been thought, the results of the coincidence method would be expected to be too large. However, very few protons were identified in the photographs obtained in the present experiment.

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Latitude and Altitude Dependence of the Local Hard Showers of Cosmic Rays*

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The latitude effect of the local hard showers penetrating at least 350 g/cm² of lead has been measured at two airplane altitudes, and found to be (12±2) percent between Rome, New York, and Canal Zone.

The two separate latitude effects, obtained respectively at 30,500 ft. (300 g/cm²) and at 25,000 ft. (383 g/cm²) coincide within the experimental errors. This slow dependence on altitude of the latitude effect seems to allow an estimate of the energy of the hard shower producing particles as they arrive at the apparatus. An average energy of 20 to 30 Bev is obtained from the present data and the current ideas on the absorption of the nucleonic component. This large value is discussed in connection with other experiments and in view of the fact that at sea level or at mountain altitudes pi-mesons of that energy have a large probability of undergoing a nuclear collision before decaying into mu-mesons.

The measured altitude dependence of hard showers gives for the absorption mean free path of the producing radiation in air, the value of 112±2 g/cm², if interpreted in terms of a simple exponential. However, because of the geometry of the apparatus, the value 140 g/cm², as obtained from the data according to the Gross transform, seems to be more acceptable when referred to strictly vertical particles.

The latitude effect of the normal penetrating component was 1.33 at 30,500 ft., 1.24 at 25,000 ft., and 1.08 at sea level.

I. INTRODUCTION

LOCAL hard showers (*HS*) have been the object of several investigations[1] and their connection with the nucleonic component of the cosmic rays is now fairly well established. The present research leads to an estimate of the energy of the hard shower producing particles which are mainly protons and neutrons, at least when the observations are performed at airplane altitudes. We have obtained such an energy estimate by measuring the latitude dependence of the rate of occurrence of *HS* at two altitudes, 30,500 ft. (300 g/cm²) and 25 000 ft. (383 g/cm²).

Previous information on this subject was available before we performed our experiment. Appapillai and Mailvaganam[2] reproduced the apparatus of Broadbent and Jánossy[1] at the latitude 4°S and did not find large latitude effect at sea level. However, in general, the energies of the secondary nucleons which actually produce a *HS* are smaller than the energies of their primaries. Therefore, any estimate of the energy of the secondary particles based on latitude effect is the more reliable the smaller the depth of the atmosphere at which the experiment is performed. For this reason the present measurements were taken aboard a B-29 aircraft. Also, the apparatus (Fig. 1) was designed so that it would detect particles of lower energy than that of Appapillai and Mailvaganam. In order to obtain a measurable effect we used a relatively small thickness of absorbing material and disposed the counters in such a geometry that even a *HS* of two particles could give a registered count. Both of these features help to make the rate of registered *HS* large enough to obtain good statistical accuracy. Yet, in spite of the simple geometry, the fraction of *HS* produced by mu-mesons was, as we shall show later, as small as two percent at airplane altitudes. Like other experimenters, we believe that these spurious *HS* are produced by mu-mesons by means of knock-on electrons or by electromagnetic radiation, and that their contribution to the *HS* intensity is the greater the less severe we make the requirements for *HS* detection.

II. THE APPARATUS

As may be seen from Fig. 1, our disposition of counters is somewhat similar to that used by Tinlot,[1] but our geometry is not expected to favor vertical particles as was the case with Tinlot's geometry. Therefore, the *HS* dependence on altitude obtained by

* The present research has been carried out under the auspices of the AEC.

† Work performed in partial fulfillment of the requirements of Fordham University for the Degree of Doctor of Philosophy.

[1] We quote only a few papers in which references are made that will allow the collection of a complete bibliography: Wataghin, de Souza Santos, and Pompeia, Phys. Rev. **57**, 61 (1940). L. Jánossy and P. Ingleby, Nature **145**, 511 (1940). D. Broadbent and L. Jánossy, Proc. Roy. Soc. **A190**, 497 (1947). W. B. Fretter, Phys. Rev. **73**, 41 (1948). Rochester, Butler, Mitza, and Rosser, Rev. Mod. Phys. **21**, 20 (1949). J. Tinlot, Phys. Rev. **74**, 1197 (1948). O. Piccioni, Phys. Rev. **77**, 1 (1950).

