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(To be submitted to Nuclear Physics)

I. - INTRODUCTION. -

The spectra of many neutron sources making use of the reaction (α, n) in Be^9 (Po-Be, Pu-Be etc.) are practically undistinguishable since the α-particles energies are almost the same.

We can think of the neutrons of such sources as subdivided into three groups, substantially separated in energy, according to the C^{12} excited level from which they came, following the reaction $Be^9(\alpha, n)C^{12}$:

1) Neutrons of energy $\gtrsim 6$ MeV coming from the ground state.
2) Neutrons, whose energy ranges between about 2 MeV and 6 MeV, coming from the C^{12} 4.43 MeV level and decaying to ground state with photon emission.
3) Neutrons of energy $\lesssim 2$ MeV coming from the 7.65 MeV level. The direct transition from such a level to ground state is forbidden and the main reaction from it, is the $C^{12} \rightarrow 3\alpha$ decay.

In Fig. 1 we show the kinematic limits for the reaction (α, n) in Be^9. The three hyperbolas give the highest and lowest neutron energy versus α-particles energy for each of the C^{12} levels mentioned above.

In order to evaluate the effective limits of the energy of the three neutrons groups, we point out that the cross section for the considered processes are practically negligible for an α-particle energy lower than 1.5 MeV (see Fig. 2).

In these last years also, a great deal of experimental and theoretical work has been done(1, 2, 3, 4, 5, 6) on the neutron spectra of the sources under consideration.

At present it seems that a substantial, even though rough, agreement exists in the energy region above 2 MeV. However the situation is not very clear as long we are concerned with the low energy range and the detailed spectrum structure.

Moreover at low energy the situation is worse owing to the presence of secondary processes. Their importance is hardly valuable and they have the effect of increasing the component of low energy neutrons in a different way depending on the size and characteristics of the source.

In this work we have measured the neutron spectrum of a Po-Be source by means of the time of flight technique.

The starting signal is given by a photon from a 4.43 MeV level of C^{12}. In this way, we have selected the neutrons of the central group, whose spectrum has been obtained with a fair detail. Moreover we have been able to evaluate the effective contribution of the neutrons of such a group due to the secondary processes to the low energy region.

II. - EXPERIMENTAL APPARATUS. -

A NaI(Tl) scintillator (3.81 cm diameter, 2.54 cm long) was placed very close to the neutron source to detect the photons emitted from the 4.43 MeV level. A 56 AVP phototube was placed after the scintillator and the photon pulse, divided into two channels, was put in coincidence by means of two discriminators at high and low threshold respectively in order to reduce the time jitter due to the different pulse-amplitude.

Opposite to the γ-ray detector, at a distance d = 200 cm from the source we placed a NE102A cylindrical plastic scintillator (15.3 cm long, 12.8 cm diameter) with three 56AVP phototubes in coincidence among them as a neutron detector.

The photon and neutron signals were used to drive respectively the start and stop imputs of a time to-pulse-height converter (TPHC) whose output was connected to a LABEN 512 channels pulse height analyser. The linearity of the converter was measured by random pulses as start and stop signals: the spectrum obtained in this way was flat within 1% in the region corresponding to 0.5 ÷ 5 MeV.

The threshold of the discriminators placed at the output of the

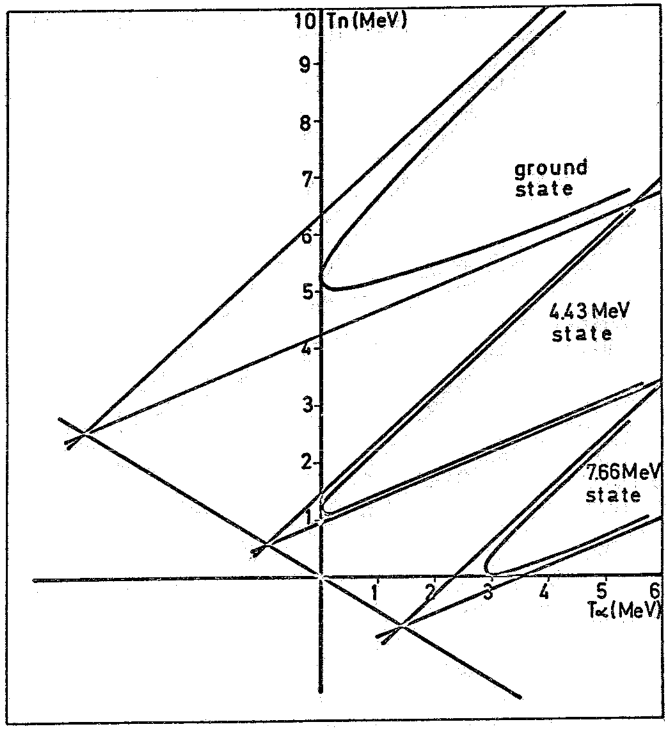

FIG. 1 - Kinematic limit for the $Be^9(\alpha, n)C^{12}$ reaction.

