could be made on the photographs selected and in most cases more precisely. Since 5 degrees is less than the angular interval used in the histograms, which is as small as is justifiable by the number of showers recorded, any error introduced in the actual measurement of the angles is of no great importance.

Theoretical calculations by M. M. Mills[6] of the angular distribution of large air showers that would trip the particular counter array used indicate a broader distribution than that observed. A considerable discrepancy is not surprising since the selections of photographs included only about one-fifth of the total number, whereas the theoretical calculation refers to all of the showers which actuate the counters. However, the type of selection used and most of the experimental errors would be expected to make the experimental distribution too broad rather than too narrow.

[6] M. M. Mills, Bull. Am. Phys. Soc. 23, 4 (1948).

For example, any scattering of the shower particles in the atmosphere, an effect which was neglected in the theoretical calculation, would tend to broaden the observed distribution. Furthermore, the method of selecting showers in these experiments, by counting only those which showed 10 or more particles, tends to favor the more dense and fully developed air showers, and therefore the directions from which the dense showers most often come. At an altitude of 31,000 feet dense showers occur more frequently at directions away from the vertical, because of the greater path lengths through the atmosphere associated with these directions.

No correction was made for the variation with zenith angle of the projected area and thickness of the plates, nor was an allowance made for any effect of the cylindrical shape of the cloud chamber. It is estimated that these factors will affect the observed distribution to only a minor degree.

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A Critique of Ionization Measurements of Nuclear Disruptions Produced by Cosmic Radiation

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Cosmic rays produce nuclear disintegrations which may be studied by the use of proportional counters. Such counters may measure slow neutrons by capture, fast neutrons by recoil, and protons. These counters will have backgrounds produced by giant showers, contamination alpha-particles and other highly ionizing processes. The counters will in general count several of these quantities simultaneously. In this paper we discuss how the counting rates produced by each of these events may be separated and evaluated. This is done by varying the shielding, counter size, pressure and nature of filling gas, and other parameters.

I. INTRODUCTION

THERE are three main techniques for the study of nuclear disruptions produced by cosmic radiation[1] at the present time. These are the uses of the cloud chamber, the ionization chamber or proportional counter, and the photographic emulsion. Each has its advantages and drawbacks, and each yields information on particular phases of the problem. These several phases are diverse, so that in general the three techniques supplement each other, and together serve to give the presently available comprehensive view of the subject. None of the techniques is, however, complete, nor can we learn all we wish to know about the processes by using any or all these procedures. It is the purpose of this

[1] S. A. Korff, Rev. Mod. Phys. 20, 327 (1938).

paper to review the salient features of ionization measurements using proportional counters and to discuss the information thus gained and the limits of the method. Ionization chambers will be regarded as a special case of the proportional counter, when the gain in the chamber is unity and pulse amplification is achieved by vacuum tubes.

About photographic emulsions and cloud chambers, we shall merely say that they provide additional sources of information about nuclear disruptions. We shall from time to time cite data thus acquired. In many cases such additional data are necessary for a comprehensive study.

It has been known for some time that pulses of various sizes would be produced by ionizing events connected with cosmic radiation. The early measurements of this type were made with ionization chambers with long time constants. Only comparatively recently have measurements been made with pulsing chambers and proportional counters. It is quite evident that measurements made with long time constant chambers will tend to integrate the larger pulses with the smaller ones, and will present to the observer the totals of ionization produced. Since there are many events in which a small amount of ionization is produced and fewer as the amount of ionization per event is increased the integrated total will be chiefly contributed by the small ones, and the large ones will only be conspicuous when by chance they exceed the normal fluctuations by large amounts. Short time constant devices will enable us to measure the amount of ionization per event, and thus help clarify the picture.