[2] V. Appapillai and A. W. Mailvaganam, Nature **162**, 887 (1948).

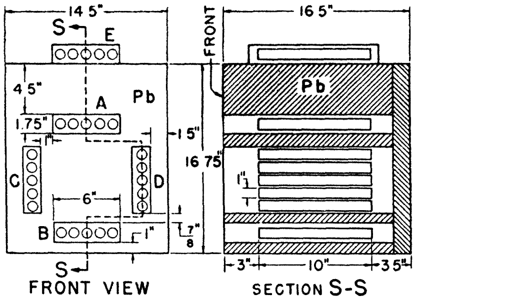

FIG. 1. Experimental arrangement of the counters and absorbers.

us will approach the value typical for a non-directional detector, while the dependence observed by Tinlot is, presumably, intermediate between that of a completely "vertical" and a non-directional apparatus.

The electronic circuit which was connected to our apparatus had a resolving time of one microsecond, and registered the coincidences AB, ABC, $AB(C+D)$, and $AB(C+D)E$. By the expression $(C+D)$ we mean that if either of the trays C or D were discharged, a coincidence was registered. The coincidences ABC were also registered in order to have a check on the behavior of the apparatus through the ratio $AB(C+D)/ABC$, which was constant over the whole period of time covered by the experiment. The counting rate of each tray, and the size of the pulses at each counter, were checked every working day. The voltages of the counters were adjusted individually such that the size of the pulses at all of the counters could be made equal to a constant value. Throughout the entire length of the experiment not a single counter needed to be replaced, and the electronic apparatus worked very satisfactorily.

The coincidences AB are due for the most part to mu-mesons, while the coincidences ABC and $AB(C+D)$ represent HS. We are interested in determining an upper limit for the percentage of spurious HS. Between sea level and 25,000 ft. the rate AB increases by a factor of about 4, and the rate $AB(C+D)$ by a factor of 118. If we call K the factor of increase for the true HS ($K\geqq 118$), the fraction S of $AB(C+D)$ associated with the normal penetrating particles at 25,000 ft. is $4(K-118)/118(K-4)$. Since K is, at most, 360 (absorption mean free path$=110$ g/cm^{-2}), S turns out to be less than 2.5 percent. An even smaller fraction would result by taking into account that the increase of AB is presumably much larger than the increase of the mu-particles having enough energy to produce a spurious HS.

The tray E was, for the first flights, an extension tray placed three feet away from the main apparatus. The $AB(C+D)E$ rate thus gave an indication of what percentage of the HS were accompanied by large air showers. Since this percentage, as expected because of previous information,[3] turned out to be very low, about two percent, the measurements with the extension tray E were discontinued. In the second series of flights at Rome, New York, and at Canal Zone, the tray E was placed on top of the apparatus and used as an additional HS tray.

The flights were performed at Rome, New York, geomagnetic latitude 55° 8′N and at the Canal Zone, geomagnetic latitude 20° 42′N. The aircraft first made a series of flights at Rome and at Canal Zone, and subsequently performed another series flying again at Rome and at Canal Zone. The data are shown in Tables I and II. The complete agreement between the results of the first and the second series gives us full confidence in the data. The errors shown in the table are the usual statistical errors, but for the HS data it has been checked that the individual measurements, made under the same conditions, did not differ from the average by more than the expected amount.

III. THE ABSORPTION MEAN FREE PATH

When we average the measurements at Canal Zone and at Rome, New York, we obtain an absorption mean free path of 112 ± 2 g/cm^2, if we take the simple exponential law for the altitude dependence; that is, if we assume that all of the detected particles were traveling vertically. However, it is reasonable to believe that our apparatus, because of its geometry, made no important selection in favor of vertical particles. This fact explains, at least qualitatively, the difference between our value of 112 g/cm^2 and the one obtained by Tinlot of 118 g/cm^2. For if our apparatus makes no selection at all as to the direction of the arriving particles, and if collisions in air, as according to Walker,[4] do not

TABLE I. Observed data at Rome, New York, and the Canal Zone.

