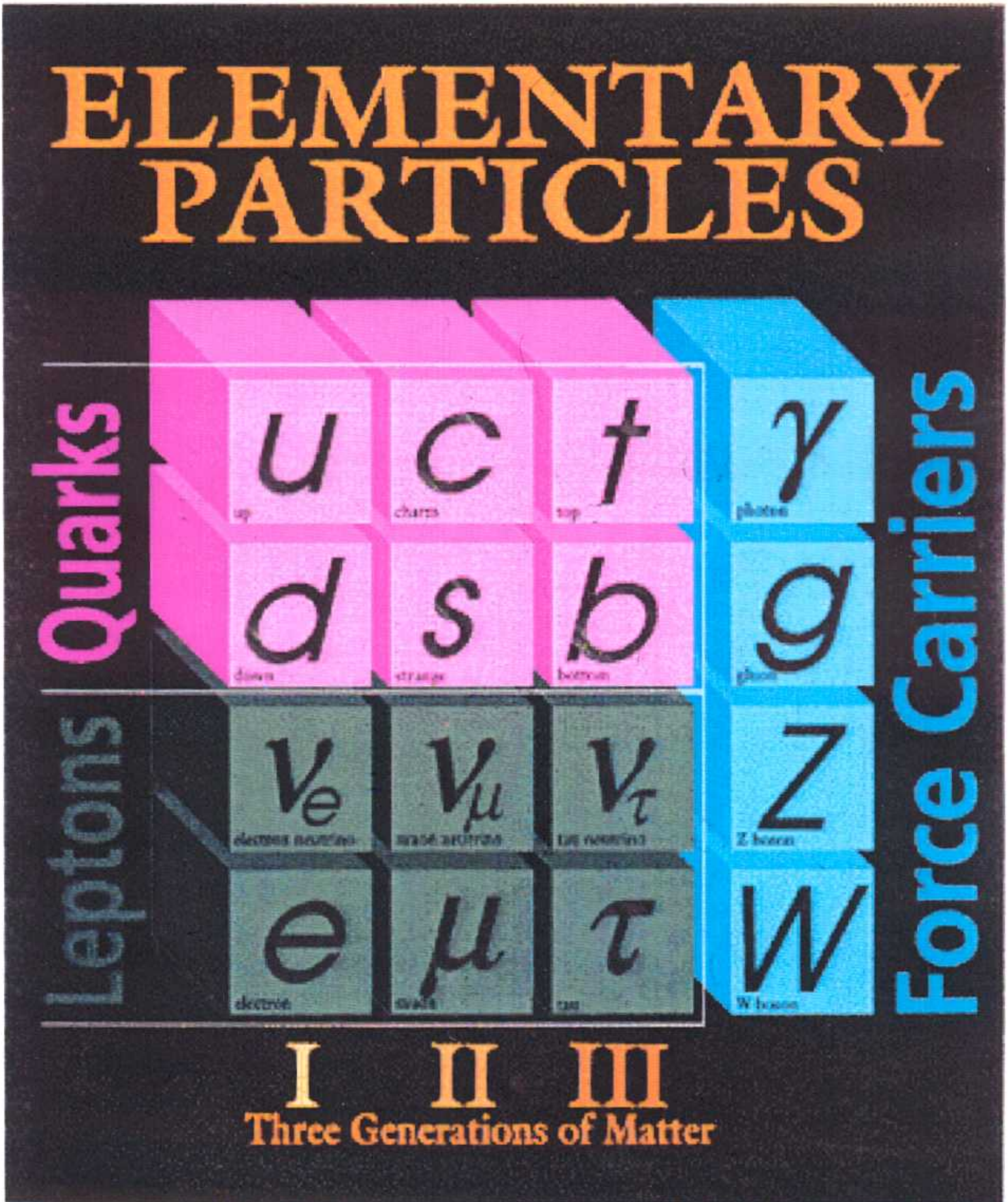
Is the Universe Made of These?



STRENGTH

Table 1.3. *The boson mediators*

Strength	Interaction	Mediator	Spin/parity
1	strong	gluon, G	1^-
10^{-2}	electromagnetic	photon, γ	1^-
10^{-7}	weak	$W^{\pm}, Z^0$	$1^-, 1^+$
10^{-39}	gravity	graviton, g	2^+

GAUGE GROUP

THE INTERACTIONS

STRONG

SU(3) BINDS QUARKS INTO PROTONS/NEUTRONS

"REMNANT" BINDS NUCLEONS IN NUCLEUS

ELECTROMAGNETIC

U(1) ATOMIC PHYSICS

MOLECULAR

CHEMISTRY

WEAK

SU(2) RADIOACTIVE β-DECAY

NEUTRINO PHYSICS

GRAVITATION

? BULK MATTER IS ELECTRICALY NEUTRAL

⇒ DOMINATES UNIVERSE

+ "WHAT ELSE" ?

