THE SPECTRUM OF NEUTRONS AT 60 hg m^{-2}

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ABSTRACT

The rate of neutron interactions has been measured in the Holborn underground laboratory for the energy range 7.5-60 MeV, using a 3.85 kg cell of liquid scintillator. The neutrons are selected by pulse shape discrimination, with anticoincidence counters used to reduce interference from muons transversing the scintillator. The observed flux is interpreted in terms of neutrons produced from environmental uranium and thorium, those resulting from the capture of negative muons in nuclei and those from fast muon interactions.

1. Introduction. This paper describes the results obtained with an improved version of the experiment reported at the last conference (Barton, 1983). A preliminary attempt is made to estimate both the source spectrum of neutrons at this depth and the proportion of these neutrons which would be detected by the present system.

2. Apparatus. The counters are arranged as shown in Figure 1. The neutron counter is a cylinder of 175 mm diameter and length, containing 3.85 kg of NE213. The two anticoincidence counters are always operated in parallel; some results have been taken with them used in coincidence with the neutron counter. The 5 cm lead screen was removed for part of the observations.

The data from the pulse shape discrimination circuits were recorded as 2-dimensional histograms. Using an Am/Be neutron source, the discrimination was found to be very satisfactory up to its maximum energy ($\sim$ 12 MeV). Of course the discrimination becomes less at higher energies but is adequate to beyond 50 MeV. The present arrangement was less satisfactory at energies below 8 MeV because the photo-electron statistics were poor; a larger diameter photomultiplier might, in principle, improve the performance at low energies, but a tube with sufficiently uniform time response was not available.

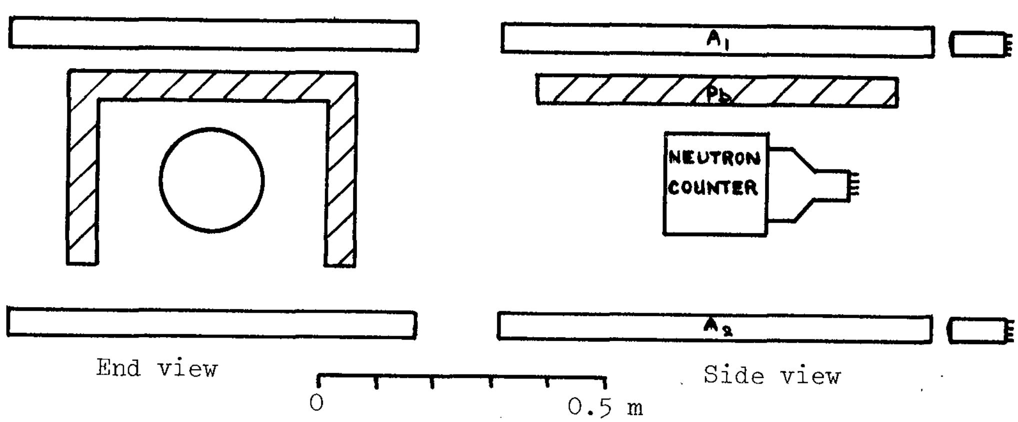

Fig. 1: Arrangement of apparatus

The discriminating properties of organic scintillators are associated with their non-linear response to more heavily ionizing particles. The position of the cosmic ray peak provides a direct calibration for minimum ionizing particles, but the energy scale for protons is not so easily established. There are no convenient calibration sources so the energy scale had to be taken from reports of calibrations made on other large NE213 counters used for accelerator experiments. The published data are not in good agreement so the neutron energy scale adopted here has an uncertainty of ± 15%.

The results have to be corrected for two types of spurious event. The trigger level for the leading-edge timing must be set low to avoid time-slewing which means that accidentals cause spurious zero-crossing times. Secondly, muons which stop in the counter may decay before the zero-crossing time (1.5 μs was used) and give distorted events. Both effects have been analysed theoretically and compared with the background events in the pulse-height/pulse-shape histograms in regions away from the muon or proton ridges. At worst the correction for the proton region was 15% and the additional uncertainty is generally less than the statistical one.

