The Development of Particle Physics

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Discovery of the muon and the pion

- Energy losses of charged particles.
  This is an important topic in experimental particle physics because the detection of elementary particles is based on their interactions with matter.
- Discovery of the muon.
- Discovery of the pion.
- Studies of pions at first accelerators - to be studied at home.

Energy losses of charged particles

Energy loss through the ionisation and excitation of atoms in a medium.

$$-\frac{dE}{dx} = 4\pi\alpha^2 N_A \frac{Z}{A}\frac{z^2(\hbar c)^2}{m_e v^2}\left[\ln\frac{2m_e v^2\gamma^2}{I} - \frac{v^2}{c^2}\right]$$

$x=\rho l$ - path length in g/cm^2 (column density);

$$\gamma = \frac{1}{\sqrt{1-v^2/c^2}} = \frac{E}{mc^2}$$

$I \approx 16\,Z^{0.9}$ eV, N_A - Avogadro number, Z and A are the atomic number and mass of the material, $\alpha \approx 1/137$ is the fine structure constant, m_e is the electron mass, z is the charge of the particle.

$N_A = 6.02\times10^{23}$ g^{-1}, $\hbar c = 197\times10^{-13}$ MeV cm,

$$4\pi N_A\alpha^2\hbar^2/m_e = 0.307 \text{ MeV/(g/cm}^2\text{)}$$

The expression has a minimum at $\gamma = 3\text{-}4$. Minimum ionisation - 1-2 MeV/(g/cm^2).