	Rome, New York (geomagnetic latitude N 55° 8′)					Canal Zone (geomagnetic latitude N 20° 42′)				
Atmos. depth (g/cm^2)	Time (hours)	$AB(C+D)$ (hr.$^{-1}$)	$AB(C+D)E$ (hr.$^{-1}$)	ABC (hr.$^{-1}$)	AB[a] (hr.$^{-1}$)	Time (hours)	$AB(C+D)$ (hr.$^{-1}$)	$AB(C+D)E$ (hr.$^{-1}$)	ABC (hr.$^{-1}$)	AB[a] (hr.$^{-1}$)
273	2.5	1585±25		885±19	17760±84					
300						8	1122±12		630±10	12352±40
383	9.2	597±8		336±6	12000±38	9.97	538±8		310±6	9710±31
1030	417.5	5.05±0.1	1.35±0.06	2.65±0.08	2940±3	28.6	4.67±0.4		2.65±3	2710±10
300 (2nd series)	6.4	1268±14	318±7	717±12	16576±51	9.4	1120±10	274±5	640±8	12416±36

[a] Errors shown are statistical errors only.

[3] J. Tinlot and B. Gregory, Phys. Rev. **75**, 519 (1949). G. Cocconi and K. Greisen, Phys. Rev. **74**, 62 (1948).
[4] W. D. Walker, Phys. Rev. **77**, 686 (1950).

result in an important angular spread of the high energy nucleons, the *HS* rate should be taken as proportional to the value given by the Gross transform:

$$G=\int_0^{\pi/2} \sin\theta \exp[-x/L \cos\theta]d\theta.$$

From this expression and our data we obtain $L=140$ g/cm^2.

In principle, the experimental curve of the altitude dependence, extended to lower altitudes than 25,000 ft. and particularly to sea level, should show whether the expression [G] or the simple exponential represents correctly the altitude dependence of the *HS* detected with our apparatus. However, the distinction is rather uncertain for the following reason. The two functions, once they are brought to fit the points at 30,500 ft. and 25,000 ft., give two sea level values whose ratio is only 1.7, and the indeterminacy of the rate of spurious *HS* produced by mu-mesons makes it impossible to estimate the true *HS* rate at sea level with an error much less than a factor of 2. On the other hand, if we should take the apparatus under a few thousand g/cm^2 of solid material, an uncertainty would still be present, since it cannot be assumed that the rate of spurious *HS* is proportional to the total intensity of mu-mesons.

IV. THE LATITUDE EFFECT

From the data we obtain readily the latitude effect for the total penetrating component (AB) and for the $HS[AB(C+D)]$, both at 30,500 ft. and 25,000 ft. We shall indicate the latitude effect by the ratio of the intensity at Rome to the intensity at the Canal Zone. The total penetrating component undergoes a latitude effect of 1.33 at 30,500 ft., of 1.24 at 25,000 ft., and of 1.08 at sea level. The *HS* rate exhibits a latitude effect of 1.12 ± 0.02, if we take the average of the measurements at 30,500 ft. and 25,000 ft.

Because of the latitude effect obtained, it is evident that a particle must have an energy above a certain limit in order to generate a *HS* recorded in our apparatus. The probability P for a particle to produce a *HS* is presumably a function $P(E)$ of the particle's energy, E. It is reasonable to assume that $P(E)$ is a monotonic function increasing with E, but we do not know how rapid this increase is. We can consider two different types of function for $P(E)$. (a) Sharp cut-off; $P(E)$ is a step function equal to zero for energies less than a cut-off value E_c, and constant for $E>E_c$. (b) Smooth cut-off; $P(E)$ is zero for $E<E_c'$, increases linearly for $E_c'<E<E_s'$, and is constant for $E>E_s'$. We can choose for E_s' a value large enough so that E_c', to be determined, will turn out to be two or three times smaller than E_s'. Then, the function (b) will be substantially different from the function (a).

For the energy spectrum of the primaries, we take a power law with the exponent -1.8 (integral spectrum), which seems to be the best value for large energies.

TABLE II. Latitude effect of hard showers.

