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TECHNIQUES OF ASTRO-PARTICLE PHYSICS

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→ FROM A PARTICLE PHYSICIST'S VIEWPOINT ←

THE OPPORTUNITY: EXPLORE THE VAST RICHNESS OF PHENOMENA GENERATED IN NATURE'S ACCELERATORS — AS OBSERVED VIA INDIVIDUAL PARTICLES.

A RESTRICTION: WE DON'T CONTROL THE SOURCE.

BREAKTHROUGHS VIA ADVANCES IN OBSERVATIONAL TECHNIQUE.

PSYCHOLOGY: FAVORS THOSE WHO STAND IN AWE OF NATURE AS IT IS. CONTRAST: WILL OF H. MOSELEY, 1915

£2,200, to the Royal Society strictly "to be applied to the furtherance of experimental research in Pathology Physics Physiology Chemistry or other branches of science but not in pure mathematics astronomy or any branch of science which aims merely at describing cataloguing or systematizing."

KNOWLEDGE: - NATURE OF ELEMENTARY PARTICLES

- MECHANISM OF ASTROPHYSICAL SOURCES

THESE LECTURES:
1. CONTRIBUTIONS TO PARTICLE PHYSICS
2. COSMIC RAY PROTONS AND PHOTONS
3. SOLAR AND SUPERNOVA NEUTRINOS
4. DARK MATTER.

I. CONTRIBUTIONS TO PARTICLE PHYSICS

A. METEORITES

PRESCIENTIFIC EVIDENCE:

- BIBLE: JOSHUA 10:11, ACTS 19:35
- CHINESE ANNALS, 687 B.C.
- PLINY, NATURAL HISTORY 2 5,8, THRACE 467 B.C.
- SACRED STONE IN N.E CORNER OF KAABA IN MECCA.
- NOV. 7, 1492, ENSISHEIM, ALSACE. 100 KG METEORITE IS OLDEST EXTANT & DOCUMENTED.

SCIENTIFIC ERA:

- ~1790, FRENCH ACADÉMIE DES SCIÉNCE DECLARES THAT METEORITES ARE IMPOSSIBLE, DESPITE RURAL REPORTS.
- APRIL 26, 1803, SHOWER IN L'AIGLE, FRANCE INVESTIGATED BY BIOT, WHO GIVES ASTRO-PARTICLE PHYSICS OFFICIAL SANCTION!

B. DISCOVERY OF COSMIC RAYS

IN EARLY 1900'S VARIOUS PEOPLE NOTE RADIOACTIVE BACKGROUNDS ON SURFACE & UNDERGROUND.

V. HESS (1912) FOUND INCREASING IONIZATION WITH ALTITUDE IN BALLOON FLIGHTS (P. 3).

SKEPTIC R.A. MILLIKEN CONFIRMS AND EXTENDS THIS RESULT, 1923-25, AND COINS THE NAME 'COSMIC RAYS'.

THE ELECTRICAL CONDUCTIVITY OF THE ATMOSPHERE AND ITS CAUSES

BY

VICTOR F. HESS, PH. D.,
PROFESSOR OF EXPERIMENTAL PHYSICS IN THE
UNIVERSITY OF GRAZ (AUSTRIA)

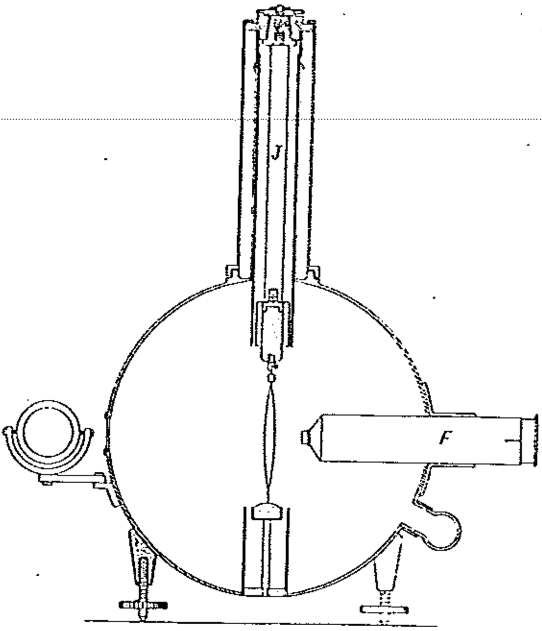

FIG. 9.—Wulf's radiation apparatus.

§ 23. The Penetrating Radiation in the Atmosphere.

1. Historical Introduction and Summary.[1]—In the year 1901 Elster and Geitel,[2] as well as C. T. R. Wilson,[3] showed that completely enclosed air is always feebly ionised, even after the radioactive substances originally present have long since disappeared. McLennan and Burton,[4] as well as Rutherford and Cooke,[5] found that the ionisation in closed vessels may be considerably reduced by surrounding them on all sides with as thick a layer as possible of a material which is itself free from radioactive impurities. A part of the ionisation, therefore, arises from some cause outside the vessel, some radiation which, like the γ-rays of radioactive substances, possesses the power of penetrating metal walls of not too great thickness ("*penetrating radiation*").

Experiments by McLennan,[6] Wulf,[7] Gockel and Wulf,[8] Wright,[9] and others have shown that the ionisation is smaller when the ionisation vessel is set up over water or ice instead of over dry land. It was, therefore, concluded that the penetrating radiation was due for the most part to the radioactive substances present in the ground. The view was held by some authors that the radium emanation and its decomposition products in the air, together with the radioactive deposits (radium A, etc.) on the earth's surface carried down by the normal electric field in the atmosphere, also contributed very considerably to the total effect; but this was contradicted by the results of experiment and calculation.

If the ground itself is the chief source of penetrating radiation, it is to be expected that this radiation will diminish rapidly as the height above the earth is increased. The earliest observations in towers actually did show a decrease, but a much smaller decrease than had been anticipated. The first balloon observations during an ascent by K. Bergwitz,[1] and on three ascents by A. Gockel,[2] were influenced by instrumental defects and yielded no quantitatively certain results. Gockel was, however, able to conclude that at heights up to 4,000 metres the total radiation is not appreciably different from that at the earth's surface. V. F. Hess [3] was the first to show, from ten balloon ascents with improved apparatus in the years 1911–12, that the penetrating radiation diminishes slightly up to 1,000 metres, but definitely increases again after 2,000 metres. From 3,000 metres upwards the increase becomes very great, and at heights of 5 km. the total ionisation in the vessel is already twice or three times as great as on the ground. *From these observations Hess concluded that there must exist a very penetrating radiation of extra-terrestrial origin which enters the atmosphere from above, and even at the earth's surface is responsible for part of the ionisation observed in the vessel.* W. Kolhörster [4] further improved the apparatus, and undertook five balloon ascents to still higher altitudes. Up to 5 km. the results of Hess were confirmed, and further rise to a height of 9 km. showed an enormous additional increase in the radiation. Later observations on mountains (Gockel, Kolhörster) also showed a definite increase in the radiation.

Although the existence of this new radiation has been

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[1] For complete bibliography, see W. Kolhörster, "Die durchdringende Strahlung in der Atmosphäre" (Hamburg: Verlag Henri Grand, 1924).

[2] *Phys. Zeitschr.*, 2, 116, 560, 590 (1900–1).

[3] *Proc. Camb. Phil. Soc.*, 11, 62 (1900); *Proc. Roy. Soc.*, A, 68, 151; 69, 277 (1901).

[4] *Phys. Zeitschr.*, 4, 553 (1902–3); *Phil. Mag.* (6), 6, 343; *Phys. Rev.*, 16, 184 (1903).

[5] *Phys. Rev.*, 16, 183 (1903).

[6] *Phys. Zeitschr.*, 9, 440 (1908).

[7] *Phys. Zeitschr.*, 10, 997 (1909).

[8] *Phys. Zeitschr.*, 9, 907 (1908).

[9] *Phil. Mag.* (6), 17, 295 (1909).

[1] *Habilit.-Schrift*, Brunswick, 1910.

[2] *Phys. Zeitschr.*, 11, 280 (1910); 12, 595 (1911).

[3] *Phys. Zeitschr.*, 12, 998 (1911); 13, 1084 (1912).

[4] *Phys. Zeitschr.*, 14 1066, 1153 (1913).

