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The Cosmic-Ray Transition Curve in Lead.

Bartow Hodge
Louisiana State University and Agricultural & Mechanical College

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THE COSMIC RAY TRANSITION CURVE IN LEAD

A Thesis

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy

in

The Department of Physics

by

Bartow Hodge
M. S., Louisiana State University, 1948
June, 1954
MANUSCRIPT THESSES

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ABSTRACT

Different workers in the field of Cosmic Rays have investigated the so-called "Rossi" curve, the shower transition curve for lead, and have disagreed as to whether or not a second maximum actually existed. A 12" G-M tube controlled cloud chamber was designed and built to use in the study of this second maximum of the shower transition curve for lead. Stereoscopic pictures were taken to study the angular divergence of the pairs produced.

Over 14,000 photographs were taken and analyzed over a range of thickness of lead from 10 to 23 cm. The frames with penetrating pairs were reprojected and the angular divergence of the tracks measured with a protractor. A definite maximum was indicated at 17.5 cm. of lead for the total plot of showers and also for the pair production.

This experiment led to the conclusion: (1) that the second maximum of the cosmic ray transition curve for lead is real, (2) furthermore, that the second maximum exists at about 17.5 cm. of lead, (3) there is a production of a special kind of shower differing from cascade showers in origin and properties.
INTRODUCTION

Since the investigation by Hess\(^1\) and Kolhorster\(^2\), it has been recognized that a primary radiation incident upon the earth from external space produces in the atmosphere various secondary phenomena. This primary radiation and the various secondary phenomena reveal themselves by setting up a general ionization caused by various kinds of elementary particles (electrons, light quanta, mesons, protons, neutrons). As a result, this primary radiation becomes weaker and weaker as it penetrates deeper into the atmosphere or the earth, until at an equivalent depth of about 1000 meters of water it has practically vanished. (See Clay\(^3\) and others.) To classify these effects of the so-called ultra-, hohen-, or cosmic radiation it has been customary for some time to divide the primary radiation, i.e. cosmic rays, in the atmosphere into components that are identified by the secondary phenomena produced. The various components differ as regards the kind of particles and their origin. At the present state of our knowledge one can distinguish four components. The existence of a fifth component, which has been noticed at very great depths, is also probable, according to a few investigators. These secondary phenomena or components may be described in the following manner:

\(^1\)V.F. Hess, Physik. Z. 14, 610 (1913).
\(^2\)H. Kolhorster, Physik. Z. 14, 1153 (1913).
\(^3\)S. Clay, Rev. Mod. Phys. 11, 123 (1939).
1. **The soft radiation** (*cascade radiation*). This radiation consists of electrons, positrons, and light quanta, which undergo transformations from one to another in accordance with the laws of the cascade theory; it represents the principle part of the cosmic radiation from a height of about 7 kilometers on up to very great heights. The well known maximum of ionization at about 16 to 20 kilometers is also probably produced by electron radiation. At sea level the intensity of this component has already shrunk to a very small fraction of its initial intensity.

2. **The penetrating radiation.** This consists of mesons which are produced in the atmosphere by another radiation (most probably protons). The intensity of this penetrating radiation increases continuously almost to the top of the atmosphere. An intensity maximum must definitely occur somewhere since the mesons as radio-active particles cannot come to the earth from external space. Recent research by rocket and high altitude airplane flights indicates a leveling out of the penetrating radiation intensity above about 7000 meters. In the middle of 1947 came the discovery of the heavy meson, the pi-meson, through the use of the nuclear photographic emulsions. The different kinds of mesons are distinguished by different values of spin moment and mean life time and make up the penetrating component with different relative intensities at different heights. This component decreases with increasing

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depth much more slowly than the soft component and has been
detected down to depths of 400 meters of water and more.

3. The soft secondary radiation of the mesons. This
consists of electrons, positrons, and light quanta which are
formed by the mesons through collision processes and through
radio-active decay. In general, it is in equilibrium with
the meson component but falls off with increasing depth some-
what more slowly than the meson intensity, a fact which is to
be associated with the increasing hardness of the meson radia-
tion.

4. The proton and neutron radiation. Its intensity
runs parallel to that of the cascade radiation up to great
heights; this fact indicates that, at least in the lower
atmospheric layers, the proton-neutron component is formed
to a large degree by the electrons, positrons, and light quanta
in the incident radiation. Moreover, strong arguments support
the view that protons are incident upon the earth from external
space, perhaps even representing the principal part of the
primary radiation and that at very great heights the proton
component is for the most part a primary radiation, which there
excites the meson components and the cascade radiation.

5. Other components. The meson components can be
followed down to depths of more than 400 meters of water; in
the greater depths it becomes weaker relatively fast. But even
in 1000 meters equivalent depth of water an ionization caused
by cosmic rays can be definitely demonstrated. (Cf. Clay\textsuperscript{6} and his associates.) Measurements by Barnothy and Forro\textsuperscript{7} indicates that here the ionization is produced principally by a soft radiation. If this is correct, the results can be explained by the assumption that the cosmic rays are carried to these depths by a new electrically neutral component; as the carrying agent, one can invoke a neutral Yukawa particle or a Pauli "neutrino". A more usual assumption is the creation of the soft component by the penetration of $\mu$ mesons. However, these questions can be answered only by further experiments and measurements.

Greisen\textsuperscript{8} and associates and Tiffany and Hazen\textsuperscript{9} have carried out experiments far underground to determine the nature of this component capable of penetrating such great depths. Recently Kessler and Maze\textsuperscript{10} have described several experiments giving evidence for existence of penetrating secondary radiation at sea level and far underground.

\begin{itemize}
\item \textsuperscript{6}J. Clay and A. Van Gemert, \textit{Physica} \textbf{6}, 497 (1939).
\item \textsuperscript{7}J. Barnothy, \textit{Z. Physik} \textbf{115}, 140 (1940).
\item \textsuperscript{10}D. Kessler and R. Maze, \textit{Physica} \textbf{18}, 528 (1952).
\end{itemize}
SHowerS WITH PenetrAtiNg ParTICLEs

The question arises whether showers containing several penetrating particles are also observed in the cosmic radiation. This is, theoretically, of fundamental significance, since from the presence of such showers one might come to some conclusion about the existence of genuine multiple processes (or explosions) in which several particles are created in a single act. This type of explosion-like shower is to be expected, theoretically, according to the Yukawa theory (Cf. W. Heisenberg\textsuperscript{11,12}). A distinction is to be made between the genuine showers and the pairs of penetrating particles which are occasionally counted in with the showers. In the discussion that follows the word "shower" will be applied only to processes involving at least three particles; the discussion of meson pairs will be dealt with separately in the section below. The word meson as used in the following part of the thesis does not necessarily mean a particle with mass lying between that of an electron and a proton. Penetrating pairs or particles were determined by a visual inspection of

\textsuperscript{11}W. Heisenberg. \textit{Z. Physik} \textbf{113}, 61 (1939).

the photographs to be tracks caused by particles of minimum ionization and capable of penetrating at least 1/2 inch plate glass. Only particles energetic enough to give straight tracks throughout the length of the chamber were used. In this definition, we may have included fast electrons and protons as well as mesons.

1. Meson pairs. The first indication of pairs of penetrating particles resulted from investigations by Maas\(^\text{13}\) and by Schmeizer and Bothe\(^\text{14}\). The latter authors investigated local showers in coincidence with extensive showers with counters at a great distance from a shower-exciting layer and under such conditions found the so-called second maximum of the "Rossi" curve strongly marked at about 17 cm. of lead. They came to the conclusion from this that rays exist with a range of about 17 cm. in lead. The various repetitions of this experiment undertaken with slightly varied geometry, however, have not led to a complete confirmation of the existence of the second maximum.

A more certain proof for the appearance of pairs of penetrating particles, and indeed of meson pairs, is supplied by the work of Braddock and Hensby\(^\text{15}\) (discussed below),

\(^{13}\text{H. Maas, Physik. Z. 35, 858 (1934).}\)
\(^{14}\text{K. Schmeizer, Z. Physik. 112, 501 (1939).}\)
\(^{15}\text{J.J. Braddock and G.S. Hensby, Nature (London) 144, 1012 (1939).}\)
Leisegang\textsuperscript{16}, Herzog and Bostick\textsuperscript{17,18}, McCusker and Millar\textsuperscript{19}, Maze\textsuperscript{20}, Pfotzer\textsuperscript{21}, and of Chang and Castillo\textsuperscript{22}.

Braddick and Hensby have undertaken counter-controlled cloud chamber pictures in a London subway 30 meters underground. They obtained 1900 photographs with single meson tracks. The mesons were recognized by their uneventful passage through 1.4 cm. and 2.5 cm. of lead in succession. Of these 1900 photographs, 5 showed double tracks of mesons with an apparently common source in the layer of earth above the chamber. With 1900 single tracks only 0.057 accidental double tracks were to be expected from the geometry of the counters.

