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Recent Studies at High Elevations

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Certain phases of counter technique are reviewed. The conditions necessary to make and operate reliable proportional counters are discussed. It is shown that certain mixtures of gases, notably argon-carbon tetrachloride and argon-boron trifluoride, when used in counters give these the property of producing large pulses over considerable voltage ranges below the threshold. The size of the pulse (in volts) will be roughly proportional to the amount of ionization produced in the counters by the passage of the ionizing particle being studied. Because of this proportionality, these counters can, for example, distinguish between alpha- and beta-rays over considerable voltage ranges without the necessity of much vacuum-tube amplification. Neutron counters are made using BF_3 gas, the B^{10} (n, α) Li^7 reaction producing the alpha-particle which is detected by the proportional counting procedure described. Flights have been made with instruments carried by small balloons and using single Geiger counters. The data were transmitted from the balloon to the ground station by automatic short wave radio. Such flights show no diurnal effect in the cosmic radiation at great elevations ($\frac{1}{2}$ meter of water) as large as four percent of the total cosmic-ray intensity. Further, the flights show that no increase in the ionization as great as two percent of that due to the cosmic-ray intensity takes place at an altitude of 20 km, which can be correlated with a solar flare, although this same flare produced abundant ionization below 80 km and caused a radio fade-out. The absorption coefficients for the flare radiation are calculated. Flights were made with neutron counters and the radio-balloon method, which yielded measurements of the neutron intensity as a function of elevation. It is found that the neutrons increase rapidly with elevation, the rate of increase being faster than that of the total intensity of the cosmic radiation, and approximately equal to that of the big bursts. The production of neutrons in the atmosphere by the cosmic radiation is discussed, and a production cross section of 10^{-25} sq. cm is computed.

1. Geiger Counter*

CONSIDER a Geiger counter connected to some type of control and recording circuit, and with sufficient voltage applied to cause it to be in a sensitive state. Further, suppose that an ionizing particle passes through it. Then, as has been shown by Danforth and Ramsay,[1] the probability that the counter will count is equal to the probability that an ion will be formed in it. As soon as one ion is formed in the counter, it is swept by the applied field toward the central wire. As it moves, it produces additional ions by collision, and finally the counter breaks down into a self-sustaining discharge which must then be quenched by a resistor or by a vacuum tube circuit. The exact mechanism of the counter discharge is not understood, although various theories have partially explained the phenomenon.

We will now discuss the efficiency of a counter. This efficiency we will define as the probability that, when a cosmic-ray particle or other ionizing particle passes through the counter, a count will be registered. We exclude photon counters by this definition. It is evident that if on the average x ions are formed along the path of a particle through a counter, the probability that no ions will be formed is e^{-x} and hence[2] we may write the efficiency E as

$$E=1-e^{-x}=1-e^{-nslp/p_0} \tag{1}$$

where s is the specific ionization of the particle under consideration in the gas used in the counter at pressure p_0, p is the actual gas pressure in the counter, l is the average path length through the counter and n is the number of simultaneous particles (in the case of a shower or burst) passing through the counter. For cylindrical counters exposed to isotropic radiation we may, without serious error, take l as the diameter of the cylinder. The exact expression for l in the general case of a cylindrical counter has not been computed and appears to be a complicated

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* At the request of certain members of the Chicago Cosmic-Ray Symposium, 1939, the above review of certain considerations regarding Geiger counters is given. This review is not intended to be complete. For a further discussion of counters, control circuits and errors met with in counter measurements, the reader is referred to the bibliography which accompanies this review.

[1] W. E. Danforth and W. E. Ramsay, Phys. Rev. **49**, 854 (1936).

[2] S. A. Korff and W. E. Danforth, Phys. Rev. **55**, 675A (1939).

function. However, Swann[3] has calculated the exact value for certain cylindrical vessels.

Equation (1) and specifically the dependence of E on s, l and p have been experimentally verified independently and nearly simultaneously by Cosyns[4] and by Danforth and Ramsay.[1] For argon, s was found to be 29, for air 21, and for hydrogen 5.9 ions per cm per atmos. Hence we may calculate E, assuming l to be 2, and n to be 1. For argon, $E=0.997$ for $P=0.1$ atmos. and 0.99997 for $P=0.2$ atmos. For hydrogen $E=0.70$ for $P=0.1$ atmos. and 0.91 for $P=0.2$ atmos.

It will be seen that the hydrogen counter filled to 7.6 cm or 0.1 atmos. is not very efficient, in contrast to the argon counters. The excellent agreement between the calculations and the observation suggests that, for cosmic-ray particles in general, the ejection of secondary electrons from the walls of the counter will be negligible.