Energy losses of charged particles

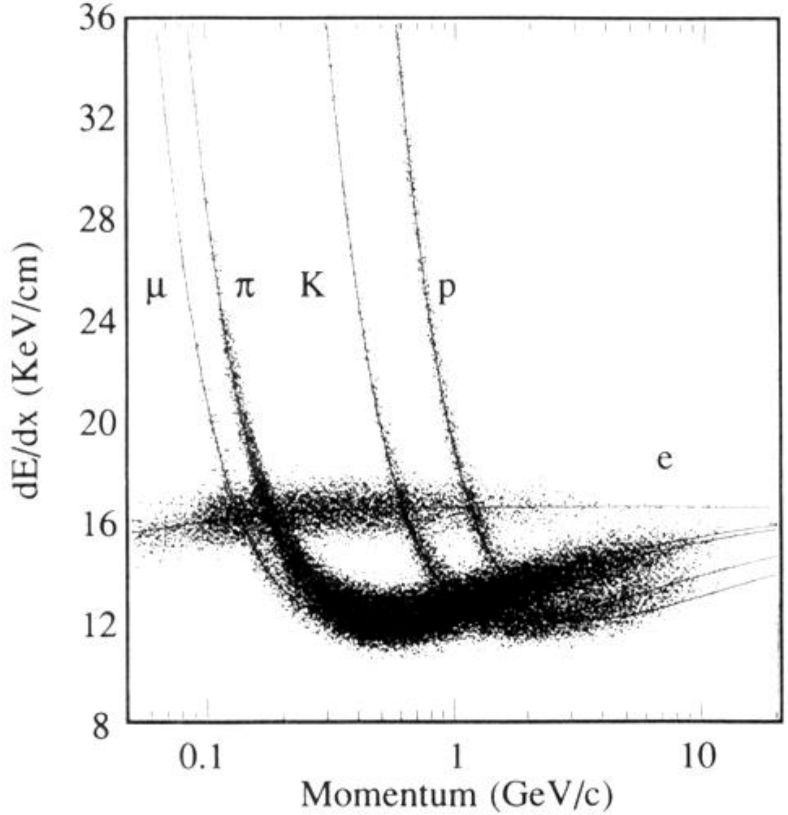


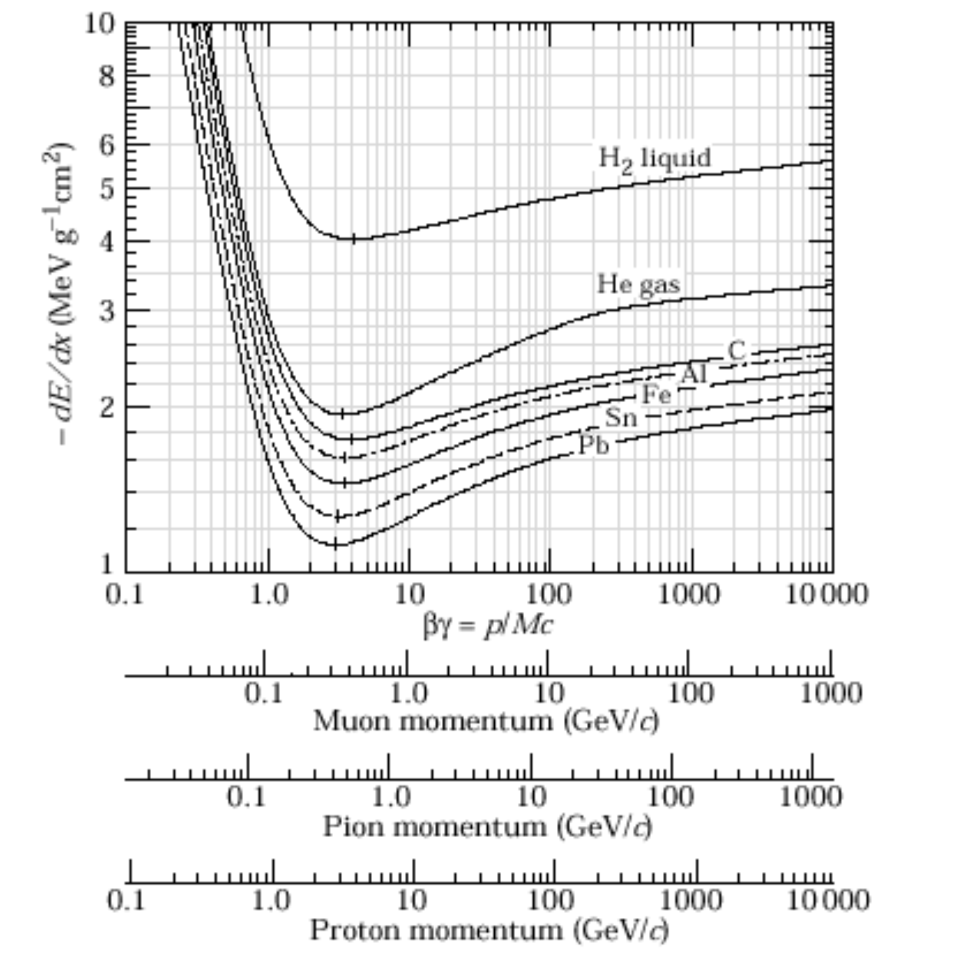
FIG. 2. Distribution in dE/dx vs momentum for particles in multihadron events. Lines indicate the predicted average dE/dx as a function of momentum for different species.

H. Aihara *et al*. *Phys. Rev. Lett*., **61** (1988) 1263.

$$p = mv\gamma$$

Energy losses of charged particles

Energy loss rate in liquid hydrogen (bubble chamber), gaseous helium, carbon, aluminium, tin and lead
The Review of Particle Physics,
The European Physical Journal, **C15**, 1 (2000).
http://pdg.lbl.gov/



Energy losses of charged particles

Energy loss through the bremsstrahlung (braking radiation):

$$-\frac{dE}{dx} = 4\alpha^3 N_A \frac{Z(Z+1)}{A} \frac{(\hbar c)^2}{m^2 c^4} E \ln \frac{183}{Z^{1/3}} = \frac{E}{X_0}$$

X_0 - radiation length, assuming the incident particle is an electron. Solving the equation:

$$E = E_0 \exp(-x / X_0)$$

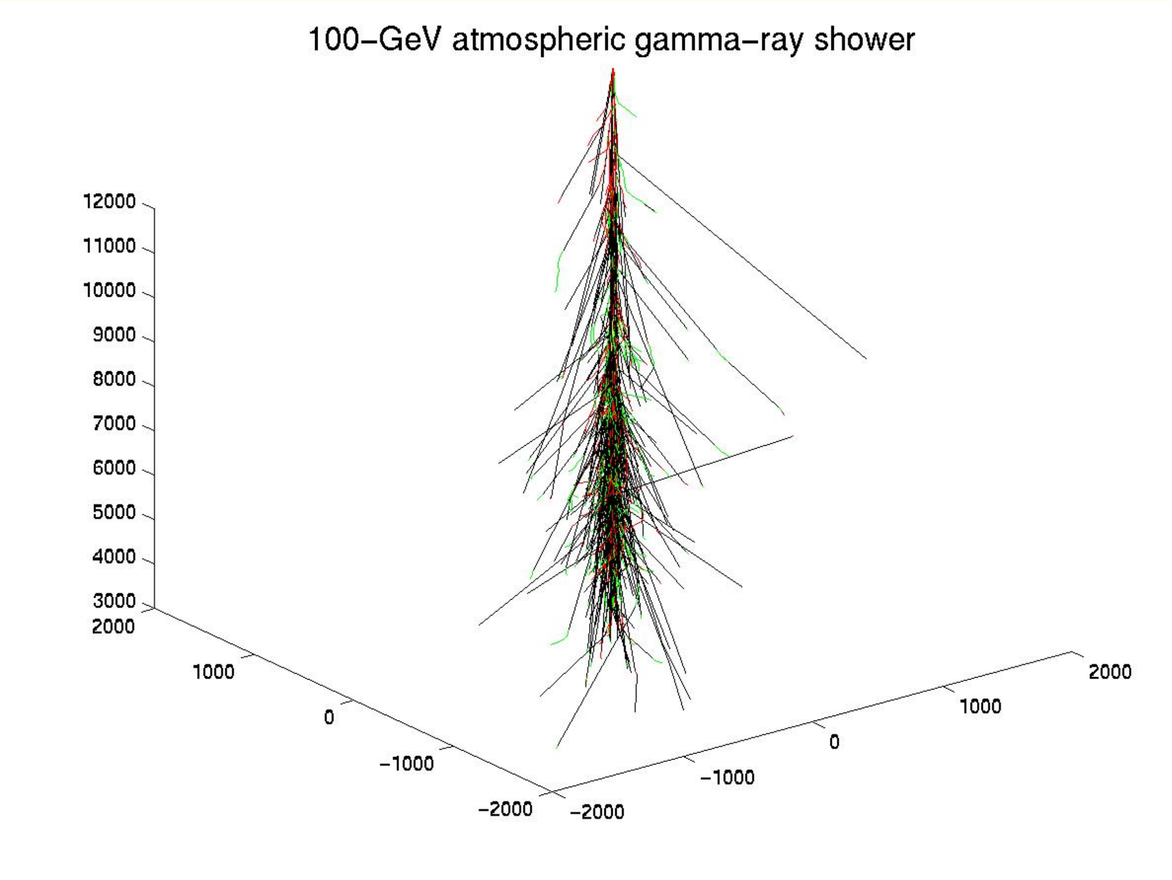
$X_0 = 6.37$ g/cm^2 in lead (0.56 cm), 13.84 g/cm^2 in iron (1.76 cm) (see *Review of Particle Physics - RPP*)