Leisegang made counter-controlled Wilson photographs, in which 11 and 16 cm. of lead in turn were placed above the chamber and a 1 cm. lead screen in the chamber. Among 900

\textsuperscript{16}S. Leisegang, \textit{Z. Physik} \textbf{116}, 515 (1940).
single meson tracks, he found 3 double tracks, the origin of which was in the producing layer. The proof of their meson character was realized in that the particles were scarcely deflected in the screen in the chamber (and were therefore energetic), and they produced no secondary rays.

McCusker and Millar investigated the ratio of penetrating particles to electrons in extensive showers at sea level and found the ratio to be 2.5 per cent.

The report by Kessler and Maze in 1952 described several experiments giving evidence for the existence of penetrating secondary radiation at sea level and far underground.

Finally, Herzog and Bostick have observed the formation of a meson pair in a cloud chamber photograph taken at high altitude in an airplane.

There can, therefore, no longer be any doubt that occasionally pairs of mesons are formed.

2. Penetrating showers. According to certain ideas regarding the formation of mesons by close interaction of nucleons, investigations of penetrating showers should provide a most fruitful source of knowledge about the laws describing the interaction of fundamental particles. (Cf. L. Janossy23). In order to see some of the problems involved in the experimental investigations of penetrating showers, it is worthwhile to consider the transition curve

23L. Janossy, Phys. Rev. 84, 345 (1943).
for showers under an absorber (the "Rossi" curve), say of lead, as indicated schematically in Figure 1. Here the counting rate $N$ of three-fold coincidences ABC for the set shown in the figure is plotted against the absorber thickness $T$. The curve rises and passes through a maximum initially and then virtually flattens out at some saturation value of counting rate. As is well known, under small thicknesses of lead most of the counts are attributable to cascade showers of electrons and photons excited in the lead by the electrons or photons of the cosmic radiation which strike the absorber. At large thicknesses, however, most of the photons and electrons in the cosmic radiation and the cascade showers excited by them, are absorbed, and we must look to some other radiation to explain the non-zero saturation value of the Rossi curve.

It has been established, primarily by Janossy and collaborators (in references quoted in the next paragraph) that most of this residual counting rate can be attributed to showers made up of knock-on electrons accompanying single penetrating particles. Practically all of the rest of the saturation counts (shown in exaggeration as the cross-hatched area in Figure 1) can be attributed to showers containing more than one penetrating particle. It is these showers only that we wish to consider in this discussion.

The existence of such penetrating showers seem to have been established first with the cloud chamber. As early as
Figure 1
Schematic diagram indicating the composition of a Rossi curve.

Figure 2
Experimental arrangement of Janossy and Rochester.
(Proc. Roy. Soc. A182, 180 (1943).)
1937 L. Fussell obtained in a cloud chamber direct evidence of showers containing several particles capable of penetrating several lead plates without deviation or multiplication, from which it was concluded that the particles were more massive than electrons. Evidence of a similar nature has been obtained since then of pairs of penetrating particles, near sea level by J. J. Braddick and G. S. Hensby, by J. G. Wilson, by S. Leisegang, by D. Kessler and R. Maze, G. Pfotzer, and by L. Seren; and at mountain altitude or moderate airplane altitudes by W. M. Powell, D. J. Hughes, G. Herzog and W. H. Bostick. SHOWERS OF more than two penetrating particles were observed with cloud chambers at sea level by L. Janossy, C. B. A. McCusker, and

20Kessler op. cit. p. 528.
21Pfotzer, op. cit. p. 353.
28W. M. Powell, Phys. Rev. 56, 474 (1940).
30D. J. Hughes, Phys. Rev. 60, 414 (1941).
G. D. Rochester, by D. M. Bose, B. Choudhuri, and M. Sinha, and by R. P. Shutt; and at mountain altitudes by W. M. Powell, E. O. Wollan, by W. H. Bostick, and by W. E. Hazen and J. Daudin. Beside these papers, G. D. Rochester has reported a systematic investigation at sea level by means of a chamber controlled with counters so as to select penetrating showers.

The clear demonstration by counter experiments that penetrating showers occur was not furnished until considerably after their detection with the cloud chamber. While the apparent existence of a second maximum in the Rossi curve was cited by W. Bothe in 1939 as evidence for penetrating showers, a later investigation on this controversial point

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by E. P. George, L. Janossy, and M. McCraig\textsuperscript{42}, showed negative results with respect to the presence of a second maximum. These authors reviewed the earlier work on this problem and suggested an explanation for some of the contrary results previously reported. However, the experiments of G. Wataghin, M. de Souza Santos, and P. A. Pompeia\textsuperscript{43}, and of L. Janossy and P. Ingleby\textsuperscript{44}, showed definitely that showers of penetrating particles are found under lead absorbers, and moreover that some of these showers are connected with extensive air showers, whereas others are not. It was shown that showers under lead absorbers could not be ordinary cascades of electrons and photons because of the large thickness of the lead shields, and that they could not be knock-on showers accompanying a single penetrating particle because of the small probability for the number of multiple knock-on processes required to give the counts obtained with the experimental arrangements used. (Cf. L. Janossy\textsuperscript{45}, Pfotzer\textsuperscript{46},


\textsuperscript{43}G. Wataghin, M. de Souza Santos, and P. A. Pompeia, Phys. Rev. 57, 61 (1940).

\textsuperscript{44}L. Janossy and P. Ingleby, Nature (London) 145, 511 (1940).


\textsuperscript{46}G. Pfotzer, Z. Naturforsch, 8a. 335 (1953).
and Kessler and Maze\textsuperscript{47}). A more informative counter investigation of the nature of the ionization producing the penetrating showers appears to be that of L. Janossy and G. D. Rochester\textsuperscript{48}. The result of their experiment is described below.

Their experimental arrangement is shown in Figure 2. The top part of the apparatus is an absorber \( \xi \), whose thickness is to be varied from \( \xi = 0 \) to \( \xi = 35 \text{ cm. lead} \), and whose purpose is to absorb the component of the cosmic radiation which produces penetrating showers. Immediately below the absorber \( \xi \) is a tray \( A \) of thirty-five high efficiency counters in parallel, which are in anticoincidence with the counters below, and whose purpose is to show which fraction of the radiation producing penetrating showers is ionizing, and which is non-ionizing.

The next part of the apparatus is a lead absorber \( T \), which serves primarily to increase the number of penetrating showers recorded, as a result of their generation in the lead by the action of incoming cosmic radiation. The block \( T \), which of course acts also as an absorber, is either absent \( (T = 0) \) or fixed at 10 cm. lead \( (T = 10) \).

Beneath \( T \) is the coincidence set \( B \) of fifteen counters, divided into three subsets \( B_1, B_2, B_3 \) each containing five

\textsuperscript{47}D. Kessler and R. Maze, \textit{Physica} 18, 528 (1952)

counters connected in parallel, and located as shown in the
figure. A three-fold coincidence $B_1, B_2, B_3$ indicates that
at least three counters of tray $B$ have been discharged simult-
aneously. The purpose of tray $B$ and its associated circuits
is to record the presence of showers below $T$.

The absorber $S_1$ is of lead 15 cm. thick and acts to
filter out the soft component. The counter tray $C$ carries
eight counters divided into two subsets $C_1, C_2$, each
containing four counters connected in parallel and located
as shown on the figure. A two-fold coincidence $C_1 C_2$ indicates
that at least two counters of tray $C$ have been discharged
simultaneously. The purpose of tray $C$ and its associated
circuits is to record the presence of showers below $S_1$.

The absorber $S_2$, like $S_1$, is of lead 15 cm. thick, and
also serves to filter out the soft component. The final
counter tray $D$, like $C$, carries eight counters divided into
two subsets $D_1$ and $D_2$, serving to record by two-fold coin-
cidences the presence of showers able to penetrate all the
absorbers above it. The two lower trays are shielded from
side showers by at least 50 cm. lead.

Observations were made of rates of seven-fold coin-
cidences $B_1 B_2 B_3 C_1 C_2 D_1 D_2$, which indicates that at least
three counters from tray $B$ and two each from trays $C$ and $D$
were discharged; and anticoincidences $A B_1 B_2 B_3 C_1 C_2 D_1 D_2$, that
is seven-fold coincidences of the type just described which
are not accompanied by discharge of any of the counters of tray A. An anti-coincidence presumably denotes the formation of a penetrating shower by non-ionizing radiation.