C. DISCOVERY OF THE POSITRON

IN AUG. 1932 C.D. ANDERSON FOUND A CLOUD CHAMBER TRACK OF A POSITIVE PARTICLE WHICH IONIZED LIKE AN ELECTRON. AN APPLIED MAGNETIC FIELD ALLOWED MEASUREMENT OF THE MOMENTUM VIA THE CURVATURE. WHEN THE PARTICLE TRAVERSED THE LEAD PLATE ITS ENERGY WAS REDUCED; THE OUTGOING SEGMENT HAS THE LOWER ENERGY. THUS THE UPWARD, POSITIVE TRACK WAS DISTINGUISHED FROM A DOWNWARD, NEGATIVE ELECTRON.

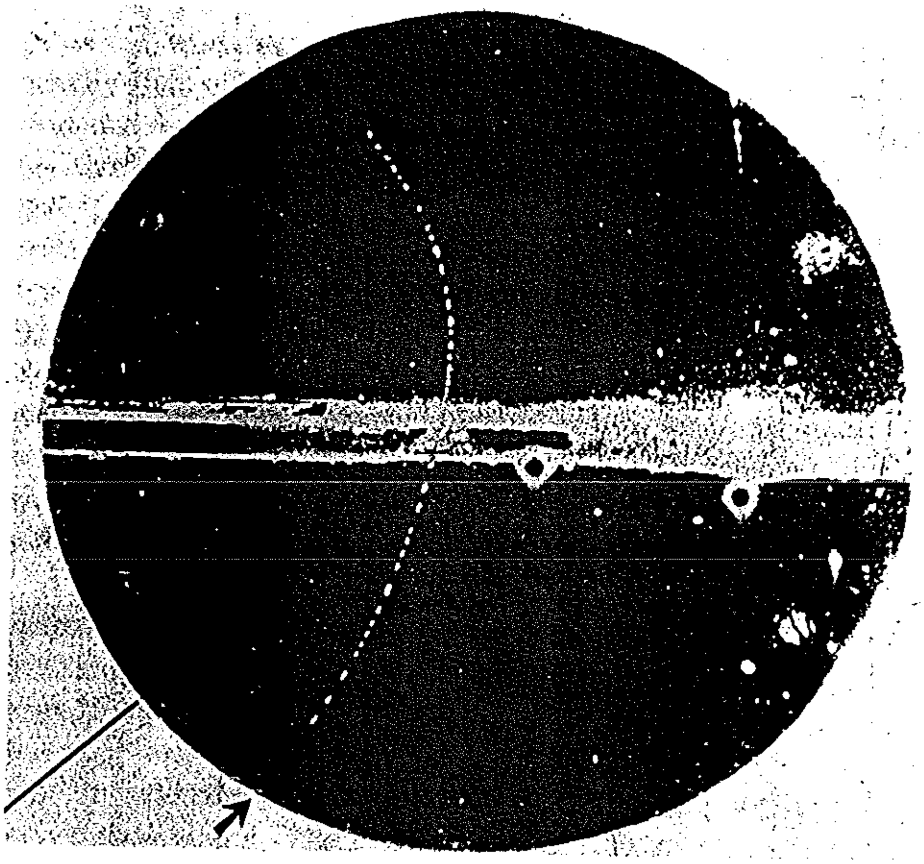

Fig. 6-3 The positron, or positive electron, was identified as the particle that entered the cloud chamber from below and produced the track curving sharply to the left after traversing the lead plate. The photograph, taken by Anderson in 1932, definitely established the existence of positrons. (From a paper in *The Physical Review*, vol. 43, p. 491, 1933.)

D. DISCOVERY OF THE μ-MESON

'WHO ORDERED THAT?'
- I.I. RABI
(1898-1988)

Ask, for example, when the muon, the main constituent of sea-level cosmic radiation, was discovered, and you will receive a jumble of answers. According to Gilberto Bernardini, "the mu meson as a peculiar ionizing fraction of the bulk of cosmic rays was revealed by an experiment by Bothe and Kolhörster in 1929.② John Wheeler considered that the theoretical work of Niels Bohr and E. J. Williams, together with the experimental work of Carl D. Anderson and Seth Neddermeyer, "established the existence of the meson" in 1936.③ By contrast, Bruno Rossi spoke of "the discovery of the μ mesons in 1937" by Anderson and Neddermeyer and by Jabez Curry Street and Edward C. Stevenson.④ Street himself credited John F. Carlson and J. Robert Oppenheimer in 1937 as first arguing for the necessity of the existence of a new particle of mass intermediate between that of the proton and the electron.⑤ Finally, Abraham Pais began an article on the birth of particle physics by stating that Cecil F. Powell discovered the mu meson in 1947.⑥ 8

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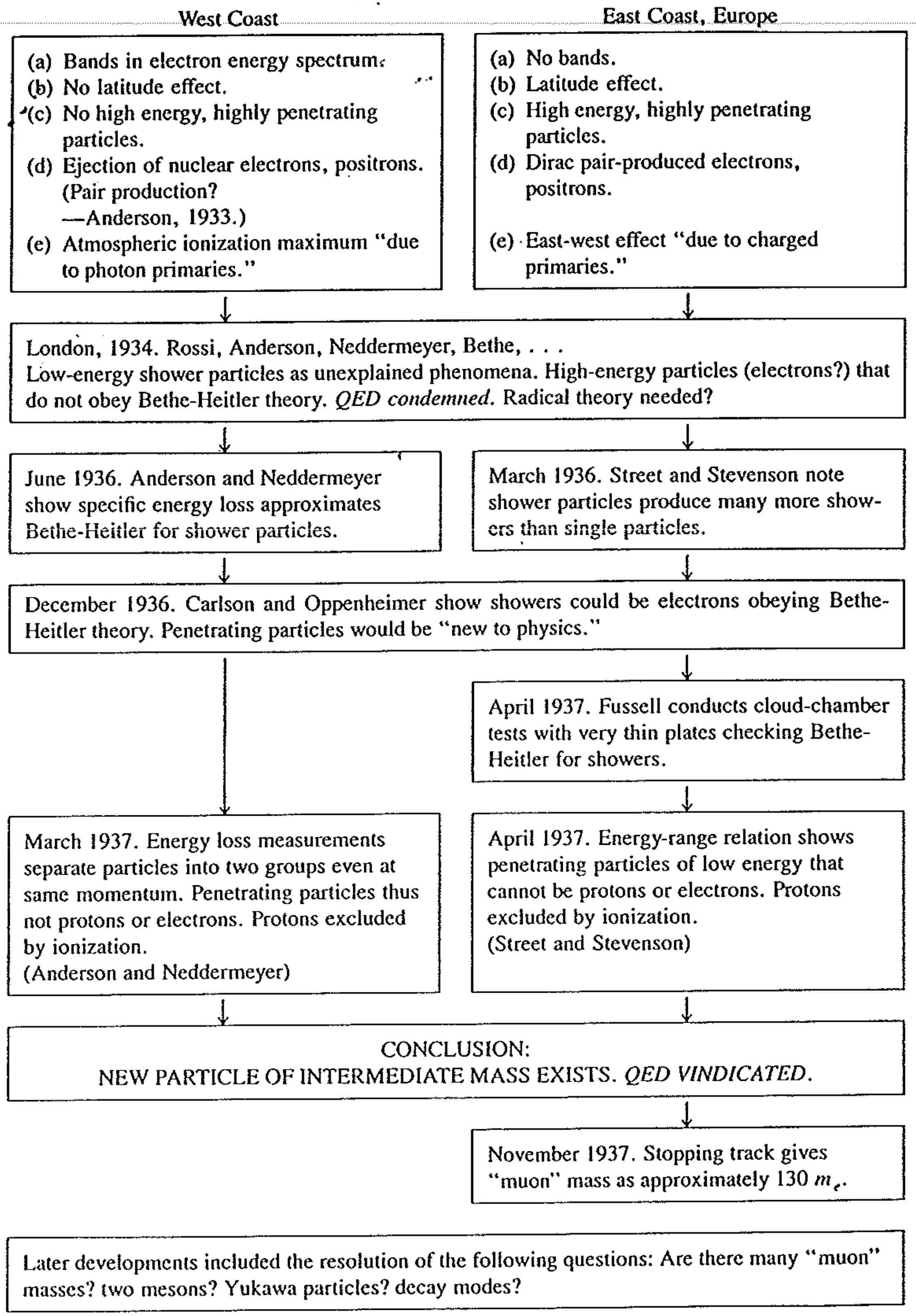


West Coast

(a) Bands in electron energy spectrum.
(b) No latitude effect.
(c) No high energy, highly penetrating particles.
(d) Ejection of nuclear electrons, positrons. (Pair production? —Anderson, 1933.)
(e) Atmospheric ionization maximum "due to photon primaries."

East Coast, Europe

(a) No bands.
(b) Latitude effect.
(c) High energy, highly penetrating particles.
(d) Dirac pair-produced electrons, positrons.
(e) East-west effect "due to charged primaries."

