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SPECTRUM OF COINCIDENT NEUTRONS FROM Am-Be NEUTRON SOURCE

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Abstract

A measurement was made of the energy spectrum of neutrons above 1 MeV emitted in coincidence with gamma radiations from the Am-Be source with an energy resolution of about 5 percent using an associated gamma-ray time-of-flight spectrometer. The measured spectrum displays peaks at 3.2 and 4.8 MeV and decreases smoothly from 5 MeV to zero above 6.5 Mev. The data are compared with previous measurements and with the predictions of nuclear reaction calculations. The number of neutrons emitted at various energies are consistent with the mechanisms of producing neutrons by populating the first excited state of ^{12}C nucleus.

Introduction

The Am-Be neutron source is used as laboratory standard in a large number of applications such as the calibration of the neutron protection instruments and the evaluation of n-γ pulse shape discriminating performance. Industrial applications include their use in soil moisture meters and in other small probes for the study of geological formations. Several attempts have been made[1-4,14] to calculate the energy spectrum of neutrons emitted from the Am-Be source. Results of the calculation do not agree with experiment[2, 3, 5-7] or with each other over the entire range of the emitted neutron energies. The calculation typically assumes interaction of α-particle with Be nucleus populating the well known states in ^{12}C and groups of neutron are emitted. The peaking in the observed spectrum is due to the recoil given to the compound nucleus and the neutron energy in the laboratory system changes with the angle of observation. The broadening of the spectrum results from a continuous α-energy distribution present, and also the observation occurs at all angles. The major mechanism in the calculation is that neutrons are emitted predominantly by populating the first excited state in ^{12}C.

In order to provide accurate and reliable data for comparison with calculations, we measured neutron evergy spectrum emitted in coincidence with gamma radiations from the Am-Be source.

Method

The neutron evergy spectrum from the Am-Be source was measured using an associated gamma-ray time-of-flight (AGTOF) technique[8]. The experimental arrangement is shown in Fig.1. Gamma rays were detected in NE-102 plastic scintillation detector D1 and neutrons were detected in NE-213 liquid scintillator D2. Detectors D1 and D2 are 5.08 cm diam by 5.08 cm thick cylinders directly coupled to RCA–type 8575 photomultiplier tubes. Photomultiplier tube bases[9] similar to Ortec 265 were used on both counters. The pulse-shape discrimination system[9], based on a zero-crossover method[10], was connected to the main electronic system to reduce the gamma-ray background. Constant fraction-timing discriminators were used on both counters. Fig.2. shows the diagram the electronic system. The timing resolution of the system is 0.78 nsec (FWHM) for a 10 : 1 dynamic range using two gammas from the ^{60}Co radioactive source.

The pulse height from each counter was calibrated with a series of radioactive gamma sources, namely ^{137}Cs, ^{22}Na, and ^{60}Co. The Compton peak in the gamma-ray spectrum was used as a calibration point. The peak channel was associated with an electron energy equal to 0.95 that of the maximum Compton energy[11]. The pulse-height threshold for the neutron counter D2 was set at 195 keV equivalent electron (= 1 MeV proton) energy. A typical TOF spectrum of neutron in coincidence with gamma-ray is shown in Fig.3. The TOF spectrum displays time-independent (flat) backgrounds before and after the spectral region of interest.

In order to check the consistency of the measurement the discriminating threshold of the gamma counter D1 was increased. The contribution of neutrons resulting from populating the second excited state of ^{12}C which decays by emitting 3.22 MeV gamma ray is negligible. The second excited state of ^{12}C decays predominantly by emitting alpha particles[12].

