An Introduction to Particle Physics and Detector Concepts

(A Bluffer's Guide to Bubble Chambers!)

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Yn torri at rawd yr atom
Dal gwead y Gread grom

John Eilian (1963)

Tearing at the rotation of the atom
Revealing the weave of the curved universe

A Bluffer's Guide to Bubble Chambers

What is particle physics?

The aim of particle physics is to study the fundamental building blocks of nature and the forces they exert on each other.

A typical fixed target experiment consists of taking charged particles from a machine called an 'accelerator', colliding them with atomic nuclei in a 'target', and measuring what comes out in a machine called a 'detector'.

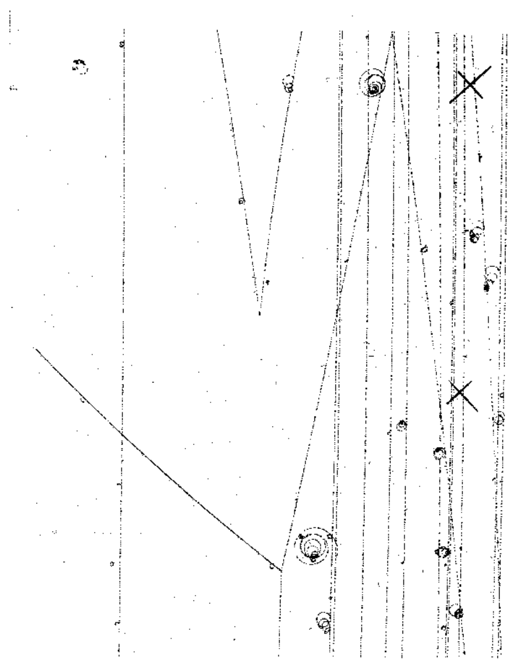
The bubble chamber, a detector that served particle physics well from the 1950s until the 90s, played a crucial part in showing that neutrons and protons (the building blocks of atomic nuclei) are made of smaller, more fundamental particles, called 'quarks', held together by other particles called 'gluons'.

How does a bubble chamber work?

A bubble chamber consists of a tank of liquid that has been raised above its boiling point by the application of pressure. (It is 'superheated'.) Such a liquid is unstable and boils, producing a trail of bubbles along the paths of charged particles that pass through it. It does this by 'ionising' the atoms near its path - knocking electrons out the atoms by exerting electrical forces[1] on their electrons. The trails of bubbles formed can be photographed yielding a permanent record.

Particle physicists used bubble chambers to record, on photographs, every charged particle associated with a collision between a beam particle from an accelerator and the (target) nucleus of an atom of the liquid.

Here is an example:



[1]The force responsible for this is the 'inverse square law of electrostatics' first published by Joseph Priestley in 1767, while he was based as a tutor at the Warrington Academy, UK. (See Feynman Vol II, ch. 5.) This was the first step of the Standard Model, the last being the discovery of the (a?) Higgs boson in 2012.

The parallel lines represent the paths of a beam of about 12 negative particles entering the 2-metre-long bubble chamber at CERN from the bottom of the picture. Here the bubble chamber is filled with liquid hydrogen - hydrogen atoms consist of one negative electron moving around a positively charged proton - which means that the only nuclear particle a beam particle can collide with is a proton, the simplest situation possible.

All but one of the parallel beam particles go through the whole length of the bubble chamber without interacting with a proton - atoms are mainly empty space. (If you imagine the proton at the centre of a hydrogen atom to be expanded to about a millimetre across and placed at the centre-spot of the Millennium Stadium, the electron would be somewhere in the stands and invisibly small to the naked eye.)

> **Problem 1** Assuming that the diameters of a proton and a hydrogen atom are, respectively, 10^{-15} m and 10^{-10} m, estimate the chance of a random proton entering a hydrogen atom actually hitting the nucleus. (You may assume that the incoming proton has enough energy to overcome the Priestley-Coulomb repulsion.)
>
> Then estimate how many atoms the incoming proton would have to cross to have a roughly 100% chance of making a collision. How far is that?!
>
> **Answers** to all problems at the end.

The one beam particle that has interacted with a proton has produced two charged particles:

(1) One goes to the left producing a dark track; this is the proton that was struck; such dark tracks are almost always slow protons from the hydrogen atoms that have received, by chance, a fairly gentle 'knock' during the interaction with the beam particle. Notice that this track curves to the right.

(2) The second track curves (almost imperceptibly) to the left.

(What causes the tracks to curve will be discussed in the next section.)

Notice that, just above the interaction, a pair of charged tracks emerges from a point. The track on the left curves to the left, while the other curves to the right, The two tracks together look like a letter 'vee' and are, indeed, called 'vees' by particle physicists. We will discuss their significance later.

Notice also that there are a few smallish spiralling tracks that appear to be attached to some tracks; they all curve to the left? These are produced by electrons that by chance receive a bigger kick than is required just to produce a bubble and have enough energy themselves to produce a small track of their own.

Key point You can now recognize electrons and slow protons: electrons spiral and slow protons produce short dark tracks.

Question What is the significance of the fact that the charged particles have curved paths?

<u>Movement of charged particles in magnetic fields</u>

A bubble chamber without a magnetic field passing through it is like a bird without wings! A moving charged particle in a magnetic field experiences a force that curves its trajectory.

Which way it curves depends on the charge of the particle - a positive charge curves one way, a negative the other.

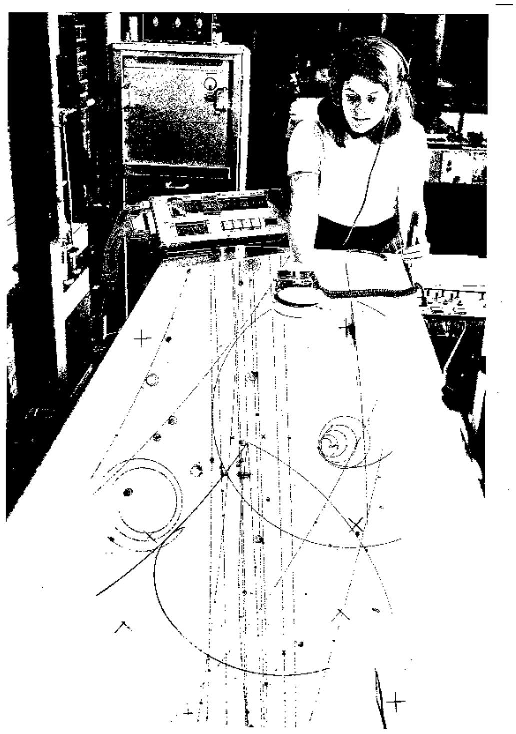
How much it curves depends on its speed (strictly speaking, its momentum which is mass times speed) - the faster a particle is moving the harder it is to make it deviate from its path. (If two identical bullets are shot horizontally at different speeds, the faster one will curve towards the ground less than the slower.)

Key point Measuring the direction and radius r of curvature of a charged particle track in a magnetic field B gives us two important quantities: its charge, q, and its momentum p. This is also true for particles produced in collisions at the Large Hadron Collider (LHC). (Formula: $p = (Bq)r$ - see Appendix A for derivation.))

Further remarks about the picture

We can see immediately that the 'knock-on' electron spirals curve to the left. So we would expect the short dark track of the slow proton to curve the other way, which it does.

A tip for looking at bubble chamber pictures: you get a much better feel for what is happening if you do not look down at the paper at 90 degrees, but at a very small angle. If you do this, it is fairly easy to see that the track that goes to the right from the vee is positive.

> [This picture gives an impression of how bubble chambers photographs were examined. They were projected onto 'scanning tables' about 2 metres long, and every collision of interest to physicists was recorded.
>
> 
>
> The key piece of information needed by the physicists is the radius of curvature of each track which, in a magnetic field of known strength, gives its momentum.
>
> This was provided by a sophisticated programme which needed, as input, measurements of:

(1) the positions of several points on each track on a photograph of a collision - taken on 3 different cameras, without which reconstruction in 3 dimensions would not be possible;

(2) the position on the 3 views of several 'fiducial' marks; these are crosses marked on bubble chamber windows or walls whose positions are accurately surveyed and known. (In Latin, 'fiducia' means 'confidence', 'trust', 'reliance' ....)]

So, what is this vee that we were discussing?

Decays of neutral particles

The vee appears to be coming from the collision point[2]: it represents the decay of an unstable (or radioactive) neutral particle - produced in the collision - into one positive and one negatively charged particle. (The law of conservation of charge - one of the great laws of nature - is respected: the total charge is zero before and after the decay.)

