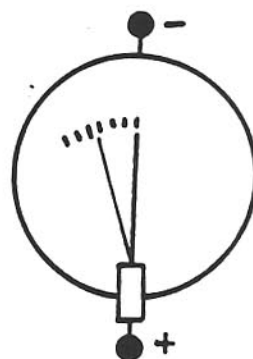


Chapter 1: Cosmic Rays

Several of the experiments in 180F utilize cosmic ray muons as elementary particles. It will be useful to give an introductory survey on cosmic rays.

I) History:

By 1910, x-rays had been known for 20 years and the rays emitted by radioactive nuclei were also well understood. One instrument used in detecting these radiations was the electroscope. The particles of the radiation strip electrons from the molecules of the gas –this requires energy– and a current is created by the electric field which in turn discharges the electroscope. By 1910 it was well known that regardless of how much matter was placed around the electroscope a small *ionization* current remained. This was initially blamed on radioactivity in the environment. However, some remarkable discoveries demonstrated that there was a new phenomenon:



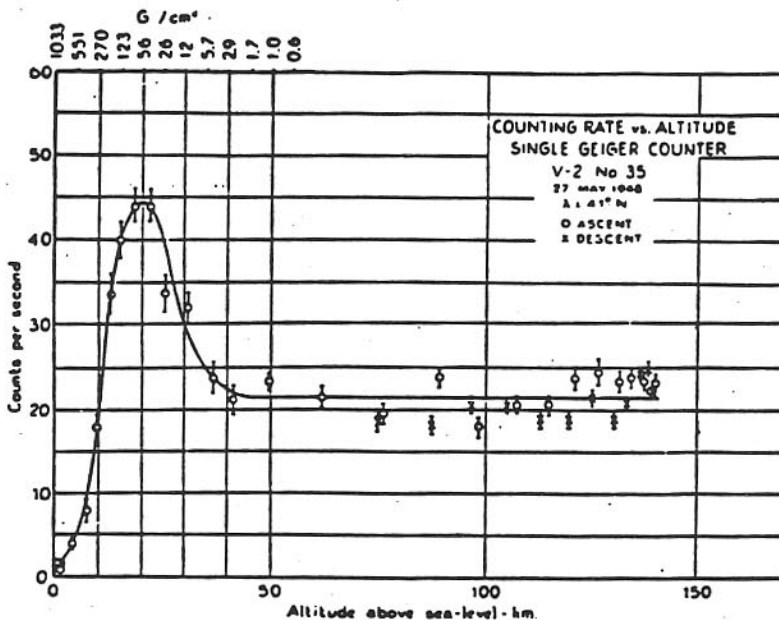
1910 Gockel ascended to 4500 m and found that the current *increased!*

1911 Hess ascended to 5500 m. He found an even greater increase and also observed no difference between day and night.

1913 Hess and Kohlhorster rose to 9000 m to find an increase by a factor of 12 with respect to the earth!

1922 Millikan and Bowen used balloon-sondes which reached 15,000 m. They found first an increase, then a decrease at the highest altitudes. They concluded that ionizing rays were produced at some intermediate height.

Let's jump ahead 25 years and examine some early rocket data in the figure below.



Counting rate as a function of altitude for a single Geiger counter carried in a V.2 rocket (GANGNES [1949]). (2)

Above 50 km, the rate of ionization is fixed. It would decrease if the atmosphere were the source. Interpretation: "something" comes in from the outside, *first multiplies by interaction with the atmosphere and then is absorbed by the remaining atmosphere*. Of course this was not known in the twenties and had to be deduced by a great deal of painstaking work.

Note that it is not height (in kilometers) that is relevant, but the amount of matter traversed. For an isothermal atmosphere

$$\rho = \rho_0 \exp(-h/h_0)$$

where $\rho_0 = 0.001205 \text{ gm/cm}^3$ for NTP (76 cm Hg, 20°C)

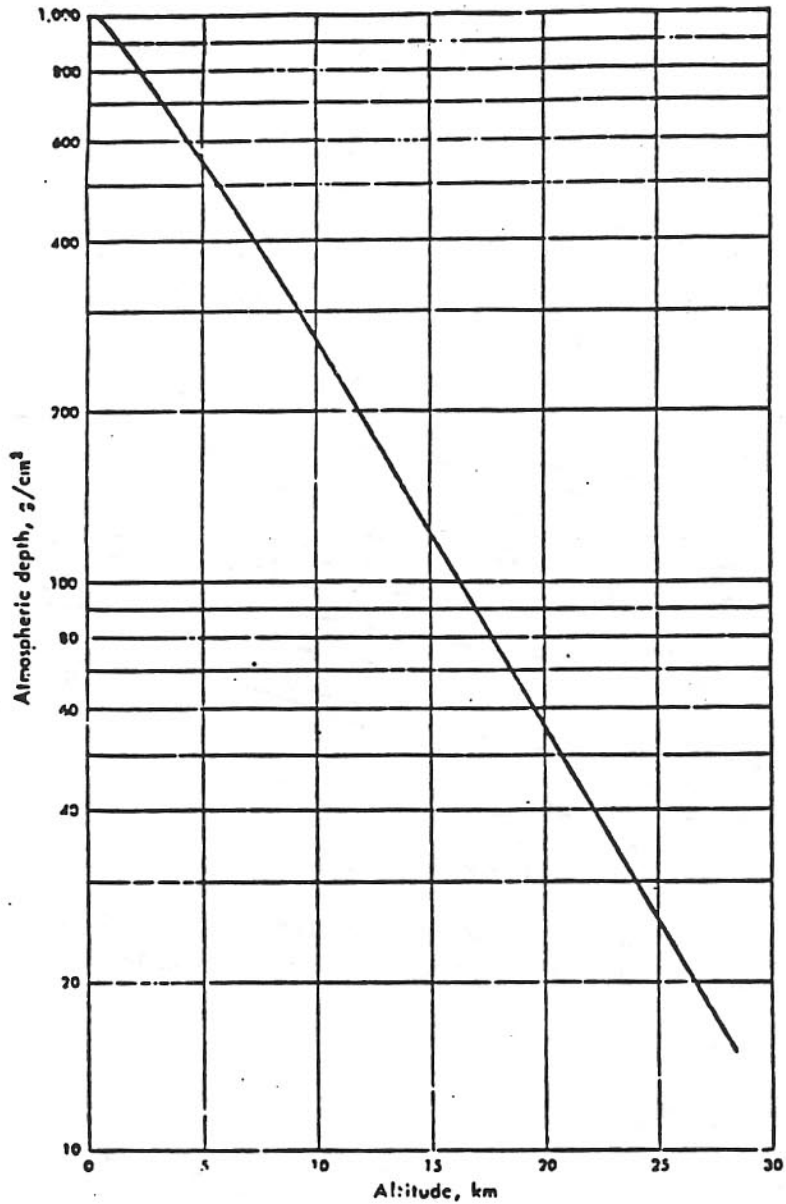
The parameter h_0 can be evaluated as follows. The mass of a 1 cm^2 column of mercury (as in a barometer reading 760 mm) is 1.03 Kg. This is balanced by a 1 cm^2 column of air of mass:

$$M = (1 \text{ cm}^2) \int_0^\infty \rho \, dR = (1 \text{ cm}^2) \rho_0 h_0 \int_0^\infty \exp(-h/h_0) \frac{dh}{h_0}$$

which gives

$$\begin{aligned} h_0 &= \frac{1.03 \text{ Kg} \times (1 \text{ cm}^2)}{.001205 \text{ (g/cm}^3\text{)}} \\ &= 8.6 \text{ Kilometers} \end{aligned}$$

The figure below shows atmospheric depth in grams/cm² as a function of altitude.