The efficiency is measured experimentally by arranging a vertical quadruple coincidence set, the top and bottom counters being small compared to the central pair in order to define the path length l through the latter with some precision. The quadruple counting rate is then determined by using cosmic-ray coincidences. Next one of the central two counters is disconnected and the triple coincidence rate measured. The ratio of triple to quadruple coincidences will be the efficiency.[5]

The construction of Geiger counters should be undertaken with the above considerations in mind. It is obvious that the formation of a single ion by any agency other than the particle measured will produce a "spurious" count, and that the background introduced by such counts will fluctuate in an unpredictable manner, and hence tend to vitiate quantitative measurements. For example, sharp points or dirt on the wire or cylinder can produce such spurious counts. A technique has been described by Locher[6] for making counters which shall be free from such effects. This consists briefly of (a) thoroughly washing the counter with cleaning solution, (b) thoroughly outgassing it by baking under vacuum and flashing the central wire, (c) oxidizing or reducing the cylinder, and (d) pumping again and then filling. Further, as he has emphasized, it is essential to avoid passing a heavy current through a finished counter, for such heavy discharges frequently damage the central wire and often produce projections easily visible in his microphotographs which will initiate spurious discharges. Counter control circuits which permit the flow of heavy currents should therefore be avoided.

Once a discharge has been initiated by the formation of an ion, it must be quenched in order that the tube shall be restored to a sensitive condition. This may be accomplished by the use of a quenching resistor or an equivalent vacuum tube control circuit. Such arrangements have been discussed in detail elsewhere.[7]

Certain substances, if added to the filling gases generally used in counters, appear to quench the discharge inside the counter and the counters so filled have been called "self-quenching" counters. The exact mechanism of operation of these counters has never been adequately explained, although extensive studies have been carried out, especially by Trost.[8] He has found that nearly any organic liquid will produce such "quenching" action, and has obtained especially stable operation with good plateaus for a filling with 6 cm argon plus one cm ethyl alcohol. It should be pointed out that the argon-alcohol counters are not, in general, true proportional counters (see below) but are actually operating above the threshold. The analysis given below for proportional counters does not apply in this case.

As has been pointed out by May,[9] statistical fluctuations in the discharge in an ordinary counter permit the counter to be extinguished by momentarily dropping the counter voltage below the critical maintaining potential. Now if the organic vapors, by forming negative ions which

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[3] W. F. G. Swann, J. Frank. Inst. **216**, 559 (1933).

[4] M. Cosyns, Bull. Tech. de l'Assoc. Ing. sortis de l'Ecole Polytech. de Bruxelles (1936).

[5] The obvious procedure, to measure the ratio of double to triple coincidences, is subject to a much larger shower correction than the ratio of triple to quadruples.

[6] G. L. Locher, Phys. Rev. **55**, 675A (1939).

[7] T. H. Johnson, Rev. Mod. Phys. **10**, 193 (1938); John Strong, *Procedures in Experimental Physics* (Prentice-Hall, 1938); S. Werner, Zeits. f. Physik **92**, 705 (1934); H. V. Neher and W. W. Harper, Phys. Rev. **49**, 940 (1936); H. V. Neher and W. H. Pickering, Phys. Rev. **53**, 316 (1938); I. A. Getting, Phys. Rev. **53**, 103 (1938); T. H. Johnson, Rev. Sci. Inst. **9**, 218 (1938).

[8] A. Trost, Zeits. f. Physik **105**, 399 (1937).

[9] A. N. May, Proc. Phys. Soc. London **51**. 26 (1939).

attach the positive ions in the discharge, introduce larger fluctuations, then the discharge may be quenched with a lower resistance. The pulses produced by these counters, since they represent a true breakdown into a discharge, will in general be of roughly the same size regardless of the number of ions formed in the events which initiated them.

2. SPECIAL TYPES OF COUNTERS

For certain measurements it is desirable that the size (in volts) of the pulse given by a counter shall be proportional to the amount of ionization produced in that counter by the ionizing particle passing through it. This condition may in general be realized by operating the counter below its threshold voltage. The threshold is defined as that voltage at which, in the absence of a resistance, the counter breaks down into a continuous, self-sustaining discharge. If the counter is operated below this threshold, ions produced in the gas of the counter by the passage of ionizing particles will be swept to the central wire by the field due to the applied voltage. These ions will produce additional ions by collision, and the number of additional ions thus produced will be a function of the voltage. An "avalanche" of ions arrives on the central wire. Since we are dealing with sub-threshold operation, there is no self-sustaining discharge following the production of such an avalanche. The size P of the pulse in volts produced on the central wire will be:

$$P=(1/c)Nf(v)=\sigma lpnf(v)(k/c), \tag{2}$$

where c is the capacity of the wire, tube grid and connecting leads, N is the number of ions formed along the track of the ionizing particle passing through the counter, σ is the specific ionization characteristic of the particle in the gas employed (ions per cm per atmos.), l is the length of the path through the counter, p is the pressure in atmospheres of the gas in the counter, k is the electronic charge in volts, n is the number of simultaneous particles passing through the counter in the case of a shower or burst, and $f(v)$ is the "gas amplification," or the average number of additional ions produced by one ion as it is swept toward the central wire by the voltage v. Statistical fluctuations in $f(v)$ may be quite large. They are especially large in counters with the usual argon and mixed fillings when operated just below the threshold. For counters operated above the threshold this analysis does not apply, since, in effect, $f(v)$ becomes infinite.