Janossy and Rochester were able to show that about three-quarters of the coincidences were caused by penetrating showers, the contributions from cascade showers, triple knock-on electrons, and accidental coincidences making up the remainder. These workers showed further that not more than one percent of the anti-coincidences could be attributed to sources other than penetrating showers. Further it was concluded that penetrating showers, as detected with the apparatus described in their report, are produced by both ionizing and non-ionizing radiation. About half are produced in the lead of the apparatus and the rest in the air above the apparatus. Furthermore, while there is no evidence that photons do not produce penetrating showers, it follows that most of the penetrating showers observed were produced by a radiation more penetrating than photons. The frequency of anti-coincidences decreased when the top absorber was increased in thickness from 5 to 35 cm. of lead, thus it is clear that the range of the penetrating radiation must exceed 5 cm. of lead. But in this thickness of lead low and medium energy photons would be absorbed, and high energy photons would be virtually certain to produce showers (and hence would discharge the anti-coincidence counters and not be recorded as non-ionizing particles.) Thus it appears that the non-ionizing
radiation which produces the penetrating showers is not
genic in nature. From additional measurements it was deduced
that the intensity of this radiation at sea level is about
10\(^{-5}\) times the total intensity of cosmic radiation.

Janossey and Rochester speculated on the nature of the
radiation which produces penetrating showers, remarking that
neutrons and photons might be the non-ionizing and ionizing
particles, respectively. Further analysis on this basis is
given by L. Janossey\(^49\), who modified the theory of J. Hamilton,
W. Heitler, and H. W. Peng\(^50\). This theory postulates that
during fast collisions mesons are emitted singly. At high
energies of emitted mesons, the packing of the nucleons in
the nuclei of the target atoms has very little effect, but
at moderately high energies (below about 10\(^{11}\) ev) this
modification of the theory produces two main results: first,
that an incident nucleon is likely to collide several times
with the target nucleons if a collision takes place at all,
and hence that several mesons are likely to be emitted in a
single impact with a nucleus; and second, that at these
moderately high energies the mean free path of the incident
nucleons will be greater than expected on the original
Hamilton-Heitler-Peng theory, because the cross section of
the target nucleons overlap, and produce an effective net

\(^49\) L. Janossey, Phys. Rev. 64, 345 (1943).

\(^50\) J. Hamilton, W. Heitler, and H. W. Peng, Phys. Rev. 64, 78 (1943).
area smaller than the sum of the individual cross sections (see also W. Heitler and P. Walsh\textsuperscript{51}). With these modifications Janossy was able to effect a rough confirmation of the theory with the results of the experiment previously described, as well as with some other results by these workers. Janossy compared the predictions of the modified Hamilton-Heitler-Peng theory with cloud chamber experiments also, but without much correlation.

To extend the possibility of comparison with the Hamilton-Heitler-Peng theory, Janossy and Rochester\textsuperscript{52} examined the transition effect of penetrating showers, that is the dependence on thickness of absorber $T$, of counting rate of penetrating showers as measured with an apparatus of the type shown in Figure 2, but simplified in such fashion as to count penetrating showers whether initiated by ionizing or non-ionizing radiation. Their results could be accounted for in terms of a radiation of about $5$ cm. range in lead, just as was to be expected from the theory as modified by Janossy. Certain results in this investigation however, suggested that the phenomena might be more complex than it appeared at first, a supposition verified by experiments of Broadbent and Janossy\textsuperscript{53}.

\textsuperscript{51}W. Heitler and P. Walsh, Rev. Mod. Phys. 17, 232 (1945).


It is worthwhile to mention that the penetrating showers discussed above show a barometric coefficient much greater than the total cosmic radiation$^{54}$. The experiments of P. Auger and J. Daudin$^{55}$, and of M. Cosyns$^{56}$ lead to a barometric coefficient for extensive showers of between minus ten and twenty per cent per centimeter Hg, which is about the same as the Cornell group$^{54}$ found for the local penetrating showers.

Part of the connection between penetrating showers and extensive showers is clarified by the work of Broadbent and Janossy. Their essential finding is that the penetrating showers associated with extensive showers ("extensive penetrating showers") are of a different type from penetrating showers not associated with extensive air showers ("local penetrating showers"). They concluded that the transition effect is mass proportional only and not dependent on the atomic number $Z$.

In summary we may state that it seems definitely established, at least at sea level, that penetrating ionizing


$^{55}$P. Auger and J. Daudin, Phys. Rev. 61, 91 (1942).

particles occur in groups of low density, that these showers show a much stronger barometric effect than the total radiation, that these showers are of two types, the local penetrating showers excited by both ionizing and non-ionizing radiation (presumably nucleons) in the transition layer of absorber immediately above the detecting instrument, and the extensive penetrating showers, accompanying or excited by the photons or electrons in extensive air showers. While there seems to be no evidence that penetrating showers do not contain ordinary mesons, it has been conclusively established that other particles such as recoil nucleons are also present.

Although some attempts have been made to determine the relations between penetrating showers and the variation of certain components of the cosmic radiation throughout the atmosphere, the clarification of these connections demand further experimentation, particularly at high altitudes.

If it is true that mesons are produced in penetrating showers, then the clarification of the processes involved become of greatest interest. Repetition and extension of the experiments described at various altitudes and latitudes are strongly called for. While the rather infrequent occurrence of penetrating showers, together with their complex nature, makes their investigation none too simple, the possible fruits would seem to justify the required effort.
If the frequency of shower production due to cosmic rays is measured below an absorber, for instance lead, and if the frequency is plotted against the thickness of absorbing material, a curve will be obtained which rises to a maximum at about 1.5 centimeters of lead and diminishes with corresponding rapidity, until at a thickness comparable to 4 or 5 centimeters it attains a condition in which the curve decreases slowly and approximately linearly with the thickness of absorber. Such curves are called "Rossi" curves. Ackemann and Hummel\textsuperscript{57}(1934) observed such curves with the additional feature of a second maximum in the neighborhood of 15-18 centimeters of lead. The existence of the so-called second maximum has been questioned. Schwegler\textsuperscript{58}(1936), Morgan and Nielsen\textsuperscript{59}(1937), Auger, Maze, Ehrenfest, and Freon\textsuperscript{60}(1939), Altmann, Walker, and Hess\textsuperscript{61}(1940), and Weaver\textsuperscript{62}(1953) failed to observe the second maximum. On the other hand the second maximum has been observed

\textsuperscript{57} Ackemann and Hummel, \textit{Naturwiss.} \textbf{22}, 169 (1934).
observed by equally prominent men in cosmic ray work including Priebach\textsuperscript{63}(1936), Swann and Ramsey\textsuperscript{64}(1940), Bothe\textsuperscript{65}(1939 and 1950), Clay\textsuperscript{66}(1951), and Broussard and Graves\textsuperscript{67}(1941); also Nielsen and Morgan\textsuperscript{68} found the second maximum with one counter arrangement and failed to observe it with another arrangement. In the determinations discussed, only Broussard and Graves used a cloud chamber; the others used different arrangements of G–M tubes.

Greisen and Nereson\textsuperscript{69} have discussed the inefficiency and other sources of error in cosmic ray measurements with self-quenching counters and arrived at the conclusion that the errors studied could account for the absence of the second maximum in the experiments performed by the workers previously cited.

Chaudhury\textsuperscript{70}(1951) discussed the controversial existence of the Rossi second maximum of cosmic rays in light of his

\begin{thebibliography}{99}
\bibitem{64} W.F.G. Swann, \textit{Rev. Mod. Phys.} \textbf{11}, 242 (1939).
\end{thebibliography}
experiments with lead using triple coincidence arrangements of counters under different geometrical conditions and obtains definite evidence of the existence of a second maximum at about 18 cm. lead and a third maximum at about 23 cm. lead. Except with a drop in coincidence at about 20 cm. of lead, both these maxima might be considered as a single maximum from 16 to 24 cm, similar to the work reported by Schopper and others.

From a careful analysis of all the investigations made by other workers, it seems that the failure of some workers to confirm the existence of these maxima may be due to: (a) overlapping by oblique showers when all counters are placed very near the absorber and (b) much greater percentage of side showers of external and internal origin when all the three counters without appreciable vertical separation are placed too far below the absorber for narrow angle showers. An ideal arrangement as follows from this investigation, is that one of the counters should be placed immediately below the absorber and the two others as far below the absorber as possible, or the use of a cloud chamber.

Aiya\textsuperscript{71} has reported a sudden drop in meson intensity after passing through 21 centimeters of lead.

Cocconi\textsuperscript{72} has proposed the theory that the second maximum, if real, may be due to narrow angle showers.

To investigate the existence of the second maximum in the transition curve for lead for local penetrating showers, and to check the work of Aiya, a large Wilson cloud chamber was constructed and operated continuously over a two and half month period to obtain sufficient data to be statistically sound. The arrangement of the triggering counter tubes and the lead used as the penetrating material as well as the cloud chamber construction is discussed below under the section on mechanical construction. The Wilson chamber was chosen in preference to counter tube arrangements in order to eliminate errors such as discussed above.

