The Use of Cloud Chambers with Pulsed Accelerators

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AS LONG AS physicists have been studying charged particles, they have been developing new instruments to detect them or adapting the old ones to new circumstances. Although the Wilson cloud chamber (*5, 7*) is one of the oldest such devices, it is still being used extensively, especially in cosmic ray experiments and more recently in experiments in connection with high energy particle accelerators.

A cloud chamber is a machine that makes visible, and therefore enables one to photograph, the paths of charged particles: electrons, protons, mesons, etc. The chamber itself consists of a closed volume of gas saturated with a vapor. If the volume of the chamber is suddenly increased, droplets of the vapor will condense on the ions that any charged particle leaves behind as it passes through the gas. Immediately following the expansion, the chamber is illuminated by the flash of a very intense light and a camera then records the number and position of the drops, each one representing an ion produced during the flight of a charged particle and the whole group forming a trail that tells part of the particle's history.

The quantities that are most often measured with a cloud chamber are the ionization produced by a particle in going through the gas, its range, or its deflection by a magnetic field. The measurement of these quantities may serve simply to reveal the velocity, energy, or momentum of the particle or, if the identity of the particle is unknown, to determine its mass and charge.

As a charged particle traverses matter, it loses energy by ionization of the surrounding atoms, and as it does so, its velocity decreases so that it spends more time in any given region and hence produces more ion pairs per centimeter as it nears the end of its range. Since the energy loss varies with the density of the medium, a charged particle loses more energy per unit length of path in lead than in air. But for a given kind of particle (electrons excepted) moving in a given material, there is a unique relationship between its energy and both its range and its rate of energy loss by ionization. The ionization produced by a particle in traversing the gas of a cloud chamber may be measured by allowing the ions to diffuse before the expansion so that the droplets that condense on them are separated and can be counted. More often the density of a sharp track is observed and used as a qualitative indication of the ionization. The range of a low energy particle may be determined from the length of track it makes in the cloud chamber; the range of a more energetic particle may be obtained from the number and thickness of solid absorbers required to stop it.

Further, if a particle is moving in and perpendicular to the direction of a magnetic field, it experiences a force that is directed at right angles to the direction of both the field and the velocity of the particle. As a result the particle moves in a circle the radius of which is proportional to its momentum. Cloud chambers are therefore very often placed in magnetic fields so that curvature measurements may be made. It is desirable (although expensive) to have a magnetic field large in magnitude as well as extent, so that the deflection will be appreciable over a measurable length of track. In addition, it is necessary to make certain that the curvature of the track is produced by the force of the magnetic field on the particle and neither by the multiple scattering of the particle by the atoms of the gas nor by the distortion of the track by mechanical motions of the gas.

Application to Pulsed Accelerators

In the last few years, cloud chambers have been used in connection with pulsed accelerators. It is the purpose of this paper to discuss some of the special techniques that may be applied under these circumstances and to point out their advantages (as well as their disadvantages) in comparison with cloud chamber techniques for, say, investigating cosmic rays.

To date, cloud chambers have been successfully operated in the x-ray beams from synchrotrons or betatrons and in the neutron beams from cyclotrons. An x-ray beam may be obtained from a betatron or synchrotron by allowing the circulating electron beam to strike an internal target. The electrons radiate and a beam is obtained which consists of quanta of all energies up to the energy of the electrons. Cyclotrons

[1] I wish to thank Doctors Baldwin, Gaerttner, Koch, and Kruger for their courtesy in allowing me to include examples of their photographs. The previously unpublished pictures from Berkeley were taken by W. D. Hartsough, W. M. Powell, and the author under the auspices of the Atomic Energy Commission.

usually accelerate either deuterons or protons and by allowing these particles to strike a target a beam of neutrons may be obtained. In either case, the resultant beam is one that does not directly produce many ions, but in its interaction with matter, secondary particles are produced which do ionize heavily. This is an ideal situation for a cloud chamber. If a cloud chamber is placed in an x-ray or neutron beam, several thousand quanta or neutrons may traverse the chamber but only those that interact with matter will be detected.

