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On the Interpretation of Neutron Measurements in Cosmic Radiation

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The measurements of cosmic-ray neutrons are essentially determined by the energy distribution of neutrons in the atmosphere. The various factors influencing this distribution are investigated (§ 1). It is found that diffusion equilibrium exists in the atmosphere except for about one meter of water at the top and one meter above ground (§ 2). It is probable that the energy distribution below 100 kev can be represented by the simple Eq. (2, 3); it does not contain an appreciable number of thermal neutrons. The calculation of the number of neutrons originally produced from the present experimental data is uncertain because of capture of fast neutrons (§ 1). As an example of the influence of the ground, the neutron distribution is calculated in the air above a water surface (§ 3). Measurements in the water may be most suitable for a quantitative determination of the neutron intensity.

The various experimental arrangements are discussed in § 4, 5. A $1/v$-detector such as a BF_3 counter measures essentially the density of neutrons if care is taken to minimize the effect of recoil nuclei by using a high bias (§ 4). The evaluation of experiments using hydrogenic material to slow down the neutrons is discussed in § 5. From these two types of experiments, provisional results for the neutron production are obtained which are in agreement with each other. From the altitude distribution of neutron intensity it can be concluded that the production of neutrons of very long range is not very important (§ 7). The role of neutrons for the energy budget of cosmic radiation is discussed (§ 8).

I. THE NEUTRON INTENSITY IN COSMIC RAYS

MEASUREMENTS of the neutron intensity in cosmic radiation were made by several authors[1–16] using various experimental techniques and working at different altitudes. In order to interpret these experiments, we must know the energy distribution of the neutrons in the atmosphere and the relative sensitivity of the detectors for neutrons of various energies. In the following we shall determine the energy distribution arising from the diffusion in the atmosphere (§1). We shall further show that a neutron diffuses only

[1] L. H. Rumbaugh and G. L. Locher, Phys. Rev. **44**, 855 (1936).
[2] E. Schopper, Naturwiss **25**, 557 (1937).
[3] E. Schopper and L. Schopper, Physik. Zeits. **40**, 22 (1939).
[4] W. Heitler, C. F. Powell and G. E. F. Fertel, Nature **144**, 283 (1939).
[5] G. L. Locher, Phys. Rev. **44**, 774 (1933).
[6] G. L. Locher, Phys. Rev. **45**, 296 (1934).
[7] G. L. Locher, Phys. Rev. **50**, 394 (1936).
[8] G. L. Locher, J. Frank. Inst. **224**, 555 (1937).
[9] D. K. Froman and J. C. Stearns, Phys. Rev. **54**, 969 (1938).
[10] E. Fünfer, Naturwiss. **25**, 235 (1937).
[11] E. Fünfer, Zeits. f. Physik **111**, 351 (1938).
[12] C. G. and D. D. Montgomery, Phys. Rev. **56**, 10 (1939).
[13] S. A. Korff, Phys. Rev. **56**, 210 (1939).
[14] S. A. Korff and W. E. Danforth, Phys. Rev. **55**, 980 (1939).
[15] S. A. Korff, Rev. Mod. Phys. **11**, 211 (1939).
[16] H. v. Halban, M. Magat and L. Kowarski, Comptes rendus **208**, 572 (1939).

over a limited part[17] of the atmosphere. From this it follows that the energy distribution is very nearly the same at different altitudes, with the exception of the regions near the top and bottom of the atmosphere. This makes it possible to interpret the measured dependence of the intensity on altitude as giving the altitude distribution of the production of neutrons of moderate energy (cf. footnote 17 and §7).

§ 1. Energy distribution of neutrons in the atmosphere

The energy distribution is determined by the diffusion of the neutrons in the atmosphere. In treating this process, we shall restrict ourselves to those phenomena for which the theory is reasonably certain, i.e., to neutron energies for which the concept of the compound nucleus is applicable; we shall assume that this is the case up to about 30 Mev. Up to this energy, the interaction between particle and nuclei will certainly be at least as great as the kinetic energy of the particle, and under these conditions the result of a collision does not depend appreciably on the nature of the forces. For higher energies, the analytical form of the interaction will be essential, and since we do not know it we cannot make predictions about collisions of very fast neutrons.[18]

We shall therefore assume that a certain number of neutrons below 30 Mev is produced at a given point in the atmosphere. We shall leave it open whether these neutrons are directly produced by other particles or whether they arise from the slowing down of faster neutrons. In any case the neutrons must be produced in the atmosphere because, according to present ideas about β-disintegration, the neutron has a finite lifetime of about one hour. Some more information about the production process can be obtained from the analysis of the experiments, cf. §7.

Neutrons below about 30 Mev can be treated with the Bohr method of the compound nucleus.[19] In colliding with nuclei, neutrons may disappear due to n, p or n, α reactions, etc., or their number may increase due to $n, 2n$ or similar reactions, or we may have simple inelastic scattering. In any case, if a neutron comes out from the reaction, its energy will only be of the order of the nuclear temperature, i.e., much smaller than the energy of the incident neutron.

This process of energy loss due to excitation of nuclei can take place if the energy of the incident neutron is greater than the lowest excited level of the nuclei present in air. The lowest excited level in O^{16} is almost certainly[20] at 6 Mev. In nitrogen, an excitation level[21] of 4 Mev has been found but there is not yet sufficient experimental evidence to show or exclude the existence of lower levels. We shall assume in the following that 4 Mev is the lowest excited level.

One or two inelastic collisions are in general sufficient to reduce the energy of a neutron below that of the first excitation level of nitrogen. The cross section for neutrons in the energy range considered, is of the order of the geometrical cross section of the nucleus, i.e., about 0.5×10^{-24} cm^2 for nitrogen and oxygen. This is equivalent to a mean free path of about[22] 50 g/cm^2.

Below the first excited state of N^{14} which we tentatively assume at 4 Mev, there will be no more inelastic collisions. Any further slowing down must therefore be due to elastic collisions with N^{14} and O^{16} nuclei. Since these nuclei are quite light, elastic collisions will be quite effective in reducing the energy of the neutrons. The amount of the average energy loss per collision depends to some extent on the angular distribution of the elastically scattered neutrons which is not known. If we assume it to be spherically symmetrical in the center of mass system the average energy loss will be $2/M$ times the initial energy of the neutron where M is the atomic weight of the nucleus. Seven collisions with nitrogen are as effective as one with hydrogen, reducing the average neutron energy to $1/e$ of its initial value.

[17] This may not be correct for extremely fast neutrons (cf. §1) but it can be shown from the experimental altitude dependence that the neutrons for which it is incorrect are not very important (§7).

[18] Earlier theories of Heisenberg (Naturwiss. **25**, 749 (1937)) and Williams (Nature **142**, 431 (1938)) were based on special assumptions about the nuclear forces which can no longer be regarded as well founded.

[19] N. Bohr, Nature **137**, 344 (1936). N. Bohr and F. Kalckar, Kgl. Danske Vid. Selsk. Medd. **14**, 10 (1939).

[20] W. A. Fowler and C. C. Lauritsen, Phys. Rev. **56**, 840, 841 (1939).

[21] M. S. Livingston and H. A. Bethe, Rev. Mod. Phys. **9**, 245 (1937).

[22] We measure mean free paths in g/cm^2 rather than in physical dimensions. One g/cm^2 is the same as one cm water equivalent, the unit customary in cosmic-ray investigations.

TABLE I. *Cross sections of nitrogen and oxygen (in* 10^{-24} *cm*^{2}).

