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Neutron Spectrum from the 4.43 MeV Level of the ^{12}C in a Po-Be Source.

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1. – Introduction.

It is known that the neutron spectra of high-intensity neutron sources, using the (α, n) reaction of the compounds Po-Be, Pu-Be, etc. are pratically undistinguishable, being substantially equal to the corresponding α-particles energy spectra.

We may consider three different parts of the neutron spectrum. These components, substantially separed in energy, correspond to the ^{12}C excited levels in the reaction $^{9}Be(\alpha, n)^{12}C$:

1) the neutrons of energy greater than about 6 MeV coming from the ground state;

2) the neutrons whose energy ranges between about 2 MeV and 6 MeV, coming from the 4.43 MeV level which decays to ground state via photon emission;

3) the neutrons of energy lower than about 2 MeV coming from the 7.65 MeV level. The direct transition from such a level to ground state is forbidden and the mean reaction is the decay $^{12}C \rightarrow 3\alpha$.

A great deal of experimental and theoretical works has been done [1-6] on the neutron spectrum of the considered sources.

At present it seems that a substantial agreement exists in the energy region about 2 MeV. However, the situation is not very clear as for the low-energy region and the detailed spectrum structure.

Moreover, at low energy the situation is worse owing to the presence of secondary processes. It is hard to estimate their contribution, indeed they increase the low component of the neutron spectrum in a different way depending on the size and characteristics of the source.

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(1) W. N. HESS: *Ann. Phys.*, **6**, 115 (1959).
(2) S. NOTARRIGO, R. PARISI, R. RICAMO and A. RUBBINO: *Nucl. Phys.*, **29**, 507 (1962).
(3) M. E. ANDERSON and W. H. BOND jr.: *Nucl. Phys.*, **43**, 330 (1963).
(4) R. L. LEHMAN: *Nucl. Instr. and Meth.*, **60**, 253 (1968).
(5) O. SADEH, A. L. COTZ and S. AMIEL: *Nucl. Phys.*, **52**, 25 (1964).
(6) A. RUBBINO, O. ZUDKE and C. MEIRNER: *Nuovo Cimento*, **44** B, 178 (1966).

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

The starting time is given by a photon from a 4.43 MeV level of ^{12}C. 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 in the low-energy region via the secondary processes.

2. – Neutron spectrum and discussion of the results.

We have measured the spectrum of a Po-Be source containing about 250 mg of Be, of intensity $2 \cdot 10^5$ n/s. The experimental spectrum in time is shown in Fig. 1: 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.

The energy spectrum of neutrons is obtained after background subtraction using efficiency curve from ref. (7) and is shown in Fig. 2 (full dots). In the same Figure the horisontal intervals represent the energy resolution. Except in the low-energy region the errors are substantially the statistical ones.