London, 1934. Rossi, Anderson, Neddermeyer, Bethe, . . . Low-energy shower particles as unexplained phenomena. High-energy particles (electrons?) that do not obey Bethe-Heitler theory. *QED condemned.* Radical theory needed?

June 1936. Anderson and Neddermeyer show specific energy loss approximates Bethe-Heitler for shower particles.

March 1936. Street and Stevenson note shower particles produce many more showers than single particles.

December 1936. Carlson and Oppenheimer show showers could be electrons obeying Bethe-Heitler theory. Penetrating particles would be "new to physics."

April 1937. Fussell conducts cloud-chamber tests with very thin plates checking Bethe-Heitler for showers.

March 1937. Energy loss measurements separate particles into two groups even at same momentum. Penetrating particles thus not protons or electrons. Protons excluded by ionization. (Anderson and Neddermeyer)

April 1937. Energy-range relation shows penetrating particles of low energy that cannot be protons or electrons. Protons excluded by ionization. (Street and Stevenson)

CONCLUSION:
NEW PARTICLE OF INTERMEDIATE MASS EXISTS. *QED VINDICATED.*

November 1937. Stopping track gives "muon" mass as approximately 130 m_e.

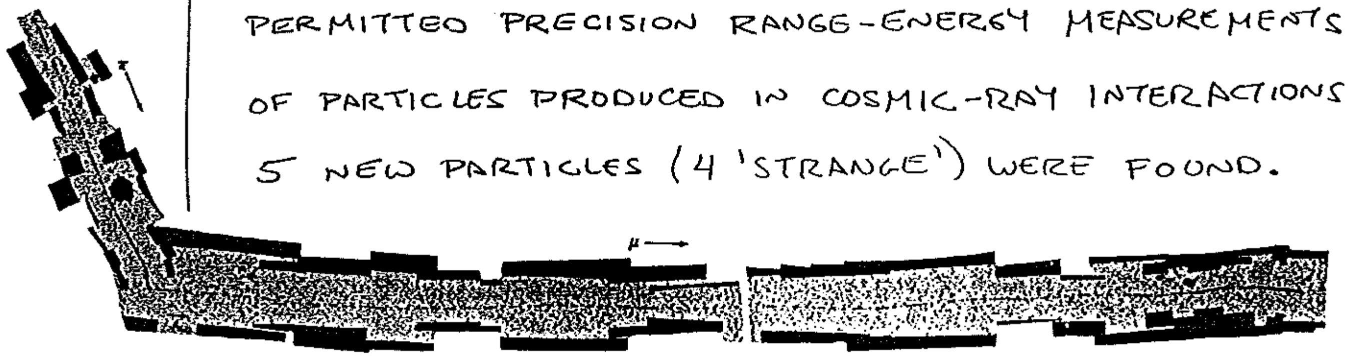
Later developments included the resolution of the following questions: Are there many "muon" masses? two mesons? Yukawa particles? decay modes?

FIGURE 3.16. Summary of East and West Coast discovery of muon.

FROM P. GALISON, 'HOW EXPERIMENTS END', (U. OF CHICAGO, 1987)

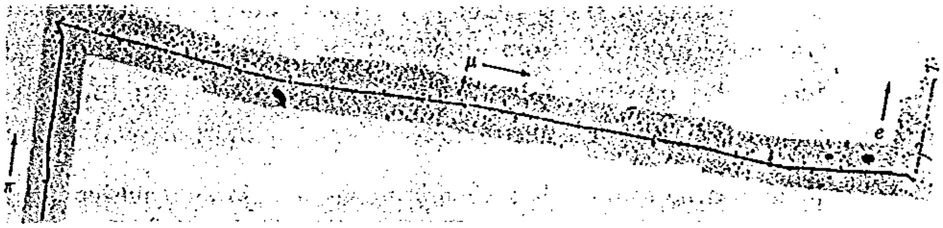
E. DISCOVERY OF THE π & K MESONS, Λ, Σ & Ξ HYPERONS

IN 1947-53 THE USE OF NUCLEAR EMULSIONS PERMITTED PRECISION RANGE-ENERGY MEASUREMENTS OF PARTICLES PRODUCED IN COSMIC-RAY INTERACTIONS. 5 NEW PARTICLES (4 'STRANGE') WERE FOUND.

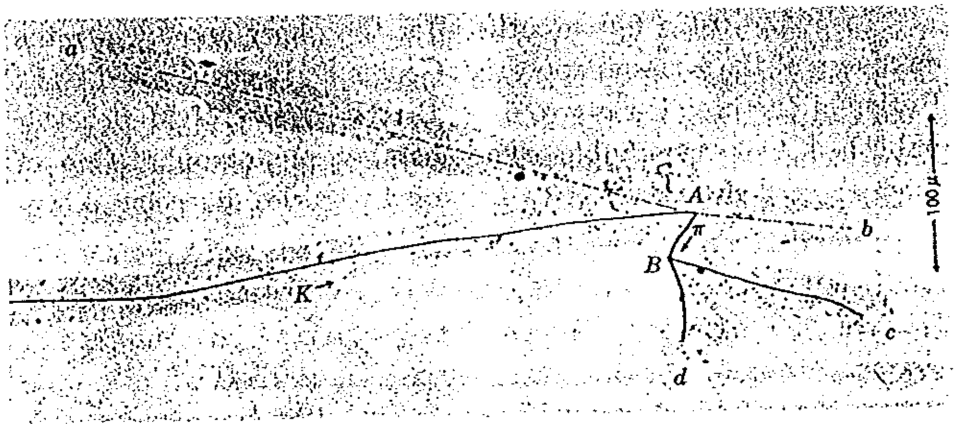


4 **Fig. 9-3** Photomicrograph showing a π meson (π) coming to rest in a nuclear emulsion and a μ meson (μ) arising from the end of the π-meson track. (From C. M. G. Lattes, H. Muirhead, G. Occhialini, and C. F. Powell, *Nature*, vol. 160, p. 453, 1947.)

THE NUCLEAR-EMULSION METHOD HAS THE RESOLUTION TO DETECT THE PRODUCTION & DECAY OF 'CHARM' AND 'BOTTOM' MESONS - BUT THE PRODUCTION RATES ARE TOO LOW FOR COSMIC RAY STUDIES ...



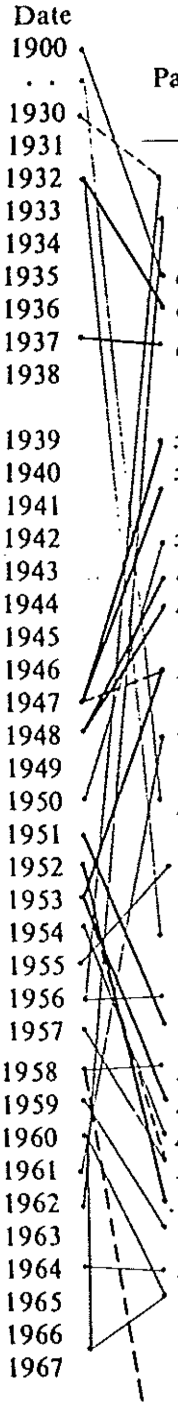
5 **Fig. 9-4** Photomicrograph of tracks in a nuclear emulsion, showing a π meson (π) that comes to rest and decays into a μ meson (μ). The μ meson in turn comes to rest and decays into an electron (e). (From R. H. Brown, U. Camerini, P. Fowler, H. Muirhead, C. F. Powell, and D. M. Ritson, *Nature*, vol. 163, p. 47, 1949.)



6 **Fig. 10-7** Decay of a heavy meson into three π mesons, observed by Powell's group at the University of Bristol in 1949. The heavy meson K comes to rest at A. There it decays into two fast π mesons (tracks a and b) and a slow negative π meson, which comes to rest at B. The negative π meson is captured by a nucleus, which explodes, ejecting two heavily ionizing fragments (c and d) and, presumably, one or more neutrons, which leave no visible track. (From R. Brown, U. Camerini, P. H. Fowler, H. Muirhead, C. F. Powell, and D. M. Ritson, *Nature*, vol. 163, p. 82, 1949.)

TABLE 3.2. THE DISCOVERY OF THE ELEMENTARY PARTICLES

This table, an expansion of one given by Powell, Fowler and Perkins (1959), shows how and when the relatively stable elementary particles were discovered (antiparticles being included somewhat arbitrarily). The heavy lines show the discoveries made using cosmic rays. The particles are listed in order of increasing mass, except within charge multiplets.