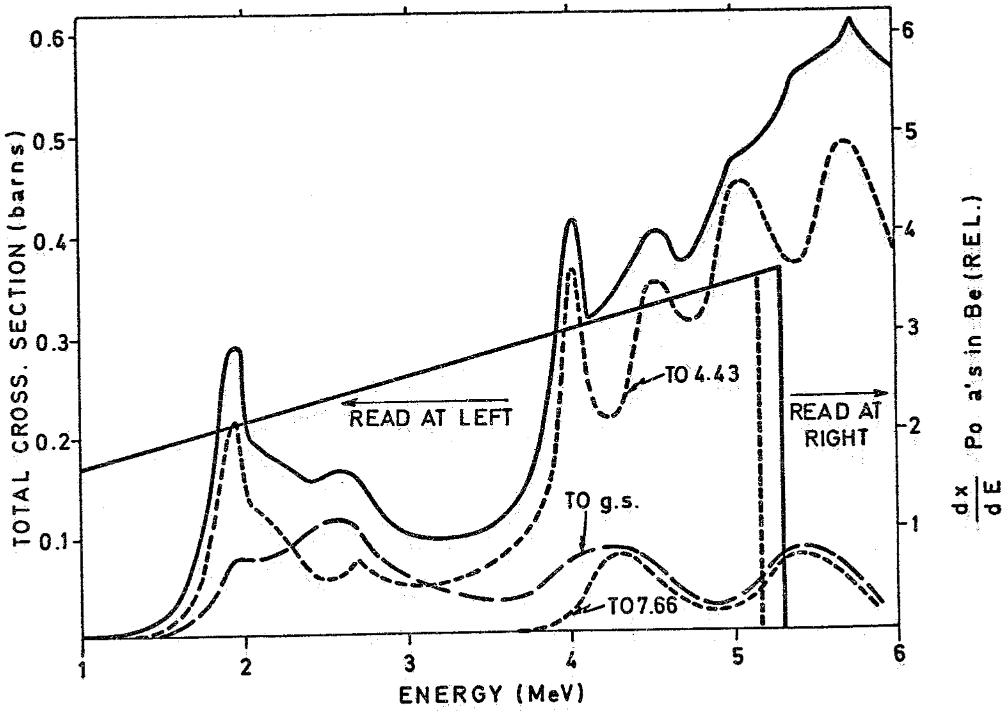

FIG. 2 - Cross section for the $Be^9(\alpha, n)C^{12}$ leading to different states of C^{12}.

three phototubes of the neutron detector, had a value such that, at 20 keV electrons equivalent to about 200 keV protons, 30% of the events was detected. The high discriminator threshold, for photon detector, was at 1 MeV, and the time resolution for the above mentioned threshold values was $\simeq$ 5 nsec.

III. - EFFICIENCY OF THE NEUTRON DETECTOR. -

The efficiency $\mathcal{E}$ of the neutron detector can be written as the product

$$\mathcal{E} = \mathcal{E}_I \times \mathcal{E}_S \tag{1}$$

where $\mathcal{E}_I$ is the probability that a neutron undergoes at least an interaction in the scintillator with an hydrogen nucleus, while $\mathcal{E}_S$ is the probability that such an event is detected.

The following expression for $\mathcal{E}_I$ is calculated under some approximations and assumptions which are developed and discussed in the appendix.

$$\mathcal{E}_I = \frac{1-\exp\left[-\Sigma_T(T_n)L\right]}{\Sigma_T(T_n)} \left[\Sigma_H(T_n) + \Sigma_C(T_n)\,\frac{\Sigma_H(0.85\,T_n)}{\Sigma_H(0.85\,T_n)+\frac{1}{2}\,\frac{L+R}{LR}}\right] \tag{2}$$

where:

L, R are the scintillator length and radius;

$\Sigma_H = \sigma_H n_H$, $\Sigma_C = \sigma_C n_C$, $\Sigma_T = \Sigma_H + \Sigma_C$

σ_H, n_H; σ_C, n_C are the total cross sections and the atom numbers for unit volume of hydrogen and carbon respectively[7,8];

T_n is the incident neutron energy.

In Fig. 3, the curve b) is a plot of the expression (2), while the curves a) and c) represent the interaction probability[7] $\mathcal{E}_I$ corresponding respectively to the two following extreme assumptions:

curve a) - the carbon does not scatter the neutrons at all.

curve b) - every diffusion on the carbon nucleons eliminates the scattered neutrons.

By comparing the three curves in Fig. 3 we can deduce that, in the case of a scintillator of the same size as that used by us, the neutron spectrum is not very affected by the choice of the curve. In fact, within the energy resolution of our device and in the energy range of interest, the three curves are proportional within (2-3)%.

