PARTICLE PHYSICS WITH BUBBLE CHAMBER PHOTOGRAPHS

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Abstract

A few bubble chambers photographs for illustration of high-energy physics *events* at the high school level are here presented after briefly recalling some basic concepts of particle accelerators, bubble chambers and conservation laws in particle physics. Each photograph has a relevance for the understanding of particle physics concepts and of the methods used for analysis.

1 Introduction

The existence of several elementary particles may be easily demonstrated from the analysis of bubble chamber photographs. Each photograph carries much information and only a few pictures are needed to establish the main properties of some elementary particles.

Ordinary matter is made of protons (p), neutrons (n) and electrons (e^-), to which is associated the electromagnetic radiation, also known as photon or gamma radiation (γ). The analysis of bubble chamber photographs reveals the existence of other elementary particles which are not present in ordinary matter. These particles may be created in a collision of two high-energy particles, for instance a fast proton against a stationary one. In these collisions, part of the kinetic energy is transformed into matter and forms the mass of the newly formed particles. This possibility of creating new particles makes particle physics completely different from atomic and nuclear physics, although photons are also created in atomic and nuclear transitions.

The analysis of bubble chamber photographs may be done at a qualitative level, in order to establish the existence of new elementary particles and to determine some of their basic properties. A quantitative evaluation requires measurements and the use of relativistic formulae (1-5). In the present article the information will be mainly of a qualitative type, although some of the examples can be used quantitatively.

Some concepts about particle accelerators, bubble chambers and relativistic formulae used for quantitative analysis of the bubble chamber pictures will be briefly recalled. Sections 2 and 3 describe particle accelerators and bubble chambers and are intended for those who have no knowledge of the field; sections 3 and 4 recall some basic formulae and concepts and are rather technical. Their reading may be omitted if the information is judged to be superfluous.

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2 Particle Accelerators

Particle accelerators are made to accelerate particles, like protons or electrons, by means of electromagnetic fields. As an example, the familiar television set is basically a low-energy electron accelerator.

A proton accelerator is made of a source of protons, an accelerating field and a guiding field to keep the protons on a chosen trajectory. In order to reduce to a minimum the collisions with the surrounding material and the resulting energy losses, acceleration takes place in a high vacuum.

A high energy accelerator consists of several accelerators in cascade, each of them increasing the energy by about one order of magnitude. The Super Proton Synchrotron (SPS) of the European Laboratory for Particle Physics (CERN) consists of the following accelerators (fig. 1) :

- an electrostatic accelerator, which accelerates protons up to 1 MeV of energy;

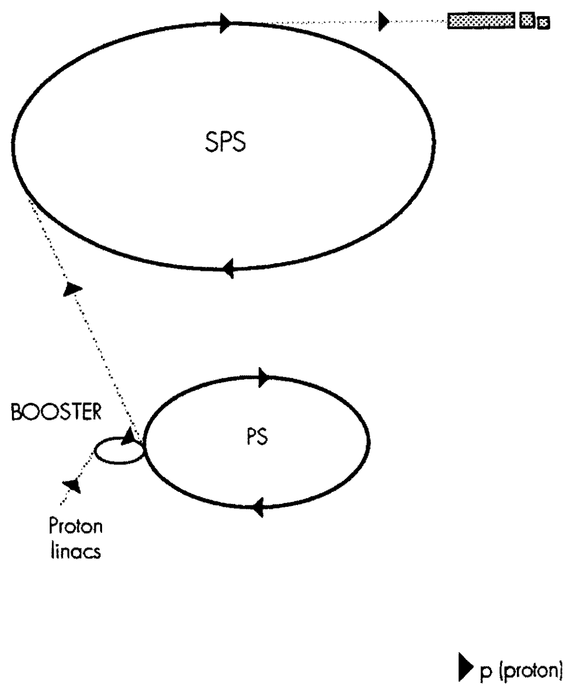
- a linear accelerator, where protons describe a linear trajectory and are accelerated to 50 MeV;

- a "booster" Proton Synchrotron, where protons moving in a circular trajectory of fixed radius are accelerated by radiofrequency (RF) electric fields to 800 MeV and are guided by magnetic fields;

- a Proton Synchrotron of 28 GeV;

- a Super Proton Synchrotron of 400 GeV.

A Proton Synchrotron accelerates protons by means of radiofrequency electric fields in resonant cavities located in a place along the circumference, which protons follow because they are immersed in a magnetic field which increases during the acceleration cycle. The magnetic field is produced by a series of dipole magnets placed along the circumference. Only the protons in phase with the accelerating radiofrequency are accelerated.

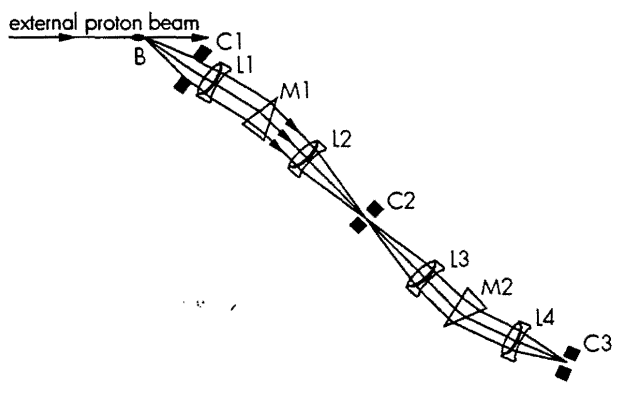


⇑ **Fig. 1**
The CERN Super Proton Synchrotron chain, consisting of an electrostatic accelerator (1 MeV) and a linear accelerator (50 MeV) –linacs–, a "booster" Proton Synchrotron (800 MeV), a Proton Synchrotron (28 GeV) and finally the Super Proton Synchrotron where particles are accelerated to the planned maximal energy (400 GeV). (This complex of accelerators now is also used to produce electrons and positrons which are then injected into the LEP accelerator having 27 km in circumference and accelerating particles to a nominal energy of 50 GeV per colliding beam). At the end of the accelerating cycle protons are extracted and form an external beam.

The circulating protons are grouped in "packets" with small transverse dimensions (a few millimetres) and few centimetres long. One speaks of "packets" or "bunches" or "sausages" of protons which move inside the vacuum chamber of the synchrotron.

At the end of the accelerating cycle (which takes a few seconds), the accelerated protons are extracted from the accelerator, formed into an extracted proton beam and sent against a target, usually a cylinder of beryllium. In the collision of an incident proton with a beryllium atomic nucleus of the target, several new particles may be produced. The produced charged particles emitted at a certain angle may be formed into a beam, as illustrated in fig. 2, using quadrupole and dipole magnets. The beryllium *target acts as a "source" of particles, the magnetic quadrupoles act as "magnetic lenses" and the dipole magnets have the same function of the "prisms" in optics, that is they separate in "colour"; in our case they select the charge and the momentum of the particles. A series of collimators may define the accepted solid angle and the monochromaticity of the beam. One thus has a monochromatic, monoenergetic beam of charged particles, which contains particles of different mass, for instance electrons, negative mesons and antiprotons. One may also obtain a monoenergetic beam with only one type of particles, by performing on the beam a mass separation. This requires an electrostatic separator, an instrument which produces an electric field beside a magnetic one.*

The optimum beam to be used in conjunction with a bubble chamber for teaching purposes is a low intensity beam (with about 10 particles per cycles) well defined in momentum and in mass and of about 1 GeV kinetic energy.