II. AVAILABLE INSTRUMENTATION

Because of their versatility, counters particularly lend themselves to a useful study of the problem of nuclear disruptions. First, counters may be used with a variety of shields, and by this means the counting rates, and hence the numbers of nuclear events may be studied as a function of the nature and thickness of the absorber. For example, in the case of neutrons, the use of boron and cadmium shields have proved their worth. Second, counters may be filled with various gases at various pressures. The nature of the gas, such as boron trifluoride or methane determines the nature of the particle to which the counter preferentially responds, while the pressure of the gas in the counter can be used to determine its efficiency, and in some cases bears on the range of the particle being counted. Third, the matter of which the walls of the counter are made can be varied, and the dependence of the processes on, for example, atomic number from lead to aluminum can be investigated. Fourth, the size of the counter can be varied while other parameters such as filling gas and cathode material are kept constant. Fifth, counters can be arranged in many multiple dispositions, both in coincidence and in parallel, so that effects which are volume-dependent can be separated from those which vary as the exposed sensitive area. Finally any or all of these studies can be made at various elevations, and thereby the altitude dependence of the processes in question may be investigated.

III. NEUTRON MEASUREMENTS

Nuclear disruption processes will in general cause the emission of neutrons and protons. Since these two particles are seldom studied in the same experiment, we shall consider them separately and discuss syntheses later. Neutron detectors have sensitivities which usually depend markedly on the neutron energy. In the practical case, we have a detector which is placed into a region in which there is a gas of neutrons of various energies. The energy spectrum will be determined by (a) the mechanisms of the neutron production processes, and (b) the nature and distribution of the surrounding matter in which the neutron spends its life before capture.

The detector operates by several processes simultaneously.[2] For example, a boron trifluoride counter detects slow neutrons by disintegrations and fast neutrons by recoil processes simultaneously. Such a counter also has a background determined by large ionizing events, including (a) nuclear evaporations (stars), (b) giant showers, (c) natural contamination alpha-particles, (d) slow protons and possibly even slow mesotrons. It is clear therefore that any one single observation measures the sum total of a number of factors, and that several observations under different but controllable conditions will be necessary to enable a separation of variables to be made. Considering

[2] S. A. Korff and E. T. Clarke, Phys. Rev. 61, 422 (1942).

the above-mentioned causes of background, only factor (c), natural contamination, is independent of altitude. This quantity can be readily evaluated. At high elevations, factors (b) and to some extent (d) can be eliminated by anti-coincidence counters. However, the detected nuclear evaporations (a) will take place in the gas and in the walls of the counter itself, and will thus provide a background which is hard to eliminate and which does increase with altitude.

Consider now a boron trifluoride counter detecting cosmic-ray neutrons. It is well known that the neutrons detected by the capture process will depend on the capture cross section, and that since this quantity varies inversely with the velocity, the counting rate is proportional to the neutron-density. Thus it is clear that the number of counts per second, N, will be related to the neutron flux, i, of neutrons crossing each square cm per second, and the density of neutrons per cc, ρ, of all energies, through the equations:

$$N = VLP\int_{v=v_B}^{v=v\infty} i(v)\sigma(v)dv, \tag{1a}$$

$$= VLP\rho\sigma_B v_B, \tag{1b}$$

where V is the volume of the counter in cc, L the Loschmidt number, P the pressure in atmospheres, v the velocity, and σ the capture cross section.

Now the neutron density is related to the rate of production q of neutrons per cc per second by

$$\rho = qt, \tag{2}$$

where t is the lifetime of the neutrons in question. Since in the atmosphere most neutrons will be captured by nitrogen, because (a) the capture cross section is larger for nitrogen than for oxygen, and (b) nitrogen is the most abundant constituent of the atmosphere, the lifetime will be determined by the nitrogen capture cross section. The capture cross section of nitrogen σ_n, will be related to the lifetime t, through the equation

$$1/t = v_n L p_n \sigma_n, \tag{3}$$

where p_n is the partial pressure of nitrogen in atmospheres, and v_n the mean velocity of the neutrons.

We may next eliminate p and t between Eqs. (1), (2), and (3), and relate q to the counting rate. We then obtain

$$q = (N/V)(\sigma_n/\sigma_B)(p_n/P_B). \tag{4}$$

This equation is substantially the result obtained by Bethe, Korff and Placzek,[3] and permits the rate of production to be inferred from the counting rate, if we assume uniform distribution of surrounding matter.