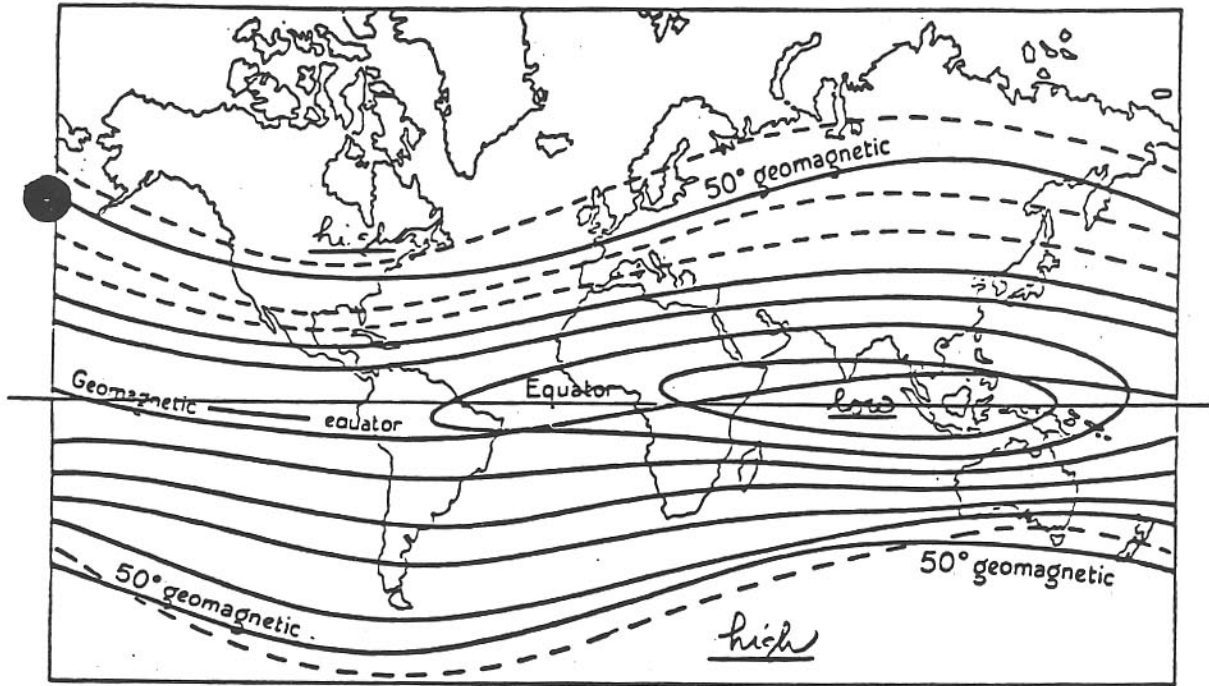


Atmospheric depth, in grams per square centimeter, as a function of altitude above sea level, in kilometers. ③

Let us return to the historical development. By the end of the 1920's it was known that

- Cosmic rays were more penetrating than any radiation previously studied. (using electroscopes submerged in lakes)
- Temporal variations were very slight. The period from 1933 to 1937 was one of worldwide intensity surveys at sea level (electroscopes on ships).

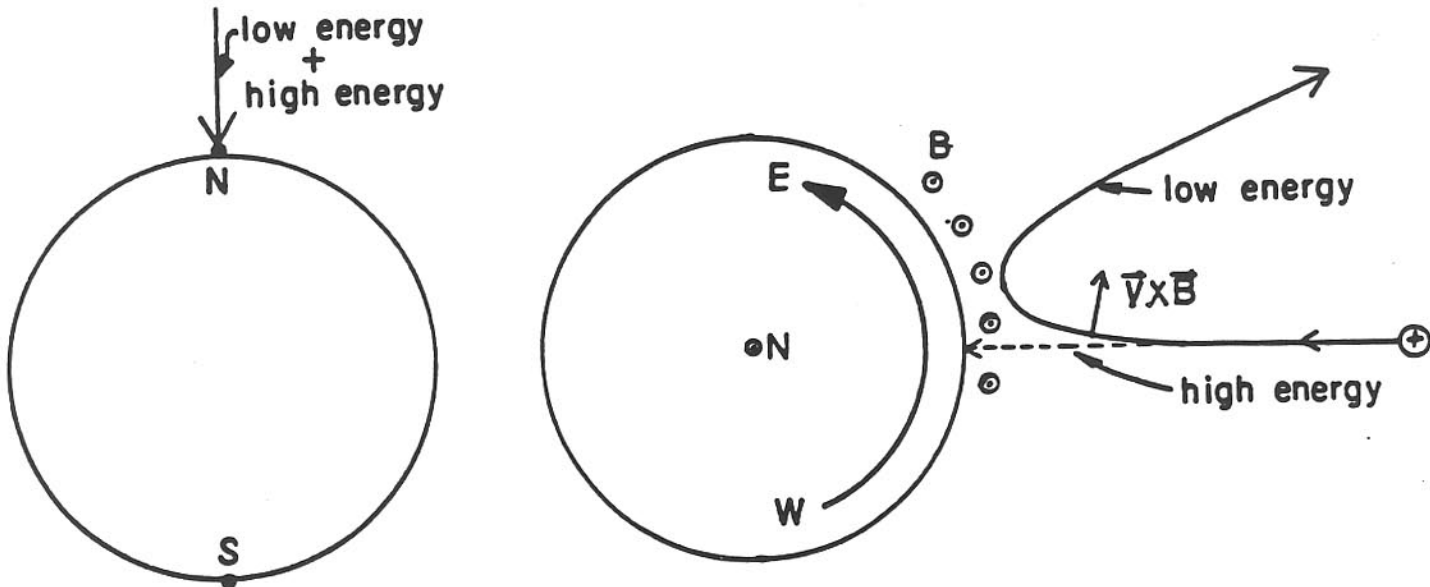
In 1936 Millikan and Neher and in 1937 Compton and Turner determined that the cosmic ray intensity at sea level is related to *geomagnetic latitude*.



Map of the 'isocosms' (according to Compton). The analogy between isocosms and geomagnetic parallels can be observed.

④

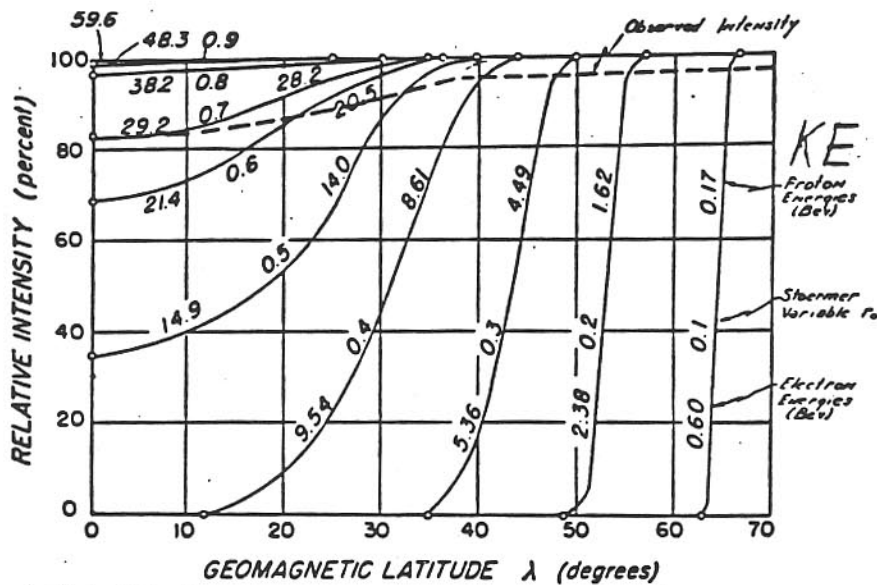
Under action by the earth's magnetic field, charged particles of all energies reach the geomagnetic poles, but low energy charged particles are turned away at the equator.