PROPERTIES OF CONSTITUENTS

- FERMIONS → MATTER — 6 QUARKS, 6 LEPTONS

LEPTONS				$Q/\|e\|$
	e	μ	τ	-1
	ν_e	ν_μ	ν_τ	0

spin $\frac{1}{2}\left(\frac{\hbar}{2}\right)$

$\longrightarrow$ MASS

- UNSTABLE
  - τ — 2.9×10^{-13} s
  - μ — 2.2×10^{-6} s

- STABLE
  - e ← EXPERIMENTAL LIMIT
  - $\tau(e \to \gamma \nu) > 4 \times 10^{23}$ y

- FLAVOUR — e, μ, τ

Table 1.4. *Lepton masses in energy units mc^2*

Flavour	Charged lepton mass	Neutral lepton mass
e	$m_e = 0.511$ MeV	$m_{\nu_e} \leq 10$ eV
μ	$m_\mu = 105.66$ MeV	$m_{\nu_\mu} \leq 0.16$ MeV
τ	$m_\tau = 1777$ MeV	$m_{\nu_\tau} \leq 18$ MeV

- FLAVOUR CONSERVED
  ↳ WE'LL SEE WHAT THIS MEANS
- WHY DO e, μ, τ HAVE THESE MASSES?
- WE NOW KNOW ν_s HAVE FINITE MASSES; BUT DO NOT KNOW THEIR VALUES

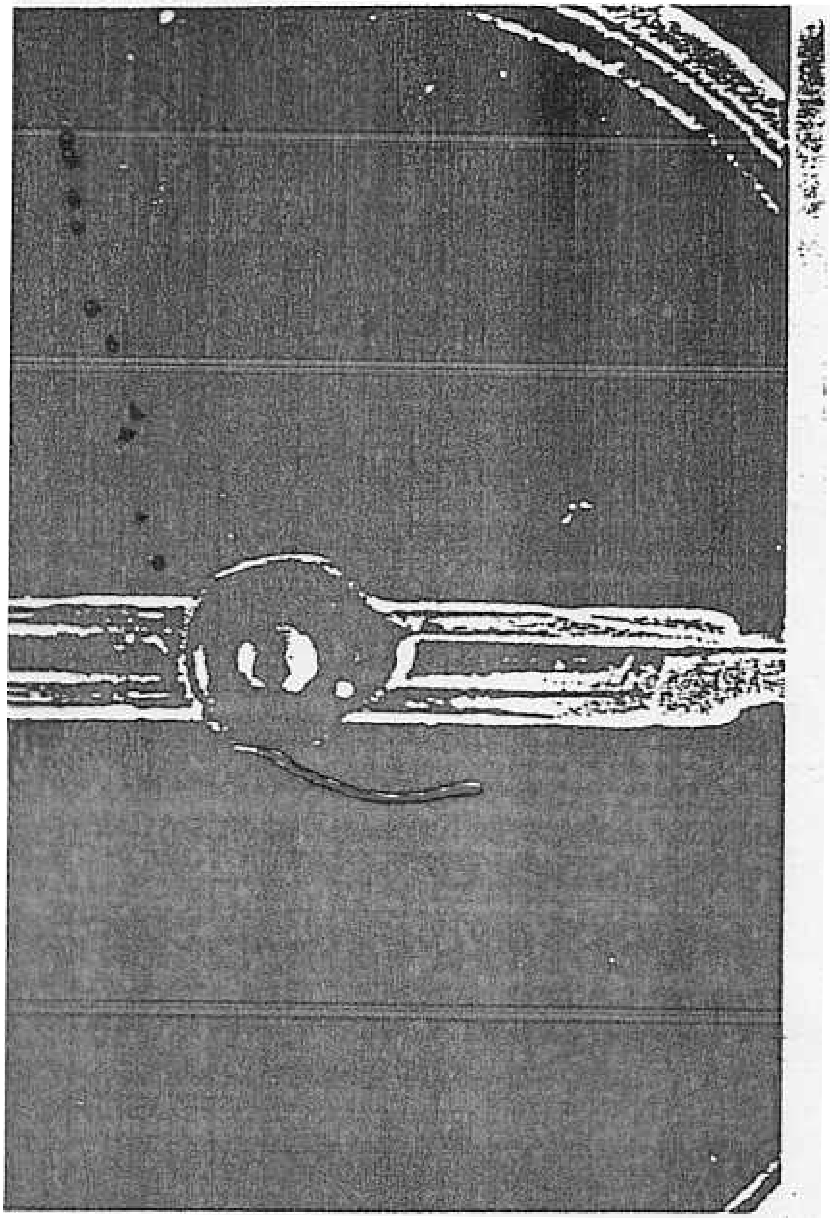


Fig. 5.6 *A photograph by Anderson and Neddermeyer of a positive muon coming to rest before it decays in a cloud chamber that was activated by a Geiger counter inside the chamber. (The counter lies horizontally across the centre of the picture; the circular structure is part of the counter.) The incoming muon leaves a faint track at the upper left of the picture. The track curls round and becomes thicker after the muon loses energy in traversing the glass walls and copper cylinder of the Geiger counter. The chamber was not sensitive enough to record the track of the positron produced in the muon's decay. The muon travels 2.9 cm after emerging from the counter.*

THE MUON

- MISTAKEN FOR YUKAWA PION
- FIRST SIGN OF GENERATION STRUCTURE

I.I. RABI: "WHO ORDERED THAT !?"