PROCESS	D+D NEUTRONS σ	REF.	PHOTO-NEUTRONS σ	REF.	THERMAL NEUTRONS σ	REF.
N^{14}, elastic scattering	1.4	23	1.6	25	10.7	26, 27, 28
O^{16}, elastic scattering	1.2	23	1.8	25	4.2	26, 27
$N^{14}+n=C^{14}+H^1$	0.04	24	—	—	1.3	29
$N^{14}+n=B^{11}+He^4$	0.16	24	0		0	

The elastic collisions would slow all the neutrons down to thermal energies if no capture processes occurred. In reality such processes do occur and are quite frequent both at high energies (of the order of millions of volts) and very low energies (of the order of volts). The fraction of neutrons of initial energy E_1 which get down to energy E_2 without being captured is given by[30]

$$\exp\left(-\tfrac{1}{2}M\int_{E_2}^{E_1}\frac{\sigma_c}{\sigma_s}\frac{dE}{E}\right), \qquad (1)$$

where σ_c is the capture cross section, σ_s the scattering cross section and σ_c/σ_s is to be taken as a function of energy. In deriving this formula, it has been assumed that the angular distribution of the scattered neutrons is spherically symmetrical. For σ_c and σ_s we must insert the average values for nitrogen and oxygen, taking account of the concentrations.

Cross sections have been measured for neutrons of 2.6 Mev obtained from the D−D reaction, for photoneutrons arising from the photoelectric disintegration of beryllium with RaC γ-rays (neutron energy about 150 kev), and for thermal neutrons. The results are given in Table I, in units of 10^{-24} cm^2 which we shall use throughout in this paper.

Considering first the elastic cross section of N^{14}, we notice a large increase between 150 kev and thermal energies. At what energy this change occurs is unknown; the fact that it occurs indicates the presence of resonance levels. For a nucleus as light as nitrogen it would be unreasonable to assume a resonance level of less than, say, 10 kev width; therefore we shall take as extreme assumptions for the energy at which the cross section changes, $E_S=10$ and $E_S=150$ kev, respectively. For the average elastic cross section of an "air" nucleus we have then about $1.3_5\times10^{-24}$ for energies greater than E_S, and 9.4×10^{-24} cm^2 for smaller energies. This corresponds to a mean free path of the neutrons of 18 and 2.6 cm water equivalent, respectively.

The process $N^{14}(n,\alpha)B^{11}$ is impossible for low energy neutrons, being endothermic by about 0.3 Mev. Above the threshold of 0.3 Mev the cross section will increase with increasing neutron energy because the α-particles will have a greater chance to escape through the Coulomb potential barrier. Taking for the radius of the compound nucleus N^{15}, $R=1.5\times10^{-13}A^{\frac{1}{3}}=3.7\times10^{-13}$ cm, and taking account of the recoil and of the reaction energy of −0.3 Mev, we find that neutrons of 4.2 Mev will produce α-particles which go over the top of the barrier. Therefore a considerable increase of the cross section for the n, α process may be expected when the energy increases to 4 Mev; on the other hand, the n, α process will be of negligible importance below 2 Mev neutron energy.

The process $N^{14}(n,p)C^{14}$ is exothermic by about 0.7 Mev; the height of the barrier (with the same nuclear radius as above) is 2.2 Mev. Thus the small cross section at 2.6 Mev suggests that the process is intrinsically improbable. The thermal cross section of 1.3 is relatively even smaller; namely if we would assume that the capture cross section σ_H is proportional to the penetrability P_H for the proton, divided by the velocity v of the neutron, extrapolation from the measured cross section at 2.6 Mev would give about 15 times more for the cross section at thermal energy. This shows again that resonances must play an important role, and that it is therefore difficult to make any definite statements about the cross

[23] W. H. Zinn, S. Seely and V. W. Cohen, Phys. Rev. **56**, 260 (1939).
[24] E. Baldinger and P. Huber, Nature **143**, 844 (1939).
[25] E. Fedorow and N. Perfiliewna, Sow. Phys. **11**, 660 (1939).
[26] J. R. Dunning and H. Carroll, Phys. Rev. **54**, 541 (1938).
[27] M. Goldhaber and G. H. Briggs, Proc. Roy. Soc. **A162**, 127 (1937).
[28] Dunning and Carroll measured directly the total cross section $\sigma=12.0$ from which we have to subtract the capture cross section $\sigma_c=1.3$ (cf. reference 24). Goldhaber and Briggs have made a direct measurement of the elastic cross section and obtain 8.2. The experimental error given by Dunning and Carroll being smaller, we have used their value. All measurements may be influenced by interference effects between the neutrons scattered from different nuclei in the molecule or crystal.
[29] O. R. Frisch, H. v. Halban, J. Koch, Kgl. Danske Vid. Selsk. Medd. **15**, 10 (1938); Nature **140**, 895 (1937).
[30] G. Placzek, Phys. Rev., to appear shortly.

section. Nevertheless it is quite possible that the resonances above the $1/v$-region do not appreciably reduce the number of neutrons because of the small intrinsic probability of the reaction. Below 10 kev we can, for a nucleus as light as nitrogen, assume that the capture cross section is proportional to $1/v$ and calculate it from the measured value at thermal energy. If we assume that the cross section for the n, α and n, p processes are determined mostly by the penetrability of the potential barrier, we should find that about 70 percent of all neutrons of 3 Mev initial energy, and about 40 percent of all 4-Mev neutrons are slowed down to the region of validity of the $1/v$-law (below 10 kev). The underlying assumptions and therefore these figures are of course very uncertain but it seems likely that the capture will not reduce the number of neutrons by orders of magnitude. The reduction will be less if the first excited state of nitrogen is lower, but will be greater if there is strong resonance capture.

From this discussion we see that not enough experimental data are available above the $1/v$-region. Since the more accurate experiments consist in the determination of the number of relatively slow neutrons in cosmic radiation (cf. §4, 5), we shall in the following refer only to those neutrons which escape capture at high energies, i.e., capture above the $1/v$-region.

We denote by q the number of neutrons produced per gram and sec. which escape capture at high energies, and by v_1 the smallest velocity at which high energy capture takes place. The energy $E_1=\frac{1}{2}mv_1^2$ may be as low as 10 kev but possibly as high as 2 Mev. Then the number of neutrons per cm^3 having a velocity between v and $v+dv$ (for $v<v_1$) is given with sufficient accuracy by[30]

$$N(v)dv = Mq\,l(v)\frac{dv}{v^2} \times \exp\left\{-M\int_v^{v_1}\frac{\sigma_c(v')}{\sigma_s(v')}\frac{dv'}{v'}\right\}. \quad (2)$$

According to our assumption about v_1, the exponential will only become important when σ_c obeys the $1/v$ law, so that it may be written

$$\exp\left\{-M\frac{\sigma_{cth}}{\sigma_s}\left(\frac{kT}{E}\right)^{\frac{1}{2}}\right\}, \quad (3)$$

where σ_{cth} is the capture cross section at energy kT. The observed values are (cf. Table I)

$$\sigma_s = 9.4 \text{ per "air atom"};$$
$$\sigma_{cth} = 1.04 \text{ per "air atom."} \quad (4)$$

With $M=14$, the exponent in (3) becomes unity for

$$E_{capt} \sim 2.4kT, \quad (4a)$$

i.e., the neutrons will on the average be slowed down to $2.4kT$ before being captured.