In most gases $f(v)$ is a rapidly varying function of v. For example in counters filled with argon, argon-hydrogen, argon-oxygen, noen-hydrogen or hydrogen, if N be kept constant, P will drop from 1 volt or more to less than 0.01 volt as the counter voltage v is lowered by only about two to five volts. Moreover, v must be kept very near the threshold in counters with these fillings in order that P shall be large, and hence a small accidental increase in voltage may result in a breakdown of the counter. At lower values of v, the pulse size P is so small as to require considerable vacuum-tube amplification. Hence with the gases mentioned, stable proportional counting and freedom from extremely critical voltage control can only be achieved with the aid of high gain amplifiers.

However, certain gases have a characteristic $f(v)$ which is a slowly-varying function of v. Examples of such gases and gas mixtures are argon-carbon tetrachloride, argon-boron trifluoride, and hydrogen-methane-carbon monoxide (illuminating gas). Counters filled with these gases produce pulses of size $P>0.01$ volt over ranges of v, in many cases, of two hundred volts below the threshold. Characteristic curves of argon-hydrogen and of argon-carbon tetrachloride counters are shown in Fig. 1. The argon-hydrogen counter is operated as an ordinary Geiger counter with a quenching resistance. The curve for the argon-carbon tetrachloride filling of the same counter is made with no quenching resistor other than the 1-megohm gridleak of the vacuum-tube amplifier. The carbon tetrachloride counter was exposed to both alpha- and beta-rays. The right-hand portion of the curve and the dotted extension represent the counting rate due to beta-rays, while the left-hand extension is due to alpha-rays. No beta-rays are counted below 2035 volts. It will be seen that the counting rate of the carbon tetrachloride counter falls off much more slowly with voltage than does that of the argon-hydrogen counter. Because of the statistical fluctuations in the collision process, exact proportionality between P and N will not be obtained while a large amount of gas-amplification (large $f(v)$) is used. However, the discrimination of the argon-carbon tetrachloride counter is sufficiently good so that counts due to alpha-rays may be distinguished from those due to beta-rays over a range of some 200 volts.

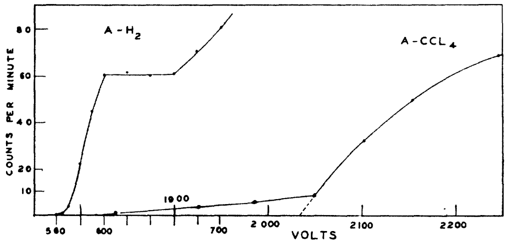

FIG. 1. Characteristic curves of counters. The curve on the left is that of a nonproportional Geiger-Müller counter, using a quenching resistance of 10^9 ohms. The threshold of this counter is at 575 volts. The curve on the right is for the same counter after 1 cm of CCl_4 has been added. The voltage scales are overlapped but different. The CCl_4 counter is exposed to both alpha- and beta-rays. Below 2035 volts it counts alpha-particles but no beta-particles. The right-hand portion of the curve and the dotted extension is the beta-particle response curve. The quenching resistance is 10^6 ohms in this case.

The operation of the BF_3 counters in detecting neutrons has been previously described.[10] A neutron entering such a counter may collide with a B^{10} nucleus and will then produce an alpha-particle by the $B^{10}(n, \alpha)Li^7$ reaction. The alpha-particle is of about the right energy (roughly 600 kev) to ionize heavily along its track. Since BF_3 gas produces a counter with the same characteristic slow variation of $f(v)$ with v discussed above in the case of CCl_4, the proportional counting method described may be used. The pulses due to the (n, α) reaction when amplified by a single 6C6 tube are of sufficient size to operate a recorder, and to permit discrimination between the alpha- and beta-pulses over a sub-threshold counting range of 200 volts below the beta-ray starting potential.

