NEUTRON FLUXES UNDERGROUND*

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Eugster (1954) reported the neutron flux under 2100 m rock (5880 m water equivalent) to be 26 times that at the ground surface and suggested that radiation was coming from the centre of the Earth. An attempt has been made to confirm this interesting finding by comparing the neutron flux in the Broken Hill mines with that at ground level. Although the counting statistics are rather meagre they should be sufficient to reveal such a marked effect as claimed in the Swiss experiment.

The purpose of the present note is to report a negative result for the experiment and to draw attention to the factors which may have led to erroneous values in Eugster's experiment.

Ilford C2 boron-loaded plates, 200 μ thick, were located at various levels of the Zinc Corporation and North Broken Hill mines, controls being situated in the offices adjacent to the respective head frames of the mines. Plates were contained in sealed tins along with silica gel which served as a dehydrant to minimize the influence of fading of the latent image. Prevailing temperatures were mild at the surface ($\sim$60 °F) but increased to $\sim$85 °F at the deepest level which was 3060 ft underground (2500 m water equivalent) in the Zinc Corporation mine. Exposures lasted for approximately one month.

The plates employed were cleared of tracks by exposure to hydrogen peroxide vapour after arrival from Britain, flown to Broken Hill in cadmium-covered boxes, and returned in the same way at the conclusion of the exposure.

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The short flights resulted in a small background of α-tracks due to cosmic ray neutrons in free space and this was determined and subtracted by despatching a group of identical plates over the same route under the same conditions but not permitting any other exposure. The difference should therefore be due strictly to neutrons reaching the plates when they were located on the site.

The combined results from both mines are shown in Table 1. The very low density of tracks ($\sim$20–200/cm^2) made scanning very tedious and the statistics poor. Uncertainties in the values shown are based on counting statistics only. The total number of tracks recorded was 173.

TABLE 1

DENSITY OF α-TRACKS FROM THE $^{10}B(n,\alpha)^7Li$ REACTION DUE TO NEUTRON FLUXES UNDERGROUND

The background figure (column 3) should be subtracted from all other values

Depth of Rock below Ground (ft)		α-Tracks per cm^3 (measured)	α-Tracks per cm^3 (background)
NBH* & ZC	Surface ($\sim$1000 ft above sea-level)	$(0\cdot96\pm0\cdot14)\times10^4$	$(0\cdot18\pm0\cdot03)\times10^4$
NBH	1000	$(0\cdot29\pm0\cdot06)\times10^4$	
NBH	2000	$(0\cdot17\pm0\cdot03)\times10^4$	
ZC	3000	$(0\cdot24\pm0\cdot04)\times10^4$	

* NBH=North Broken Hill mine, ZC=Zinc Corporation mine.

Assuming that the α-yield from the $^{10}B(n,\alpha)^7Li$ reaction correctly reflects the prevailing neutron flux, it is apparent that there is little difference between the various plates with the exception of the surface exposure which is significantly higher. There is no indication of a trend towards higher neutron fluxes underground, in direct contradiction of the 26-fold increase claimed by Eugster for a depth of 6900 ft underground.

The danger exists in experiments of this kind that track fading during the long exposure will lead to erroneous absolute values, which, if conditions are not identical at the several sites, tend to make comparisons hazardous. The much longer exposure period (116 days) employed by Eugster for his surface plates would tend to depress the neutron flux estimate there, if fading effects were significant, relative to the underground value which was based on a 37-day exposure. This point has been referred to previously (Mather 1954).

In the present experiment also, fading could be present and would tend to operate in the opposite direction because, although exposure times were identical, the underground temperature was considerably higher and fading is generally accelerated by elevated temperatures. A useful check on this can be obtained by comparing the density of contamination tracks on all the plates scanned. Both the emulsion and glass of a photographic plate contain detectable thorium traces which gradually build up a background of α-stars and single tracks. If fading is also present an equilibrium track density is reached, after a time depending on the fading rate, when the generation of new tracks is exactly compensated by the loss of old ones. This contamination background was compared on the various plates with a view to comparing the prevailing fading rates. There was no significant difference, the α-track distribution being constant at a figure of about $6\times10^4/\mathrm{cm}^3$ over the whole series.

While the underground measurements listed in Table 1 are rather crude and not very consistent, they appear to average somewhat higher than the background value, perhaps by about 500 α-tracks/cm^3, or 16 α-tracks cm^{-3} day^{-1}. It is of interest to compare this yield with that expected from neutron generating processes which are feasible in the crust of the Earth.