Energy loss for bremsstrahlung are less important for particles heavier than electrons.

For mixtures: $$\frac{1}{X_0} = \sum_i \frac{w_i}{X_i}$$

where w_i and X_i are the fraction by weight and the radiation length for the *i*th element.

Electromagnetic shower



Primary photon can be converted into **e^+ e^--pair**; electron and positron generate **bremsstrahlung photons** which produce pairs in their turns. The shower develops until the energies of electrons decrease to a level at which the energy loss of electrons due to ionisation start to dominate over the energy loss due to bremsstrahlung.

Discovery of the muon

1937 - **S. H. Neddermeyer and C. D. Anderson, measurements of energy loss of cosmic-ray particles**. They used cloud chamber with 1-cm platinum plate inside. By measuring **the curvature of the tracks on both sides of the plate, they were able to determine the loss in momentum.**

p = 100 – 500 MeV/c from track curvatures;

$E=pc$ assuming particles were electrons or positrons (relativistic).

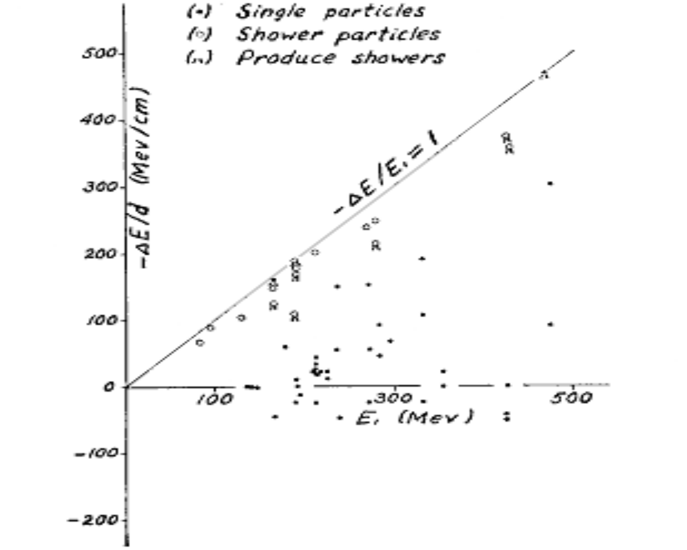


FIG. 1. Energy loss in 1 cm of platinum.

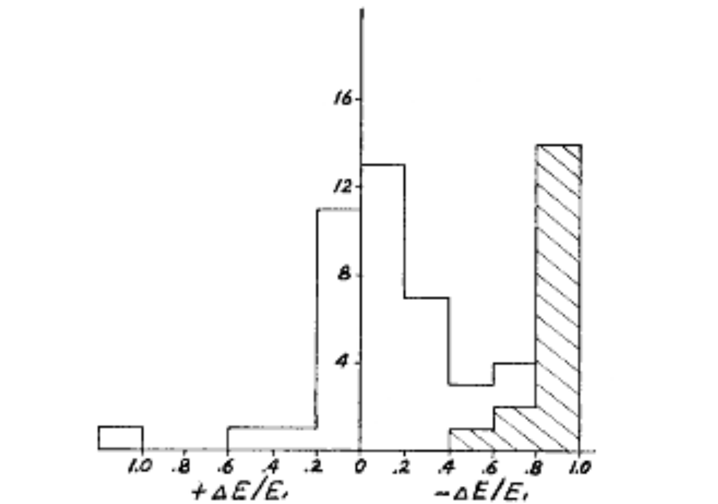


FIG. 2. Distribution of fractional losses in 1 cm of platinum.