In this way the problem of the efficiency is reduced in practice to that of the instrumental efficiency measurement. It consists in the evaluation of the electronic threshold effect on the proton recoil spectrum corresponding to neutrons of fixed energy. This electronic threshold effect was measured making use of a Co^{60} source.

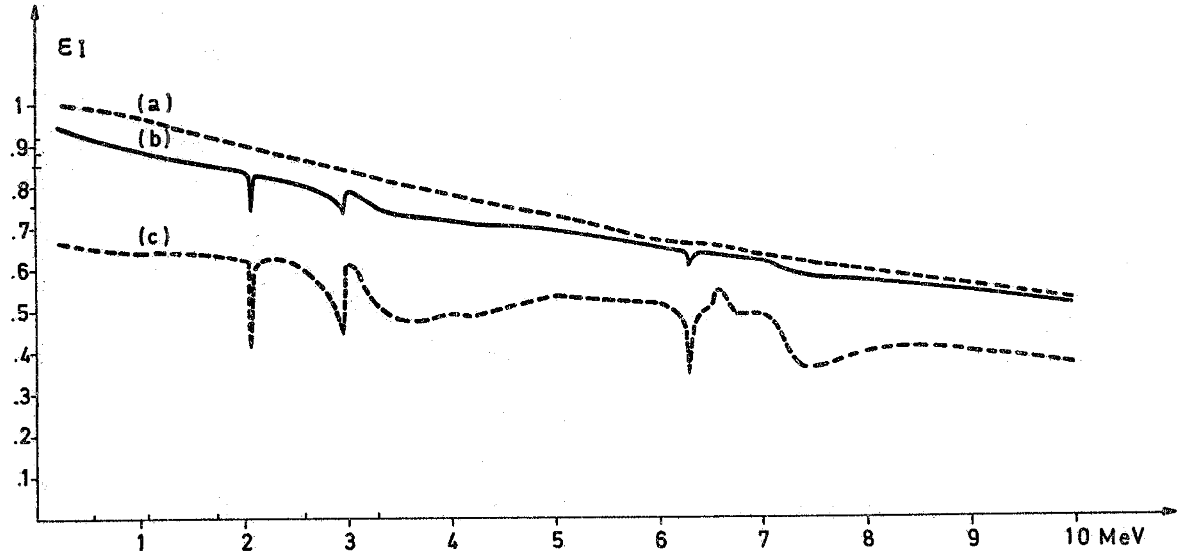

FIG. 3 - Interaction efficiency versus neutron energy.

We have performed the proton recoil spectra by selecting suitable energy regions with the time of flight technique. In Fig. 4 we show a number of measured spectra: the full line is a plot of the experimental data, while the dashed one corresponds to the experimental spectrum corrected taking into the account of the electronic threshold effect.

The experimental results concerning the instrumental efficiency of our detector are summarized in the Table I.

TABLE I

T_n (MeV)	ΔT_n (MeV)	ε_S	ε'_S	ε	$\Delta\varepsilon$
.56	$.53 \le T_n \le .6$	0.38	0.40	0.35	0.05
1.08	$1.0 \le T_n \le 1.16$	0.79	0.75	0.70	0.06
1.75	$1.6 \le T_n \le 1.9$	0.90	0.86	0.77	0.03
2.6	$2.3 \le T_n \le 2.9$	0.94	0.92	0.75	0.02
3.3	$3.0 \le T_n \le 3.7$	0.96	0.94	0.73	0.02

