particles, heavier than mesotrons, with several delta-rays similar to those observed with alpha-particles.

Summary

This flight shows that slow mesotrons occur in appreciable numbers above 20,000 feet altitude. There seem to be also some heavy nuclei present. These could be the result of nuclear reactions created by neutrons. It is planned to make further flights to get better numerical information.

Acknowledgment

I wish to thank Mr. W. H. Bostick who assisted in the flight and who was very helpful in computing the results. Mr. Leonard Miller was kind enough to help in the construction of the timing set. I have, further, to thank the United Air Lines and their engineer, Mr. W. Davies, for valuable help and cooperation. My special gratitude belongs to Dr. A. H. Compton, who was always ready to give helpful advice and encouragement.

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Cloud-Chamber Pictures of Cosmic Rays at 29,000 Feet Altitude

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Cloud-chamber pictures (115 in number) of cosmic rays were taken during an airplane flight. The range of slow mesotrons was investigated by inserting a copper plate across the middle of the chamber. The slow mesotron rate above 15,000 feet is 9.6 percent of the occurrence rate of electrons and fast mesotrons. The formation of a pair of positive and negative slow mesotrons was photographed. Statistical evidence is given that mesotrons do not always disintegrate when stopped. One proton was photographed.

RECENTLY one of us[1] reported photographs of cosmic rays made with a cloud chamber at altitudes up to 29,300 feet. The apparatus was installed in a Douglas DC3 airplane, and consisted of a cloud chamber 6 inches in diameter mounted in the gap of a permanent magnet which gives a homogeneous field of 708 oersteds. The results of this first flight indicated that there is a good chance to photograph slow mesotrons at higher altitudes. This conclusion was drawn from an evaluation of the ion density of the tracks combined with a measurement of the momentum of the particle (curvature in the magnetic field).

On April 30th we used the same equipment for a second flight.[2] With a total flying time of four hours and 10 minutes we stayed for three hours above 20,000 feet and reached a top altitude of 29,000 feet. Figure 1 shows the altitude-time record of this flight.

About half of the expansions were made at random, the other half were controlled by the same anticoincidence arrangement of G–M counters as previously described. Because of difficulty with the temperature control in the airplane cabin, convection currents in the cloud chamber caused occasional distortions in the tracks.

In order to obtain additional information two changes were made in the cloud chamber. The first was to mount a horizontal copper plate across the center of the chamber. Careful investigations in the laboratory proved that the plate does not appreciably distort the tracks. The purpose of the plate was to slow down or stop some of the slow mesotrons. For the range of a track which is stopped in the plate, one can give an upper limit. This range determination, together with the curvature measurement, gives

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[1] G. Herzog, Phys. Rev. **59**, 117 (1940) preceding paper, referred to as I.
[2] We wish to thank the United Air Lines for their support in carrying out this flight and Mr. W. Davies, research engineer of this company, for his valuable help.

TABLE I. *Data for electrons, mesotrons ($\mu=200$), and protons for the two ranges of 0.06 cm and 0.32 cm copper.*

Particle	Max. Total Energy Mev	Max. Kinet. Energy Mev	Max. Momentum pc Mev	Max. Velocity v/c	Max. Radius of Curvature cm	Min. Ionization $\frac{\partial E/\partial x}{(\partial E/\partial x)_{\text{electron}}}$
			The stopping power for 0.06 cm copper			
Electron	1.6	1.1	1.5	0.96	7.3	1
Mesotron $\mu=200$	106	6	34.6	0.33	165	3.5
Proton	942	22	200	0.22	950	6
			The stopping power for 0.32 cm copper			
Electron	4.55	4.05	4.5	0.99	21.4	1
Mesotron $\mu=200$	119	19	64	0.54	305	2
Proton	967	47	294	0.32	1400	4

the second possibility of evaluating the mass of the particle. The ionization *vs.* curvature method can of course also be used, and sometimes an estimate of the ionization together with the range determination is helpful in discussing the nature of the particle involved. The combination of all these methods is extremely valuable.

In order to cover a larger set of data with one flight, the thickness of the copper plate was 0.06 cm across one half of the chamber and 0.32 cm across the other half. These values were chosen according to information from the first flight, which showed many mesotrons having only a few million electron volts kinetic energy. Such particles should be stopped by a thin plate. The insertion of the plate cuts the length of the tracks in the upper and the lower halves of the cloud chamber to half of its previous value. This reduces considerably the accuracy of the curvature measurements.