Discovery of the muon

- Two types of particles: **"shower" particles and "penetrating" particles**.
- Bethe-Heitler theory predicted **large energy loss for electrons and smaller losses for heavier particles. Neddermeyer and Anderson concluded that penetrating particles are heavier than electron.**
- They could not be protons because protons would be slower and would ionise medium stronger.

1937 - J. C. Street and E. C. Stevenson - **determination of the mass of the new particle.**

- **Simultaneous measurement of particle momentum and ionisation:** $p=mv\gamma$, $dE/dx \propto 1/v^2$.
- The ionisation depends weakly on the velocity except when the velocity is low, that is when the particle is near the end of its path.
- Cloud chamber was triggered by **3-fold coincidence and anticoincidence** (method invented by Blackett and Occhialini)

Discovery of the muon

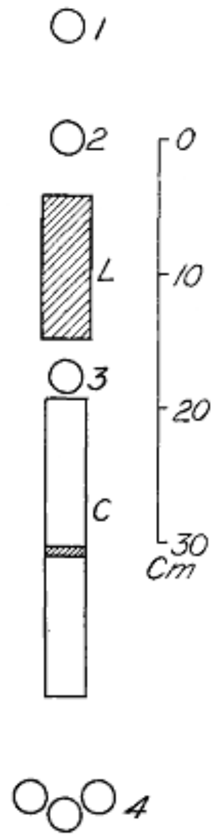


FIG. 1. Geometrical arrangement of apparatus.

Scheme of the experiment:
1, 2, 3 - counters in coincidence;
L - lead filter to remove shower particles;
C - cloud chamber with 3500 gauss magnetic field;
4 - group of counters in anticoincidence.
Only particles which stop in the cloud chambers were photographed.

Ionisation density is 6 times as great as normal thin tracks (electrons). If the ionisation density varies inversely as velocity squared, the **rest mass is approximately 130 times the rest mass of the electron.**

Yukawa particle

1935 - H. Yukawa predicted the existence of a particle of **mass intermediate between the electron and the proton.**

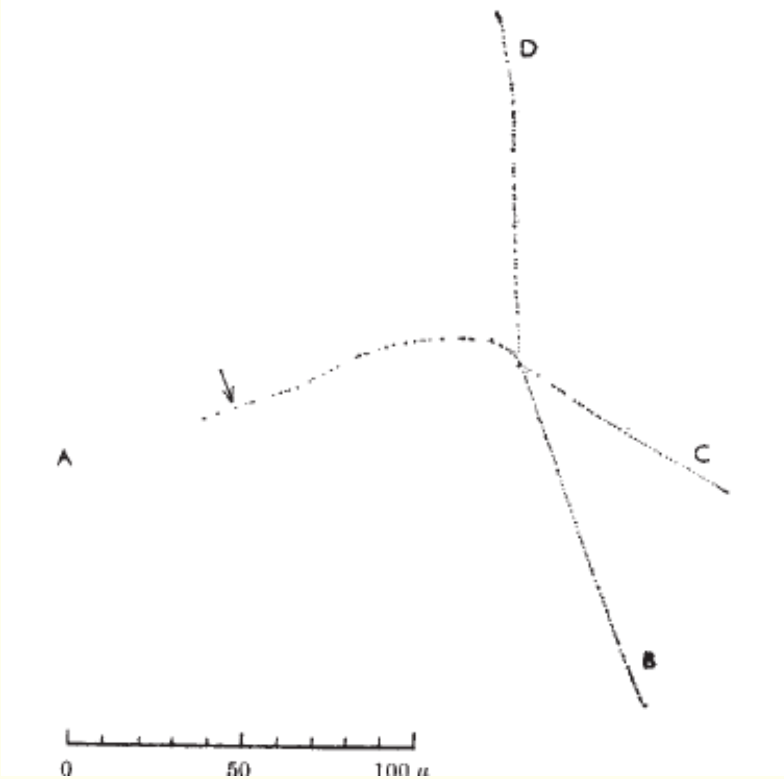
- This particle was to carry the nuclear force in the same way as the photon carries the electromagnetic force.
- In addition it was to be responsible for beta-decay.
- The predicted mass of the particle was about **200 MeV/c^2**.
- The mass of the new penetrating particle, seen by **Neddermeyer and Anderson** and by **Street and Stevenson** was determined (after improved measurements) to be about 100 MeV/c^2, close enough to the theoretical estimate to make natural the identification of the penetrating particle with the **Yukawa** particle.

