THE

PHYSICAL REVIEW

A journal of experimental and theoretical physics established by E. L. Nichols in 1893

SECOND SERIES, VOL. 77, NO. 1 JANUARY 1, 1950

Local Production of Mesons at 11,300 Feet*

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(Received September 6, 1949)

Mesons produced in association with local penetrating showers have been investigated at 11,300 ft. above sea level. The apparatus recorded delayed coincidences arising from the 2.2-μsec. decay process of μ-mesons and distinguished the delayed coincidences which were associated with a local penetrating shower from those which were not. It is found that the fraction of penetrating showers which gives a delayed coincidence is in accordance with the assumption that the local penetrating showers are the typical events in which mesons are produced. The comparison of the delayed coincidences rate using carbon as the material stopping the mesons, with the rate using sulfur shows that the locally produced particles are π-mesons.

Since a recent latitude experiment on local penetrating showers indicates that the average energy of the particles producing such events is above 10 Bev, the result of the present work extends to that energy the conclusion originated from observations in photographic emulsion, that only π-mesons, and not μ's are directly created in the collision of fast particles.

I. INTRODUCTION

LOCAL penetrating showers, or hard showers (HS) have been observed by Wataghin, De Souza Santos and Pompeia, and by Janossy, Ingleby, Rochester, and others. The main characteristic of these events is that one observes a number of penetrating particles crossing simultaneously an absorber, the thickness of which is equal to a large number of radiation units. Also, HS are only rarely accompanied by other particles falling on the area surrounding the apparatus which detects their occurrence. This experimental fact makes the HS easily distinguishable from the large Auger showers, and proves that the many penetrating particles observed in a HS are actually produced locally in the apparatus itself. Even more compelling evidence for local production is given by cloud-chamber pictures.[1]

Not enough information is yet available about the identity of the secondary particles. Rochester, Butler, Mitra, and Rosser[2] operated a cloud chamber triggered by showers containing penetrating particles, and identified a number of low energy particles. Almost all of them were protons. However, five heavily ionizing particles were identified as mesons. The values of their masses could not be determined with good accuracy, but an indication was there that some of those five particles might have been μ-mesons. Though not definite, the indication was particularly interesting after the experiments showing small interaction between μ-mesons and nuclei[3] and the observations in photographic plates regarding the existence of π-mesons and their decay into μ-mesons.[4] Indeed, both those lines of investigations strongly suggested that in the very act of the creation only π-mesons arise, which then decay in μ's. However, one should not forget that the events observed in photographic emulsions, as well as the experiments on the non-capture of μ-mesons, concerned mesons of small energies. On the contrary, an event such as a penetrating shower produces mesons of energy of the order of the Bev.

Further investigation on the identity of the penetrating particles, secondaries of a HS, seemed therefore desirable, both to prove that the produced mesons are

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* Reported at the New York meeting of the American Physical Society (Phys. Rev. **75**, 1281A (1949)).

[1] W. B. Fretter, Phys. Rev. **73**, 41 (1948), see other references there.

[2] Rochester, Butler, Mitra, and Rosser, reported by G. D. Rochester, Symposium of Cosmic Rays, California Institute of Technology (June 21–23, 1948), Rev. Mod. Phys. **21**, 20 (1949).

[3] Conversi, Pancini, and Piccioni, Phys. Rev. **71**, 318 (1947); T. Sigurgeirson and A. Yamakawa, Phys. Rev. **71**, 318 (1947); G. E. Valley, Phys. Rev. **72**, 772 (1947); S. Tomonaga and G. Araki, Phys. Rev. **58**, 90 (1940); Fermi, Teller, and Weisskopf, Phys. Rev. **71**, 314 (1947).

[4] Lattes, Occhialini, and Powell, Nature **160**, 486 (1947).

π-mesons, and to see if the HS are the typical events in which mesons are produced.