This shows that no thermal equilibrium will be established among the neutrons in the atmosphere because the capture probability is too large. The value of the limiting energy is probably not exactly $2.4kT$ because at neutron energies below $\frac{1}{3}$ volt $=13kT$ the chemical binding in the nitrogen molecule and the velocity of the nitrogen molecules will be important[30] and will reduce the slowing effect of the collisions. This will also modify the velocity distribution (2) at the lowest energies.

Another modification is introduced by the presence of water vapor. If the partial pressure of water vapor is p_W and the total pressure is p_0, the average energy loss of a neutron will be increased in the ratio

$$1+14p_W/p_0.$$

If we admit an increase by 20 percent, p_W must be less than 11 mm at ground and correspondingly less at higher elevations. For saturation, this means that the temperature should be less than 14° at sea level or 8° at 3 meters of water elevation. Usually the humidity is far from saturation, and therefore the water vapor will be unimportant even near ground except on hot humid days.

§ 2. Spatial distribution of the neutrons

Thus far we have calculated the energy distribution with the tacit assumption that the nitrogen in the atmosphere is sufficient to slow the neutrons down to below one volt. We shall now verify this assumption by calculating the mean square distance from the point of origin of the neutrons to the point of absorption.

As we pointed out above (§1), only one or two collisions, and a path of about 50 cm water equivalent, will be needed to reduce the energy

of the neutron to below 4 Mev, this value being again taken for the position of the first excited level of N^{14}.

When the slowing down is done by elastic collisions, i.e., below the first excited level of N^{14}, the mean square distance traveled is

$$(r^2)_{Av}=M_{\text{eff}}\int_{E_2}^{E_1} l^2(E)\frac{dE}{E}, \tag{5}$$

where E_1 is the initial, E_2 the final energy, l the mean free path as a function of the neutron energy and $M_{\text{eff}}=15.6$ (cf. reference 30). In (5) we have again assumed that the scattering is isotropic; if the scattered neutrons go preferentially forward, $(r^2)_{Av}$ will be larger. From the measurements (cf. §1) we have $l\approx 18$ cm water equivalent for $E>E_S$ and $l\approx 2.6$ cm water for $E<E_S$ where the critical energy E_S is unknown but probably lies between 10 and 150 kev. Taking $E_2=2.4kT=0.06$ ev (cf. 4a) we find $[(r^2)_{Av}]^{\frac{1}{2}}$ in cm of water equivalent (see Table II).

The spatial distribution of neutrons produced at height x_0 after the slowing down process will be

$$N(x)dx=\pi^{-\frac{1}{2}}L^{-1}\exp\left[-(x-x_0)^2/L^2\right], \tag{5a}$$

where

$$L=((r^2)_{Av}/3)^{\frac{1}{2}} \tag{5b}$$

is between 72 and 103 cm. For neutrons below 30 Mev initial energy, these figures will be raised by only 10–15 cm when the path above 4 Mev is included. For such neutrons, the results are probably correct within 50 percent.

This calculation shows that the neutrons measured at a given point in the atmosphere have in general originated close to that point. Therefore a measurement of the neutron intensity as a function of altitude is significant for the production of neutrons at various altitudes, provided the production is approximately constant over a distance of one meter of water. That this is so is shown by the fact that the detected neutron intensity changes only by a factor of two per meter of water (cf. §6). Therefore it is legitimate to use Eqs. (2) to (4a) for an approximate determination of the number of neutrons produced as a function of altitude. In these statements neutrons of high energy (>30 Mev) have been excluded. Some evidence on these very fast neutrons can be obtained from the effects observed near the top of the atmosphere (cf. §6).

TABLE II. *Root mean square distance of diffusion in air* $[(r^2)_{Av}]^{\frac{1}{2}}$, *in cm of water equivalent.*

	$E_1=2$ MEV	$E_1=4$ MEV
$E_S=150$ kev	124	135
$E_S=10$ kev	169	178

The approximate proportionality between measured intensity and neutron production is no longer true within a distance of the order L from the upper and the lower boundary of the atmosphere. The effects at the top of the atmosphere are easier to discuss in principle but more difficult to evaluate quantitatively.

If $q(x_0)$ is the number of neutrons produced per gram and sec. at a depth x_0 below the top of the atmosphere, then at a depth x the number per cm^3 of neutrons of velocity between v and $v+dv$ is[31]

$$N(v,x)dv=Ml(v)\frac{dv}{v^2}(2\pi)^{-\frac{1}{2}}L^{-1}(v)\cdot\int\left\{\exp\left(-\frac{(x-x_0)^2}{2L^2(v)}\right)-\exp\left(-\frac{(x+x_0+2l/\sqrt{3})^2}{2L^2(v)}\right)\right\}q(x_0)dx_0. \tag{6}$$

This formula can be obtained from (2) by using standard procedures of diffusion theory. $L(v)$ can be calculated from (5), (5b) and is about 1 meter of water (cf. Table II) for small v.

The actual distribution in depth will depend on the production probability q as a function of x_0. However, irrespective of the altitude dependence of the neutron production, the neutron density must *decrease* with increasing altitude within a distance L from the top of the atmosphere. For if we assume that all neutrons are produced at the very top of the atmosphere, the neutron density will be

$$N(v,x)\sim x\exp\left(-x^2/2L^2\right) \tag{6a}$$

and will thus have a maximum at $x=L$. If the production is at a depth between 0 and L, the maximum of the density will shift only slightly to

[31] H. A. Bethe, Phys. Rev., to appear shortly.

greater depth. Since we know from experiment that the neutron density increases with elevation at the lower altitudes we must expect that a maximum will be reached at a depth greater than $L\approx 1$ meter water below the top of the atmosphere.

The position of the maximum as determined from experiments permits some conclusions on the properties of the neutrons originally produced. (Cf. §7.)

§ 3. Effects near the surface of the earth

Near the surface of the earth, the energy and altitude distribution of the neutrons will again be modified. This modification will depend on the chemical composition of the earth at the point in question. Therefore measurements made at ground are very difficult to interpret and do not give the neutron intensity in the free atmosphere. If one wants to measure this intensity, the essential point is not to go to high altitudes but away from the earth's surface. A distance of at least 1 meter of water from ground is required which necessitates the use of airplanes or balloons. It should be investigated in each case whether the amount of material of the airplane or balloon is ineffective in changing the energy distribution of the neutrons coming from the atmosphere.

In order to show how large the effects of the earth can be we shall investigate a case which is simple enough for mathematical treatment, namely that of an extended water surface. In this case, both water and air will participate in the diffusion process. The theoretical treatment shows that the production of neutrons in water is unimportant for the effects observable near the surface. The most important effects will be due to neutrons which are produced in air and diffuse into the water while they have energies between 4 Mev and 0.06 ev. These neutrons will then not be subject to capture by nitrogen nuclei near E_{capt} (cf. Eq. (4b)) but will continue to be slowed down to thermal energies. Some of the thermal neutrons will then emerge back into the air so that the air near a water surface contains a considerable amount of thermal neutrons, in contrast to the free atmosphere.