The efficiency, E, of such a counter is defined as the probability that an alpha-producing reaction will take place when a neutron passes through the counter. In the special case, when it is desired to measure the current of thermal neutrons, this may be expressed as

$$E = Np\sigma_B c_B l, \tag{3}$$

where N is the Loschmidt number, p the pressure in the counter in atmospheres, σ_B the thermal neutron capture cross section of B^{10}, l the average length of path through the counter, and c_B the concentration of B^{10} in the BF_3 used. If we take $\sigma_B = 3000 \times 10^{-24}$ cm^2, Np as 2.7×10^{18}, l as 2 cm and c_B as (1/6) for the isotope ratio B^{10}/B^{11} in commercial BF_3, then $E = 3 \times 10^{-3}$. This figure is calculated for a counter of size and filling which has been found convenient in experiments described below. It is obvious that the efficiency can be improved by increasing the counter size and the BF_3 pressure (p). However, practical considerations will generally limit E.

This efficiency has been experimentally checked by (a) exposing the counter to a known intensity of thermal neutrons, and observing the counting rate. The chief uncertainty in this method lies in the lack of precision in our knowledge of the thermal neutron intensity. Also, (b), the efficiency has been measured by comparing the counting rate of this counter at a fixed distance from a neutron source with the counting rate of a silver cylinder counter, the silver having been activated by exposure to the same neutron source. The silver cross section[11] may be assumed to be known with some accuracy. The chief source of error in this comparison will arise from the difficulty of calculating exactly the path distribution of the beta-rays emitted from the radioactive silver. However, both methods check the above calculation surprisingly well.

These considerations do not apply for the measurement of neutrons other than thermal. Inasmuch as the capture cross section of B^{10} decreases with increasing neutron energy according to the familiar $1/v$ law, it is obvious that at energies of roughly 10^4 volts the capture cross section will be roughly equal to the scattering cross section. At neutron energies above 10^4 volts, recoil nuclei will produce large spurts of ionization, and hence will be counted. The calculation applicable to the case of the measurement of the neutrons in the cosmic radiation is given below.

It should be pointed out, however, that these counters measure the neutron density (neutrons per cc) if they are exposed to a flux of neutrons of

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[10] S. A. Korff and W. E. Danforth, Phys. Rev. **55**, 980 (1939).

[11] Livingston and Bethe, Rev. Mod. Phys. **9**, 340 (1937).

various energies within the $1/v$ region, and not neutron currents (neutrons per cm^2 per sec.). The number of counts recorded is independent of velocity since the $1/v$ law changes both the detecting sensitivity and the density at the same rate. Hence the neutron current cannot be calculated unless the velocity is known. Since the $1/v$ region for the B^{10} reaction extends up to about 10^4 volts, the counters measure the density of neutrons at much greater than thermal energies. The counting rate of this counter, n counts per second, in the presence of a distribution of neutrons of all energies within the $1/v$ region will then be:

$$n = \rho\sigma_B v_B N p_B c_B V, \tag{4}$$

where σ_B is the capture cross section of B^{10} for neutrons of velocity v_B, N is the Loschmidt number, p_B is the pressure of BF$_3$ in the counter, V the volume of the counter in cc, and ρ is the density of neutrons per cc, of all velocities within the energy range for which the $1/v$ law holds.

For the region of higher neutron energies, where recoil nuclei form the counting mechanism, the counting rate n_r (number of recoils per second) will be given by:

$$n_r = VNp_B\left\{\int_{v_{rB}}^{v_i}\sigma_{rB}(v)i(v)dv + 3\int_{v_{rF}}^{v_i}\sigma_{rF}(v)i(v)dv\right\}, \tag{5}$$

where σ_{rB} is the recoil cross section of Boron nuclei for neutrons of velocity v, σ_{rF} that for fluorine nuclei, i is the neutron current per cm^2 per sec., and the limits of integration v_i the velocity of the fastest neutrons measured, and v_{rB} and v_{rF} the minimum velocities, for B and F, respectively, for which the energy of the recoiling particle is just large enough to be counted.

3. Cosmic-Ray Intensity Measurements in the Stratosphere[12]

The total intensity of the cosmic radiation in the upper atmosphere has been measured with single Geiger counters. The impulses from these counters were scaled down about 50 : 1 using a circuit described by Johnson,[13] and transmitted to the ground station by automatic short wave radio, using technique previously described.[14] The data thus obtained were analyzed to test for the presence of a solar component in the radiation. Such a component might manifest itself in two ways, (a) by producing a diurnal effect at high elevations, or (b) by producing an increase in the ionization at high elevations at the time when the surface of the sun is known to be emitting an ionizing radiation, namely at the time of a solar flare which produces a radio fadeout. To test hypothesis (a), flights were made during the day and during the night. The counter sets were standardized by operating them in the laboratory at a fixed distance from a known standard radioactive sample, the radiation from which corresponded roughly to that which the instrument later measured in the stratosphere. The result of the series of flights was[15] that no diurnal effect as large as four percent of the total intensity of the cosmic radiation was observed. The data from the several flights are presented in Fig. 2. It may be seen that the night time intensity may be as much as two percent below the daytime intensity, but this effect is within the experimental uncertainty.