$Q_\mu = Q_e$

$m_\mu = 105.65839 \pm 0.00006$ MeV/c^2

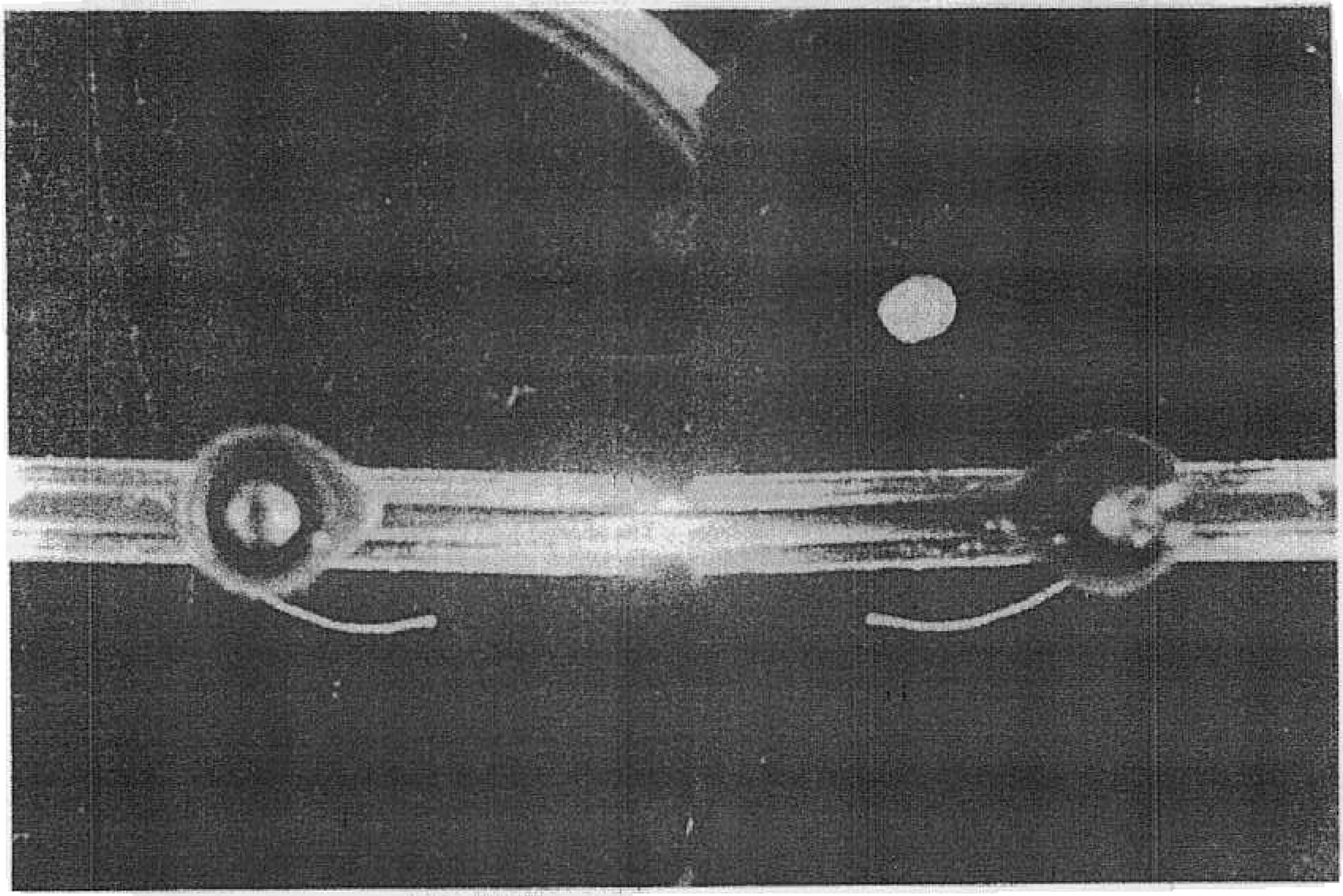
$= 207 \times m_e$

$L_\mu = 1$

POINT PARTICLE

$g_\mu = g^\mu_{DIRAC}$

$\approx g_e$



A muon enters the cloud chamber from above with a momentum of 52 MeV/c. It passes through a Geiger counter and comes to rest. From the measured range the mass was determined to be 220 ± 35 electron masses. S. H. Neddermeyer and C. D. Anderson, Phys. Rev. 54, 88 (1938).