Particle	Source of radiation	Instrument used	Specific observation made
$\bar{\nu}_e(\nu_e)$	nuclear reactor	liquid scintillator	Capture by proton
ν_μ	accelerator	spark chamber	Production of μ and not e
e^-	discharge tube	fluorescent screen	Ratio e/m
e^+	cosmic rays	cloud chamber	Charge, mass
μ^+, μ^-	cosmic rays	cloud chamber	Absence of radiation loss in Pb; decay at rest; mass
π^+	cosmic rays	nuclear emulsion	$\pi-\mu$ decay at rest
π^-	cosmic rays	nuclear emulsion	Nuclear interaction at rest
π^0	accelerator	counters	Decay into γ-rays
K^+	cosmic rays	nuclear emulsion	$K_{\pi 3}$ decay
K^-	cosmic rays	nuclear emulsion	Nuclear interaction at rest
K^0	cosmic rays	cloud chamber	Decay into $\pi^+\pi^-$ in flight
η	accelerator	bubble chamber	Total mass of decay products
p	discharge tube	spectroscopes; mass spectrometers	Charges and masses of ions
$\bar{p}$	accelerator	Cerenkov counter	e/m measured; annihilation
n	radioactivity	ionization chamber	Mass from elastic collisions
$\bar{n}$	accelerator	counters	Annihilation
Λ	cosmic rays	cloud chamber	Decay to $p\pi^-$ in flight
$\bar{\Lambda}$	accelerator	nuclear emulsion	Decay to $\bar{p}\pi^+$ in flight
Σ^+	cosmic rays	nuclear emulsion	Decay at rest
Σ^-	accelerator	diffusion chamber	Decay to $n\pi^-$ in flight
Σ^0	accelerator	bubble chamber	Decay to $\Lambda\gamma$ in flight
Ξ^-	cosmic rays	cloud chamber	Decay to $\Lambda\pi^-$ in flight
Ξ^0	accelerator	bubble chamber	Decay to $\Lambda\pi^0$ in flight
Ω^-	accelerator	bubble chamber	Decay to $\Xi^0\pi^-$ in flight
Very many "resonance" particles with lifetimes $\sim 10^{-23}$ to 10^{-19} s	accelerator	bubble chambers	Total mass of decay products
?"Fireballs"	cosmic rays	nuclear emulsion	Angles of meson emission
Quarks?	not found with accelerators; being sought in cosmic rays		Charge $\frac{1}{3}$ or $\frac{2}{3}e$

F. DISCOVERY OF HYPERNUCLEI

IF A K^- MESON IS ABSORBED BY A NUCLEUS IT IS POSSIBLE THAT A BOUND Λ^0 HYPERON IS FORMED. THE Λ MAY REMAIN INSIDE THE 'HYPERNUCLEUS' UNTIL IT DECAYS.

$$\underset{f}{\underset{\shortparallel}{B_\Lambda}} \to \underset{1}{\underset{\shortparallel}{B_e}} + \underbrace{\underset{2}{\underset{\shortparallel}{p}} + \underset{3}{\underset{\shortparallel}{\pi^-}}}_{\Lambda^0 \to p\pi^-}$$

SPECULATIONS EXIST [WITTEN, PHYS. REV. D $\underline{30}$, 272 (1984)] THAT STARS MAY BE IN A STABLE STATE OF STRANGE NUCLEAR MATTER, SOMEWHAT ANALAGOUS TO A NEUTRON STAR.

Delayed disintegration of a nucleus at the end of its range

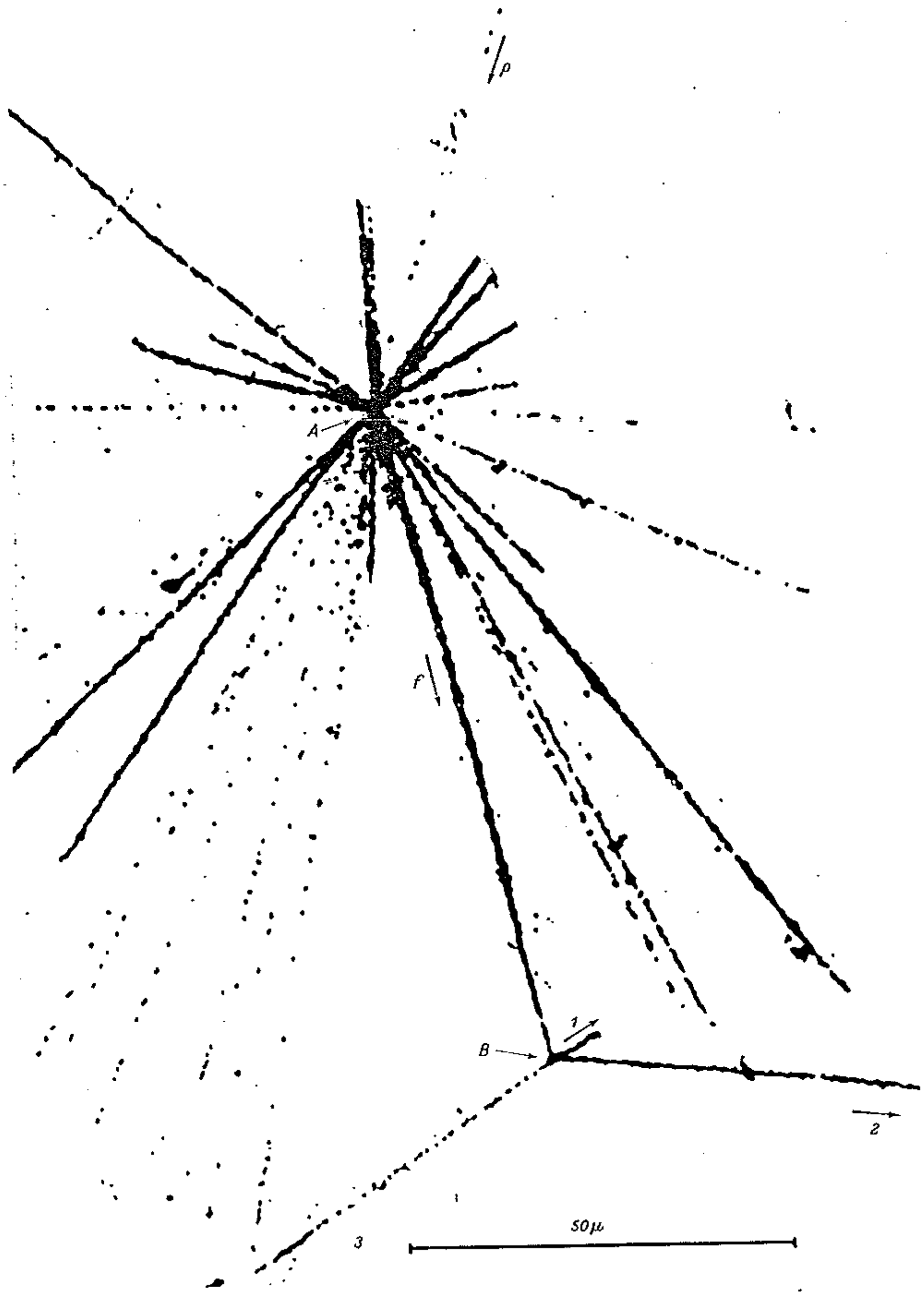


PLATE 11–10

Ilford G5 emulsion.

DANYSZ and PNIEWSKI (1953).

7 First observation of the 'delayed' disintegration of a nucleus. A nuclear fragment, *f*, of charge $\sim 5e$, reaches the end of its range at *B* and disintegrates with the emission of three fast charged particles. It is possible that the track (3) is due to a π-meson. If so, the total release of kinetic energy in the disintegration is about 40 MeV, in good accord with the assumption of a Λ^0-particle as a component of the nuclear fragment.

II. PARTICLE INTERACTIONS IN DETECTORS

ALTHOUGH A PARTICLE EVENT OF INTEREST MAY BE DUE TO A STRONG OR WEAK INTERACTION, THE DETECTABLE ENERGY TRANSFER IS DUE TO THE ELECTROMAGNETIC INTERACTION OF THE PRIMARY OR SECONDARY PARTICLES.

THE INITIAL UNDERSTANDING OF PARTICLE INTERACTIONS ABOVE A FEW MeV ENERGY WAS DUE TO COSMIC-RAY STUDIES IN THE 1930'S. STILL THE BEST SUMMARY OF BASIC PHYSICS OF DETECTION: B. ROSSI, 'HIGH-ENERGY PARTICLES', (PRENTICE-HALL, 1952).

