Tracks from a Diffusion Cloud Chamber

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Abstract

A diffusion cloud chamber is constructed and data is recorded on a microcomputer using a CCD video camera. The cloud chamber shows the tracks of charged particles, and these tracks are later analyzed and their origins and identities are discussed. The speculations are not well supported by an abundance of quantitative measurements but values regarding the make-up of the cosmic radiation, and the sources placed near the chamber are discussed as well as an estimate of the cosmic ray particle flux, which is ~0.02 ± 0.003 particles per second per cubic centimeter.

Introduction and Theory

The particle zoo, as it has come to be known, becomes more crowded with the introduction of new record high accelerators and more sophisticated detectors. The hunt for a fundamental particle seems to elude detection behind the facade of the growing number of particles, despite the ever increasing energies the accelerators are capable of. The strategy is clear and even simple in principle; the collision of a composite particle with another composite particle will, if the kinetic energies are high enough, result in the emergence of that of which they are composed. The same may be done with the resultant particles until finally the new resultant particle is no longer composite but fundamental, unable to be divided into anything else. More than one philosopher has hinted at the subjective danger of microcosms, and high energy particle physicists are beginning to learn the truth in that danger. There are some theories that attempt to explain things in terms of something fundamental like a one-dimensional string or twister, but not enough physical evidence exists to support them.

The Wilson cloud chamber, invented by C.T.R Wilson, made possible the visualization of tracks left by sub-atomic and other high-energy particles. A cylindrical volume of dust-free air, saturated with water vapor, is expanded adiabatically to produce a short-lived state of supersaturation during which water condenses on molecular ions present. The cloud chamber constructed in this experiment, a diffusion cloud chamber, differs from the Wilson cloud chamber in that the vapor pressure and supersaturation are established by a temperature gradient instead of by the rapid expansion. The key advantage is that viewing in a diffusion cloud chamber is continuous, whereas in the Wilson cloud chamber the chamber was good for less than a second and then the chamber had to be recycled. Eventually cloud chambers were replaced by bubble chambers, photographic emulsions, large arrays of various forms of ionization tubes, and even more sophisticated detectors, but the diffusion cloud chamber remains a simple, elegant, and inexpensive way to track particles.

Even without large accelerators and complex detection devices, recording the tracks of high energy particles is possible. The cosmic radiation background consists of particles much higher in energy than anything we can produce in a laboratory. These extra-terrestrial particles (primaries) interact with the earth's upper atmosphere, resulting in a mixture of energetic primaries and secondaries and lower energy secondaries detectable near the surface of the earth. The nearer one is to the upper atmosphere where this shower of particles takes place, the higher are the energies of the particles and the greater is the number of particles detected. The primary flux consists of high energy ($>10^9$ eV) protons, Alpha-particles, and a few light nuclei, whereas the secondary cosmic rain caused by these primaries consist of a flux of protons, neutrons, and pi-mesons (neutral and charged). Neutral pi-mesons quickly decay into a shower of photons, and the charged pi-mesons decay into muons plus neutrinos. Muons (+ or -) carry the same charge as an electron but are 207 times as heavy. Their energy ranges from zero to many GeV. The negatively charged muons will either spontaneously decay into an electron and neutrino-anti-neutrino pair after coming to rest, or it can be captured by a nucleus resulting in the emission of a neutrino and a neutron. The positively charged muons are repulsed by the nucleus and have only the spontaneous decay route upon coming to rest. About 80% of the cosmic rays at sea level are muons, the rest are mainly electrons and a fewer number of protons.