The most striking feature of using a cloud chamber with an accelerator is that the experimenter is able to control the time at which the pulse from the accelerator will arrive. If the curvature in a magnetic field is to be measured, the tracks should be distortion-free and as narrow as possible. It is, therefore, desirable to introduce the pulse at the end of the expansion after the gas stops moving but before thermal gradients between the gas and the chamber walls can produce convection currents. Distortions are thus minimized and the tracks are very sharp, since the ions do not have a chance to diffuse before the liquid is condensed on them. It should be pointed out that the opposite situation obtains in the most familiar type of cosmic ray experiment, where the cloud chamber is expanded by the pulse from a Geiger counter after the particle has gone through it. Any irregularities in the motion of the gas during the expansion are then superimposed on the track, and in addition the ions diffuse slightly between the time of passage of the particle and the time that they become laden with water.

The fact that the experimenter can control the time of arrival of the pulse is a great asset as far as the design of the magnet is concerned. The magnet does not have to be on all the time, but can be pulsed and synchronized with the cloud chamber cycle so that the field is at a maximum when the particles go through the chamber. This serves to minimize the heating of the magnet and as a result high currents may be used during the magnet pulse.

In ordinary cloud chamber operation an electric field is applied to remove ions between expansions and is then shorted out just before the fast expansion. Following the fast expansion the droplets fall toward the bottom of the chamber, although some of them evaporate en route. Those that exaporate remain floating around in the gas, since they are still too large to be removed by the clearing field; they would then be nuclei for condensation of vapor in the next expansion. Usually they are dissipated by one or more slow expansions, during which vapor is again condensed on them and they fall out. Slow expansions are extremely time-consuming, since after each expansion the chamber gas must be allowed to come to the temperature of the walls. Gaerttner and Yeater (*6*) have very effectively eliminated the need for slow expansions. They "overcompress" the cloud chamber right after the photograph is taken; in this way the gas is heated up and the charged drops evaporate so that they are light enough for a strong clearing field to remove them. This technique has been developed to such an extent that photographs may be taken at the rate of one every five seconds. Since the usual time of a cloud chamber cycle is a minute or more, this development appears to be a real advance for those experiments that combine the use of a cloud chamber with an accelerator.

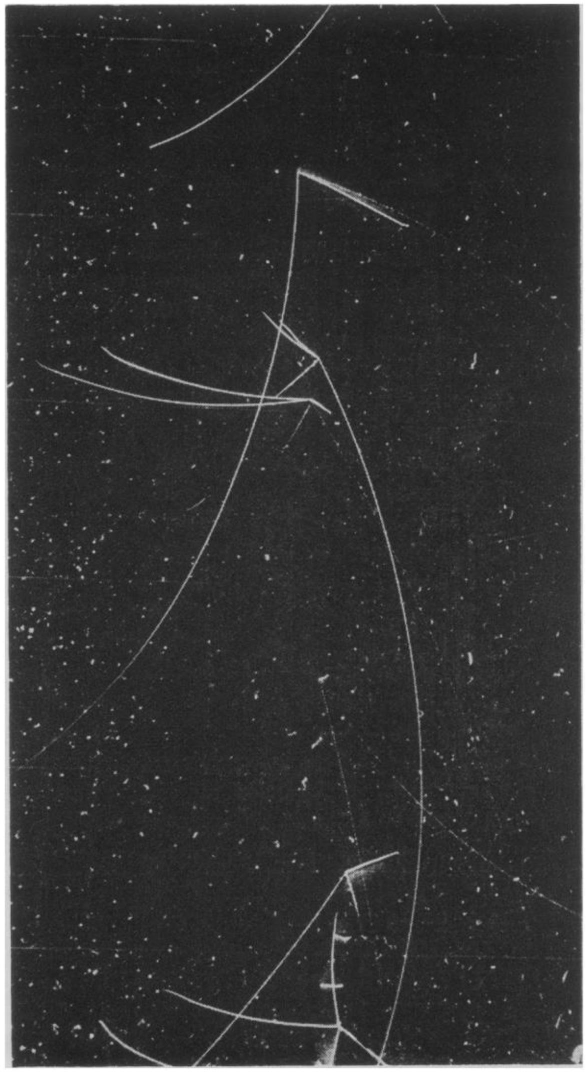

FIG. 1.

Illustrations. To illustrate the work that has been done to date, I have tried to collect examples of the different phenomena that have been observed with pulsed accelerators. The first eight pictures show events produced by neutrons (*3, 4, 8, 11*) and the last four, events produced by x-rays (*1, 2, 9, 10*). Each photograph represents events that follow a single pulse from the accelerator; each one shows the result of several hundreds or even thousands of traversals of the chamber by neutrons or photons.