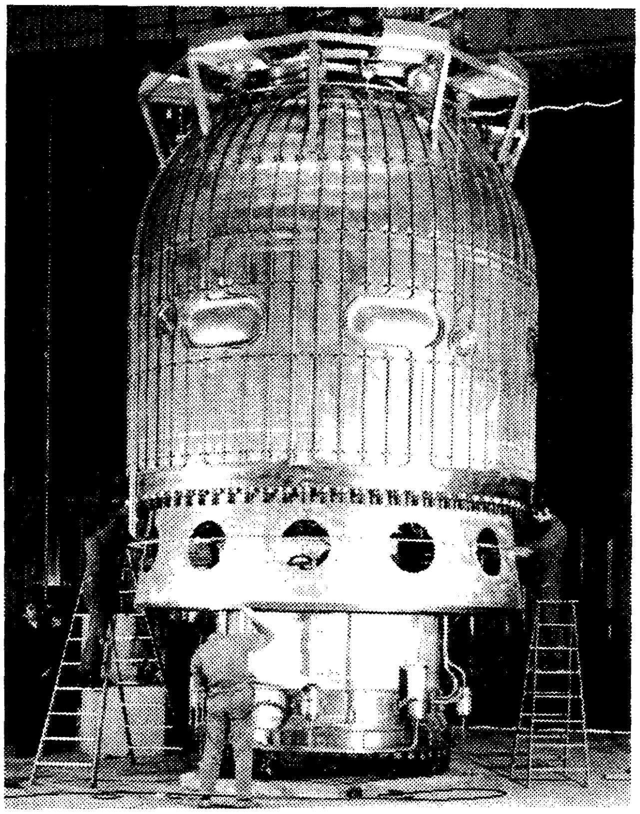


⇑ **Fig. 2**
Layout of a typical secondary beam. The symbols are similar to those of optical lenses and prisms. The first stage is made by a system of quadrupolar magnetic lenses adjusted so as to have as source the beryllium target where secondary particles are produced. The magnetic lenses yield a parallel beam. The beam is separated in momentum by a dipole magnet which acts as a prism in optics (a prism separates in color, a dipole magnet in momentum). A second system of magnetic lenses gives a point image. A collimator C1 defines the accepted solid angle; C2 allows only those particles in the chosen momentum band to continue; C2 defines the accepted momentum band. In the figure is also indicated a second stage analogous to the first one, that is with lenses, prisms and collimators.

* An example of such condition is water at a temperature of 110 degrees centigrade and at one atmosphere of pressure. The water should boil, but for a small fraction of a second it will not (water however is not suited as a bubble chamber liquid).

3 *Bubble chambers*

A bubble chamber (fig. 3) is a detector for fast charged particles which allows to visualize their paths in the liquid of the chamber. A bubble chamber contains a liquid which at the time of passage of the charged particles is in a metastable state. The liquid starts boiling where impurities exist, at the borders of the vessel and also around the ions left along the path of a fast charged particle.*



⇑ **Fig. 3**
The chamber body of the Big European Bubble Chamber (BEBC).

A fast charged particle traversing the bubble chamber ionizes the atoms of the liquid, by removing one or more electrons from the atoms. In each of such interactions the fast particle loses a small fraction of its energy and is essentially not deviated. Along the path of the fast particle one thus has a number of free electrons and positive ions. Boiling starts around the ions and small vapour bubbles are formed. The bubbles increase gradually in size. A photograph is taken at the time when the bubbles have dimensions of about half a millimetre.

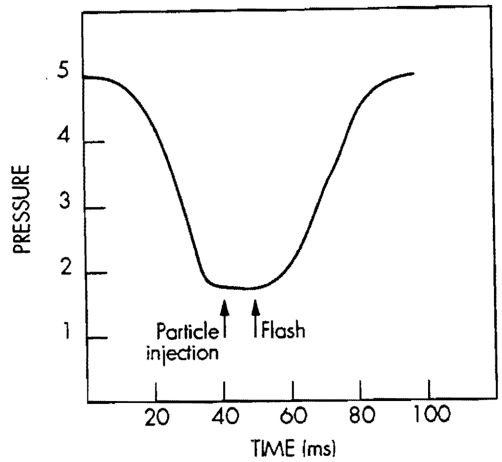
To stop the boiling, the bubble chamber pressure is raised. For a new cycle the pressure must be reduced and the chamber is again ready. The timings have to be synchronized as the lowering of the pressure has to precede only by few milliseconds the arrival of the fast particles.

A bubble chamber is usually surrounded by a large magnet, which produces a strong magnetic field in the chamber. Thus the fast charged particles traversing the chamber are deflected by a quantity which depends on their momentum. The analysis of the tracks yields information about the particle momentum and velocity.

There are bubble chambers with hydrogen, deuterium or heavier liquids. The hydrogen bubble chamber allows the study of collisions on free protons. The liquid hydrogen density is low (0.06 g cm^{-3}); the interaction probability is therefore low and one observes well defined tracks, but rarely from gamma ray interactions. In bubble chambers with heavy liquids, instead, many of the incoming particles interact, and many gamma ray interactions can be observed.

Fig. 4 illustrates the time sequence of events for a hydrogen bubble chamber. Until time zero the bubble chamber is in normal conditions. At time t=0 a piston is expanded and the pressure is thus reduced from 5 to 2 atm. At this pressure the chamber is sensitive. At t=40 ms a beam is sent to the chamber; the particles cross the chamber in few ns ionizing the medium and bubbles start forming and enlarge. At t=50 ms, when the bubble dimensions are slightly less than 1 mm, a flash is operated and pictures are taken simultaneously with 4 cameras located in different positions, so as to allow later a stereoscopic reconstruction of an interaction. At t=80 ms the liquid is compressed to 5 atm and the chamber becomes ready for a new cycle.

The bubble chamber was born at the beginning of the '50s, giving the best results in the particle physics field in the '60s-'70s, with the study of



⇑ **Fig. 4**
Pressure cycle in a bubble chamber exposed to a particle beam at an accelerator. The chamber becomes sensitive after reducing the pressure. About 10 ms after reducing the pressure, the particle beam is sent to the chamber. The flash is activated about 10 ms later and the cycle is terminated about 20 ms later when the bubble chamber pressure is increased.

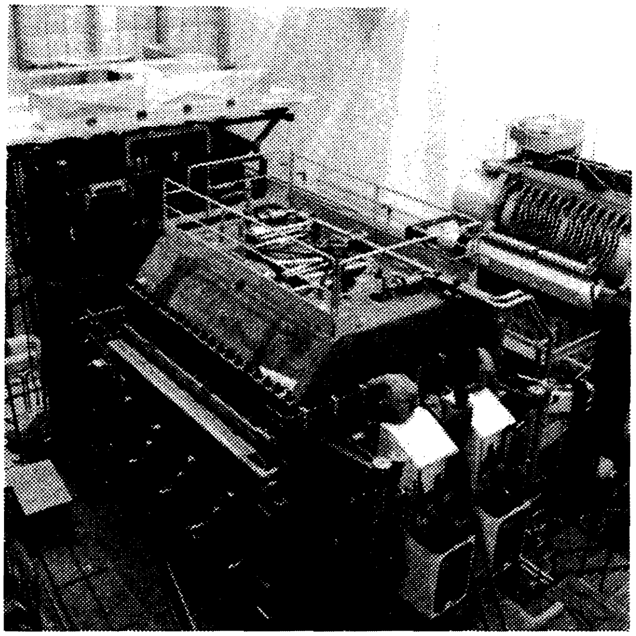
strange particles, their resonances and finally of the neutrino interactions. The first experiments where performed with small bubble chambers; later intermediate dimensions chambers were used like Gargamelle at CERN (fig.5), then big dimensions chambers like the Big European Bubble Chamber (BEBC, fig. 3) also at CERN, filled with tons of liquid hydrogen, or deuterium or a mixture of hydrogen and neon.

4 Conservation laws and common formulae

Before discussing some bubble chamber pictures it is appropriate to stress the fact that non relativistic formulae are totally inadequate and cannot be applied to these processes because of the high energies involved. Therefore, concepts of relativistic mechanics, of conservation laws, a few formulae, units and orders of magnitude are recalled.