LEPTON FLAVOUR

- e, μ, τ INTERACT VIA EM, WEAK
- $\nu_e\ \nu_\mu\ \nu_\tau$ " " WEAK
- $L_e\ L_\mu\ L_\tau = +1$ FLAVOUR
- ANTILEPTONS HAVE CHARGE AND FLAVOUR OF OPPOSITE SIGN
- LEPTON FLAVOUR CONSERVED

NOT A LEPTON (π^+)

$$\pi^+ \to \mu^+\ \nu_\mu$$

	π^+	μ^+	ν_μ
L_μ	0	-1	+1

($-1 + 1 = 0$)

$$\nu_e\, n \to p\, e^-$$

	ν_e	n	p	e^-
L_e	+1	0	0	+1

$$\nu_e\, n \not\to p\, \mu^-$$

	ν_e	n	p	μ^-
L_e	+1	0	0	0

$$\nu_\mu\, n \to p\, \mu^-$$

	ν_μ	n	p	μ^-
L_μ	+1	0	0	+1

THIS IS HOW WE KNOW $\nu_e \not\equiv \nu_\mu$

CAVEAT :→ MASSIVE ν CAN CAUSE SLIGHT VIOLATION OF LEPTON FLAVOUR CONSERVTN.

Table 1.5. *Constituent quark masses*

Flavour	Quantum number (FLAVOR)	Rest mass, GeV/c^2
up or down	—	$m_u \simeq m_d \simeq 0.31$
strange	$S = -1$	$m_s \simeq 0.50$
charm	$C = +1$	$m_c \simeq 1.6$
bottom	$B = -1$	$m_b \simeq 4.6$
top	$T = +1$	$m_t \simeq 180$

			$Q/\lvert e \rvert$
u	c	t	$+2/3$
d	s	b	$-1/3$

- QUARKS INTERACT VIA COLOUR (STRONG)
  EM
  WEAK

- QUARK FLAVOUR
  - CONSERVED BY STRONG INTERACTION
  - NOT CONSERVED BY WEAK INTERACTION

FIRST EVIDENCE FOR FLAVOUR

$$\pi^+ n \rightarrow K^+ \Lambda$$

- $\Lambda \rightarrow p\pi^-$
- $K^+ \rightarrow \pi^+\pi^0$

} VERY SLOWLY

- PRODUCED VIA STRONG INTERACTION
- DECAY SLOWLY VIA WEAK INTERACTION
  - BECAUSE STRONG CONSERVES "S" CAN NOT DECAY QUICKLY
  - WEAK DOES NOT CONSERVE "S"
- PRODUCED IN PAIRS OF OPPOSITE "S"
  - SINCE STRONG CONSERVES "S"

$$\pi^+ n \xrightarrow{\text{STRONG}} K^+ \; \Lambda$$

S: $0 \rightarrow +1 \; -1$

WEAK:

$K^+ \rightarrow \pi^+\pi^0$, S: 0

$\Lambda \rightarrow p\pi^-$, S: 0

EVIDENCE FOR THE EXISTENCE OF NEW UNSTABLE ELEMENTARY PARTICLES

By Dr. G. D. ROCHESTER

AND

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AMONG some fifty counter-controlled cloud-chamber photographs of penetrating showers which we have obtained during the past year as part of an investigation of the nature of penetrating particles occurring in cosmic ray showers under lead, there are two photographs containing forked tracks of a very striking character.

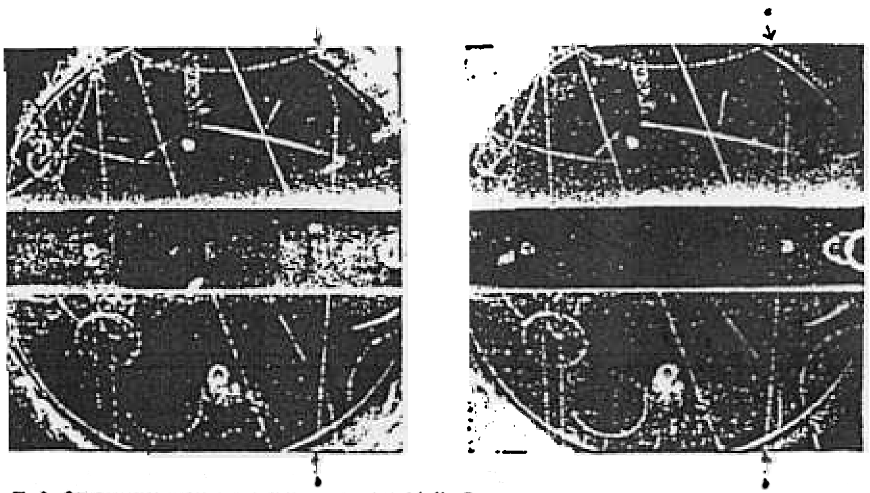


Fig. 2. Stereoscopic photographs showing an unusual fork (a b). The direction of the magnetic field is such that a positive particle coming downwards is deviated in a clockwise direction