Since this picture corresponds more-or-less to the full length of the 2-metre bubble chamber, we can estimate that the decaying particle travelled about 80 cm before it decayed. Using this distance, and knowing that most of the particles produced in high energy physics travel close to the speed of light, we can estimate how long it took the neutral particle to get from its 'birth' at the collision point to its 'death' where it decays.

$$Time \;=\; \frac{distance}{speed} \approx \frac{80cm}{30{,}000{,}000{,}000\ cm/sec} \;\approx\; 2.7\ nanoseconds^3$$

Notice, to leave visible vees in the bubble chamber the particles must have lifetimes of the order of nanoseconds. If they had lifetimes of, say, a thousandth of a second they would travel 300 km and would not decay in the 2 metre chamber. Similarly, if they had lifetimes of a billionth of a billionth of a second (and there are such particles), they would not get out of the first bubble and, again, there would be no visible vee. (It is not necessary, here, to discuss how relativity qualifies the above discussion.)

Key point Vees in bubble chambers signify the decays of unstable neutral particles with lifetimes of the order of nanoseconds. Only a handful of these exist and there are ways of identifying them by measuring their masses. (See Appendix B for some detail.)

(Take a moment and wonder: if you spot a vee on your bubble chamber photograph, and think you can see where it is coming from, you are witnessing both the creation and the decay of something that existed for only about a billionth of a second.)

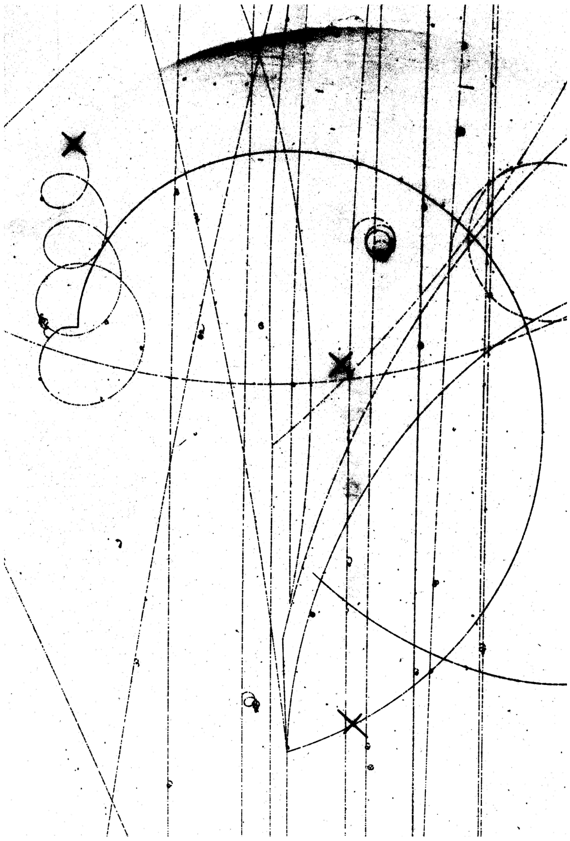
Decays of charged particles

Let us now examine the next collision which is considerably richer. Again, we have a beam of about 10 negative particles entering the CERN 2 metre hydrogen-filled bubble chamber from the bottom. One of them - the fourth parallel track from the left - collides near the bottom of the picture producing a spray of 4 particles.

Before we address the collision of interest, let us check which way negative particles curve by looking for the tell-tale knock-on electron spirals: there are two on the right hand side of the picture about 2/3 the way up. They spiral to the right; one of them goes out of the picture and comes back in again. (Can you find another one?)

[2]This can be shown by measuring the momenta of the two outgoing tracks, adding them, and showing that the resultant momentum goes through the collision point.

[3]1 nanosecond = 1 thousand millionth of a second = time light takes to travel about a foot (30.48 cm)!



(For the moment, do not be distracted by the spiralling track on the left of the picture which spirals to the left: it is a positron - or anti-electron - coming from the decay of a particle called a muon. Anti-electrons spiral very much like electrons, but in the opposite direction because they are positively charged.)

Having established that negative particles curve to the right, let us return to the collision with 4 outgoing tracks.

Consider the second of these from the left. After a short distance, two things happen:

- it suddenly changes direction (it 'kinks'), veering to the right;
- it becomes more curved, showing that it has lost momentum; since it curves to the right, it is negative.

This 'kink' is an important signature in particle physics because it characterises the 'decay of a charged particle'. Some particles are unstable or radioactive and can only travel a certain distance before decaying. Since this picture corresponds to about a half of the length of the 2-metre bubble chamber, we can estimate that the decaying particle travelled about 12 cm before it decayed.

> **Problem 2** One could ask at this point why we cannot interpret the kink as being a collision between the particle track we are considering and a proton in a hydrogen atom. The answer can be found by applying the law of conservation of charge; try it.

Key point Kinks in bubble chambers signify the decays of unstable charged particles with lifetimes of the order of nanoseconds. Only a handful of these exist and there are ways of identifying them by measuring their masses.

(Each charged particle decay involves the emission of one or more neutral decay products which leave no tracks: they are usually 'neutrinos' - another story! Their presence is essential to ensure that all relevant conservation laws are obeyed.)

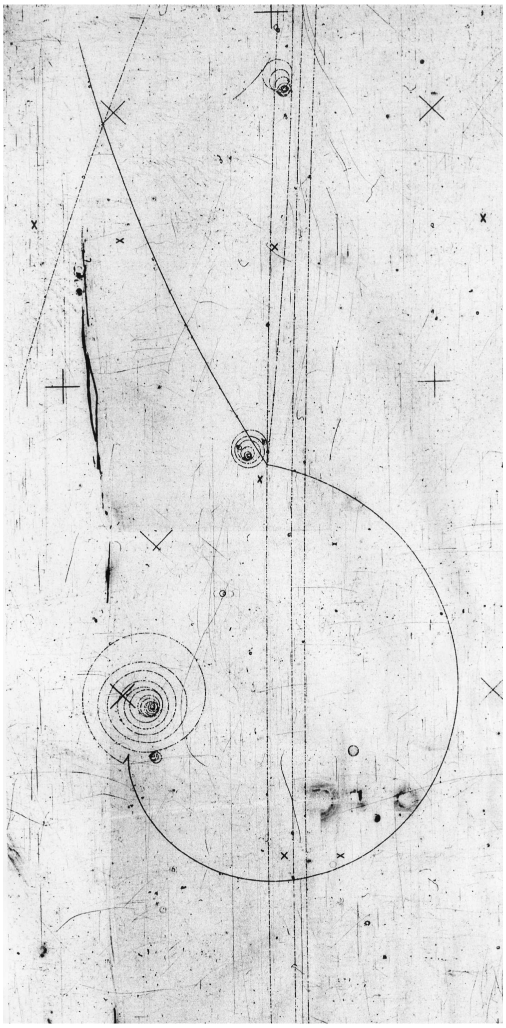
A digression on kinks

At this point we can return to the positron spiral on the left of the picture. We see that this track starts from a short dark track which kinks; the short dark track itself started at a kink at the end of the rightmost track coming from the collision we are studying.

So here we are witnessing two consecutive charged particle decays: a positive pion, π^+, has looped round in a big arc before stopping; this has then decayed at rest into a positive muon, μ^+, which travels a short distance before decaying into a spiralling positron, e^+.[4]

This decay sequence is quite common and is referred to as a 'pi-mu-e' or '$\pi - \mu - e$'.

Here is another:



Exercises
(i) Convince yourself that this example of a pi-mu-e is positive.
(ii) Assuming the bubble chamber is filled with hydrogen (or otherwise), convince yourself that the beam is positive

[4] If the π had not stopped, the μ would 'carry' some of its momentum and travel further.

A summary of relatively common signatures to look for on bubble chamber collisions in hydrogen

- A spiralling track is almost always a negatively charged electron. (Anti-electrons or positrons are comparatively rare, so you would be lucky to find one. The most likely occurrence is in 'pair-production' which will be discussed later.)
- A shortish dark positive track which does not kink is almost certainly a slow-moving proton.
- A vee/kink usually signifies the decay of a neutral/charged particle with a lifetime in the nanosecond range.
- A pi-mu-e: this usually appears as a looping slow pion track kinking at its end into a short, dark, slow-moving-then-stopping muon track; this in turn ends by kinking into an electron or positron track, depending on whether the original pion was negative or positive.

Question - with a medical connection: Why are slow-moving particle tracks dark?

Answer: See Appendix C

What do we learn from identifying the particles in bubble chamber collisions?

In a typical bubble chamber experiment, hundreds of thousands of collisions between a beam particle and a target proton might be taken. For example, in the two pictures we've just examined in some detail, both interactions were produced by a negative particle called a K^- (pronounced 'kay-minus') with a momentum of 8.25 GeV/c.