4.1 Formulae of relativistic mechanics

For one particle in motion one defines the following quantities:



⇑ **Fig. 5**
General view of the heavy liquid (freon or propane) bubble chamber Gargamelle. In 1973 the Gargamelle group announced the discovery of the neutral current in neutrino interactions. This supported the existence of Z° particles, later discovered at CERN

linear momentum	$\vec{p}=m_0\vec{v}\gamma$	(1)
kinetic energy	$T=(\gamma-1)m_0c^2$	(2)
energy connected to mass	$E_0=m_0c^2$	(3)
total energy	$E=T+E_0=\gamma m_0c^2=$	(4)
	$=\sqrt{(p^2c^2+m_0{}^2c^4)}$	(5)

m_0 is the rest mass of the particle, v is its velocity, $\gamma=1/\sqrt{(1-\beta^2)}$, $\beta=v/c$ and c is the velocity of light in vacuum.

4.2 Conservation laws

In each reaction between two particles the following quantities must be conserved:

i) the linear momentum;
ii) the total energy (also the kinetic energy in an elastic collision);
iii) the angular momentum;
iv) the electric charge;
v) the baryon number;
vi) the three lepton numbers.

In the reactions due to strong or electromagnetic interactions also the strangeness and charm quantum numbers must be conserved.

4.3 The Lorentz force

A particle with charge q and momentum p moving in a magnetic field B perpendicular to the velocity v, is subject to the Lorentz force $F=qvB$; the particle describes an arc of circumference of radius R such that:

$$p = qRB \qquad (6)$$

This relation allows the determination of the quantity p/q by means of the measurement of the radius of curvature R, if the field B is known.

4.4 Units

Some of the units used in high energy particle physics will be recalled.

Energy *- The energy of a submicroscopic system is usually expressed in electronVolts (1 eV is the energy acquired by an electron in an electric field with difference of potential of 1 V). 1 Joule corresponds to:*

$$1J = 1/1.6x10^{-19}\ eV = 6.2x10^{18}\ eV = 6.2x10^{15}\ keV = 6.2x10^{12}\ MeV = 6.2x10^{9}\ GeV \qquad (7)$$

Mass *- The mass is an intrinsic property of matter and it is a measure of its quantity. Because of Einstein law ($E=m_0c^2$) it may be expressed in energy units. The proton has $m_p=1.67x10^{-27}(3x10^8)^2/(1.6x10^{-13})=938.3\ MeV/c^2 \rightarrow 938.3\ MeV$.*

For other masses:

n	939.6 MeV
π^+,π^-	139.6 MeV
π°	135.0 MeV
e^+, e^-	0.511 MeV
γ	0 MeV

Linear momentum *- The linear momentum p is defined in classical mechanics by $p=mv$, where m is the mass of the particle and v its velocity.*

In relativistic mechanics this value is multiplied by $\gamma = 1/\sqrt{(1-\beta^2)}$, which depends on the velocity of the particle.

The formula that relates energy, momentum and mass of a particle may be written in energy units as follows:

$$E = \sqrt{(p^2c^2 + m_0{}^2c^4)} \rightarrow \sqrt{(p^2 + m_0{}^2)} \qquad (5')$$

Formula (6) may also be written as :

$$p(GeV/c)=0.30\ R(m)B(T) \qquad (8)$$

Thus the linear momentum expressed in GeV/c is equal to the product of a constant (0.30) multiplied by the radius of curvature in meters times the magnetic field in Tesla.

4.5 *Orders of magnitude*

In chemical reactions energies of few eV per atom are involved; in nuclear reactions the energies are of the order of few MeV per nucleus; in particle physics the energies are orders of magnitude higher. In fact one must use projectile particles (against stationary protons) such that their associated De Broglie wave-lengths are smaller than the proton size:

$$\lambda = \frac{h}{p} < 1fm \qquad (9)$$

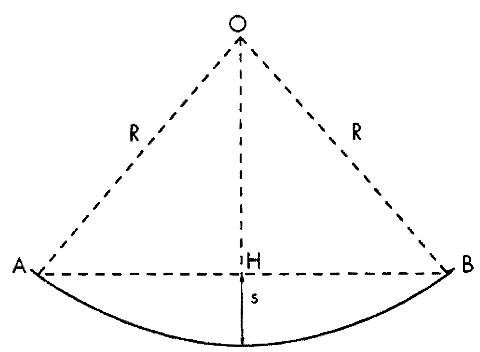
which, if expressed in energy units, yields

$$p = \frac{h}{\lambda} = \frac{4.1x10^{-21}MeVs\ x3x10^{10}cm/s}{10^{-13}cm} = 1.2GeV/c \qquad (10)$$

It must be noted that the appropriate unit of distance for elementary particles and of atomic nuclei is the fermi, where 1 fermi = 1 fm = 10^{-15} m (f = femto = 10^{-15}).

4.6 *Practical considerations*

From formula (8): in a magnetic field (B) of 2T, a particle of 1 GeV/c momentum describes an arc of circumference with radius (R) equal to 1.67 m. If the trajectory is measured for a tract (AB) of 50 cm (fig. 6) the corresponding sagitta is described by s ≅ $AB^2/8R \cong 50^2/(8x167)=2cm$, which is easily measurable. The sagitta of a 10 GeV/c particle is instead only 2 mm, which is more difficult to measure. It is thus clear that for teaching purposes it is better to consider particles with momenta of the order of 1 GeV/c or less. It is also clear that we should use tracks lying in planes perpendicular to the optical axis of a camera and such that the optical axis direction is the same as the magnetic field direction.



⇑ **Fig.6**
Measurement of the radius of curvature of a charged particle trajectory in a magnetic field. The trajectory is measured between the points A and B. One may measure the distance l = AB and the sagitta s. The radius of curvature R is given by : $R= l^2/8s + s/2 \sim l^2/8s$.

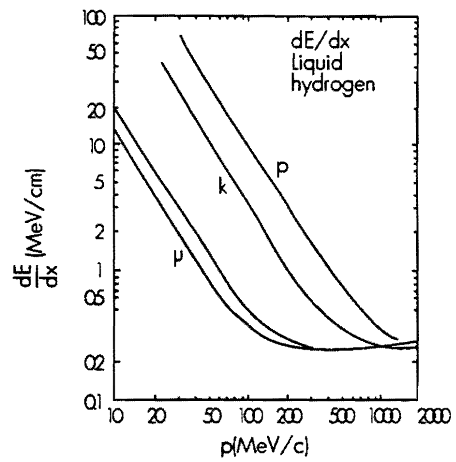
One has also to remember that the photographs are not of the real size and that therefore a magnification factor g must be included in formula (8):

$$p=0.3RB/g \qquad (8')$$

A simple measurement of the radius of curvature may be made with the use of "templates", arc of circumference designed on a plastic transparent sheet. These arcs are superimposed one after the other to the trajectory to be measured and one should individuate the arc which best fits the trajectory. An estimate of the radius may also be made via the measurement of the sagitta as illustrated in fig. 6.

4.7 Energy loss

A fast charged particle traversing the bubble chamber liquid loses continuously energy by interactions with the atoms of the medium, which become ionized. The energy losses for muons, pions, kaons and protons in liquid hydrogen are shown in fig. 7 versus their momentum. At low momenta the losses are large and have a dependence of the type $1/v^2$; the losses for v=c tend to a constant value of about 0.27 MeV/cm in liquid hydrogen. The losses are furthermore proportional to the square of the particle charges; all elementary particles have charge +1 or -1 times the proton charge.



⇑ **Fig. 7**
Ionization energy losses of various particles in liquid hydrogen as a function of the particle momenta.