Yukawa particle

- **Tomonaga and Araki** showed in 1940 that positive and negative **Yukawa** particles should produce **different effects when they stopped in matter**.
- **Positive particle should decay**.
- **Negative particle should be captured into atomic-like orbits**, but with very small radii. As a results, the orbits should overlap the nucleus. The particle should interact with the nucleus and **be absorbed before it could decay**.
- The life time of the penetrating particle was measured as 2.2×10^{-6} s.
- **Conversi, Pancini and Piccioni** during the World War II investigated the decays of positive and negative penetrating particles in different materials.
- They found that **positive particles always decayed when stopped in matter, while negative particles were absorbed by the nuclei in iron but decayed in carbon**, in contradiction to the **Tomonaga-Araki** predictions.

Yukawa particle

- In **1947 D. H. Perkins used photographic emulsion** to record with extremely fine resolution an event of the type predicted by **Tomonaga and Araki**.
- The event had a **slow negative particle which stopped in the emulsion**. After the particle was absorbed by the nucleus, the nucleus was blasted apart and three fragments were observed in the emulsion.
- Track A was identified as the incoming track because of increased grain density and increased scattering as the track reaches the vertex.

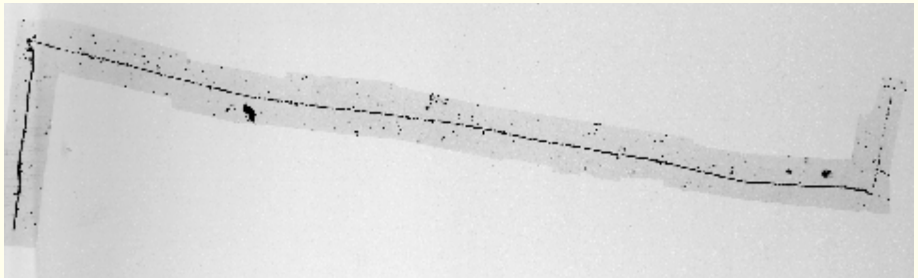


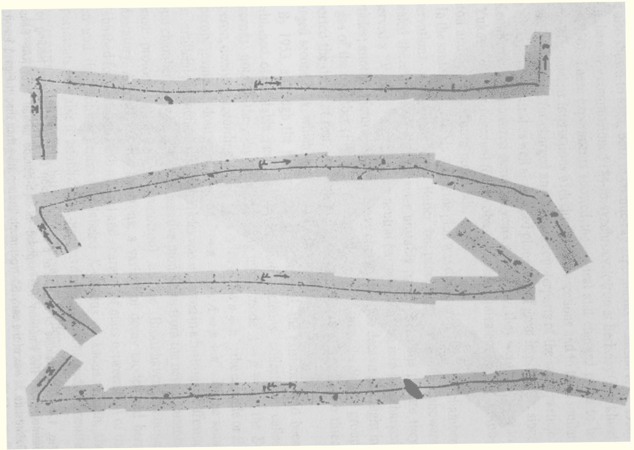
Yukawa particle

- **The mass of the particle causing track A is deduced to be between that of the electron and the proton.** The ionisation is too big and the scattering too small for it to be an electron and the scattering is too big for it to be a proton.
- The range-energy curve was calculated for several intermediate masses by scaling the curve for protons. The result was consistent with the mass of the meson.
- Kinematics of the event shows that the mass is 60-100 MeV.
- This event showed the behaviour predicted by **Tomonaga and Araki**, contrary to the result of the Italian group.

Discovery of the pion

- **Lattes, Occhialini and Powell** from Bristol found the connection between the results of Italian group and the observations of **Perkins**.
- They observed **two different particles**, one of which decayed into another one.
- The observed decay product appeared to have fixed range in the emulsion. This indicates that it was always produced with the same energy and the decay was into two particles, one of which is invisible (**Pauli's** neutrino). The pion (seen by **Perkins**) decayed into muon (discovered by **Neddermeyer and Anderson** and seen also by **Conversi et al.**) and neutrino.



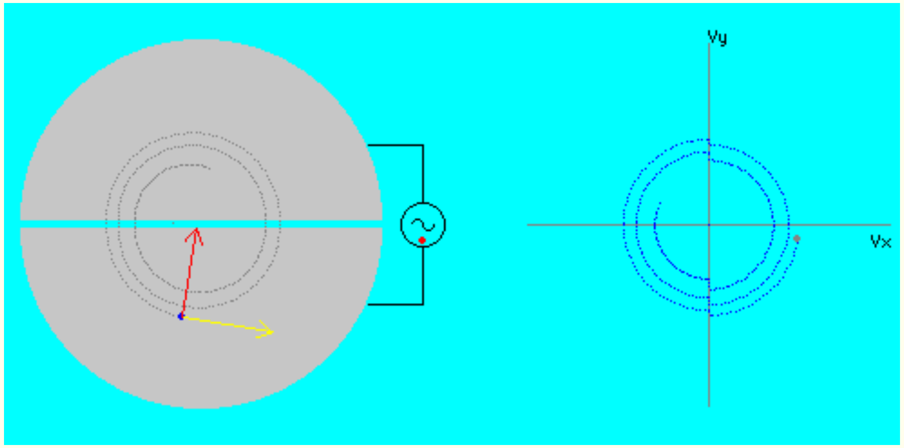


Muons and pions

- Pions are **hadrons** - they can interact strongly, as well as electromagnetically and weakly.
- Muons are **leptons** - they interact only electromagnetically and weakly.
- Negative pions are always absorbed due to the strong interaction between pions and nuclei.
- Negative muons can be captured and absorbed by a nucleus (proton is transformed into neutron and a neutrino is emitted) like electrons but the radius of muon orbit and the probability of absorption depends on the *Z* of the nucleus. For high-*Z* nuclei the muon is absorbed.