	Latitude effect = Intensity at Rome / Intensity at Canal Zone			
Atmos. depth (g/cm²)	$AB(C+D)$	$AB(C+D)E$	ABC	AB
300	1.13 ± 0.015	1.16 ± 0.035	1.12 ± 0.02	1.33
383	1.11 ± 0.02		1.08 ± 0.03	1.24
1030				1.085

The geomagnetic cut off, averaged over a solid angle of semi-aperture 30°, is 11 Bev at the Canal Zone, while at Rome it is 2 Bev.

In evaluating the energy cut-off introduced by the apparatus, the process by which high energy nucleons are absorbed in the atmosphere plays an important role. The value of the absorption mean free path alone does not allow us to give a unique interpretation of the observed latitude effect. The nucleonic absorption may be due either to catastrophic collisions with a cross section about half of the geometrical cross section of air nuclei, or to collisions causing a partial loss of energy with a cross section equal to the geometrical value. If the collision cross section is independent of the nucleonic energy, then under the first hypothesis the observed exponential law for the intensity of fast nucleons *versus* atmospheric depth is immediately explained. The energy spectrum of the nucleons would be the same at any depth and the latitude effect would not depend on altitude. The last two consequences are obvious, because the nucleons detected, say, at 30,500 ft., in any arbitrary interval of energy, would be the primary nucleons which did not have any collision before arriving on the apparatus. Thus, their number would be an energy-independent fraction of the number of the primaries in the given energy interval. On the other hand, one can conceive, and this is more likely to be true, that the collisions of fast nucleons with air nuclei do not result in a total energy loss for the colliding nucleons. If, as Heitler and Jánossy[5] assume, the probability of a certain energy loss is a function of the fractional energy loss only, we can account for the observed exponential absorption if we take for the energy spectrum of the primaries the function $E^{-(\gamma+1)}dE$. The collision cross section may then be equal to the geometrical cross section of air nuclei.

As to the interpretation of our experiment in the scheme of Heitler and Jánossy, one notices that nucleons of energy E_s detected at a certain atmospheric depth, x, are secondaries of primaries of energy E_p larger than E_s. The average ratio between E_p and E_s increases with x, with the result that the latitude effect of *HS* would decrease with increasing atmospheric depth. This last point would allow a very significant check on the type of absorption process which takes place in the atmosphere. However, the two altitudes at which we have

[5] W. Heitler and L. Jánossy, Proc. Phys. Soc. London **A62**, 374 (1949).

experimented do not differ sufficiently to allow us to reach a definite conclusion concerning the altitude dependence of the latitude effect. We obtain a latitude effect of 1.13 ± 0.015 at 300 g/cm^2 and 1.11 ± 0.02 at 383 g/cm^2, the difference being smaller than the statistical error. A computation performed following the mathematical scheme of Heitler and Jánossy predicts a difference slightly larger than our experimental error. Thus, rather than proving the validity of a certain type of absorption process, the present experiment indicates that the true process is such that it gives a non-rapid increase of the latitude effect with altitude. Consequently, our conclusions concerning the energy of the hard shower producing particles seem not to be critically bound to any particular absorption process. In computing the minimum energy and the average energy for our *HS* events we shall distinguish four cases according to the two above mentioned schemes for the nucleonic absorption and the two types of functions for $P(E)$.

Aa. Catastrophic collisions; sharp cut-off: in this case, the energy cut-off E_c is obtained from the equation $(E_c/11\text{ Bev})^{-1.8}=1.12$, where 11 Bev is the geomagnetic cut-off for the vertical at the Canal Zone. The geomagnetic cut-off at Rome plays no part because it is clearly smaller than the cut-off of the apparatus. For the Canal Zone we take the value for the vertical direction, since it is close to the average for all of the useful directions. The above equation gives $E_c=10.5$ Bev and $(E)_{\text{Av}}$, the average energy of a hard shower producing particle, is $(1.8/0.8)\times10.5$, or 24 Bev.