If we neglect the production of neutrons in water, the number of neutrons of velocity v in the water per cm^3 is approximately

$$N_W(v,x)dv=\frac{Mq_A l_A}{1+\kappa}\frac{dv}{v^2}\left\{1-\Phi\left(\frac{x}{L_W}\right)\right\}, \quad (7)$$

where x is the depth below the water surface in cm, the subscript A refers to air and W to water, l is an average of the mean free path in g/cm^2 for neutrons between 1 ev and 4 Mev, q the number of neutrons escaping high energy capture per gram and sec., $3L^2$ the mean square distance traveled by a neutron from $\sim$4 Mev energy to velocity v, Φ the error function, and

$$\kappa\approx(3M/2)^{\frac{1}{2}}, \quad (7a)$$

where $M=14.4$ is the atomic weight of an average air atom. From (7a), $\kappa=4.6$; a more accurate calculation (including the effect of oxygen in the water) gives $\kappa=4.1$. L_W is about 20 cm; therefore at more than $\sim$20 cm below the surface, only neutrons produced in the water itself will be found (cf. Eq. (10a)).

In air, the number of neutrons of energy $>E_{\text{capt}}$ becomes

$$N_A(v,x)dv=\frac{Mq_A l_A}{1+\kappa}\frac{dv}{v^2}\left\{1+\kappa\Phi\left(\frac{x}{L_A}\right)\right\}, \quad (8)$$

where x is the height above the water surface. The density of neutrons of $E>E_{\text{capt}}$ in air directly above the water is thus reduced by a factor $1+\kappa\approx 5$ as compared with the free atmosphere. This reduction is of course due to the diffusion of neutrons into the water. It will make itself felt up to heights of the order of L_A, i.e., about 1 meter of water above ground. The density in water exactly at the surface is the same as in air.

The density of *thermal* neutrons immediately above the water surface is

$$N_{\text{th}A}(x=0)=N_{\text{fast}}(x=\infty)\frac{l_{Ws}Z^{\frac{1}{2}}}{2l_{Wf}(1+\kappa)}\times\left(\frac{\pi E_{\text{capt}}}{4kT}\right)^{\frac{1}{2}}, \quad (9)$$

where $N_{\text{fast}}(x=\infty)$ is the total density of neutrons above E_{capt}, as given by (4a); l_{Ws} and l_{Wf} are the mean free paths for thermal and 1-ev neutrons in water ($l_{Wf}/l_{Ws}\approx 2.8$), $Z\approx 200$ is the

average number of collisions of a neutron in water before capture, and $(4/\pi)kT$ is an average energy for thermal neutrons. Evaluation of (9) gives

$$N_{\mathrm{th}A}(0)=0.88N_{\mathrm{fast}}(\infty). \tag{9a}$$

Remembering that the density of fast neutrons is reduced to 20 percent of $N_{\mathrm{fast}}(\infty)$ near the surface of the water, we find that the total intensity is about the same near water as in the free atmosphere (which, of course, is accidental); but more than 80 percent of the neutrons are thermal as against only about 15 percent in the free atmosphere. The number of thermal neutrons decreases very rapidly with the distance from the water surface because of absorption in air; at a distance of about 10 cm water equivalent ($\sim$100 meters of air), the ratio of thermal to fast neutrons will be practically the same as in the free atmosphere, and therefore the total density of neutrons (fast+slow) will be only about one-fifth of that in the free atmosphere.

Inside the water, we have for the density of thermal neutrons

$$N_{\mathrm{th}W}(x=0)\approx N_{\mathrm{th}A}Z^{\frac{1}{2}}\approx 12N_{\mathrm{fast}}(\infty), \tag{10}$$

if we measure at a depth large compared with the diffusion length $L_{Ws}=l_{Ws}(Z/3)^{\frac{1}{2}}\approx 2.5$ cm but small compared with $L_W\approx 20$ cm. In the surface layer, the number of thermal neutrons is smaller because of diffusion into the air; at greater depths, it is again smaller because neutrons produced in air cannot penetrate there. The number of neutrons per cc at great depth is

$$N_W(x=\infty)=q_W\tau_W\rho_W \tag{10a}$$

$$=N_{\mathrm{air}}(x=\infty)\frac{q_W}{q_A}\frac{\tau_W}{\tau_A}\frac{\rho_W}{\rho_A}$$

$$=2.4\frac{q_W}{q_A}N_{\mathrm{air}}(\infty), \tag{10b}$$

where q_W is the number of neutrons produced per gram of water and second, τ is the lifetime of the neutron in the respective medium, and ρ the density. If we assumed that production as well as multiplication and absorption of neutrons were the same in oxygen and nitrogen, the neutron density in water below 20 centimeters would be about twice the density in the free atmosphere; actually, it seems likely that the absorption is greater in nitrogen which would shift the ratio more in favor of the water.

We have investigated the case of water mainly in order to demonstrate the great influence of the earth on the neutron distribution in air. In addition, however, we have shown that measurements in water would be valuable in themselves. Measurements directly below the water surface ($\sim$5 cm) would be rather accurate because of the high density of neutrons in the water (cf. 10) and because it can be most easily ascertained that actually neutrons are counted, by taking the difference of the counts with and without cadmium.

Measurements at greater depths (>30 cm) would be free from the effects of neutron absorption in air (10a) and would therefore furnish a more reliable measurement of the number of neutrons produced. The absorption of neutrons above thermal energies in water can be expected to be very slight, firstly because the neutrons are slowed down very rapidly by collisions with hydrogen, and secondly because the reaction $O^{16}(n,\alpha)C^{13}$ which is the only one giving rise to appreciable capture, is endothermic with 2.2 Mev and will therefore not become important below about 5 Mev neutron energy. It is particularly fortunate that the diffusion of neutrons in water goes only over about 20 cm, i.e., a distance over which the intensity of the cosmic radiation, and therefore the neutron production, do not change very much. A comparison of the number of neutrons in water below 30 cm, and at a point of the same elevation in the free atmosphere, would permit an estimate of the fraction of fast neutrons captured in air.

Experiments in water near its surface ($\sim$5 cm depth) must be made at least one kilometer from shore because part of the diffusion is through air. Experiments at greater depth (>30 cm) do not require this precaution. In salt water, a correction must be made for the capture of neutrons by chlorine.

II. Experiments

§ 4. Thin, unshielded 1/v detector

Let us assume a detector of sensitivity varying as $1/v$ between neutron energies of 0 and 10 kev

and not responding to neutrons of energy higher than 10 kev. This detector will measure the total number, per cm³, of neutrons ($\int N(v)dv$) in this energy region. This number is $q\tau_A\rho_A$ where q is the number produced per gram and second (cf. §4), ρ_A is the density of air, and τ_A the lifetime of a neutron in air.

The activation (number of counts per second) n of the detector is

$$n=q\frac{\tau_A}{\tau_D}\frac{\rho_A}{\rho_D}m_D=q\frac{l_A}{l_D}m_D=q\frac{\sigma_D}{\sigma_A}\frac{\mu_A}{\mu_D}m_D \qquad (11)$$

(τ_D lifetime of neutrons in the detector, m_D mass of the detector, ρ density, μ molecular weight, l mean free paths for capture in g/cm² in air and detector, respectively, σ capture cross section per molecule). If the detector is a gas,

$$m_D=\mu_D V_D p_{0D}/(2.24\times 10^4)$$

(V_D volume of the detector, p_{0D} pressure in atmospheres of the detector gas at 0°), and hence

$$q=(n/V_D)(\sigma_A/\sigma_D)(780/p_{0D}). \qquad (12)$$

The question arises now how a detector of the required properties can be realized. We will discuss how far it can be approximated by an ionization chamber lined with thin boron, or a BF_3 chamber. The following points must be considered. First, the extension of the $1/v$ region in boron is not known. Second, also neutrons of more than 10 kev will produce boron disintegrations and will be counted. Third, neutrons and other particles of the cosmic radiation may produce recoils in the gas of the chamber, which may also influence the count, unless special precautions are taken. Fourth and finally, also slow electrons, produced as secondaries of the soft component of the cosmic radiation may produce effects.