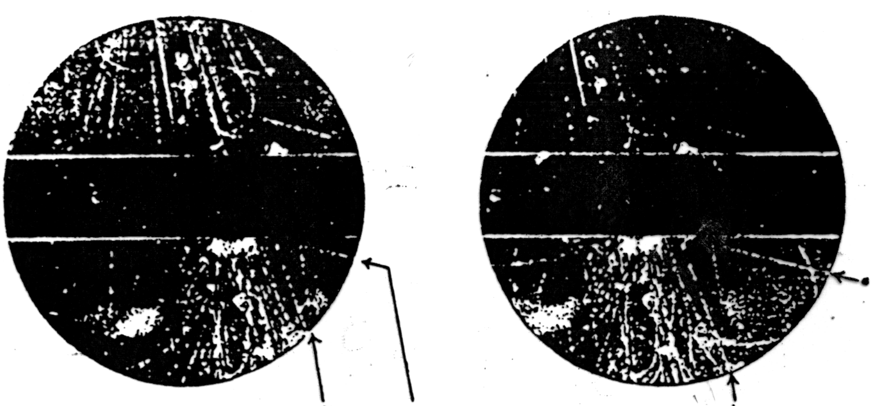


Fig. 1. Stereoscopic photographs showing an unusual fork (a b) in the gas. The direction of the magnetic field is such that a positive particle coming downwards is deviated in an anticlockwise direction

Fig. 12.

COLOUR

- IN ADDITION TO ELECTRIC CHARGE

  QUARKS CARRY COLOUR CHARGE

  ↳ SOURCE OF STRONG INTERACTION

- γ COUPLE TO ELECTRIC CHARGE
- g COUPLE TO COLOUR CHARGE
- ONE ELECTRIC CHARGE +e
- THREE COLOUR CHARGES RED GREEN BLUE

- SINGLE FREE QUARKS NEVER OBSERVED

  ONLY COLOUR NEUTRAL BOUND STATES

  PROTON u d u + PERMUTATIONS

  PION π^+ $u\bar{d}$

  ↳ ANTIRED

Table 1.6. *Quark composition of some meson and baryon states (masses in MeV/c² in parentheses), together with values of strangeness, S*

Meson	Composition	S	Baryon	Composition	S
$\pi^+(140)$	$u\bar{d}$	0	$p(931)$	uud	0
$K^0(498)$	$d\bar{s}$	+1	$\Lambda(1116)$	uds	−1
$K^-(494)$	$\bar{u}s$	−1	$\Xi^0(1315)$	uss	−2
$\rho^-(770)$	$\bar{u}d$	0	$\Sigma^+(1189)$	uus	−1
$\omega^0(783)$	$u\bar{u}$	0	$\Omega^-(1672)$	sss	−3

ANTIPARTICLES

- SAME MASS, SPIN, LIFETIME
  OPPOSITE CHARGE, COLOUR, FLAVOUR

- PROFOUNDLY CONNECTED WITH LORENTZ INVARIANCE
  (SEE FORCE OF SYMMETRY!)

$$E^2 = p^2 + m^2 \qquad c = 1$$

$$E = \pm\sqrt{p^2 + m^2}$$

- MEANINGLESS FOR CLASSICAL PARTICLE

- QM → FREE PARTICLES → PLANE WAVE

$$\psi = A e^{-i(Et - px)} \qquad \hbar = 1$$

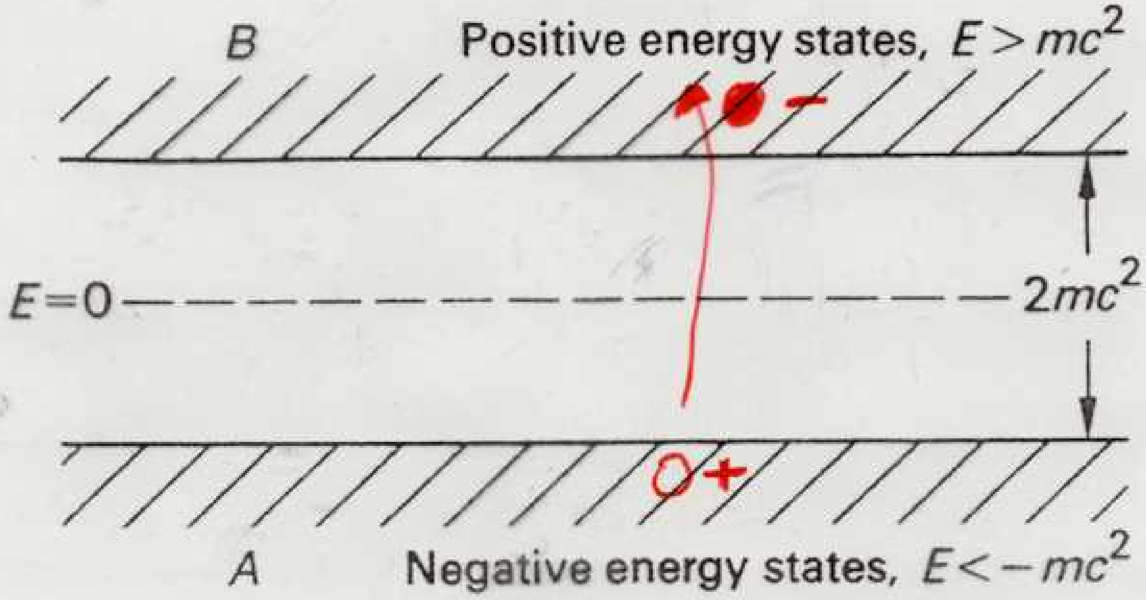
$t \rightarrow +ve$; PHASE INCREASE FOR x +ve