\textsuperscript{72c} Cocconi, Phys. Rev. 72, 964 (1948).
The history of the cloud chamber begins with the investigation of C. T. R. Wilson who showed by direct experiments that nuclei other than dust particles could act as centers of condensation for water droplets from a supersaturated vapor, and who speculated also as to whether or not these nuclei could be charged particles. J. J. Thompson demonstrated that ions, generated by an x-ray beam, could act as condensation centers. Following additional experimentation along these lines, Wilson was able to obtain tracks due to x-rays, and alpha, beta, and gamma rays. His cloud chamber method may be described as follows. A chamber is filled with a noncondensable gas saturated with a condensable vapor. The chamber is suddenly expanded, the resulting temperature decrease causing supersaturation of the gaseous mixture. Excess vapor condenses around ions as nuclei to form droplets. A column of droplets formed on the ions produced by passage of a charged particle makes its track visible. While the basic technique of cloud chamber operation has not been changed since the first tracks were obtained, the constant

Improvement made by Wilson and others has increased its value greatly. (Cf. Das Gupta and Ghosh\textsuperscript{77} and Wilson\textsuperscript{78,79}.)

Theory of droplet formation.

1. Supersaturation. Suppose that we have two substances, the first of which (gas) can exist by itself only in the gaseous state for the ranges of temperature and pressure to be considered, and the second of which (vapor) can exist by itself in the liquid as well as in the gaseous state at some values of temperatures and pressure to be considered.

Now suppose that these two substances are mixed within a closed container in such proportions and at such temperature and pressure that some liquid is in contact with a gaseous phase. The liquid phase will contain molecules of both the gas and the vapor, but this phenomenon is not of immediate interest. We are here concerned with the fact that the gaseous phase contains molecules both of the gas and of the vapor, in concentration determined by their partial pressures. If equilibrium in time has been attained, the gas is said to be


saturated with the vapor, and the partial pressure of the vapor is known as the saturation vapor pressure. The concentration of vapor in the gas may then be measured experimentally, or may be computed from a knowledge of the vapor pressure of the liquid as a function of temperature. If the concentration of vapor is greater than the value at saturation, the gas is said to be supersaturated with the vapor; if less, unsaturated.

We may define "supersaturation" $\mathcal{S}$ as the ratio of the density of the vapor in the gaseous mixture (mass of vapor per unit volume of gaseous mixture) in the supersaturated state to the corresponding density in the saturated state at the same temperature. A supersaturation of unity corresponds to a saturated gas, of less than unity to an unsaturated gas, and of greater than unity to a "bona fide" supersaturated gas.

In the cloud chamber the supersaturation is produced by expanding the chamber rapidly and smoothly so that to a good approximation an adiabatic isentropic expansion results, at least away from the walls. Before expansion the gas is saturated with vapor, as it is in contact with liquid. The temperature drops from its initial value $T_1$ to the value $T_2'$ before condensation, then rises slightly to $T_2$ just after condensation because of the latent heat released. It is possible to compute the supersaturation as a function of expansion ratio, $1 + \gamma$, the ratio of final volume $V_2$ to initial volume $V_1$, provided we know the initial temperature and pressure
of the gas mixture, and some properties of the gas and of the vapor separately. Das Gupta and Ghosh note how this calculation may be made and cite results.

From the results of Das Gupta and Ghosh, it may be seen how the final temperature decreases with increasing $\gamma$, the supersaturation also increasing (although $\delta$ depends not merely on the amount of cooling, but also on the values of the vapor pressure at the initial and final temperatures.) We note moreover that with argon a high supersaturation occurs for a given expansion. This is a consequence of the high value of $\gamma$ characteristic of monatomic gases. This large cooling with the inert gases is frequently taken advantage of in filling cloud chambers, since the small expansion obviates many mechanical difficulties. The saturated vapor pressure of a given vapor depends only on the temperature and is independent of total pressure, but the partial pressure of the gas is equal to the total pressure of the gaseous mixture minus the partial pressure of the gas. By increasing the total pressure at constant temperature we raise the partial pressure of gas without altering the partial pressure of the vapor, and hence increase the proportion of gas molecules in the mixture, with subsequent increase in the ratio of specific heats. This is the reason for the increased cooling at high initial pressures for a given expansion, and consequently, increased supersaturation.

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77 Das Gupta, op. cit. p. 225.
2. **Droplet Formation.** "The attractive forces between molecules are the agency which keeps a liquid confined to a definite volume. The disposition of these forces at the surface of a droplet condensed about an uncharged condensation nucleus differs from the disposition at the surface of a plane sheet, in such a manner that a molecule tends to escape more easily from the droplet. At a given temperature $T$, the effect of surface tension $\gamma$ causes a decrease in the vapor pressure $p_r$ of a liquid above a droplet of radius $r$ from the value $p_\infty$ above a droplet of radius infinity, that is, a plane sheet. It is this latter value which is ordinarily known as the vapor pressure of a liquid.

In the event that the droplet is formed about a nucleus carrying a charge $e$, it may be shown that\(^\text{80}\)

$$\ln \frac{p_r}{p_\infty} = \frac{M}{RT^2} \left( \frac{4T}{\pi} - \frac{e^2}{8\pi\varepsilon_0 r^2} \right)$$

Eq. 1

where $R$ is the gas constant, $\rho$ the density of the liquid, $M$ its molecular weight, and $\varepsilon$ its dielectric constant.\(^\text{81}\) The first term on the right hand side of Eq. 1 shows that the vapor pressure of the droplet tends to be raised over that of a plane sheet by the action of the surface tension, while the


second term indicates that the vapor pressure tends to be lowered by the action of the electric charge. (It is difficult to see how this expression applies for single point charges, as it is derived on the basis of charge distributed throughout a sphere. Nevertheless, it seems to give a partially satisfactory explanation.) Whether an increase or a decrease actually occurs depends of course upon the relative magnitudes of the two terms.

The solid lines in Figure 3a, b, give the pressure ratio \( \frac{P}{P_{\infty}} \equiv \frac{r}{r} \) as a function of radius \( r \) for water at 18°C, as calculated from Eq. 1, both for droplets condensed around uncharged nuclei and around singly charged nuclei. A vertical line at \( r \approx 2 \times 10^{-8} \) centimeters indicates the radius of a single water molecule. On these same graphs we may use the vertical scale of pressure ratio to represent supersaturation \( \mathcal{S} \), since at constant temperature a vapor density ratio equals a partial pressure ratio. The horizontal line at a pressure ratio of unity indicates saturation. With the aid of these figures it is easy to predict the behavior of droplets in a mixture of gas and water vapor.

First consider droplets condensed on uncharged nuclei (Figure 3a). To fix our ideas, suppose that after expansion the supersaturation \( \mathcal{S} \) equals 5.0, and that the radius \( r \) of the uncharged droplet is \( 5 \times 10^{-8} \) centimeters corresponding to a point A in the figure. We see that the vapor pressure of the droplet is greater than the partial pressure of water.
in the gas, with the consequence that the droplet begins to evaporate. As its radius grows smaller, its vapor pressure goes up, in most cases far faster than the increase in supersaturation resulting from the increased number of water molecules now in the gaseous phase which have been lost from droplets. Hence the droplets evaporate completely, the supersaturation following a path such as shown by the dashed curve from A, the pressure ratio following the solid curve (if we neglect the slight temperature variation caused by heat absorbed by the evaporation). A similar fate awaits other uncharged droplets under conditions such that their "initial state" is represented by a point to the left of the solid curve in Figure 3a. On the other hand, if an uncharged droplet has a radius say of $10 \times 10^{-8}$ centimeters for a supersaturation of 5.0 (point B), the figure shows that the partial pressure of the water in the gaseous phase is greater than the vapor pressure of the droplet, whence condensation begins. The vapor pressure of the drop falls, and additional condensation occurs, the supersaturation falling along some dashed curve until it approaches unity. The exact course of the dashed curves from A to B depends on the amount of vapor per droplet, but unless this quantity is very small the qualitative conclusions outlined are valid (the slopes are much exaggerated from the usual conditions). Thus in the absence of neutral condensation centers above a certain critical size, no stable visible droplets can be formed.
Now suppose that we consider droplets condensed about a single electrical charge, for which case Figure 3b is applicable. For the point A in this figure the partial pressure of the water in the gaseous phase is greater than the vapor pressure of the droplet, and hence condensation occurs and the droplet grows, the behavior being practically identical with that in the case of the uncharged droplet. Suppose however that we start at a point such as B. Again condensation occurs, but at the intersection of the dashed curve from B with the solid curve for $\pi$ the partial pressure equals the vapor pressure and equilibrium is attained at a droplet radius of only several Angstrom units, too small to be visible. If we start at C, the droplet evaporates until the intersection of the dashed curve with the solid curve is reached, with formation of an invisible droplet. We expect then visible droplets only if the supersaturation $\pi$ always lies above the pressure ratio $\pi$. The initial supersaturation must then exceed some lower limiting value, equal to 4.1 for water at 18°C at maximum of the curve in Figure 3b, in order to get visible droplets condensed about singly charged ions. With air as a gas, a supersaturation of 4.1 requires an expansion ratio of 1.25 at 18°C, in close agreement with experiment."