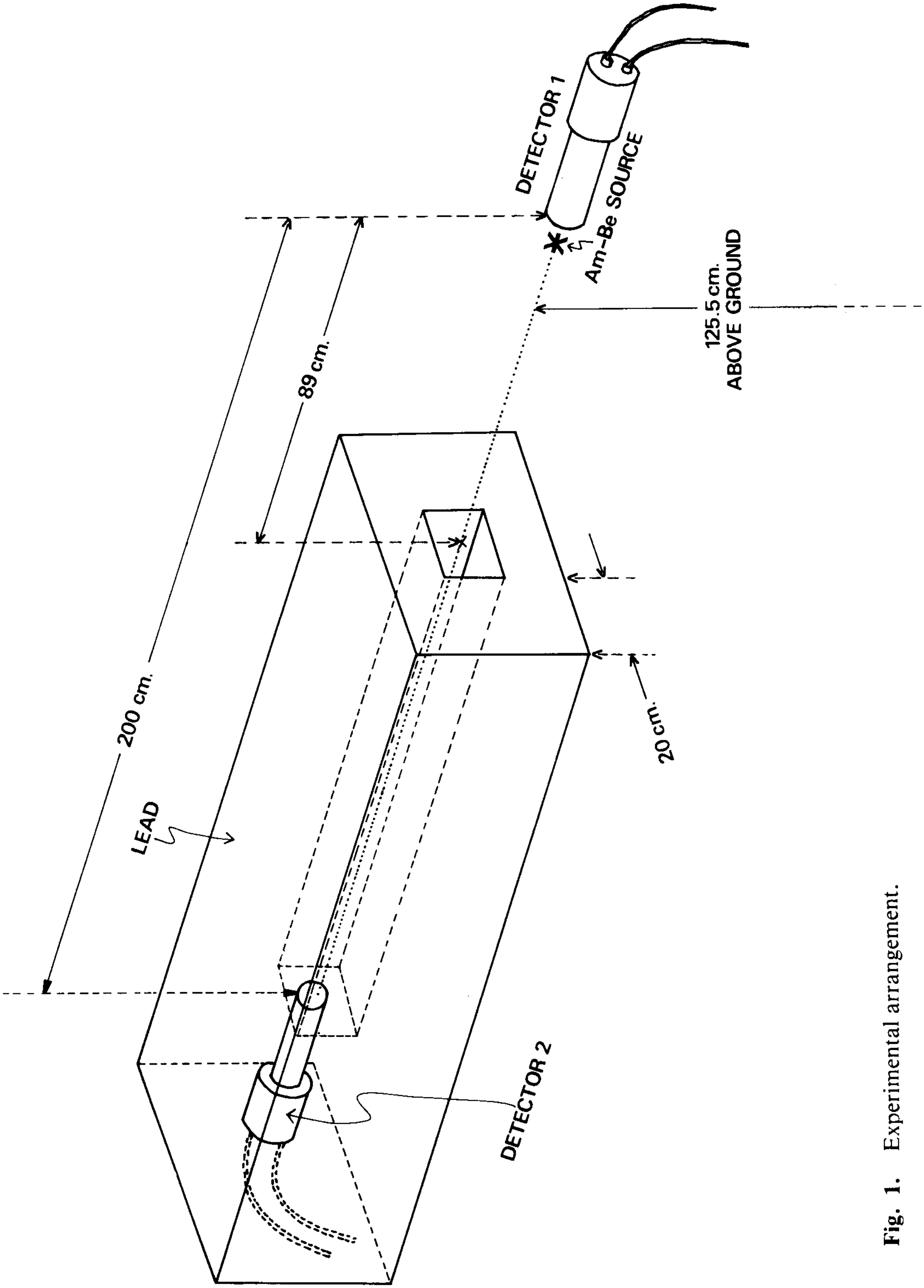

Fig. 1. Experimental arrangement.