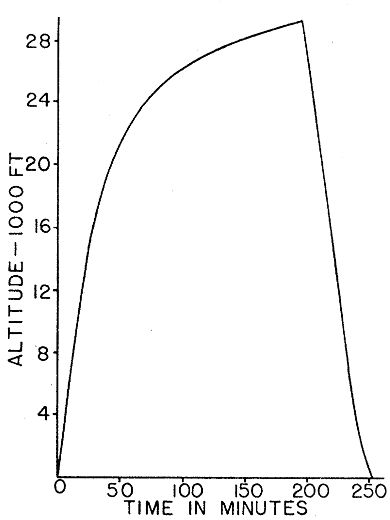

FIG. 1. Altitude-time record of airplane flight.

The second change consisted in replacing the argon in the chamber with helium. Thus we reduced the curvature resulting from multiple scattering in the gas. The scattering increases with the square of the atomic number and is much less in helium than in argon.

Stopping Power of Copper Plates for Various Particles

Any particle entering the plate vertically and being stopped in it has a range in copper which is less than the plate thickness. Corresponding to this maximum range one can calculate an upper limit to the energy and to the momentum of the particle before it enters the plate, if the particle is stopped by ionization and radiation processes only. The energy thus calculated depends of course on the mass of the particle. For each assumed mass there is a corresponding maximum radius of curvature which the particle can have in the magnetic field of the cloud chamber (708 oersteds). One also can compute the specific ionization in the gas of the chamber. This ionization decreases with increasing energy for the small energies under consideration.

These data are listed in Table I for electrons, mesotrons ($\mu=200$), and protons for the two ranges of 0.06 cm and 0.32 cm copper. The specific ionization is expressed in terms of the specific ionization of an electron having the same momentum.

The table shows that it is easy to distinguish whether a stopped particle is heavier than an electron. The maximum curvatures for electrons are so small that they can easily be measured with our field. The distinction between a mesotron and a proton is more difficult because

TABLE II. *Data for particles traversing or ending in the copper plates. Electrons are indicated by ϵ, mesotrons by μ, and protons by π.*

PICTURE	ρ CM	SIGN	IONIZATION FROM INSPECTION	PROBABLE NATURE	PICTURE	ρ CM	SIGN	IONIZATION FROM INSPECTION	PROBABLE NATURE
Particles passing through 0.06 cm copper					*Particles passing through 0.32 cm copper*				
699	>200		=fast ϵ's	ϵ or fast μ	712	>300		=fast ϵ's	ϵ or fast μ
724	>400		= "	"	721	>400		= "	"
738	>400		= "	"	722	>400		= "	"
738–1	>100		> "	"	723	>400		= "	"
738–2	>100		> "	"	739	>400		> "	"
746	14	−	= "	ϵ	768	>400		= "	"
759	>150		= "	ϵ or fast μ	793	>200		= "	"
770	>300		= "	"	803	>300		= "	"
792–1	>200		= "	"	806	>400		= "	"
792–2	>200		= "	"	833	>300		= "	"
797	>400		= "	"	879	>300		= "	"
813	>400		= "	"	900	>200		= "	"
					705	>180		= "	"
Particles ending in 0.06 cm copper					*Particles ending in 0.32 cm copper*				
680–1	2	+	=ϵ's	ϵ	680–2	3	−	=ϵ's	ϵ
705–3	>150	−	>fast ϵ's	slow μ or π	684	>150		>fast ϵ's	slow μ or π
755	150	+	> "	slow μ	696	>300		> "	"
813–1	2	−	=ϵ's	ϵ	707	150		= "	slow μ
813–2	2	−	=ϵ's	ϵ	715	64	−	> "	slow μ
					748	>200		= "	slow μ or π
					754–1	82	−	≫ "	slow μ
					754–2	75	+	≫ "	slow μ
					760	>100		= "	slow μ or π
					785	>300		= "	"
					807–2	28	+	= "	ϵ
					807–1	>100	−	= "	slow μ or π
					822	>150		≫ "	π
					828	>150		= "	slow μ or π
					900	>150		= "	"
					802	>300		= "	"

the radius of curvature limits are rather large with the magnetic field employed. An estimate of the ionization along the track is very helpful here. This holds especially for slow particles where the ionization losses for mesotrons and protons differ by a factor of two or more. It must be noted, however, that if protons are stopped by processes in which neutrons are ejected, protons of radii of curvature greater than 950 and 1400 may be stopped in the copper plates.