In order to explain the presence of a general fog throughout a chamber at quite high supersaturations it has been assumed that clusters of vapor molecules are formed by a mechanism not very well understood. With water the upper limit of
FIGURE 3

Diagrams to illustrate the behavior of (a) uncharged and (b) single-charged droplets of water upon expansion of a cloud chamber. The solid curves represent $\Pi$, the ratio between the vapor pressure of a droplet of radius $r$ and the vapor pressure over a plane sheet of liquid ($r = \infty$). The dashed curves represent supersaturation $S$, the ratio between the density of water vapor in the gaseous mixture and the density of water vapor in a saturated gaseous mixture at $18^\circ$C. Further description is given in the text.
radius of droplets formed by these clusters seems to be about $5 \times 10^{-8}$ centimeters. For supersaturation above 3.0, such droplets are represented by points to the right of the solid curve in Figure 3a, and hence will grow into visible droplets. This phenomenon places an upper limit on the allowable supersaturation. A more complete explanation of the processes at high expansion ratios requires modification of Eq. 1 to take account of the variation of surface tension with the radius of the droplet.

An important phenomenon originally discovered by C. T. R. Wilson is that with most vapors ions of one sign of charge are more effective as condensation nuclei than ions of the opposite sign. For the commonly used mixture of ethanol with a minor fraction of water, the positive ions are more effective than the negative. The explanation offered for this class of phenomena is the assumption that a layer of one sign of electrical charge is formed at the surface of the drop, close to a layer of opposite sign in the gas, the polarity depending on the nature of the liquid and of the gas. The solid curve in Figure 3b is thus split into two curves, displaced in opposite directions from the original.

As a practical guide, we note that W. E. Hazen\textsuperscript{82,83} has shown for the very common vapor mixture 75 percent ethanol, 25 percent water that the condensation efficiency for the


positive ions is 95 percent when the observed negative ionization density is one-tenth that of the positive; that the condensation efficiency for the positive ions is virtually 100 percent when the observed negative ionization density is greater than one-fifth the positive. Since it is difficult to maintain a constant concentration of ethanol, Nielsen has investigated as well as the 75-25 concentration the two mixtures 40-60 and 87-13, and found that as long as the negative ion column density is at least half the positive, the condensation of the positive ions is virtually 100 percent efficient.

Beck\textsuperscript{84} found that mixtures of two pure alcohols were unsuitable for critical supersaturation. They required higher expansion ratios, but produced poorer tracks and higher background fogs than for either pure alcohols or water-alcohol mixtures. His investigations indicate that the condition for best tracks is obtained with a minimum expansion ratio of 1.125 for 65 percent ethyl alcohol and 35 percent water when air is used as the non-condensing gas. But still better results are obtained with 50 percent ethanol or normal propyl alcohol, 25 percent acetone, 25 percent water at an expansion ratio of 1.112. The presence of acetone increases the contrast between the tracks and background fog.

Illumination.

It is advantageous to obtain as brilliant illumination in the chamber as possible in order to permit stopping down the photographic lens and thereby increasing the depth of focus and the definition, or in order to secure high intensity of scattered light if weak tracks are being photographed. Since light is scattered much more readily through small than through large angles, it is possible to secure substantial gain in the effective illumination by making the angle between the axis of the camera and the direction of the incident illumination small. A fifty or hundred fold increase for an angle of 20° is possible over the illumination for an angle of 90°. With narrow chambers there is usually no choice in this matter, and the axis of the camera must be at right angles to the direction of illumination; but with deep chambers a considerable improvement may be made. Typical sources of illumination have been spark discharges through mercury vapor, capillary mercury lamps, and tungsten filament lamps operated at excess voltages for a fraction of a second. Usually the light is concentrated and collimated by condensing lenses and/or mirrors. Commercial lamp bulb manufacturers have developed quite recently xenon-filled tubes of very large luminous output. (Eg. Amglo, Chicago, Ill.)
Optics and photography of cloud droplets.

A cloud track offers two distinct types of objects for photography. Single vapor drops, of diameter of the order of $10^{-3}$ centimeters, give images of size and shape determined entirely by instrumental factors; i.e., by the diffraction disk of the lens aperture, by the lens aberration and the resolution of the photographic emulsion. The small close drops of clusters, on the other hand, formed by slow secondary electrons, yield images which reproduce to some extent the shape and scattering power of the cluster. Since these extended images are essentially the result of superposition of single-drop images, it follows that they are more easily photographed, and under poor conditions, they alone appear in the photograph. The tracks of alpha particles, slow protons and of heavier nuclei are extreme examples of drop clusters. The technique appropriate to good cloud chamber work requires that single-drop formations be recorded.

Inspection of a photograph on which single drop images can be distinguished shows that all of the images are of approximately the same size. In fast emulsions, the diameter of the drop image is between $2x10^{-3}$ and $3x10^{-3}$ centimeters, and the image is thus considerably larger than the purely optical image in the plane of focus. The size of the photographic image is therefore set entirely by the properties of the emulsion, by grain size and turbidity. It follows that the conditions for recording a drop image are that:
(a) the camera lens must collect enough scattered light from the drop to provide the necessary threshold intensity spread over an image disk of diameter, say, \(2 \times 10^{-3}\) centimeters, and

(b) it must focus this light into an optical image disk which is of appreciably smaller diameter.

The degree of blackening required in such small, disk-like images before they can readily be identified, is, of course, very much greater than would be required to differentiate extended areas, and is essentially a quantity to be determined experimentally. Only if there is a large excess of light will any appreciable number of larger images, corresponding to out-of-focus drops, be observed.

Since the light collected by the camera lens is distributed over a disk of constant area, the scattered intensity of illumination and the properties of the emulsion together define a certain minimum solid angle, subtended by the camera aperture at the drop, for image formation. Hence, when illumination and photographic equipment have been chosen, there is a maximum distance at which it is possible to photograph single-drop images. At this distance the depth of focus in the object space over which drops can be photographed will be a maximum.

The conditions in the exploratory photographs which are of particular importance in cosmic-ray research today offer a
variety of ways in which a given intensity of illumination can usefully be applied, and the conditions actually used must represent a balance between competing requirements. For example, suppose that photographs are being taken at a given level of illumination, and that the intensity of available light incident on the object drop is increased. The extra light may be applied (a) to give greater depth of focus at a given magnification, thus allowing a larger volume of chamber to be surveyed in each photograph, (b) to increase the magnification, thus increasing the separation of drop images, and allowing more accurate conclusions about ionization density in tracks, (c) to permit an emulsion of high resolution (but slower) to be used to the same purpose, (d) to increase the diffusion time of tracks without decreasing the precision of geometrical measurements. The second of these involves an actual reduction in the diameter of drop-images disks and thus its potentialities is limited by the standard of performance of optical equipment readily available.

Longer growth time of drops may be used to increase light utilization where possible. It is important to remember that the growth time is likely to be at least as long as the expansion time from the passage of the controlling particles until expansion is complete. The best compromise must be reached between the longest growth time feasible and the time limit imposed by distortions due to the usually dominant steady
convection currents of the chamber. In an example recently given by Adams and others, the growth time is nearly twenty times the expansion time, but this example is abnormal in so far as it refers to an exceptionally fast chamber, while the growth time could probably have been reduced at the expense of other factors involved in the supply and use of the illuminating flash.

\[\text{Adams, Anderson, Lloyd, Rau, and Sazena, Rev. Mod. Phys. 20, 334 (1948).}\]
The cloud chamber is of the rubber diaphragm type and has an inside diameter of about 12 inches. Figure 4 shows the assembly. The expansion ratio is varied by means of a system of three adjustment screws. The back stop, a 10-1/2 inch brass plate, is supported rigidly by the adjustment screws. The diaphragm is a 1/64 inch Fairprene® sheet. The glass window (one inch lime-glass disk) and the glass cylinder (cut from a battery jar®) are held together against the bottom ring (D) by the top ring and 1/4 inch brass screws. Synthetic rubber gaskets® are used for the vacuum seals. In this way the least amount of material surrounds the chamber. This is an advantage for studying cosmic-ray processes taking place inside the chamber, for the number of useless pictures due to the same process at the chamber wall is small. The thickness of the overall dead space at the back is about 2 inches. With argon gas saturated with ethanol, the chamber depth can be increased up to 8 inches. The depth used has been 4 inches. The chamber had very little turbulence. The expansion ratio may be read from the engineering scales along