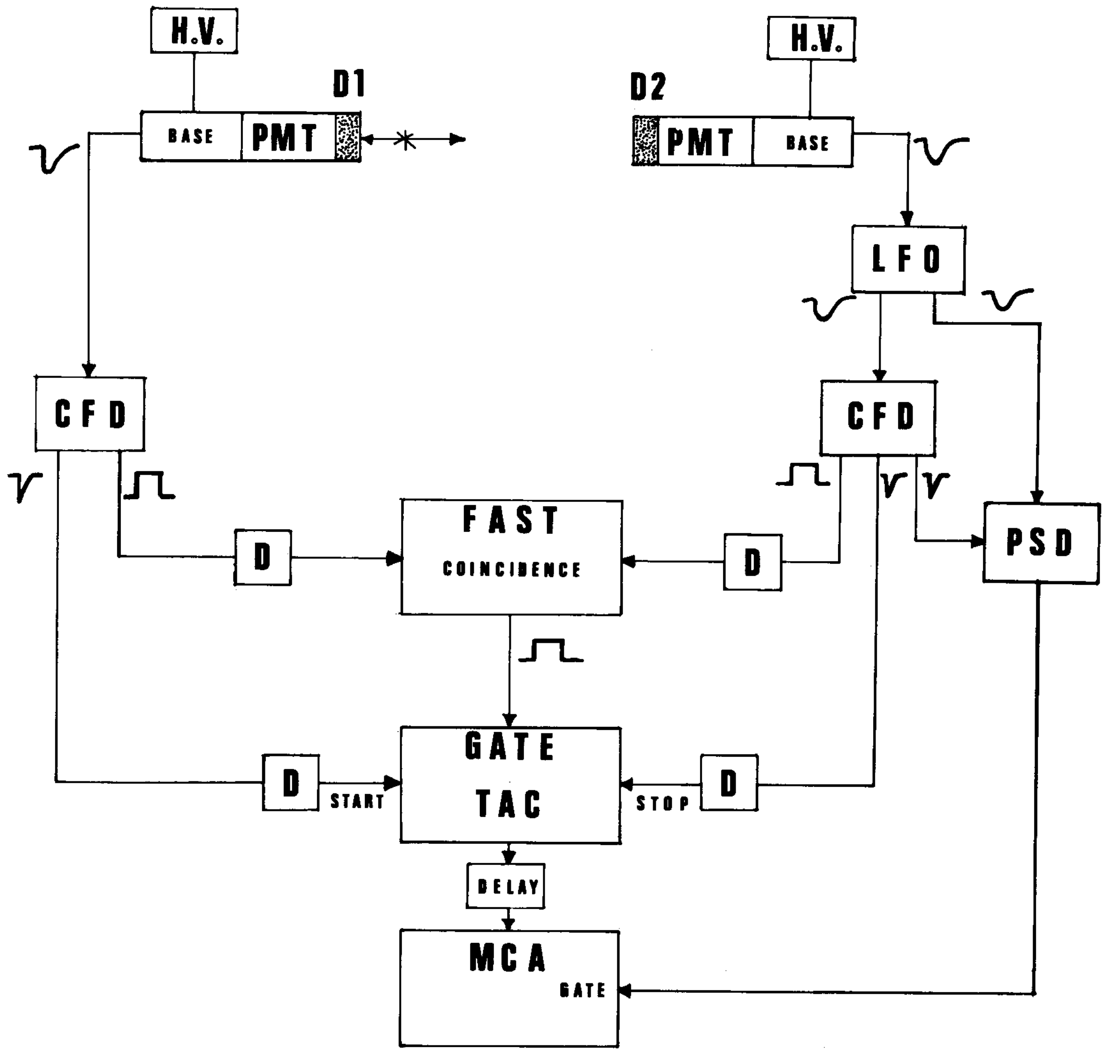

Fig. 2. Electronic block diagram for neutron time-of-flight spectrometer : LFO = linear fan out, CFD = constant fraction discriminator, PSD = pulse shape discriminator, TAC = Time to amplitude converter, D = delay, MCA = multichannel analyser

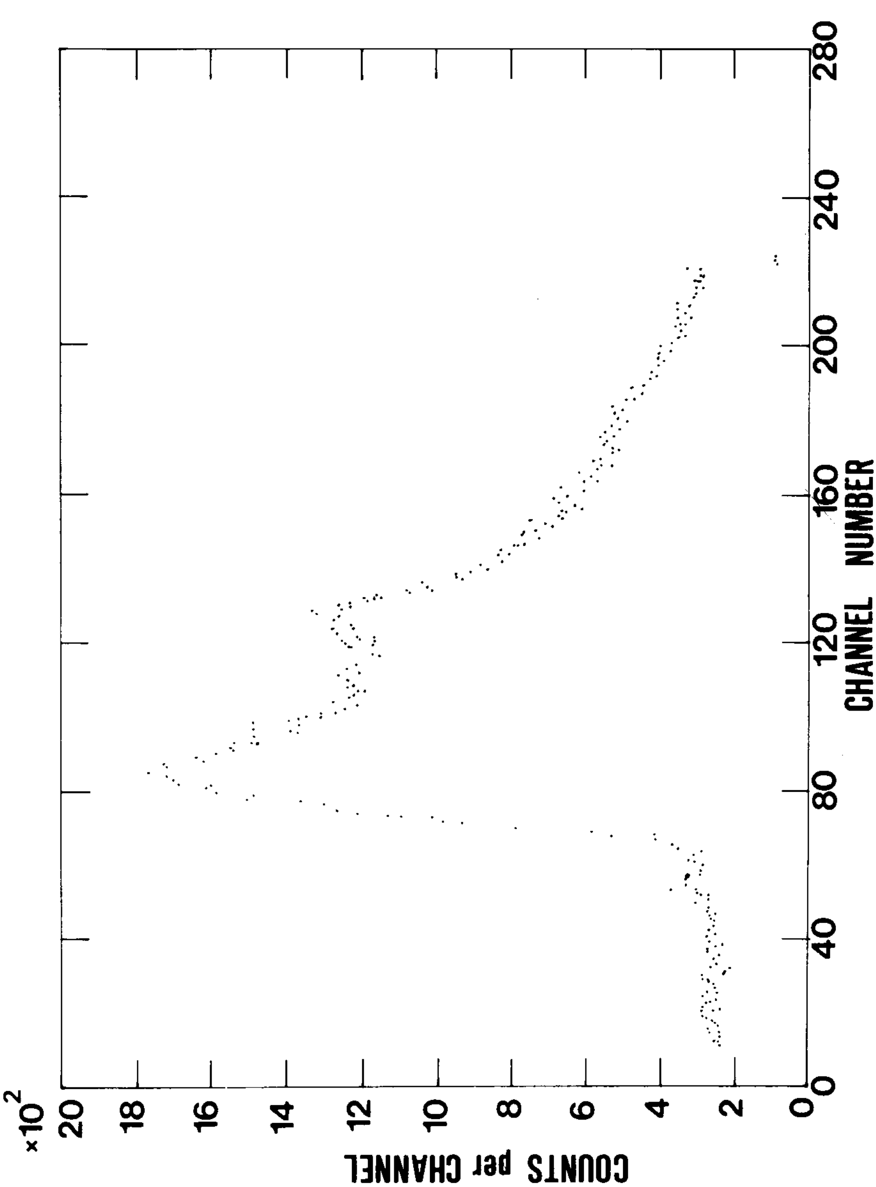

Fig. 3. Typical time-of-flight spectrum from the Am-Be source.