1. The $1/v$-law in boron will certainly hold up to about 10 kev because the levels of the compound nucleus will be fairly wide as for any light element. For the energy distribution (3) this is quite sufficient provided no large maxima of the capture cross section in boron occur at higher energies. The occurrence of maxima which play any role in comparison with the cross section at low energies is much less likely than in nitrogen mainly because the low energy cross section of B^{10} is about 2000 times larger.

2. The capture cross section of B^{10} for high energy neutrons has not been measured but it can certainly not be larger than the geometrical cross section of the nucleus, i.e., about 10^{-24} cm². If the cross section had this value whenever it is greater than the value following from the $1/v$-law, and if there were no capture of neutrons below 4 Mev in air, the contribution of the capture of high energy neutrons in boron would be less than one percent of the slow neutron effect. The capture in air will tend to increase the relative effect of fast neutrons but even under unfavorable assumptions it will be unimportant.

3. Fast neutrons of energy E will produce recoil nuclei of atomic weight M_r with an average energy of $(2/M_r)E$ and a maximum energy of $(4/M_r)E$. In a proportional counter, the recoil nuclei will only be counted when they lose more than a certain minimum energy E_r in the counter. As long as the range of the recoil nuclei is smaller than the dimensions of the counter, they will be counted if their energy is greater than E_r which corresponds on the average to a neutron energy greater than $\frac{1}{2}M_rE_r$. If the boron is used in the form of BF_3 gas, the ratio of the number of recoils to the number of disintegration alphas is approximately[32]

$$n_r/n=\int_{v_r}^{\infty}N(v)\sigma_r(v)dv\Big/\int_0^{\infty}N(v)\sigma_c(v)dv, \qquad (13)$$

where v_r is the velocity of a neutron of energy $\frac{1}{2}M_rE_r$, $N(v)dv$ the number of neutrons in the velocity interval dv, $\sigma_r(v)$ the elastic cross section and $\sigma_c(v)$ the capture cross section of one BF_3 molecule for neutrons of velocity v. Integration gives

$$\frac{n_r}{n}=\frac{q_{Av}}{q}\frac{l_f}{l_s}\frac{\sigma_{rAv}}{\sigma_c(E_{capt})}\frac{1}{2}\log\frac{2E_i}{M_rE_r}, \qquad (14)$$

where l_f and l_s are the mean free paths of fast and slow neutrons in air ($l_f=18$ cm, $l_s=2.6$ cm), $\sigma_c(E_{capt})$ is the capture cross section of boron at

[32] In (13), the effect from the walls of the counter have been neglected. They will in general give a small contribution because the range of the recoil nuclei is small. An exception may occur if the material of the walls is of low atomic weight (e.g., boron) and the gas very heavy. In such a case it would be necessary to know the range-energy relation for the atoms in the wall.

the energy E_{capt} given in (4a), E_i is an energy of the order of the first excited level of N^{14}, $\sigma_{r\text{Av}}$ is an average of the recoil cross section σ_r over the energy region from $M_r E_r$ to E_i, and q_{Av} is an average over the same region of the expression (cf. 3)

$$q(v) = q \exp\left\{ M \int_{v_1}^{v} \frac{\sigma_c}{\sigma_s} \frac{dv'}{v'} \right\}. \qquad (14a)$$

The factor q_{Av}/q takes account of the capture of fast neutrons. In the experiments of one of us[13,14] the value of E_r was certainly more than 40 kev and probably of the order of 100 kev (cf. below). We take $E_i = 4$ Mev, $M_r = 16$ as an average between B and F. The scattering cross section σ_r varies from 23 at 0.15 Mev [25] to 8 at 2.6 Mev.[23,33] Since $M_r E_r \approx 800$ kev, the average σ_r may be about 10 to 12. Then

$$\frac{n_r}{n} \approx 0.2 \frac{q_{\text{Av}}}{q}. \qquad (14b)$$

With reasonable assumptions about the capture of fast neutrons in air, n_r/n will be somewhat smaller than unity. It must be remembered, however, that our assumptions about the constants are very crude.

In any case, the recoils will constitute an appreciable fraction of the total counts, and the exact ratio of recoils to disintegrations cannot be calculated at present. Experimental information on this question can be obtained in two ways. One possibility is the use of a counter sensitive only to recoils (see §6) but in this case there will remain a considerable uncertainty in the ratio of the recoil cross sections as a function of energy between the substance used in the recoil counter and BF_3. The second possibility is to change the value of E_r in the BF_3 counter experiments. Raising of E_r will exclude the weaker recoils but a limit is set by the consideration that E_r must not be greater than the energy lost by a disintegration α-particle in the counter. It would be most advantageous to choose the dimensions of the counter equal to or larger than the range of the α-particles. If this is done, E_r can be raised to about 2 Mev which will exclude all recoils from neutrons below 4 Mev and will leave only the recoils from the rare faster neutrons. Investigation of the count as a function of E_r will give a direct measure of n_r/n which is much more accurate than the crude theoretical estimate in Eq. (14b). It may turn out that such experiments would indicate that a moderate value of $E_r (\approx \frac{1}{2}$ Mev) is sufficient to make the effect of recoils unimportant.

Recoils from particles other than neutrons can be shown to be unimportant. In the first place there will be recoils due to protons produced in the same processes as the neutrons. For the same rate of production, the current of protons per cm^2 and sec. is smaller in the ratio of the ranges (total distance traveled), i.e., about 1 in 10^3. It can easily be seen that the electrostatic interaction of the protons with the nuclei of the gas is unimportant for the production of fast recoils; the nuclear interaction is the same as for neutrons; therefore the number of recoils produced by protons will be negligible.

Secondly, there may be primary fast protons in cosmic radiation. If we assume ten percent of the incident radiation to be protons, we should have 1 proton per cm^2 and min. With a cross section of 10^{-24} cm^2 for boron as well as fluorine, the number of recoils in a BF_3 chamber of $\frac{1}{10}$ atmosphere pressure would be 10^{-5} per cm^3 and min., as compared with an observed number of counts of 0.1 per cm^3 and min. at a depth of 1 meter of water. The same conclusion will also hold for recoils produced by mesons, the meson intensity at its maximum being about 10 per cm^2 and min.[34]

Recoils produced by electrons are also unimportant. It is true that the number of shower electrons is about 1000 per cm^2 and min. at a depth of one meter water. But the cross section for production of boron recoils of more than 100 kev energy is only 1.6×10^{-27} cm^2 if we use the Rutherford formula which has been shown to be approximately correct for the scattering of fast electrons.[35,36] This means a cross section of only 1/1000 of nuclear dimen-

[33] H. Aoki, Proc. Phys. Math. Soc. Japan **21**, 232 (1939).

[34] M. Schein, W. P. Jesse and E. O. Wollan, Phys. Rev. **57**, 68 (1940).

[35] P. M. S. Blackett and J. G. Wilson, Proc. Roy. Soc. **165**, 203 (1938).

[36] W. A. Fowler and Jaquenette Oppenheimer, Phys. Rev. **54**, 320 (1938).

sions, and therefore a negligible number of recoils.

4. Now let us consider the influence of electrons themselves. An electron will be counted if its energy is E_r. The slowest electron which can be counted is one of energy E_r, provided that its range lies entirely within the chamber. The fastest electron to be counted must lose E_r in the chamber. However, if the range of an electron of energy E_r is greater than the maximum dimension of the chamber then no electrons at all will be counted.