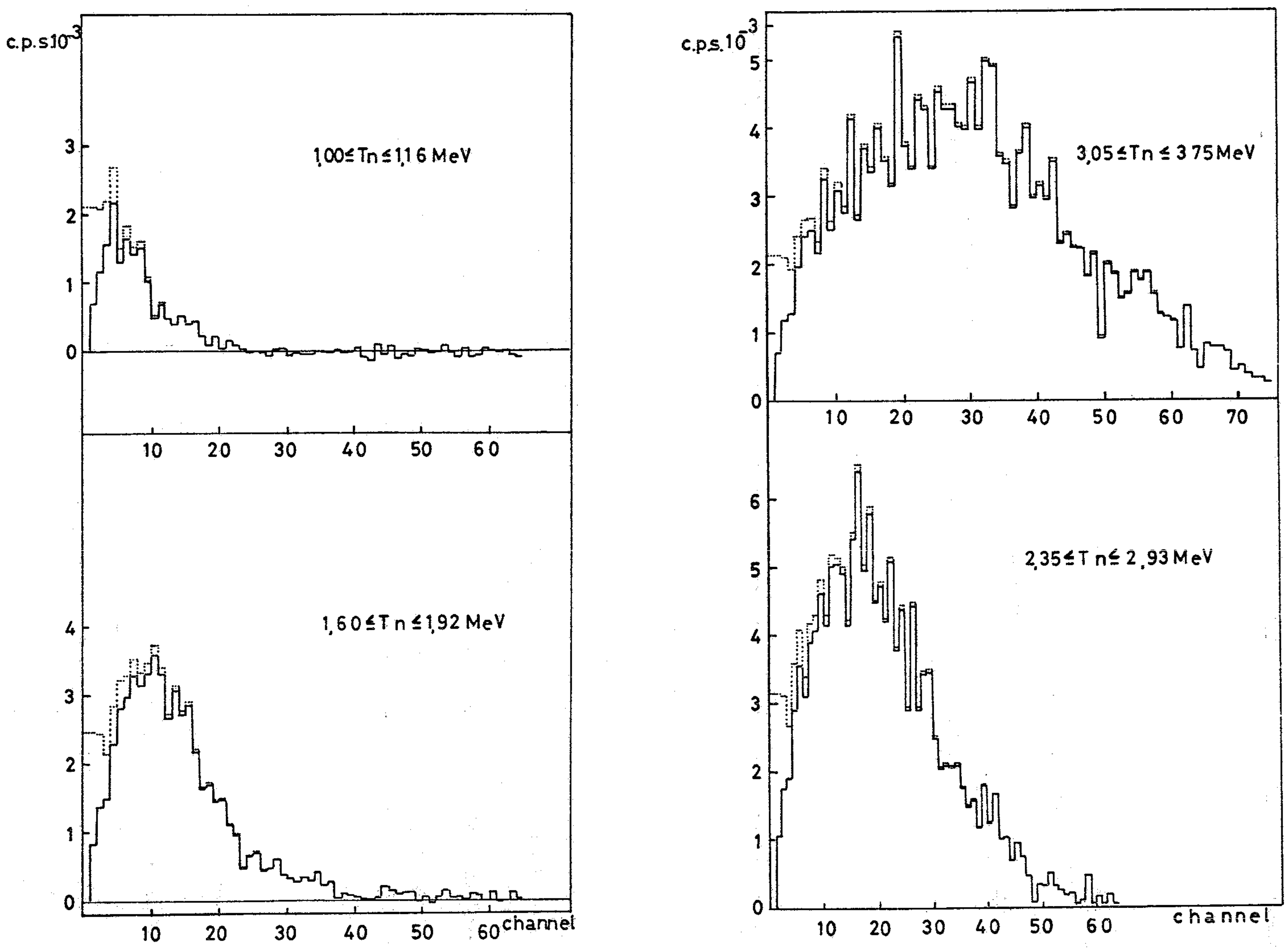

FIG. 4 - Recoil protons spectra of indicated neutron energy: Experimental results (full line) and correction from electronic suppression (dashed line).

In this table we report also the efficiency ε'_S calculated from the proton response-curve of the NE102A(9,10) scintillator for an ideal proton recoil spectrum neglecting resolution, wall and multiple scattering effects.

Finally in Fig. 5 we show the efficiency ε as obtained from equations (1) and (2).

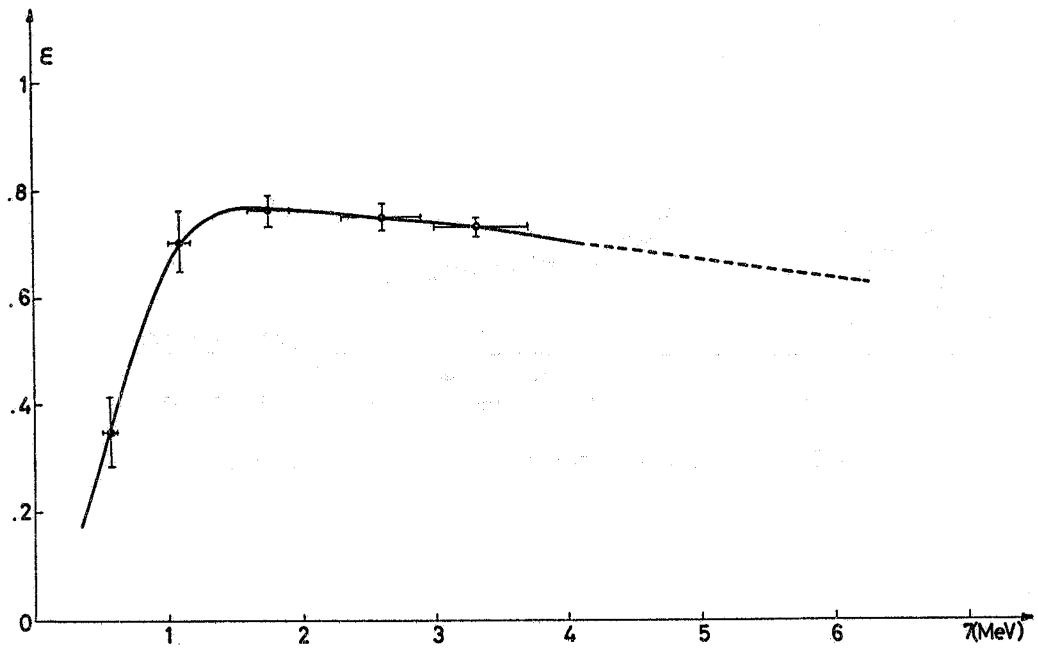

FIG. 5 - Neutron counter efficiency versus energy.

