HISTORY OF FUNDAMENTAL PARTICLES AND INTERACTIONS

HISTORY SHOWS THAT DESPITE NOTABLE STROKES OF GENIUS, THE PATH TO KNOWLEDGE IS LONG. THE TIME LAG BETWEEN NEW OBSERVATIONS AND THEIR SATISFACTORY EXPLANATION IS OFTEN QUITE LONG. NEW MINDS ARE VITAL AND WELCOME IN THE QUEST FOR UNDERSTANDING OF NATURE.

1800'S FUNDAMENTAL INTERACTIONS: ELECTROMAGNETISM & GRAVITY
ELECTROMAGNETISM IS A FIELD PHENOMENON
FUNDAMENTAL PARTICLES: ATOMS

1886 GOLDSTEIN: CANAL RAYS — BERLIN. BERICHT. 39, 691 (1886)
FREE PROTONS OBSERVED IN A GAS DISCHARGE TUBE - A PRIMITIVE ACCELERATOR

1895 RÖNTGEN: X RAYS (γ RAYS) — ELECTRICIAN 36, 415, 850 (1896)
PENETRATING RADIATION OBTAINED BY SMASHING ENERGETIC ELECTRONS INTO METAL

1896 BECQUEREL: RADIOACTIVITY OF URANIUM — COMPT. REND. 122, 420, 501 (1896)
TECHNIQUE: EXPOSURE OF PHOTOGRAPHIC EMULSIONS BY PENETRATING RADIATION

1897 THOMSON: THE ELECTRON — PHIL. MAG. 44, 293 (1897)
MEASURED e/m BY DEFLECTION WITH $\vec{E}$ & $\vec{B}$ FIELDS

1899 RUTHERFORD: α-RAYS AND β-RAYS — PHIL MAG. JAN (1899)
TWO FORMS OF RADIOACTIVITY. TECHNIQUE: IONIZATION CHAMBER

1905 EINSTEIN: LIGHT QUANTA — ANN d. PHYS. 17, 132 (1905)

1905 EINSTEIN: BROWNIAN MOTION — ANN d. PHYS 17, 549 (1905)
PROVES TO ALL THAT ATOMS ARE REAL

1905 EINSTEIN: SPECIAL RELATIVITY — ANN d. PHYS 17, 891 (1905)

1905 EINSTEIN: $E=mc^2$ — ANN d. PHYS 17, 639 (1905)

1908 RUTHERFORD & GEIGER: GEIGER COUNTER — PROC. ROY. SOC. A81, 141 (1908)

1909 GEIGER & MARSDEN: LARGE ANGLE SCATTER OF α-RAYS — PROC. ROY. SOC. A82, 495 (1909)
THOMSON MODEL OF ATOM NOT VIABLE, TECHNIQUE: ZnS SCINTILLATION

1911 EINSTEIN: GRAVITATIONAL DEFLECTION OF LIGHT — ANN d. PHYS 35, 898 (1911)
1ST LINK BETWEEN GRAVITY AND ELECTRICITY (ALSO A VISION OF FARADAY)