A HIGHLY USEFUL SUMMARY OF FACTS ABOUT ELEMENTARY PARTICLES AND DETECTORS IS AVAILABLE IN LONG AND SHORT FORM:

'REVIEW OF PARTICLE PROPERTIES'
'PARTICLE PROPERTIES DATA BOOKLET'

WRITE TO: TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
BERKELEY, CA 94720 USA

OR CERN SCIENTIFIC INFORMATION SERVICE
CH-1211 GENEVA 23, SWITZERLAND

A. ELECTROMAGNETIC INTERACTIONS

1. THE BASIC APPROXIMATION IS THAT A RELATIVISTIC ($\gamma = E/M > 2$) CHARGED PARTICLE LOSES ABOUT $2 z^2$ MeV PER GRAM OF MATERIAL TRAVERSED (STRICTLY: PER GRAM/cm^2) THE ENERGY LOSS IS TO ATOMIC ELECTRONS, MANY OF WHICH ARE IONIZED, SO THE PHRASE 'MINIMUM IONIZING PARTICLE' IS USED.

THE DETAILS ARE MORE COMPLICATED:

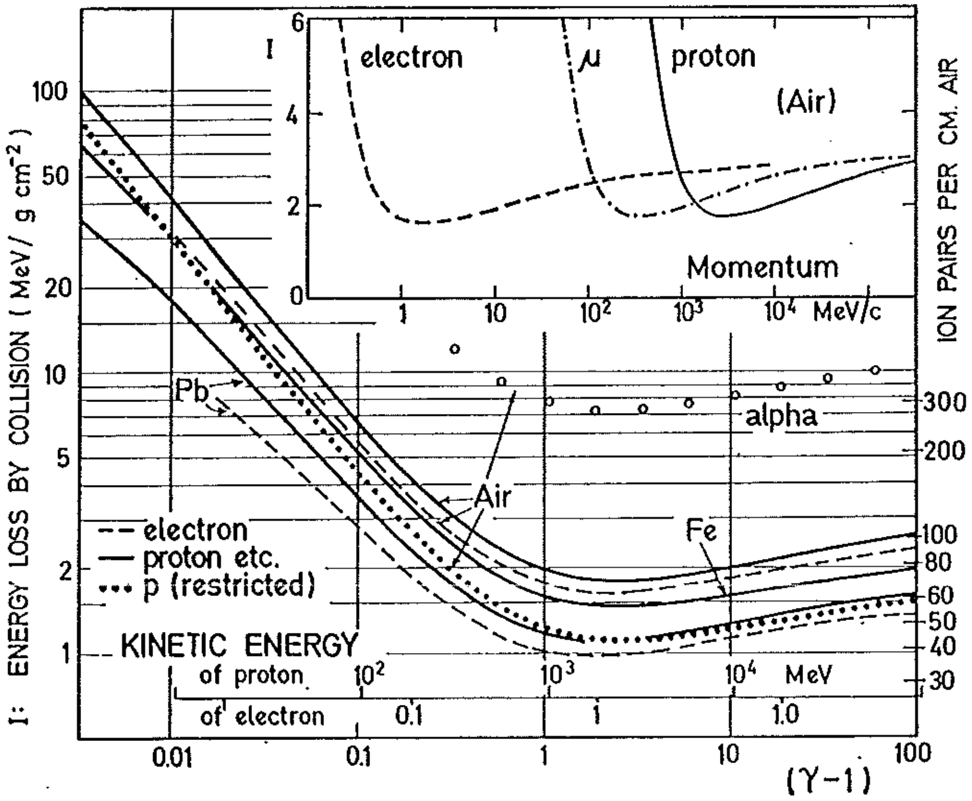


FIG. 8. Rate of loss of energy by ionization in various materials. ($\gamma - 1$) is the ratio of kinetic energy to rest energy: actual kinetic energies are also given for protons and electrons. Inset shows energy loss (in air) as function of momentum, which is often measurable.

THE COMPLICATIONS ALLOW PARTICLE IDENTIFICATION:

MEASURE THE TOTAL ENERGY (VIA TOTAL IONIZATION (IF THE PARTICLE STOPS) OR MOMENTUM (VIA DEFLECTION IN A MAGNET)), AS WELL AS THE IONIZATION LOSS, dE/dx. OR, MEASURE THE TOTAL RANGE IN GRAMS. THEN COMPARE WITH GRAPHS →

THE MASSES OF THE POSITRON, μ- AND π-MESONS WERE FIRST DETERMINED BY THIS TECHNIQUE.

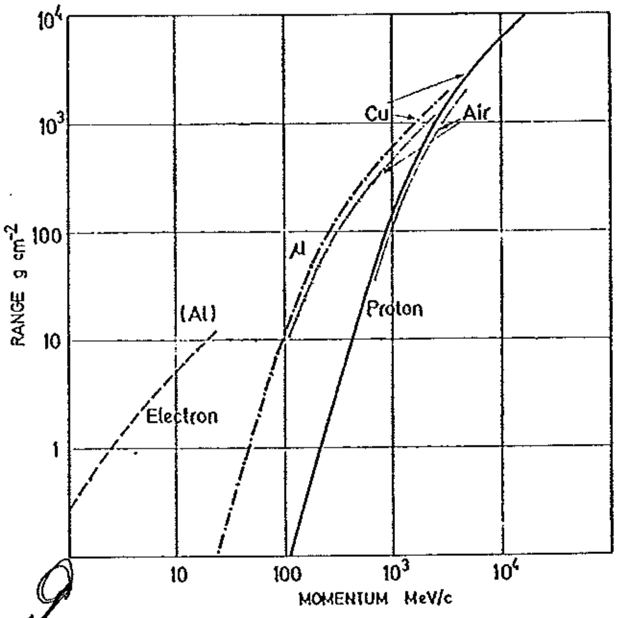


FIG. 9. Range of particles as function of energy.

THE SENSITIVITY OF A DETECTOR TO THE dE/dx LOSS DEPENDS ON THE DETECTION MECHANISM:

IONIZATION DETECTORS COLLECT THE ELECTRONS (AND + IONS)

MATERIAL	ENERGY DEPOSITION PER ION PAIR
ARGON	$\sim 100\,eV$ BUT ~ 2 ADDITIONAL SECONDARIES PER PRIMARY ION PAIR
SILICON	$3.6\,eV$ PER ELECTRON-HOLE PAIR
GERMANIUM	$3.0\,eV$
SUPERCONDUCTOR	$\sim 10^{-3}\,eV$ TO BREAK UP A COOPER PAIR

SCINTILLATION DETECTORS COLLECT LIGHT FROM ION RECOMBINATION.

MATERIAL	ENERGY DEPOSITION PER OPTICAL PHOTON
AIR	$\sim 50\,KeV$ - ULTRAVIOLET LIGHT ONLY
PLASTIC SCINTILLATOR	$\sim 100\,eV$
NaI	$25\,eV$

NUCLEAR EMULSION - $\sim 200\,eV$ PER $1\,\mu m$ GRAIN $\Rightarrow$ SENSITIVE TO MINIMUM IONIZATION ONLY IF δ-RAY FLUCTUATIONS OCCUR.

EXAMPLE: IN A SILICON CCD ARRAY THE ACTIVE DEPTH OF DEPLETED Si IS ABOUT $20\,\mu m$ THICK.

$\rho_{Si} = 2.3\ gm/cm^3 \Rightarrow$ THICKNESS $= 4.6 \times 10^{-3}\ gm/cm^2$

$dE/dx|_{MIN} = 1.7\ MeV/(gm/cm^2) \Rightarrow 7.8\ KeV$ DEPOSITED

$\Longrightarrow$ 2200 ION PAIRS PER MINIMUM IONIZING PARTICLE.

2. FOR <u>RELATIVISTIC ELECTRONS</u> A MAJOR FORM OF ENERGY LOSS IS BREMSSTRAHLUNG IN THE FIELD OF A NUCLEUS. THIS LEADS TO THE ELECTROMAGNETIC CASCADE SHOWERS DISCOVERED IN CLOUD CHAMBERS IN THE 1930'S.

THE THIRD IMPORTANT PARAMETER OF MATERIALS IS THE RADIATION LENGTH, X_0, WHICH IS THE DISTANCE OVER WHICH AN ELECTRON RADIATES $2/3$ (ACTUALLY $1-1/e$) OF ITS ENERGY. FOR ELECTRON ENERGIES ABOVE $\sim 100\,\mathrm{MeV}$, X_0 IS ESSENTIALLY CONSTANT, AND VARIES WITH NUCLEAR CHARGE AS $X_0 \sim \dfrac{120\ \mathrm{gm/cm^2}}{Z^{2/3}}$. EXAMPLE: $X_0(\mathrm{AIR}) = 37\ \mathrm{gm/cm^2}$.