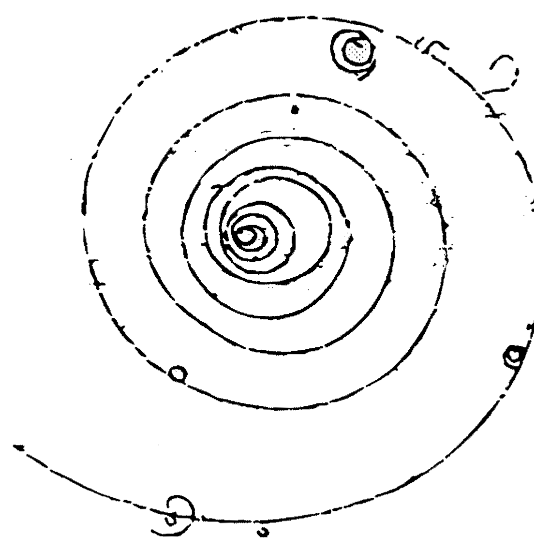
A fast particle, with v=c, produces in a bubble chamber slightly less than 10 bubbles per centimetre. The number of bubbles increases for particles of lower velocities and reaches the maximum when the particle is close to stopping in the chamber. An electron with more than few MeV has always a velocity close to the velocity of light; it loses a relatively small energy by ionisation and more by radiating photons (the bremsstrahlung process). A fast electron thus yields a track with slightly less than 10 bubbles per centimetre and which spirals because of the large energy loss by radiation.

The number of bubbles per centimetre of track is inversely proportional to the square of the particle velocity. This number may only be measured with rough precision. Even so it may be useful to yield information on the particle mass.

We now have the information to analyze some bubble chamber photographs, starting with the simple situations.

5 An electron spiral

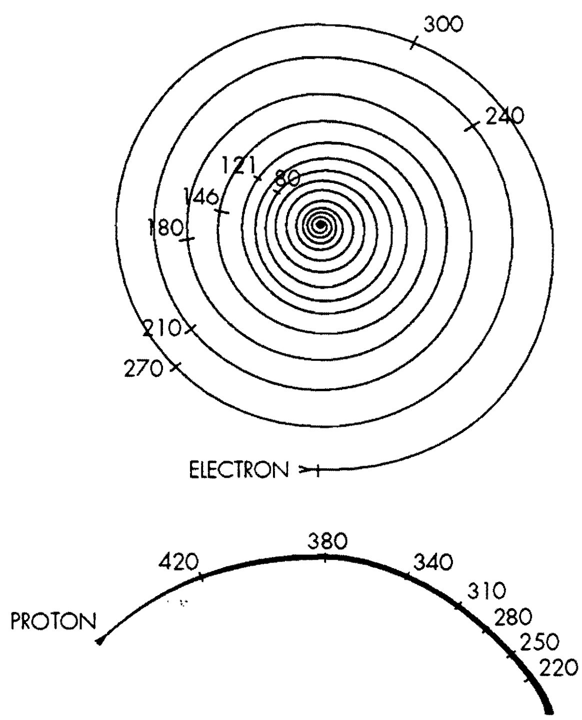
Fig. 8 shows the characteristic spiral track with few bubbles per centimetre left by a fast *electron* in a hydrogen bubble chamber (the electron enters from the bottom left, directed to the right). There is no other particle which may describe such a spiral, with this small radii of curvature and this small number of bubbles. The small number of bubbles per unit length tells us that the speed of the particle is essentially the speed of light; the small radius of curvature, remembering that $R \cong p/q$, gives the



⇑ **Fig. 8**
An electron spiral in a hydrogen bubble chamber; the picture has a magnification g=0.67 with respect to reality. The incoming electron track starts from the left. The bubble chamber is subject to a magnetic field B=1.2 Tesla perpendicular to the plane of the drawing. The electron is thus forced to move in a circular path by the Lorentz centripetal force; the radius of curvature R of the path is connected with the momentum of the electron. In this picture one has p=54R, with p in MeV/c and R in cm. The electron loses energy by ionization of the medium and by deceleration radiation (bremsStrahlung) and thus spirals. (from Harward project, Elementary Particles).

information that the momentum is small. Since m=p/v (non relativistically), one concludes that the particle mass must be very small.

Fig. 9 shows by comparison the computed tracks for a *proton* of 470 MeV/c momentum and an *electron* with 330 MeV/c momentum in a hydrogen bubble chamber to which a magnetic field of 2 Tesla is applied. Note that the proton leaves many bubbles per cm and that the number of bubbles increases fast with decreasing velocity till when the proton is stopped. The electron yields instead a characteristic spiral trajectory, with constant number of bubbles per cm of continuously smaller radius. This is due to an almost continuous energy loss by radiation.



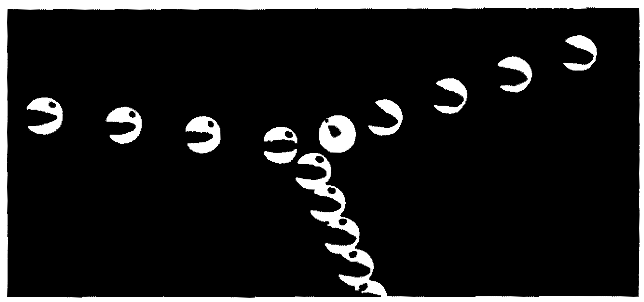
⇑ Fig. 9
Computed tracks left in a hydrogen bubble chamber immersed in a 2 Tesla magnetic field by a proton of 470 MeV/c (dark track at the bottom) and by an electron of 330 MeV/c (spiral above). The tracks start from the left.

6 An elastic scattering event

In fig. 10a few positive particles of 0.9 GeV/c momentum enter from the left and are curved toward the bottom while moving toward the right.

⇑ Fig. 10a
K^+ mesons of 0.9 GeV/c momentum observed with the 82 cm hydrogen bubble chamber from Saclay , which had a magnetic field of 2 T and was exposed at the CERN Proton Synchrotron. Most of the K^+ mesons, incoming from the left, go through the chamber almost undisturbed. The event at the centre of the photograph is an elastic collision of the K+ with a hydrogen nucleus, $K^+ + p \rightarrow K^+ + p$.

⇓ Fig. 10b
Photograph of the elastic glancing collision between an incoming and a stationary billiard balls. The moving ball comes from the left. The picture was taken with multiple flashes at regular time interval of 30 milliseconds (from PSSC).



The number of bubbles per centimetre of track is slightly larger than that characteristic of electrons (positrons) and smaller than for protons. This suggests that the tracks are due to particles with a mass intermediate between the electron and proton masses. Such particles were originally called mesons. In reality the particles of fig. 10a are *K^+ mesons* with mass of 494 MeV, this because the electrostatic separator is adjusted to such mass value; it would be clearly impossible to determine this from fig. 10a.

Most of the K^+ mesons traverse the chamber without suffering any appreciable interaction, beside continuous energy losses. Let us now concentrate our attention to the "event" in the middle of the picture: one K^+ meson seems to have been deflected up right, with the contemporary emission of a positive particle ("dark" track towards the bottom); this last track stops in the chamber. Let us compare this "event" with the "event" of fig. 10b, which is due to an elastic scattering of one incoming billiard ball on a stationary one. The photograph was obtained using a camera with an open shutter, but sending light flashes at regular intervals of time (one thirtieth of a second one from the other). The incoming ball has been slightly deflected, while the ball originally at rest recoils slowly at a large angle. The similarity between the K^+ event in fig. 10a and the elastic scattering of the billiard ball reported in Fig. 10b is quite spectacular and suggests that the K^+ meson undergoes elastic scattering. But against what? Since our bubble chamber contains hydrogen, the collision may happen either against a proton or an electron. The dark stopping track, with many bubbles, cannot have been produced by an electron and is consistent with having been produced by a proton. It is difficult to see the direction of the curvature of the track, though it is consistent with being due to a positive particle.