Let E_m be the energy of the fastest countable electron; this energy can be determined from the well-known formulae for the energy loss of electrons. Then, if k is the number of shower particles per cm² per min. and N the number of electrons per cm³ of the substance, the number of secondaries of energy between E_r and E_m per cm³ and min. is

$$\frac{2\pi e^4 N k}{mc^2}\left(\frac{1}{E_r}-\frac{1}{E_m}\right). \tag{15}$$

This number is of the same order as the observed effect from neutrons if E_m is about $2E_r$.

In the case of the experiments of one of us, it was ascertained that the counter did not count in the presence of a strong γ-ray source. Since such γ-rays will produce abundant electrons of all energies inside the counter by various processes, we can conclude that slow cosmic-ray electrons were not counted either in our counter. Furthermore, it follows that the range of an electron of energy E_r is greater than the maximum dimensions of the counter, *viz.*, 20 cm (at 0.1 atmos. BF_3). The energy corresponding to this range is 40 kv which we thus establish as a minimum value for E_r in our experiments. (Cf. above, after Eq. (14a).)

We can now proceed to a provisional evaluation of the experiments. From the previous discussion it follows that the chief uncertainty lies in the effect of the recoils produced by neutrons. If we would assume, that the whole measured effect (of 0.1 pulse per cc and min. at 1 m H_2O) is to be attributed to α-disintegrations we would obtain from (12)

$$q=0.05 \text{ neutron/g sec. at 1 m } H_2O. \tag{16}$$

Because of the recoils this figure represents an upper limit to q.

On the other hand, we can derive from (16) a lower limit to q_{Av} (cf. 14) (which in turn is a lower limit to the number of neutrons below 10 Mev produced because such neutrons can only be captured and not be multiplied). Let c_α and c_r be the efficiencies of counting α-disintegrations and recoils, respectively, then the number of counts will be

$$qc_\alpha+q_{Av}c_r.$$

If the experiments are evaluated assuming only α-disintegrations to be counted, the apparent q will be

$$q_{app}=q+q_{Av}(c_r/c_\alpha). \tag{16a}$$

But since $q<q_{Av}$

$$q_{Av}>q_{app}/(1+c_r/c_\alpha), \tag{16b}$$

where c_r/c_α has the approximate value 0.2 according to (14b).

§ 5. Measurements using hydrogenic material together with a 1/v-detector

A considerable increase of the measurable effects can be achieved by using hydrogen either surrounding or otherwise combined with the detector. Then the hydrogen slows down the incident neutrons so that they can be more easily captured by the detector. Experiments of this type were carried out by v. Halban, Kowarski and Magat. They exposed a vessel filled with ethyl bromide C_2H_5Br to the cosmic radiation and measured the bromine activity by the method of isotope separation.[16] The vessel used was a flat box of 10 cm thickness, which, by number of hydrogen atoms, is equivalent to 6 cm of water.

In order to discuss experiments of this type we must know how many incident neutrons of a given energy E_0 will be slowed down sufficiently in the vessel so that they may be captured. Many of the neutrons will be scattered in such directions that they will leave the vessel again on the same side from which they entered, and others will leave on the far side. The number of neutrons which get lost in this way before being slow enough for capture, will depend on the

shape of the vessel and will increase with increasing number of collisions necessary for slowing down the neutron, i.e., with increasing E_0.

For a flat vessel of thickness D and infinite extension in the two other directions, the probability that an incident neutron of initial energy E_1 is still in the vessel when it has been slowed down to E_2, is

$$p=4\pi^{-1}\sum_{n\ \text{odd}}\frac{1}{n}\sin\frac{\pi n a l_H}{D+a l_H}\times\exp\left(-\frac{1}{6}\frac{n^2\pi^2(r^2)_{Av}}{(D+a l_H)^2}\right), \quad (17)$$

where l_H is the mean free path between two collisions with hydrogen (1.5 cm in ethyl bromide), $a=3.14$ is a constant connected with the diffusion of neutrons in ethyl bromide, and $(r^2)_{Av}$ the mean square distance traveled from energy E_1 to E_2. The index n takes all odd integral values but in most cases it is sufficient to consider the term $n=1$. Equation (17) is valid if the thickness D is large compared with $\frac{1}{2}al_H\approx 2.35$ cm ethyl bromide which is not very well fulfilled for the dimensions used in the experiments of v. Halban, Kowarski and Magat ($D=10$ cm). With these dimensions, the probability that a neutron reaches thermal energy in the vessel without being scattered out,[37] is about 87 percent for an initial energy of 1 ev, 65 percent for 100 ev, 40 percent for 10^5 ev, and 16 percent for 1 Mev. It might be thought desirable to increase the thickness of the vessel in order to make $D\gg\frac{1}{2}al_H$. However, faster neutrons ($>10^5$ ev) will then have a considerable probability of being slowed down to the thermal region, and for such neutrons (17) is no longer valid because of the rapid variation of l_H with energy.

If the energy distribution of the incident neutrons is given by (2), the total number of neutrons slowed down in the vessel to thermal energies is

$$N_{th}=\pi^{-3}Mql_AS\left(\frac{D+a l_H}{b l_H}\right)^2\sin\frac{\pi a l_H}{D+a l_H}\times\left\{\exp\left(-\frac{1}{6}\frac{\pi^2(r^2)_{Av}(E_{capt})}{(D+a l_H)^2}\right)-\exp\left(-\frac{1}{6}\frac{\pi^2(r^2)_{Av}(E_1)}{(D+a l_H)^2}\right)\right\}, \quad (18)$$

where l_A is the mean free path in air, $b=0.82$ is a factor taking account of the collisions with carbon and bromine in the C_2H_5Br, S is the surface of the flat vessel (on one side) and $(r^2)_{Av}(E)$ the mean square distance traveled by a neutron of initial energy E before it is captured in the vessel. E_{capt} is given by (4a), and E_1 is approximately the energy at which the mean free path $\frac{1}{2}al_H$ becomes larger than D, i.e., about 1 Mev. To obtain Eq. (18) it must be assumed (1) that the mean free paths in the substance and in air are constant for all initial energies which contribute appreciably to the activity produced in the vessel and (2) that there is no appreciable capture in air for neutrons of these energies. We have mentioned above that the probability to be captured in the vessel used by v. Halban *et al.* is about $1/e$ for a 100-kev neutron and falls rather rapidly at higher energy. Now if the mean free path in air, l_A, did not increase with energy, the energy distribution of the neutrons incident upon the measuring vessel would be as dE/E, and then neutrons above 100 kev would give only a small contribution to the number of neutrons detected. Actually we know that l_A *does* increase with energy, and we know that this increase takes place below 150 kev (§1). This will make the neutrons of higher energy more important, and the necessary correction to (18) will be the greater the lower the energy E_S at which the mean free path in air increases to its high energy value. The importance of high energy neutrons will be further enhanced if there is strong capture of neutrons in air for such energies which are still important for the effects detected, because such capture will increase the number of fast neutrons in air relative to the slow ones.

The uncertainties at high energies will be even

[37] In ethyl bromide, the capture does not occur immediately after the neutrons are slowed down to thermal energies. The capture cross section of Br is unknown but probably smaller than 10×10^{-24} cm^2. This would mean that at least 25 elastic collisions with H occur before capture. The probability that a neutron diffuses out after reaching thermal energy is therefore at least 5 percent. An upper limit of 30 percent is set by the capture in hydrogen.

more important for larger thicknesses D because then faster neutrons will contribute more to the bromine activity. Moreover, Eq. (17) will then become invalid because of the variation of l_H with energy.