1911 HESS: DISCOVERY OF COSMIC RAYS — PHYS. ZEIT. 12, 998 (1911)
TECHNIQUE: IONIZATION CHAMBER IN A BALLOON ASCENT

1911 WILSON: THE CLOUD CHAMBER — PROC. ROY. SOC. A85, 285 (1911)

1911 RUTHERFORD: IDEA OF THE NUCLEUS — PHIL. MAG 21, 669 (1911

1912	THOMSON: DISCOVERY OF NUCLEAR ISOTOPES	PHIL. MAG. 24, 209 (1912)
1913	GEIGER & MARSDEN: VERIFICATION OF RUTHERFORD'S MODEL	PHIL. MAG. 25, 605 (1913)
1913	BOHR: QUANTUM MODEL OF ATOMIC STABILITY	PHIL. MAG 26, 1 (1913)
1913	MILLIKAN: CHARGE OF ELECTRON	PHYS. REV. 2 109 (1913)
1914	CHADWICK: CONTINUOUS β-RAY ENERGY SPECTRUM	VER. DEUT. PHYS. GES. 16, 383 (1914)
1915	EINSTEIN: GENERAL RELATIVITY	PRUSS. AKAD. WISS 844 (1915)
1919	RUTHERFORD: FIRST NUCLEAR REACTION $\alpha + N^{14} \to O^{17} + p$	PHIL. MAG. 37, 581 (1919)
1919	WEYL: GAUGE INVARIANCE — ATTEMPT TO UNIFY GRAVITY & E-M	ANN d. PHYS 59, 101 (1919)
1922	STERN & GERLACH: ATOMIC BEAMS SPLIT BY $\vec{B}$ FIELD — EVIDENCE FOR A NEW INTERNAL QUANTUM NUMBER	Z. PHYS. 9, 349 (1922)
1922	COMPTON: CHANGE IN λ OF LIGHT SCATTERED BY ELECTRONS — CONVINCED PEOPLE THAT PHOTONS EXIST & ENERGY CONS. HOLDS	PHYS. REV 21, 483 (1923)
1923	DE BROGLIE: MATTER WAVES	COMPT. REND. 177, 503 (1923)
1924	BOSE / EINSTEIN: STATISTICS OF PHOTONS	Z. PHYS. 26, 178 (1924); PRUSS. AKAD. WISS. 261 (1924)
1925	PAULI: EXCLUSION PRINCIPLE	Z. PHYS. 31, 765 (1925)
1925	RUTHERFORD & CHADWICK: RADIUS OF PROTON	PHIL. MAG. 50, 889 (1925)
1925	HEISENBERG: MATRIX MECHANICS	Z. PHYS. 33, 879 (1925)
1925	GOUDSMIT & UHLENBECK: ELECTRON SPIN	NATURWISS. 13, 953 (1925)
1926	FERMI / DIRAC: STATISTICS OF ELECTRONS	Z. PHYS. 36, 902 (1926); PROC. ROY. SOC. A112, 661 (1926)
1926	SCHRÖDINGER: WAVE MECHANICS	ANN d. PHYS. 79, 489 (1926)
1926	BORN: PROBABILITY INTERPRETATION OF Q.M.	Z. PHYS 37, 863 (1926)
1926	KLEIN / GORDON: TRY TO COMBINE RELATIVITY & Q.M.	Z. PHYS 40, 117 (1926); Z. PHYS 41, 407 (1926)
1927	HEISENBERG: UNCERTAINTY RELATIONS	Z. PHYS. 43, 172 (1927)
1927	WIGNER: CONCEPT OF PARITY CONSERVATION	Z. PHYS 43, 624 (1927)

1927: DAVISSON & GERMER: ELECTRON DIFFRACTION PHYS. REV. 30, 705 (1927)

1928: JORDAN & PAULI: QUANTUM ELECTRODYNAMICS Z. PHYS. 47, 151 (1928)

1928 DIRAC: RELATIVISTIC QUANTUM MECHANICS PROC. ROY. SOC. A117, 610 (1928)
$\Rightarrow$ ANTIPARTICLES

1928 KLEIN & NISHINA: CALCULATION OF COMPTON X-SEC Z. PHYS 52 853 (1929)
1ST QED CALCULATION OF A HIGH ENERGY PROCESS

1928 COX ET AL: OBSERVATION OF PARITY VIOLATION PROC. NAT. ACAD SCI. 14, 544 (1928)
A SMALL EFFECT, IGNORED BY ALL

1928 WIDEROE: LINEAR ACCELERATOR WITH R.F. CAVITIES ARCH. ELEC. 21, 387 (1928)

1929 MOTT: QED CALC. OF e-NUCLEUS SCATTERING PROC. ROY. SOC. A124, 425 (1929)

1930 PAULI: THE NEUTRINO LETTER TO TÜBINGEN CONF.

1931 DIRAC: MAGNETIC MONOPOLE PROC. ROY. SOC. A133, 60 (1931)
MIGHT EXPLAIN CHARGE QUANTIZATION

1931 VAN DE GRAAFF: ELECTROSTATIC ACCELERATOR PHYS. REV 38, 1919A (1931)

1931 ROSSI: OBSERVATION OF MULTIPARTICLE COSMIC RAYS Z. PHYS. 68, 64 (1931)

1932 CHADWICK: DISCOVERY OF THE NEUTRON PROC. ROY. SOC. A136, 6?? (1932)
$\alpha + Be^{9} \rightarrow C^{12} + n$

1932 HEISENBERG: ISOSPIN Z. PHYS. 77, 1 (1932)

1932 ANDERSON: DISCOVERY OF POSITRON PHYS. REV. 43, 491 (1933)

1932 COCKROFT & WALTON: ELECTROSTATIC ACCELERATOR PROY. ROC. SOC. A136, 619 (1932)

1932 LAWRENCE: THE CYCLOTRON PHYS REV. 40, 19 (1932)

1932 WIGNER: CONCEPT OF TIME REVERSAL INVARIANCE NACHT. AKAD. WISS. GÖTT. 31, 546 (1932)

1933 DIRAC: VACUUM POLARISATION; CHARGE RENORMALISATION PROC. CAMB. PHIL. SOC. 30, 150 (1934)

1933 WIGNER: NUCLEAR FORCE IS SHORT RANGE PHYS. REV. 43, 252 (1933)

1934 ČERENKOV: ČERENKOV RADIATION COMPT. REND. URSS 8 451 (1934)