How can we be sure that the event is really an elastic event? This can be done by checking if energy and momentum are conserved.

I) Conservation of energy:

(Total energy of the K^+) + (mass energy of a stationary proton) is equal to (Total energy of the outgoing K^+) + (total energy of the outgoing proton)

In formulae (the quantities related to a K^+ and p after scattering are indicated with a primed: ')

$$E_{K^+}+m_pc^2 = E'_{K^+}+E'_p \qquad (12)$$

II) Conservation of linear momentum.

(Momentum of incident K^+) + (0) is equal to (momentum of outgoing K^+) + (momentum of outgoing proton)

In formulae:

$$\vec{p}_{K^+} = \vec{p}'_{K^+} + \vec{p}'_p \qquad (13)$$

(It must be remembered that the initial proton is at rest; therefore its momentum is zero and its energy is only that connected with the mass). The momentum being a vector, the momentum conservation is given by 3 scalar equations. The conservation law, expressed in a coordinate system with the x-axis in the direction of the incoming K^+, the y-axis passing through the vertex of the interaction in the plane of the drawing and perpendicular to the x-axis, the z-axis perpendicular to the plane of the drawing, gives:

x-axis $\quad p_K = p'_K \cos\theta_K + p'_p \cos\theta_p \qquad (14a)$

y-axis $\quad 0 = p'_K \sin\theta_K - p'_p \sin\theta_p \qquad (14b)$

z-axis $\quad 0 = 0 \qquad (14c)$

where θ is the angle of the outgoing K^+ with respect to the direction of the incoming K^+. The first equation says that the momentum of the incoming K^+ is found after collision mainly in the momentum of the outgoing K^+ and also in part in the momentum of the outgoing proton; the second equation states that there must be a balance along y of the K^+ and proton momenta after collision; the third equation says that the collision takes place in the plane of the paper.

In order to check if the the two conservation laws are satisfied in the case of the event of fig. 10a, one has to measure the tracks and their momenta; then compute the components of the momenta and check if the two conservation laws are satisfied within the experimental errors, that is if the left hand side of the equations are equal to the right hand side. This was verified for the event in question and therefore one concludes that the event is an elastic interaction.

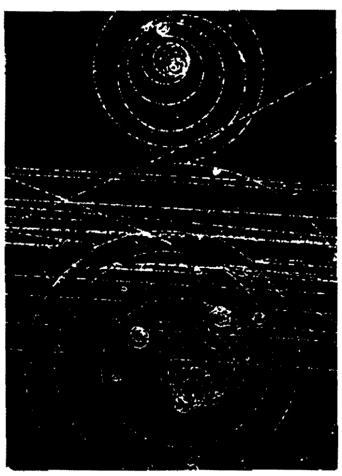
The analysis of many photographs like fig. 10a shows that there are many elastic K^+ p events with an appreciable deflection of the K^+ ; instead one *doesn't find any K^+ electron elastic scattering with an appreciable deflection of the K^+. One may thus conclude that the interaction of the K^+ with the proton is stronger than that with the electron or that the dimensions of the proton are larger that those of the electron.*

7 An electron-positron pair

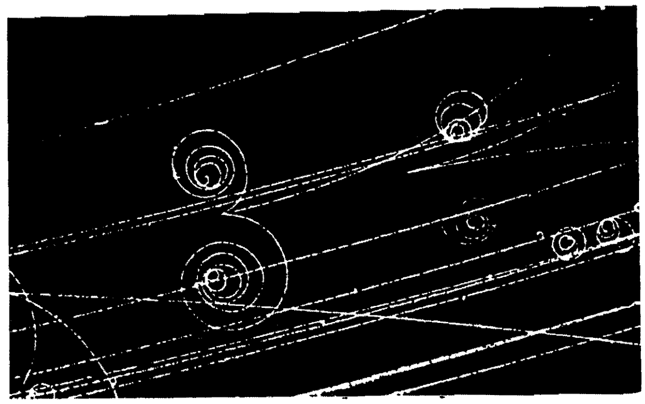
In fig. 11 one observes one event with 2 spiraling tracks starting from a point. The up higher track is an electron, whereas the other spiral track deflected downward, rotates in the opposite direction as indicated by accurate measurements, and is the signature of a particle having exactly the same mass of the electron and the same charge but opposite sign. This track is left by a *positron,* the antiparticle of the electron and the event is resulting from an interaction of the type:

$$\text{photon+proton} \rightarrow \text{electron} + \text{positron} + \text{proton} \quad (15)$$

where the incoming photon cannot be seen directly in a bubble chamber and the recoiling proton has too little energy and thus too little range to be observable.



⇑ **Fig. 11**
An electron positron pair produced by a high energy photon hitting a stationary proton. The lower clockwise track is produced by a positron; the smaller clockwise upper spiral was produced by an electron. The photon is not directly observed in a bubble chamber because it is neutral and thus does not leave a track. The proton in the collision recoils a distance which is too small to be observed in a bubble chamber. Note that this picture is like a negative of that of Fig. 8 (by courtesy of Brookhaven National Laboratory, USA).



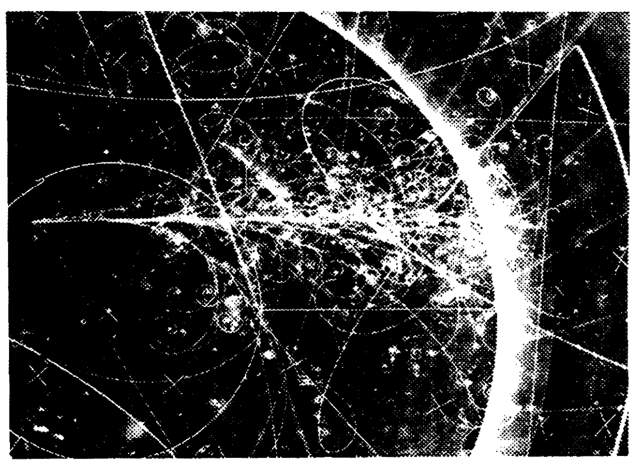
⇑ **Fig. 12**
An electron positron pair produced in the coulomb field of an electron in a hydrogen bubble chamber (by courtesy of Lawrence Berkeley Laboratory, USA).

In fig. 12 there is an event with an electron and a positron plus a third track which looks like an energetic electron. In effects we are with the latter observing the production of an electron-positron pair in the coloumb field of an atomic electron:

$$\gamma + e^- \rightarrow (e^+ + e^-) + e^- \quad (16)$$

8 A "tree" of electrons and positrons

In figure 13 are shown the particles resulting from the interaction of a high energy neutrino with a neutron of a heavy nucleus of the bubble chamber liquid. The neutrino, which comes from the left, is an electrically neutral particle and thus is not directly visible in the bubble chamber. In the primary neutrino-neutron collision are created six



⇑ **Fig. 13**
Particles produced after the collision between a high energy neutrino and a nucleus of the heavy liquid in the bubble chamber (by courtesy of CERN, Geneva).

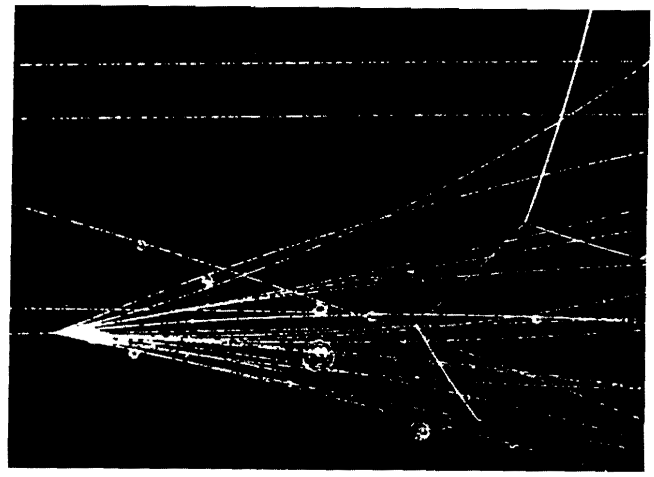
charged particles and several neutral ones, like π° mesons, immediately decaying into high energy photons. These will eventually interact with the heavy nuclei (neon) of the bubble chamber liquid, producing electron-positron pairs.