Fig. 1—We want to study the events that result from the collisions that very energetic particles make with atomic nuclei. This photograph shows six nuclear disintegrations or stars produced when a single pulse of the 90-Mev neutrons (about 30,000 neutrons) from the Berkeley cyclotron traversed the cloud chamber. The chamber was filled with hydrogen and saturated with a mixture of alcohol and water vapor. Since the hydrogen nucleus consists merely of a single proton, its collision with a neutron would yield a single detectable fragment. The events in this picture must, therefore, represent the complete breakup of the carbon and oxygen nuclei present in the vapor. The most common isotopes of carbon and oxygen have nuclei consisting of equal numbers of protons and neutrons, six and eight respectively. Since a neutron bears no charge, it produces no ions and hence leaves no trace in a cloud chamber. This is unfortunate. It means that at least one fragment in most disintegrations is unaccounted for; since the observations are made on the charged components only, the interpretation is usually difficult and often impossible. In the photograph there are six stars, and starting from the top they have three, four, five, two, three, and four prongs. The first thing to notice is that the tracks are all bent into arcs of circles; this is, of course, the result of the force of a magnetic field on a moving charged particle. Since all of the particles are positively charged, they are curved in the same sense, clockwise. Notice how the heavier tracks steer a rather irregular course near the end of their range. Since they are moving rather slowly and are multiply charged, the collisions that they suffer with the nuclei of the gas are important enough to cause large deflections. Curvature measurements on these tracks are, therefore, not meaningful. The fine tracks are most certainly those of singly charged fragments and are probably protons. The fourth star is the most common type; it consists of one very fast proton track projected forward and a small blob of ionization produced by the recoiling nucleus. The last star at the bottom of the picture is made up of four doubly charged particles. In order to have eight charges in the first place, it must have been an oxygen nucleus and it is quite likely that all four fragments are alpha particles, since the alpha particle (two protons and two neutrons stuck together) is one of the more stable configurations. These stars are at least consistent with the idea that the fast neutron strikes the nucleus, projecting forward one fast particle and leaving the nucleus excited so that in a very short time it explodes, sending lower energy particles in every direction. When a fast particle is not observed moving forward, it may mean that the fast particle is really a neutron, which makes no cloud chamber track.

Fig. 2 is taken from a study (*4*) of the fast particles that are projected forward when an energetic neutron strikes a nucleus. Instead of using the chamber gas as a target, the neutrons were allowed to strike a small piece of carbon placed within the cloud chamber. Many particles emanated from the target and some of them stayed in the plane of the cloud chamber long enough to pass through a glass absorber across a diameter of the chamber. The purpose of the absorber was to help in the identification of the particles; for a mere curvature measurement tells only the momentum, but if the curvature of a particle can be measured on two sides of an absorber of known thickness, then its mass may be determined at least well enough to identify the particle. The two tracks indicated by the arrows have almost the same radii as

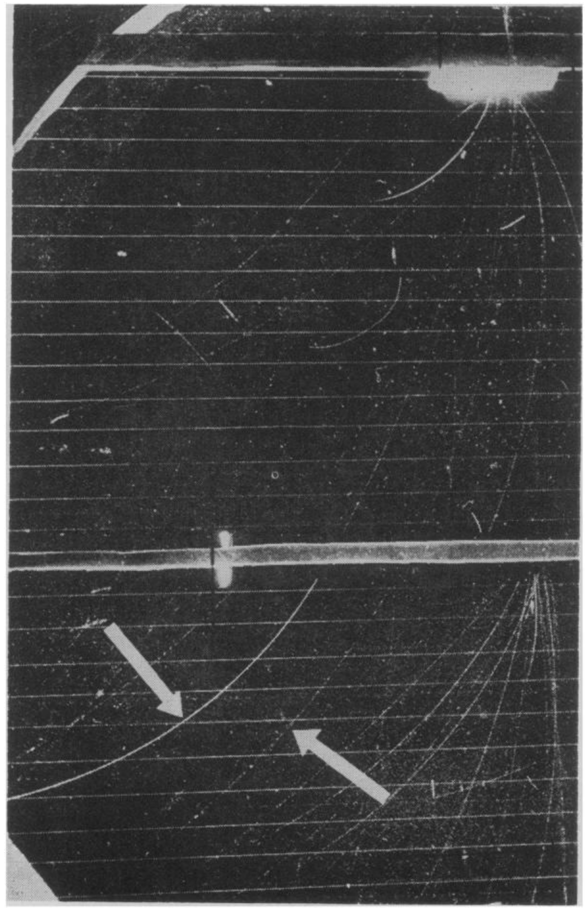

FIG. 2.