IV. - NEUTRON SPECTRUM. -

We have measured this spectrum by using a Po-Be source containing about 250 mg of Be, whose activity is 2×10^5 n/sec and we have recorded 1.5×10^4 events in two runs of 10 hours each one. The experimental spectrum in time is shown in Fig. 6: the peak on the left is due to spurius γ-γ correlated coincidences while the following region is flat until a time of flight corresponding to neutron energy of about 6 MeV. This level agrees with the background level measured in the same experimental conditions.

After background subtraction, the energy spectrum of neutrons is obtained from the following relation:

$$\frac{dN}{dT_n} = \frac{1}{\varepsilon(T_n)} \frac{dN}{dt} \frac{dt}{dT_n}$$

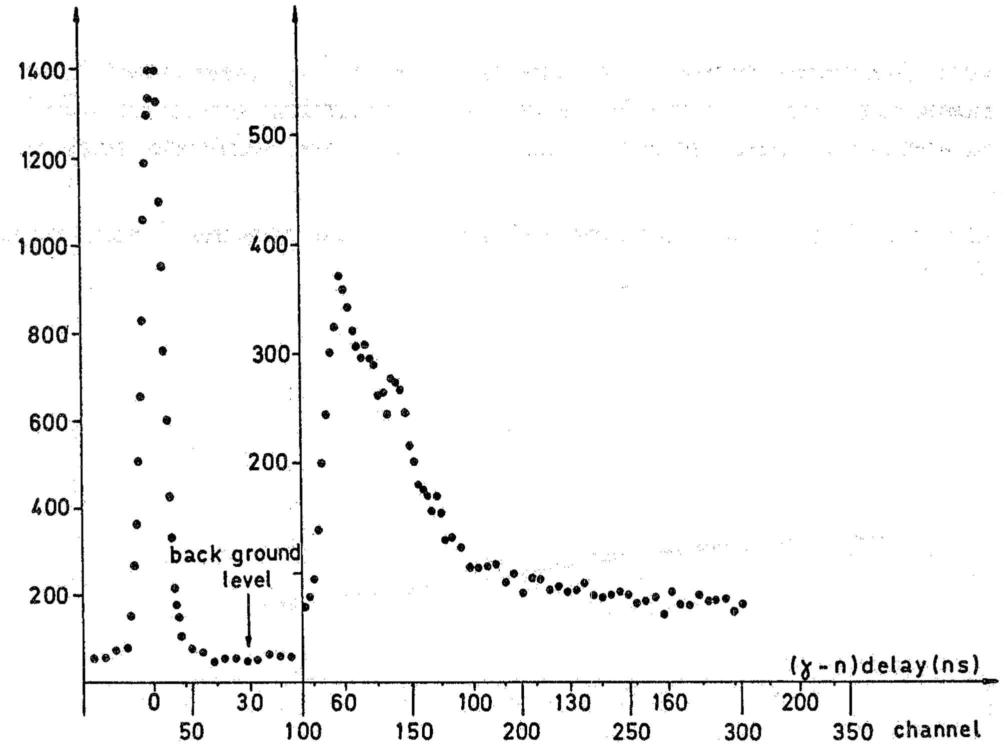

FIG. 6 - Experimental time-spectrum.

