choice of the most appropriate plasma model.

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