RESULTS

Altogether 115 successful pictures were taken. These show 12 particles traversing the 0.06-cm plate and 12 particles going through 0.32 cm copper. 5 particles are stopped in 0.06 cm copper and 16 in 0.32 cm copper. The stopped tracks are listed in Table II, where column 1 is the number of the picture, column 2 is the radius of curvature, column 3 is the sign of the electric charge assuming that the particle moves downward, column 4 indicates whether the visual inspection shows stronger ionization than for an electron track, and column 5 gives the probable nature of the particle. In several cases only a lower limit for the curvature can be given, and therefore the sign of the charge cannot be determined.

With the exception of picture 746 all the particles which pass through the plate have curvatures above 200 cm. According to Table I both electrons and mesotrons of such curvatures are theoretically able to penetrate the plate and no conclusions can be drawn as to their mass.

Picture 746 is reproduced in Fig. 2. A particle traverses the whole length of the chamber through the thinner half of the plate. Its curvature is $\rho=14.7$ cm above the plate, and $\rho=11.7$ cm below it. The visual inspection identifies the track as an electron. Its energies are then 2.6 Mev above and 2.0 Mev below the plate, which gives an energy loss of 0.6 Mev for 0.06 cm of copper. The theoretical energy loss by ionization

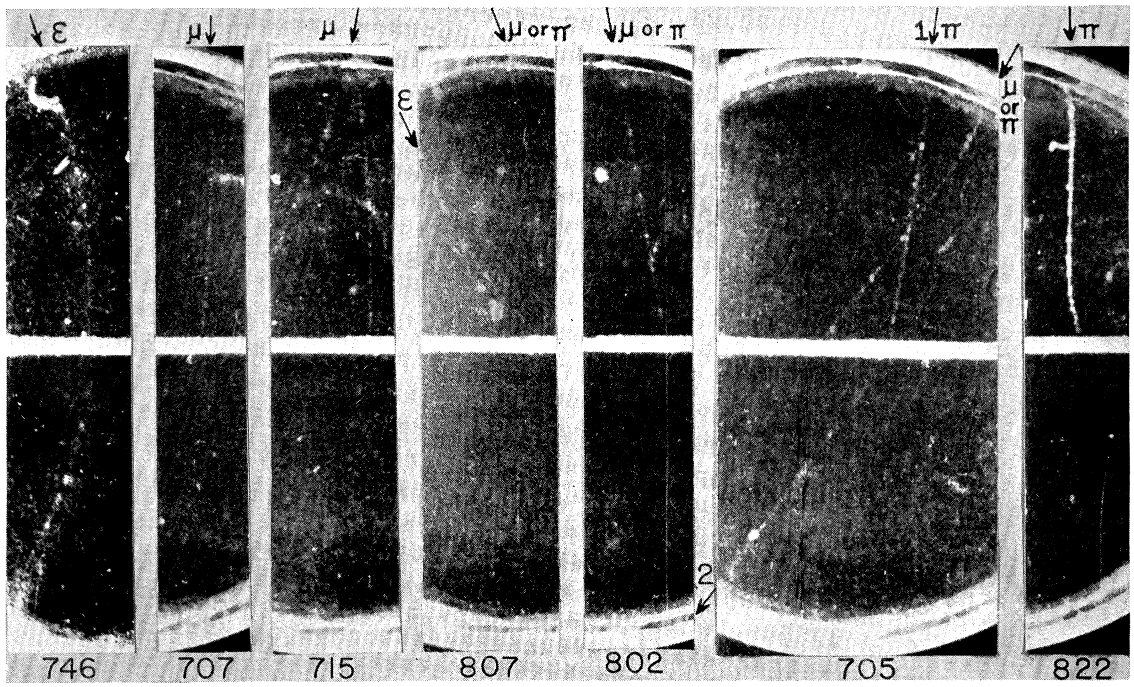

FIG. 2. Cloud-chamber photographs.

and radiation in 0.06 cm copper for an electron of this energy is 0.61 Mev. The agreement between the calculated and the measured values justifies the assumption that the particle is an electron.