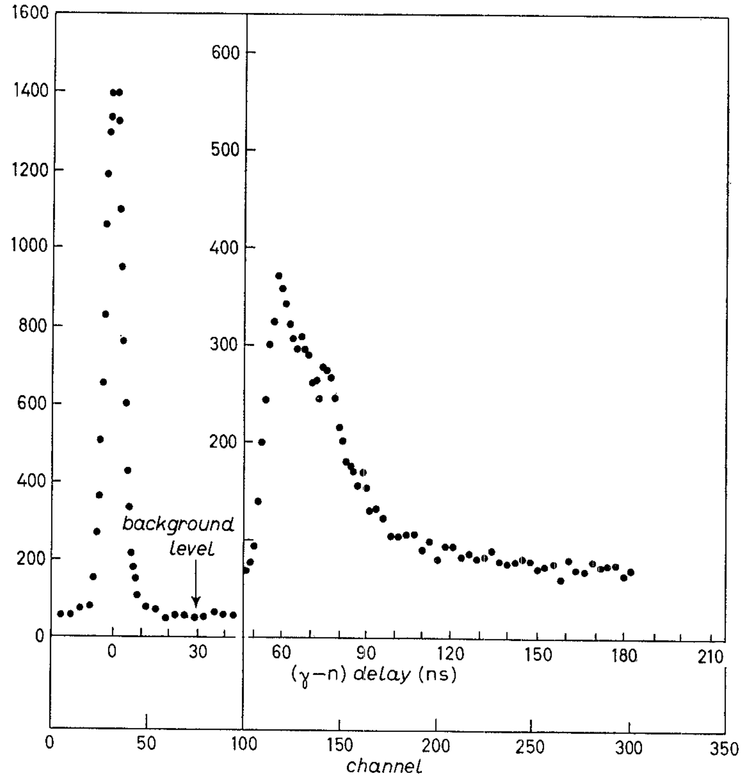

Fig. 1. – Experimental-time spectrum.

(7) R. Del Fabbro, G. Matone and M. Roccella: Frascati Report LNF-69/11 (1969).

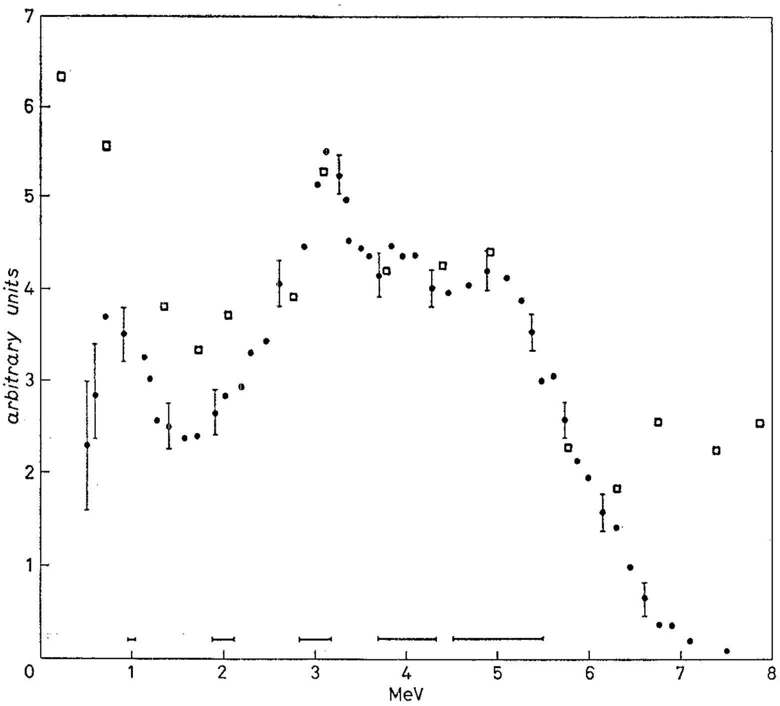

Fig. 2. – Measured-neutron-energy spectrum from 4.43 MeV level of ^{12}C.

2'1. *Neutron spectrum between* 2 *and* 6 MeV. – We remark in the measured spectrum 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 the spectrum of these authors is due to the neutrons of the ^{12}C ground state, which in our case cannot be detected. Some authors [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.

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 (γ, n) reaction on the neutron spectrum is not considered in a satisfactory way.

In a recent work [8] this problem has been examined and on the basis of the available data [9,10], the two peaks at about 3 and 5 MeV has been explained. The presence of a third peak at 4 MeV with a good accordance with the our experimental observations was also predicted.