These studies produced two conclusions:

1. Primary Cosmic Rays are Charged.
2. Primary Cosmic Rays come with energies such that Earth's Field plays a role.

Such measurements initiated an intense program of orbit calculation of relativistic charged particles in the earth's dipole field.

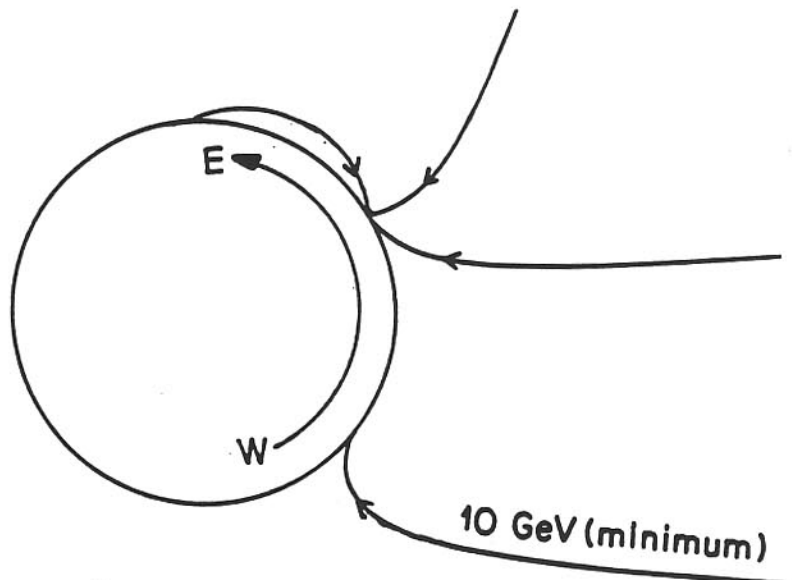


Bev \equiv GeV

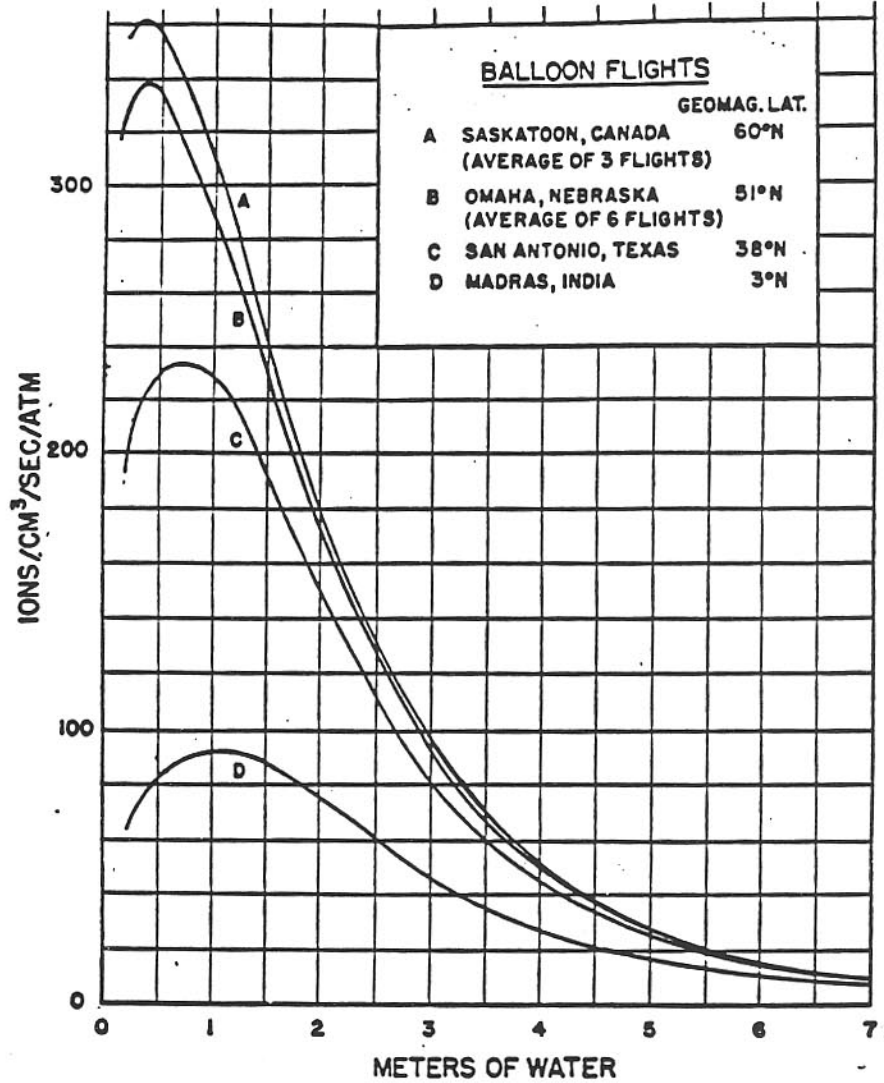
Relative intensity of cosmic radiation, in per cent, as a function of geomagnetic latitude λ in degrees (Lemaître and Vallarta). Solid curves: intensity under the assumption that the radiation at infinity is homogeneous in energy with the values shown. Dashed curve: intensity of the hard component as actually observed (averaged over both hemispheres). (6)

The figure above is one example of the calculations. Note that 1 GeV is one GIGA electron volt, i.e., 10^9 electron volts. Also note that in general only a fraction of primaries going in all directions can reach as close as the atmosphere. At the equator particle energies must be greater than 10 GeV to reach the earth's surface.

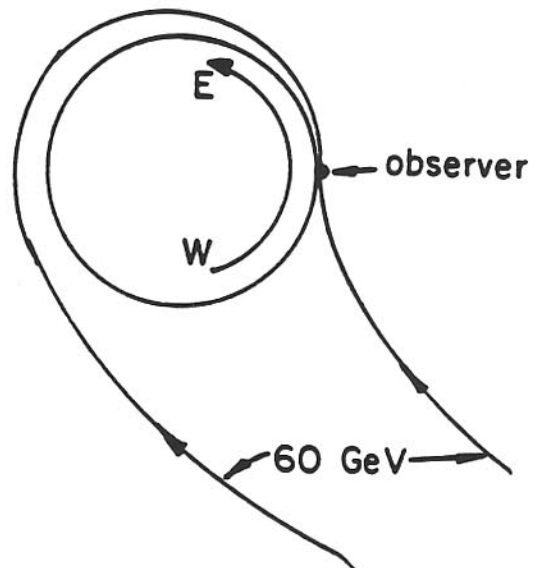
Note the observed intensity at sea level. The knee can be understood if we consider that while a low energy primary can reach the top of the atmosphere at a high geometric latitude, it will not manage to reach the surface of the earth because of absorption in the atmosphere.



This is borne out by observation that the knee of the latitude curve moves to ever higher latitudes as one goes higher in the atmosphere. These observations largely ruled out neutral particles as cosmic ray primaries, *but* are they negative-electrons? positive-protons?