> (Such a particle will have been accelerated through 8.25 billion volts and is highly relativistic. If you are lucky enough to have some bubble chamber film, you may well see this figure on the bottom right of the picture, together with some other information such as the name of the beam particle, the date the picture was taken ...)

The reason for taking so many pictures is that many outcomes are possible and it is the relative amounts of each that gives the whole picture. This is what we compare with theoretical predictions based on the latest ideas. For example, it is possible to establish from the existence of the particles we detect in the bubble chamber - including the decays - the existence of other particles with such short lifetimes that they decayed within the first bubble, leaving no direct evidence: we learn about the existence of the short-lived 'parents' by studying their longer-lived 'children'.

This is the way particle physics still operates. No Higgs bosons emerged from the LHC beam pipe. The discovery of the Higgs boson was based on a study of what it decayed into, 'ordinary' particles like photons and muons that were discovered in the huge electronic detectors - ATLAS and CMS. Such modern detectors - miracles of modern electronic technology that, itself, is the product of the particle physics of the early 20$^{\text{th}}$ century, namely atomic physics - have far superceded bubble chambers in their ability to look deep into the heart of matter, or equivalently, at the conditions that existed about a millionth of a millionth of a second after the Big Bang.

However, there is one thing they cannot produce - an actual photograph showing, step-by-step, the story of what happened in an individual collision.

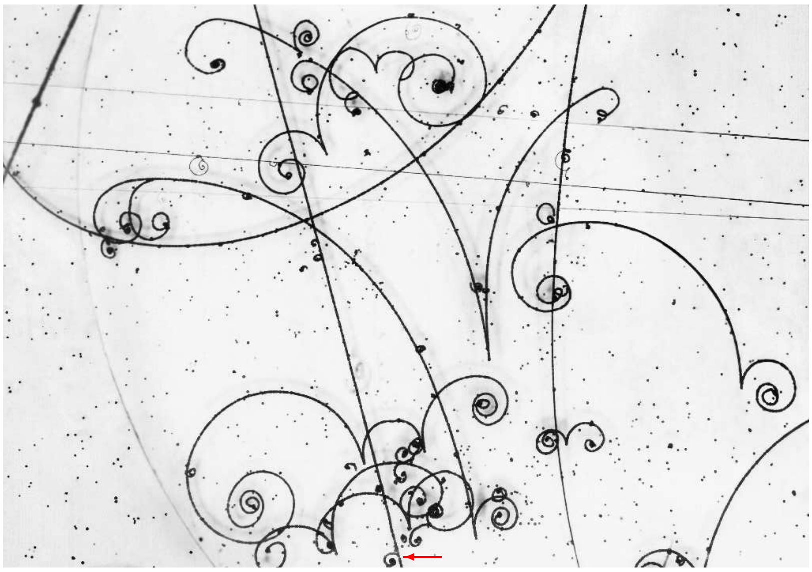
So, treasure your own individual bubble chamber picture. It is a record of a unique collision between particles. In years to come, we may never be able to read LHC data because computer technology will have moved on - but you will have your picture[5]

[5] CERN recently threw away many millions of such pictures which were stored in an unlit cavern-like basement under the hall where the Big European Bubble Chamber (BEBC) operated - denying future archaeologists, or space-travellers, a special insight into human civilization in the 20th century!

A selection of bubble chamber pictures

Since they show actual trails of bubbles that are formed as charged particles force their way through an unstable liquid, bubble chamber pictures are perceived by non-particle physicists as 'real' (not computer-generated as many people think that really real LHC events are!), and therefore a good way to introduce particle physics. The pictures themselves are quite often easy to understand in an intuitive, qualitative way. People who are not particle physicists often compare them to vapour trails left by aeroplanes ('contrails' in the US).

The pictures, moreover, possess a mysterious, cosmic beauty that is particularly appealing to the non-scientist.



Some liken them to Miro drawings.

What can one learn from this picture?

What one is actually seeing here is a small electromagnetic shower - starting at the bottom of the picture - consisting of 3 different kinds of particles:

(1) Electrically neutral gamma-ray **photons**, γ, which you can't see because they leave no trails of bubbles as they travel through the bubble chamber liquid (here it is mainly neon). However, when it passes close to a neon nucleus, such a photon may - if it has enough energy - produce a pair of charged particles[6].

(2) a negatively charged **electron**, e^-, and

(3) a positively charged **anti-electron** (usually called a **positron**), e^+.

These charged particles do leave tracks and there are several examples of this process - known as 'pair-production' - in this picture: two tracks emerge from a point with zero opening angle and then curve in opposite directions, .

[6]This 'pair-production' process is induced by the charge of the neon nucleus, which is 10 times that of the proton; and the probability of pair-production is proportional to the square of the charge. At the LHC, even more highly charged nuclei are used to capture all the energy of huge electromagnetic showers in quaintly named electronic detectors called 'electromagnetic calorimeters'.

The perceptive reader might at this point comment that there seems to be no systematic difference between the tracks which curve to the left, and those which turn to the right; so how can we tell which are the electrons and which are the anti-electrons, matter or antimatter?

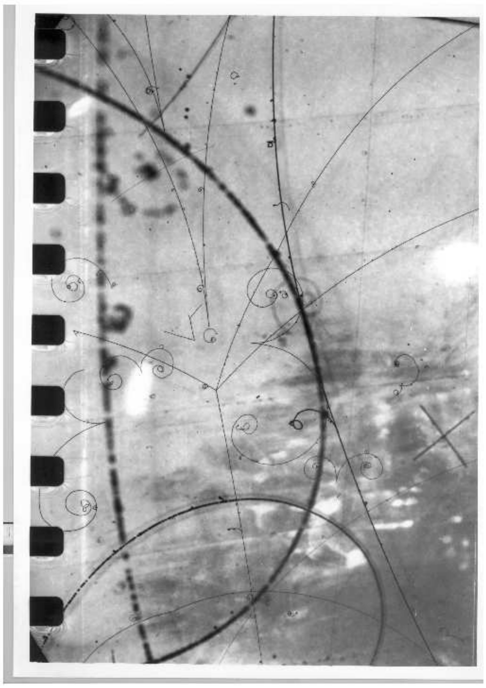
This is almost true, but if you look very carefully, there is a tell-tale difference. There are a few tiny knock-on electron spirals on some of the tracks (e.g. see arrow), and they all curve to the left. There is also a big one on the electron track on the left side of the picture.

[In passing: you have now 'seen' positrons - examples of antimatter. Antimatter is more or less non-existent in the universe, but can be created in high energy physics interactions. Eventually, usually at the end of their spirals for the ones we've considered, the positrons annihilate with electrons from ordinary matter producing two back-to-back gamma-rays. This is the process used in hospitals in PET scanners - **P**ositron **E**mission **T**omography[7]. Once something is discovered, never underestimate the ability of the applied scientist to make something useful with it!]

The Cosmic Connection

Occasionally, cosmic rays appear on a bubble chamber picture, reminding us of the intimate link between cosmology and particle physics. There is a big accelerator, in the sky, far more powerful than the LHC! (Sorry, Lyn!)

The next picture, entitled 'The Cosmic Cradle', shows a particle interaction: a charged particle track enters from the bottom and, near the middle of the picture collides with the nucleus of an atom, producing a spray of three charged particles (plus some other activity that you are invited to associate with the interaction; for example, can you see any electron-positron pairs?).



[7]The positrons used in PET scanners come from the decays of made-made radioactive nuclei; fluorine-18, for example.

The cosmic connection consists of the two thick out-of-focus tracks, produced by cosmic rays that happened to pass through the bubble chamber at the same time as the interaction of interest, and appear to cradle it.

Notice that the straighter cosmic track has two fuzzy (rather vague but nevertheless genuine) spirals on it: the educated eye sees that these are electrons that have been knocked out of atoms as the cosmic ray makes its way DOWN the picture, in the opposite direction to the flow of the collision that we are studying. Both these (negative) electrons curve to the left as they leave the cosmic ray track - so now we know which way all the tracks will curve: negatives to the left, positives to the right.

> **Exercise** Can you find another example of a 'knock-on' electron on the track that comes into the picture from near the bottom right-hand corner? Check that it curves to the left.