The first accelerators

- The earliest accelerators were cyclotrons. Cyclotron consists of two D-shaped objects (dees) with a potential difference between them. A stream of particles moved in a plane perpendicular to a uniform magnetic field, which bended the particle tracks so that they passed through an electric field in a gap between dees and were accelerated.



For non-relativistic particles the frequency of the machine was determined by the Lorentz force law, $F = e\,v\,B$, and the formula for centripetal acceleration, $v^2 / r = F / m = e\,v\,B / m$, so the angular frequency is given by: $\omega = e\,B / m$.

The first accelerators

- The cyclotron frequency is independent of the radius of trajectory: as the energy of the particle increases, so does the radius in just such a way that the rotational frequency is constant. It was thus possible to produce a steady stream of high energy particles spiraling outwards from a source at the centre.
- At relativistic energies $\omega = e\,B / \gamma\, m$ and the frequency depends on energy. When protons were accelerated to relativistic velocities, the required frequency decreased. This problem was solved in the synchrocyclotron by using bursts of particles which were accelerated by a system whose frequency decreased in just the right way to compensate for the relativistic effect.
- In **1948**, the 350-MeV, 184-inch proton synchrocyclotron at Berkeley became operational and charged pions were observed in photographic emulsions.

Charged and neutral pions

- From the experiments mentioned above it was found that pion has two charge states, π^+ and π^-, which decayed into μ^+ and μ^-, respectively.
- It was also known that cosmic-ray showers had a 'soft' component - photons and electrons. It was suggested by **Lewis, Oppenheimer and Wouthuysen** that this component was due to the decay of neutral mesons.
- Strong evidence for the existence of a neutral meson with a mass similar to that of charged pion was obtained by **Bjorklund et al.** using the 184-inch synchrocyclotron.
- They used a pair spectrometer to measure the photons produced by the collisions of protons with carbon and beryllium. The pair spectrometer consisted of a thin radiator in which photons produced e^+e^- pairs whose momenta were measured in a magnetic field.

Neutral pion

- When the incident proton beam had an energy less than 175 MeV, the observed yield of photons was consistent with expectations from bremsstrahlung from protons.
- However, when the incident energy was rised to 230 MeV, much more photons were observed and their spectrum showed a clear peak.
- The most likely explanation of the data was the production of a neutral meson decaying into two photons.
- Direct confirmation of two photon decay of a neutral meson was provided by **Steinberger, Panofsky and Steller** using the electron synchrotron at Berkeley. The electron beam was used to generate photon beam with energies up to 330 MeV. Two photon detectors were placed near beryllium target. Events were accepted only if photons were seen in both detectors.

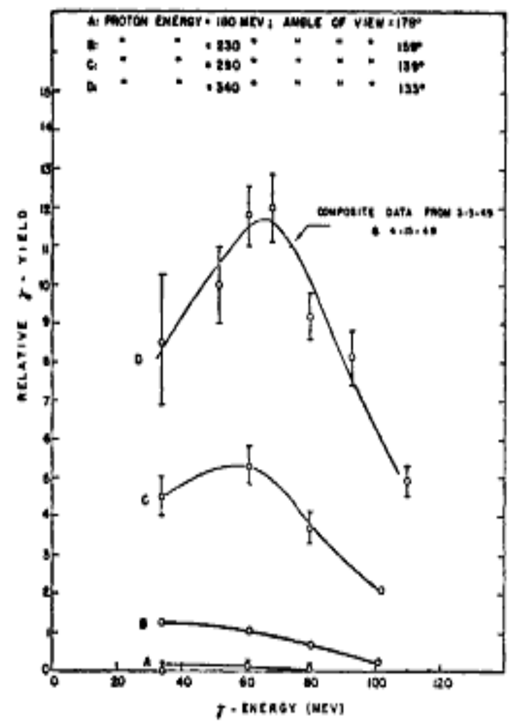


FIG. 4a. Relative gamma-yield from ⅛-in. carbon target at various proton energies.