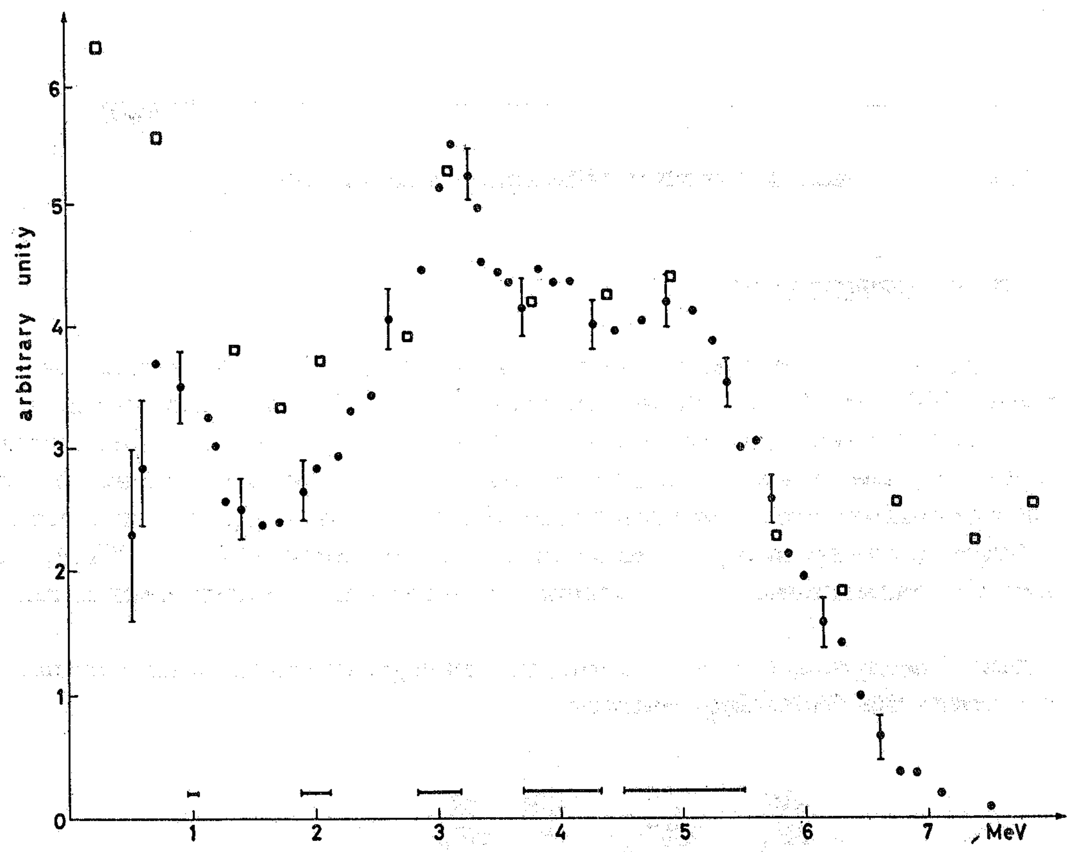

FIG. 7 - Measured neutron energy spectrum from 4.43 MeV level of C^{12}.

where:

T_n = neutron kinetic energy
t = $(d/C)/(M/2T_n)^{1/2}$
d = distance between the NaI scintillator and neutron detector
c = light velocity
M = neutron mass.

Such a spectrum is shown in Fig. 7 (full dots). In the same figure the horizontal intervals represent the energy resolution. Except in the low energy region the errors are substantially the statistical ones.

a) - Neutron spectrum between 2 and 6 MeV. -

We remark in the measured spectrum quite clearly the presence of two peaks at 3 and 5 MeV, whose amplitude and position agree substantially with those of many other authors. For example we report (squares in the figure) the results obtained by Anderson and Bond[3] with emulsions and a Po-Be source. The component above 6 MeV in spectrum of these researches, is due to the neutrons of the C^{12} ground state which in our case cannot be detected. Some researchers[6] have observed the presence of a peak at about 4 MeV, while there is no evidence of it in the work of Anderson and Bond: our spectrum does not exclude this possibility. We point out that in a previous measure performed with the time of flight technique[5], the two peaks of the central group have been observed at 3.8 and 5.5 MeV respectively.

The agreement between our experimental data and theoretical calculations[1, 3] is very rough; however we remember that, in the mentioned calculations, the effect of the angular distribution of the (α, n) reaction on the neutron spectrum is not considered in a satisfactory way.

In a recent work[11] such a problem has been examined in a more systematic way and on the basis of the available data[12, 13] the two peaks at about 3 and 5 MeV has been explained. The probable presence of a third peak at 4 MeV with good accordance with the our experimental observations was predicted also.

b) - Neutron spectrum under 2 MeV. -

In order to understand where the considerable component of low energy neutrons cames from, some tests have been carried out in order to exclude some possibilities:

i) that the low energy neutrons coming directly from the 7.65 MeV level of the C^{12} are accompanied by the emission of two photons of 3.22 MeV and 4.43 MeV in cascade. Although the probability of such a process has been evaluated[14] of the order of 10^{-3}, we have measured the photon spectrum in coincidence with neutrons whose energy was fixed by the time of flight between 0.9 and 1.1 MeV. In such a spectrum, shown in Fig. 8, there are two peak at about 4.4 and 4 MeV, both due to the 4.43 MeV photon, while there is no evidence of a 3.22 MeV photon.