[In passing: one of the wonders of science over the last century has been the realisation that we 'see' (understand) the physics of the very large through the 'eyes' of the very small:

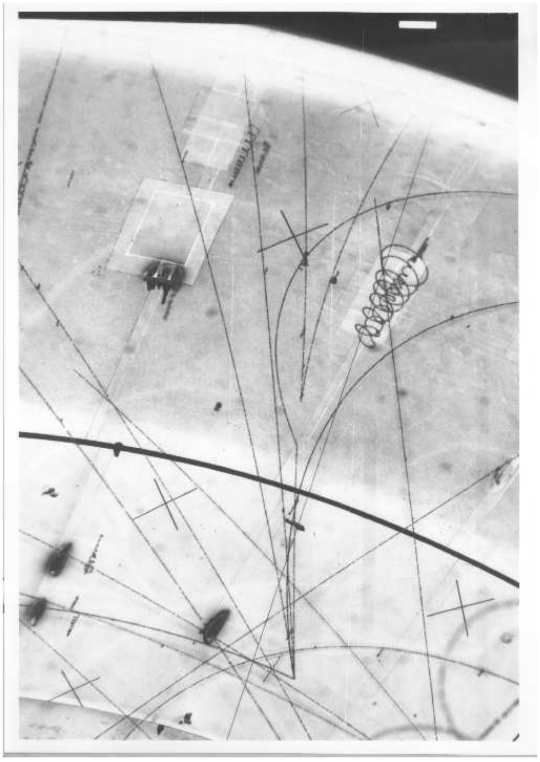
- Our understanding of the spectra of atoms has enabled us to identify different elements in the spectra of light coming from distant stars and galaxies.
- On the deeper, higher energy, level of nuclear physics we can describe the evolution of stars from their births in collapsing clouds of matter to their deaths - in some cases - as explosive supernovae. The 1987A supernova created great excitement because physicists were able to capture particles called neutrinos emitted during this event, neutrinos that had been on their way for nearly 200000 years; magically, we were ready for them, just!
- On an even deeper, and higher level of energy still, we can go back about 13.7 billion years to within a millionth of a millionth of a second of the Big Bang in the Large Hadron Collider.

  We are not, of course, really travelling backwards in time: we are re-creating, albeit on a tiny scale, the hot dense conditions that - according to our theories - existed in the earliest moments of the universe's existence.

The same physics appears to work throughout the visible universe. Any deviation from this would be very exciting.]

Production of a Ξ^- (xi-minus) in a collision between an antineutrino and a proton

Here is a picture taken in the hydrogen-filled Big European Bubble Chamber (fondly known as BEBC, pronounced 'beps') at CERN. The beam was of neutral particles called anti-muon-neutrinos, $\bar{\nu}_\mu$.



The long spiralling track tells us that negative particles turn to the right. The collision has 3 positive tracks which curve to the left and 2 negatives which turn to the right, a final state total charge of +1. This is consistent with an initial state consisting of a neutral $\bar{\nu}_\mu$ beam particle and a target proton.

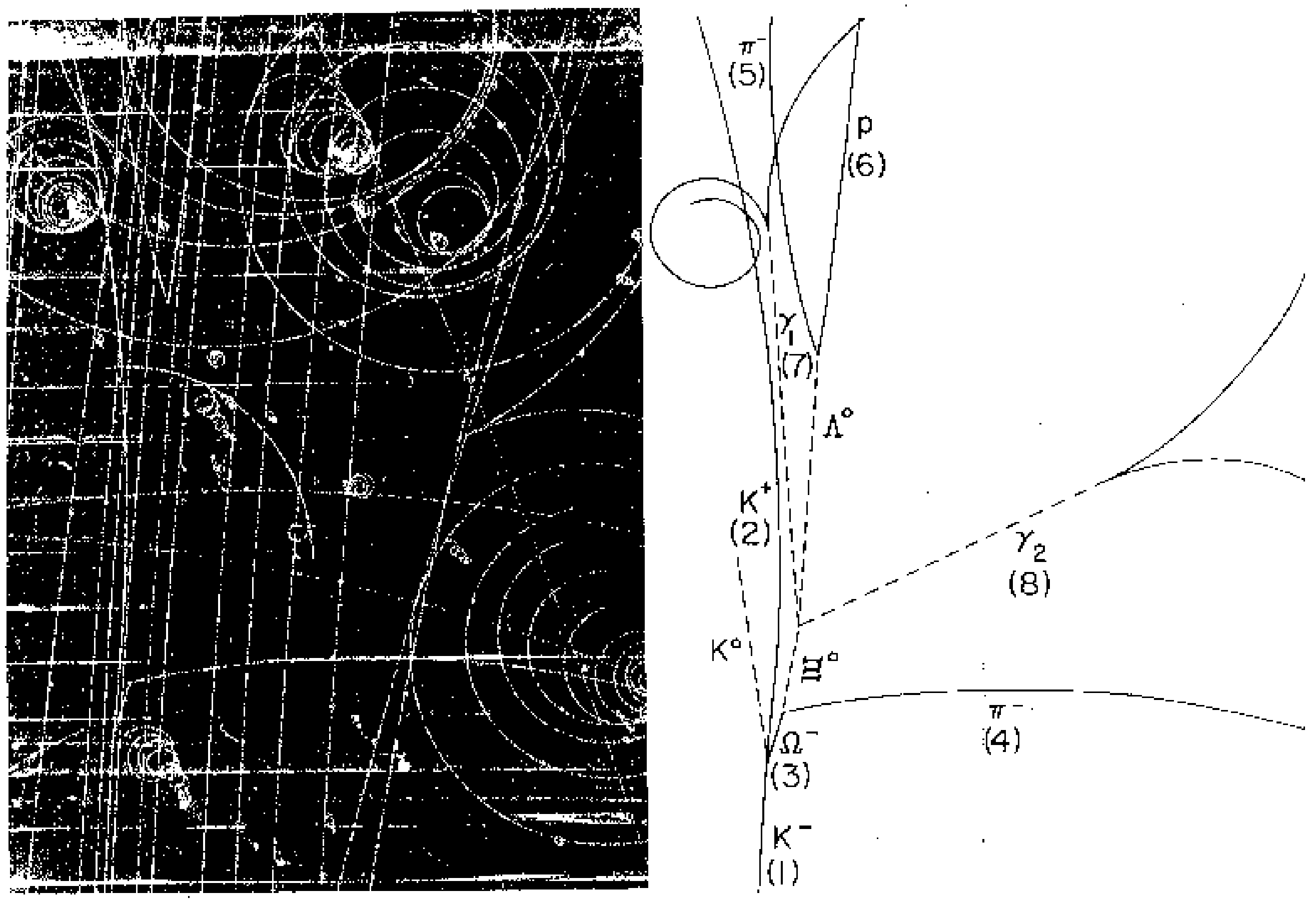
The decays here are spectacular: we have a kink to which a vee is pointing. This tells particle physicists that the decaying charged track producing the kink must be one of only two possible particles, a Ξ^- or an Ω^- (omega-minus). We cannot tell just by looking, but a measurement[8] clinches the Ξ^- identification.

(Ξ^- production by neutrinos is so rare that no publication on this process has been produced; so this event is a bit of a collector's item!)

[8]Measurements involve determining the momenta of the tracks from their curvatures and then applying the relativistic versions of the laws of energy and momentum conservation to see which, out of all possible interpretations, best fits the measurements (taking their errors into account).

One of the most famous bubble chamber pictures of all: the discovery of the Ω^-

This picture was taken in Brookhaven National Laboratory 80 inch hydrogen bubble chamber in 1964 and was central to the discovery that neutrons and protons consist of smaller particles called quarks.



Despite the rather poor quality of this film, the physicist who was on the night shift was able to satisfy himself on the basis of what was on the picture (and a 'back of the envelope' calculation) that this was the first Ω^-. This was the particle that the Brookhaven laboratory had set out to find, the particle that won Murray Gell-Mann of Caltech the Nobel Prize: he had predicted not only its existence but also its mass, based on the idea of quarks. If that wasn't enough, the night-shifter had the pleasure of waking up his boss in the middle of the night to tell him the good news!