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86 Obtained from DuPont, Wilmington, Delaware.
87 Corning Glass Co. Stock No. 6940.
88 Buna S rubber compounded Sulphur free by Esso Laboratories, Baton Rouge, Louisiana.
THE DIAGRAM SHOWS A VERTICAL SECTION OF THE CLOUD CHAMBER THROUGH THE AXIS

A. Pyrex glass cylinder - 12" O.D., 3/8" wall, 4" height.
B. Plate glass disk, 12" dia., 1" thickness, 1/8" plexiglass safety shield in front.
C. Specially compounded rubber gaskets, 1/16" thick-front gasket coated with aquadag -- clearing field electrode.
D. Front Stop - Duralumin, 1/8" dia. holes on 3/16" centers.
E. Faireprene diaphragm - 1/64" or 1/32" thick.
F. Back Stop - brass plate, 5/16" thick, 10-1/2" dia., 3/16" dia. holes on 1/4" centers.
G. Natural rubber gasket to act as sealing agent for piston armature.
H. Magnet assembly controlling operation of release valve.
I. Magnet release coil - 20 turns of #20 wire.
J. Expansion ratio adjustment screws - 32 thds. per inch.
K. Engineering scale to indicate expansion ratio.
L. Valve inlet assembly - to allow evacuation for cleaning and to admit argon and alcohol for the desired operating conditions.
side the adjustment screws. The air passage to the expansion valve is smoothly constricted. The brass plate back stop has 3/16 inch diameter holes on 1/4 inch centers. For good photography, a black velvet cloth covers the front stop. There are only 3 vacuum seals needed, the gaskets between the glass window and cylinder, between the glass cylinder and the aluminum ring which is actually the front stop and the diaphragm between the front and back chambers.

All the material inside the chamber must be very clean, not soluble in the liquid mixture, and not giving off disturbing volatile substances. Synthetic rubber for the diaphragm and gaskets gave a much smaller background than gum rubber. If lead is used inside the chamber, the oxide layers found on the surfaces must be carefully cleaned with steel wool or sand paper and then washed thoroughly with alcohol or the lead must be chrome plated. No water is used for cleaning purposes, for lead is oxidized very readily by water. Thus the background at expansion ratios, smaller than the ion limit, will be very small.

The fast expansion valve.

The fast expansion valve is of the permanent magnet type. The Magnavox Company specially ground the Alinco V

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89 Obtained from The Magnavox Company, Fort Wayne, Ind. From their blueprint No. 10858, 3.2 pound Alinco V magnet, top of assembly surface ground flat before charging.
magnet assembly before charging. A 1/2 inch hole was drilled in the center of the pole piece. The piston was of 1/2 inch aluminum rod. The valve closing the opening port was a 2-1/2 inch aluminum disk. The armature was soft iron plated with chrome for protection. The entire piston and armature assembly weighed 70 grams. Twenty turns of No. 20 copper wire was wound in the pole piece gap. Air pressure was held in the back chamber at 20 psig by a Mason-Neilan regulator valve, the top compartment of the valve being sealed against the atmosphere. In this way the air pressure behind the diaphragm is regulated against a constant pressure but not the atmospheric pressure, which varies. Better regulation is obtained with a small leak provided in the back chamber.

To operate the valve, a 320 Micro-farad condenser bank (Cf. Figure 5) charged to 250 volts was discharged through the 1D21/Sh4 cold cathode tube. This action in turn temporarily counteracted the permanent magnetic field and the excess air pressure quickly forced the piston out of range of the magnetic field.

The photographic equipment and arrangement.

A Sept 35 mm movie camera and a xenon flash lamp90 have been used for taking photographs. The lamp is connected across

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90 Obtained from the Am glo Corp., Chicago, Ill. 19" length, 8m/m glass, operating voltage-2000 to 2500 V., hold-off voltage - approximately 3500 V., input - 200 watt-seconds, rear surface half-aluminized.
a bank of condensers of 80 to 130 micro-farads charged at a voltage of about 2500 volts. The focusing of the illuminating beam was accomplished by using a 3 inch glass cylinder filled with distilled water and a series of parallel slits. The rear surface of each flash lamp was aluminized to increase the intensity of the light beam. The collimated beam was approximately 2 to 2-1/2 inches in width. The duration of light was only a few hundred microseconds, and therefore the focusing of the beam was tested by using quick developing Kodak Bromide paper. Two front surface mirrors and a prism arrangement to give a 30° angle between pictures was used for the purpose of stereoscopic photography.

In order that the ion clusters can grow to a size large enough for future condensation, the chamber expansion was delayed about 5 milliseconds after the particle has entered the chamber. Again to allow the liquid drops to grow large enough to be photographed, the lamp was flashed at 50 to 200 milliseconds after the particle entry into the chamber. Eastman Kodak Plus X and Super XX film were used throughout the experiments.
ELECTRONIC CIRCUITS

A penetrating cosmic ray particle actuates the counter telescope (Figure 6) beginning the cycling process through the coincidence circuit and the electronic gate. The expansion valve, clearing field removal, flash lamp, camera shutter and film advance, mechanical counter, and finally the reset of the gate proceeds according to a preset time schedule, determined by the electronic flip-flop circuits and the mechanical clock motors, all with adjustable recovery times.

The preamplifier and coincidence circuit.

The preamplifier and the coincidence circuit, Figure 7, operates as follows. The three bottom G-M tubes, Bank M and the top G-M tube, A, act as the counter telescope to fire the chamber. When a particle fires A and any one of group B within a time interval of less than 10^-4 seconds, as determined by the dead time of the counter, the coincidence tube sends a pulse through the blocking diode to the cathode follower and out at C. The blocking diodes, IN34s, are used to isolate the grids of the preamplifier tubes, the 1L4s. Polarizing voltages were obtained from batteries to eliminate noise and spurious pulses.

The control circuit.

The output pulse from the cathode follower of the coincidence circuit is fed through a coaxial cable to the control
circuit (Figure 5). This pulse is then amplified and inverted in phase by the 6J5. Its output flips the blocking circuit, a 12AU7 bistable multivibrator, to its insensitive condition thus preventing another pulse from getting through until the timing cycle is complete. At the same time the multivibrator feeds a pulse to the impedance matching and isolating cathode follower. The output pulse from the cathode follower then simultaneously (1) trips the magnet coil, (2) triggers the light time delay, and (3) actuates the camera opening relay through its univibrator time delay. The magnet coil, consisting of 20 turns of No. 20 copper wire wound in the pole piece gap of the permanent magnet; is actuated by the discharge of the 320 microfarad condenser charged to 250 volts through the coil by the action of the SN4 cold cathode switch. This allows the pressure within the cylinder to force open the exhaust valve and produce the desired expansion. The light source, an 18 inch xenon filled flash tube especially constructed by the Amglo Corporation, Chicago, Ill., is also fired by a SN4 switch. The SN4 is triggered by the delayed pulse from the light delay univibrator. This delay is variable from 35 to 400 milliseconds. The clearing field and solenoid operating the camera are connected to opposite sides of a double pole single throw relay. Thus as the camera shutter opens, the clearing field is removed and when the camera closes, the clearing field is restored.
FIGURE 5

Cloud Chamber Control Circuit
FIGURE 6

G-M Tube and Cloud Chamber Geometry
FIGURE 7

Preamplifier and Coincidence Circuit
The exhaust valve is closed by a solenoidal plunger controlled by switch contacts operated by a Hayden synchronous motor. After a preset time, the switch contacts cause a solenoid to reset the valve, and after the timing cycle is completed, the blocking circuit is reset by the clock contacts. The control circuit is now ready to accept another pulse from the coincidence circuit and to repeat the control sequence.
DATA AND RESULTS

Method of Calculations. For a particular series of runs, with a selected thickness of lead above the chamber, the total number of pictures taken, the total time elapsed and the average resetting time of the chamber were recorded. The total active time of the chamber was thus the difference between the total elapsed time and the product of the number of pictures and the dead time of the chamber. The pictures were then scanned and those with penetrating pairs or showers marked. The total number of pictures in each series with three or more particles (showers) were counted and recorded. The frames with penetrating pairs, (two particles) were reprojected and the angular divergence of the tracks measured with a protractor.