Data Reduction and Analysis

The relative yields of neutron N (T) for each energy interval $\triangle T$ of the spectrum is given by the expression :

$$N(T) = \frac{R(T)}{\varepsilon_n(T)\ \varepsilon_\gamma(T)} \tag{1}$$

where R(T) is the number of real neutron counts within an energy interval of width $\triangle T$, ε_n (T) is the detection efficiency of the counter for a neutron with a mean kinetic energy T, and $\varepsilon_\gamma(T)$ is the detection efficiency of the counter for a gamma ray with a kinetic energy T. The width $\triangle T$ of the energy interval was taken to be equal to 0.2 MeV. The energy resolution ($\triangle T/T$) of the system is calculated from the relativistic expression :

$$\frac{\triangle T}{T} = \gamma(\gamma + 1)\ \left[\left\{\frac{\triangle x(1-\beta n)}{x}\right\}^2 + \left(\frac{\triangle t}{t}\right)^2 \right]^{1/2} \tag{2}$$

where $\triangle x$ is the uncertainty in the neutron flight path, β is the neutron speed in unit of the speed of light, n is the refractive index of the scintillator, and $\triangle t$ is the intrinsic time dispersion of the system. The factor βn is included to account for the finite speed of light in the scintillator. The energy resolution varies from 4.8 percent at 1 MeV to 5.1 percent at 8 MeV for counter D2.

The neutron detection efficiency ε_n (T) was calculated with the Monte Carlo computer program of Cecil *et al.*[13]. The uncertainty in the Monte Carlo calculation of the efficiencies is estimated to be about 4 percent for a well-known threshold. The number of detected neutrons were corrected for neutron interaction with the iron casing of the Am-Be source. The magnitude of this correction varies from 1 to 3 percents.

The overall experimental error was obtained from the following estimated uncertainties summed in quadrature : (1) statistical uncertainty from counting; (2) ±4 percent for the neutron detection efficiency. The uncertainties in estimating the following quantities were neglected: (1) correction for neutron interaction in source iron casing; (2) neutron loss in the PSD system; (3) determination of pulse-height threshold.

Result and Discussion

The neutron energy spectrum T, measured by using time of flight technique is tabulated in Table 1 and is compared to those obtained by Geiger and Zwan[4] and Lutkin and McBeth[6] as shown in Fig. 4. The spectra were normalized at 3.2 MeV. In the region between 2.5 MeV and 5.5 MeV the results agree well with the measurements of Geiger and Zwan, but, there was less satisfactory agreement with those of Lutkin and

TABLE 1. RELATIVE SPECTRUM OF COINCIDENT NEUTRONS FROM Am-Be SOURCE.

T (MeV)	Rel. Neutron[a]
1.2 - 1.4	0.21 (0.03)
1.4 - 1.6	0.63 (0.02)
1.6 - 1.8	1.17 (0.02)
1.8 - 2.0	1.92 (0.03)
2.0 - 2.2	2.80 (0.03)
2.2 - 2.4	3.29 (0.03)
2.4 - 2.6	3.53 (0.04)
2.6 - 2.8	3.87 (0.04)
2.8 - 3.2	4.31 (0.04)
3.2 - 3.4	5.32 (0.04)
3.4 - 3.6	4.80 (0.04)
3.6 - 3.8	4.49 (0.04)
3.8 - 4.0	4.22 (0.04)
4.0 - 4.2	4.03 (0.04)
4.2 - 4.4	3.97 (0.04)
4.4 - 4.6	4.16 (0.04)
4.6 - 4.8	4.39 (0.04)
4.8 - 5.0	4.47 (0.04)
5.0 - 5.2	4.24 (0.04)
5.2 - 5.4	3.87 (0.04)
5.4 - 5.6	3.23 (0.04)
5.6 - 5.8	2.61 (0.03)
5.8 - 6.0	2.05 (0.03)
6.0 - 6.2	1.29 (0.03)
6.2 - 6.4	0.53 (0.02)
6.4 - 6.6	0.12 (0.01)

[a]Uncertainties shown are statistical only.