Ab. Catastrophic collisions; smooth cut-off: $P(E)=0$ for $E<E_c'$; $P(E)=1$ for $E>E_s'$; $P(E)=(E-E_c')/(E_s'-E_c')$ for $E_c'<E<E_s'$. The value of E_c' is derived from the two equations:

$$\frac{1}{E_s'-E_c'}\int_{E_c'}^{E_s}(E-E')E^{-2.8}dE+\int_{E_s'}^{\infty}E^{-2.8}dE=1.12K \quad \text{(Rome, N. Y.)}$$

$$\frac{1}{E_s'-E_c'}\int_{11}^{E_s'}(E-E_c')E^{-2.8}dE+\int_{E_s'}^{\infty}E^{-2.8}dE=K. \quad \text{(Canal Zone)}$$

For $E_s'=20$ Bev the value of E_c' which best fits the two equations is $E_c'=8.5$ Bev, which in turn gives an average energy $(E')_{\text{Av}}=35$ Bev. As expected, a function of type *Ab* gives a smaller value for the minimum energy and a larger value for the average energy, than the step function, *Aa*.

Ba. Non-catastrophic collisions; sharp cut-off: following the scheme of Heitler and Jánossy we computed the value $E_c''=9$ Bev for the cut off energy, and the value $(E'')_{\text{Av}}=20$ Bev for the average energy.

Bb. Non-catastrophic collisions; smooth cut-off: the exact computation in this case is somewhat tedious, and was not carried out in view of the approximations and uncertainties already presend in the adopted scheme for the nucleonic absorption and in the assumed cut-off function $P(E)$. One notices that according to the Heitler-Jánossy theory the nucleonic spectrum at airplane altitude is already close to a power law for energies around 10 Bev. Therefore, the value of E_c''' deduced from (*Ba*) through the proportion $E_c'''/E_c''=E_c'/E_c$ is not expected to differ substantially from the value one would obtain by a detailed calculation. With an analogous proportion for $(E''')_{\text{Av}}$, we have $E_c'''=7.3$ Bev; $(E''')_{\text{Av}}=30$ Bev. Thus, the minimum energy which a fast particle arriving on our apparatus must have in order to produce a *HS* with any appreciable probability, appears to be between 7 and 11 Bev, and the average energy between 20 and 35 Bev.

The above values are rather large if we consider that, in the limit, a *HS* producing two penetrating particles of range larger than 300 g/cm^2 is all that is required by the apparatus. One would think that nucleons of 2 or 3 Bev should be able to produce a *HS* in our apparatus, and the fact that a much larger energy is needed deserves a special explanation. One such explanation, could be the following. All of the secondary particles produced in a *HS* interact strongly with nuclei and undergo severe absorption in the lead of the apparatus. Thus the energy necessary to penetrate the absorber is much larger than we would compute from ionization losses. However, this assumption is not absolutely necessary to explain the present results. First, the production of photo-electron showers by the colliding nucleon presumably represents an important energy loss. Second, from the latitude effect of our *AB* coincidence rate, due mainly to mu-mesons, one can argue that the primary particles producing these mu-mesons with enough energy to reach tray *B*, have a minimum energy not much smaller than the minimum energy computed for the *HS* producing particles. Thus one would draw the conclusion that the very process of meson production is such that the mesons produced are not likely to have energies of the order of 1 Bev unless the producing nucleons have energies of the order of 10 Bev.

A good confirmation of our conclusions on the minimum value for E_c lies in the findings of McMahon, Rossi, and Burditt,[5a] who observed a latitude effect of

[5a] McMahon, Rossi, and Burditt, Echo Lake Conference on Cosmic Rays, 1949, Phys. Rev. **80**, 157 (1950).

1.17 ± 0.03 for the nucleons able to produce bursts in an ion chamber. From the size of the bursts the authors computed that the minimum energy of such nucleons was appreciably larger than 5 Bev.

V. THE ABSOLUTE INTENSITY

It is of interest to deduce from our experiment an approximate value for the absolute intensity of fast nucleons, in order to see how it compares with the known measurements of the primary flux. Such a comparison is most conveniently done with the Canal Zone data, since the obtained latitude effect is small enough to make it clear that most of the primaries arriving at high latitudes do not contribute to our *HS* counting rate.