The selection criteria for defining a track as a meson or penetrating particles were (1) it must be a minimum ionization particle as indicated by the track in the photograph, (2) it must not scatter but be energetic enough to give a straight track through the chamber, (3) pairs or showers must appear to have originated in the lead above the chamber, i.e., the reprojection of the tracks must intersect within the lead block. Under the third criteria, parallel tracks were thus counted as single particles and not as a very narrow angle pair.
Only a very few pictures, less than one percent, showed no tracks, and few pictures showed tracks which were not representative of penetrating particles as defined by criteria (1) and (2). This indicated that the equipment as a whole was functioning reliably and that the geometry and performance of the G-M telescope was satisfactory. Very few multi-track pictures failed to show divergence from a region within the lead and therefore fail to be counted under criterion (3).

The thickness of lead used was 7.0, 10.4, 14.0, 15.2, 16.3, 17.5, 19.0, 20.5, 21.5, and 23.0 centimeters. The lead blocks covered an area of approximately 4 inches by 10 inches. A 7.0 centimeter thick lead block was placed 1-1/2 inches above the top of the chamber with a G-M tube between the lead and the chamber. (See Figure 6). Data was taken over a period of time covering about two months. One thickness was used for one particular day, for instance 14.0 centimeters and the next day a 20.5 cm. thickness might be used. The thickness of lead to be run on a particular day was selected at random to minimize barometric effects or other systematic errors. The penetrating pairs were separated into groups having angular divergence ranging between 0-5°, 5-10°, 10-15°, 15-20° and greater than 20° series, each for the particular thickness of lead being studied. This data shown in Table I was then tabulated and plotted. The fractional probable error \((\frac{1}{\sqrt{N}})\) was indicated for each data point, assuming a
Poisson distribution, (i.e., a random distribution of events in time). (Cf. W. C. Elmore\textsuperscript{91}).

Figures 8 through 12 show the plots of the data. The frequency per hour of the total events (pairs plus showers) versus absorber thickness in centimeters of lead, is plotted in Figure 8. A maximum at about 17.5 centimeters is definitely marked. The plot of showers (events with more than two particles originating from a common source in the lead) is shown in Figure 9. Again a definite maximum is shown at about 18.0 centimeters of lead. This plot indicates that the frequency per hour for showers flattens out after about 20 centimeters of lead. Figure 10 is a plot of the total pair production. Again a maximum is definitely established but now the maximum is at about 17.0 centimeters of lead. The right side of the curve shows an increasing downward trend as absorber thickness is increased. Figures 11 and 12 represent a breakdown of Figure 10 into pairs with angular divergence larger and smaller than 20° respectively. Pairs with angular divergence greater than 20° show a definite maximum at about 17.0 centimeters of lead. In contrast, the plot of pairs with angular spread less than 20° indicates three maxima at 14.0, 17.5, and 21.5 centimeters of lead, although not enough data is available to definitely establish the shape of the

Figure 8
Rossi Transition Curve for Pb.
(Total events-Meson pairs plus showers)

Figure 9
Cosmic Ray Shower Transition Curve for Pb.
(All showers > two particles)
Figure 10
Cosmic Ray Transition Curve for Meson Pair Production in Pb.
(Total pair production)

Figure 11
Cosmic Ray Transition Curve for Meson Pair Production in Pb.
(Pair production > 20° angular divergence)

Figure 12
Cosmic Ray Transition Curve for Meson Pair Production in Pb.
(Pair production < 20° angular divergence)
Figure 13

Plot of Total Intensity and Singles Versus Pb Thickness
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<th>10-15*</th>
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curve in this region. Figure 13 shows a plot of the single penetrating particles counted versus absorber thickness and also shows the total cosmic ray intensity (singles plus pairs and showers) versus the lead thickness.

The results as shown by Figure 13 agree with what other investigators in the field have reported. The maximum is not indicated by the intensity of the penetrating particles. The upward trend as indicated by the last two points on the right field of the graph may be discounted because of an inadequate number of counts.

Photographs of penetrating pairs and showers are shown on the following pages. Pictures of unusual events are also given as a matter of interest. The accompanying legend explains each photograph.

Location and Pertinent Facts. This experiment was performed at Baton Rouge, Louisiana, in the basement of the Physics building. The chamber was located in the room roughly four feet from a concrete block wall on the east side, eight feet from the wall on the west side, and ten feet on the north and south sides. The chamber rested on a wooden table 30" above the concrete floor, the reinforced concrete ceiling being ten feet above the table. Three floors were above the chamber with concrete approximately 6" thick in each for a total of approximately 18" of concrete. The lead blocks were 4" x 10" in horizontal cross sectional area and varied in thickness from 1.5 to 7.0 cm. The chamber, 12" in diameter
PLATE I
A Penetrating Shower
(Under 20 cm. Pb)

PLATE II
Single Penetrating Track

PLATE III
Large Penetrating Shower
(Under 19 cm. Pb)

PLATE IV
Typical Penetrating Shower
(Under 20 cm. Pb)
(Note the recoil electrons.)
PLATE V

Typical Penetrating Shower
(Note recoil electrons and the slow electron at the top of the chamber.)

PLATE VI

Very Large Penetrating Shower
(Probably a part of an extensive shower)

PLATE VII

Alpha V-Track
The two alpha tracks have a common origin but no evidence of an incoming particle or ray. Probably a neutron.

PLATE VIII

Typical Penetrating Pair
PLATE IX
Typical Penetrating Pair

PLATE X
Very Narrow Penetrating Pair.

PLATE XI
Penetrating Pair.
(Note the narrow angle pair close to left chamber wall.)

PLATE XII
Typical Penetrating Particle
operated in the vertical plane. Lead was placed 1-1/2" above and centered over the chamber. G-M tube A was placed between the lead and the chamber and in the center of the 4" depth of the chamber. G-M tube bank B was placed immediately under the chamber and covered an active area about 3" x 10".
CONCLUSIONS

These experiments led to the conclusion that the second maximum for the cosmic ray transition curve for lead (the Rossi curve) is real. This leads to the further conclusion that the second maximum indicates production of a special kind of shower differing from cascade showers in origin and properties. From considerations of penetrating power and rate of shower production it seems almost certain that the primaries can only be mesons or protons. Assuming this, the shower-producing cross section of the lead atom can be estimated as a few percent of the geometric nuclear cross section. The plot of the total meson pair production and showers definitely indicates a second maximum. This maximum cannot be assumed to be due to pair production alone because showers and meson pair plots each show a definite maximum at about 17.5 centimeters of lead. Figure 11 indicates that the influence of pairs with an angular divergence of greater than 20° is the contributing factor for the second maximum for pair production. Figure 12 would seem to indicate a series of maxima at about 14.0, 17.5, and 21.5 centimeters of lead, but here the statistics are not sound enough to draw firm conclusions.

It would be interesting to extend the data to see the effect of narrow angular spread on the second maximum for mesons pairs and check to see whether or not the three maxima
shown on the curve of Figure 12 are real. A further interesting extension would be to investigate the effect of a different material, such as Fe and Paraffin, to see if it is the number of atomic nuclei per volume that is effective or the number of nucleons (protons and neutrons). Further extension to greater thickness of lead is needed to investigate the possible existence of a third or perhaps fourth maximum. Clay\textsuperscript{92} and Bothe and Thurn\textsuperscript{93} have indicated the possible existence of a third maximum at about 28 centimeters of lead. Recently Allegretti\textsuperscript{94} and Pfotzer\textsuperscript{95}, working with G-M tubes, have reported maxima at 15, 25, and 37 cm. corresponding to a second, third, and fourth maxima. An arrangement to distinguish between ionizing and non-ionizing radiation may give some clue as to the nature of the shower producing radiation. If real, the third and fourth maxima would indicate shower production by some non-ionizing radiation.

\textsuperscript{95}G. Pfotzer, \textit{Z. Naturforsch} \textbf{6a}, 353 (1953).
SELECTED BIBLIOGRAPHY


BIOGRAPHY

Bartow Hodge was born in Winn Parish, Louisiana, on January 11, 1920. After graduating from Winnfield High School in 1936, he entered a business college in New Orleans, Louisiana, and graduated in the summer of 1937. In the fall of 1939, he entered Louisiana State Normal College and attended until December, 1941, when he volunteered for the Army Air Forces, receiving a commission as a Statistical Officer from Harvard Graduate School of Business in December, 1942. He served overseas with the 314th Troop Carrier Group until November, 1945. After being released from service with the rank of Major in February, 1946, he entered Louisiana State University.

In November, 1946 he married Elsie Rae Stokes of Baton Rouge, Louisiana, and now has two children, Barbara Gail, born October 13, 1949, and Bartow Michael, born September 27, 1951.

He received the B. S. degree in Physics in June, 1947, and the M. S. degree in Physics from Louisiana State University in August, 1948. Then in September, 1948, he enrolled in the Graduate School of Louisiana State University to continue work toward the Ph. D. in Physics.