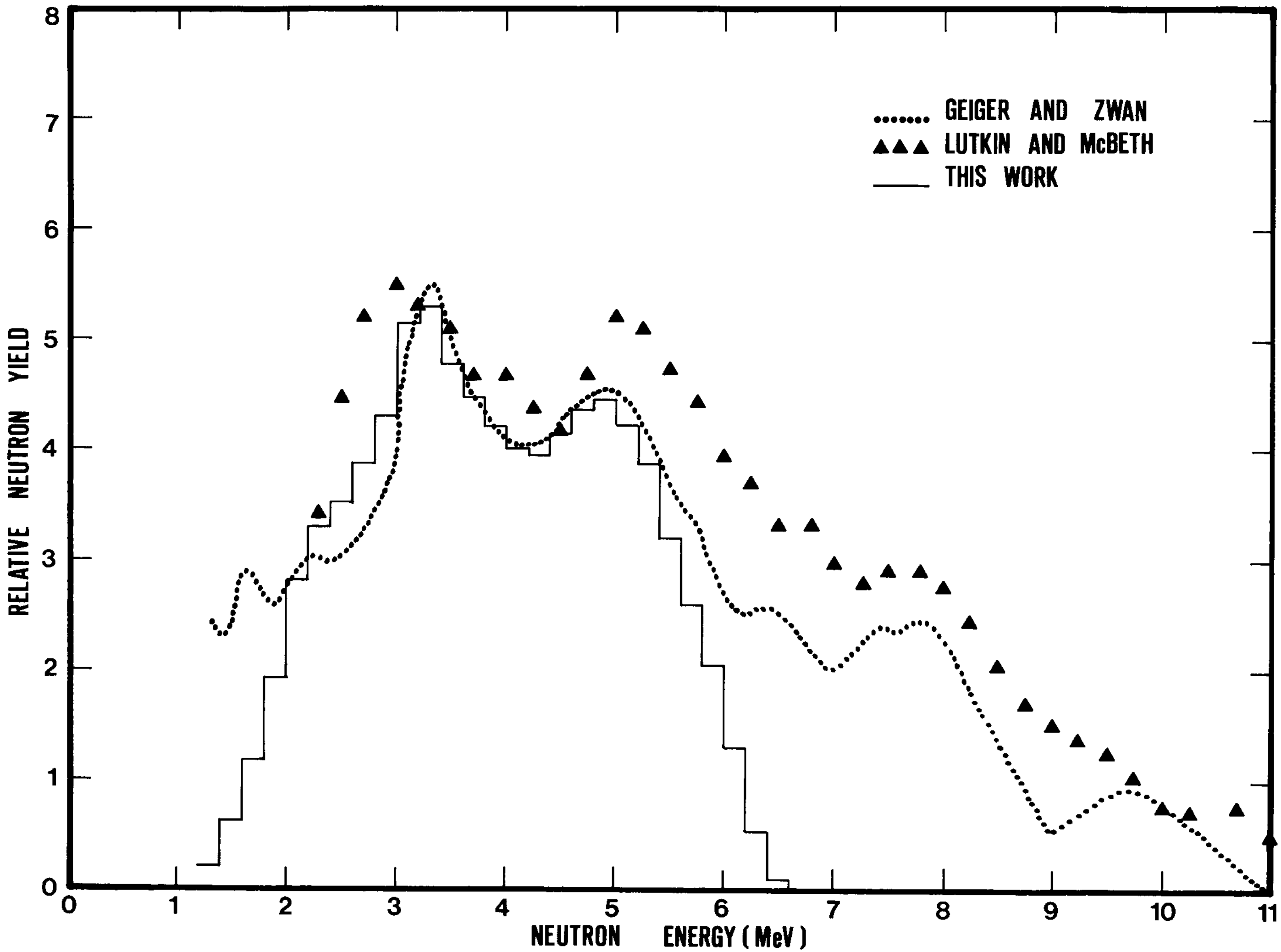

Fig. 4. Neutron spectrum from the Am-Be source. The data of Geiger and Zwan[4] and Lutkin and McBeth[6] are shown for comparison.

FIG.