The stopped particles, of $\rho<21$ cm and low ionization, are obviously electrons.

As a second group of the stopped particles we may consider those whose radius of curvature, though larger, could exactly be measured, i.e., numbers 755, 707, 715, 754–1 and 2, and of which examples are shown in Fig. 2. Their maximum curvature is 150 cm, a value which is smaller than the critical curvature for mesotrons which is 165 cm and 305 cm, respectively, for the thin and the thick halves of the plate. Thus they can be identified as mesotrons or protons. A differentiation between these possibilities can be made from a consideration of the ionization produced in the gas. Even for the highest curvature of these 5 tracks, which is 150 cm, a mesotron ionizes about 3.5 times as much as a fast electron, whereas a proton ionizes about 30 times as much as a fast electron. Such a strong specific ionization could not be missed in the visual inspection of the photographs. These 5 tracks are thus distinguishable from either electrons or protons, and may be identified as mesotrons.

Of special interest is picture 754 (Fig. 3) with two stopping particles which was recently discussed in a letter to *The Physical Review*.[3] The two particles are stopped in 0.32 cm copper. One has a positive charge with $\rho=75$ cm. The other is negative with $\rho=82$ cm. The curvature measurement, an estimate of the ionization, and the fact that the particles are stopped, give definite evidence for their mesotron nature. They diverge from the same region in the glass ring of the cloud chamber, and may therefore be classified as a mesotron pair. The electron going upwards from the plate is of so low energy that it can hardly be the decay electron from one of the mesotrons.

Examples of photographs of tracks stopped but with radii of curvature for which only a lower limit can be given are shown in Fig. 2,

[3] G. Herzog and W. H. Bostick, Phys. Rev. **58**, 278 (1940). The curvature of the negative mesotron was given wrongly as 45 cm instead of 82 cm. This does not change the conclusions.

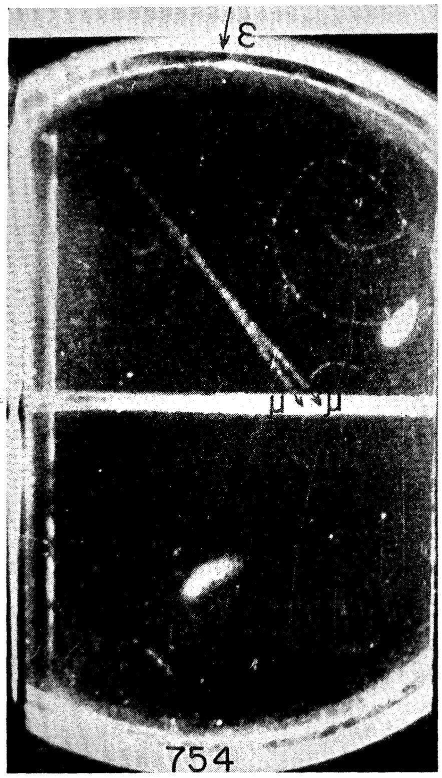

FIG. 3. Cloud-chamber photograph showing two particles stopped in 0.32 cm copper.

pictures 807, 802, 822, 705. Because of the large radii of curvature involved it is clear that electrons are excluded. These particles are either mesotrons or protons.

In picture 705 (Fig. 2) track 2 emerges from the plate where 1 enters and has as angle of 30° with the direction of 1. Either track 1 and 2 are produced by the same particle which is scattered at a large angle in the plate, or 1 actually stops in the plate and produces 2 as a secondary. The stereoscopic viewer indicates a higher ionization for 1 than for 2. Unfortunately nothing conclusive can be said from the curvature measurement. Track 1 has $\rho > 180$ cm and track 2 has $\rho > 200$ cm. If in a similar case one could measure the energies precisely and prove that 2 has a momentum larger than 1, this would show that 2 is the decay electron of 1.

Picture 822, Fig. 2: Although gas currents have distorted this track and its energy cannot be given, this picture is very interesting. One may safely estimate that $\rho > 150$ cm. The estimated specific ionization is much larger than that observed for a mesotron of similar momentum. The heavily ionizing secondary particle at the upper end and the big clusters along the track put it in a category with the heavy track reported in the first flight. The new picture, however, gives the additional information that such a particle can be stopped by 0.32 cm copper. We may tentatively identify it with a proton.