The present experiment was thus performed, using the delayed coincidence technique to distinguish mesons by their typical decay with a mean life of 2.2 μsec. For this purpose it did not matter whether we were dealing with π- or μ-mesons, because in either case the only delay registered by the apparatus was the delay arising from the μ-decay into an electron. The π–μ-decay involves delays of $\sim 10^{-8}$ sec.,[5] much too short to be detected by an apparatus using normal G-M counters.

However, by changing the absorber in which mesons were stopped, from carbon to sulfur, it was possible to establish their identification.

II. THE APPARATUS AND THE RECORDED EVENTS

The apparatus is shown schematically in Fig. 1. The material surrounding Trays A and B was lead. Adjacent counters of Tray A were separated by $1\frac{1}{2}$ in. of lead. Absorbers of carbon and sulfur were put in the place marked "absorber," at different times. The electronic circuit was designed to register the following types of coincidences[5] AB, prompt coincidences between A and B; ABC, prompt coincidences between A, B, and C; A_2BC, prompt coincidences between A, B, C, in which at least two counters of Tray A were discharged. ABC_{del}, prompt coincidences between A and B with *no more than one counter* discharged in A, followed by a delayed pulse in C; A_2BC_{del}, prompt coincidences between A and B with *two counters or more* being discharged in A, followed by a delayed pulse in C.

All the prompt coincidences were detected within a resolving time of five μsec. The delayed coincidences[**] were registed if the amount of delay was more than 1.3 μsec. and less than 8.4.

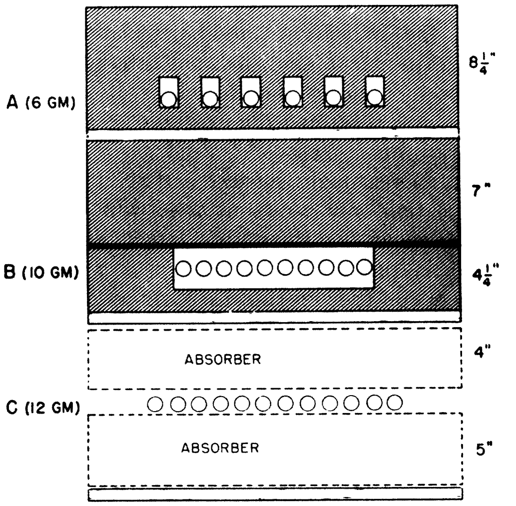

FIG. 1. Sketch of the apparatus. The Geiger-Müller counters (G-M) have an active length of 22 in. Their diameter is approximately 1 in.

If such was the case, for instance, in an event ABC_{del}, the delayed coincidence was registered in one of four registers, according to the actual amount of delay. The limits for the first register were 1.3 and 3.3 μsec., and for the others were 3.04, and 5.04, 4.76 and 6.76, 6.51 and 8.51. In the following, the four delay registers will be sometimes referred to as the "four channels." The same division in four channels was made for the coincidences of types A_2BC_{del}. While this obviously required four other registers, the same electronic circuit supplied the discrimination as to the amount of delay for both ABC_{del} and A_2BC_{del}. The distinction between the two types of delayed coincidences was made after the delay discriminators. This allowed a continuous check of the important part of the apparatus by means of the ABC_{del} events, which obviously occurred at a much higher rate than A_2BC_{del}.

It is rather important to mention that Tray C fed its pulses to a circuit of very short recovery time. Even if all but one of the 12 counters were discharged at the time zero, and the remaining counter was discharged one microsecond later, the corresponding delayed pulse was very much the same as if only one counter were discharged with a delay of one microsecond. The coincidence ABC_{del} or A_2BC_{del} was therefore registered whether or not a prompt coincidence ABC or A_2BC was also registered in the same event. This feature is desirable if one wants to register decay electrons arising from mesons generated in a local penetrating shower, since it permits the registration of a delayed coincidence also in the case that an undelayed particle and a delayed one cross the same tray. Of course the individual counter which has been crossed by the undelayed particle cannot detect the decay electron. However, the average number of counters discharged in Tray C when a local penetrating shower occurs is about one and the correspondent decrease in the efficiency is not serious.