The mechanism of detection in a cloud chamber is that of ionization. Energy is transferred from radiation to the alcohol vapor causing it to ionize and the vapor ions leave a track where the particle has traveled. This track is contingent upon just the right conditions and for this reason, the tracks of particles are only seen in a small volume of the chamber near the bottom. The principal processes for energy loss are that of inelastic

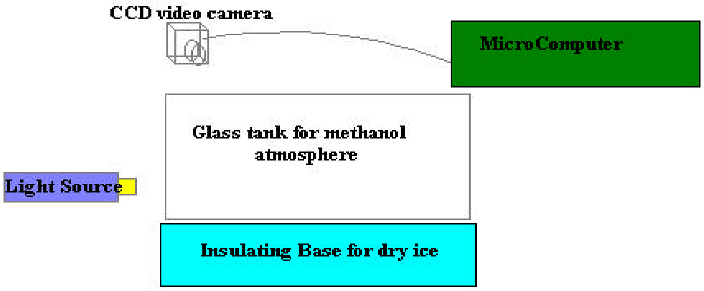

Figure 1 Illustration of the diffusion cloud chamber constructed for the detection of charged particles. The region of activity is near the bottom of the tank.

collisions with energy transferred to the electrons of the vapor (primary mechanism of electrons, beta-rays, and muons), and bremsstrahlung which is the emission of electromagnetic radiation by the decelerating particle (Primary source of energy loss for relativistic particles E>>mc^2).

With the addition of a magnetic field in the cloud chamber, the curvature of particles can be estimated and this in turn leads to an estimate for the momentum of the particle. The force experienced by a charged particle from a magnetic field is:

Equation 1:

$$F = BQn$$

where B is the magnetic induction in teslas, Q is the charge of the particle, and ν is the particles velocity. From Newton's second law describing a curved path,

Equation 2:

$$\frac{mn^2}{r} = BQn$$

with m as the mass of the particle in question, and r is the radius of curvature. Equation (2) lends itself to an estimate of the particles momentum based on the estimated radius of curvature;

Equation 3:

$$P = BQr$$

and from equation (3) the kinetic energy of the particles is,

Equation 4:

$$E^2 = P^2c^2$$

where c is the speed of light. The estimated energy value in conjunction with the physical characteristics of the track, (the larger the mass of the particle the more prominent is the track), make possible a probable guess as to the identification of the particle, which is the primary objective of this experiment. As a secondary objective, the flux density in terms of particles per second per volume is sought for the cosmic background and for some radioactive sources placed near the apparatus.

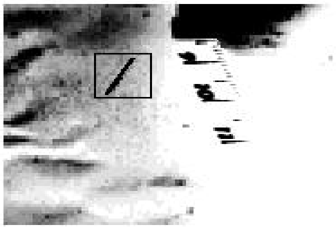

Figure 2 Track due to an Alpha particle. They are characterized by a heavy track and usually require a large magnetic field for deflection.

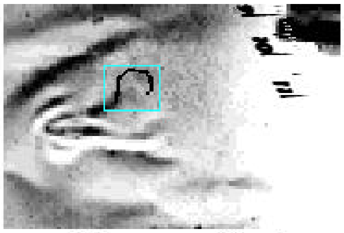

Figure 3 Electron resulting from compton scattering due to a gamma ray.

Apparatus

A glass shell is needed to contain the alcohol vapor with a black metal surface in contact with dry ice to establish the temperature gradient. Within the artificial environment a means of providing the alcohol vapor is accomplished with a blotter. A light source is needed to illuminate the vapor and hence the tracks of any particles. Finally, a means of recording tracks is necessary and is usually accomplished with a camera or video camera. For the acquisition of quantitative measures, a magnetic field is also desirable. Everything in the chamber, except the glass, should be a dull black to facilitate visualization of the tracks since they appear as a white vapor trail.

We used a fish tank with dimensions 54 cm X 26.5 cm X 40 cm to contain the artificial environment. The tank had a curtain of black felt with holes cut for viewing and illumination around the inside to serve as a blotter for the methanol (the preferred alcohol).[1] The tank was placed with its glass bottom up in contact with a thick black aluminum foil pan which was in thermal contact with dry ice contained in a Styrofoam case. The Styrofoam case contained approximately twenty pounds of dry ice. A slide projector lamp with lens was used to illuminate tracks with the light entering the chamber from the side near the base. Approximately 1 liter of methanol was used inside the chamber to provide the vapor. The base of the chamber where the dry ice and chamber meet was insulated using newspaper, felt and cotton cloth, and then a layer of aluminum foil to aid in preventing heat loss through the metal pan into the air. A CCD video camera with a 50 mm lens in conjunction with a microcomputer was used to record the tracks. This was placed at a thirty degree angle with the normal of the plane of the pan, viewing at 0.4 meters above the metal pan and focused at a distance of 0.36 meters. An illustration of this setup is contained in figure 1.