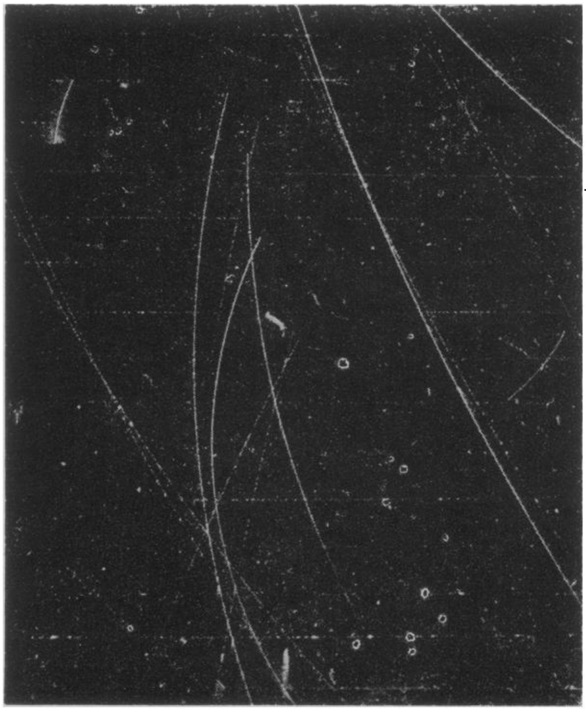

FIG. 3.

they leave the target, but on the far side of the absorber, one has a much smaller radius and an obvious increase in ionization. The other shows no apparent change in either. The first is a deuteron and the second, a proton.

Fig. 3 is a photograph from the data of an experiment (*3*) to determine the angular distribution of the protons that are scattered in elastic collisions with 90-Mev neutrons. Scattering experiments of this type give important information about the interactions between elementary particles. Here we see the tracks of six such protons that begin in the gas (H_2) after having been struck by an invisible but energetic neutron. The energy of the neutron may be obtained by applying the laws of elastic collisions and by simply measuring the curvature of the proton track and the angle it makes with the direction of the neutron beam.

Fig. 4 is from the data of a similar experiment (*11*) that used the 13-Mev neutrons from the Illinois cyclotron. Here the chamber was filled with CH_4 to 22 atmospheres, so that the knock-on protons would both start and stop in the gas. Since their energies could be obtained from their ranges, no magnetic field was necessary.

Mesons are the particles newest to nuclear physics. The term meson includes all the particles having masses between those of the electron and proton; we are now quite familiar with two kinds, π mesons and μ mesons. The π mesons have a mass of 276 electron masses, bear both positive and negative charges, and interact very strongly with nuclei. They have attracted a great deal of interest because they are supposed to be responsible for the forces that hold nuclei together. A meson may be ejected in a collision in which there is available an amount of energy equivalent to its mass; it will be one of the fragments from a star produced by a very energetic particle. Fig. 5 is a photograph of just such an event. It was taken in the neutron beam that is produced when the 350-Mev protons of the Berkeley cyclotron strike a target. We have here a four-pronged star, the disintegration of an argon nucleus, in which one of the fragments is deflected by the magnetic field in the direction opposite to the others. It must therefore have a negative charge. This is believed to be an example of the production of a negative π meson; its energy is 60 Mev. Though we cannot measure the ionization of this track, its density is certainly consistent with such an explanation.

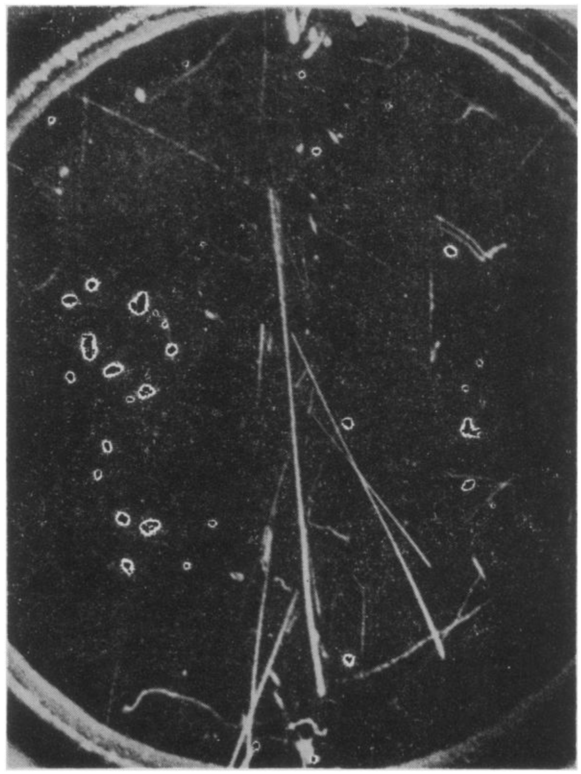

FIG. 4.