$t \rightarrow -ve$; " " x −ve

$$Et \rightarrow (-E)(-t) \qquad px \rightarrow (-p)(-x)$$

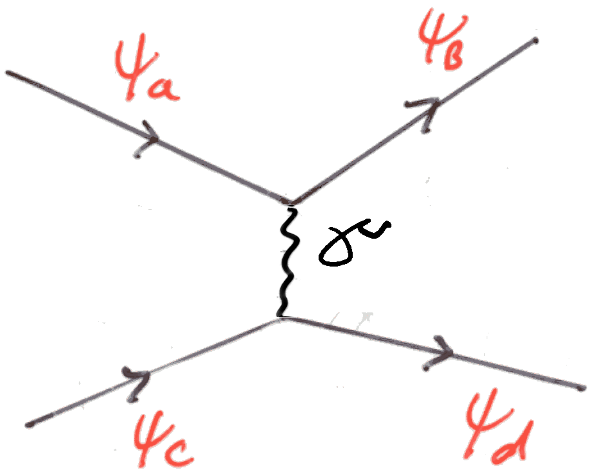
$E > 0$ $\qquad$ $E < 0$

$t_1 < t_2$ $\qquad$ $t_1 < t_2$



- −VE ELECTRONS FLOWING BACK ($E<0$) IN TIME ≡ +VE FLOWING FORWARD WITH $E>0$
- EQUAL & OPPOSITE CHARGES
- DIRAC "HOLE IN SEA"
  −VE SEA FULL FROM PAULI
- NON REL QM $\psi \rightarrow$ SINGLE PARTICLE
- FIELD THEORY $\rightarrow \psi$ CREATES **OR** DESTROYS PARTICLES