For full details:

`https://teachers.web.cern.ch/teachers/archiv/HST2005/bubble_chambers/BCwebsite/articles/03.pdf`

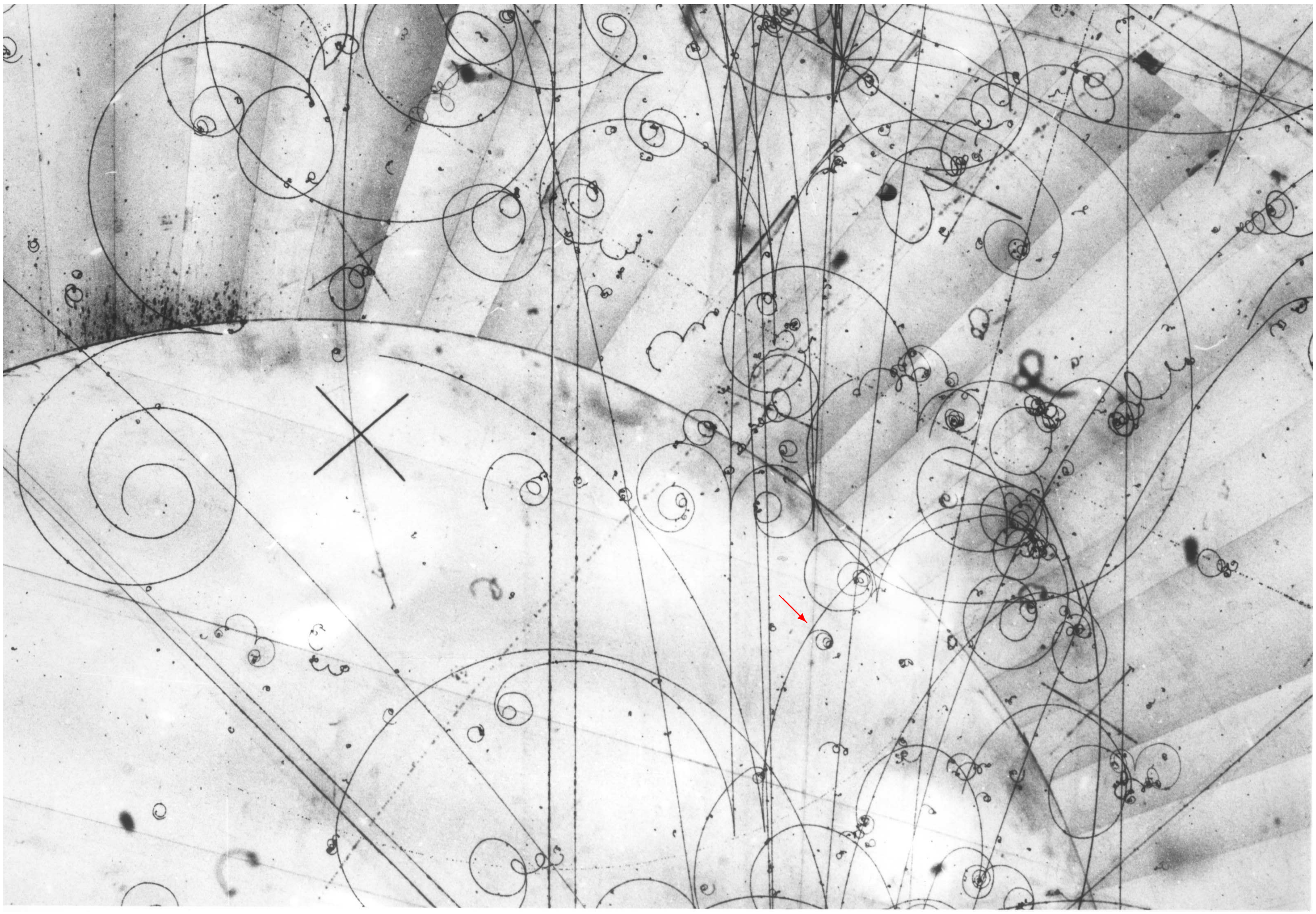
This picture displays a large number of the special signatures we have discussed:

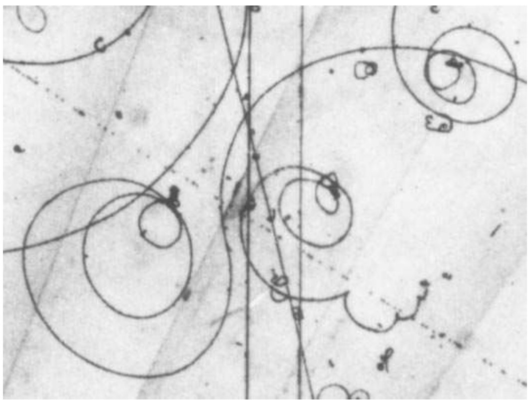
- Knock-on spiralling electrons.
- Decays of both a neutral and a charged particle - both a vee and a kink.
- Two examples of pair-production, e^+e^-.

An exceptional pair of positrons

Most of the tracks in this picture are part of a large electromagnetic shower produced in a neutrino-induced collision (that is below the bottom of this picture, taken in the 15-foot bubble chamber at Fermilab, filled with a mixture of hydrogen and neon).

In what is essentially a side-show to the main neutrino collision, the shower contains two rare occurrences. Let us examine it:





Question

In this blow-up of a part of the picture above, a track enters near the top right, curving to the left; then, in the middle, it appears to change curvature and spiral

What is going on?

First, one needs to find a tell-tale knock-on electron to see which way negative particles curve. There aren't many, but there is a small one about 1/3 of the way up from the bottom, showing that negative particles curve to the right. (See arrow!)

Next, find where the positive track entering the blow-up picture comes from by looking at the main picture: it can be seen to be a positron, e^+, from a slightly obscured e^+e^- pair.

In the blow-up, the apparent change in curvature of the incoming e^+ is followed by an e^- track - it spirals. So, a positron appears to have changed into an electron mid-flight: impossible - this would violate charge conservation.

What has happened is that the e^+ has run directly into an e^-, transferring all its momentum to the e^-. This tells us that - within our experimental errors of measuring the curvature before and after the change in curvature - the mass of the positron equals that of the electron[9]. Just by looking at a picture of something that happened in about a nanosecond, you have weighed a piece of antimatter. Wow!

At this point, people ask, 'Why did the positron and the electron not annihilate each other in the collision? Everybody knows that you get annihilation when matter and antimatter meet.'

The answer lies in the fact that the phenomena we are observing obey the rules of quantum mechanics. Within that realm, anything that doesn't violate conservation laws can happen. So sometimes an e^+ and an e^- can just bounce off each other as we've just seen; and sometimes they annihilate as, by a remarkable chance, happens in the same picture nearby: on the left hand side of the picture, just above a dark fiducial cross, an e^+ from an e^+e^- pair appears to stop mid-flight. If you look in the direction in which the e^+ was going you will see an e^+e^- pair pointing back.

What has happened is the following: the original e^+ annihilated in flight with an electron in its path. Then, one of the photons produced in the annihilation went in the direction of the original e^+ and, after travelling 11cm in the bubble chamber, pair-produced a new e^+e^- pair.

(The relative probability of the momentum transfer and the annihilation process depends on the energy of the original positron - and involves post-graduate level quantum mechanics; so don't worry about it.)

For more details:

`https://teachers.web.cern.ch/teachers/archiv/HST2005/bubble_chambers/BCwebsite/`

Click on "BC Teaching Materials", then on "extra materials (articles)", then on "positron Annihilation in Flight" and/or "A Simple Estimate of the Mass of the Positron".

[9]On a snooker table, it is possible to play a shot in such a way that the projectile ball stops and transfers all its momentum to the stationary 'target' ball. This can only be done because snooker balls have the same mass. If you imagine the projectile ball to be made of polystyrene, say, it would bounce back from the target. On the other hand, a lead projectile would continue on its path after running into the ordinary snooker ball.

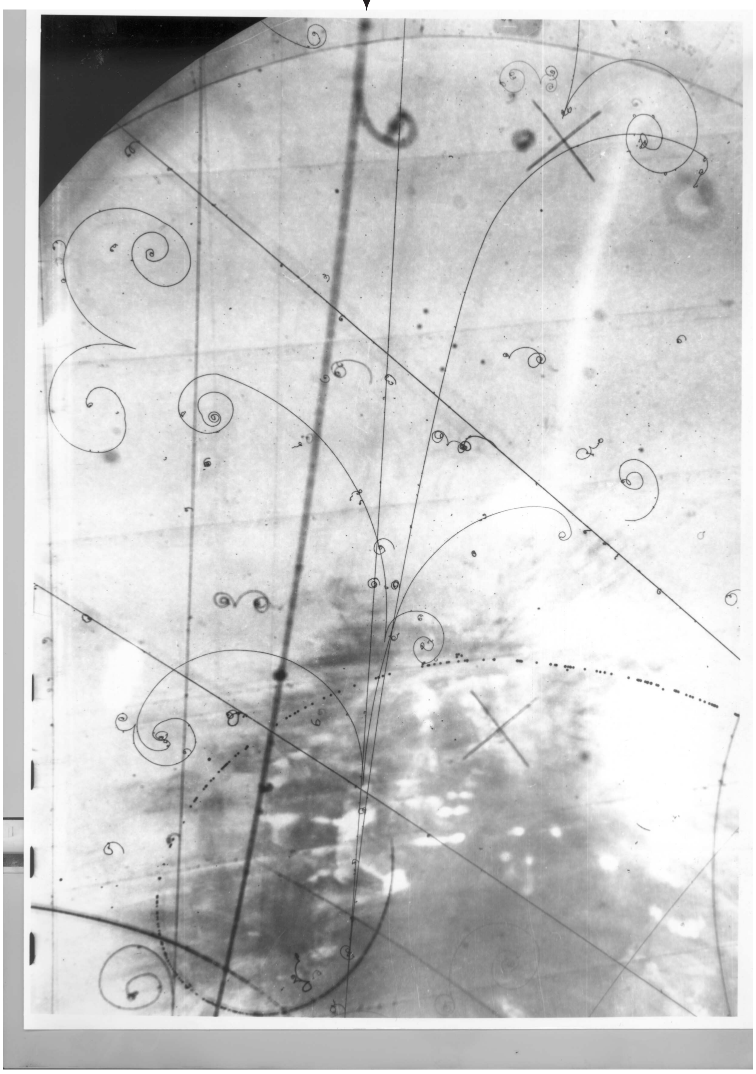
Accelerated charges emit electromagnetic radiation

We are bathed in electromagnetic radiation, from the light that enables us to see to the radio frequencies that our smart phones depend on. They all start somewhere from accelerating charges. (Someone once flippantly described a radio transmitter as a bunch of electrons running up and down a pole!)