3. <u>PHOTONS</u> OF ENERGY GREATER THAN A FEW MeV INTERACT WITH MATTER PRIMARILY VI PAIR PRODUCTION $\rightarrow e^+e^-$

AGAIN, THE RADIATION LENGTH SETS THE SCALE OF THE INTERACTION DEPTH. (STRICTLY, $7/9\ X_0$)

IN A CASCADE WE HAVE

$$\begin{array}{l} e \rightarrow e\,\gamma \\ \qquad\ \ \hookrightarrow e^+e^- \\ \qquad\qquad \hookrightarrow e\gamma \ \ldots\ldots \end{array}$$

IN EACH GENERATION OF THE CASCADE THE NUMBER OF ELECTRONS DOUBLES. THE CASCADE DIES OUT WHEN THE ELECTRONS LOSE THEIR ENERGY VIA IONIZATION.

EXAMPLE: IN LEAD $dE/dx = 1.1\ \mathrm{MeV/gm}$, $X_0 = 6.4\ \mathrm{gm}$.

IN ONE GENERATION AN ELECTRON TRAVELS $\sim 2X_0 = 13\ \mathrm{gm} \Rightarrow 14\ \mathrm{MeV}$.

THE TOTAL NUMBER OF GENERATIONS, N, IS THEN RELATED BY

$$E_0 = (14\ \mathrm{MeV})\cdot 2^N \quad\Rightarrow\quad N \sim 1.4\ \ln\left(E_0/14\ \mathrm{MeV}\right)$$

ATOMIC AND NUCLEAR PROPERTIES OF MATERIALS*

Material	Z	A	Nuclear[a] total cross section σ_T [barn]	Nuclear[b] inelastic cross section σ_I [barn]	Nuclear[c] collision length λ_T [g/cm^2]	Nuclear[c] interaction length λ_I [g/cm^2]	dE/dx min[d] $\overline{\Delta E}$ $\left[\frac{\text{MeV}}{\text{g/cm}^2}\right]$	dE/dx min[d] ΔE_{mp}, 1 cm [MeV] () is for gas [keV]	Radiation length[e] L_{rad} [g/cm^2]	Radiation length[e] L_{rad} [cm] () is for gas	Density[f] [g/cm^3] () is for gas [g/ℓ]	Refractive index n[f] () is $(n-1)\times10^6$ for gas
H_2	1	1.01	0.0387	0.033	43.3	50.8	4.12	(0.19)	61.28	865	0.0708(0.090)	1.112(140)
D_2	1	2.01	0.073	0.061	45.7	54.7	2.07	(0.17)	122.6	757	0.162(0.177)	1.128
He	2	4.00	0.133	0.102	49.9	65.1	1.94	(0.16)	94.32	755	0.125(0.178)	1.024(35)
Li	3	6.94	0.211	0.157	54.6	73.4	1.58	0.70	82.76	155	0.534	—
Be	4	9.01	0.268	0.199	55.8	75.2	1.61	2.61	65.19	35.3	1.848	—
C	6	12.01	0.331	0.231	60.2	86.3	1.78	3.57	42.70	18.8	2.265[g]	—
N_2	7	14.01	0.379	0.265	61.4	87.8	1.82	(0.93)	37.99	47.0	0.808(1.25)	1.205(300)
O_2	8	16.00	0.420	0.292	63.2	91.0	1.82	(1.31)	34.24	30.0	1.14(1.43)	1.22(266)
Ne	10	20.18	0.507	0.347	66.1	96.6	1.73	(0.75)	28.94	24.0	1.207(0.90)	1.092(67)
Al	13	26.98	0.634	0.421	70.6	106.4	1.62	3.81	24.01	8.9	2.70	—
Si	14	28.09	0.660	0.440	70.6	106.0	1.66	3.36	21.82	9.36	2.33	—
Ar	18	39.95	0.868	0.566	76.4	117.2	1.51	(1.30)	19.55	14.0	1.40(1.78)	1.233(283)
Fe	26	55.85	1.120	0.703	82.8	131.9	1.48	10.7	13.84	1.76	7.87	—
Cu	29	63.54	1.232	0.782	85.6	134.9	1.44	11.85	12.86	1.43	8.96	—
Sn	50	118.69	1.967	1.21	100.2	163	1.26	8.3	8.82	1.21	7.31	—
Xe	54	131.30	2.120	1.29	102.8	169	1.24	(3.57)	8.48	2.77	3.057(5.89)	(705)
W	74	183.85	2.767	1.65	110.3	185	1.16	21.1	6.76	0.35	19.3	—
Pb	82	207.19	2.960	1.77	116.2	194	1.13	11.7	6.37	0.56	11.35	—
U	92	238.03	3.378	1.98	117.0	199	1.09	19.3	6.00	≈0.32	≈18.95	—
Air, 20°C, 1 atm. (STP in paren.)					62.0	90.0	1.82	(1.12)	36.66	(30420)	0.001205(1.29)	1.000273(293)
H_2O					60.1	84.9	2.03	1.72	36.08	36.1	1.00	1.33
Shielding concrete[h]					67.4	99.9	1.70	3.68	26.7	10.7	2.5	—
SiO_2 (quartz)					67.0	99.2	1.72	3.28	27.05	12.3	2.64	1.458
H_2 (bubble chamber 26°K)					43.3	50.8	4.12	0.20	61.28	≈1000	≈0.063[i]	1.100
D_2 (bubble chamber 31°K)					45.7	54.7	2.07	0.22	122.6	≈900	≈0.140[i]	1.110
H-Ne mixture (50 mole percent)[j]					65.0	94.5	1.84	0.59	29.70	73.0	0.407	1.092
Ilford emulsion G5					82.0	134	1.44	4.79	11.0	2.89	3.815	—
NaI					94.8	152	1.32	4.13	9.49	2.59	3.67	1.775
BaF_2					92.1	146	1.35	5.72	9.91	2.05	4.89	1.56
BGO ($Bi_4Ge_3O_{12}$)					97.4	156	1.27	8.07	7.98	1.12	7.1	2.15
Polystyrene, scintillator (CH)[k]					58.4	82.0	1.95	1.72	43.8	42.4	1.032	1.581
Lucite, Plexiglas ($C_5H_8O_2$)					59.2	83.6	1.95	1.98	40.55	≈34.4	1.16–1.20	≈1.49
Polyethylene (CH_2)					56.9	78.8	2.09	1.68	44.8	≈47.9	0.92–0.95	—
Mylar ($C_5H_4O_2$)					60.2	85.7	1.86	2.24	39.95	28.7	1.39	—
Borosilicate glass (Pyrex)[ℓ]					66.2	97.6	1.72	3.32	28.3	12.7	2.23	1.474
CO_2					62.4	90.5	1.82	(1.92)	36.2	(18310)	(1.977)	(410)
Methane CH_4					54.7	74.0	2.41	(0.91)	46.5	(64850)	0.423(0.717)	(444)
Isobutane C_4H_{10}					56.3	77.4	2.22	(3.43)	45.2	(16930)	(2.67)	(1270)
Freon 12 (CCl_2F_2) gas, 26°C, 1 atm.[m]					70.6	106	1.62	4.49	23.7	4810	(4.93)	1.001080
Silica Aerogel[n]					65.5	95.7	1.83	0.28	29.85	≈150	0.1-0.3	$1.0+0.25\rho$
G10 plate[o]					62.6	90.2	1.87	2.7	33.0	19.4	1.7	—

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* Table revised April 1986 by W. Carithers. σ_T, σ_I, λ_T, and λ_I are energy dependent. Values quoted apply to high energy range given in footnote *a* or *b*, where energy dependence is weak.

[a] σ_{total} at 80–240 GeV for neutrons ($\approx \sigma$ for protons) from Murthy et al., Nucl. Phys. B92, 269 (1975). This scales approximately as $A^{0.77}$.

[b] $\sigma_{inelastic} = \sigma_{total} - \sigma_{elastic} - \sigma_{quasielastic}$; for neutrons at 60–375 GeV from Roberts et al., Nucl. Phys., B159, 56 (1979). For protons and other particles, see Carroll et al., Phys. Lett. 80B, 319 (1979); note that $\sigma_I(p) \approx \sigma_I(n)$. σ_I scales approximately as $A^{0.71}$.

[c] Mean free path between collisions (λ_T) or inelastic interactions (λ_I), calculated from $\lambda = A/(N \times \sigma)$, where N is the Avogadro number.