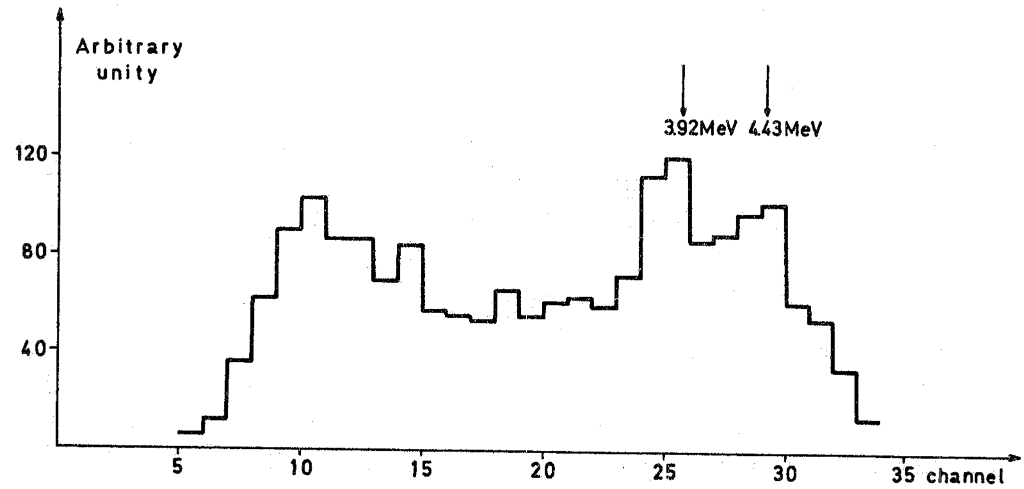

FIG. 8 - Spectrum of γ-rays in coincidence with neutrons in the energy interval (0.9 - 1.1) MeV.

ii) that the low energy neutrons come from scattering by the materials surrounding the source (substantially the γ-ray detector). To this purpose we have measured the number of coincidences relative to the neutrons of energy between .9 and 1.1 MeV for two different distances from the NaI scintillator. The coincidence ratio in the two cases turned out to be the same as the solid angle ratio within the statistical error of the order of 5%: in this way a considerable contribution of this effect can be excluded.

iii) that the neutrons have an energy higher than that corresponding to the time of flight and reach the detector after scattering from the surrounding devices, covering in this way a larger distance. In this case we have used the previously measured proton recoil spectra (see table and Fig. 4) in order to draw the response curve of our scintillator as a function of the energy selected by the time of flight technique. The result is shown in Fig. 9: the straight line represents the response curve to the electrons obtained with a source of Cs^{137} and Co^{60}. The response-curve to the protons agrees very well with that of NE102A[9,10] scintillator.

The results of the reported tests exclude a remarkable contribution of these effects to the low energy neutron spectrum and therefore support the hypothesis that such a component is due to secondary processes inside the source. In this way the considerable disagreement at low energy with the spectrum of Anderson and Bond can be partially explained taking into account of the difference in the characteristics and sizes of the sources used in the two cases.

Essentially the secondary processes which can occour in a Po-Be source are the following:

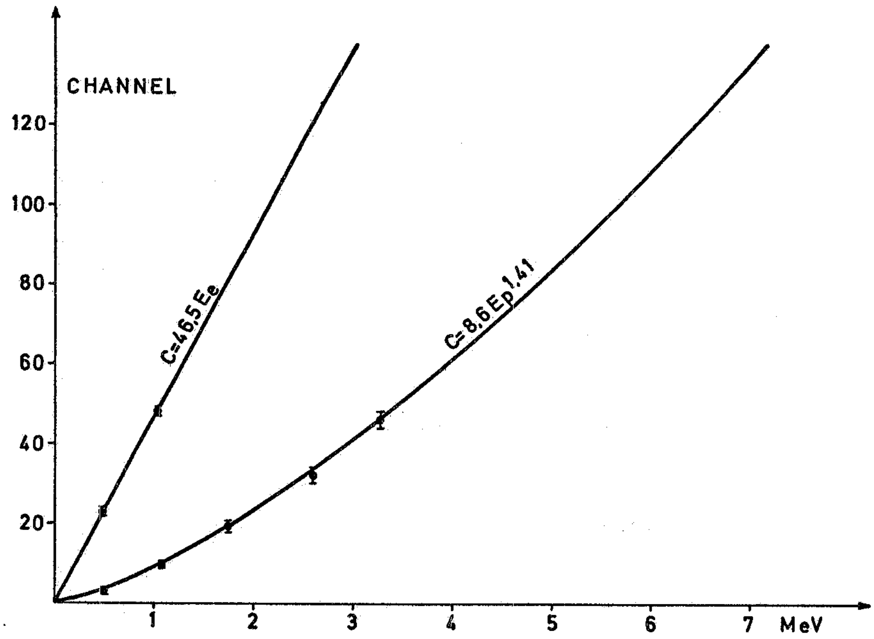

FIG. 9 - Response of neutron detector to electrons and protons.

1) elastic scattering in Be^9;
2) anelastic scattering (n, 2n) in Be^9. We can espect that one half of the neutrons arising from such a reaction have an energy of about. 0.8 MeV(15,16).
3) anelastic scattering in the source container (substantially Fe).

Neglecting the neutrons undergoing the elastic scattering in Be^9 which do not lose much energy, we have made a rough estimation of the contribution due to the processes 2) and 3) on the basis of the existing data(17,19) for the relative cross sections. The results of such an estimation give a percentage of about 5% of low energy neutrons. Taking into account of the rough approximation in our calculations this extimation can be considered in accordance with experiment that gives a percentage of about 10%.

Finally we point out that the peak at 0.9 MeV, clearly observed in our experimental spectrum, can be explained recalling our remarks about (n, 2n) reaction in Be^9.