The events like AB, ABC are due to the normal penetrating particles, which for the large majority, are μ-mesons generated in the higher levels of the atmosphere. The π-mesons, having a mean life two hundred times smaller than μ-mesons, cannot constitute any appreciable fraction of such coincidences.

The intensity of fast protons and neutrons, which also could give an ABC coincidence, is not known with good accuracy. However, from several delayed coincidence experiments performed at sea level, and considering that the lead of our apparatus is about equivalent to the amount of air between 11,300 ft. and sea level, one can easily argue that the fraction of ABC coincidences caused by protons or neutrons in our apparatus is no more than a few percent. Finally, electrons and photons cannot give any appreciable contribution to the rate ABC, due to the large thickness of lead which they should cross in order to reach Trays B and C.

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[5] J. R. Richardson, Phys. Rev. 74, 1720 (1948).

[**] Our acquaintance with the delay discriminator built by M. Sands at M.I.T. was very helpful in designing the circuit.

TABLE I.

Absorber (4 in. above C, 5 in below C)	ABC (NP)	ABC_{del} 1.30–3.27 μsec. I	 3.04–4.97 μsec. II	 4.76–6.74 μsec. III	 6.51–8.40 μ-sec. IV	Casuals per each channel*	True delays in all four channels per hour	Time (hr.)	Ratio C/S
Graphite	1,303,500	4556	2337	1339	873	550±15	30.4±0.5	227.95	1.85±0.05
Sulfur	1,225,100	2581	1338	938	650	495±15	16.4±0.4	216.50	
	A_2B(HS)		A_2BC_{del}						
Graphite	21,824	134	77	38	16	3.0	1.17±0.07	216.13	1.11±0.1
Sulfur	22,040	137	58	31	15	2.9	1.06±0.07	216.50	

* For ABC_{del}, this number is equal to the resolving time (1.94×10^{-6} sec.) multiplied by the background counting rate of C (71 sec.$^{-1}$ for graphite and 67.5 sec.$^{-1}$ for sulfur) multiplied by the coincidence rate AB (1.75×10^4 hr.$^{-1}$) multiplied by the number of hours. While the statistical error in the computed casuals is only one percent, a larger error has been put in the table to take account of time variations of the rate AB, which was not constantly measured. The casuals for HS delays are computed analogously to the ABC casuals substituting to the AB rate the A_2B, which was constantly measured.

In the following we will often refer to the ABC coincidences as the NP (normal particles).

The ABC_{del}, when the casuals are subtracted, are then to be interpreted as given by the decay electrons of μ-mesons, and their frequency-*versus*-delay distribution is expected to follow the exponential law of the typical 2.2-μsec. decay.

The A_2B coincidences as well as the A_2BC, are meant to give the rate of the local penetrating showers. They imply the presence of two penetrating particles, except for the cases in which a single penetrating particle produces secondary electrons which cause the discharge of another counter of the same tray. However, the presence of $1\frac{1}{2}$ in. of lead between adjacent counters of A, makes those cases improbable. The fractions of the A_2B and A_2BC coincidences due to the normal hard component can be computed from the altitude dependence, as we will see later.

Large air showers, also can give an A_2BC or A_2B coincidence. Checking on this point, we found that such showers contribute not more than eight percent of the total rate at 11,300 ft. This is in agreement with the results of Gregory and Tinlot, as well as of Cocconi and Greisen.[6]

The factors by which the rates of the various coincidences increase, between sea level and 11,300 ft. (690 g/cm^{-2}), have been measured with the same apparatus of Fig. 1, having only 9 G-M counters in Tray C instead of 12, spread more apart, in order that the distance between extreme counters was kept equal to that shown in Fig. 1. The electronic circuit registered coincidences of Type A_2BC_n, where the subscript n indicates that the discharge of *n or more* counters of C was required. The result was:

$$R=\text{ratio}:\frac{\text{rate at 11,300 ft.}}{\text{rate at sea level}}\quad\begin{array}{cccccc} ABC & A_2B & A_2BC_1 & A_2BC_2 & A_2BC_3 & A_2BC_4 \\ 1.95 & 8.6 & 10.9 & 17.1 & 17.6 & 15.5 \\ & \pm0.25 & \pm0.5 & \pm1.6 & \pm2.2 & \pm2.3 \end{array}$$