A black ruler scaled in both millimeters and inches with white numbers was placed on the metal pan to provide calibration of track lengths. This also aided in the estimates of the radius of curvature for the tracks. Helmholtz coils would have been ideal

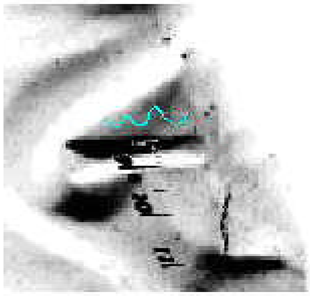

Figure 4 Track of an electron spiral, knocked out of its orbit via compton scattering.

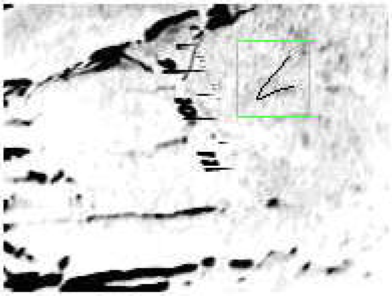

Figure 5 Track of a V collision. The ncident particle is probably a gamma ay resulting in perhaps an electron ositron pair. The gamma could be ither cosmic or from one of the gamma sources placed near the hamber.

to use for the magnetic field because of their uniformity, but the coils we had were not capable of generating an intense enough field to curve anything but the lowest energy particles. Instead a pair of neodymium magnets with an average field strength of 0.05 ± 0.001 T between them was used and placed inside the chamber with a C clamp for support and elevation. The region between the magnets provided the viewing area, and is thus where the CCD video camera was focused. The field is of course not uniform and has a maximum strength near the poles of 0.1 ± 0.001 T. They were separated in the chamber by a distance of ~10 cm. Four different sources were placed on the top of the tank to provide gamma and beta radiation; they are: Cessium-137 (Beta and Gamma), Strontium-90 (exclusively Beta), Cadmium-109 (Gamma source), and Cobalt-57 (Gamma source).

Procedure

The dry ice was crushed and placed in the insulated base. Within ten to fifteen minutes after the glass tank with the blotter material soaked in about a liter of methanol, tracks began to appear. The video camera began recording as soon as the tracks appeared but only continued for ~ five minutes because of the limited hard drive storage space on the microcomputer. The tracks remained visible, though, for around twenty minutes. The video tapes were later reviewed carefully, and the total number of tracks that appeared were enumerated and choice tracks were recorded separately frame by frame. These still pictures were modified by a photo-imaging program; the tracks were made more visible by tracing in zero color(white) the trajectories, and the contrast and sharpness were also

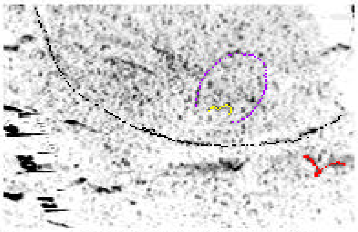

Figure 6 Large track is a beta particle most likely from a source of Sr-90 placed near the chamber.

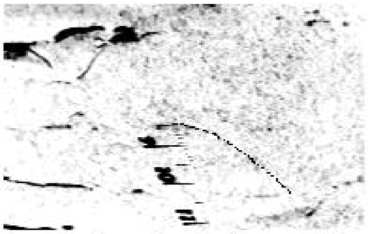

Figure 7 A track of a beta particle which is probably from a source of Cs-137 which was placed near the chamber.

modified. The tracks whose radii were estimated were estimated mostly by paper and pencil, but some higher energy tracks with little observable curvature were analyzed using a fitting function algorithm in Mathematica. The fitting function was then used to estimate the radius of curvature of the particle by the following from basic differential geometry:

Equation 5:

$$r = \frac{1}{k} = \left| \frac{\left[(1 + (D_x f(x))^2)^{\frac{3}{2}} \right]}{(D_{xx} f(x))} \right|$$

where f(x) is the fitting function, and k is the magnitude of the curvature vector. From this the momentum and energy are calculated as prescribed in the theory. This data in conjunction with the physical aspects of the track is used to obtain a probable guess as to the particles identity.