Electrons and positrons may then emit high energy photons by "bremsstrahlung" that is, in the deceleration of an electron, caused by a distant interaction with a heavy nucleus. The photons produce then electron-positron pairs. In conclusion there is a fast multiplication of the number of electrons and positrons and the picture acquires the characteristic tree-structure, well visible in a heavy liquid bubble chamber (it is not so in a hydrogen bubble chamber; in fact the pair production and "bremsstrahlung" processes are proportional to the square of the charge of the nuclei and the charge of the proton is small).

Electron-positron pairs are produced abundantly in all collisions of medium and high energy particles in a medium of high atomic number. One may ask if a similar situation holds for the production of other particle-antiparticle pairs, like proton-antiproton. The production of proton-antiproton pairs is much less frequent, but it increases with energy and one expects that it becomes large at energies much larger than the rest energy of the proton and antiproton.

9 Energy-matter transformations

In figures 11-13 are shown examples of transformations of energy into matter with the creation of new particles not existing in ordinary matter. Another striking example is that of fig. 14 where many charged particles (16 in total) are created in a single collision. One may think that when two particles collide there is a small interaction region where, for a very short time, there is a large quantity of energy and that it is here that new particles are produced via transformation of energy into matter, according to the Einstein

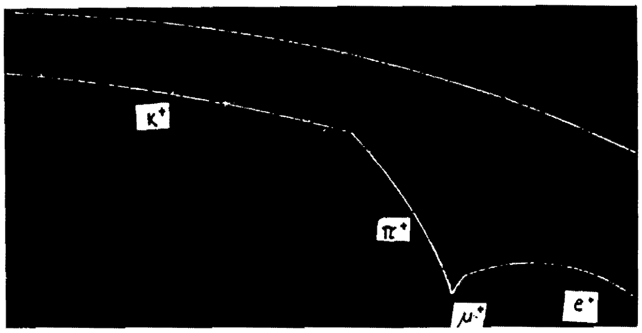


⇑ **Fig. 14**
Interaction between a proton of 28 GeV/c and a proton of the hydrogen bubble chamber. In the interaction are produced 16 charged particles beside several neutral particles (by courtesy of CERN, Geneva).

equation $E = m_0 c^2$ where m_0 is the total rest mass. The more is the available energy, the larger is the number of resulting particles, the production of which follows well defined selection rules and conservation laws.

The transformation of energy into matter particles in a repeated series of interactions is well illustrated in fig. 13. This picture shows on one hand that the creation of an electron-positron pair by a photon is a common process of medium and high-energy interactions and moreover that *in high-energy collisions are produced an equal number of positrons and electrons*. This is very important: the laws of nature in the subatomic world do not express a preference towards matter or antimatter, as stated in the two outstanding physics theories of the XXth century: relativity and quantum mechanics. This is so in all the cases when the collision energy is much larger than the energy associated with the rest mass of the created particles and antiparticles. For the electron-positron pair, this "threshold" is of only a few MeV. For protons and antiprotons the "threshold" is at much higher energy.

The particle-antiparticle symmetry, evident in high-energy interactions, does not exist in the low energy world of protons, neutrons and electrons, surrounding us.



⇑ Fig. 15
A decay chain $K^+ \rightarrow \pi^+ \rightarrow \mu^+ \rightarrow e^+$ (BGRT experiment, by courtesy of CERN, Geneva).

10 Particle decays

10.1 Decay into one charged prong

Fig. 15, an interesting hydrogen bubble chamber photograph, shows an incident track generating 3 successive "events": the incident positive track (indicated as K^+) gives rise to a second track (π^+), which in turn leads to a third track (μ^+) and to a fourth one (e^+).

Let us analyse the first "event", that is what happens at the kink between the K^+ and the π^+ tracks. We know that the incoming particle is a K^+ meson; let us suppose that at the first kink the K^+ meson has a collision with a proton: in this case two positive particles should come out from the collision. In the picture there is only one. Could it be that the collision is a glancing one where the hit proton suffers only a very small recoil? This is not the case as the angle between the K^+ and the π^+ tracks is large which would indicate a more central collision. With the same reasoning one can exclude the collision with an electron.

What is then this event? An indication may be obtained by analysing the second track and determining the mass of the particle. A detailed analysis of the momentum and of the energy loss of the track leads to the conclusion that the mass of the particle (140 MeV) is about one third the mass of the K^+. We can assume then that the track is due to a π^+ *meson (pion)*. This leads us to think that the K^+ disappears, giving rise at the same time to a new particle, the π^+ meson (the positive pion). Thus this event is classified as a decay of the type:

	$K^+ \rightarrow \pi^+ +$ neutral particle	(17)
electric charge	(+1) (+1) (0)	

Notice that in the reaction the electric charge is conserved, as it should be. In the final state there must be one or more neutral particles, otherwise there would not be the simultaneous conservation of energy and momentum. A particle cannot decay into one particle, but it must decay at least into two.

The analysis of many events of the type shown in fig. 15 proves that the π^+ meson is always produced with the same momentum. It follows that the K^+ meson decays into two particles, a positive pion (π^+) and a neutral pion (π^0). In effect the decay is:

$$K^+ \rightarrow \pi^+ + \pi^\circ \qquad (18)$$

where the π° *meson* is a partner of the π^+ and of the π^- *meson.* The π° can be observed via its decay into two photons, $\pi^\circ \rightarrow \gamma + \gamma$, and the subsequent interactions made by one or both photons.

Let us now turn to the second event of fig. 15: the positive track due to a π^+ meson leads to another positive track. Following the same reasoning as for the first event, we can conclude that also this is a decay. The outgoing positive particle is that of a *positive muon,* μ^+, having a mass of 110 MeV*. The μ^+ track hass always the same length and always stops in the chamber; where the neutral particle is never observed, neither in hydrogen nor in heavy liquid bubble chambers, nor with other techniques. One concludes that the second event is therefore a decay into an elusive *muon neutrino,* ν_μ:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \qquad (19)$$

* The muon was also called "mu meson"; this name was coined when one did not know that the muon is not a meson, since it does not interact via the strong force; thus the term muon is more appropriate. The μ^+ is like a heavy positron.

Muon neutrinos may be observed only in high energy scattering experiments using very large and very massive detectors.

We now analyse the third and last event of fig. 15, that it is a decay of the type

$$\mu^+ \rightarrow e^+ + 2 \text{ neutral particles} \qquad (20a)$$

In the final state appears the now familiar e^+ and two neutral particles. In fact the analysis of many events has shown that in the final state the e^+ is emitted with a spectrum of energies and this implies the associated presence of more than one neutral particle. However as the two neutral particles are never observed, one may conclude that they also must be two neutrinos (in reality one neutrino and one antineutrino) on the basis of the conservation laws for the lepton numbers. The event is then a decay of the type:

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \qquad (20b)$$

In a single bubble chamber photograph we have seen 4 charged particles which do not exist in ordinary matter (K^+, π^+, μ^+, e^+) and we have also indications for the existence of several other neutral particles.

Let us now try to understand the meaning of *"decay of a particle"*. As already said, mass may be transformed into energy and viceversa. Moreover, E. Fermi had shown for radioactive nuclei, and also for the neutron, that they could not be contained inside an electron, therefore the electron or positron emitted in a radioactive decay is created at the time of decay .