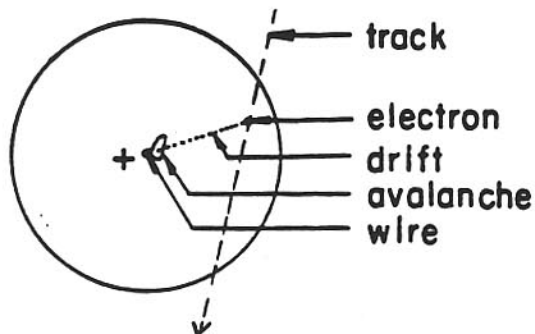
Cosmic ray intensity as a function of altitude, as measured with an unshielded ionization chamber. The ordinate gives the ionization in ion-pairs/sec-cm³ air at 76 cm Hg and 20°C; the abscissa gives the altitude, expressed as pressure in meters of water equivalent. Curves are shown for flights at four different geomagnetic latitudes. (I. S. Bowen, R. A. Millikan, and H. V. Neher, *Phys. Rev.* 63, 856 (1938).)



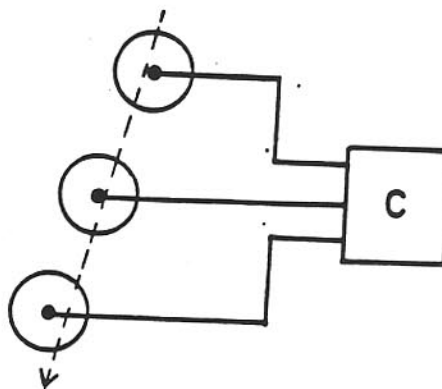
If the particles are positive, then many more should be coming from the West than the East, if negative more from East than West!

An electroscope is not enough to determine the direction of a particle. A better device was needed. Two inventions were joined to make possible directional measurements:

1. Geiger Counter



2. Coincidence Circuit: (Bothe)

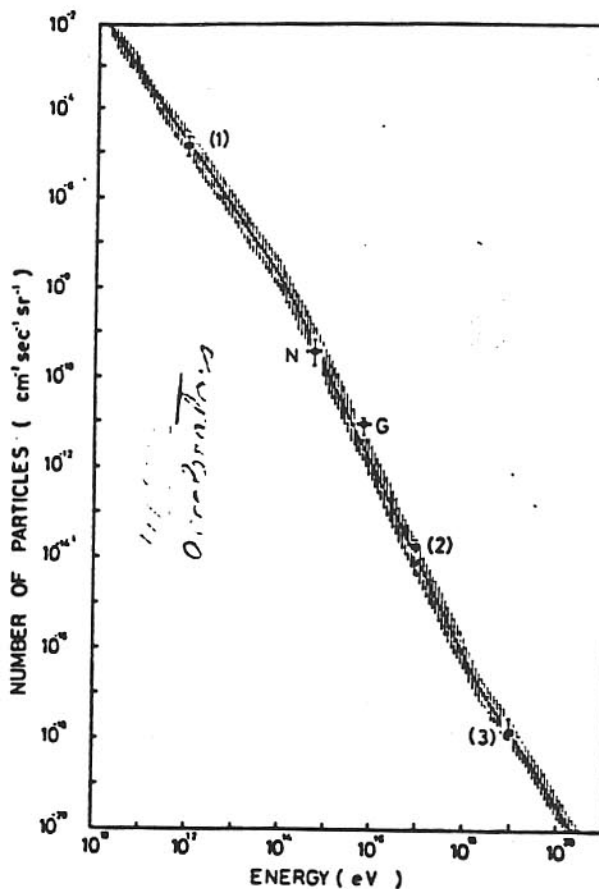


Cosmic ray experiments with these devices led to the conclusion:

Cosmic Ray Primary Particles are Positively Charged

II) Primaries:

a) It is now known that most primaries are protons. The integral flux for energies greater than E follows the relationship: $j(> E) = K(E/E_0)^{-\alpha}$



Integral energy spectrum of primary cosmic rays. Curves 1, 2, and 3 represent the spectra given in respective lines in Table 6.19. N—EAS data by Nikolsky 62; G—EAS data by Greisen 56; the EAS data are given in Table 5.9.

The empirical values of the constants are:

| E(ev) | E_0 (ev) | K (per sec per cm^2 per steradian) | α |
|--|------------|---|----------------|
| 10^{10} to 3×10^{13} | 10^{12} | $(1.6 \pm .8) \times 10^{-5}$ | $1.60 \pm .05$ |
| 8×10^{14} to 4×10^{17} | 10^{17} | $(2 \pm .4) \times 10^{-14}$ | $2.20 \pm .15$ |
| 10^{17} to 10^{20} | 10^{19} | $(2 \pm 1) \times 10^{-18}$ | ~ 1.7 |

Recall that $1 \text{ eV} = 1.6 \times 10^{-19}$ joule, and $10^{19} \text{ eV} = 1.6$ joule. Such particles are not trapped by galactic magnetic fields.

The acceleration mechanism is still a puzzle but the energy spectrum can be empirically understood. Suppose

$$dE = aE dt$$

then

$$E = E_0 \exp(at)$$

where E_0 is the injection energy. Thus the cosmic ray's age is

$$t = (1/a) \ln(E/E_0)$$

But if cosmic rays collide with interstellar dust with mean free path λ ,

$$n = n_0 \exp(-x/\lambda) = n_0 \exp(-ct/\lambda)$$

$$\ln(n/n_0) = -(c/a\lambda) \ln(E/E_0) = \ln[(E/E_0)^{-c/a\lambda}]$$

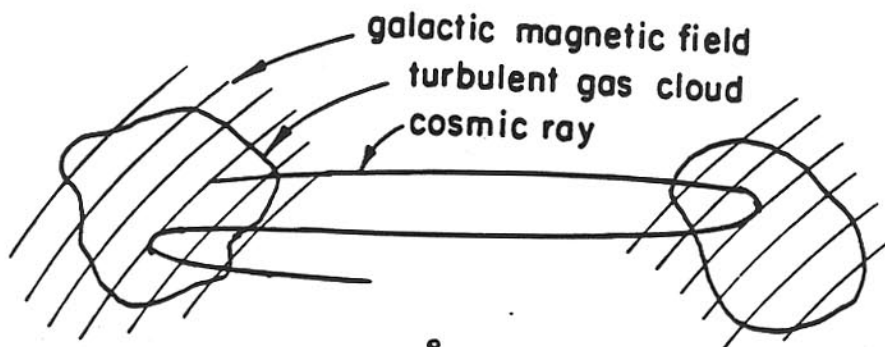
$$n = n_0 (E/E_0)^{-c/a\lambda}$$

The Energy Density of cosmic rays in the galaxy is about 1 eV/cm^3

\cong Energy Density of Turbulent gas Clouds

\cong Energy of Galactic Magnetic Field.

This is a result of equipartition.