When operating the main counter in coincidence with the others, a well-resolved proton ridge was not observed. This is understandable, as the signal would be due to both muon and proton in proportions varying from event to event. These events would fall in the valley region between the two main ridges. Similarly, events with indications of particles ionizing more strongly than protons are ascribed to nuclear disintegrations in the scintillator. For the anticoincidence events both effects were sufficiently small that the true proton events could be separated with less difficulty.

3. Results. There was no clear difference between the anticoincidence results with or without the lead in position. The combined results are therefore used for Figure 2. The coincidence rates are also shown but, as explained above, there is much greater uncertainty about these.

4. Predicted source spectrum of neutrons. All rocks contain a small proportion of uranium, typically from 1-5 μg g^{-1}, about three times as much thorium and a few per cent of potassium. Neutrons can therefore result from spontaneous fission of ^{238}U, from (α,n) reactions and (γ,n) reactions. For a rock in the middle of the range indicated above, these processes give, respectively, about 5×10^{-8} g^{-1} s^{-1}, 1.2×10^{-7} g^{-1} s^{-1} and $< 10^{-9}$ g^{-1} s^{-1}. These values depend on the other constituents of the rock but not very strongly, except in particular ores. The spectra of neutrons from fission and (α,n) processes in thick targets are known to fall off rapidly above 2 MeV.

The stopping rate of all muons at this depth is $(21 \pm 2) \times 10^{-3}$ g^{-1} d^{-1} and for "standard" rock with $Z = 11$ about 0.5×0.5 will be captured and produce, on average, 1.2 neutrons each (Mukhopadhyay, 1977) giving a total yield 6×10^{-3} g^{-1} d^{-1}. The spectra given by Sundelin (1973) show that about a fifth of the neutrons have energy greater than 10 MeV and decreasing $\sim e^{-E/7}$.