Another problem is the behavior of slow neutrons in ethyl bromide. We have assumed thus far that only thermal neutrons are appreciably captured. However, it is also possible that the lower resonance levels of bromine capture an appreciable number of neutrons coming from high energies; in this case, the necessary $(r^2)_{Av}$ for a fast neutron would be reduced and its probability p of capture correspondingly increased.

In spite of these many uncertainties we shall assume (18) to be approximately valid. It is then permissible to replace the first exponential in the curly bracket by 1 and the second by zero, further to replace the sine by its argument and to neglect al_H compared with D. Then (18) reduces to[38]

$$N_{capt}=0.47MqVl_A/l_H, \tag{18a}$$

where $V=SD$ is the volume of the vessel. This simple formula is valid if

$$\tfrac{1}{2}al_H \ll D \ll [(r^2)_{Av}]^{\frac{1}{2}}.$$

Since $(r^2)_{Av}$ is only 5 times $\frac{1}{2}al_H$, this condition is never very well fulfilled but, due to a cancellation of corrections, the difference between (18) and (18a) is only 2 percent for ethyl bromide and $D=10$ cm.

For thicknesses $D\approx(r^2)_{Av}$ Eq. (18) must be used instead of (18a). For $D\gg(r^2)_{Av}$, the number of neutrons captured will become proportional to the surface rather than the volume of the vessel. However, (18) is then no longer correct, because of the uncertainties at high energies discussed above. For still larger thicknesses, we get again a volume effect due to the production of neutrons in the vessel itself; if we assume this production to be q_V per gram and sec., we obtain in this limit:

$$N_{capt}=q_V V\rho_B \tag{18b}$$

(ρ_B the density of ethyl bromide) which is about 7 times smaller than (18a) if we assume $q=q_V$.

[38] It should be noted that in this formula l_A is measured in g/cm² and l_H in cm.

An infinite flat vessel cannot be realized in practice. For a large flat vessel, (18) will still be approximately valid because there will be a compensation of the neutrons which diffuse out by the side walls, and those which come in from the side. For a sphere, the theory gives one-half of the expression in Eq. (18), with D replaced by R. For $l_H 3^{\frac{1}{2}} \ll R \ll [(r^2)_{Av}]^{\frac{1}{2}}$ the final result is then $\frac{3}{4}$ of Eq. (18a).

V. Halban, Kowarski and Magat[16] found about 100 neutrons per cm² and minute at an altitude of 9500 m, corresponding to 3 meters of water pressure. According to (18) this gives $q\approx 0.010$ neutron per gram and second.

The value of q deduced from these experiments is again an upper limit to the actual q because of the effects discussed after Eq. (18). The apparent values of q deduced here and in Eq. (16) are, of course, influenced in different ways by the capture of neutrons in air, etc.

Other arrangements belonging to this category are $1/v$ detectors surrounded by paraffin or by borax. The latter type has been used for the measurement of cosmic neutrons.[10–12] It is, however, less apt to give interpretable results than the bromine method. Some discussion of it will be found in reference 31. In contrast to statements in the literature it must be pointed out, that the absorbing effect of a borax shield is not confined to thermal neutrons. Irrespective of the energy dependence of its sensitivity such an arrangement will give the correct dependence of q on altitude, provided the energy distribution of neutrons does not depend on altitude, i.e., at distances larger than about 1 m water equivalent from the top of the atmosphere as well as from the ground. So far, all the measurements available have been carried out on the ground.

§ 6. Recoil measurements

The investigation of neutron recoils may yield information about the energy distribution of faster neutrons. Such measurements can be made using ionization chambers with linear amplifiers, proportional counters or photographic plates. In evaluating the experiments it must be remembered that the measurements give directly only the energy distribution of the recoil atoms, and that a neutron of energy E produces recoils ranging from zero energy to $(4/M_r)E$. The energy

distribution of the neutrons can therefore only be obtained by a differentiation of the distribution of recoils. Unless the range distribution of the recoils is measured directly by a linear amplifier, it must again be deduced from the number of recoils as a function of the bias which requires another differentiation. A similar evaluation is necessary for photographic plates. The present experiments[39] do not yet allow an analysis along these lines.

The energy distribution which could be deduced from recoil measurements will not give much relevant information for energies below the first excited level of N^{14}, because for these energies the neutron distribution will be determined mostly by the mechanism of slowing down in nitrogen which could more adequately be investigated by laboratory measurements of the cross sections for various energy neutrons. The number of high energy neutrons is very small; moreover measurements of their energy distribution could only be made with heavy recoil nuclei because if hydrogen were used the number of recoil protons from fast neutrons would only be of the same order as the number of protons directly produced by the cosmic radiation.

III. Discussion of the Experimental Results

§ 7. The altitude dependence

We have shown at the end of §2 that the neutron intensity must decrease with altitude at least within a distance L from the top of the atmosphere. The experiments of one of us show, on the other hand, an increase with altitude up to 1 meter water pressure. This means that L must be 1 meter water or less for most of the neutrons observed at high altitudes. In §2, we have found that L is approximately 1 meter for a neutron of initial energy below 30 Mev. Therefore we can conclude that either (1) the neutrons observed at high altitudes are mostly produced with energies below 30 Mev, or (2) the mean free path for inelastic collisions is of the same order for neutrons of higher energies than 30 Mev as for slower neutrons.

Which of the two conclusions is correct cannot be decided. There is no *a priori* argument against either of them; but older theories of nuclear forces predicted[18] a considerable increase of the mean free path for energetic neutrons (above 100 Mev). If these theories were proved correct we should have to draw conclusion (1).

We cannot draw any similar conclusions about the neutrons observed at lower altitudes. E.g., it would be entirely possible that these neutrons are partly or wholly produced by very energetic neutrons which themselves originated near the top of the atmosphere. If such energetic neutrons have a long range, as predicted by the theories of Heisenberg and Williams,[18] they could penetrate to lower altitudes and there produce slower neutrons which then diffuse as discussed in §1, 2. If this should be the origin of the neutrons at lower altitude, we should have to draw conclusion (1) about the neutrons observed at high altitude; and since the neutron intensity is much smaller at lower altitude, we could then say that most of the neutrons produced altogether have moderate initial energies (100 Mev, say). In any case, only a small fraction of the neutrons produced can have long mean free path.

The altitude dependence of neutron intensity permits some further conclusions on the neutron production. According to the experiments of one of us,[15] the neutron intensity increases by about a factor two for each meter of water. This figure may be considered as safe from about 4 to 1 meter water. This result shows that the neutrons cannot be produced by mesons because, according to Schein, Jesse and Wollan,[34] the meson intensity increases only by a factor of 11 over the whole atmosphere. Since the increase seems fairly uniform at the lower altitudes,[40] an increase by a factor of only about 2–2.5 is to be expected from 4 to 1 meter. On the other hand, the soft component of cosmic radiation (electrons +photons) increases with altitude about as much as the neutron intensity.

§ 8. Number of neutrons. Energy considerations

We have shown that there are many uncertainties in the evaluation of the present experiments on neutrons in cosmic radiation, and that they might be to a large extent eliminated by somewhat different experimental arrangements (§4, §3) and by laboratory measurements on the

[39] S. A. Korff, Phys. Rev. **56**, 1241 (1939).