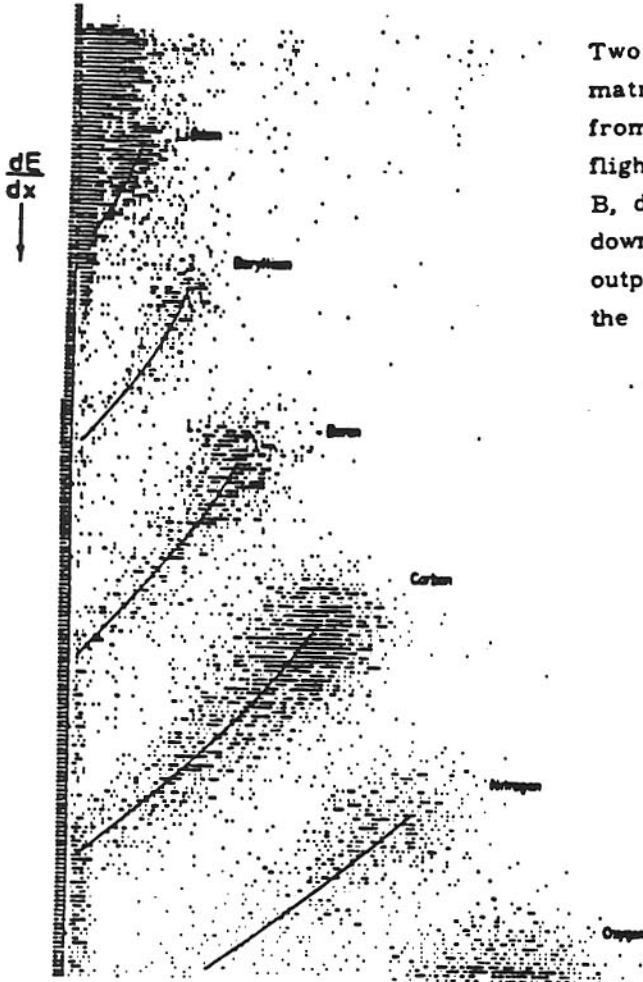


b) In addition to protons, cosmic ray primaries also include fully stripped heavier nuclei—their abundance is similar to cosmic abundance of elements, roughly:

Protons : alphas : heavy nuclei = 1 : 1/7 : 1/60

Thus for every seven incident protons there is one alpha (2 protons + 2 neutrons) so that about 25 per cent of all primary nucleons are actually neutrons bound in nuclei. The energy spectra of alphas and heavy primaries are the same as for protons, a fact of consequence for possible acceleration mechanisms.

CERENKOV →



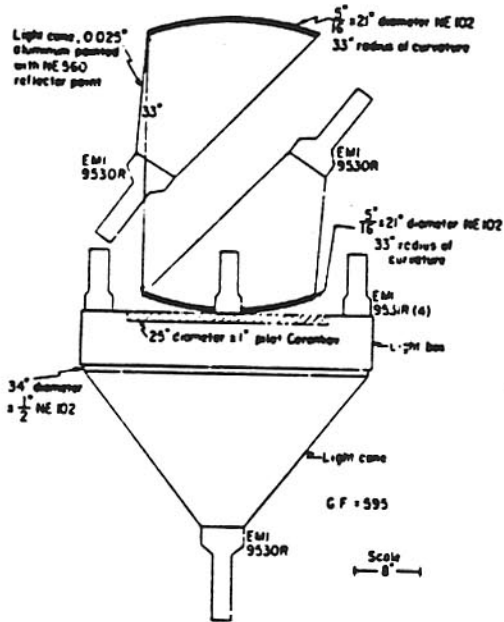
Two dimensional matrix of events from part of 1970 flight of Telescope B, dE/dx increasing downwards, Cerenkov output increasing to the right.

Recall

$$E = \gamma m$$

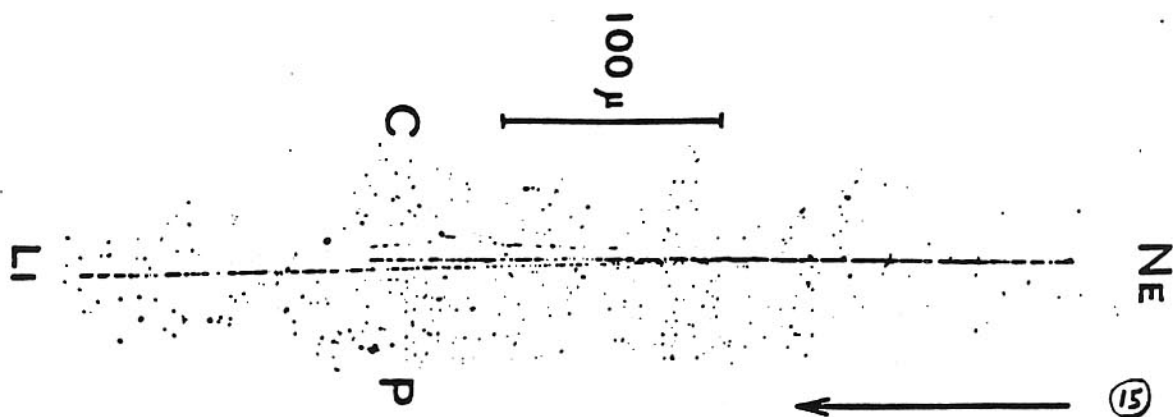
$$P = \beta \gamma m$$

$$= \sqrt{\gamma^2 - 1} m$$



Outline drawing of dE/dx - (13)
Cerenkov-Range Telescope.



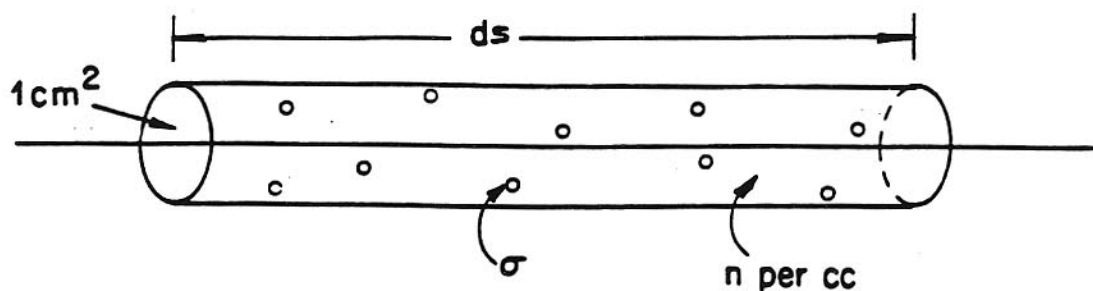


A neon nucleus collides with a proton and breaks up into a nucleus of lithium and a carbon (or nitrogen) fragment.

Compared to their prodigious kinetic energies the binding energy of primary heavy nuclei is tiny and they tend to break up into nucleons near the top of the atmosphere. For our purposes we need not distinguish the nuclei from the dominant proton component in the primary cosmic rays.

III) Interactions of Primaries in the Atmosphere

Suppose now that primaries enter the atmosphere. Sooner or later they will collide with air nuclei. What is the mean free path for such a collision?



$$dN = nds; \quad dP = (\sigma dN) = \sigma nds = \rho \sigma N_0 ds / A$$

$$dP = (\sigma N_0 / A) \rho ds = (\sigma N_0 / A) dx$$

$$-dN / N = (\sigma N_0 / A) dx = dx / \lambda \quad \text{where } \lambda = A / (N_0 \sigma)$$

$$N = N_0 \exp(-x / \lambda)$$

Here A is the atomic weight of air, about 14 grams/mole.

$$\lambda = \frac{A}{6.03 \times 10^{23} \times \pi [1.45 \times 10^{13} A^{1/3}]} = 25 A^{1/3}$$

$$= 60 \text{ g/cm}^2$$

What happens in a collision?