When a positive π meson comes to rest, it decays into a μ meson (210 electron masses) plus some neutral particle. The μ meson that is produced always has an energy of 4 Mev and when it stops it decays into an electron and two neutrinos. The energy contained in the mass of the μ meson is divided between the rest energies and kinetic energies of the three particles. The conservation laws impose the condition that the maximum energy available to the electron is 55 Mev, although it may have any energy smaller than this. Fig. 6 shows a π meson that enters an absorber and decays. It has been identified as a π meson because it has the appropriate curvature and ionization for one that could stop in the absorber; a μ meson of the same curvature would get through. The μ meson, which is its decay product, also stops in the absorber and the track of the electron that results from its decay is the small, faint circle in the corner of the cloud chamber.

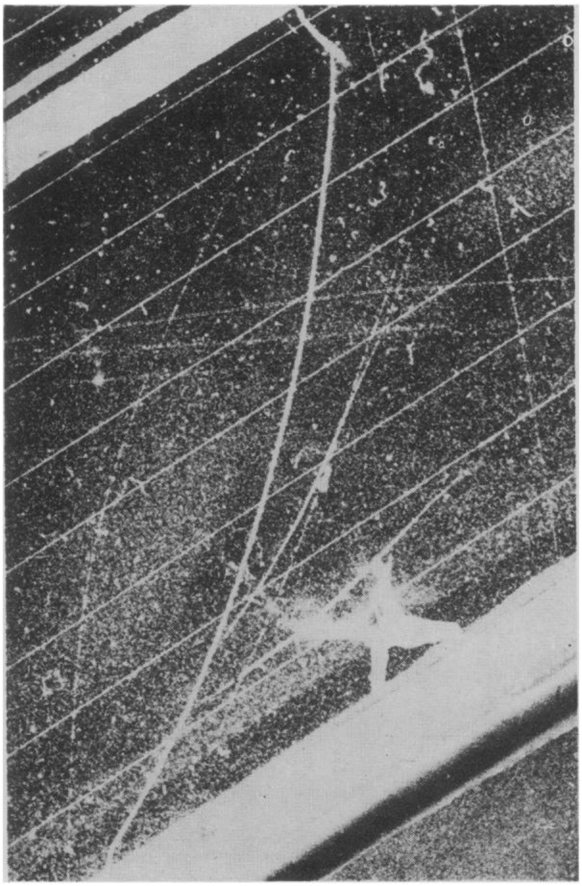

FIG. 5.

When a negative π meson stops in matter, it is captured by a nucleus; the nucleus is thus supplied with some extra energy which causes it to break up. Fig. 7 shows the track of a negative π meson, which shows a decrease in radius of curvature as its ionization increases until it finally stops and is captured by an argon nucleus. This star consists of a single prong produced by the recoiling nucleus; presumably neutrons are emitted as well.