FIELD THEORY



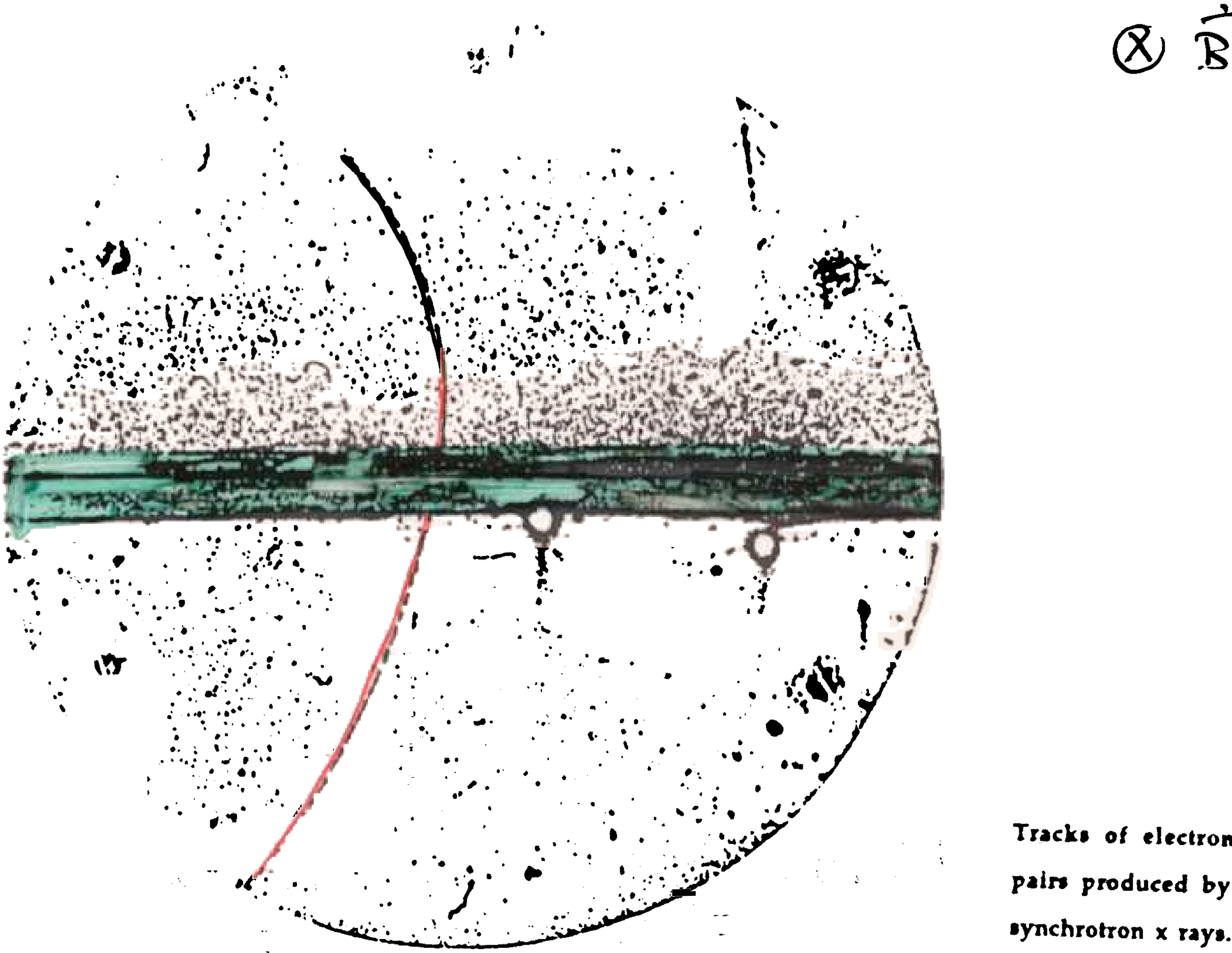
$$\text{AMP} \sim \bar{\Psi}_B \, \psi_A \; \frac{1}{q^2} \; \bar{\Psi}_d \, \psi_c$$

CREATE B → $\bar{\Psi}_B$

ANNIHILATE A → ψ_A

PROPAGATE γ^μ → $\frac{1}{q^2}$

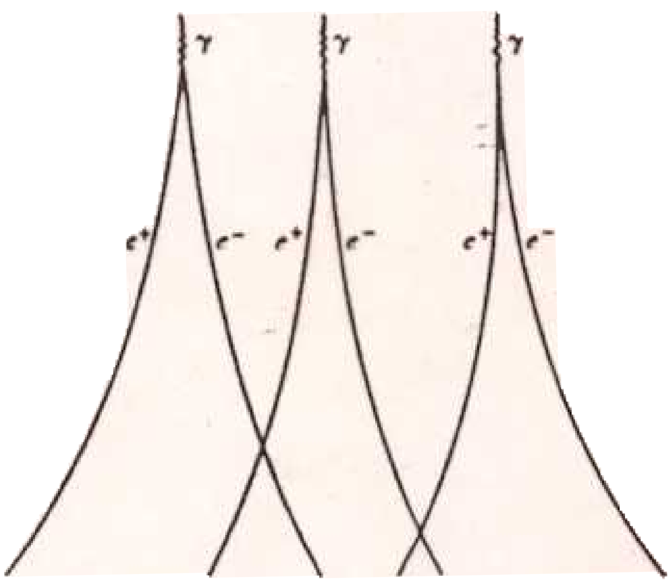
- ABOVE IS VERY SCHEMATIC!



. A 63 million volt positron ($H\rho = 2.1\times10^5$ gauss-cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ($H\rho = 7.5\times10^4$ gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

10 X POSSIBLE PROTON PATH LENGTH

Tracks of electron-positron pairs produced by 300-MeV synchrotron x rays. (*Courtesy Lawrence Radiation Laborato University of California, Berkeley.*)



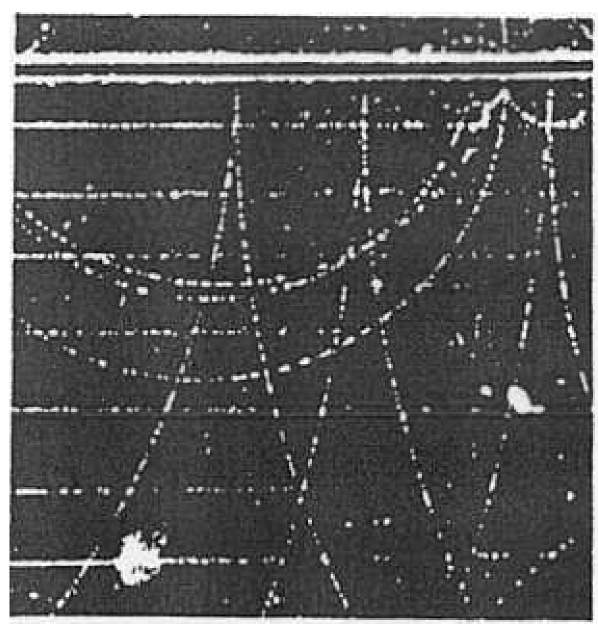


Fig. 3.