To test hypothesis (b), the data from one flight were analyzed.[16] During this flight, and while the instrument was floating at 20 km elevation, an intense solar flare took place. The flare was accompanied by a radio fadeout, and hence ionization was known to have been produced by the flare radiation at elevations below 80 km. The flight measurements showed no effect as large as two percent in the radiation at 20 km.

This negative result has been analyzed in terms of an ionizing photon component of the radiation. It was shown that if the radiation were of the nature of x-rays, the mass absorption coefficient must lie between 0.1 and 25 per gram; and hence that the x-radiation must be of 0.1 to 1.5A wave-length.

The intensity measurements of the cosmic

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[12] Abstract. Detailed papers are published elsewhere.

[13] T. H. Johnson, Rev. Sci. Inst. **9**, 218 (1938).

[14] S. A. Korff, L. F. Curtiss and A. V. Astin, Phys. Rev. **53**, 14 (1938); S. A. Korff, Rev. Sci. Inst. **9**, 256 (1938); T. H. Johnson and S. A. Korff, Rev. Sci. Inst. **10**, 82 (1939).

[15] S. A. Korff and T. H. Johnson, Phys. Rev. **55**, 600A (1939).

[16] T. H. Johnson and S. A. Korff, Terr. Mag. **44**, 23 (1939).

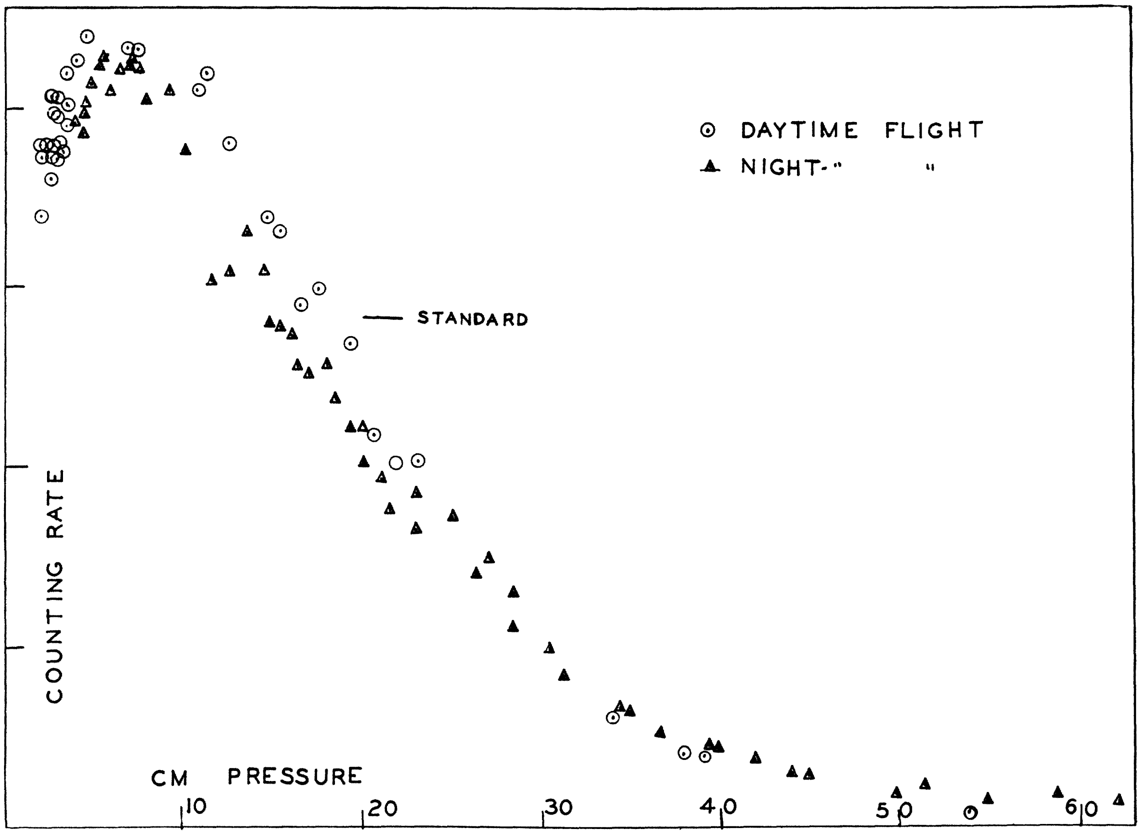

FIG. 2. Counting rate obtained in flights made during the day and night; two flights in each category. All counting rates are given in terms of the radium standardization indicated. The observations indicate no diurnal effect greater than the probable error of 4 percent, but suggest a night time intensity about 1 to 2 percent lower.