This bubble chamber photograph of an electromagnetic shower contains several examples of electrons and positrons emitting gamma-ray photons which then herald their existence by producing electron-positron pairs.

We can make use of the fact that a cosmic ray entered the bubble chamber while the shower was occurring. The tell-tale knock-on electron on it tells us that negative charges turn to the left.

A cosmic ray enters



The first example of an accelerating charged particle radiating can be seen on the left side of the picture just above half-way up the picture: an electron from an e^+e^- pair suddenly curls up showing that it has lost momentum (slowed down). This acceleration caused the electron to radiate a gamma-ray photon, γ, which travelled on a bit before pair-producing a new e^+e^- pair.

(Note: in physicist-speak, any change in velocity - speeding up, slowing down, changing direction - is an acceleration.)

On the opposite side of the picture, a positron track curls up, showing that it has 'accelerated' and emitted a photon. This time, however, the photon does not pair-produce: instead, it knocks a single electron out of an atom which appears as a lone electron just ahead of where the e^+ radiated. (This is called a 'Compton electron'.)

Qu: How is it that electron and positron tracks end by curling up in a tight little spiral, while other particles like protons and pions seem just to curve gently?

Ans: The fact that they have spiralled in means that the e^+ and e^- tracks have lost speed (or momentum) relatively quickly, by a mechanism that seems not to apply to other charged particles such pions and protons. This process is known as 'bremsstrahlung', a German word meaning 'braking radiation': charged particles travelling in a medium will experience electrical forces F due to the charges on the atomic nuclei; these forces produce accelerations a, and the accelerated particles radiate, losing some energy in the process; so they slow down (hence the word 'braking').

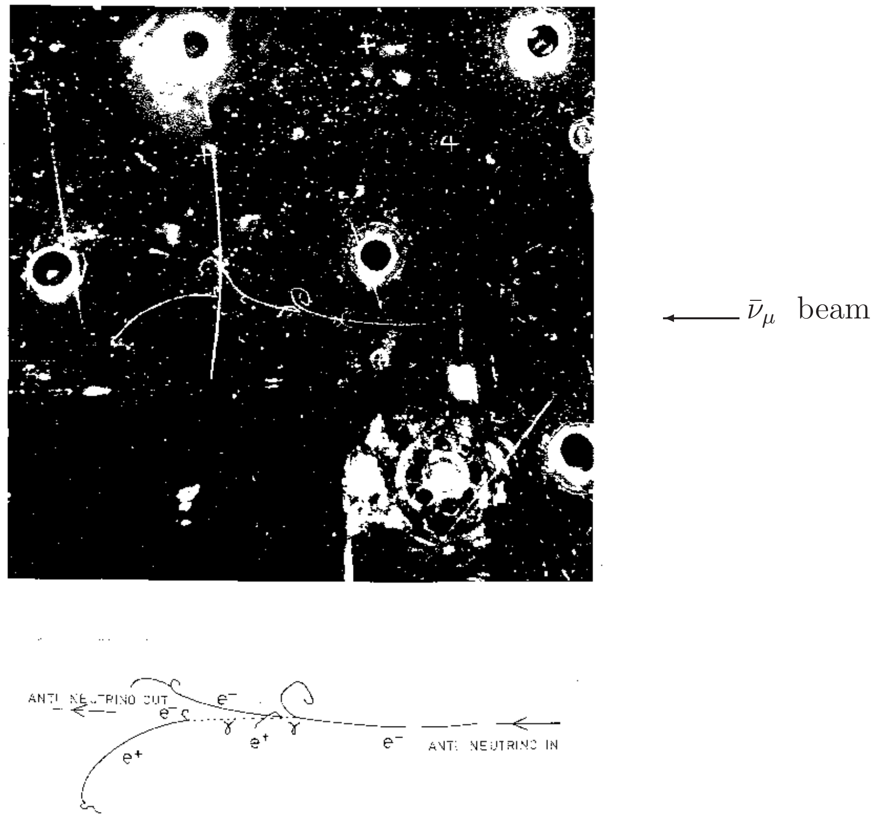
The amount of radiation depends on the acceleration a which is given, according to Newton's Second Law, by $a = F/m$, where m is the mass of the accelerated particle.

Electrons and positrons have a much lower mass m than all other known charged particles, so their a is much greater; so they lose much more energy by this process than the other particles - the origin of the pretty, iconic spirals that characterise bubble chamber pictures!

The discovery of neutral currents at CERN in the Gargamelle bubble chamber

This unassuming picture is one of the bubble chamber 'greats': a tiny electromagnetic shower demonstrates the existence of a very simple, but rare, collision between an anti-muon neutrino $\bar{\nu}_\mu$ beam particle and an atomic electron e^- in the bubble chamber liquid:

$$\bar{\nu}_\mu e^- \longrightarrow \bar{\nu}_\mu e^-$$



The first e^- is the one that was knocked out of an atom by the $\bar{\nu}_\mu$. The two little e^+e^- pairs are produced by bremsstrahlung photons emitted from this first electron, thus identifying it.

Nearly 750000 pictures were scanned before this was found - the first observed 'neutral current' candidate.

Some have argued that this discovery was in the Nobel Prize category, which is why the conclusion to the paper announcing it is so charmingly guarded:

> *We conclude that the probability that the single event observed in the $\bar{\nu}$ film is due to non-neutral current background is less than 3%.*

For full details:

https://teachers.web.cern.ch/teachers/archiv/HST2005/bubble_chambers/BCwebsite

An example of '$E = mc^2$'

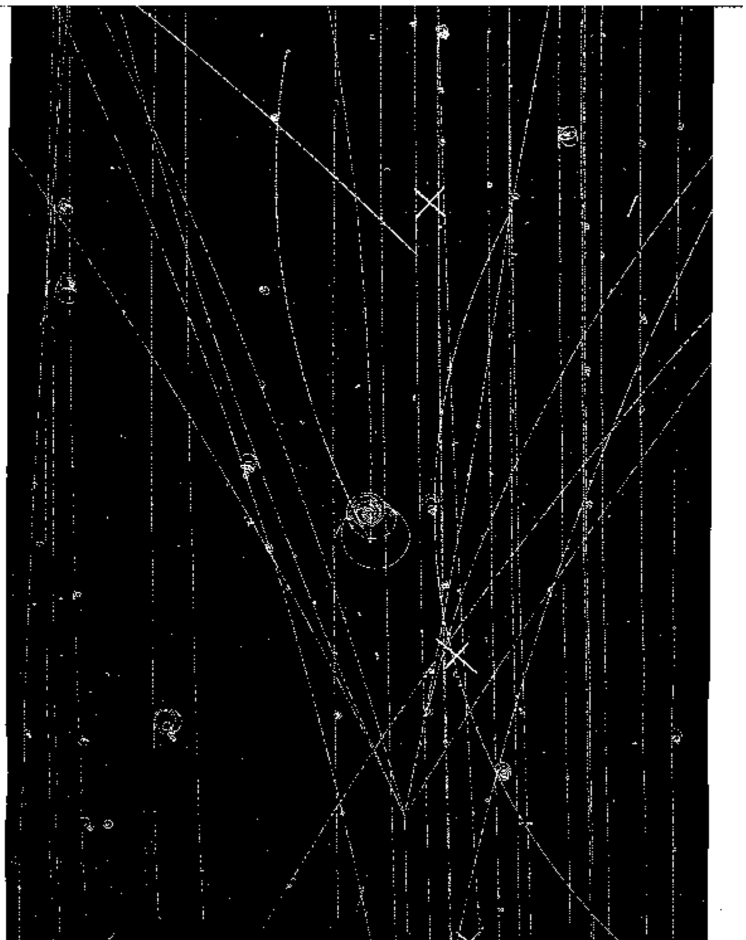
This is one of 5.3 million pictures taken in the CERN 2 metre hydrogen bubble chamber to study the interactions of 8.25 GeV/c K^- particles.