We must thus think that in a decay of an unstable particle like the μ^+, the unstable particle disappears with the creation of two or more particles, of smaller mass. The decaying particle is therefore *not* composed of the objects into which it decays.

If furthermore the principle of conservation of energy is applied to the decay

$$K^+ \rightarrow \pi^+ + \pi^\circ$$

we have:

(rest mass energy of K^+) = (rest mass energy of $\pi^+$and π°) + (kinetic energy of π^+, π°)

In formulae:

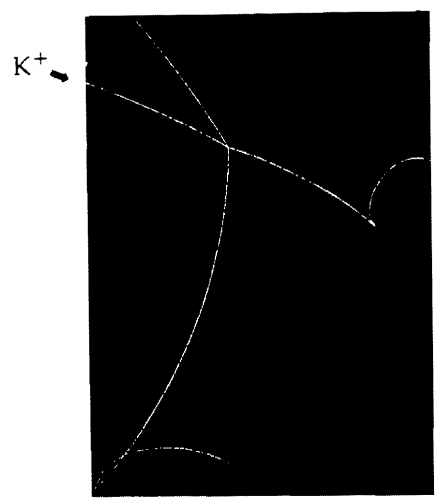
$$m_{K+}c^2 = (m_{\pi+} + m_{\pi^\circ})c^2 + T_{\pi+} + T_{\pi^\circ} \qquad (21)$$

The sum of the rest masses of the final state particles is smaller than the rest mass of the decaying particle. This is valid for any decay.

The lifetimes of the particles observable in bubble chambers (like for the K^+ and π^+) are of the order of 10 nanoseconds. It is thus obvious why in ordinary matter there are no unstable particles like the π^+: if there were some, they would immediately decay. The positron, althought being a stable particle, annihilates with an electron.

10.2 <u>Decay into three charged particles</u>

Fig. 16 shows one event in which the positive track of a K^+ gives rise to three charged tracks, two positives and one negative. Each one of these three tracks gives rise to a one-prong decay, as explained in the previous section.



⇑ **Fig. 16**
A K^+ meson decays in 3 π mesons ($K^+ \rightarrow \pi^+ + \pi^+ + \pi^-$); the π mesons then decay (BGRT experiment, by courtesy of CERN, Geneva).

Applying again the principle of charge conservation to the event of fig. 16, we establish that it is a decay, not an interaction. The analysis of the momenta and of the number of bubbles in the three outgoing tracks suggests that the three particles have the same mass, thus we have the decay

$$K^+ \rightarrow \pi^+ + \pi^+ + \pi^- \quad (22)$$

where the π^- meson has the same mass as the π^+. The successive one-prong decays are:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \quad (23)$$

$$\pi^- \rightarrow \mu^- + \nu_\mu \quad (24)$$

Here we find the *negative muon*, μ^-, which has the same mass as the μ^+. The last decays are:

$$\mu^+ \rightarrow e^+ + 2 \text{ neutral particles} \quad (25)$$

$$\mu^- \rightarrow e^- + 2 \text{ neutral particles} \quad (26)$$

In conclusion: after two successive types of decays, the incoming K^+ has disappeared and has given rise to: $(2e^+ + 1e^-)$ + (3 neutral particles associated to muons) + (6 neutral particles associated to $\mu \rightarrow e$ decays). In total the K^+ meson has turned into 3 charged particles and 9 neutral ones.

11 Production and decays of strange particles

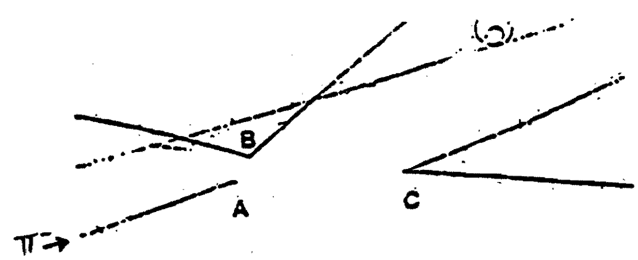
"Strange particles" are the particles which seemed strange to the physicists who discovered them, because of their abundant production via strong interaction and their slow decay* via weak interaction. Moreover these particles are produced in pair. Physicists invented the strangeness quantum number, conserved by strong and electromagnetic interaction, violated in weak decays.

The bubble chamber is a perfect instrument to detect and study strange particles, because they are abundantly produced in high energy collisions, have lifetimes corresponding to tracks of several centimetres and decay into well detectable particles.

11.1 An example of associated production of strange particles

In fig. 17, a beam of π^- mesons enters from the left into a liquid hydrogen bubble chamber. Beside some beam particles one may note two pairs of tracks, each pair forming a V, with two tracks of opposite sign, coming from the same point, called vertex (points B and C). Both V seem to come from the end point of a beam track (point A).

At point A the incoming π^- track disappears; this cannot be due to a decay, because it would lead to an odd number of charged tracks; it also cannot be an interaction with an electron, because one should



⇑ **Fig. 17**
Associated production of two strange particles (K° meson and Λ° baryon) and their decays. In A the associated production. The K° meson travels from A to B, where decays in two charged particles; the Λ° baryon travels from A to C, where decays (by courtesy of Berkeley, USA).

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* "slow" here means decays with lifetimes longer than 10^{-20} seconds. The strange particles have lifetimes of the order of 10^{-10} seconds. To understand the meaning of lifetime it should be remembered that if at some time, which we define as time zero, we have N_0 particles, their number at time t is reduced to:

$$N = N_0 \exp(-t/\tau_0) \quad (27)$$

where τ_0 is the lifetime for a particle at rest. If the decaying particle moves with velocity v, the lifetime increases to $\tau = \gamma\tau_0$, where:

$$\gamma = 1/\sqrt{(1-v^2/c^2)}$$

according to the laws of special relativity.

see two negative tracks in the final state. It can only be an interaction on a proton leading to the production of neutral particles:

$$\pi^- + p \rightarrow \text{neutral particles} \quad (28)$$

But what happens in each of the points B and C? If we assume that in each of these points a neutral particle decays into a positive and a negative particle, this will conserve the charge, while if we assume an interaction of a neutral particle with a proton or an electron this would not. The detailed analysis of the charged products yields information on the neutral, decaying particles.

The explanation of the series of events at the three vertices A, B, C of fig. 17 is thus the following: in A are produced two neutral strange particles, the *meson* K° and the *baryon* Λ°, according to the reaction

$$\pi^- + p \rightarrow K^\circ + \Lambda^\circ \quad (29)$$

The K° meson travels from A to B in a straight line since it is neutral and the magnetic field has no effect on it. In B the K° decays into two charged pions:

$$K^\circ \rightarrow \pi^+ + \pi^- \quad (30)$$

The baryon Λ° travels in a straight line from A to C, where it decays into a proton and a π^-:

$$\Lambda^\circ \rightarrow p + \pi^- \quad (31)$$

In the picture, the proton is the darker, positive track. Everything may be verified by measuring the direction and the curvature of each track and applying the principle of conservation of energy and momentum. In particular one notices that the direction of the K° meson, from A to B, when prolonged passes in between the positive and negative track. In jargon one says that the V° due to the K° meson *"points"* to point A, which is a crude way of saying that the principle of conservation of momentum is qualitatively verified.

In conclusion the 3 events of fig. 17 prove the existence of two new particles: the K° meson with a mass of 497 MeV and the baryon Λ° with a mass of 1115 MeV. The event is also interesting for the illustration of the conservation laws of the electric charge, of the baryon number and of the strangeness quantum number.

We have already checked charge conservation; we shall now discuss the other two conservation laws.

<u>11.2 The Baryon number and its conservation</u>

The proton and the unstable particles which have one proton as one of their decay products, are called baryons. The Λ° which decays into $p + \pi^\circ$ is therefore a baryon. Baryons are defined to have baryon number +1. The antiproton and the antiparticles which have one antiproton as one of their decay products are antibaryons and have baryon number -1.

