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The Production of Nuclear Disruptions by the Cosmic Radiation

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INTRODUCTION

EARLY work[1] with the Millikan-type electroscopes showed that, from time to time, sudden large increases occurred in the ionization produced by cosmic radiation. These "bursts" of ionization have been identified; some being produced by large electron showers developing as cascade process in the walls of the chamber or in surrounding matter, and some being the results of nuclear disruptions in which heavily ionizing particles are ejected into the sensitive volume of the chamber. Both in cloud chambers and in photographic emulsions, these nuclear disintegrations may be readily seen. They take the form of heavily ionizing tracks emanating from a common center, and are frequently called "stars" because of their appearance. It is apparent that these nuclear disuptions are evidences of an interesting complex of phenomena which may in turn yield further information on nuclear forces. These stars are, in any event, an important integral part of the effects produced by the cosmic radiation. Thus a phase of the cosmic-ray investigation in which Millikan was much interested, and to which he devoted considerable attention, led directly to the modern study of nuclear disintegrations.

Study of these star processes shows that under any one set of conditions a distribution of particle types and energies is involved, while by varying attendant circumstances the distributions may also be found to differ. Therefore, it is today well understood that we are dealing with a complex set of phenomena. We may formulate the problem accordingly. The questions which a physicist asks about the processes of nuclear disintegration are the following:

A. Concerning the projectile, or initiating entity:

What is the distribution and energies of types of the initiating entity or entities?

B. Concerning the emergent particles:

1. What is the distribution of emergent particle types and energies?
2. How do these distributions depend on the atomic weight of the target atom? (For example, shall we find larger disruptions in lead than in aluminum?)

C. Concerning the disruption process:

1. Are there various types of disruptions?
2. Are there critical energies for various processes?
3. What is the energy balance in the reactions, i.e., are the processes endoergic or exoergic?
4. What is the altitude dependence of the number and energy distribution of the reactions?
5. What is the life history of the various particles:
    a. Does the incident particle lose its identity?
    b. Do the emergent particles produce further processes?
    c. What is the long-time effect?
        1. In ionization?
        2. In building up new isotopes?

Let us next consider the experimental techniques used in this study and what has been learned to date.

DETECTION TECHNIQUES

There are, in the main, three techniques suitable for the study of nuclear disruptions, which are in common use at the present time. These are the cloud chamber, the photographic emulsion, and the ionization chamber or proportional counter. Let us consider each of these, and see what can and what cannot be learned from each.

Many photographs have been published show-

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[1] R. A. Millikan and I. S. Bowen, Phys. Rev. **27**, 353 (1926); R. A. Millikan and R. M. Otis, Phys. Rev. **27**, 645 (1926); R. A. Millikan and G. H. Cameron, Phys. Rev. **28**, 260 (1926) and **31**, 163 and 930 (1929).

ing nuclear disruptions in cloud chambers.[2–10] From these we may learn whether the producing entity was or was not a charged particle, and, if charged, we may (but cannot in every case) ascertain its energy. We may further learn the number of emergent charged particles, and usually the nature and momentum of each. We may further observe whether the event was associated with other events such as cascade showers. We can see whether the directions of the emergent particles were principally in the forward direction, with respect to the producing entity, or were isotropic. In some cases it is possible to draw an inference that a non-charged producing particle was or was not a photon, by observing whether the expected associated cascade processes occur. However, we cannot observe neutrons, and thus, in general, cannot obtain enough information to draw up a balance of energy or to implement a meaningful discussion of incident *versus* emergent energy and momentum. Further, we usually observe the disruptions to occur within the solid plates of the chamber, and it is only possible to observe those charged particles which emerge into the gas. Since the range of a charged particle in a solid is, for the usually observed energies, extremely small, the chance of missing a substantial number of particles is excellent. In a cloud chamber if special arrangements are made to enable neutrons to be observed, such as by using boroniferous substances, we still find it hard to associate the observed neutrons with other events. Further, the probability of observing the recoil produced by a fast neutron, and having this recoil so located as to permit connective inferences to be drawn, is so minute as to constitute luck rather than a phenomenon which one may reasonably anticipate.