2'2. *Neutron spectrum under* 2 MeV. – In order to understand where the considerable component of low-energy neutrons comes from, some tests have been carried out in order to exclude some possibilities:

(8) S. NOTARRIGO, F. PORTO, A. RUBBINO and S. SAMBATARO: *Boll. S.I.F.*, **62**, 82 (1968).
(9) J. B. GARY, J. M. CALVERT and N. H. GALE: *Nucl. Phys.*, **19**, 264 (1960).
(10) N. H. GALE and J. B. GARY: *Nuovo Cimento*, **19**, 742 (1961).

i) That the low-energy neutrons, coming directly from the 7.65 MeV level of the ^{12}C, 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 ([11]) 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 this spectrum there is no evidence of a 3.22 MeV photon.

ii) That the low-energy neutrons come from scattering on the materials surrounding the source (substantially the γ-rays detector). To this purpose we have measured the number of the coincidences relative to the neutrons of energy between 0.9 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 the corresponding to the time of flight and reach the detector after scattering from the surrounding devices, covering in this way a larger distance. As shown in Fig. 3, neutron energy selected with the time of flight and pulse height obtained from corresponding proton-recoil spectra agree very well with the response curve of NE102A ([12,13]). Then it seems negligible the contribution of these neutrons in our energy range.

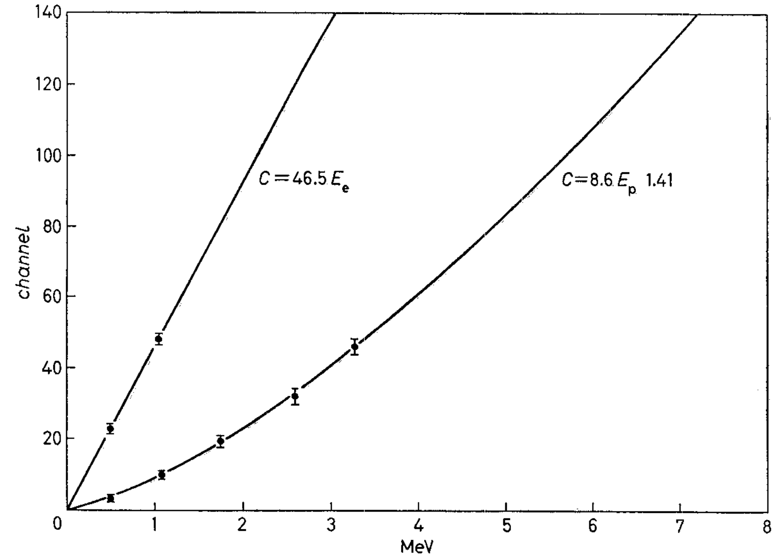

Fig. 3. – Response of neutron detector to electrons and protons.

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 consider-

([11]) T. H. KRUSE and R. D. BENDT: *Phys. Rev.*, **112**, 931 (1958).
([12]) H. C. EVANS and E. H. BELLAMY: *Proc. Phys. Soc.*, **74**, 483 (1959).
([13]) J. B. BIRKS: *The Theory and Particle of Scintillation Counting* (London, 1964).

able disagreement at low energy with the spectrum of ANDERSON and BOND can be partially explained taking into account the difference in the characteristics and sizes of the sources used in the two cases.

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

1) Elastic scattering in ^{9}Be.

2) Anelastic scattering (n, 2n) in ^{9}Be. We can expect that one half of the neutrons arising from such a reaction have an energy of about 0.8 MeV ([14,15]).

3) Anelastic scattering in the source container (substantially Fe).

Neglecting the neutrons undergoing the elastic scattering in ^{9}Be 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 ([16,17]) for the relative cross-sections. The results of such an estimation give a percentage of about 5% of low-energy neutrons. Taking into account the rough approximation in our calculations this extimation can be considered in accordance with the 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 ^{9}Be.

([14]) K. PARKER: AWRE Report No. 0-27/60 (1960).

([15]) R. WAGNER and P. HUBER: *Helv. Phys. Acta*, **31**, 89 (1958).

([16]) Y. G. ZUBOV, N. S. LUBEDEVA and V. M. MOROZOV: (Consultation Bureau, 1963).

([17]) J. SALMON, H. CHARPENTIER, J. GUILLOUD, B. LEMAIRE and P. MILLIES: *Théorie cinétique des neutrons rapides* (Paris, 1961).