The reaction involved is $K^-p \longrightarrow K^0\pi^-\pi^-\pi^-\pi^+\pi^+p(\pi^0)$ followed by the decay of a neutral kaon, K^0, into two pions: $K^0 \longrightarrow \pi^+\pi^-$.

(The (π^0) in the above equation tells us that, by calculating the mismatch in energy and momentum in the event after it has been measured, we can infer that a neutral particle called a pi-zero, π^0, was also produced. This always decays to 2 photons which usually escape from a hydrogen bubble chamber undetected. In the earlier picture of the discovery of the Ω^-, where the 2 photons from a π^0 pair-produced, they were just very lucky!)

This picture is an example of a very common occurrence in particle physics, the creation of new particles from the kinetic energy involved in the collision. Here, beginning with two particles in the initial state K^- and proton p, we end up with 8 particles.

As particle physicists would say, kinetic energy E from the K^- beam particle has been 'converted' into mass m, the 'exchange rate' being given by c^2, where c is the speed of light. The word 'converted' is in quotes because, if one wishes to be pedantic, one cannot convert energy, which is measured in joules, into mass which is measured in kilograms.



At the LHC, hundreds of particles can be produced in a single pp collision!

Odds and ends

CERN High School Teachers' Bubble Chamber Website - further information

For more information on bubble chambers there is a work-in-progress site produced by several cohorts of teachers attending the International CERN High School Teachers 3-week Summer School.

`https://teachers.web.cern.ch/teachers/archiv/HST2005/bubble_chambers/BCwebsite/`

(You could just GOOGLE "bubble chambers website".)

This should get you to the "Introduction to the BC" page which contains links to

- a tutorial on how to read bubble chamber pictures;
- a gallery of
  - examples of most of the particles seen in bubble chambers with detailed descriptions;
  - examples of concepts such as
    - charge conservation;
    - momentum conservation;
    - $E = mc^2$;
    - accelerated charges radiating;
    - ...
- useful educational articles.

Solutions to problems

Problem 1 Assuming that the diameters of a proton and a hydrogen atom are, respectively, 10^{-15} m and 10^{-10} m, estimate the chance of a random proton entering a hydrogen atom actually hitting the nucleus. (You may assume that the incoming proton has enough energy to overcome the Priestley-Coulomb repulsion.)

Then estimate how many atoms the incoming proton would have to cross to have a roughly 100% chance of making a collision. How far is that?!

Answer Probability of collision $\sim \frac{area\ \ of\ \ proton}{area\ \ of\ \ atom} \approx \frac{(10^{-15})^2}{(10^{-10})^2} = 10^{-10}$.

The proton would need to cross about 10^{10} atoms, which is about a metre. (So now you should understand why CERN built a 2 metre long bubble chamber to study interactions like this. Many other similar bubble chambers were used at various high energy physics labs.)

Problem 2 One could ask at this point why we cannot interpret the kink as being a collision between the particle track we are considering and a proton in a hydrogen atom. The answer can be found by applying the law of conservation of charge; try it.

Answer Since the beam particle is negative (given earlier) and the proton is positive, the collision would have an initial total charge of zero; this means that the total charge of the 4 final state particles must also be zero - 2 positive and two negative tracks, one of the negative tracks being the kinking track under discussion. If this had collided with a proton, the total charge after would have to be zero. But it is not; it is -1 corresponding to the negative track after the kink.

Appendix A **Measuring momentum p using a magnetic field B.**

A particle with charge q travelling through a magnetic field B with a speed v experiences a force at right angles to its motion. If the motion is perpendicular to the field, the force is given by Bqv.

This makes the particle follow a circular path with radius r, the motion being described by

$$Bqv = \frac{mv^2}{r}$$

Re-arranging, and using $p = mv$ gives $\underline{p = (Bq)r}$.

This tells us that, for a given field B and charge q, the momentum is proportional to the radius: $p \propto r$.

Here. nature has been kind: all charged particles that live long enough to travel a measurable distance have a charge equal to or opposite to the charge of the electron (1.6×10^{-19} coulomb). If this were not so, we would not be able to use charge conservation in a simple way when discussing particle interactions.

Appendix B **Measuring the masses of particles moving with relativistic speeds**

In non-relativistic (Newtonian) physics, mass m, speed v, momentum p and kinetic energy T are related by

$$p = mv, \quad T = \tfrac{1}{2}mv^2, \quad \text{and} \quad T = \frac{p^2}{2m}.$$

So, we can see that, given any two of v, p and T we can calculate the mass m. Also, knowing m and any one of v, p and T we can calculate the other two.

The same is true for relativistic particles but the formulae need to be generalised to build in the experimental fact that no material particle can travel with the speed of light. The relevant formualae are

$$p = \frac{mv}{\sqrt{1 - \frac{v^2}{c^2}}}, \quad p = v\frac{E}{c^2}, \quad \text{and} \quad E^2 = p^2c^2 + m^2c^4.$$

where E is the total energy, which we'll discuss briefly in a moment, and c is the speed of light.

The purpose of detectors is to provide physicists with information on p, v and E.

Sometimes a particle will be immediately recognisable: for example, a pion might show up as a characteristic pi-mu-e decay. Knowing it is a pion is equivalent to knowing its mass, 0.13957 GeV/c^2.

If we can then measure its momentum p from the curvature of its track, we can calculate its energy from $E^2 = p^2c^2 + m^2c^4$.

Before moving on to an example of how we determine the mass of a decaying neutral particle, let us digress for a moment to discuss the units of E, p and m used by particle physicists.

Use of 'GeV-type' units rather than SI in Particle Physics

Consider $E^2 = p^2c^2 + m^2c^4$. Re-arranged this gives $m = \sqrt{\frac{E^2 - p^2c^2}{c^4}}$.
Given E in joules, p in kg m/s, and $c = 3 \times 10^8$ m/s, this yields m in kg.

However, particle physicists measure energy in GeV, where 1 GeV = 10^9 eV = energy gained by an electron or proton accelerated through 10^9 volts.

Qu; So how does one use $E^2 = p^2c^2 + m^2c^4$ to measure mass using 'GeV-type' units?

Ans: Look at the equation! For the units of each term to be the same, if E is given in GeV, then p must be in GeV/c and m must be in GeV/c^2.

Then $$E^2(\text{in GeV}^2) = p^2(\text{in GeV}^2/c^2)c^2 + m^2(\text{in GeV}^2/c^4)c^4$$

You can see that the velocity of light c 'cancels' in the p^2 and m^2 terms. So, physicists often like to 'simplify' this by writing it as

$$E^2 = p^2 + m^2$$

You will see this last formula many times during your visit; don't worry about it. To build up your confidence we will now do an explicit example using it (and you will see that the cs 'look after themselves'!).

- **How can one determine the mass of a neutral particle decaying into a 'vee'.?**

By good fortune we still have the momentum measurements for the two tracks of the vee in the figure on page 2.

Track	p_x (GeV/c)	p_y (GeV/c)	p_z (GeV/c)
Negative	2.80879	-0.51130	0.45166
Positive	0.76380	0.04410	0.04419

where p_x, p_y and p_z are the components of the momentum 3-vector $\mathbf{p}$.

(Ignore the large number of digits - they are the results of some fitting procedures; the errors are typically a few percent.)

Now, we know that only three particles exist in nature that can decay into a vee like this:

- a K^0 (pronounced kay-zero) which has a mass of 497 MeV/c^2, and which decays to a $\pi^+\pi^-$ pair;

– a Λ^0 (pronounced lambda-zero) which has a mass of 1116 MeV/c^2, and which decays into a π^- and a proton (mass 938.3 MeV/c^2);

– an $\bar{\Lambda}^0$ (pronounced anti-lambda-zero) which has a mass of 1116 MeV/c^2, and which decays into a π^+ and an anti-proton (mass 938.3 MeV/c^2).

How can we tell whether it is a K^0, Λ^0 or $\bar{\Lambda}^0$?

What bubble chamber physicists had to do, and LHC physicists still have to do, is to try all 3 possibilities - with sophisticated computer programmes - and see if the errors are tight enough for a unique assignment to be made.

Here, for the first time in my life, I'll do it by hand with a pocket calculator!