From those values it appears that NP contribute to the rate of A_2B and A_2BC_1, but A_2BC_2, A_2BC_3, A_2BC_4 are practically all caused by fast nucleons. The value 17 seems to be the exact value of R for the "true" HS detected by our apparatus. Using the absorption coefficient $L=118$ g/cm^{-2} found by Tinlot[7] we would find $R=18$.

From the data $R=18$ for HS, and $R=1.95$ for NP, one can easily evaluate how many of the events which we call HS are "true" HS, and how many are possibly caused by the normal hard component. At 11,300 ft., 92 percent of the A_2BC_1 coincidences and 87 percent of the A_2B are due to HS events, which means that the large majority of the A_2BC coincidences are the result of the collision of a fast nucleon with a nucleus of the lead above Tray A. When the same type of collision happens in the lead *below* Tray A, the probability for more than one counter in A to be discharged must be small. Therefore, not much preference, if any, is made by the apparatus between protons and neutrons, as particles producing a HS coincidence or a HS delayed coincidence. This last type of coincidence has then to be interpreted as follows: a HS is initiated above A, and among the secondary particles is a meson which stops in the absorber either above or below Tray C, giving rise to a delayed electron which crosses C. As we have already said, the double decay π-μ- and μ-electron gives exactly the same result as the μ-decay alone.

III. RESULTS

The delayed coincidence rates are shown in Table I, both for HS and NP. If we refer to the same number of particles crossing the bottom Tray C, we see that, using sulfur as absorber, the apparatus registered 3 A_2BC_{del} coincidences per 1000 ABC coincidences, while per 1000 A_2BC coincidences the number of A_2BC_{del} coincidences registered was 15. This was to be expected, and furnishes an additional proof that the HS delayed coincidences are given by locally produced mesons. Indeed, while the differential spectrum of NP is depleted in the low energy end by the 2.2-μsec. decay during the long flight through the atmosphere, such a decay can

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[6] J. Tinlot and B. Gregory, Phys. Rev. **75**, 519 (1949); G. Cocconi and K. Greisen, Phys. Rev. **74**, 62 (1948).

[7] J. Tinlot, Phys. Rev. **74**, 1137 (1948).

have no effect on the spectrum of the locally produced mesons, because of the small distance between the top of the apparatus and Tray *C*. This fact has also the consequence that while 92 percent of A_2BC represent HS event, 97 percent of A_2BC delayed coincidences are actually associated with a HS.

The rate A_2BC_{del} is 6.5 percent of the ABC_{del}. However, we cannot assume that the apparatus will always register a HS event as such, even if it originated in the lead above *A*. A real evaluation of the efficiency of the apparatus as a HS detector cannot be made, and therefore the fraction of the locally produced mesons to all mesons cannot be considered as accurately measured. Assuming any reasonable value for the "over-all efficiency," for instance, less than 50 percent, and considering the altitude dependences of the HS ($\sim\exp[-x/118]$),[7] and of the slow mesons ($\sim\exp[-x/240]$),[8] one expects that if our apparatus had been working at a residual pressure of 200 g/cm^{-2}, and if it had 100 percent efficiency, the HS delayed coincidences would have been just as many as the NP delayed coincidences. At a higher altitude, the HS delayed coincidences would be in large prevalence.

We are thus led to conclude that the *local penetrating showers* of the very same type as detected by our apparatus, *constitute the main process where mesons of relevant energy are produced.*

In the preceding discussion, the comparison of A_2BC_{del} with ABC_{del} has been done referring to the data with sulfur as the material stopping mesons, in order not to favor the μ-mesons with respect to π's. This will be clear after the next section of this paper.