Photographic plates[11–20] have much in common with cloud chambers, in what can and what cannot be deduced thereform. Ionizing particles leave developable tracks in photographic emulsions, so again we may investigate the charge and momentum of the producing and the emerging entity or entities. However, since the emulsions are chemically complex, it is generally impossible to be certain whether the target nucleus was one of silver, a halogen, or some other substance. Again, neutrons are unobservable, or if observed by boron impregnation, unconnectable with the disruption being studied. Further, photographic plates will integrate all events taking place from the time of manufacture to the time of development. While it is possible, as controls, to take other plates from the same manufactured batch and develop them at the same time, the identification of a particular event as being due to the difference in exposure of the two plates rests on statistical rather than on logically certain grounds. Since the total number of disruptions observed in plates is not large, the possibility of a fluctuation remains. In particular, the time, place, and attendant circumstances of an especially interesting event can never be established with certainty. Thus if a plate has participated in a balloon flight to a high elevation, one can say that, compared to the controls, so many events per unit area occurred. But a particularly significant disruption may already have been a latent image before the flight took off. Some method of sensitizing and desensitizing the plates at predetermined times would be of the utmost value. Photographic emulsions, therefore, may be thought of as similar to a continuously sensitive cloud chamber, and one in which heavily ionizing

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[2] R. B. Brode and M. A. Starr, Phys. Rev. **53**, 3 (1938).

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

[4] S. H. Neddermeyer and C. D. Anderson, Phys. Rev. **54**, 88 (1938).

[5] L. Leprince-Ringuet, M. Lheritier, and R. Richard-Foy, J. de phys. et rad. **7**, 69 (1946).

[6] G. Herzog and W. H. Bostick, Phys. Rev. **59**, 122 (1941).

[7] G. L. Locher, Phys. Rev. **45**, 296A (1934); **50**, 394 (1936).

[8] W. B. Fretter and W. E. Hazen, Phys. Rev. **70**, 230 (1946).

[9] W. M. Powell, Phys. Rev. **69**, 385 (1946); **58**, 474 (1940).

[10] W. E. Hazen, Phys. Rev. **65**, 67 (1944).

[11] L. H. Rumbaugh and G. L. Locher, Phys. Rev. **44**, 855 (1936).

[12] M. Blau and H. Wambacher, Nature **140**, 585 (1937).

[13] A. Widhalm, Zeits. f. Physik **115**, 481 (1940).

[14] M. M. Shapiro, Rev. Mod. Phys. **13**, 58 (1941).

[15] E. Schopper, Naturwiss. **25**, 557 (1937).

[16] T. R. Wilkins and H. J. St. Helens, Phys. Rev. **54**, 783 (1938).

[17] E. Schopper and E. M. Schopper, Phys. Zeits. **40**, 22 (1939).

[18] M. Blau and H. Wambacher, Akad. Wiss. Wien **145**, 609 (1936); **146**, 259, 469, and 623 (1937).

[19] G. Stetter and H. Wambacher, Phys. Zeits. **40**, 702 (1939).

[20] W. Heisenberg, *Cosmic Radiation* (Dover Publications, New York, 1947).

tracks are especially distinct while electrons are barely detectable.

Proportional counters and ionization chambers have also been used[21–30] in this investigation. Proportional counters can measure the total amount of ionization produced in an ionizing event, but do not directly determine the number of particles which produced this ionization. For example, a proportional counter may tell us that 20 Mev has been liberated in an ionizing event, but will not say whether one proton or six are involved. In ionization chambers the collection time, and the shape of the collected pulses, may be used to identify[31] the process producing the ionization, for example, distinguishing between cascade showers and nuclear disruptions.

Both proportional counters and ionization chambers can detect neutrons by employing neutron-sensitive gases,[21,25,27] such as boron-trifluoride. Various shields with different dependences of absorption cross section on neutron energy can be used to assist in the study of neutron energy distribution. The walls of counters may be made of any metal of any thickness, to help investigate the effects of the target atom. Counters and chambers can be used in coincidence, and in conjunction with other identical detectors, or detectors of different types. For example, a boron-trifluoride counter can be operated in coincidence with a set of ordinary Geiger counters, disposed to measure the soft component or arranged to study the producing entity.