It is surprising that out of 5 slow mesotrons and 11 possible mesotrons stopped in the plate only one shows evidence of a disintegration electron, and even in this case the evidence is not conclusive.

Besides the pictures mentioned above, we have good evidence for a total of 28 slow mesotrons on pictures taken above 15,000 feet altitude. The same pictures contain 290 electron-like tracks. We therefore find the number of slow mesotrons to be 9.6 percent of the sum of electrons and fast mesotrons. This agrees well with the value of 9 percent found in the previous flight.

We wish to express our sincere thanks to Dr. A. H. Compton for his continued interest in this work.

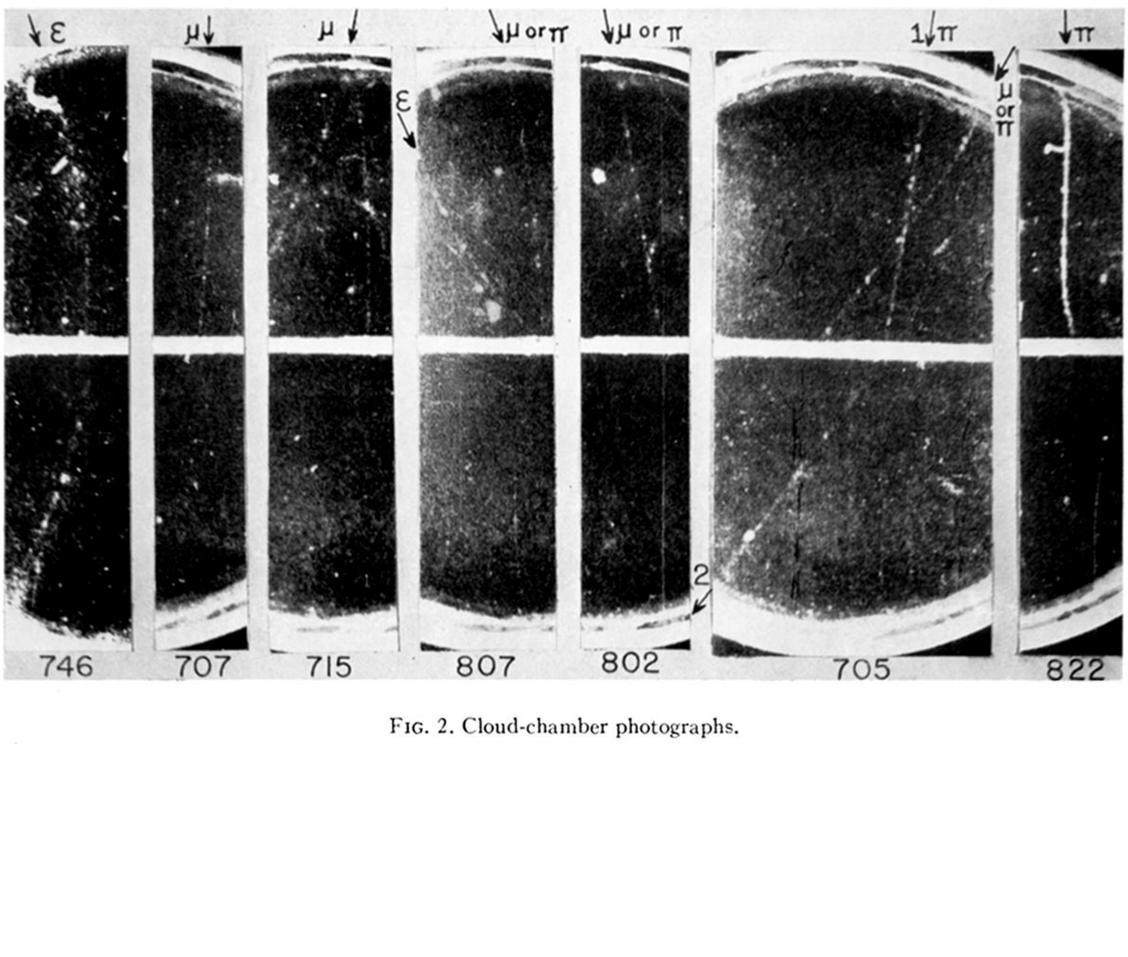

FIG. 2. Cloud-chamber photographs.

Fig. 3. Cloud-chamber photograph showing two particles stopped in 0.32 cm copper.