IV. DISTINCTION BETWEEN π- AND μ-MESONS

The differential decay curves of Fig. 2, which are based on measurements using either carbon or sulfur as the absorber, show beyond any doubt that the A_2BC_{del} are caused by the 2.2-μsec. decay process typical of μ-mesons.

The separate measurements with carbon and sulfur as absorbers enable us to specify the nature of the mesons directly produced in the nuclear collisions, namely, whether they are π or μ. We only need to recall the typical behavior of the negative μ-mesons, concerning their capture by nuclei.[3]

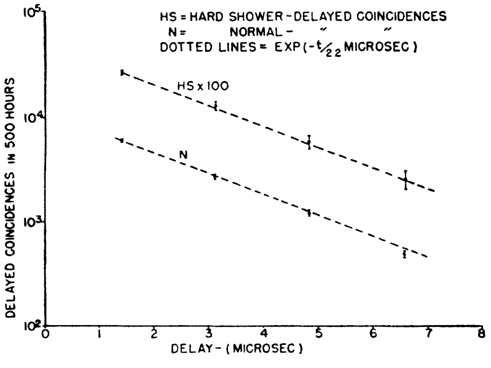

FIG. 2. Differential decay curves.

In carbon, practically all negative μ-mesons decay, while in sulfur 72 percent of them undergo nuclear capture, according to Ticho.[9] The remaining 28 percent undergo the decay process with a mean life of 0.55 μsec., again after Ticho. Therefore, by setting the minimum registered delay at 1.3 μsec. in our apparatus, we detect the decay of only 2.8 percent of all the negative μ-mesons. With the same minimum delay, we detect the decay of 60 percent of the positive μ-mesons. For the accuracy needed in the conclusions that will follow, we can very well assume that in sulfur all the delayed coincidence are due to positive μ-mesons.

If now mesons are created as μ's with a positive excess of 20 percent (we shall return later to this point), the ratio C/S (delayed coincidence rate in carbon/delayed coincidence rate in sulfur) will be the ratio of the total number of mesons to the number of positive ones, namely, 1.8.

If, on the contrary, mesons are created in our apparatus as π's the ratio C/S is expected to be 1, since in both carbon and sulfur the positive π always decays to μ, which in turn decays into an electron, while the negative π will always be captured at the end of its range, and never decays to μ. On the other hand, for the μ-mesons registered as NP we do expect for the ratio C/S the value 1.8, since the positive excess of μ-mesons arriving at sea level can be accepted for our NP.

It pays to make two remarks. First, the probability that locally produced π-mesons would decay before the end of their range, turns out to be less than five percent, on the basis of the measured mean life of 10^{-8} sec. and the dimensions of the apparatus.

Hence, locally produced π-mesons would practically always decay at rest, and the μ-mesons produced by them would have a range of about one millimeter.

As a second remark, one sees that into the ratio C/S also enters, as a factor, the ratio of the ranges of the decay electrons in carbon and sulfur. However, this factor which is not much different from unity, appears in the case of π-mesons as well as in the case of μ-mesons, without influencing the comparison between the two cases.

The thickness of the counter walls was 0.33 g/cm^2 of glass, and could not introduce an appreciable effect, considering also that the absorber was both above and below Tray *C*.

We thus expect, for the ratio C/S, the value $1+k$ for π-mesons, and $1.8(1+k)$ for μ-mesons. The correction k represents the difference in the ranges of decay electrons. The experimental values, which can be deduced from Table I, are the following:

$$\text{Hard showers } C/S = 1.1 \pm 0.1,$$
$$\text{Normal particles } C/S = 1.85 \pm 0.05$$

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[8] Rossi, Sands, and Sard, Phys. Rev. **72**, 120 (1947).

[9] H. K. Ticho, Phys. Rev. **74**, 1337 (1948).

Such a result strongly indicates that the locally produced mesons are π-mesons. If we would want to interpret the disparity between 1.85 and 1.1 in terms of a large positive excess of locally produced μ-mesons, we would have to assume that practically all locally produced mesons are positive.