OBSERVED DATA

With the above methods of observation in mind as the chief sources of our present knowledge, let us consider what is known about the disruption processes. Let us divide the data into three parts, the information about (1) the incident entity, (2) the nature of the target atom, and (3) the emergent particles.

The following information about the producing entity is available. First, nuclear disruptions increase very rapidly[23,26] with altitude. Second, as a general thing,[2,3,8] the producing entity is not ionizing. Only rarely is an ionizing particle seen, in cloud-chamber photographs or emulsions, to enter and apparently to cause the disruption. However, enough cases of ionizing particles entering have been observed to caution us that we are dealing with a complex set of phenomena and not with just one type of reaction. The observed ionizing particles[9] were fast and lightly ionizing. Hence they were probably fast electrons, although fast mesotrons or protons cannot be excluded.

Subsidiary experiments have been carried out to ascertain whether the non-ionizing initiating entities were photons or neutrons. A photon may be expected to be associated with a cascade. In the cloud chambers, only occasionally[9] do we find cascade processes appearing in the same photograph as a set of heavy particle tracks. Similarly with proportional counters,[27] it has been found that while coincidences between neutrons and cascades do occur, it is impossible, as we shall show below, to account for all the neutrons as having been produced in the cascades.

About the nature of the target atom, much less information is available. In cloud chambers, lead nuclei have been observed to disrupt, while in emulsions the nature of the disrupting nucleus can usually not be established. Ordinary emulsions consist[20] of about 20 percent silver halide and 80 percent gelatine. Hence about one star in five might be expected to be due to the disruption of a silver or a bromine nucleus, while four out of five would be oxygen, carbon, or nitrogen, with many hydrogen atoms per molecule capable of giving rise to single-proton tracks.

An experiment[27] was conducted with proportional counters, to throw light on the problem of the effect of the target atom, by employing counters, otherwise identical, whose cylinders were made of aluminum, copper, and lead. It was observed that, on the average, more par-

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

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

[23] S. A. Korff, Rev. Mod. Phys. **11**, 211 (1939).

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

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

[26] E. Funfer, Naturwiss. **25**, 235 (1937); Zeits. f. Physik **111**, 351 (1938).

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

[28] S. A. Korff and B. Hamermesh, Phys. Rev. **69**, 155 (1946).

[29] S. A. Korff and B. Hamermesh, Phys. Rev. **71**, 842 (1947).

[30] M. Lazareva, Phys. Rev. **70**, 439 (1946).

[31] M.I.T. Progress Report, July 1, 1947, on ONR Contract N5Ori 78, Task Order VI.

ticles per disruption came from the heavier elements. The number of emergent particles or the total energy expended as ionization in the counter increased somewhat more slowly than a direct dependence on Z.

The number, type, and energy of the emergent particles have been studied. First, as is not surprising, both protons and neutrons are known to be produced. Second, it is known that both single and multiple[9, 29] ejections of both types of particles occur. Third, the average energy[14] of the protons is known to be of the order of a few Mev. For neutrons, the evidence about energies is somewhat less good, but points to the same conclusion.[24] Both number and energy distribution for protons[20] have been studied. Balancing incident and emergent energies and momenta has been tried, but any such balances are quite inconclusive because neutrons and protons are not observed in the same experiment.

As for the number distribution, the number of stars showing one, two, three, or more protons per disruption is found to decrease rapidly with an increasing number of emergent protons. Thus, the most frequent event to be expected in any one type of experimental arrangement is a single proton. These, however, are not observed and classed as stars, but are classified as "single proton tracks." The next most frequent is a disruption containing two, then three, and so forth. For example, the following are observed: 10 disruptions with 3 emergent protons; 5.7 with 4; 2.8 with 5 protons, and so forth. These points, if plotted on a semilogarithmic graph of number of stars R as a function of particles N per star, are found to yield a straight line whose equation is