Three ~five minute trials were taken over a two-day period. The first trial was done with no radioactive sources near the chamber. The purpose of this trial was to estimate the flux density of the cosmic radiation background. The other two trials had radioactive sources placed on the chamber at ~ 0.36 meters away from the viewing area. The beta emitters Sr-90 and Cs-137 were also analyzed with a Geiger-Mueller tube to estimate the number of particles detected as a function of separation distance. The counting statistics from both the cloud chamber and Geiger-Mueller tube are used to establish some probabilities of witnessing radiation from these sources.

Analysis

The analysis will attempt to provide a reasonable interpretation of the events and the particles observed with our version of the diffusion cloud chamber. The identities were

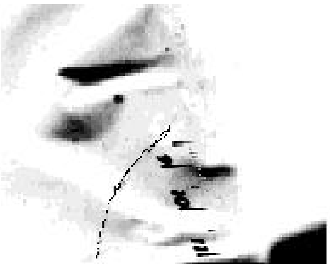

Figure 8 Track of a proton of ~ 3 MeV, probably a cosmic secondary.

Figure 9 Anomalous track outlined in red. Probably an electron colliding with another electron, but appears to be three particles.

chosen and their origins were based on the energies and the physical makeup of the track, using the logic that bigger particles leave heavier tracks, and that tracks curve in a direction characteristic of the sign of their charge. The analysis is concluded with some statistics based on the flux density from the observed number of tracks.

We appear to have observed a few alpha particles, and one is represented in figure 2. These particles are really too heavy to be deflected significantly by the magnetic field within the chamber, and this is well supported by the data. There were a total of four heavy tracks, and none of these were deflected significantly by our magnetic field. It is possible that these heavy tracks are some other heavy nuclei, but most likely they are alpha particles due to radioactive dust in the air around and inside the chamber. The actual source could be thorium or radium, or a number of other common alpha emitters.

The term Beta particle really refers to higher energy electrons but here will be used as an electron above the KeV range. The majority of the tracks were highly deflected particles in the range of 15 to 60 KeV. The track in figure 3 is representative of most of the tracks, and is probably a result of Compton scattering by either a cosmic secondary gamma from the decay of a muon or due to a gamma ray from either of the two sources placed near the chamber. There are also a few nice spirals in the data similar to the one in figure 4. These are also probably due to the same source but have much less energy of the order of a few KeV. The erratic behavior of the spiral is due to the nonuniform magnetic field which it traversed.

There were several possible beta particles in the range of .1 to 1.2 MeV that are most likely due to the Sr-90 and Cs-137 sources placed near the chamber in the latter two trials. The energy of beta decay in Sr-90 is 0.546 MeV, and that in Cs-137 is 1.176

MeV.[2] Only one of the tracks was really near the cesium value, but this is to be expected because it radiates mostly gamma (whereas strontium is solely a beta emitter). Data was taken using a Geiger-Mueller tube to empirically express the dependence of particles detected as a function of distance from the detector. The values at 0.4 meters were, for Sr-90, 0.33 ± 0.02 particles/sec volume, and for Cs-137, 0.37 ± 0.02 particles/sec volume. This is much higher than that observed in the chamber, but in addition to air between the source and the detector there was also ~1mm of glass and methanol vapor to impede the path of particles in the cloud chamber. The average energy of tracks due to the Sr-90 source is 0.46 ± 0.1 MeV, which is close to the beta decay value of 0.546 MeV. The energy of the track that is most likely a beta from the Cs-137 is 1.2 ± 0.1 MeV, which is also very close to the energy value corresponding to beta decay for Cs-137. These are illustrated in figures 6 and 7.

There were a number of V collisions like the one in figure 5, and these are probably due to gamma ray collisions with the nucleus of an atom of the vapor or an atom in the air. The most common resultant particles are an electron and a positron. Unfortunately, the tracks did not last long enough to estimate the curvature, and so no data is available to support any theories as to their existence.