RELATIVISTIC WAVE EQUATION

SCHRÖDINGER — NON RELATIVISTIC

START FROM NON-RELATIVISTIC ENERGY MOMENTUM

$$E = \frac{p^2}{2m} - V$$

QUANTIZE:

$$p \rightarrow -i\hbar \nabla$$

$$E\psi = -\frac{\hbar^2}{2m} \nabla^2 \psi - V\psi$$

$$E \rightarrow i\hbar \frac{\partial}{\partial t}$$

$$i\hbar \frac{\partial \psi}{\partial t} + \frac{\hbar^2}{2m} \nabla^2 \psi = -V\psi$$

= 0 FOR FREE PARTICLE

CAN GO THRU SAME PROCESS FOR RELATIVISTIC WAVE EQUATION.

KLEIN – GORDON – RELATIVISTIC

START FROM RELATIVISTIC ENERGY MOMENTUM

$$E^2 = p^2 + m^2 \quad \text{(FREE)}$$

$$E \to i\hbar \frac{\partial}{\partial t} \qquad p \to -i\hbar\nabla$$

$$-\hbar^2 \frac{\partial^2 \psi}{\partial t^2} = -\hbar^2 \nabla^2 \psi + m^2$$

$$\frac{\partial^2 \psi}{\partial t^2} = \nabla^2 \psi - m^2 \psi$$

$$\frac{\partial^2 \psi}{\partial t^2} = (\nabla^2 - m^2)\psi$$

IN 4-VECTOR NOTATION

$$p^\mu p_\mu = m^2$$

$$p^\mu \to i\partial^\mu$$

$$(\partial^\mu \partial_\mu + m^2)\psi = 0$$

$$= -V\phi$$

IF POTENTIAL

OK FOR "SPINLESS" PARTICLES

$$\frac{\partial^2 \psi}{\partial t^2} = (\nabla^2 - m^2)\psi \quad ①$$

- $E = \pm\sqrt{p^2 + m^2}$ SEEN AS BOTHERSOME

DIRAC LOOKED FOR EQUATION

1ST ORDER IN SPACE-TIME

FOR A MASSLESS PARTICLE, ①

$$\frac{\partial^2 \psi}{\partial t^2} = \nabla^2 \psi$$

IF YOU "TAKE $\sqrt{\ }$"

SOME PARAMETER → $\bar{\sigma}$

$$\frac{\partial \psi}{\partial t} = \pm \bar{\sigma} \nabla \psi$$

$$\frac{\partial \psi}{\partial t} = \pm\left[\sigma_1 \frac{\partial \psi}{\partial x} + \sigma_2 \frac{\partial \psi}{\partial y} + \sigma_3 \frac{\partial \psi}{\partial z}\right] \quad ②$$

① IS JUST ENERGY-MOMENTUM

SO MUST STILL BE SATISFIED

↳ SQUARE ②

$$\frac{\partial^2 \psi}{\partial t^2} = \sigma_1^2 \frac{\partial^2 \psi}{\partial x^2} + \sigma_2^2 \frac{\partial^2 \psi}{\partial y^2} + \sigma_3^2 \frac{\partial^2 \psi}{\partial z^2}$$

→ ∇^2 IF $\sigma_1^2 + \sigma_2^2 + \sigma_3^2 = 1$

$\nabla^2 \psi$

0 $\quad + \sigma_1 \sigma_2 \frac{\partial \psi}{\partial x} \frac{\partial \psi}{\partial y} + \sigma_2 \sigma_1 \frac{\partial \psi}{\partial x} \frac{\partial \psi}{\partial y}$

$\frac{\partial \psi}{\partial x}, \frac{\partial \psi}{\partial x} \quad + \sigma_1 \sigma_3 \frac{\partial \psi}{\partial x} \frac{\partial \psi}{\partial z} + \sigma_3 \sigma_1 \frac{\partial \psi}{\partial x} \frac{\partial \psi}{\partial z}$

$\quad + \sigma_2 \sigma_3 \frac{\partial \psi}{\partial y} \frac{\partial \psi}{\partial z} + \sigma_3 \sigma_2 \frac{\partial \psi}{\partial y} \frac{\partial \psi}{\partial z}$

ALL THESE MUST BE 0

$\sigma_1 \sigma_2 + \sigma_2 \sigma_1 = 0$

$\sigma_1 \sigma_3 + \sigma_3 \sigma_1 = 0$

$\sigma_2 \sigma_3 + \sigma_3 \sigma_2 = 0$

CANNOT

NUMBERS

↓

MATRICES