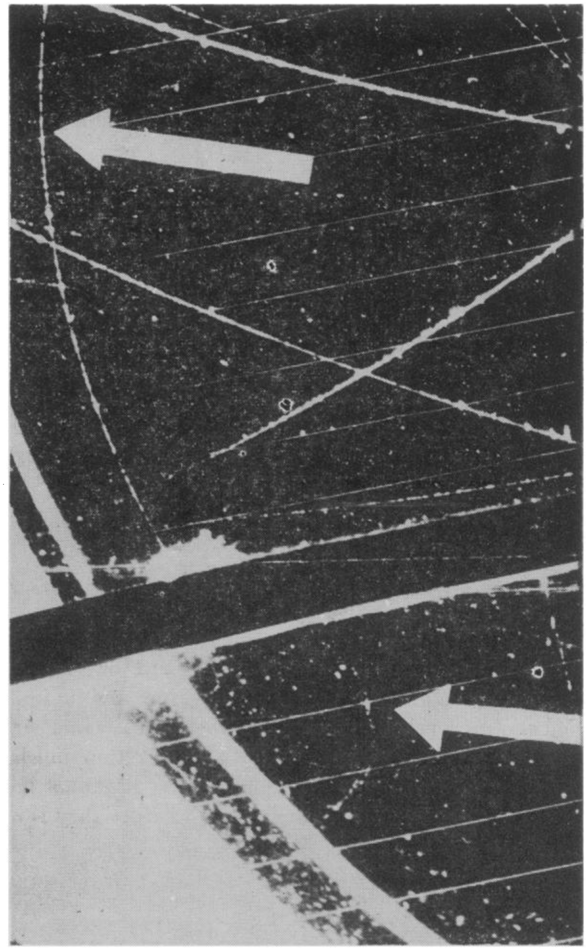

FIG. 6.

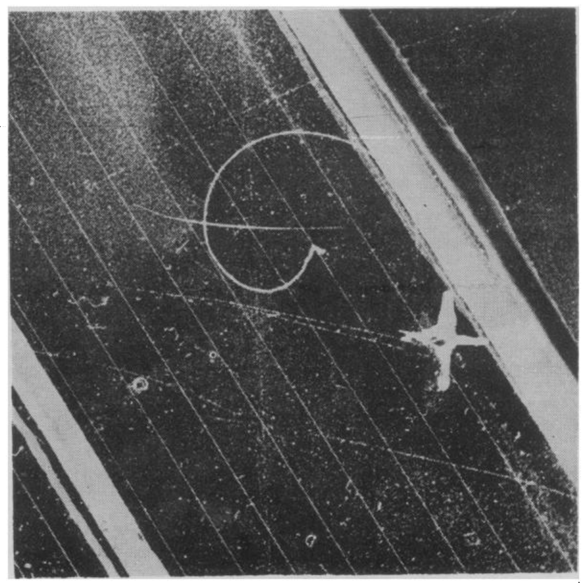

FIG. 7.

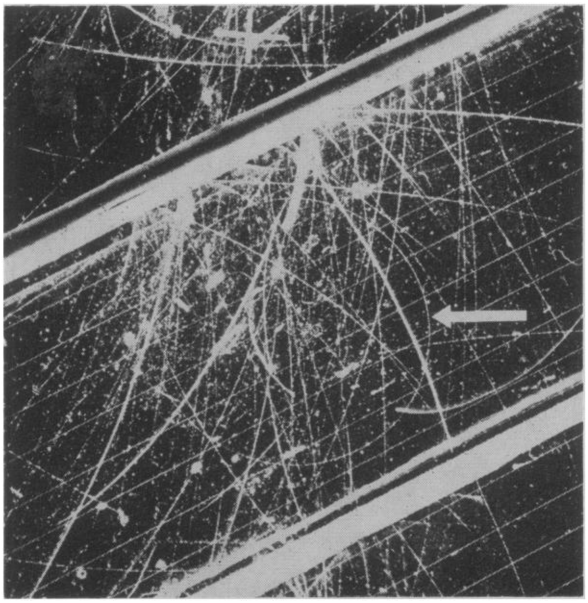

FIG. 8.

Fig. 8 is included to demonstrate how a low energy meson may be identified from its curvature and ionization against a rather high background of heavy nuclear fragments. It shows a density of ionization much greater than that of an electron and yet it cannot be a proton because protons always stop before they can be wound up into such small circles. It is a meson, but it would be impossible to say whether it is a π or a μ.