First consider spontaneous fission: ^{238}U having a fission rate of $6\cdot9\times10^{-3}$ g^{-1} sec^{-1} (Segre 1952) is the most prolific isotopic contributor in any given percentage abundance. On the average $2\cdot2$ neutrons are emitted per spontaneous fission so that its source strength (neutrons cm^{-3} day^{-1}) is $3\cdot5\times10^3 f$, where f is the fractional concentration of uranium in the ground, by weight, and the density of ground has been taken as $2\cdot7$ g/cm^3.

Another source of ground neutrons of comparable strength is provided by (α, n) reactions on the major elements (oxygen, silicon, and aluminium) present in the ground, the α-particles coming from radioactive inclusions in the ground. The number of α-particles released per unit time depends on the radioactive series present and their state of equilibrium. In the Broken Hill region uranium is certainly present in trace quantities. If in complete equilibrium UI emits 10^5 α-particles g^{-1} sec^{-1}, which may be taken as an upper limit for the actual emission rate in the present case. Thick target (α, n) yields have been measured for polonium $5\cdot3$ MeV α-particles, giving $0\cdot07$ neutrons/10^6 α-particles for oxygen, $0\cdot16$ for silicon, and $\sim0\cdot7$ for aluminium (Segre 1953). Taking a weighted average of $0\cdot14/10^6$ for earth and reducing this to a half to allow for the reduced barrier penetration of lower energy uranium α-particles leads to a neutron yield of $1\cdot6\times10^3 f$ cm^{-3} day^{-1}, where f is the uranium concentration as before. (However, quite small concentrations of certain other elements could alter this figure appreciably. For instance, the (α, n) yield on beryllium is $40/10^6$ U α-particles.)

Other processes which suggest themselves are: (1) (γ, n) reactions. The natural γ-ray energies from the uranium series are below the photo-neutron thresholds. (2) The μ-meson–star process releasing neutrons. While this will contribute to the exposure of plates at the surface, and in fact some distance underground, its contribution will be negligible at the great depths employed in the present experiment (see Wilson 1952). Both these processes may therefore be excluded as significant neutron sources.

Combining spontaneous fission and (α, n) yields leads to a total source strength:

$$q\simeq5\cdot1\times10^3 f\ \mathrm{cm}^{-3}\ \mathrm{day}^{-1}. \qquad (1)$$

If it is assumed that the ground consists of a homogeneous mixture of elements and also that no neutrons are absorbed during slowing down, an upper limit can be obtained for the corresponding neutron flux:

$$\varphi=q\Lambda, \qquad (2)$$

where Λ is the absorption mean free path $(=1/N_v\sigma_a)$ of thermal neutrons. N_v is the number of atoms/cm^3 and σ_a their absorption cross section. The flux is related to $I(\alpha)$, the number of α-tracks formed in the emulsion per cm^3 per day, by :

$$\varphi=I(\alpha)/N_{vB}\sigma_B, \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

where σ_B is the effective cross section for the (n, α) reaction and N_{vB} the number of boron atoms/cm^3 of emulsion $(1\cdot28\times10^{21})$. Hence

$$q=I(\alpha)/\Lambda\sigma_B N_{vB},$$

and

$$f\simeq3\cdot5\times10^{-6}I(\alpha). \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

An average ground composition similar to that listed for the Earth's crust (Forsythe 1954) has been assumed in order to obtain a rough estimate of Λ for ground. The result is $\sim$200 g/cm^2.

It follows that $I(\alpha)\sim16$ would require f to be $\sim0\cdot006$ per cent. in order to account for the magnitude of the neutron flux underground. However, this figure is based on the difference between two small numbers and should not be taken to indicate better than the order of magnitude. On the other hand to account for the surface yield of α-particles would call for a uranium concentration of $\sim0\cdot1$ per cent., which certainly does not exist in the Broken Hill area.

The greater part of the exposure to neutrons at the ground surface presumably arose from cosmic radiation. Taking it to be responsible for $0\cdot7\times10^4$ α-particles/cm^3, i.e. $\sim$230 α-particles cm^{-3} day^{-1}, the cosmic ray neutron flux would have to be (by equation (**3**)) approximately 290 neutrons cm^{-2} day^{-1} at 1000 ft altitude (995 g/cm^2). This is a reasonable agreement with measurements made at a similar geomagnetic latitude in Australia several years ago (Mather 1954) which indicated $\sim$230 neutrons cm^{-2} day^{-1}.

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