radiation made by Geiger counters have been compared with those made by electroscopes.[17] Inasmuch as the counters count the numbers of ionizing events which take place inside them, and the electroscope integrates the total amount of ionization which accompanies all ionizing particles or "events," a comparison yields the amount of ionization which, on the average, accompanies each ionizing event at any elevation. In this way it was found that the radiation was, on the average, about 1.10±0.1 times as ionizing (per event) at 0.75 meter of water equivalent below the top of the atmosphere as it was at 4 meters. This difference may be attributed to (a) the passage of electron pairs through the measuring instrument, (b) the passage of occasional showers or cascades of many simultaneous particles, and (c) the much less frequent passage of particles of high specific ionization. Each of these processes of high ionization would be counted by the counter as one event, but would be recorded by the electroscope as integrated total ionization.

4. NEUTRONS IN THE COSMIC RADIATION

a. Introduction

Various investigators have studied neutrons associated with the cosmic radiation. A good determination of the sea-level intensity has been made by the Montgomerys,[18] and Fünfer has reported an increase in neutron intensity with elevation up to the top of the Zugspitze, 7.5

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[17] S. A. Korff and W. E. Danforth, Phys. Rev. **55**, 675A (1939); J. Frank. Inst. **228**, 159 (1939).

[18] C. G. Montgomery and D. D. Montgomery, Phys. Rev. **56**, 10 (1939); E. Fünfer, Zeits. f. Physik **111**, 351 (1938); H. v. Halban, L. Kowarski and M. Magat, Comptes rendus **208**, 572 (1939); L. H. Rumbaugh and G. L. Locher, Phys. Rev. **49**, 855 (1936); E. Schopper, Naturwiss. **25**, 557 (1937); S. A. Korff and W. E. Danforth, Phys. Rev. **55**, 980 (1939); S. A. Korff, Phys. Rev. **56**, 210A (1939).

meters of water. At higher altitudes, the neutron intensity has been measured by v. Halban, Kowarski and Magat, by studying the radioactivity induced in bromine carried in an airplane to altitudes of about 3 meters of water, while several investigators have reported evidence from photographic plates, following the Blau technique, to greater elevations. Because of the difficulty in making an exact quantitative interpretation from the results of the plates, it was thought worth while to make a direct measurement in the upper atmosphere with neutron counters.

b. Observations

The neutron intensity in the cosmic radiation was measured with the neutron counters described above. The counts produced by these counters were automatically transmitted to the ground station by short wave radio. The circuit used is shown in Fig. 3. The atmospheric pressure was also transmitted, by means of technique previously described,[14] and the resulting counting rate produced by neutrons was plotted against the depth, in meters of water equivalent, below the top of the atmosphere. The counters were 20 cm long and 2 cm in diameter, and were filled with BF_3 to a pressure of 0.1 atmos., plus about 1 cm of argon. The argon was added to reduce the operating voltage of the counter.

In the foregoing section it was shown that the quantity measured by these counters is the neutron density ρ per cc according to Eq. (4). Since the neutron counters counted at a rate of about 4 counts per minute at an elevation of 1 meter of water equivalent, the experimental value of ρ at this elevation is therefore 3.7×10^{-6} neutrons per cc.

The flights attained a maximum altitude of about $\frac{1}{2}$ meter of water (70,000 feet) and the counting rate at this level was about 7.5 counts per minute. While this level is actually above the top of the familiar cosmic-ray intensity-*vs.*-altitude curve, it is not sufficiently above to show clearly whether the neutron intensity also decreases at higher elevations, following the soft component.

c. Comparison with sea-level neutron intensity

Inasmuch as the counters used in the flights counted at a very slow rate at sea level, it is not possible to determine the sea-level intensity with these counters with precision. Comparison was therefore made with the larger ionization chamber used by the Montgomerys[19] in determining the sea-level value. It will be recalled that in their experiments the counting rate due to neutrons was 91±7 per hour, the volume V was 1540 cc, the pressure p_B was 74/76 atmos. and hence from Eq. (4) the neutron density ρ determined by them was 5.7×10^{-9} neutron per cc with energies

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[19] C. G. and D. D. Montgomery, Phys. Rev. 56, 10 (1939).