$$R=Ae^{-N}, \tag{1}$$

where A is a constant and e is the base of natural logarithms. It should be noted that the experimental evidence does not support this number distribution when N is unity. In other words, Eq. (1) does not give the right ratio of singles to doubles, leading as it does to an expectation of many fewer singles than are observed. Therefore, we may surmise that not all single particles are produced in these processes, but that some may be left over from faster particles produced elsewhere. Large numbers of single proton tracks have been reported by Leprince-Ringuet and his collaborators,[5] who find that three percent of all identifiable tracks in their cloud chamber at 3000 meters are produced by protons. It will, of course, be appreciated that if a detector is placed in a volume in which production of several kinds of particles is taking place, then if the rates of production are equal, the number of particles detected will be proportional to the ranges. Since protons have a short range compared to mesotrons, we shall expect more mesotron tracks than proton tracks. Therefore, the observed flux in any two cases, f_1 and f_2, will stand in the ratio $f_1{:}f_2=Q_1R_1G_1{:}Q_2R_2G_2$, where Q_1 and Q_2 are the rates of production of the entities in question, R_1 and R_2 their ranges, and G_1 and G_2 the efficiencies or probabilities of detection. This situation explains why there seem to be more neutrons than protons, for although neutron detection efficiencies are low, neutron ranges are much greater than proton ranges.

A similar number distribution presumably holds for neutrons,[32] although the evidence applies only to singles and doubles. The events in which two or more neutrons are produced are much less frequent[29] than those in which one emerges, the difference being about a factor of 30. Again the number distribution (Eq. (1)) breaks down and does not correctly describe the ratio of singles to doubles. Because of the low efficiency of neutron detectors, the study of four or more emergent neutrons would be impossibly tedious at the present time.

With reference to the energy distribution, data has been obtained by all three methods, and is in fair agreement. With proportional counters, the total energy per count can be measured, thus integrating the emergent energy, while in plates and cloud chambers the number of protons and the energy of each has been counted and represented as a distribution function.

The energy distributions $f(E)$ of the emergent protons[20] may be represented by the equation:

$$f(E)dE=\left[(a/\epsilon)^{\exp(-E/\epsilon)}+(b/\eta)^{\exp(-E/\eta)}\right]dE, \tag{2}$$

where $a=3.18$, $b=1.60$, $\epsilon=2.7$ Mev, and $\eta=17$ Mev. The numbers are determined[33] by inserting

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[32] M. Kupferberg and S. A. Korff, Phys. Rev. **65**, 253 (1944).

observed values, to obtain the best fit with the experiment.

The form of the equation suggests that there are two kinds of neutron-producing processes, namely, evaporation, represented by the first term, and direct ejection, corresponding to the second term. Such evaporations may be expected, according to Heitler,[34] for nuclear temperatures of the order of several Mev.

Further, if we plot the energy of the average emergent particle as a function of the number of particles per disintegration, we obtain[20] the following data:

Particles per disintegration	Energy per particle
1	4 Mev
2	5
3	6.2
4	8.2
5	8.2
6	9.3
7	12
8	15

Hence it will be seen that the larger disintegrations, i.e., those involving more emerging particles, have greater energy per particle. Moreover, there are very few of the larger disruptions; and only very rarely, any with a total energy of above 200 Mev, i.e., 10 particles of 20 Mev each. At higher energies, presumably, mesotron production becomes competitively the predominant process.

The reactions are endoergic, as a moment's consideration of the packing-fraction curve will show. They represent processes by which the cosmic-ray energy is dissipated in the atmosphere. The energy of the emergent protons will go principally[23] into adding to the total ionization. The neutrons will similarly lose energy by producing recoils which in turn ionize, while the neutrons themselves are finally captured by nuclei[24] and build up stable isotopes in the atmosphere and earth's crust at rates measurable[35] over geological time scales.

The total rates of production of protons and neutrons are found to be approximately equal. The rates of production of both neutrons and protons are determined by proportional counters,[27,28] while the rate of production of neutrons at 30,000 feet was also determined by von Halban's experiment[36] with ethyl bromide. The number of protons was estimated by Hazen[10] from cloud chambers and by Widhalm[13] from photographic emulsions.

Thus, before starting the discussion, we can summarize the data in terms of the set of questions listed in our introduction, as follows: (1) The entity originating the majority of the nuclear disruptions is non-ionizing; (2) The size of the disruption increases slowly with increasing size of the target nucleus; (3) The emergent products are neutrons and protons, mostly in the energy range between 4 and 20 Mev. Further, we know that there are a great many such events, that they increase rapidly with elevation, and that they are endoergic. The number of neutrons and protons is roughly equal. The protons contribute to the total ionization, and the neutrons build up stable new isotopes at a slow rate.