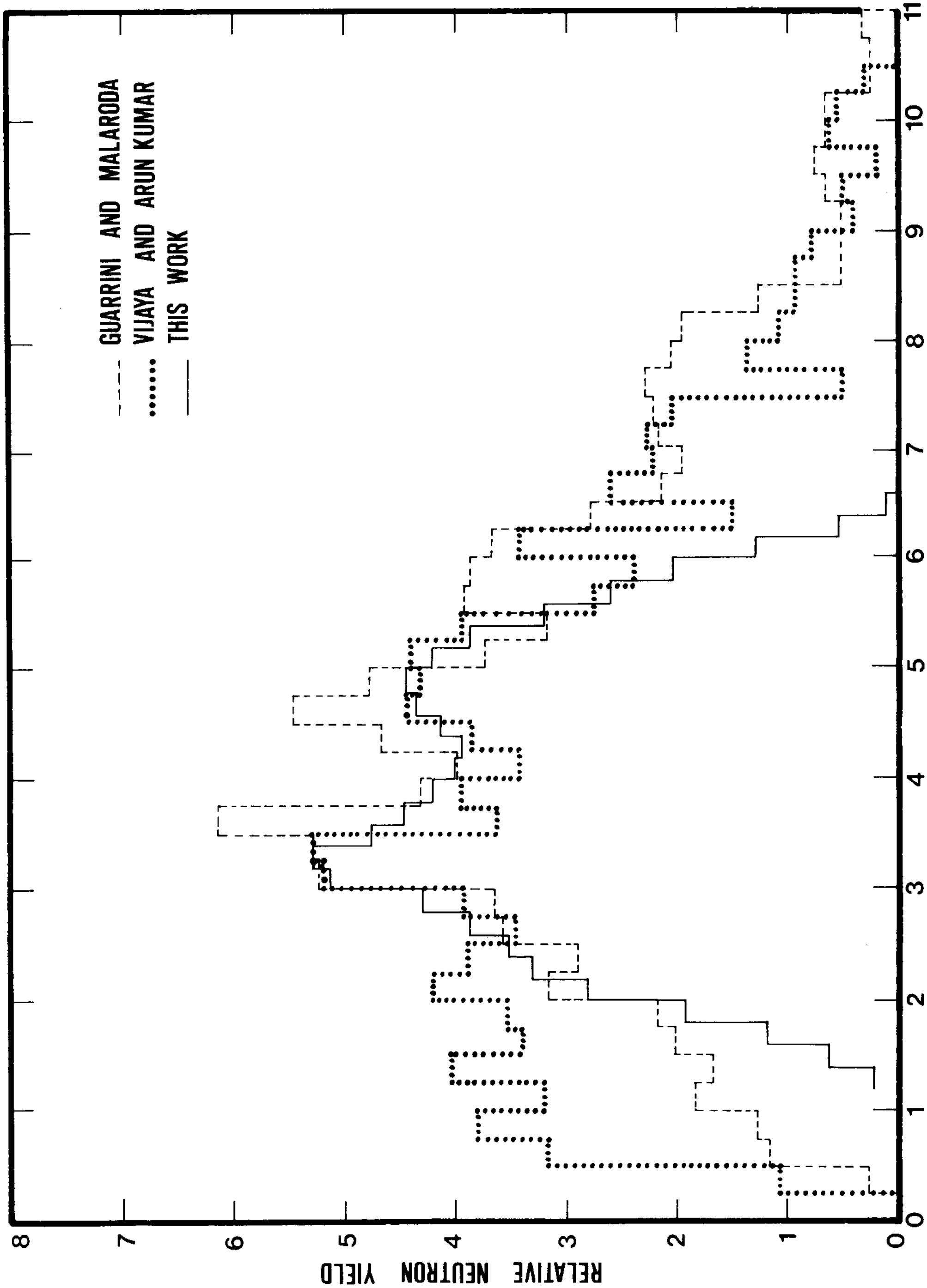

Fig. 5. Neutron spectrum from the Am-Be source. The data of Guarrini and Malaroda[2] and Vijaya and Kumar[3] obtained with nuclear emulsion technique are shown for comparison.