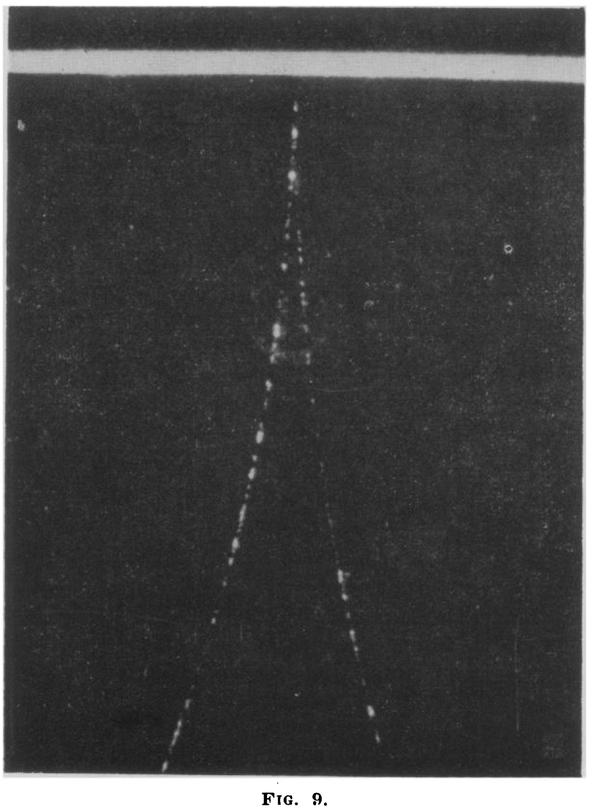

FIG. 9.

It is important to study how mesons are made, the characteristics of their decay, and how they interact with various nuclei. Physicists are hard at work trying to make observations on them. Figs. 5, 6, and 7 are the best cloud chamber pictures of artificial mesons that have been taken to date and Fig. 8 shows why there aren't any more.

The beams of photons from betatrons and synchrotrons are produced when the circulating electron beam strikes an internal target. The electrons are decelerated in the fields of the nuclei of the target material, and as a result, photons are emitted; these photons may have any energy up to the full energy of the incident electron. The beam thus consists of a continuous spectrum of x-ray energies.

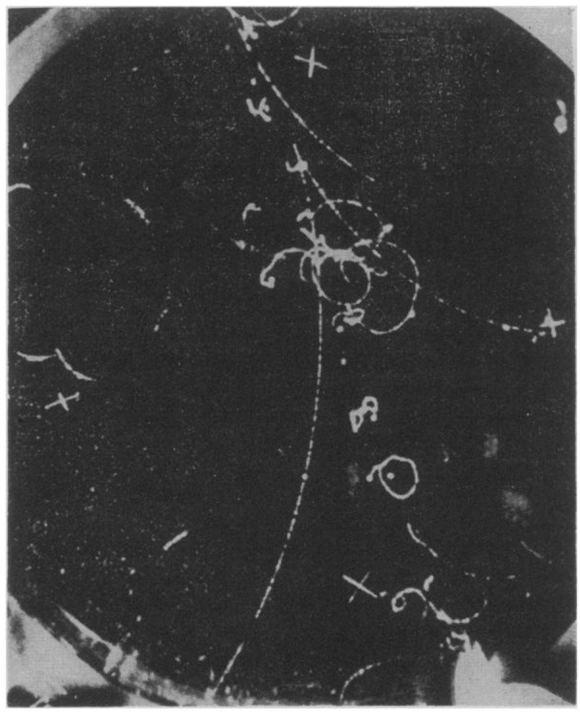

FIG. 10.

Now if a photon has energy greater than about one million electron volts (Mev), it is capable of producing an electron-positron pair when it passes near a nucleus. Approximately one Mev is used up in producing the pair, and the remaining energy goes into the kinetic energy of the positron and electron. Fig. 9 shows an example of pair production. This photograph was taken of the aforementioned "overcompression" chamber in the x-ray beam from the 100-Mev betatron at the General Electric Research Laboratory. The materializer is a lead plate oriented perpendicular to the beam direction. The electron and positron

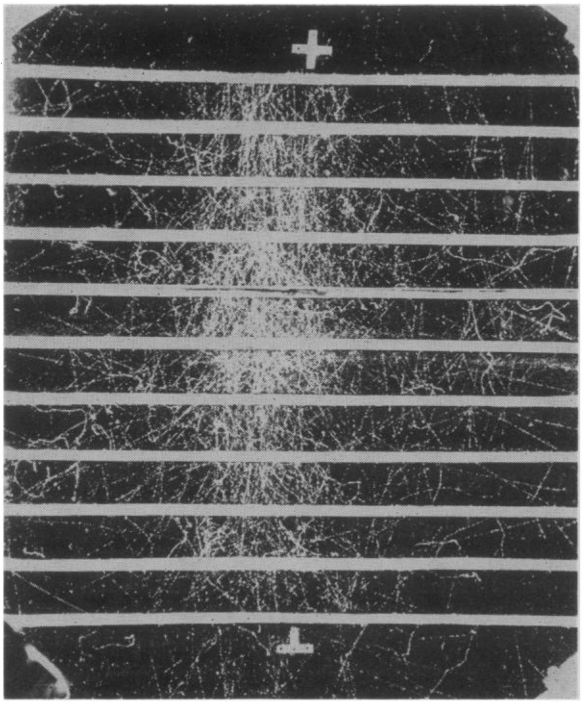

FIG. 11.