[d] For minimum-ionizing protons and pions. $\overline{\Delta E}$ is energy loss per g/cm^2 from Barkas and Berger, *Tables of Energy Losses and Ranges of Heavy Charged Particles*, NASA-SP-3013 (1964). For electrons and positrons see: M.J. Berger and S.M. Seltzer, *Stopping Powers and Ranges of Electrons and Positrons* (2nd Ed.), U.S. National Bureau of Standards report NBSIR 82-2550-A (1982). ΔE_{mp} is the most probable deposited energy in one cm, in MeV for solids and liquids, in keV for gases. E_{mp} varies with depth in a nonproportional manner. [See Sect. (1) of Passage of Particles Through Matter.] Parentheses refer to gaseous form at STP (0°C, 1 atm.).

[e] From Y.S. Tsai, Rev. Mod. Phys. 46, 815 (1974); L_{rad} data for all elements up to uranium may be found here. Corrections for molecular binding applied for H_2, and D_2. Parentheses refer to gaseous form at STP (0°C, 1 atm.).

[f] Values for solids, or the liquid phase at boiling point, except as noted. Values in parentheses for gaseous phase at STP (0°C, 1 atm.). Refractive index given for sodium *D* line.

[g] For pure graphite; industrial graphite density may vary 2.1 - 2.3 g/cm^3.

[h] Standard shielding blocks, typical composition O_2 52%, Si 32.5%, Ca 6%, Na 1.5%, Fe 2%, Al 4%, plus reinforcing iron bars. The attenuation length, $\ell = 115 \pm 5$ g/cm^2, is also valid for earth (typical $\rho = 2.15$), from CERN-LRL-RHEL Shielding exp., UCRL-17841 (1968).

[i] Density may vary about ±3%, depending on operating conditions.

[j] Values for typical working conditions with H_2 target: 50 mole percent, 29°K, 7 atm.

[k] Typical scintillator; e.g., PILOT B and NE 102A have an atomic ratio H/C = 1.10.

[ℓ] Main components: 80% SiO_2 + 12% B_2O_3 + 5% Na_2O.

[m] Used in Cerenkov counters. Values at 26°C and 1 atm. Indices of refraction from E.R. Hayes, R.A. Schluter, and A. Tamosaitis, ANL-6916 (1964).

[n] $n(SiO_2) + 2n(H_2O)$ used in Cerenkov counters, ρ = density in g/cm^3. From M. Cantin et al., Nucl. Instr. Meth. 118, 177 (1974).

[o] G10-plate, typical 60% SiO_2 and 40% epoxy.

THE MOST IMPORTANT PAGE FOR AN EXPERIMENTAL PARTICLE PHYSICIST.

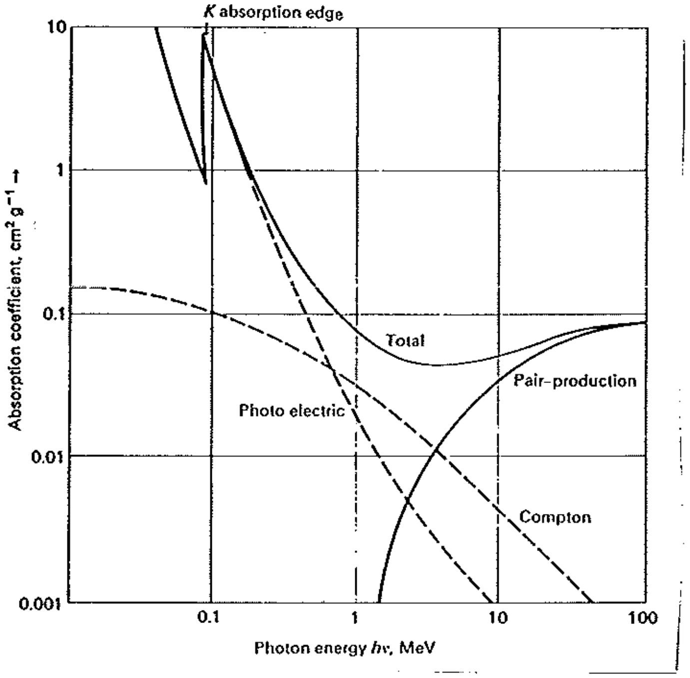
EXAMPLE: THE ATMOSPHERE IS ~ 1000 gm/cm^2 DEEP, OR

$28 X_0$. ⇒ NEED 14 GENERATIONS TO REACH THE SURFACE

⇒ NEED $E_0 \gtrsim 700$ GeV.

— MANY OF THE ESSENTIAL PROPERTIES OF MATTER FOR HIGH-ENERGY PARTICLE DETECTORS ARE SUMMARIZED ON p. 13.

4. PHOTONS OF ENERGY LESS THAN A FEW MeV LOSE ENERGY PRIMARILY VIA THE PHOTOELECTRIC EFFECT, AND COMPTON SCATTERING. DETAILED CONSIDERATIONS REQUIRE INFORMATION AS IN THE FIGURE ⟶ (FOR LEAD)



THE PHOTOELECTRIC CROSS SECTIONS ARE QUITE LARGE, AND X-RAYS DON'T PENETRATE TO THE SURFACE OF THE EARTH.

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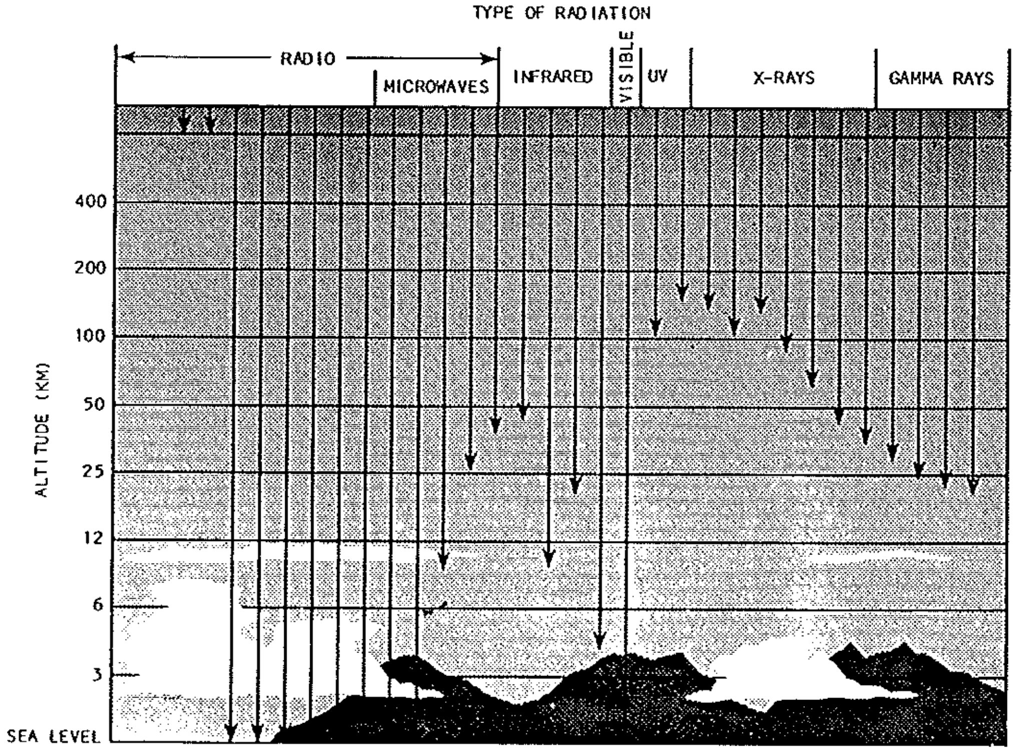
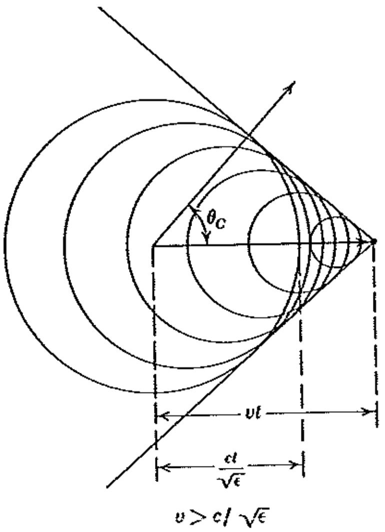


The absorption of radiation by the atmosphere. (From D. Goldsmith, *The Evolving Universe* (Menlo Park, Calif.: Benjamin Cummings, 1981))