According to Dwight, Sabin, Stix, and Winkler,[6] the vertical primary flux at 20°N is 0.031 ± 0.001 cm^{-2} sec.$^{-1}$ sterad.$^{-1}$. Since it is presumed that, at the top of the atmosphere, the primary intensity is constant for all directions in the upper hemisphere, a sphere of 1 cm^2 cross section would be crossed by $2\pi\times0.03$ particles sec.$^{-1}$, that is, the value of the flux integrated over all directions. Using the Gross transform ($L=140$), one finds that the integrated flux would equal 5.77×10^{-3} particles sec.$^{-1}$ cm^{-2} at the atmospheric depth of 300 g/cm^2. At that depth the $[AB(C+D)]$ counting rate of our apparatus was 0.31 sec.$^{-1}$. That is, the apparatus would be equivalent to a sphere of 55-cm^2 cross section which would detect all nucleons of energies larger than the geomagnetic cut-off at the Canal Zone (11 Bev). Such a cross section is small enough compared with the active surface of each tray, 300 cm^2, to show that our *HS* rate, I, and the large value of approximately 10 Bev for the minimum energy E_c are not in conflict with the value of the primary flux. Indeed, the product IE_c is too small, so that either a value of the primary flux smaller than 0.03 particles cm^{-2} sec.$^{-1}$ sterad.$^{-1}$, or a value of E_c larger than 10 Bev would lead to an estimated cross section of the apparatus reasonably larger than 55 cm^2.

A primary flux of 0.03 particles cm^{-2} sec.$^{-1}$ sterad.$^{-1}$ thus appears to be about the maximum value compatible with the present experiment.

As to a lower limit for the primary flux, we notice that the useful cross section S of the apparatus must be smaller than 500 cm^2, which is the geometrical cross section of the lead assembly. Actually, the data with the additional tray E on top of the apparatus indicate that S is appreciably less than 500 cm^2, for otherwise the fraction of *HS* detected by E should be less than the experimental value ($\sim$1/4), taking into account that presumably half of the *HS* producing particles are not ionizing. Our lower limit for the primary flux would thus be some five times smaller than our upper limit of 0.03 particles cm^{-2} sec.$^{-1}$ sterad.$^{-1}$. Both values, however, do not result from a direct determination. Our main purpose, in comparing our limits for the primary flux with the value given by Dwight and others, was to see whether the comparison would show the computed *HS* energy to be too large. It does not.

[6] Dwight, Sabin, Stix, and Winkler, Phys. Rev. **78**, 324(A) (1950).

In agreement with our conclusions, Sitte,[7] working at mountain altitudes, argued that the absolute rate of the *HS* indicates a large value for the energy of the *HS* producing particles.

VI. DISCUSSION

The large value of the average energy of the *HS* producing particles, as deduced from the 12 percent latitude effect at 30,500 ft., is based on the current ideas concerning the process by which the nucleonic component arises from the primary particles, and the process by which it is absorbed in the atmosphere. If these processes should actually be entirely different from the assumed ones, our conclusion concerning the energy of *HS* producing particles might need to be changed. As an obvious example, the small latitude effect obtained for the mu-mesons does not allow us to conclude that the average energy of detected mesons is over 10 Bev.

As far as the absorption process is concerned, we have computed the minimum energy E_c for the *HS* producing particles according to two different schemes of nucleonic absorption: by catastrophic collisions and by non-catastrophic collisions. The difference between the two values is not very important. If we assume some other absorption process which would lead to a larger degradation of the energy, we could hardly avoid the consequence that the latitude effect should depend on the altitude much more than is shown experimentally. Thus, it is unlikely that the true absorption process would lead to a value for E_c substantially lower than we have computed.

As to the process by which the nucleonic component arises from the primary particles, we believe it to be the same process which causes the absorption throughout the atmosphere. Indeed, for all nuclear phenomena, like ion chamber bursts, photographic emulsion stars, and slow neutrons, it appears that when the observations are performed above airplane altitudes up to very small atmospheric depths, no change is observed which could not fit our current ideas on the birth of the nucleonic component, except perhaps some dependence of the cross sections on particle energy.