$N + N \rightarrow N + N + \text{pions}$
 + kaons
 + nucleon-antinucleon
 pairs
 + other exotica

In brief:

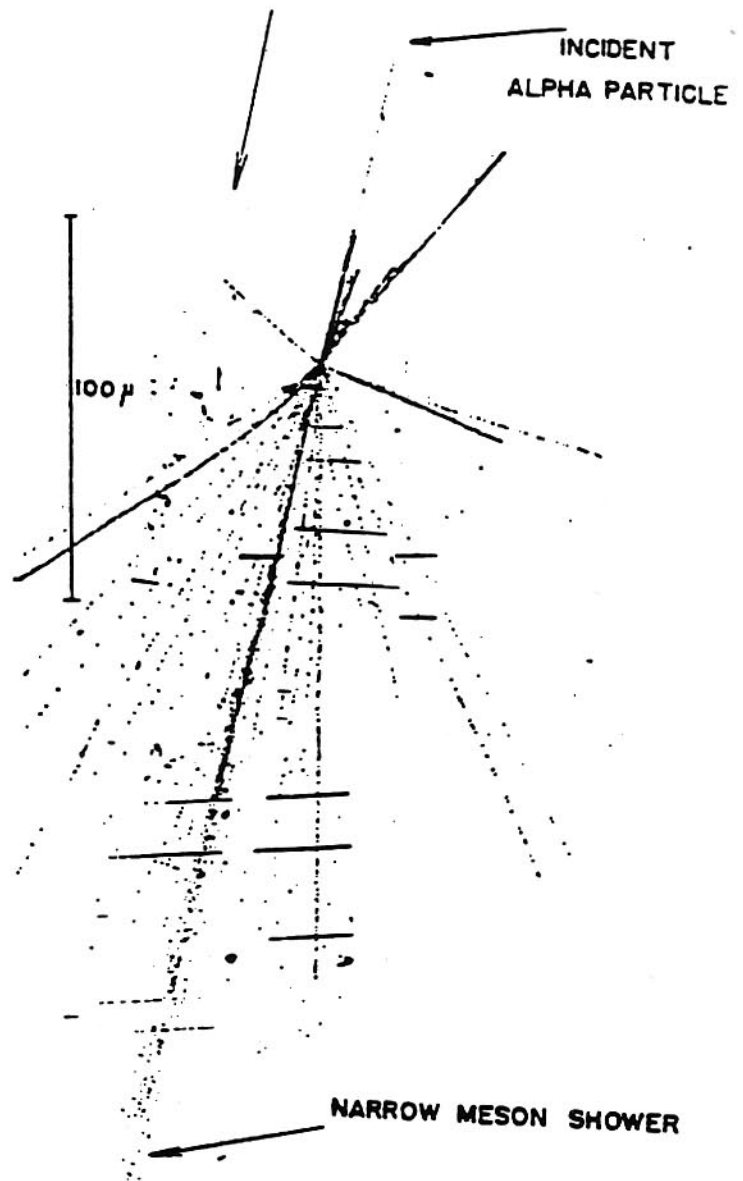
$N + N \rightarrow \text{hadron shower}$

The shower particles fly through the atmosphere towards Earth and sooner or later interact again with mean free path

$$\lambda = 60 \text{ g/cm}^2$$

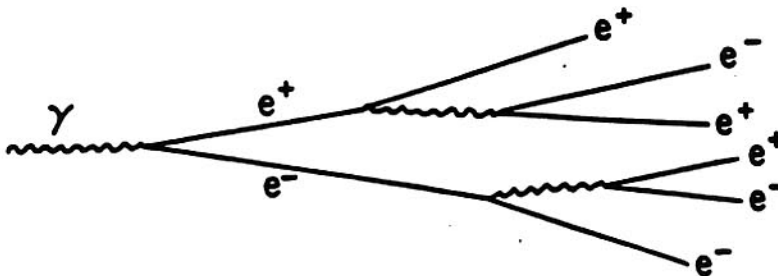
We get more and more hadrons of lower and lower energy. Thus a *hadronic cascade* is formed which is ultimately absorbed by the atmosphere. At sea level it is essentially gone.

This →

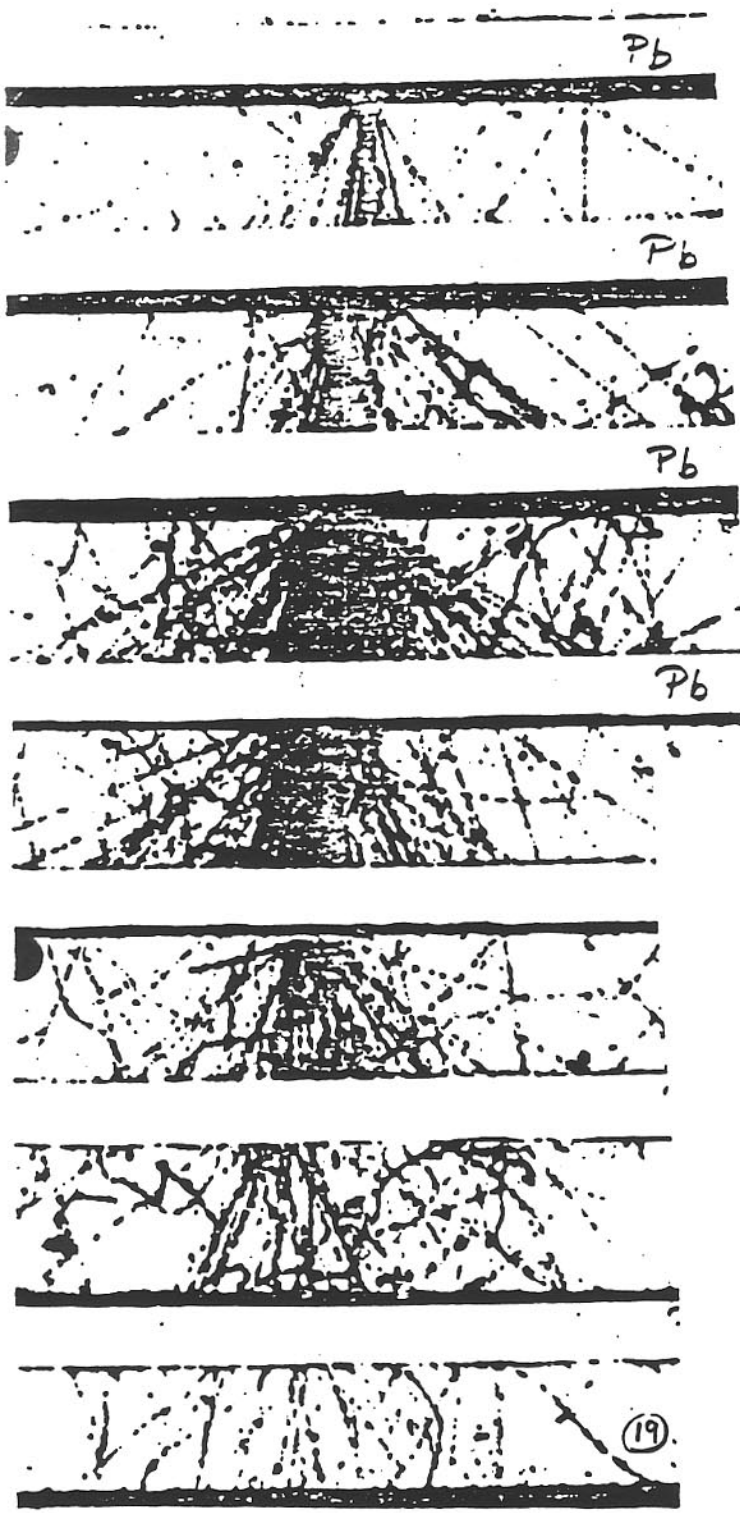


Then where do cosmic rays at sea level come from? We have neglected two processes:

- 1) $\pi^0 \rightarrow 2\gamma$ with lifetime $\tau = (.83 \pm 0.06) \times 10^{-16}$ sec, or $c\tau = 2.5 \times 10^{-8}$ meters

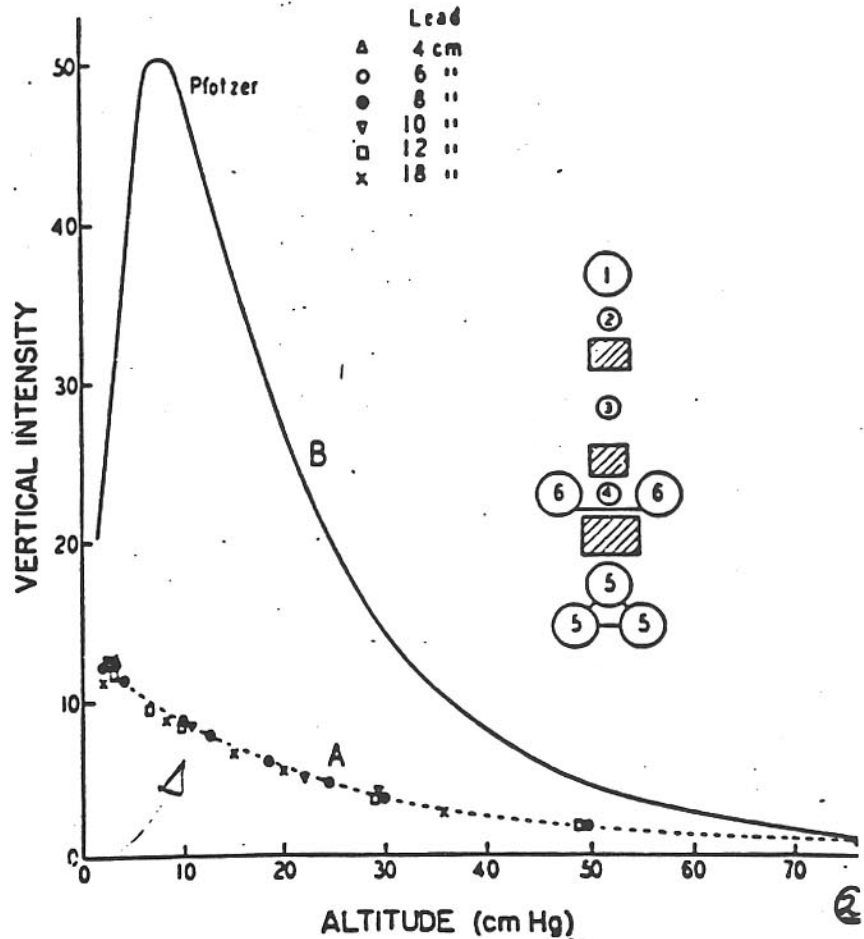


The photons interact and produce an *electromagnetic cascade air shower*.



The picture to the left shows an electromagnetic cascade in a cloud chamber with lead plates. Note the characteristic growth of the particles and subsequent decay as the energies of individual shower particles become exhausted. The same process goes on in the atmosphere.

At sea-level most of the air showers are gone—a few extensive air showers are left. Note the “hard” component, curve A.



2) While air showers contribute to the sea-level cosmic ray flux, there is a second important component.

$$\begin{array}{ll} \pi^+ \rightarrow \mu^+ + \nu_\mu & \text{The meanlife for charged pions} \\ \pi^- \rightarrow \mu^- + \bar{\nu}_\mu & \text{is } (2.603 \pm .002) \times 10^{-8} \text{ seconds.} \end{array}$$

Pions (and also kaons) can, as they penetrate the atmosphere, either decay or be destroyed in collision with air nuclei. While the charged pion lifetime is about 26 nanoseconds for pions at rest, we must take special relativity into account to determine the mean pathlength.

$$\begin{aligned} L_d &= \nu\gamma\tau = \beta\gamma c\tau & \beta &= v/c \\ E &= \gamma m_0 c^2 P = \gamma\beta m_0 c & \gamma &= \frac{1}{\sqrt{1-\beta^2}} \\ L_d &= \frac{P}{m_0 c} c\tau \end{aligned}$$

For pions, the mean free path for decay is therefore

$$\begin{aligned} L_d &= [P(\text{MeV}/c)/139.6(\text{MeV}/c^2)] \times 7.80 \text{ meters} \\ &\text{or } 5.6 \times P(\text{MeV}/c) \text{ cm} \end{aligned}$$

For a 20 GeV/c pion (2×10^4 MeV/c), $L = 1.12 \times 10^5$ cm = 1.12 km. The material in the atmosphere traversed in one decay mean free path is, correspondingly,

$$L_d = 1.12 \times 10^5 \times .0012 = 135 \text{ g/cm}^2 \text{ at sea level}$$

$$L_d \text{ (in cm)} = 135 \exp(-10/8.6) = 42 \text{ g/cm}^2 \text{ at 10 km height.}$$