Neutral pion

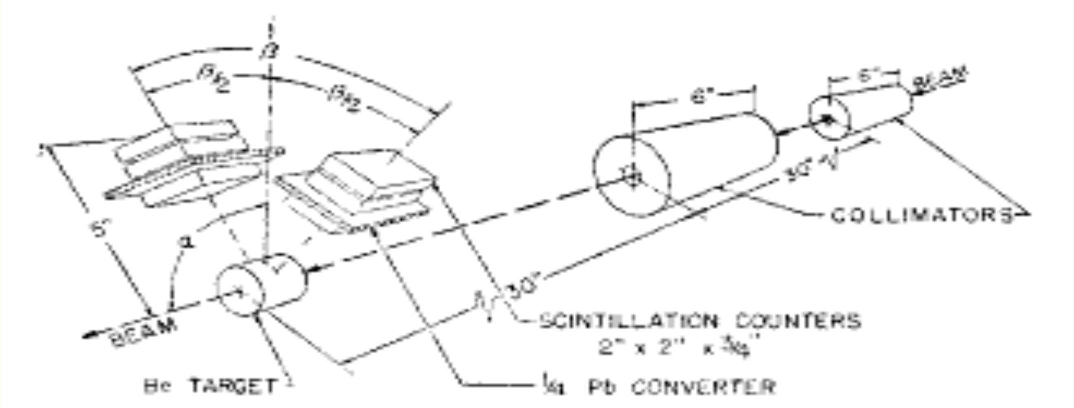
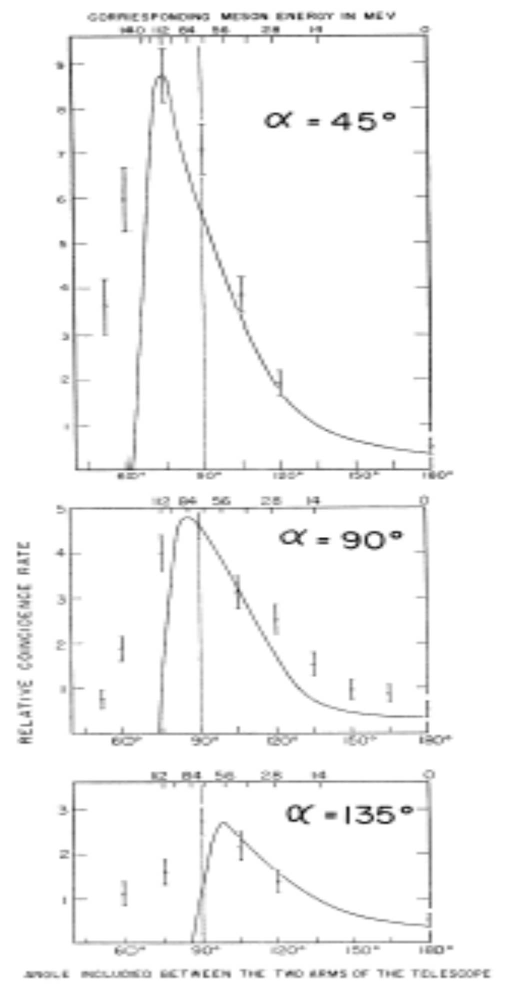


Fig. 1. Experimental arrangement.



- The rate for these coincidences was studied as a function of the angle between the photons and the angle between the plane of the final state photons and the incident beam direction.
- The data were consistent with **the decay of a neutral meson into two photons with a production cross-section for the neutral meson similar to that for the charged mesons.**

Properties of pions

- In **1951 Panofsky, Aamodt and Hadley** published a study of negative pions stopping in hydrogen and deuterium. Their results expanded knowledge of the pions.
- The reactions studied were:

$$\pi^- p \rightarrow \pi^0 n \qquad \pi^- p \rightarrow \gamma n$$

$$\pi^- d \rightarrow n\, n \qquad \pi^- d \rightarrow \gamma\, n\, n \qquad \pi^- d \rightarrow \pi^0 n\, n \text{ (not seen)}$$

The pair spectrometer was used in the experiment. 14 kG magnetic field perpendicular to the plane shown bent electrons and positrons into the Geiger counters on opposite sides of the spectrometer.

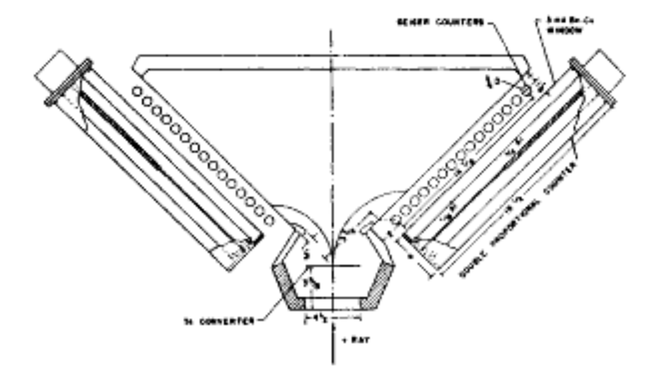


FIG. 4. Outline diagram of pair spectrometer. The converter, Geiger counter array, and the proportional counters are shown. Note the geometry of the pole piece to give a uniform field in the area of the converter.