The value of about 10 Bev for E_c seems, therefore, to be acceptable on the basis of the observed latitude effect. We have already remarked that our rate of occurrence can well be accounted for as given by particles of such a high energy, descendants of primaries the flux of which is known.

The large value obtained for the energy of the *HS* producing particles suggests that in the measurements of the altitude dependence of the *HS*, performed between sea level and mountain altitudes, one might

[7] K. Sitte, Proc. Phys. Soc. London **A63**, 295 (1950).

expect a contribution from pi-mesons. Such a contribution could result in an increase of the absorption mean free path of the *nucleons*, with respect to the case in which pi-mesons decay before interacting. That is because at a given absorber depth there could be production of nucleons by pi-mesons, if the absorber is dense enough that pi-mesons undergo nuclear interactions before decaying. With the value found for the mean energy of the *HS* producing particles, we see that at sea level or at mountain altitudes, the decay process does not prevent the interaction. Let us consider the experiment of George and Jason[8] (GJ), who used an apparatus with 60 cm of Pb and required sevenfold coincidences. The energy required by their apparatus must be several times larger than that required in our experiment. To make a rough estimate of the energy difference we observe that our *HS* rate, interpolated to 3450 meters above sea level, is about $40h^{-1}$, while the apparatus of GJ recorded a rate of $5h^{-1}$ even though it had a useful cross section twice as large as ours. Interpreting the difference between the two rates, normalized for equal cross sections of the apparatuses, as due to two different energy cuts in the integral spectrum $E^{-1.8}$, we find that the apparatus of GJ was detecting *HS* of energy four times as large as ours. One would thus think, as a rough approximation, that the mean energy of the particles producing *HS* in their apparatus was about 80 Bev. Now, at sea level or at mountain altitudes, a pi-meson of about 20 Bev has an equal probability of colliding with an air nucleus as it has of decaying. Then, at the energy of the experiment of GJ the contribution of pi-mesons is expected to be almost as important as if the absorber were a dense material. On the contrary, in our experiment, as well as in Tinlot's, performed with small apparatuses and at airplane altitudes, the decay process is expected strongly to prevent the collision processes. Now, GJ measured an absorption mean free path of 115 g/cm², which is about the same value as was obtained by Tinlot and by ourselves at airplane altitudes. Thus, there is no evidence of an important contribution of pi-mesons to the reproduction of the *HS* component. The possibility that the other parameters which determine the absorption mean free path, like the exponent of the power spectrum and the fractional energy loss (see Heitler and Jánossy[5]), would change at high energy just to balance the effect of pi-mesons does not seem likely.

[8] E. P. George and A. C. Jason, Proc. Roy. Soc. (to be published).

One may see that in the scheme of Heitler-Jánossy the absorption mean free path of the fast nucleons is increased by less than 20 percent if one assumes that for one-half of the events all of the energy lost in one elementary collision goes into the production of one pi-meson which has the same properties of interaction as a nucleon. For the other half of the events it is assumed that a neutral meson is produced. Therefore, our conclusion does not imply any limit for the interaction cross section of pi-mesons; it implies, however, that even in a dense material the high energy nucleonic component would decrease with a mean free path not much larger than in air, if the only difference between the absorption in air and in dense material were due to pi-mesons.

On this subject Rediker and Bridge[9] have recently performed an experiment which shows that the nuclear interactions detected with an ion chamber decrease, under a graphite absorber, as $\exp(-X/500)$, where X is in g/cm². The energy of such nuclear interactions is presumably not much lower than that of our *HS* events. This result seems to show a strong contribution of unstable particles, most likely pi-mesons, to the interacting component. The question arises whether such evidence can be brought into agreement with our conclusions. We can think of two possibilities. (a) Pi-mesons have a larger absorption mean free path than nucleons have in air; then the energy at which the contribution of pi-mesons becomes appreciable in air would be larger than we have computed. (b) The nucleonic component under graphite does not decrease with a mean free path of 500 g/cm², but that value represents the decrease of the rate of all the events produced by pi-mesons and by nucleons. Possibly, the energy of the pi-mesons is smaller than the energy of the nucleons which produce the same events.

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[9] R. H. Rediker and H. S. Bridge, Phys. Rev. **79**, 206(A) (1950).