5. RELATIVISTIC CHARGED PARTICLES TRAVERSING A TRANSPARENT MEDIUM EMIT ČERENKOV RADIATION.



THE THRESHOLD CONDITION, $v = c/n$, IS USEFULLY WRITTEN

$$\gamma_{MIN} = \frac{E}{mc^2} \sim \frac{1}{\sqrt{2\Delta n}} \quad \text{FOR } n = 1 + \Delta n \sim 1$$

IN AIR $\Delta n \sim 10^{-6} \Rightarrow \gamma_{MIN} \sim 1000$

PROTONS : $E_p > 1000$ GeV

PIONS : $E_\pi > 140$ GeV

ELECTRONS : $E_e > 5$ GeV

THE NUMBER OF VISIBLE PHOTONS EMITTED IS ~ 500/cm ONCE $\gamma \gtrsim 10\,\gamma_{MIN}$

ATMOSPHERIC SHOWERS OF HIGH-ENERGY ELECTRONS AND PHOTONS ARE READILY DETECTED VIA ČERENKOV LIGHT. THE RADIATION IS HIGHLY DIRECTIONAL IF $\gamma \gg \gamma_{MIN}$:

$$\Theta \sim \frac{1}{\gamma_{MIN}}\left(1 - \frac{\gamma_{MIN}^2}{2\gamma^2}\right) \sim \frac{1}{\gamma_{MIN}}$$

B. STRONG INTERACTIONS

WHILE THESE ARE COMPLICATED IN GENERAL, RATHER BASIC CONSIDERATIONS SUFFICE FOR PARTICLE DETECTORS.

FOR PROTONS OF $E \gtrsim 1$ GeV THE NUCLEAR (INELASTIC) SCATTERING CROSS SECTION IS $\sigma_p \sim A^{2/3} \cdot 30$ MBARN $(1 \text{ BARN} = 10^{-24} \text{ cm}^2)$

WHILE FOR PIONS, $\sigma_\pi \sim A^{2/3} \cdot 20$ MBARN

EXAMPLE, IN AIR THE PROTON INTERACTION LENGTH IS 90 gm/cm², SO NO PRIMARY PROTONS REACH THE SURFACE.

THE ATMOSPERE IS ~11 PROTON INTERACTION LENGTHS DEEP, LEADING TO NUCLEAR CASCADES FROM PRIMARY PROTONS. ANY π^0 MESONS IN THE CASCADE IMMEDIATELY DECAY TO 2 PHOTONS, LEADING TO ELECTROMAGNETIC CASCADES.

MOST CHARGED PIONS WILL HAVE DECAYED (OR INTERACTED) BEFORE REACHING THE SURFACE, SO MUONS ARE THE MAIN CHARGED COMPONENT OF A COSMIC RAY SHOWER DUE TO PROTONS.

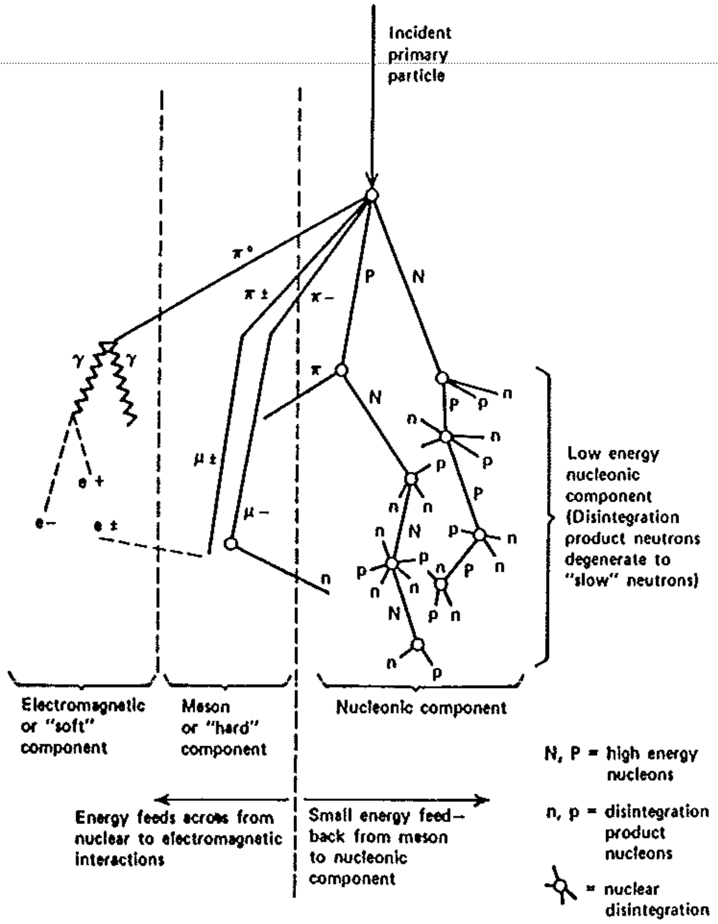


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FIG. 3.3. Schematic representation of the results of an interaction of a cosmic ray particle with the atmosphere. (From Simpson, Fonger, and Treiman 1953, p. 936.)

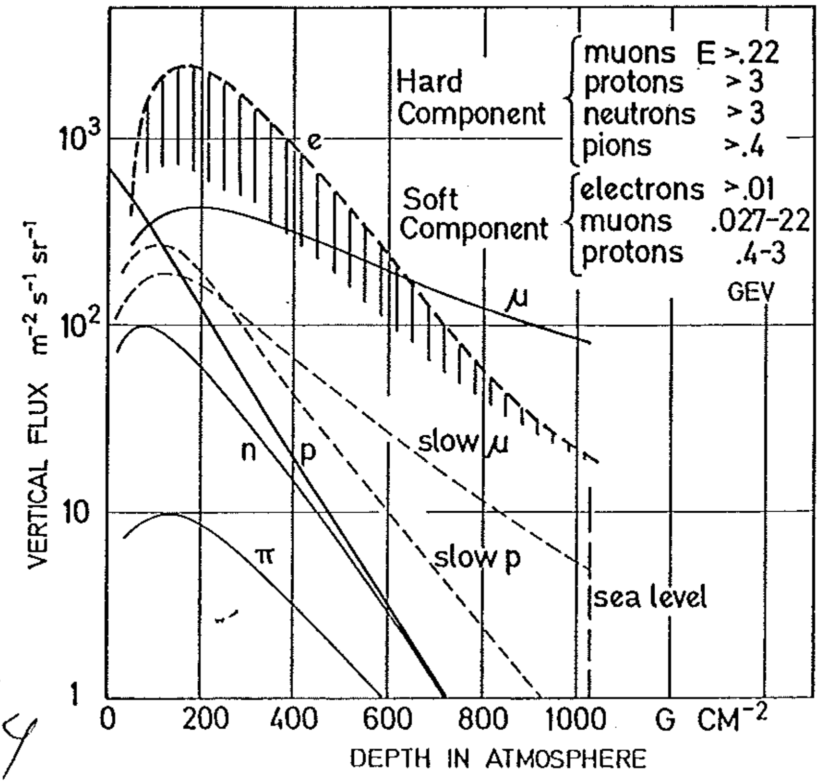

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FIG. 12. Components of the radiation in the atmosphere, after Peters.

C. WEAK INTERACTIONS

THESE ARE SO WEAK WE ARE LUCKY TO SEE EVEN ONE!

THE NEUTRINO IS THE ONLY LONG-LIVED PARTICLE WHICH INTERACTS ONLY WEAKLY (THUS FAR OBSERVED!). A TYPICAL NEUTRINO ABSORPTION CROSS SECTION IS

$$\sigma_\nu \sim 10^{-42}\,\mathrm{cm}^2$$

FOR 10 MeV ν's IN WATER. THUS AN ABSORPTION LENGTH IS $\sim 10^{19}$ CM $\approx$ 1 PARSEC!

CLEARLY, ν DETECTORS MUST BE BIG.

D. DETECTOR TRENDS

IN THE FOLLOWING 3 LECTURES WE EXPLORE RECENT DEVELOPMENTS IN DETECTORS WITH NOTABLE ASTRO-PARTICLE APPLICATIONS. THE GENERAL TRENDS ARE:

- MODEST POSITION/ANGLE RESOLUTION COMPARED TO OPTICAL STANDARDS.
- GOOD TIME RESOLUTION. MOST NOTEWORTHY RESULTS HAVE DEPENDED ON THIS.
- IMPROVING ENERGY RESOLUTION. MOST PROGRESS IN THE NEAR FUTURE WILL COME HERE.
- LARGE SCALE IMPLEMENTATION - DRIVEN BY SEARCHES FOR VERY HIGH ENERGY PHOTONS, AND LOW ENERGY NEUTRINOS.