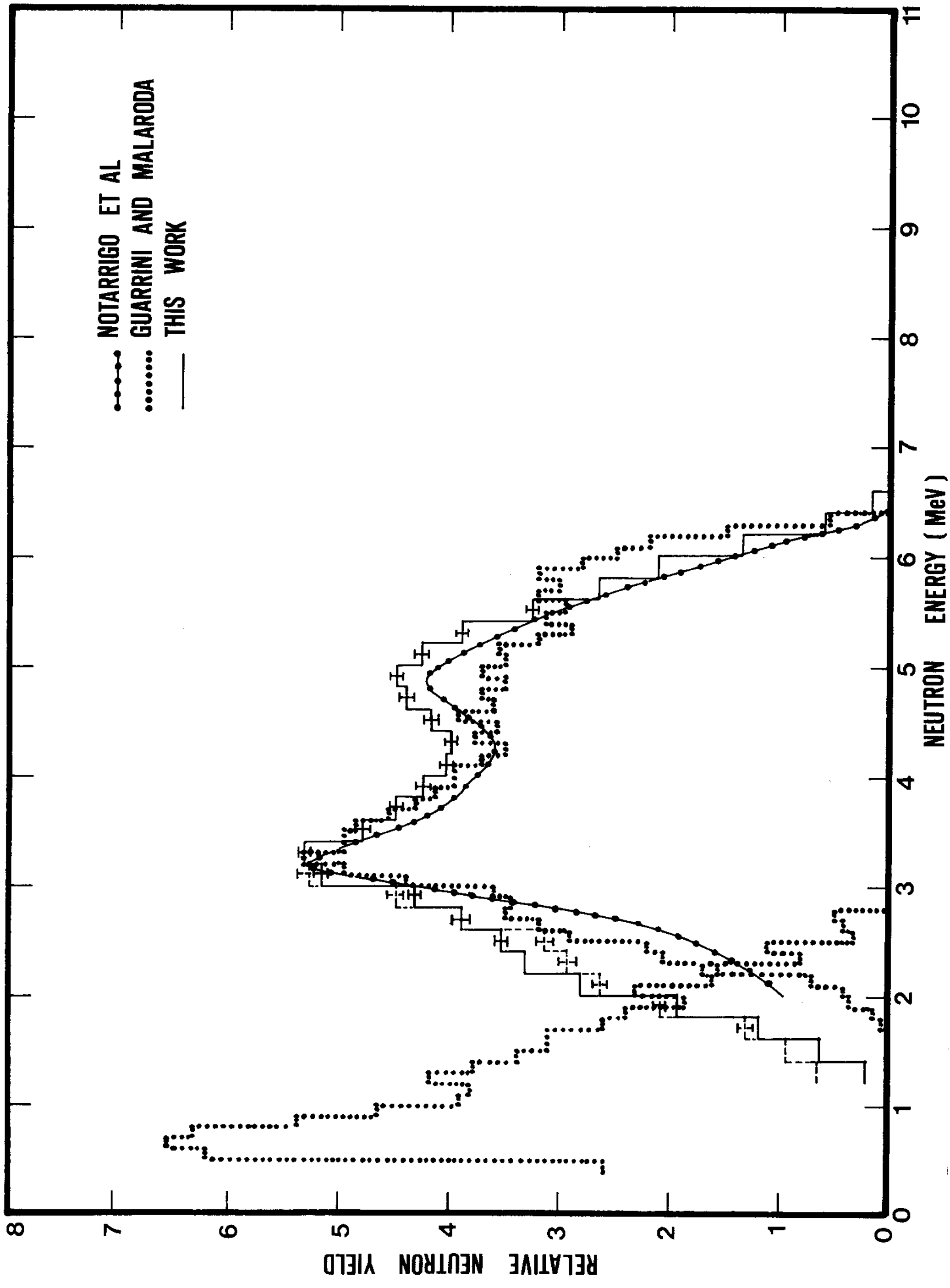

Fig. 6. Comparison of the measured spectrum of neutrons from the Am-Be source with the calculated spectrum of Notarrigo *et al.*[1] and Guarrini and Malaroda[2].

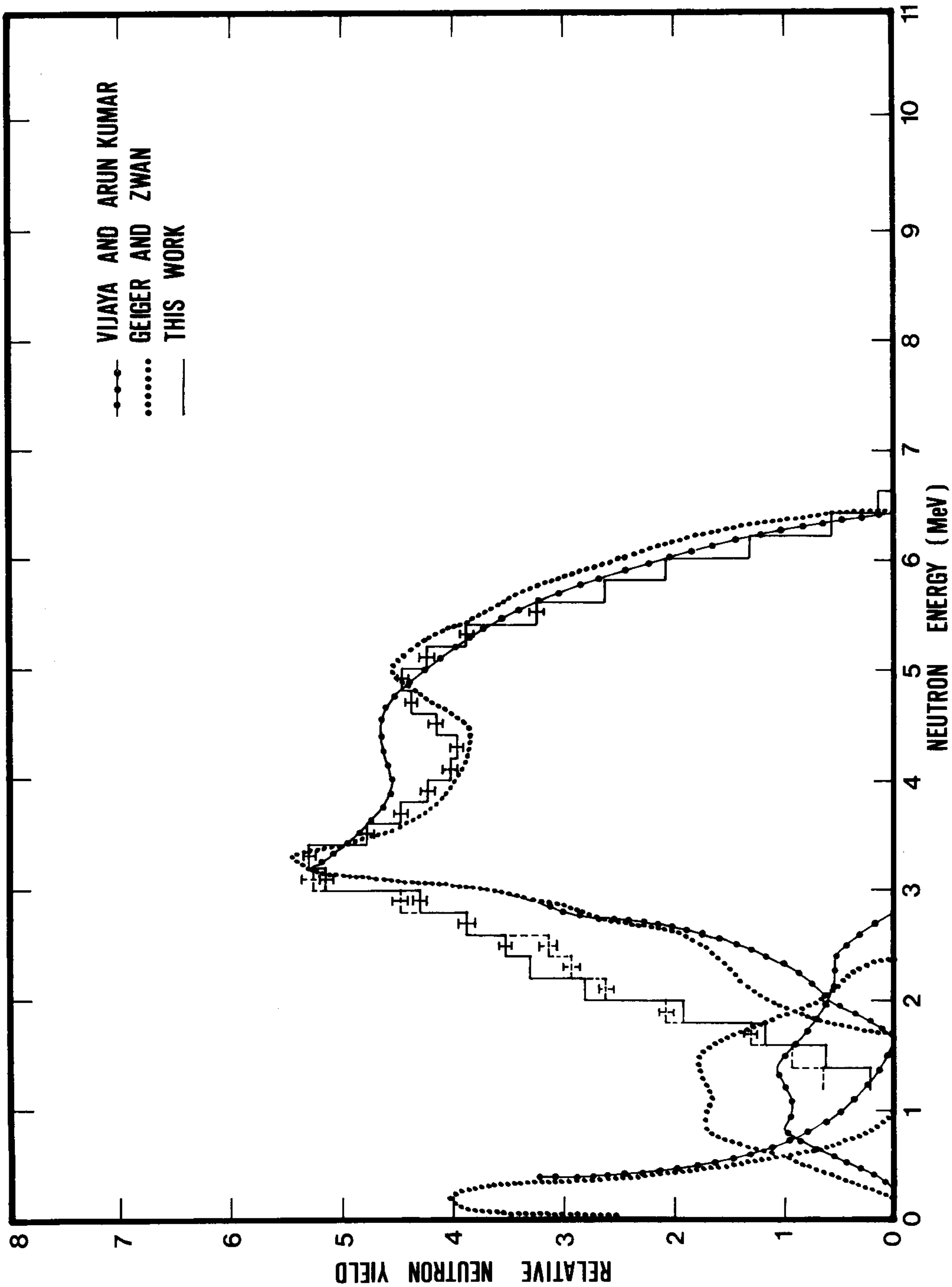

Fig. 7. Comparison of the measured spectrum of neutrons from the Am-Be source with the calculated spectrum of Vijaya and Arun Kumar[3] and Geiger and Zwan[4].