Moreover we can say that, also for the small Po-Be sources generally used, the low energy neutrons due to secondary effects, can alter completely the spectrum of neutrons coming from the 7.65 MeV level of C^{12}.

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APPENDIX. -

If $\mathcal{E}_H$ and $\mathcal{E}_C$ are the probabilities that the first neutron scattering in the scintillator takes place on hydrogen or carbon respectively we can write:

$$\mathcal{E}_H = \frac{\Sigma_H}{\Sigma_T}\left[1 - e^{-\Sigma_T L}\right] \qquad \mathcal{E}_C = \frac{\Sigma_C}{\Sigma_T}\left[1 - e^{-\Sigma_T L}\right]$$

then the interaction efficiency $\mathcal{E}_I$, turns out to be

$$\text{(A.1)} \qquad \mathcal{E}_I = \mathcal{E}_H + \mathcal{E}^* \mathcal{E}_C = \frac{1}{\Sigma_T}\,(1 - e^{-\Sigma_T L})\,(\Sigma_H + \Sigma_C \mathcal{E}^*)$$

where $\mathcal{E}^*$ is the probability that, after a first scattering on carbon, the subsequent scattering is on hydrogen.

We will suppose that the carbon scattering is isotropic and that the energy loss is the same for each scattering and equal to the average energy loss. Therefore a neutron of initial energy T_n, after a scattering on carbon, will have an energy of .85 T_n.

If $s(\vec{r})$ is the neutron fraction per unit volume and unit time undergoing the first scattering on carbon, at the position $\vec{r}$, the calculation of $\mathcal{E}^*$ for neutron of initial energy T_n, is equivalent to the calculation of the number of neutrons, yielded by an isotropic source with energy 0.85 T_n and with a specific activity at $\vec{r}$ equal to $s(\vec{r})$, and interacting at least once on hydrogen before coming out from the scintillator.

If $\Psi(\vec{r}, \vec{\Omega})$ is the angular density of neutrons[19], we get:

$$\text{(A.2)} \qquad \Psi(\vec{r}, \vec{\Omega}) = \int_0^{L(\vec{r}, \vec{\Omega})} \left[\frac{\Sigma_C}{4\pi}\, n(\vec{r}\,') + \frac{s(\vec{r}\,')}{w}\right] e^{-\Sigma_T |\vec{r} - \vec{r}\,'|}\, d|\vec{r} - \vec{r}\,'|$$

where w is the neutrons velocity, $n(\vec{r}) = \int \Psi(\vec{r}, \vec{\Omega})\, d\Omega$ is the neutrons density and $L(\vec{r}, \vec{\Omega})$ is the scintillator thickness as seen from r in the direction $\vec{\Omega}$.

Supposing that the quantity in parenthesis in (A.2) is about independent on $\vec{r}\,'$, we have:

$$\Psi(\vec{r}, \vec{\Omega}) \simeq \text{const} \cdot (1 - e^{-\Sigma_T L(\vec{r}, \vec{\Omega})})$$

Now, for large size scintillators and well inside the scintillator the expression

$$(1 - e^{-\Sigma_T L(\vec{r}, \vec{\Omega})})$$

will change very slowly with $\vec{r}$ and $\vec{\Omega}$.

Then we can write:

$$\varphi(\vec{r}, \vec{\Omega}) = \text{const} = \varphi' \qquad \text{inside the scintillator}$$

$$\varphi(\vec{r}, \vec{\Omega}) = \begin{cases} \varphi' & \text{for } \vec{\Omega}\cdot\vec{\nu} \geq 0 \\ 0 & \text{for } \vec{\Omega}\cdot\vec{\nu} < 0 \end{cases} \qquad \text{near the walls}$$

where $\vec{\nu}$ is the perpendicular unit vector from the scintillator surface. In such an approximation we get for the neutron density and for the total number of scattering events on hydrogen in the unit time:

$$n(\vec{r}) = 4\pi\varphi' \qquad N = \int_V \Sigma_H w n(\vec{r}) dV = 4\pi\varphi' V \Sigma_H w$$

where V is the scintillator surface.

For the neutron current density $\bar{J}_\nu$ and for the current I on the walls we have:

$$J_\nu = \int_{4\pi} w\,\varphi(\vec{r}, \vec{\Omega})\,\vec{\Omega}\cdot\vec{\nu}\,d\Omega = 4w\varphi' \qquad I = \int_A J_\nu\,dA = \pi A w \varphi'$$

where A is the total scintillator surface.

Finally because

$$S = \int_V s(\vec{r})dV = N + I$$

we have for ε^x

$$\varepsilon^x(T_n) = \frac{N}{S} = \frac{\Sigma_H(0.85\,T_n)}{\Sigma_H(0.85\,T_n) + \frac{1}{4}\,\frac{A}{V}}$$

From this expression and from (A.1), for a cylindrical scintillator of length L and radius R, we obtain the expression (2) of the text.

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