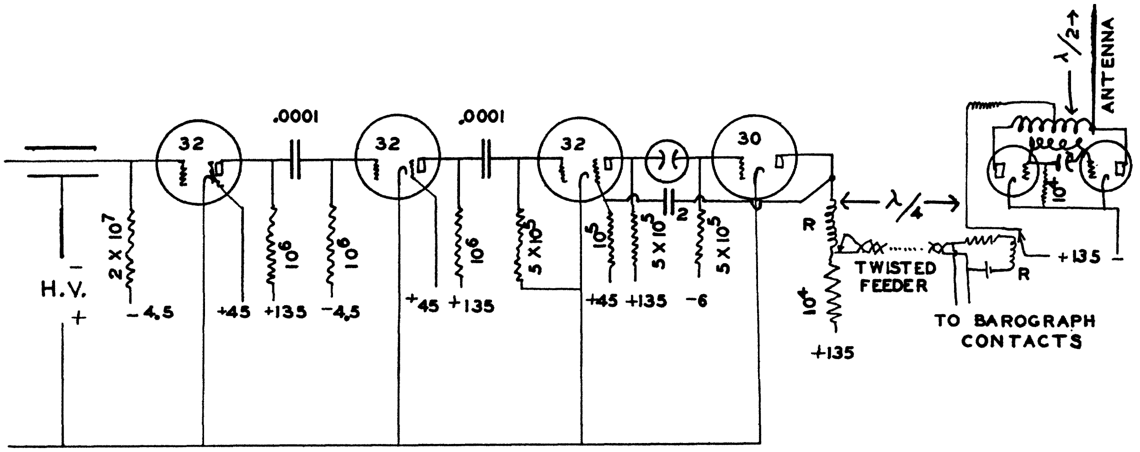

FIG. 3. Circuit used in radio-balloon measurement of neutrons in the cosmic radiation. The first two tubes on the left constitute a resistance-coupled amplifier, the second two a pulse-prolonging multivibrator, which keys the transmitter through relays. The two tubes on the right are the transmitting unit.

in the $1/v$ region.[20] It will be noted that ρ increases between sea level and 1 meter of water by a factor of about 650. The results are plotted in Fig. 4, with the sea-level intensity taken as 1, on a logarithmic scale.

In the same figure are also plotted the neutron intensities observed by Fünfer[18] at several stations between sea level and 7.5 meters of water elevation. It will be seen that the points obtained in the flights fall along a line suggested by his measurements. Further, there are also presented in Fig. 4, the rates of increase of the large bursts observed by the Montgomerys[21] for several stations between sea level and Pikes Peak (6 meters of water). The agreement between the rates of increase of the bursts and the neutrons is suggestive, and is discussed below. This rate of increase is considerably faster than that of the total intensity of the radiation.

d. Control experiment

A proportional counter, such as the BF_3 counter used to measure neutrons, records a count when an alpha-particle passes through it, or when any other ionizing event takes place which produces an equal amount of ionization. It is essential to determine the number of such other events. For this purpose a control flight was made, using an identical proportional counter, in which the filling was not BF_3 but a mixture of hydrogen, methane and carbon monoxide (illuminating gas). The other features of the flight, including the control circuit, were identical.

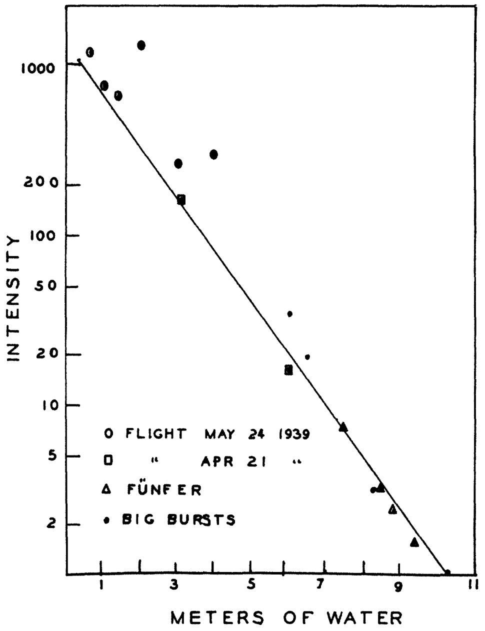

FIG. 4. Neutron intensity as a function of elevation, obtained on two flights. Also indicated are the measurements made by Fünfer and those of the big bursts made by the Montgomerys.

TABLE I. *Response characteristics for various types of counters. The columns indicate the quantities measured by the counters.*†

IONIZING AGENT	CONVENTIONAL GEIGER-MÜLLER COUNTER	BF_3 COUNTER	PROPORTIONAL COUNTER
beta-ray	yes	no	no
gamma-ray	yes	no	no
alpha-ray	yes	yes	yes
fast proton (more than 10^9 v)	yes	no	no
slow proton (less than 10^9 v)	yes	yes	yes
electron pairs or showers of less than 1000 particles	yes	no	no
big showers, bursts or cascade processes of more than 1000 particles	yes	yes	yes
slow neutrons	no	yes	no
fast neutrons	yes*	yes*	yes*

* Each counter will count if a recoil is produced. See text for calculation of probability.