1934 FERMI: THEORY OF β-DECAY Z. PHYS 88, 161 (1934)

1934 YUKAWA: MESON THEORY PROC. MATH. PHYS. SOC. JAPAN 17 48 (1935)

1936 HEISENBERG: WEAK INTERACTIONS GROW WITH ENERGY Z. PHYS 101, 532 (1936)

1936 BREIT ET AL: CHARGE INDEPENDENCE OF NUCLEAR FORCE PHYS. REV 50, 825 (1936)

1936 ANDERSON & NEDDERMEYER: DISCOVERY OF THE MUON PHYS. REV. 50, 263 (1936)
$M_\mu = 206 M_e$

1937 KRAMERS: IDEA OF MASS RENORMALIZATION NUOVO CIM. 15, 108 (1937)

1938 PIERCE: PHOTOMULTIPLIER TUBE BELL LAB. RECORD. 16, 305 (1938)

1940 PAULI: SPIN AND STATISTICS PHYS. REV. 58, 716 (1940)

1945 McMILLAN: IDEA OF THE SYNCHROTRON PHYS. REV 68, 143 (1945)
VEKSLER J. PHYS (USSR) 9, 153 (1945)

1946 CONVERSI ET AL: MUON IS NOT YUKAWA'S MESON PHYS. REV. 71, 209 (1947)

1947 POWELL: DISCOVERY OF π MESON NATURE 159, 694 (1947)

1947 PERKINS: π MESON INTERACTS STRONGLY NATURE 159, 126 (1947)

1947 ROCHESTER & BUTLER: HEAVY MESONS & HYPERONS NATURE 160, 855 (1947)

1947 PONTECORVO: UNIVERSALITY OF WEAK INTERACTION PHYS. REV. 72, 246 (1947)

1947 LAMB & RETHERFORD: THE LAMB SHIFT PHYS. REV 72, 241 (1947)

1948: SCHWINGER: RENORMALIZATION OF QED PHYS. REV 73, 416 (1948)

1949: FEYNMAN: DIAGRAM METHOD PHYS. REV. 76, 749, 769 (1949)

1949 FERMI & YANG: COMPOSITE MESONS & NUCLEONS PHYS. REV. 76, 1739 (1949)

1949 BROWN ET AL: DISCOVERY OF K MESON NATURE 163, 82 (1949)

1952 FERMI ET AL: EXCITED STATE OF PROTON PHYS. REV. 85, 936 (1952)
THE Δ (1232) RESONANCE 91, 155 (1953)

1952 PAIS: STRANGENESS PHYS. REV. 86, 513 (1952)

1952 GLASER: THE BUBBLE CHAMBER PHYS. REV. 87, 665 (1952)

1952 COURANT ET AL: ALTERNATING GRADIENT SYNCHROTRON PHYS. REV. 88 1190 (1952)

1953 LÜDERS: CPT THEOREM DANSK. VID. SELSK. 28 #5 (1954)

1954 YANG & MILLS: GAUGE THEORY OF STRONG INT. PHYS. REV. 96, 191 (1954)

1955 CHAMBERLAIN & SEGRE: DISCOVERY OF ANTIPROTON PHYS. REV 102, 1659 (1956)

1956 KERST ET AL : IDEA OF COLLIDING BEAMS IN STORAGE RINGS — PHYS. REV. 102, 590 (1956)
O'NEILL — PHYS. REV 102, 1418 (1956)