Consider next the effect of a boron shield around the neutron counter. Such a shield will not in any material way influence the background, for the nuclear evaporations will take place predominantly on the inside of the cathode while giant showers will not be appreciably diminished by an absorber only a cm or so in thickness. However, the number of neutrons I transmitted by a shield of thickness t will be given by

$$I = I_0 \exp[-N_A d\sigma t/w], \tag{5}$$

where I_0 is the number of incident neutrons, N_A is Avogadro's number, d is the density of the boron, and w is its atomic weight. It is clear, since the capture cross section of the absorber is governed by the $1/v$ law, that effectiveness of the absorber decreases with increasing neutron energy. If the boron shield is composed of boron carbide, B_4C, compressed to a density of one gram per cc, there should be about 1.2×10^{22} boron atoms per cc. The energy E at which such a shield is one e^{th} transparent is given by:

$$E = (N_A td/w)^2 \sigma_B{}^2 E_B, \tag{6}$$

where σ_B is the capture cross section at energy E_b. For a shield of thickness one cm, E is about 44 ev. The probability of a thermal neutron traversing such a shield without being absorbed is 2×10^{-4}, on the assumption that "thermal" means 0.025 ev, and that the cross section for ordinary boron[4] is 700 barns at this energy. This corresponds to a mean free path before capture for the neutron is the boron carbide of 0.12 cm.

Now the boron detector is also inefficient in precisely the same energy region as that in which the shield permits transmission of neutrons. Indeed the efficiency G at any energy E will stand

[3] H. A. Bethe, S. A. Korff, and G. Placzek, Phys. Rev. 57, 573 (1940).

[4] H. H. Goldsmith, H. W. Ibser, and B. T. Feld, Rev. Mod. Phys. 19, 259 (1947).

to the efficiency at thermal energy in the ratio

$$(G_{\text{th}}/G_E) = v_E/v_{\text{th}} = (E_E/E_{\text{th}})^{\frac{1}{2}}, \quad (7)$$

where v is the velocity and E the energy characterized by the subscripts th for thermal and E for higher energy. For a detector whose efficiency for thermal neutrons is 5 percent, the efficiency for neutrons at say an energy of 10 volts is 0.25 percent. At this energy, the capture cross section has decreased until it is about 5 barns. This is the order of magnitude of the scattering cross section. At higher energies, therefore, scattering will be competitively the dominant process rather than capture. However, scattering in the energy range between 1 volt and 30,000 volts is quite unimportant in the production of ionization. Recoiling boron nuclei of energy below 30 ev will probably not ionize at all, or at the most will produce one ion-pair. A nucleus recoiling with 30,000 ev of recoil-energy will produce not more than 1000 ion-pairs. This number of ion-pairs will roughly approximate that at the bottom of the electron-spectrum and the resulting pulse will usually be rejected by the bias of the amplifier. It is assumed in this work, that in order not to count electrons, of which there are many, the bias of the amplifier circuit is set to a value such that the electrons are not counted. An electron of 30 kev will produce 1000 ion-pairs, and will have a range of very roughly 2 cm of standard air or, say 10 cm in a counter at 0.2 atm. A higher energy electron will have a longer range, and will be less ionizing per cm, for as soon as the range is long compared to the dimensions of the counter, the majority of the ionization will be lost in the walls and not in the gas. Further, to give to a nucleus of mass ten (M) an energy (E) of 30 kev, a neutron of mass one will have to have, on the average, an energy of $(M/2)E$, or about 150 kev. The maximum possible energy transfer is twice this figure but this occurs seldom. Hence we shall not anticipate any appreciable contribution due to neutron recoils until the neutron energies are well above 150 kev.