McBeth. The results are also compared as shown in Fig. 5. with those of Guarrini and Malaroda[2] and Vijaya and Kumar[3] using nuclear emulsion technique. The measurements were in less satisfactory agreement with those of Guarrini and Malaroda[2] and Devos *et al.*[7] using proton recoil spectrometer. The different sets of measurements generally agree with each other regarding the peaks at 3.2 MeV and 4.8 MeV. It should be noted that the other workers measured single neutron spectrum whereas this work measured coincident neutron spectrum and that the energy resolution of the detecting system is considered better than those employed in other measurements.

The detailed mechanism responsible for the emission of neutrons from the Am-Be source has been proposed by many authors[14]. Various calculations have been made to predict the spectrum of the emitted neutrons. Notarrigo *et al.*[1] assummed that neutrons are emitted through the decay of ^{13}C populating the ground and first excited states of ^{12}C, taking into account the anisotropy of the neutron angular distribution. Guarrini and Maradona[2] included in their calculation the probability of populating the second excited state of ^{12}C via the decay of ^{13}C. The populated state subsequently decays through alpha emmission mode with no gamma. The emitted neutrons have energy in the region between 0 and 3 Mev. Vijaya and Kumar[3] and Geiger and Zwan[4] introduced refinements to their nuclear reaction calculations utilizing the break-up reaction $^{9}Be(\alpha, \alpha n)^{8}Be$ to produce neutrons in the continuum region between 0 and 2 MeV.

In Fig 7, the neutron spectrum was compared with the calculations of Notarrigo *et al.*[1] and Guarrini and Malaroda,[2] omitting those calculated neutrons that were assummed to result from the decay of ^{13}C populating the ground state of ^{12}C. In order to make direct comparison with the calculation of Guarrini and Malaroda[2], the coincident neutrons were separated out. These neutrons are in the region between 1.5 and 6.5 MeV. The dashed curve in the region between 1.5 and 3 MeV is the spectrum with gamma counter set at higher threshold. Better agreement was obtained with the calculation of Notarrigo *et al.*[1] Similar comparison with the results of Vijaya and Kumar[3] and Geiger and Zwan[4] is shown in Fig 7. The calculated spectra between 0 and 1.5 MeV are the break-up neutrons whereas those between 0.2 and 2.8 MeV are neutrons emitted in coincidence with alpha particles. In the region between 1.5 and 6.5 MeV the calculations predict a deficiency of coincident neutrons below 3 MeV. Above 3 MeV, the measurement agrees quite well with the result of Geiger and Zwan[4]. It should be noted that the results obtained at different gamma-ray thresholds do not differ significantly indicating that the contribution of neutrons resulting from the second excited state of ^{12}C decay via the emission of gamma-ray is negligible. The measurements show that neutrons in the region above 3 MeV are emitted predominantly through the decay of compound nucleus ^{13}C populating the first excited state of ^{12}C nucleus.

Conclusion

The energy spectrum of neutrons emitted in coincidence with gamma-rays from the Am-Be source has been measured. The measurements reported here generally agree with the measurements performed by other workers regarding the peaks at 3.2 and 4.8 MeV. The measurements were compared with several calculations and found agreement over limited spectral region. The results support the assumption that neutrons in the region above 3 MeV are emitted predominantly through the decay of compound nucleaus ^{13}C populating the first excited state of ^{12}C nucleus. In the region below 3 MeV, the calculations do not agree with the experimental data.

Acknowledgements

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บทคัดย่อ

ได้ตรวจวัดสเปกตรัมของนิวตรอนจากต้นกำเนิด Am-Be ช่วงพลังงานตั้งแต่ 1 MeV ขึ้นไป ที่ปล่อยออกมาโคอินซีเดนซ์กับรังสีแกมมาโดยระบบการวัดแบบ associated gamma-ray time-of-flight ที่มีค่า energy resolution ประมาณ 5 เปอร์เซนต์ สเปคตรัมที่วัดได้แสดงให้เห็นนิวตรอนพลังงานโดด ที่พลังงาน 3.2 MeV และ 4·8 MeV และลดลงอย่างมีระเบียบจากพลังงาน 5 MeV จนเป็นศูนย์ที่พลังงานสูงกว่า 6.5 MeV ข้อมูลที่ได้จากการทดลองได้นำมาเปรียบเทียบกับผลการทดลองที่ทำมาแล้วของคณะวิจัยอื่น และกับผลการคำนวณจากปฏิกิริยานิวเคลียร์ จำนวนนิวตรอนที่ปล่อยออกมาที่พลังงานต่าง ๆ สอดคล้องกับกลไกของการผลิตนิวตรอน โดยการ populate first excited state ของนิวเคลียส ^{12}C