Properties of pions

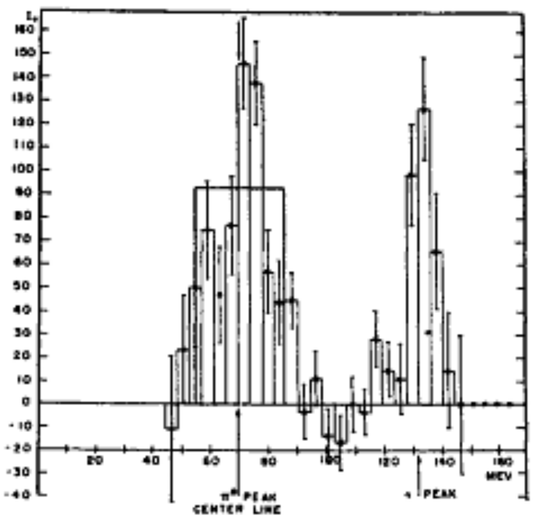


FIG. 12. Pair spectrum resulting from the absorption of π^- mesons in hydrogen. The center of the spectrometer is set near 100 Mev. The spectrum clearly shows the separation between processes (2) and (4). The branching ratio between these reactions can be derived from this spectrum.

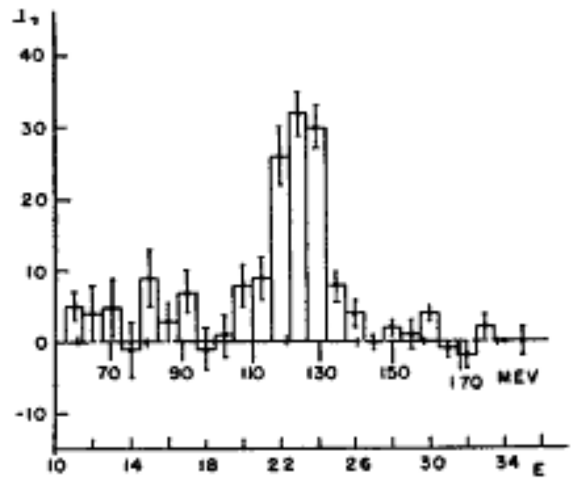


FIG. 15. Pair spectrum resulting from π^- capture in deuterium. The spectrometer center is set near 130 Mev.

The band near 70 MeV - photons from π^0-decay. The line near 130 MeV - $\pi^- p \rightarrow \gamma n$. The line near 130 MeV (right figure) - $\pi^- d \rightarrow \gamma n n$.

- They measured the mass of π^-: (275.2±2.5) m_e; and the mass difference between negative and neutral pions: (10.6±2.0) m_e.

The spin of the charged pion

- The spin of the charged pion was obtained by comparing the reactions $p\,p \to \pi^+ d$ and $\pi^+ d \to pp$. The cross-section for a scattering process with two final state particles is related to the Lorentz invariant matrix element, M, by

$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2 s}\frac{p'}{p}|M|^2$$

In this relation s is the square of the total energy in the centre of mass, p and p' are the centre of mass momenta in the initial and final states and $d\Omega$ is the solid angle element in the centre of mass. The matrix element squared is to be averaged over the spin configurations of the initial state and summed over those of the final state.

The spin of the charged pion

- The reactions $p\,p \to \pi^+ d$ and $\pi^+ d \to pp$ have the same scattering matrix elements, so their rates at the same centre-of-mass energy differ only by phase space factors (p/p') and by the statistical factors resulting from the spins:

$$\frac{d\sigma(\pi^+ d \to pp)/d\Omega}{d\sigma(pp \to \pi^+ d)/d\Omega} = \frac{(2s_p+1)^2}{(2s_d+1)(2s_\pi+1)} \frac{p_{pp}^2}{p_{\pi d}^2}$$

where s_π is the spin of the π^+, s_p and s_d are the spins of proton and deuteron, $p_{\pi d}$ and p_{pp} are the centre-of-mass momenta for the $\pi^+ d$ and $p\,p$ reactions at the same centre-of-mass energy.

The spin of the charged pion

- The proton and deuteron spins are known. From the comparison of the cross-sections of these two reactions, the spin of π^+ was found to be 0.
- Since the π^0 decays into two photons, it is a boson and has the spin 0.
- The π^0 completed the triplet of pions: π^0, π^-, π^+.

Summary

- Discovery and study of the muon produced a confusion in the scientific community over its properties. Eventually, muon was found to be a lepton with properties similar to those of electron.
- Pion was the first hadron found outside the atom (and the first meson).
- Although most discoveries were made in cosmic rays, the first accelerators became operational allowing detailed study of the particles and their interactions.

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- SLAC e-print database: http://www.slac.stanford.edu/spires/hep/
- Web of Science: http://wos.mimas.ac.uk
- Materials from the web-site http://particleadventure.org have been used for preparation of these lectures.