Let us next consider the effect of a cadmium shield. The cross section of cadmium as a function of energy has been determined by the Columbia group and is included in the summary[4] previously cited. It decreases rapidly from 2500 barns at 0.025 ev to 10 barns at 2 ev. There are about 4.5×10^{22} atoms of Cd per cc. We may slightly modify Eq. (5) to compute the transmission. A shield 1 mm thick will have a 50-percent transmission at about 0.37 ev and will be quite opaque to thermal neutrons, and quite transparent to neutrons of a volt or more in energy.

The nitrogen total cross section[4] is about 11 barns for thermal neutrons and falls slowly to 8 barns at 200 ev. In this same energy region, oxygen has a cross section of about 4 barns. Since nitrogen is about four times more abundant than oxygen, the diffusion processes in the atmosphere will be controlled by nitrogen, as has been previously[3] deduced.

Consider recoils produced by fast neutrons. A counter operates because of recoiling nuclei, produced (a) in the gas and (b) in the walls. The number of counts resulting from recoils in the gas will be given by an equation identical with Eq. (1a), with the recoil cross section substituted for the capture cross section. Since the recoil cross section is never more than a few barns, this process will be inefficient compared to the process of counting slow neutrons by capture. The limits of the integration will be determined by the energy transfer processes, for the smallest detectible pulse will be the one produced by a transfer to the recoiling atom of the minimum amount of energy capable of producing a count with the particular detecting circuit used. This energy transfer depends both on the mass of the nucleus struck and on how nearly central the collision was. Thus mono-energetic neutrons will produce a whole spectrum of recoil energies, the maximum and the average being calculable. For neutrons of various energies, we shall have a second distribution superposed on the first, rendering any interpretation difficult or impossible.

Wall recoils will have a similar distribution. For the same reasons, the spectrum of the neutron energies cannot be inferred from the pulse size distribution. For a constant flux, however, the number of wall recoil counts will depend on (a) the substance of which the wall is made, and (b) the cross-sectional area of the counter exposed to the flux. Hence this number can be evaluated by obtaining counting rates with counters of different sizes.

The number of recoils produced in the gas can similarly be determined by varying the pressure of the gas in the counter. This procedure will directly alter the number of centers capable of recoiling. The errors in this procedure are introduced by the fact that the limits of integration are also varied in this same act. When more gas is put into the counter, the amount of ionization formed along the path of a particle is altered, and hence a larger portion of the total spectrum of neutrons capable of producing recoils is included. Also, the background is altered.

The equation relating the number of wall-recoils N_r to the flux $i(v)$ of neutrons will have the general form:

$$N_r = N_A CA \int_{v \min}^{v \max} i(v)\sigma_r(v)R(v)dv, \qquad (8)$$

where σ_r is the recoil cross section, N_A is Avogardo's number, A is the cross-sectional area of the counters exposed to the neutron flux, C is a constant factor depending on the geometry and also on the atomic weight and density of the wall material, and R is the range of the recoil in the material of the wall. Since, as we have said before, even a monoenergetic neutron flux will give rise to a spectrum of recoil velocities, it will in general be impossible to evaluate $i(v)$. However, if the same counter is exposed to several neutron fluxes, say at several elevations, rates of increase with elevation may be evaluated. Again, the actual flux can only be determined by making simplifying assumptions. Further, in any one place, the size of the counter, A, can be varied.

To a first approximation, then, the number of wall-recoils can be determined by keeping the amount pV, pressure times volume, of gas in the counter constant and changing the area of the counter walls; the number of recoils in the gas can be roughly evaluated by keeping the counter size constant and varying the number of gas atoms in the counter. Neither of these procedures is strictly accurate for the reasons outlined above, but each will serve to throw a little more light on the processes at work.