DISCUSSION OF RESULTS

Let us consider next the interpretation of the above data, and the further conclusions or inferences which may be drawn about the disruption processes from experiments made so far. First, let us take up the problem of the entity producing the disintegration. We recognize that we have to deal with five entities, all of which have energies enough to produce disintegrations. These entities are protons, neutrons, photons, mesotrons, and electrons. Since under varying circumstances any of these could, energetically speaking, produce a disruption, we shall not be astonished to find that we are dealing with a complex set of phenomena and that each of these entities will, in certain cases, be identified. We are therefore primarily concerned with relative probabilities, or cross sections, for each possible process. These cross sections will vary with the energy, and with the nature of the target nucleus.

First we note that, as we have pointed out above, only very seldom does an ionizing particle enter, or is it observed as a producing entity. Therefore, we must consider non-ionizing par-

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[33] E. Bagge, Ann. d. Physik **39**, 512 (1941).
[34] W. Heitler, Phys. Rev. **54**, 873 (1938).
[35] F. W. Libby, Phys. Rev. **69**, 671 (1946).
[36] H. V. Halban, L. Kowarski, and M. Magat, Comptes rendus **208**, 572 (1939).

ticles, such as photons and neutrons. Experiments to distinguish between these two possibilities have been carried out, on the basis that photons will, in general, be associated with cascade showers. Photographic plates are of little use, since the development of a cascade shower can usually not be seen in an emulsion. On the other hand, cloud chambers and counters have both been successfully used. With cloud chambers, a few cases of cascade showers associated with disruptions have been reported, but most of the cascade and nuclear events do not seem to be associated together. This point of view is in agreement with counter data. Whereas coincidences between showers and the products of disruptions, namely, neutrons and protons, do occur, most of the events in question do not show a connection. Quantitatively, the data are as follows: A neutron counter and a shower counter were operated in coincidence, giving 0.2 coincidences per minute. The shower counter, by itself, gave 100 showers per minute. The efficiency of the counters was determined. From this, Korff and Clark[27] concluded that 2 percent of the showers were events in which neutrons were also produced, and hence these neutrons were probably photo-neutrons.

On the basis of cross sections, this view appears to be in good agreement with what may be deduced from other data. It will be recalled that the cross section for photo-neutron production at 17 Mev is about 10^{-26} sq. cm, that the value is about 10^{-30} at the threshold, and that the trend[36] appears to be toward somewhat larger values at higher energies. On the other hand, we may roughly relate the unit length in cascade theory to a cross section, through the relation

$$\sigma_r = W/N\rho l, \tag{3}$$

where σ_r is the cross section for pair production, W is the atomic weight, N is Avogadro's number, l is the unit length in radiation theory or average distance the quantum goes before producing a pair of electrons, and ρ is the density of the substance. Let us consider lead, for which W is 207, ρ is 11 g/cc, and l is 0.4 cm. Then the cross section σ_r turns out to be 7.7×10^{-23} sq cm, which is considerably larger than nuclear dimensions or cross sections for most nuclear processes. Hence, for the two competing processes, it is evident that pair production is perhaps 10^3 to 10^4 times more probable than neutron production. The photo-proton process will have slightly smaller cross sections than the photo-neutron process, and the same arguments will apply.

The multiple processes,[37] in which two or more neutrons and/or protons are ejected from the same nucleus have been observed experimentally with the 100-Mev betatron. Although no cross sections have as yet been published, it is evident from the data[38–41] that these processes are less probable than the production of single particles, in qualitative agreement with Eq. (1). The minimum photon energy required to produce multiple processes appears to increase with increasing numbers of particles produced per process, and will evidently have to be of the order of 5 or 10 Mev per particle, in order to overcome binding forces. The cascade process will terminate at about 20 Mev or a trifle less, because of the minimum energy for pair production. Hence, in a large cascade shower, we may expect occasional coincidences with nuclear disintegrations but, especially with small showers, many showers with no accompanying nuclear events are to be expected. Thus, for example, a large cascade shower, starting at an energy of 10^{10} ev, and terminating with 500 electrons and/or quanta of 20 Mev, will, on the average, have about 0.1 disintegration associated. Indeed, an experiment was performed to throw light on this point. The bias on the shower counter in a neutron-shower coincidence experiment[27] was increased so that only showers of four or more particles would be counted if associated with neutrons. There are many fewer showers of four than showers of two. Yet the coincidence rate did not decrease as fast as the shower rate. Thus the experiment points to larger showers as the more probable source of neutrons.