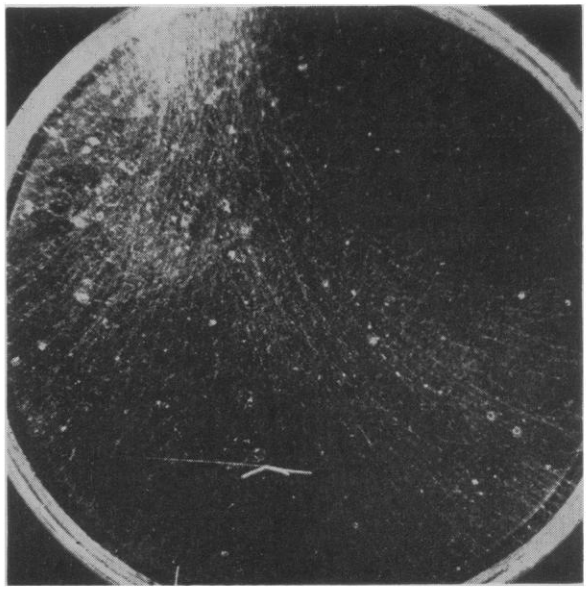

FIG. 12.

curve away from each other in the magnetic field. The energy of the incident photon has been determined from their radii of curvature to be 25 Mev. Fig. 10 is a similar photograph taken in an experiment (*10*) to determine the energy spectrum of the photons from the 20-Mev betatron at the University of Illinois. The pair represented here was produced in the gas, in the field of an argon nucleus. The low energy electrons do not bend into smooth curves because they are scattered rather badly by the gas.

If the electron or positron continues through a medium of heavy nuclei, it will radiate quanta and these quanta will make more pairs and so on until the average energy of the electrons and photons is so low that they cannot radiate and produce pairs as efficiently as they can lose energy by other means. Then the electrons are absorbed by ionization and the photons by their collisions with electrons which are in turn absorbed by ionization.

The best way to observe this so-called shower is to place a series of lead plates in a cloud chamber in the x-ray beam. See Fig. 11. This cloud chamber was in the beam that is produced when the 335-Mev electrons of the Berkeley synchrotron strike an internal target. The shower is due to the several hundred photons that are contained in a single pulse from the synchrotron. The photograph shows how the number of electrons increases rapidly with thickness up to a maximum under the fourth lead plate (they are each $\frac{1}{8}$ inch thick) and after that the number decreases slowly as the lower energy electrons are absorbed. Notice how the low energy electrons scatter in the gas (argon).

Fig. 12 (*2*) shows a star produced by a photon from the 100-Mev betatron. It is analogous to those made by high energy neutrons but a much rarer event. This particular star is probably the disintegration of a nitrogen nucleus, since the chamber was filled with air. Notice the large numbers of electrons and positrons that make up the background; their presence is sufficient to show that a photon is much more likely to make a pair than a nuclear disintegration.

References

1. BALDWIN, G. C. and KLAIBER, G. S. *Phys. Rev.*, 1946, **70**, 259.
2. *Ibid.*, 1948, **73**, 1156.
3. BRUECKNER, K. *et al.* *Phys. Rev.*, 1949, **75**, 555.
4. BRUECKNER, K. and POWELL, W. M. *Phys. Rev.*, 1949, **75**, 1274.
5. DAS GUPTA, N. N. and GHOSH S. K. *Rev. mod. Phys.*, 1946, **18**, 225.
6. GAERTTNER, E. R. and YEATER, M. L. *Rev. sci. Instr.*, 1949, **20**, 588.
7. GENTNER, W., MAIER-LEIBNITZ, H., and BOTHE W. *Atlas der Typischer Nebelkammerbilder.* Berlin: Julius Springer, 1940.
8. HARTSOUGH, W., HAYWARD, E., and POWELL, W. M. *Phys. Rev.*, 1949, **75**, 905.
9. KLAIBER, G. S., LEUBKE, E. A., and BALDWIN, G. C. *Phys. Rev.*, 1947, **71**, 649.
10. KOCH, H. W. and CARTER, R. E. *Phys. Rev.*, 1949, **75**, 1950.
11. LAUGHLIN, J. S. and KRUGER, P. G. *Phys. Rev.*, 1948, **73**, 197.