It is easy to check that the Λ° decay satisfies the conservation of the baryon number:

$$\begin{array}{llll} & \Lambda^\circ \rightarrow & p \; + \; \pi^- & (32) \\ \textit{baryon number} & (+1) & \underbrace{(+1) \;\; (0)}_{+1} & \\ \textit{total} & (+1) & & \end{array}$$

The baryon number is +1 before and after decay, and it is thus conserved; furthermore it is conserved by all types of interactions. The proton is the baryon with the smallest mass. On the basis of baryon conservation the proton cannot decay and should be completely stable. But Grand Unified Theories of the interactions predict a very small probability of proton decay, with a lifetime much longer than the age of the Universe. Proton decay has not been observed until now.

<u>11.3 Strangeness and its conservation</u>

Hadrons, elementary particles subject to the strong interaction, may be also classified according to the strangeness quantum number S.

S is an integer with a value of -1 for strange hadrons, +1 for strange antihadrons and 0 for ordinary hadrons. One may think about strangeness as a kind of charge, which is conserved by strong and electromagnetic interactions, but not by the weak interaction. The true explanation of strangeness is found if we think in term of quarks, the building blocks of hadrons. An ordinary hadron is made only of quarks u, d; a strange particle contains at least a strange quark s and a strange antiparticle at least one anti-strange anti-quark $\bar{s}$. Conservation of strangeness means simply that a quark s may appear or disappear only when it is accompanied by an antiquark $\bar{s}$ A quark s may decay and disappea, but this process is due to the weak interaction which violates strangeness conservation.

The production of Λ° and of K° is abundant since it is due to the strong interaction. Furthermore in the reaction

	$\pi^- + p =$	$K^\circ + \Lambda^\circ$	(33)
Strangeness	$\underbrace{(0)\ \ (0)}$	$\underbrace{(+1)\ \ (-1)}$	
Total strangeness	(0)	(0)	

the total strangeness is conserved, being 0 before and after interaction. The phenomenon of associated production is explained with the requirements of strangeness conservation in the strong interaction.

The K° and Λ° have relatively long lifetimes, of the order of 10^{-10} seconds, typical of the weak interaction. Their decays violate strangeness conservation:

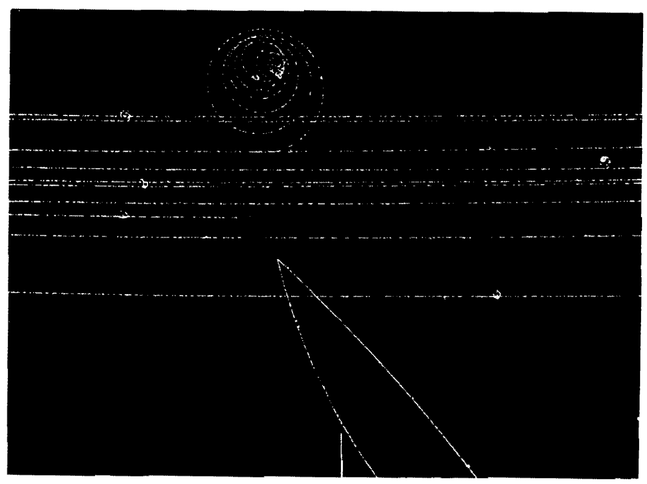
	$\Lambda^\circ \rightarrow$		$p + \pi^-$	(34)
Strangeness	(-1)		$\underbrace{(0)\ \ (0)}$	
Total strangeness	(-1)	$\neq$	(0)	

It may be worth noting that the K system is a complicated system: the mesons K^- and $\bar{K}^\circ$ have $S = -1$ and each contains a quark s; the mesons K^+, K° have strangeness +1 and each contains an antiquark $\bar{s}$.

11.4 Another example of production and decay of strange particles

That bubble chamber is well suited for the study of strange particles, is confirmed by the example in fig. 18. K^- mesons arriving from the left interact with the liquid hydrogen in the bubble chamber. One K^- track terminates in the middle of the photograph and a V seems to come from that end point (the term V is only meant to denote the aspect of the event). The primary reaction is illustrated below and, as shown, the electric charge, the baryon number and the strangeness are all conserved

	$K^- + p$	$\rightarrow \Lambda^\circ + \pi^\circ$	(35)
electric charge	$\underbrace{(-1)\ \ (+1)}$	$\underbrace{(0)\ \ (0)}$	
total charge	(0)	(0)	
baryon number	$\underbrace{(0)\ \ (+1)}$	$\underbrace{(+1)\ \ (0)}$	
	(+1)	(+1)	
strangeness	$\underbrace{(-1)\ \ (0)}$	$\underbrace{(-1)\ \ (0)}$	
total strangeness	(-1)	(-1)	

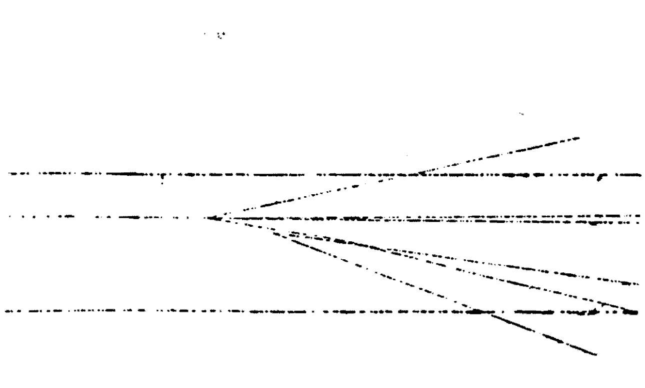


⇑ **Fig. 18**
Strange particle production and decay. In the main vertex, I, a K^- interacts with a proton producing a Λ° baryon, and a π° meson, according to relation $K^- + p \rightarrow \Lambda^\circ + \pi^\circ$. The Λ° travels from I to V and in V decays in a proton and a π^- ($\Lambda^\circ \rightarrow p + \pi^-$) (from Van de Walle, Natuur en Technieck, CERN, Geneva).

Conclusions

In conclusion, bubble chamber photographs can be used for pedagogic purposes,allowing a qualitative analysis of subnuclear phenomena and a quantitative analysis of reactions producing only few new particles. This use was developed in France, where big photos of bubble chamber events have been used in many secondary schools.

Bubble chambers were used world wide by all the most famous physics centres (Berkeley, Brookhaven, Fermilab, CERN, etc.). The bubble chamber was invented in the 1950's; it gave its major scientific contributions in the years 1960-1970, first with the study of strange particles, then the studies of resonances and finally the studies of neutrino interactions. The chambers grew in size from few centimetres to one metre, reaching a maximum of 4 metres. As for all technologies there was the birth time, the period of maximum development and the fall. But there were also periods of "return"; for instance small bubble chambers were made and optimized for very small bubbles, down to 30 μ in diametre. This in order to study very short lived particles, such as the charm particles. An example of an interaction leading to charmed particles is shown in Fig. 19.



⇑ **Fig. 19**
High resolution bubble chamber photograph (CERN-LEBC without magnetic field). The incident particles are π^- mesons of 340 GeV/c. The bubbles have 40 μm in diametre. Notice the four prong interaction; one of them, the lowest one, decays subsequently into a one prong. There is also one V° (at the bottom right). Both decays are charmed particles decays.

Other technologies have now replaced the bubble chambers in the hunt for new particles and for the study of some crucial physics phenomena leading to the unification of the forces acting in nature.

However one question may arise: what is the use of studying and discussing particles which live for extremely short times and that are so far away from our ordinary experience? One may recall that we are continuously bombarded by high energy particles, the *cosmic rays*, where particle production is the rule: in fact about 30 muons of the cosmic radiation pass through our body every second. It may also be recalled that the particle phenomena discussed here were dominant in the first millisecond of our Universe life.

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