We may next inquire what fraction of all the neutrons and protons are produced by photons, and what fraction by some other agency. To

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[37] M. Schein, A. J. Hartzler, and G. K. Kaliber, Phys. Rev. **69**, 248 (1946); **70**, 435 (1946).

[38] G. C. Baldwin and H. W. Koch, Phys. Rev. **67**, 1 (1945).

[39] G. C. Baldwin and G. S. Klaiber, Phys. Rev. **70**, 269 (1946).

[40] E. C. Pollard, Phys. Rev. **69**, 689 (1946).

[41] V. Wiesskopf, Phys. Rev. **52**, 295 (1937).

estimate this, let us consider the total number of neutrons and the total number of showers, and consider rates of production. Here again, we have good experimental evidence available. The neutron production rates at sea level and at an altitude of 14,150 feet (corresponding to about 6 meters of water equivalent below the top of the atmosphere) have been measured and found to be about 2×10^{-5} and 2×10^{-4} per gram per second, respectively. The rate of production[27] of showers of three or more particles at the 6-meter level is about 10^{-4} gram per second. If only two percent of the showers are events in which neutrons are also produced, we see at once that the number of showers is inadequate to account for the observed number of neutrons, protons, and nuclear disruptions. We must, therefore, look to another source.

The other source must also be able to account for number and energy distribution and altitude dependence. The producing agency must be nonionizing. We therefore consider high energy neutrons. If such neutrons were to have a cross section of about 3×10^{-25} sq. cm, for collisions with nuclei resulting in a disruption, then such fast neutrons would on the average by Eq. (3) go a distance of about 1 meter of water equivalent through air between collisions. Hence their number would be reduced by a factor of two in each meter of water equivalent. It is no doubt a confusing coincidence that this is the same as the rate of decrease with depth in the atmosphere of the soft component of cosmic radiation. This will suffice to explain the observation that neutrons increase with altitude at the same rate as the soft component, and faster than the hard component. Indeed, this altitude dependence by itself eliminates mesotrons as the predominating entity in the production of disruptions.

Let us next consider the total number of neutrons, and hence the number of producing events. It has been estimated[23] that the number of neutrons at high elevations is of the same order as the number of ionizing particles. This number is, in turn, some 10 to 15 times the number per unit area and per unit time, of primary particles. Hence there must be between 10 and 15 neutrons produced, per primary. If the fast neutrons have an average energy of 50 Mev. each, and assuming an equal number and energy of protons, then about 1 Bev of the total energy of each primary will go into the high energy neutron production, which, in turn, become the parents of the disruption processes at lower elevations. Since no primaries can penetrate the earth's field at these latitudes with energies less than 6 Bev, we conclude that between 10 and 20 percent of the primary energy goes into high energy neutrons, which in turn make lower energy neutrons, further down in the atmosphere. This leaves the bulk of the primary energy for mesotron production, and for originating the soft component, and still accounts for all the neutrons and protons. Some of the low energy neutrons and protons are in turn produced by the soft component.

Thus, in summary, the experimental evidence available today suggests the following picture: The primary radiation, presumably protons of more than 6 Bev each, produce large nuclear disruptions in the upper atmosphere, from which fast neutrons and protons and mesotrons originate. These radiations, in turn, give rise to the soft component. The secondary protons, in general, do not reach sea level because of ranges which are short compared to those of the mesotrons. The fast neutrons come down through the atmosphere, producing nuclear disintegrations and hence giving rise to more neutrons and slow protons. The soft component operates primarily through the cascade process, but also gives rise to some neutrons and protons.