Next let us consider what we may learn about the actual numbers of neutrons producing the recoils. From the point of view of the cosmic ray problem, this is the important question, but at the same time it is the one with the most unsatisfactory answer. We are essentially trying to evaluate $i(v)$ in Eq. (1a) by measuring the counting rate under various circumstances. First, it is evident that whereas the constants of the counter can be varied at will, the counter can be calibrated, and pulse size can be translated into particle energy, yet the integral equation cannot be solved unless we make a simplifying assumption about the dependence of the recoil cross section on energy. Fortunately, this quantity is one which varies slowly. Recoil cross sections lie between one and ten barns for most nuclei, in the energy-range with which we are concerned, i.e., between 0.1 and 50 Mev. The larger and heavier nuclei have slightly larger cross sections than the small ones, and for almost all, the cross section decreases slowly with increasing neutron energy. It is fortunate that this decrease is slow, for one can in this manner take the cross section as a constant, guessing at the middle of the energy range. This procedure is admittedly unsatisfactory, but if it is not done, then the experiments are uninterpretable. If we do take the cross section as constant, we can then determine the flux of neutrons producing recoils in the above mentioned energy range.

The energy range has a lower limit determined, as we mentioned above by the minimum energy capable of producing a detectible pulse. On the top end, neutrons of very high energy will produce recoils, especially in hydrogen, of such high energies that they will not ionize enough to be counted. Both upper and lower energy-limits will be functions which will vary widely with the substance in the counter. For hydrogen, protons down to 30 kev can be counted, and hence the neutron energy has a lower limit of about this value. In argon, a neutron to produce a 100-kev recoiling argon nucleus must have an energy of 2 Mev on the average, at least above 1 Mev, and hence no lower energy neutrons will be counted. For upper limits in hydrogen, a proton of about 10 Mev will lose about 100 kev of energy per cm of air-equivalent in the gas, and hence protons much faster than this will not be counted. In argon, the recoiling of an argon nucleus at 100 Mev will produce abundant ionization, and hence the upper limit will be much higher. However, the recoil cross section decreases with increasing energy, so that even if neutrons capable of producing such nuclei were abundant, the number of counts due to this agency will still be small. Moreover, it is doubtful whether a recoil would be produced in argon at such energies, for these energies are large compared to the nuclear binding. Very energetic neutrons will presumably therefore produce nuclear disruptions especially among the heavier nuclei. Disruptions will in turn usually be manifest by the emission of one or several particles from the target nucleus, and the rare very large ionizing events, other than giant showers, are more likely to be manifestations of disintegrations in which a number of protons or other nuclear fragments with average energies of a few Mev each, are ejected.

The number of such large ionizing events, usually nuclear disruptions, may be related to the number of high energy neutrons or other agents producing them, by making some assumption of the size of the cross section. This calculation is further aided by examining the altitude dependence. The number of nuclear evaporations and perhaps of high energy neutrons increases with increasing altitude at a rate corresponding to about a factor of two or a trifle less per meter of water equivalent, a meter of water corresponding to about 800 meters of air at STP. A mean free path of this length means a cross section of about half a barn. Such a cross section does not appear at all unreasonable. If this cross section be adopted for high energy processes, we can then evaluate the flux from the counting rate. Further by varying the material of which the counter cylinder is made, we may study the dependence of cross section on atomic weight.

Nuclear disruptions which produce a number of protons and neutrons, usually show energies of the order of a few Mev per particle. Since a 10-Mev proton has a range of about a meter of air, no disintegrations arising more than 1 mm from the innermost surface of the counter cylinder will be counted. A fairly thin cylinder is sufficient to exclude disintegrations produced in the glass outer walls and elsewhere. Further, the ratio of the number produced in the walls n_w to those produced in the gas n_g will be given by the ratio of the number of atoms per volume in the wall of depth one range, to the number of atoms in the gas. Thus we shall find

$$n_w/n_g = d_w\sigma_w W_g R_w / d_g\sigma_g W_w l_g, \tag{9}$$

where d is the density, σ the cross section, and W the atomic weight of the wall-material or the gas, designated by the subscripts w or g, R is the range of the disruption particles in the wall and l is the average path length through the gas which the producing agent follow. If we take the cross sections as roughly equal, R_w as one mm, l_g as one cm at STP, the atomic weight ratio as 3, the densities per cc as 5 and 0.001 grams, respectively, we have 1500 times as many events produced in the walls as in the gas. Varying the parameters for different counters of practical size will not alter, in the main, the conclusion that most of the observed effects are produced in the walls rather than in the gas.