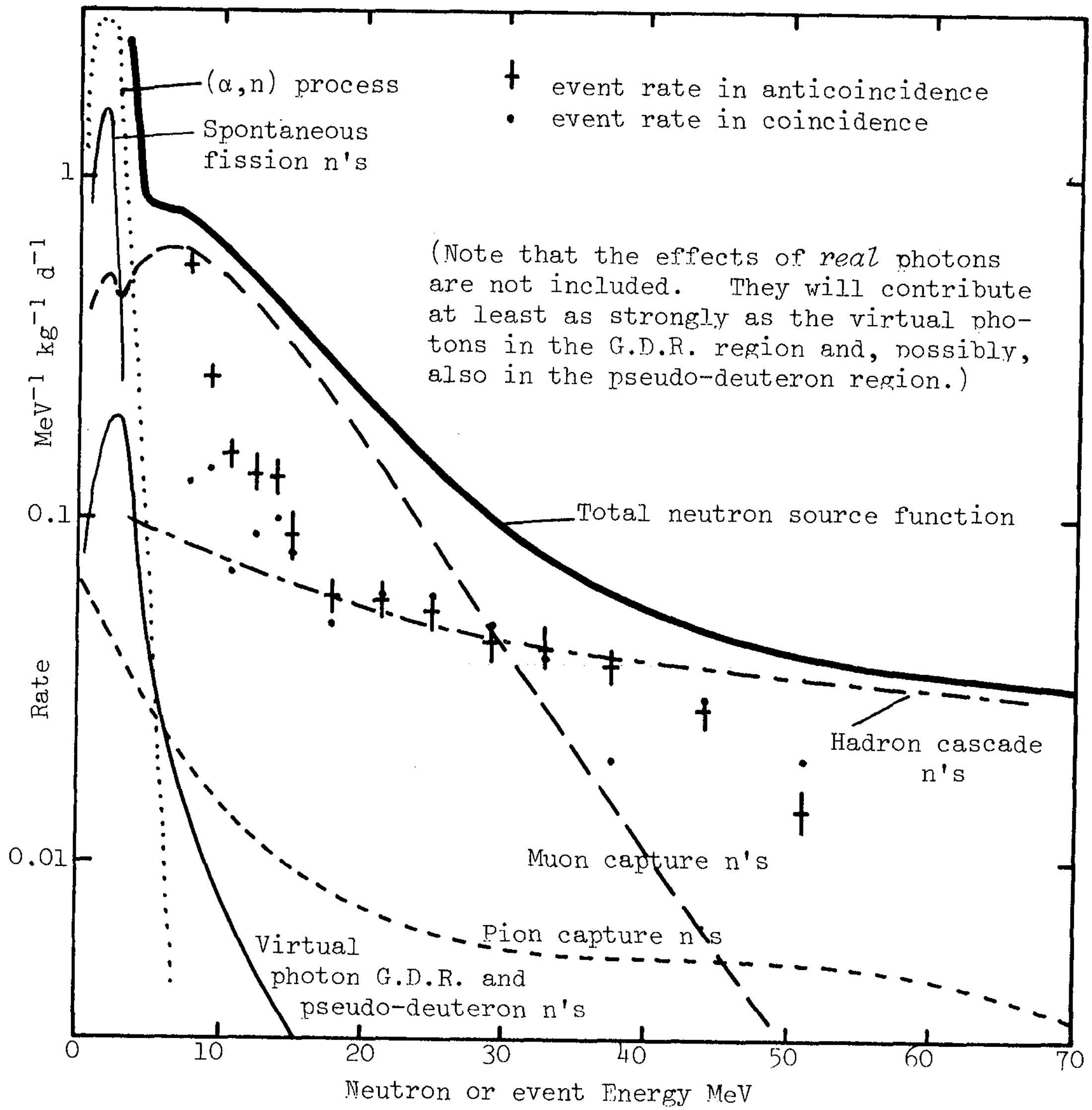

Fig. 2: Observed event rate compared to neutron source spectra

The fast muons traversing the rock produce neutrons through both real and virtual photo-nuclear interactions. For energies below 100 MeV most of the real photons result from bremmstrahlung of knock-on electrons and have a spectrum of the form $\sim E^{-2}$. In the same energy region the virtual photons have a spectrum $\sim E^{-1}$ so, at sufficiently high energies, will always be more important than the real photons. Although the various electromagnetic interaction processes producing real photons are well understood, the detailed Monte Carlo calculations required to estimate the absolute intensity of photons with energy comparable to the critical energy do not seem to have been carried out. For the spectrum of virtual photons, the plane wave Born approximation has been shown to be valid at low energies (Orth et al, 1981), whilst at energies above the pion production threshold the refined calculations of Bezrukov and Bugaev (1981) are available.

Photo-nuclear reactions are usually considered in three energy regions. Below 30 MeV the giant dipole resonance provides the mechanism and the resulting neutrons have a spectrum similar to those from the evaporation process. Between 30 and 150 MeV the pseudo-deuteron model of Levinger has recently received more precise experimental support for light and medium nuclei (Homma et al, 1983). The neutron usually receives half the energy of the photon, less the binding energy. Above the pion production threshold neutrons are produced both directly in the hadron cascade and from the capture of negative pions by nuclei. The spectrum of the neutrons in the cascade falls off as $\sim E^{-2}$ between 10 and 50 MeV but more rapidly at higher energies (Metropolis et al, 1958), with the absolute values estimated from the total amount of energy transferred via muon nuclear processes. Negative pions produced by the same mechanism are captured by pseudo-deuterons in nuclei and produce one or two neutrons with a rather flat spectrum up to $\sim$ 100 MeV (Madey et al, 1982); the number of pions stopping at 60 m.w.e. has been determined experimentally (Slade, 1966). Figure 3 includes estimates of the main contributions to the neutron source spectrum.

In the present experiment, as was pointed out earlier, only the anticoincident results enable the neutron events to be separated unambiguously. Those neutron sources in which the originating muon is closely collimated with the neutron will therefore be excluded. A further complication is that the neutrons may be scattered and lose energy before reaching the detector. Overall, it must therefore be expected that the observed anticoincidence spectrum will be softer than the source spectrum and substantially lower in magnitude. Examination of Figure 2 shows this to be true but it is not yet possible to say whether the difference can be accounted for quantitatively.

5. Conclusions.

1. The observed spectrum of neutron events at 60 hg cm^{-2} falls sharply up to 15 MeV and then decreases rather slowly.
2. The observed intensity of neutron interactions, not closely accompanied by muons, above 15 MeV at this depth is 1.8 ± 0.3 kg^{-1} d^{-1}.
3. The total intensity is at least double this value and is not in disagreement with what can be predicted from known processes.

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