There were a few particles of higher than normal energy, from 3 to 4 MeV and one at 10 ± 0.1 MeV. They appeared to curl in the opposite direction as most of the other tracks but perspective limits the ability to place the 2-D picture in 3-D. These tracks were not as heavy as the alpha tracks, but were considerably more prominent than the beta tracks. If these tracks are due to protons either from secondary or primary cosmic radiation, their energy values are reasonable. For this reason I feel they are probably protons. An illustration of a characteristic track is in figure 8.

The last track of importance is the anomalous track in figure 9. The curvatures correspond to around the 100 KeV range. If these are the emergence of three particles from a neutral particle collision, charge would not be conserved and the only combination I can think of is that of three pions, but pions are usually of much higher energy. If this represents a charged particle colliding with a nucleus and resulting in two charged particles of equal sign then I cannot find a standard collision in the literature that corresponds to such a reaction. The pattern in figure 9 is repeated four times so I doubt it is some kind of exotic collision. I believe the best possibility is that it may be an electron elastically colliding with another electron such that there are not three particles but two with the trajectory of the incident electron being modified by the energy loss in the elastic collision.

A little number crunching of the data from the three trials yields some potentially useful information. From the first trial, in which there were no radioactive sources placed in the vicinity of the cloud chamber, an estimate of the cosmic ray particle flux density is obtained with a value of 0.02 ± 0.003 particles per second per cubic centimeter.[3] This is of the order of magnitude of the particle flux density reported by Professor Derose at the California Institute of Technology which is reported as 10^{-2} particles per second per cubic centimeter. The statistics for the particle occurrence based on my interpretation yields the following distribution: alphas comprised 2%, betas from cosmic sources comprised 41%, betas from Sr-90 comprised 13%, betas from Cs-137 comprised 3%, protons comprised 10%, and particles resulting from a gamma ray comprised 56 % with 18% from V collisions. I suspect that a lot of the cosmic betas are probably muons, since 80% of cosmic rays at sea level are muons.

Conclusion

The results from this experiment were exciting in that the tracks represented particles which, without devices such as the cloud chamber, would remain a mystery to mankind. The glimpse into the subatomic and high-energy particle world was as enticing as Alice's looking glass but left a lot to be desired in the interest of analysis. The experiment required at least ten times as much work as did the usual experiments in a box that most undergraduates are accustomed to, and the results were probably ten times as inaccurate as the boxed counterparts. The apparatus was difficult to get functioning, whereas the commercial versions, as I understand it, require little effort to achieve results and sustained performance for sometimes hours is common. I think the difference is a good thing, though, because Wilson probably put a million times more work into inventing the cloud chamber than did we in just constructing from a rough set of plans. I can appreciate more now, the efforts of those who are seeking results not yet found or creating that not yet created.

The results, despite their gross inaccuracy, are good in that the basic particles of nature, and I mean basic as the most common, are represented here. Though some of the electrons may be muons and the protons may be high energy betas, the alphas could be heavier nuclei, and the V collisions could be from something other than gammas, I feel the present interpretation is as good as can be made from the data. The uncertainties are more guesses than estimates because the possible variation in the magnetic field could be twice the average value, and the radii estimated with Mathematica could be as much as 1/20th of the reported value depending on the point where the estimate is made. The energies for the most part are probably within 20% of the value reported, for I cannot imagine them being much more without having randomly selected a radius of curvature. Even the number of particles detected could be as much as four times the observed value, because the video camera recorded at four frames a second, and a lot of the low energy tracks lasted no more than a brief instance. Despite all this, the experience was good and the data could have been worse. These particles have eluded mankind for thousands of years and I don't feel disappointed about not having mastered their domain.

[1] Kruglak, Haym and Don Kangas. "A simple cloud chamber for television display." Am.J.Phys **54** (5). May 1986:473-474.

[2] Brown, Laurie M.,ed. Pions to Quarks. Cambridge: Cambridge Univ. Press. 1989.

[3] Derose, http://WWW.PMA.CALTECH.EDU/~derose/labs/exp15.html

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