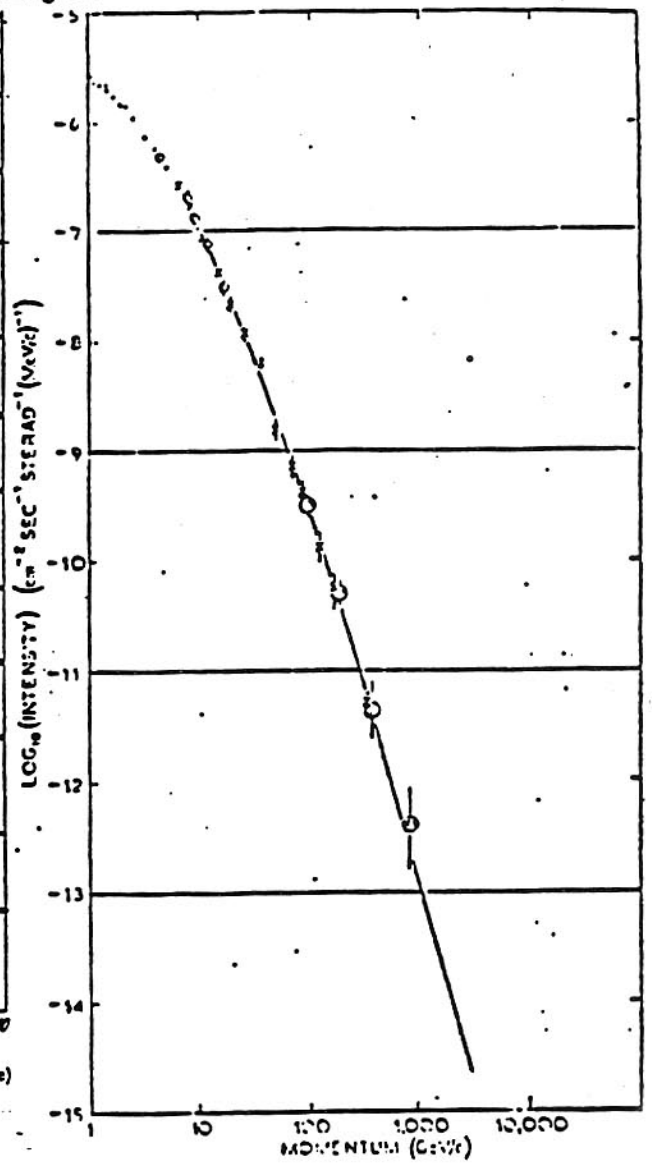
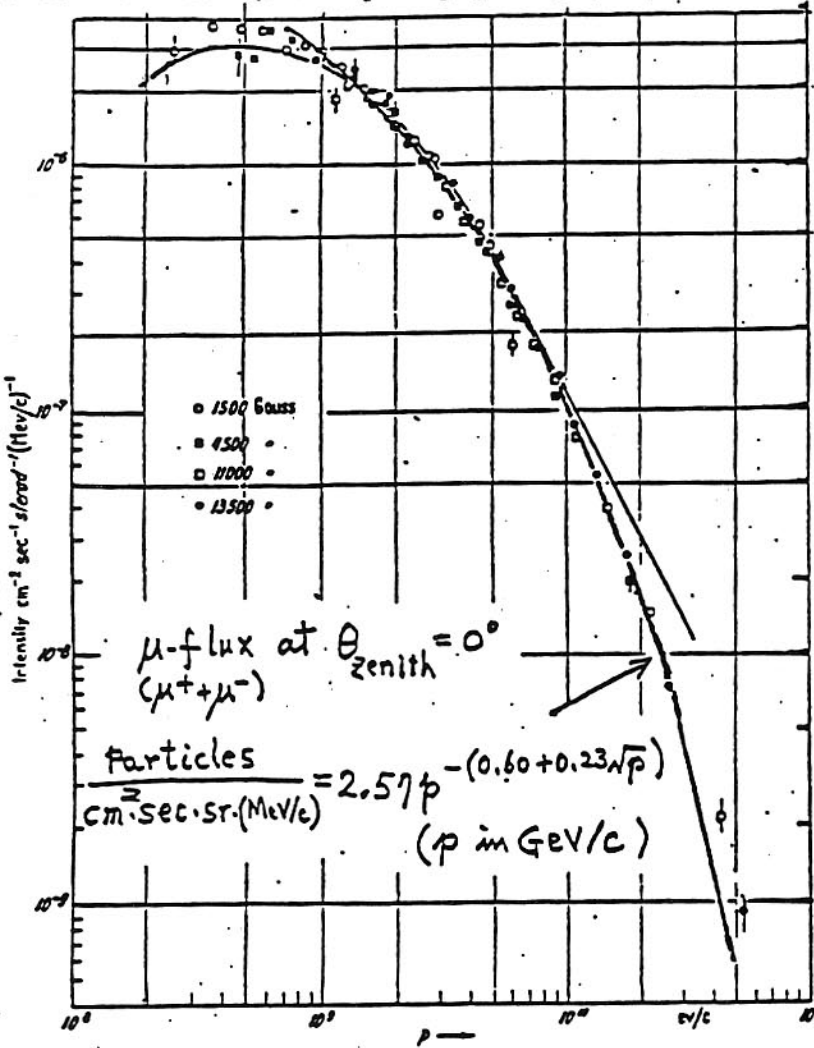
Therefore, near the top of the atmosphere where the air is thin many pions will decay before they collide with air nuclei. The decay muons are *leptons*: they have no nuclear interaction and hence continue towards Earth without further interaction. B. Rossi [1948: Reviews of Modern Physics] gives the following data:

| | Hard | Soft | Total |
|---|-----------------------|-----------------------|-----------------------|
| I_v ($\text{cm}^{-2} \text{ sec}^{-1} \text{ sterad}^{-1}$) | 0.83×10^{-2} | 0.31×10^{-2} | 1.14×10^{-2} |
| J_1 ($\text{cm}^{-2} \text{ sec}^{-1}$ vertical) | 1.27×10^{-2} | 0.52×10^{-2} | 1.79×10^{-2} |
| J_2 ($\text{cm}^{-2} \text{ sec}^{-1}$ all) | 1.68×10^{-2} | 0.73×10^{-2} | 2.41×10^{-2} |

Measurements by the Manchester group. These measurements have been extended and extended by a similar but larger instrument at Manchester (HYAMS OWEN and WILSON¹). The spectrograph employed counter recording for

(14)

Hand. der Physik Vol 46 C (1951)



A comparison of the sea level momentum spectra of Cano et al., see footnote 4, p. 274, (broken line) see footnote 2, p. 274, (full line). (21)

THE DIFFERENTIAL SPECTRUM OF μ -MESONS IN THE VERTICAL DIRECTION AT DURHAM (1950). (The spectrum is normalized to the intensity given by Row 22' (1949) at 1 GeV/c).

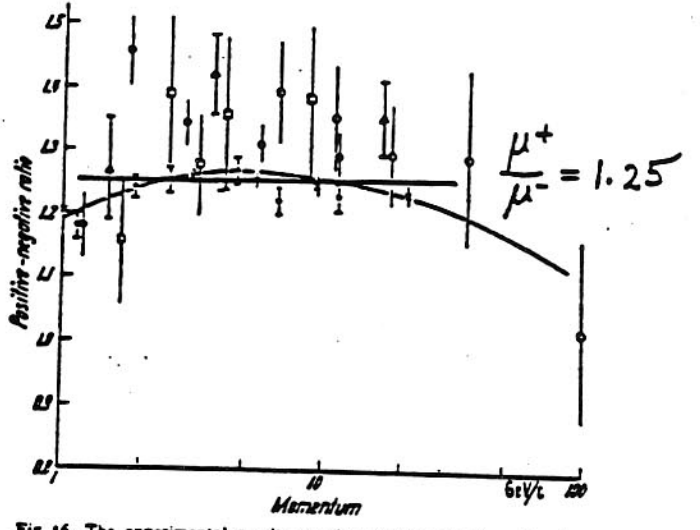
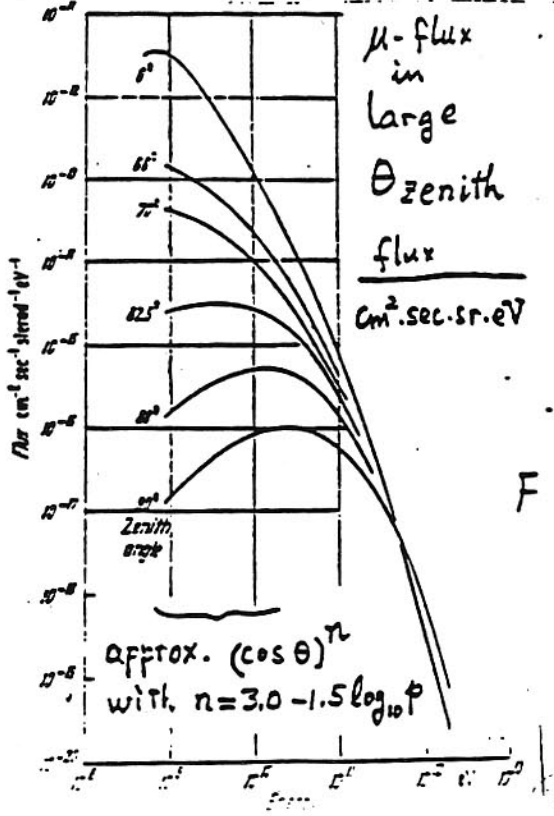


Fig. 16. The experimental results on the positive-negative ratio of μ -mesons at sea level. The curve represents an attempt to draw the best smooth curve through the experimental points. \circ ROGERS: cloud chamber arrangement (footnote 2, p. 279). \bullet ROGERS: counter hodoscope (same apparatus as OWEN and WILSON). \ominus OWEN and WILSON¹. \square HONEY and PARRY (footnote 1, p. 322). \times FILSORO et al. (footnote 3, p. 294). Δ CANO et al. (footnote 4, p. 274). (21)