This assumption clearly appears to be very far from the truth. We would like to discuss what is the maximum value which we may expect for the locally produced mesons. Such a value will also have a bearing on the quantitative conclusions of the next paper on the nuclear interactions of π-mesons.

There is a fair agreement between various determinations of the positive excess of μ-mesons arriving at sea level. Recently, Conversi[10] reported an experiment where he and Nappo measured the positive excess, at sea level, in the energy band between 310 and 430 Mev. They obtained 1.24±0.05 for the ratio N_+/N_-. Of course, that represents the positive excess of the μ-mesons produced in the atmosphere, and provides no direct information as to the positive excess of the mesons locally produced in our apparatus. But we may recall the experiments of Quercia, Rispoli, and Sciuti, at 17,000 and 25,000 ft.[11] where they detected mesons produced respectively in 530 and 380 g/cm^{-2} of air above the apparatus, therefore in a similar condition to our HS experiment. We have to take into account the already noted fact that the rate of our HS delayed coincidences implies that HS events such as those registered by us constitute the main process for the production of mesons. Thus we consider that the results at 17,000 and 25,000 ft., which show no indication of a large increase of the positive excess respect to the sea level value, stand to prove that we cannot expect for our HS mesons a positive excess much larger than 20 percent.

Another datum, which supplies the same indication, from a different point of view, is the latitude effect of HS recently obtained by Walsh and Piccioni[12] which shows that the average energy of the particles producing HS in an apparatus substantially similar to the present one, is above 10 Bev. Actually the latitude effect for HS, was 1.1 and for the normal hard component was not larger. Now, we consider very reasonable the qualitative assumption that the positive excess decreases when the energy of primary particles increases, and therefore, recalling that our apparatus does not favor protons with respect to neutrons as producers of a HS, we are led to the conclusion that the HS positive excess is not much larger than 20 percent.

On the other hand, let us suppose that not all mesons are produced in our apparatus by high energy nuclear collisions above Tray A of Fig. 1, as implicitly we have assumed so far, and allow for some of them to be produced in secondary low energy collisions between nuclei of lead and nucleons of few hundreds Mev arising from a conspicuous nucleonic cascade process.*** Then we must think that of the secondary nucleons a substantial fraction consists of neutrons, and therefore we cannot expect a large positive excess. Indeed in photographic emulsions positive and negative π-mesons are found in comparable numbers.[13] It seems therefore quite safe to take a value like 1.4 as a maximum value for the ratio of positive to negative mesons produced in our HS events.

The result of the comparison of carbon and sulfur cannot then be interpreted in terms of μ-mesons being created only with a positive charge. The locally produced mesons are of a different type from μ's, and at the end of their range they undergo a process which is practically independent of the atomic number of the material where they are absorbed, at least for $Z \geqslant 6$. They ultimately give rise to μ-mesons, since the obtained decay curve is very characteristic for such particles. Therefore, their identification as π-mesons appears to be quite reliable.

ACKNOWLEDGMENTS

Thanks are due Dr. T. H. Johnson for his continuous encouragement of the work. Mr. C. S. Kemic assembled most of the apparatus and assisted very helpfully in taking data and checking the apparatus throughout the duration of the experiment. Mr. M. Lustgarten and Mrs. B. Lustgarten contributed by building part of the equipment.

The writer and Mr. C. S. Kemic also wish to thank Mr. S. S. Huntington, President of the "Berthoud Pass Lodge, Inc.," for his kind cooperation during their stay at Berthoud Pass, Colorado.

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[10] M. Conversi (to be published).

[11] Quercia, Rispoli, and Sciuti, Phys. Rev. **74**, 1728 (1948).

[12] T. G. Walsh and O. Piccioni, Echo Lake Conference on Cosmic Ray (June 22–28, 1949).

*** An experiment (III) reported in our next paper shows that from these low energy processes do not arise more than 20 percent of the HS delayed coincidences.

[13] Lattes, Muirhead, Occhialini, and Powell, Nature **159**, 694 (1947); Lattes, Occhialini, and Powell, Nature **160**, 453 (1947).