[40] Rossi, Hilberry and Hoag, Chicago Meeting, No. 10 (1939).

interaction of neutrons with nitrogen. At the present time we can only give estimates of the number q of neutrons which escape capture at high energies. The number of neutrons produced originally is difficult to estimate at present (§1, 4). We can only say that q represents a lower limit to the actual number q' of neutrons produced.

The measurements of one of us (S.A.K.) with BF_3 counters give a neutron production 0.05 neutron per gram and second at one meter of water (§4); this figure represents an upper limit to q because part of the counts in the BF_3 chamber will be due to recoil nuclei rather than to boron disintegrations. The evaluation of the measurements of v. Halban, Kowarski and Magat with ethyl bromide at three meters of water gives 0.010 neutron per gram and second. From the experiments with BF_3 counters, it follows that the number of neutrons increases with elevation by about a factor of 2 per meter of water, so that the BF_3 measurements give about the same result as the C_2H_5Br experiments. In view of the many uncertainties, this agreement must be considered as accidental.

The total number of neutrons produced per second in a column of 1 cm² cross section is

$$Q=100q'(1\text{ meter})\int_0^\infty e^{-0.7(x-1)}dx, \qquad (19)$$

where x is the depth in meters of water from the top of the atmosphere. It is uncertain whether the production should be assumed to increase at the normal rate in the top meter as has been assumed in (19). If we take one-half of the value (19) for the top meter, and also replace q' by q we shall certainly get a lower limit to Q; *viz.*,

$$Q>10\text{ neutrons/cm}^2\text{ sec.} \qquad (20)$$

It is interesting to investigate the energetic role of the neutrons. If we assume that the initial kinetic energy of the neutrons is about 10 Mev and if we add another 10 Mev for the binding energy of the neutron in the nucleus it came from, we find that a total of more than 200 Mev must be spent per cm² and sec. to produce neutrons. This is one-twelfth of the total energy[41] spent by the cosmic radiation in producing ionization. However, it would be difficult to measure the total energy spent in *producing* neutrons; it is much more important to know how much the neutrons themselves contribute to the ionization. This quantity will be much smaller, mostly because the binding energy of the neutron in the nucleus it came from will not be transformed back into "visible" energy; the neutrons disappear finally by the $N^{14}(n,\alpha)B^{11}$ or the $N^{14}(n,p)C^{14}$ reaction so that much of the energy resides finally in protons or B^{11} nuclei. Thus cosmic radiation serves to build up nuclei of high internal energy. Only the kinetic energy of the neutrons and the small energy evolved in the n,p process (0.7 Mev) will be transformed into ionization, by producing recoils and by exciting nitrogen nuclei which subsequently emit γ-rays. But even part of the kinetic energy of a fast neutron (>8 Mev) will be consumed in disintegrating N and O nuclei by nuclear reactions in which more than one particle is emitted. Thus the energy which is actually transformed into ionization may well be as low as 5 Mev per neutron, i.e., 50 Mev per cm² and sec. when the figure of Eq. (29) is assumed, or 2 percent of the whole energy in the cosmic radiation. This figure is of course as uncertain as all the figures on neutrons in cosmic radiation.

The production of neutrons has been compared with that of protons by C. G. and D. D. Montgomery,[42] and it seems indeed likely that these particles are produced in the same process. From measurements of Neddermeyer and Anderson on Pike's Peak,[43] we can estimate that there is about 1 proton per 300 lightly ionizing particles. The number of the latter is about 0.2 per cm² and sec. on Pike's Peak. Therefore, if R is the average range of the protons in cm of standard air, the number produced per gram and second is about

$$\frac{0.2}{300R\times 1.2\times 10^{-3}}=\frac{0.6}{R}$$

(1.2×10^{-3} is the density of standard air). For $R=1$ meter (10-Mev protons) this would give

[41] I. S. Bowen, R. A. Millikan and H. V. Neher, Phys. Rev. **53**, 855 (1938).

[42] C. G. and D. D. Montgomery, Rev. Mod. Phys. **11**, 255 (1939).

[43] S. H. Neddermeyer and C. D. Anderson, Phys. Rev. **50**, 263 (1936).

6×10^{-3} proton/g sec. If we assume the neutron intensity to decrease by a factor 2 per meter water, the neutron production at 6 meters water would be about 10^{-3}/g sec. The agreement is sufficient in view of the uncertain data.

Our considerations show that the total number of neutrons is certainly considerable, and of the same order of magnitude as the total number of electrons or quanta in cosmic radiation. Thus if the neutrons are produced by quanta, each quantum must produce on the average about one neutron. Of course, it is likely that an energetic quantum when it disintegrates a N or O nucleus, produces several neutrons at once so that not every quantum will be concerned in the production process. Moreover, it is as yet unknown whether quanta or other particles are responsible for the neutron production.

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Excitation of the 455-Kev Level of Li^7 by Proton Bombardment

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The yield of gamma-rays from a thin film of lithium bombarded by protons has been investigated up to 2.08 Mev, by recording both single and coincidence counts in G-M tubes. Above 0.85 Mev proton energy most of the radiation is shown to be due to excitation of the 0.455-Mev level of Li^7 without permanent capture of the proton. The yield of 17-Mev radiation does not drop to zero above 0.440 Mev. It falls to a low value and remains approximately constant up to 1.6 Mev. The absorption coefficient in lead for the soft gamma-radiation from lithium was compared to the absorption coefficient of annihilation radiation from N^{13}. A value of 0.459 Mev was obtained for the energy of the soft lithium radiation by assuming monochromatic radiation of 0.511 Mev from N^{13}. This close agreement with the expected energy indicates that not over 10 percent as many 0.28-Mev quanta as 0.511-Mev quanta are present in the radiation from N^{13}.

INTRODUCTION

THE excitation of gamma-rays from lithium by proton bombardment was studied three years ago at this laboratory using protons in the energy region 0.4 to 1.9 Mev.[1]

A gamma-ray resonance of lithium had previously been established for protons of 0.440 Mev energy by Hafstad, Heydenburg and Tuve.[2] These gamma-rays were found by Lauritsen and his colleagues to have an energy of approximately 17.5 Mev. The previous work here showed the presence of considerable radiation caused by protons above 0.85 Mev, but no measurements were made of the energy of this radiation.

The work reported upon in this paper shows that most of the radiation above 0.85 Mev proton energy is due to the excitation of an energy level of Li^7 which was found by Rumbaugh, Roberts and Hafstad[3] to be 0.455 ± 0.015 Mev above the ground state. Their paper will hereafter be referred to as RRH.

While this paper was being written, Fowler and Lauritsen[4] reported obtaining from lead absorption measurements similar to ours, a value of 0.495 ± 0.025 Mev for the energy of the radiation due to 1.08- and 1.29-Mev protons on lithium. They attribute this to excitation of the 0.455-Mev level, but have no explanation for the high value they obtained for the gamma-ray energy.

Our values for the absorption coefficient of the radiation agreed with those of Lauritsen, but when corrections were applied for a hard component, the energy obtained for the soft component agrees with the value expected from

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[1] Herb, Kerst and McKibben, Phys. Rev. **51**, 691 (1937).
[2] Hafstad, Heydenburg and Tuve, Phys. Rev. **50**, 504 (1936).
[3] Rumbaugh, Roberts and Hafstad, Phys. Rev. **54**, 657 (1938).
[4] W. A. Fowler and C. C. Lauritsen, Phys. Rev. **56**, 841 (1938).