† *Note added in proof.*—It has since been established that the minimum energy lost by a proton ending its range in an average path through the gas of the counter is not sufficient to make the BF_3 or the proportional counter record. The probability of many electrons simultaneously traversing a volume as small as the counter, especially in the absence of shower-producing material is also small. Further, recoils must be of more than a certain minimum energy (about 50 kev) in order to record.

Table I presents the various possible sources of ionization in counters and the response characteristic of the several types of counters to these ionizing processes. It will be seen that the principal difference between the proportional counter and the BF_3 counter is in the response to slow neutrons.

The data recorded on this flight indicated a maximum counting rate of 0.6 count per minute at 4 meters of water, and about 0.1±0.1 count per minute at 1 meter of water. This is about 1/40 of the rate recorded with the BF_3 counter at this same height. This rate may be taken to indicate that probably about 3 percent* of the

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[20] This figure is not corrected for the absorption due to the walls of the measuring vessel. For thermal neutrons the correction is of the order of twenty percent, and less for higher energies.

[21] C. G. and D. D. Montgomery, Phys. Rev. **47**, 429 (1935).

* This argument assumes that the recoil cross sections of B and of F are the same as those for H and for C. Recent

counts recorded with the BF_3 counter were due to the other causes listed in Table I, and not to neutrons in the $1/v$ region producing boron disintegrations.

e. Origin of the neutrons

Consider first the possibility that the observed neutrons are primary particles which have impinged on the atmosphere and have been slowed down by scattering collisions with the nuclei in the air. We must then find the incident neutron intensity at the top of the atmosphere which can have given rise to the observed intensity at lower depths. We are not aware at the present time of any multiplicative or cascade process whereby one neutron can produce many more as it passes through air. Hence we may suppose that the number of neutrons at any elevation will be the lower limit of the number of primary neutrons. The number of primary neutrons is further increased by the consideration that of N primary neutrons incident upon a plane parallel block of scattering material thick compared to one mean free path, approximately $N/2$ will be scattered back out into space and hence not measured. We will further recall that, because of the well-known cascade mechanism, the primary electrons have been multiplied in number by a factor of about 15 in these latitudes by the time they reach about $\frac{1}{2}m$ water. Since the number of neutrons at $\frac{1}{2}$ meter of water is approximately equal to the number of electrons at this elevation it is quite clear that a number of primary neutrons far in excess (by a factor of 30 or more) of the number of primary charged particles is required if the observed neutrons are to be primaries. Moreover, if neutrons are unstable we would not expect to find them among the primary cosmic-ray particles.

Consider now the second possibility, namely that the bulk of the observed neutrons are secondaries formed in our atmosphere. The observed rate of increase of neutron intensity with elevation, coinciding as it does with that of the photon component, is strongly suggestive of a possible connection. Let us assume that the neutrons are produced by photons and examine the consequences.

The lifetime τ of a neutron in the atmosphere, considered for the moment to contain only nitrogen, will be given by

$$1/\tau = 2Np_a c_N \sigma_N v_N, \tag{8}$$

where σ_N is the capture cross section for neutrons in nitrogen at velocity v_N, p_a is the air pressure at the point considered and c_n is the concentration of nitrogen in the air, taken as 0.8. At the 1-meter elevation, τ is about $\frac{1}{2}$ second. Now if the neutrons are in diffusion equilibrium with the nitrogen as we have assumed, then

$$\rho = q\tau, \tag{9}$$

where q is the rate of production of neutrons. We may solve (4) and (8) for q and we obtain

$$q = 2\frac{n\sigma_N v_N c_N p_a}{V\sigma_B v_B c_B p_B}. \tag{10}$$

If now we take $n = 4/60$ counts per minute from the observation, and $\sigma_N v_N$ as 2.9×10^{-19} from the measurements of Frisch, v. Halban and Koch,[22] then $q = 4.6 \times 10^{-6}$ neutron produced per cc per sec. In terms of a production cross section σ_P,

$$q = m\sigma_p 2Np_a c_N, \tag{11}$$

where m is the number of photons producing the neutrons per cm^3 per sec.; and solving (10) and (11) for σ_P we obtain

$$\sigma_P = \frac{n}{mNV}\frac{\sigma_N v_N}{\sigma_B v_B p_B c_B}. \tag{12}$$

If we suppose all photons of energy $> 10^8$ Mev can produce neutrons through evaporation, then m will be about 5; and $\sigma_P = 10^{-25}$ cm^2.

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experiments suggest they may be somewhat larger. In this case, the ratio of recoils to disintegrations may be proportionally larger. Further experiments are under way, and the present data must be regarded as preliminary.

[22] O. R. Frisch, H. v. Halban and J. Koch, Nature **140**, 895 (1937).