IV. PROTON MEASUREMENTS

Consider next the problem of proton measurements. Since slow protons ionize heavily, the probability of detection is excellent and the flux may be directly evaluated from the counting-rate. Protons will ionize most heavily at the ends of their ranges, and will lose about 2.5 Mev in the last 10 cm of air-equivalent. Since 10 cm of air-equivalent corresponds to about 50 cm at the 0.2-atm. pressure frequently used in counters, pulses corresponding to more than 1 Mev will ordinarily not be produced by single protons. Larger pulses will be due to (a) more than one proton, or (b) heavier fragments. Proportional counters which do not use a gas characterized by high capture cross section for neutrons will count large ionizing events, most of which will be produced by single and multiple protons. In addition to the background, which will be produced by the same agencies we have already discussed, such counters will also count fast neutrons by the recoil process.

Separation of proton from recoil counts is not easy to accomplish unambiguously. The ratio of the counting rate for protons N_p to that of counting fast neutrons N_r by the recoil process will be given by:

$$N_p/N_r = G_p i_p / G_r i_r, \tag{10}$$

where G is the efficiency and i the flux of the quantities designated by the subscripts p for proton and r for recoil. Now the proton efficiency is very large compared to the recoil efficiency, the ratio being perhaps 10^4 to one. Unless the fast neutron flux i_r is much larger than the proton flux i_p, the majority of the counts will be a result of protons. Further, fast protons will produce recoils. For this process the cross section will be of the order of the geometrical size of the nucleus, and hence proton-produced recoils will be about as numerous as neutron recoils at comparable fluxes and energies.

Consider next the experimental task of evaluation. At any one elevation we can vary the relative detection efficiencies in Eq. (10). Increasing the pressure of the filling gas will proportionally increase the probability of a gas recoil. On the other hand it will also increase the number of protons counted, for the amount of ionization expended in the average traversal of the counter will be increased, and hence additional protons will be counted. The upper limit is determined by the fact that the higher the energy the less the proton ionizes; and when at successively higher energies it no longer produces an amount of ionization per average traversal equal to the lowest limit which the amplifier sensitivity allows to be counted, then the top energy limit of detectible protons has been reached. Further, the background will be altered by varying the gas pressure because giant showers with different cut-offs for their total energy will be recorded. The increase in number of gas recoils with pressure of filling-gas can be computed, but the increase in the number of protons expected will depend on the assumptions about the proton energy spectrum.

We may now change the nature of the filling-gas. This will in turn change the number of counts since (a) the new gas, having a different specific ionization will show different amounts of ionization per average traversal, and (b) a different nuclear mass will result in a different recoil energy. Thus, for example, a gas such as methane, with four hydrogen atoms per carbon, permits measurement by recoil of neutrons down to say 100 kev if 3000 ions-pairs produce the minimum detectible pulse. The same counter filled primarily with argon, with the same circuit sensitivity, will now not count recoils unless the neutron energies are 2 Mev or more. But since argon has a higher specific ionization than methane, the same ionizing particles will produce a larger pulse; as more of a distribution of protons will be counted.

Next we may change the size of the counter without changing the number of atoms of gas inside it. In this case we shall not change the number of gas recoils. However, we shall have a larger surface and so shall get more wall recoils, and more nuclear disintegrations and more protons from outside.

Since, in the cosmic-ray case, we have three processes occurring simultaneously in the non-capture counters, namely nuclear disruptions, protons from the outside and recoils due to fast neutrons, it is clear that we shall have to vary several parameters in order to obtain enough data to permit separation of these three effects. There does not appear to be any way of securing any effective separation by varying shielding, unless we go to great thicknesses. In practice, therefore, we proceed to evaluate the flux of slow protons, of fast neutrons and the number of nuclear disruptions by obtaining counting rates as a function of voltage, translating these curves into pulse-size and shape of the counter, the material of the walls and the nature and pressure of the filling-gas. These determinations are in general not unambiguous, and must be supplemented by information obtained from plates and cloud chambers.

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