In May, 1951, he was employed as a Physicist by Esso Laboratories and is now there engaged in Catalyst research.

Bartow Hodge is now a candidate for the degree of Doctor of Philosophy in Physics.
APPENDIX

Laboratory Techniques Involved in the Operation of a Cloud Chamber

This discussion is of an elementary and empirical nature and is intended to give the minimum general background necessary for routine chamber operation.

Constructional elements of normal chambers include windows, usually of glass or plexiglass, metal parts, rubber or synthetic rubber for piston mounting and similar purposes, and sealing materials. These must be chosen to minimize the risk of contamination in the chamber which would lead to an unacceptable onset of background contamination. The information on this subject is almost wholly empirical. Glass and plexiglass are clean materials, and can be used freely, but special properties of plexiglass must be noted. This material absorbs some organic vapors including alcohol, and when this occurs its surface layers are softened. While wet, the gelatine layers do not cause any loss in optical properties, but the sudden expansion and temperature drop will cause the plexiglass to glaze and finally adversely affect its optical property. For these reasons glass is recommended. Metals such as silver, gold, platinum, chromium, and nickel are clean, but the base metals are sources of definite contamination, and although this may be minimized if the metal is thoroughly oxidized, there is every reason for having all internal parts of the
chamber plated. Lead definitely cannot be used unless plated or thoroughly cleaned without oxidation. The qualities of aluminum are obscure; however, if thoroughly oxidized, no contamination was evident. Rubber and neoprene are clean materials when at rest. In rapid motion, as on expansion, it was found that a diaphragm of natural rubber seemed to build up a charge and caused severe contamination or background fog. Most enamels, glyptal (clear and red), and vaseline or stop-cock grease presented no problem when thoroughly dried. Solder, rubber cement, aquarium cement, and similar materials tested definitely increased the background fog to an unuseable level. The vapor used must be of the best grade. Technical grade normal-propyl alcohol and ethyl alcohol soon caused white specks to appear on the front window, causing a loss in optical properties. No trouble was encountered with USP grade alcohols.

The chamber should be scrupulously clean when assembled, and in particular the windows should be completely free from grease. If this is not the case the unclean places become much more conspicuous in time and may make it necessary to take down the chamber. This deterioration of cleanness of windows is most marked if there is any tendency for free liquid to migrate to the glass surface because of incorrect temperature gradients in the chamber.

It is essential to be able to judge visually the condition of a cloud chamber. Not only must the chamber be satisfactory when first put up, but since it must be expected that the
condition of the chamber will deteriorate with time either by loss of vapor by diffusion out of the chamber or by slight chemical action leading to traces of contamination, the gradual deterioration for these reasons in use must not be overlooked. This may easily happen unless the chamber is regularly checked in the way outlined below. The test will be visual rather than by inspection of photographs, for not only is the use of photographs much too slow, but in photographic methods the details of chamber performance may be confused with faults of photography and of timing which can be diagnosed with certainty only if the condition of the chamber is known first. It is thus most important to equip apparatus with a source of continuous illumination for visual inspection of condensation, which should be designed to come into operation with a minimum of alteration from the regular running cycle so that frequent inspection is encouraged. An intense source with good condensing system should be used, since for visual inspection it is essential that individual drops be easily seen; even with good illumination this is preferably achieved by viewing at a small scattering angle, of say 30-45°.

The cleanliness of a chamber is estimated by reference to (a) the development of background condensation over a range of expansion ratios in the neighborhood of the ion limits, and (b) to the way in which residual nuclei effective at low-expansion ratios are removed in the "cleaning Expansions."

Failure to clean satisfactorily under repeated cleaning expansions indicates either a leak of atmosphere gas with its
dust content into the chamber, or, more usually, the development of severe chemical contamination. The cleansing process in a good chamber is most characteristic: after heavy ion condensation the first one or two slow expansions appear to do little towards removing the re-evaporation nuclei formed; but after a certain point (perhaps after even two or three hundred expansions) cleaning proceeds rapidly, and a clean chamber with less than 1 drop condensing in upward of $10^{-3}$ cm$^3$ of gas results. The successful later stages of cleaning take place when few enough nuclei remain for each to grow to a large drop which is likely to fall to the bottom of the chamber before it once more evaporates. The cleaning process thus allows it to be established that there is no continuous source of nuclei effective at low-expansion ratios in the chamber.

Condensation near the ion limit offers the real test of cleanliness in the chamber, and it is necessary to establish a reliable subjective standard. A general test will consist of making expansions at gradually increasing expansion ratios from a level at which background condensation is negligible up to that at which it is certainly too thick. This is done in the presence of a weak gamma-ray (such as 1 milligram of radium enclosed in 3 cm. of lead placed above the chamber) which provides a few electron tracks, and the relationship of the development of background to the ion limits is in this way established. Although it is frequently not done, it is of the
greatest value to carry out this series of tests in terms of a known calibration of expansion ratio. This procedure is of importance in two ways: it gives a measure of the range of expansion ratio for the transition from the first onset of condensation on ions to the point at which background becomes unacceptable, thus giving to some extent a non-subjective criterion of quality; secondly, it allows day-by-day changes of condition to be followed and the development of contamination and of complete or selective drying out to be recognized. Under normal condition, the range of expansion ratio from the onset of condensation on ions to the development of unacceptable heavy background condensation should be of the order of 1 to 2 percent when using argon and ethyl alcohol.

It is most instructive to bring a clean chamber through a series of increasing expansions. The first indications of condensation on ions should come while the background is still negligible. As larger expansions are made, the appearance of tracks becomes strikingly crisp and bright as the background drop density rises to about 1-10 drops/cm³. It is not easy to account for the improvement of appearance of tracks under these conditions, but it is undoubtedly the basis of the best visual judgement of chamber conditions. The important factor is probably that until almost 100 percent condensation is taking place on ions of both signs, there will always be some ions which are fixed with appreciable delay, and as long as this is so the secondary clusters, which are visually
the conspicuous features of cloud tracks, will not appear as sharp points of light. In addition, in the early stages, there will only be half the final number of droplets present; the extra excess vapor pressure available at the higher expansions is negligible as an agent leading to brighter drops.

All stages of contamination will be encountered from the clean conditions which have just been described up to a condition in which recognizable tracks are never obtained. The purpose of the last paragraphs is to stress the importance of being able to recognize good working conditions corresponding to the early stages of the test sequences in a clean chamber.

Remedies for contamination are not so easily stated. When contamination is encountered it is often necessary to take the cloud chamber down and to work empirically until the source of contamination is identified and removed. It very often happens, however, that a chamber, initially clean, develops contamination in the course of time; this may be ascribed to slight chemical action and can usually be removed without taking down the chamber. The chamber is swept with dry gas until the initial liquid is completely removed; fresh liquid is added and the chamber will as a rule be found to be clean.

There are serious difficulties in operating a chamber in surroundings where there are large fluctuations of temperature. These difficulties are of two kinds: the free liquid in the chamber tends to distil to the coolest part (if the conditions are not controlled, sooner or later, this will be one of the
windows), and further, temperature variations lead to convection currents in the chamber which prevent geometrical measurements of high precision. The chamber should therefore be operated in a room or enclosure of steady temperature; in addition, slight cooling may be applied to the lowest point in the chamber. This local cooling is useful in two ways: it prevents the migration of liquid to unwanted places and it stabilizes the gas in the chamber, through which there is a negative temperature gradient in the upward direction. It is because of this stabilizing action that cooling must be used in moderation; for while stability at the time of expansion is important, the recovery of the chamber after the cleaning process may be greatly delayed if stability of gas is established too soon. After the last cleaning expansion, the chamber gas is compressed and warmed. Before it is in a condition for further use, it must be saturated and must also come into a condition of stability. In the early stages, the restoration of saturation is assisted by strong convection, but later if stability is reached before saturation is virtually complete throughout the gas, the remaining transfer of vapour must be by simple diffusion. This premature stability is likely to arise if the cooling at the bottom of the chamber is excessive.
PLATE XIII
Chamber condition showing effect of light mis-alignment.

PLATE XIV
Alpha Particle Contamination
(Probably Po-Alpha)

PLATE XV
Light not collimated.

PLATE XVI
Severe contamination and expansion ratio too high - showing turbulence.
PLATE XVII

Chamber conditions excellent; light collimated and focused.

PLATE XVIII

Light falling on back wall.

PLATE XIX

Severe chemical contamination. Old tracks were not swept out thus increasing background.
EXAMINATION AND THESIS REPORT

Candidate: Bartow Hodge

Major Field: Physics

Title of Thesis: The Cosmic Ray Transition Curve in Lead.

Approved:

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Lloyd W. Morris
Major Professor and Chairman

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Richard J. Russell
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EXAMINING COMMITTEE:

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Date of Examination:

April 23, 1954