Let us try the $K^0 \longrightarrow \pi^+\pi^-$ possibility and extend the table to include 2 more columns: one for mass, in which we put the pion mass, and one for energy which we can calculate using $E^2 = p^2c^2 + m^2c^4$.

For the π^-: $E = (2.80879^2 + (-0.51130)^2 + 0.45166^2 + 0.13957^2)^{\frac{1}{2}} = 2.89381$.

Track	p_x (GeV/c)	p_y (GeV/c)	p_z (GeV/c)	m (GeV/c^2)	E (GeV)
π^-	2.80879	-0.51130	0.45166	0.13957	2.89381
π^+	0.76380	0.04410	0.04419	0.13957	0.77895

[Make sure you check the π^+!]

Now, if we assume that both E and p are conserved in the decay, the sum of the energies E and and momenta p of the π^+ and π^- will equal the E and p of the decaying neutral particle, our K^0 candidate.

Let us update the table with the E and p sums:

Track	p_x (GeV/c)	p_y (GeV/c)	p_z (GeV/c)	m (GeV/c^2)	E (GeV)
π^-	2.80879	-0.51130	0.45166	0.13957	2.89381
π^+	0.76380	0.04410	0.04419	0.13957	0.77895
Sum of π^- and π^+	3.57259	-0.46720	0.49585	???	3.67276

We now use $m^2 = E^2 - p^2 = E^2 - p_x^2 - p_y^2 - p_z^2$ to calculate what particle physicists call the 'effective mass' (???) of the $\pi^+\pi^-$ system. You should check that this comes to 0.51149 GeV/c^2.

This is within about 2% percent of the known kaon mass of 0.498 GeV/c^2; so, our measurements are consistent with the vee being due to the decay of a K^0.

If you want to check the $\Lambda \longrightarrow \pi^-p$ possibility, you will need to replace the π^+ mass by the proton mass and go through the same steps. The answer for the final mass will be about 1.9 GeV/c^2 which is a long way from the Λ mass of 1.116 GeV/c^2. So this is ruled out. The $\bar{\Lambda}$ possibility can similarly be ruled out.

So, in the end, we conclude that the particle that decayed to give the vee was a K^0.

Reflection: use was made of $p = (Bq)v$ to determine the momenta, and then $E^2 = p^2c^2 + m^2c^4$ was used over and over again. For the discovery of the Higgs boson at the LHC, these formulae would have been used millions of times!

—————— // ——————

Some comments on relativity We have just seen how the basic equations of relativity have played a crucial part in experimental particle physics. Here is not the place for an introduction to relativity, but it seems appropriate to discuss briefly some of what is contained in $E^2 = p^2c^2 + m^2c^4$ in a few special extreme cases.

- A stationary particle cannot have any momentum ($p = 0$). So, making use of $E^2 = p^2c^2 + m^2c^4$, the energy of a stationary particle, traditionally called the 'rest energy', E_0, is given by $\underline{E_0 = mc^2}$.

  Rest energy is one of the great discoveries of relativity.

- For massless particles such as photons, $m = 0$ and then $E^2 = p^2c^2 + m^2c^4$ reduces to $\underline{E = pc}$.

  If we substitute this into $p = v\frac{E}{c^2}$ we get $p = v\frac{\sqrt{p^2c^2}}{c^2} = \frac{vp}{c} \implies v = c$.

  In words: a massless particle must travel with the speed of light.

  [In passing, it is worth mentioning that, for highly relativistic particles travelling very close to the speed of light, their rest energy mc^2 is tiny compared with p^2c^2, so it is acceptable to ignore the m^2c^4 term in $E = \sqrt{p^2c^2 + m^2c^4}$ and say that $\underline{E \approx pc}$.]

- The opposite extremes of speed are met in everyday situations: here, the rest energy of a particle - such as a cricket ball travelling at 60 mph (about 27 metres/second) - is large compared with its p^2c^2; mathematically we can put it this way: $\frac{p^2c^2}{m^2c^4} \ll 1$.

  Let us evaluate E in this case:

  $$E = \sqrt{m^2c^4 + p^2c^2} = mc^2(1 + \frac{p^2c^2}{m^2c^4})^{\frac{1}{2}} \approx mc^2(1 + \frac{1}{2}\frac{p^2c^2}{m^2c^4}) = mc^2 + \frac{p^2}{2m}$$

  In words: in the non-relativistic limit (speeds $\ll c$), the relativistic formula for the total energy E reduces to

  $$E = rest\ \ energy + kinetic\ \ energy.$$

  Summary: $p = v\frac{E}{c^2}$, and $E^2 = p^2c^2 + m^2c^4$ describe the kinematics of a free body for all velocities, from 0 to c.

- Final remark on the idea of mass in relativity: we have seen how the kaon mass was determined, beginning with a measurement of the momenta of its decay products. The same result would be obtained if the decaying kaon had lower or higher speeds than our example: the mass of a particle - given by $\sqrt{\frac{E^2 - p^2c^2}{c^4}}$ is INVARIANT; it does NOT depend on its speed.

  It is well known - and contained in our basic relativity equations - that as charged particles speed up under the influence of electric fields, in accelerators say, they respond to these forces 'as if' their masses were increasing with speed. So long as if you say 'as if', you are recognising that the mass is of a particle is really an invariant: if it were not, it could not be measured and the whole subject would fall apart!

Appendix C **Question with a medical connection:** Why are slow moving tracks dark?

Answer: Because slow-moving tracks deposit more energy (ionize more atoms, create more bubbles) per centimetre of path than fast ones.

Question: How is it that a slow-moving particle loses more energy per centimetre than a fast one; it seems counter intuitive?

Answer: The bottom line is that the momentum imparted to an atomic electron Δp by a passing charged particle of speed v that is in the vicinity of the electron for a time Δt is given by impulse theorem, which is essentially Newton's Second Law: $\Delta p \sim \bar{F}\Delta t$, where $\bar{F}$ is the average Priestley[10]-Coulomb force exerted during the time Δt.

Whatever we mean by the distance described by the phrase 'in the vicinity of', $\Delta t \sim \frac{1}{v}$, which means that $\Delta p \sim \frac{1}{v}$. This is the momentum transferred, so the kinetic energy E transferred - using $E=\frac{p^2}{2m}$ - must go as $\frac{1}{v^2}$.

So, more energy is imparted by the Coulomb interaction to an electron by a slow-moving particle than a faster one - and if you dwell on the derivation for a bit - it is because the slow-moving particle hangs around longer, exerting the force!

This means that in a bubble chamber the number of bubbles/cm is more - the track will be darker - for slow-moving particles.

(Any graduate students who might have strayed this way will recognise this as part of the famous equation for the rate of deposition of energy E with distance x: $\frac{dE}{dx} \sim \frac{1}{v^2}$.

A common PhD oral exam question is: Why does $\frac{dE}{dx}$ depend on the speed and not the momentum of the moving charged particle?)

Medical application: in proton cancer therapy, use is made of this by tuning the proton beam's energy to be such that it stops - runs out of energy - near the tumour. This means that most of the proton's energy will be deposited when the proton is moving most slowly, near the tumour. Also, healthy tissue, on the way to the tumour, thus receives a smaller dose.

GOOGLE 'proton therapy Bragg peak' for more information.

What is the purpose of the picture on the first page?

It is to draw attention to something already discussed - the link between the physics of the atomic and subatomic world and the large scale properties of the universe.

The bubble chamber picture has been superimposed on a picture taken on a ground-based telescope of the collision between the galaxies NGC4038 and NGC4039, known as the Antennae Galaxies (see apod.nasa.gov/apod/ap971022.html).

The bubble chamber picture shows a beautiful example of a charged kaon K^+ decaying to three π-μ-e decays. How can one tell at a glance that it is positive?!

For full details of this event, go to the CERN Bubble Chamber website; click on 'gallery', then 'charged kaon'.

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[10] Joseph Priestley had a Welsh connection: he married Mary Wilkinson from Wrexham.

If you find any errors/typos, or have any suggestions, feel free to e-mail me: gtj@hep.ph.bham.ac.uk.

Many thanks.

GTJ

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Final tip for viewing a piece of actual bubble chamber film, if you're lucky enough to get one: place it on a sheet of white paper and use a magnifying glass or suchlike.

Acknowledgements

I would like to thank Michelangelo Mangano and Mick Storr (CERN) for launching the CERN High School Teachers' Summer School in 1998, and for their long-term commitment to it. Over the years, various cohorts of teachers took part in bubble chamber 'working groups'; their contributions are represented by the 'bubble chambers website'.

Many thanks to Peter Watkins (University of Birmingham) who read early drafts of this booklet and made many helpful suggestions and comments.