1956 LEE & YANG : PARITY NON-CONSERVATION IN WEAK INT. — PHYS. REV 104, 254 (1956)

1956 WU ET AL : OBSERVATION OF PARITY VIOLATION — PHYS REV 105, 1413 (1957)

1956 COWAN ET AL : OBSERVATION OF THE NEUTRINO — SCIENCE 124, 103 (1956)

1958 FEYNMAN & GELL-MANN : V-A THEORY OF WEAK INT. — PHYS. REV. 109, 193 (1958)

1958 GOLDHABER ET AL : HELICITY OF THE NEUTRINO — PHYS. REV. 109, 1015 (1958)

LATE 1950'S HOFSTADTER : ELASTIC PROTON-PROTON SCATTERING — PHYS. REV. 124 1623 (1961)
EVIDENCE FOR STRUCTURE OF PROTON

LATE 1950'S PROLIFERATION OF KNOWN MESONS & BARYON

1962 DANBY ET AL : OBSERVATION OF 2 KINDS OF NEUTRINOS — PHYS. REV. LETT. 9, 36 (1962)

1963 GELL-MANN : CLASSIFACTION OF HADRONS VIA SU(3) — BOOK: THE 8-FOLD WAY
NE'EMAN — NUC. PHYS. 26, 222 (1961)

1964 GELL-MANN : QUARKS — PHYS. LETT. 8, 214 (1964)

1964 BARNES ET AL : DISCOVERY OF Ω^- — PHYS. REV. LETT. 12, 204 (1964)
PREDICTED BY QUARK MODEL

1964 CRONIN, FITCH : DISCOVERY OF CP VIOLATION — PHYS. REV. LETT. 13, 380 (1964)

1964 HIGGS : IDEA OF SPONTANEOUS SYMMETRY BREAKING — PHYS. REV. LETT. 13, 132 (1964)

1965 HAN & NAMBU : COLORED QUARKS — PHYS. REV. 139, 1006 (1965)

1967 WEINBERG : UNIFY WEAK & E-M INTERACTIONS — PHYS. REV. LETT 19, 1264 (1967)
SALAM PREDICT W, Z BOSONS ; NEUTRAL CURRENTS — NOBEL SYMPOSIUM # 8 (1968)

1969 SLAC-MIT GROUP : DEEP INELASTIC ELECTRON - PROTON SCATT. — PHYS. REV. LETT. 23, 930 (1969)
EVIDENCE FOR QUARKS INSIDE THE PROTON

1970 GLASHOW ET AL : HYPOTHESIS OF CHARM — PHYS. REV. D2, 1285 (1970)

1972 CCR GROUP : OBSERVATION OF HI-P_T π^0 PRODUCTION — PHYS. LETT. 46B, 471 (1973)
EVIDENCE FOR HARD SCATTERING OF QUARKS

1973 GARGAMELLE GROUP : DISCOVERY OF NEUTRAL CURRENTS — PHYS. LETT. 46B, 138 (1973)

1973 GROSS & WILCZEK : IDEA OF ASYMPTOTIC FREEDOM — PHYS. REV. LETT. 31, 1343 (1973)
POLITZER STRONG FORCE CARRIED BY GLUONS — PHYS. REV. LETT. 30, 13 (1973)

1974 TING GROUP: DISCOVERY OF J PARTICLE — PHYS. REV. LETT. 33, 1404 (1974)

1974 RICHTER-MARK I: DISCOVERY OF ψ, ψ' PARTICLES — PHYS. REV. LETT. 33, 1406 (1974)

1974 GEORGI & GLASHOW: GRAND UNIFICATION — PHYS. REV. LETT 32, 438 (1974)

1975 PERL-MARK I: DISCOVERY OF τ LEPTON — PHYS. REV. LETT. 35, 1489 (1975)

1976 GOLDHABER-MARK I: DISCOVERY OF CHARMED MESONS — PHYS. REV. LETT. 37, 255 (1976)

1977 LEDERMAN ET AL: DISCOVERY OF Υ MESONS — PHYS. REV LETT 39, 252 (1977)
INDIRECT EVIDENCE FOR A 5TH QUARK

1978 PRESCOTT ET AL: PARITY VIOLATION IN e-p SCATTERING — PHYS. LETT. B77, 347 (1978)
PREDICTED BY WEINBERG-SALAM MODEL

1979 PETRA: EVIDENCE FOR GLUONS — PHYS. REV. LETT. 43 830 (1979)

1980 CLEO GROUP: EVIDENCE FOR B MESONS — PHYS REV LETT. 46, 84 (1981)

1982 RUBBIA ET AL: EVIDENCE FOR $W^{\pm}$ BOSONS — PHYS. LETT. 122B, 103 (1983)

1983 RUBBIA ET AL: EVIDENCE FOR Z^0 BOSON — PHYS. LETT 126B, 398 (1983)

1986 + WAITING TO BE DISCOVERED:
- THE 6TH QUARK (RUBBIA THINKS HE'S ALREADY FOUND IT!)
- FREE QUARKS & GLUONS
- GLUEBALLS
- MONOPOLES
- HIGGS BOSON, AXION
- PROTON DECAY
- NEUTRINO MASS
- TECHNICOLOR, SUPERSYMMETRY
- RIGHT HANDED W, Z

⋮

AN EXCELLENT HISTORICAL SURVEY OF THE EARLY YEARS OF ELEMENTARY PARTICLE PHYSICS IS: 'INWARD BOUND', BY A. PAIS (OXFORD, 1986).

Appendix III

GROWTH OF INFORMATION

From time to time we have presented figures demonstrating the amount of experimental work which has gone into spectroscopy, and the amount of new information available as a result. The 1982 versions of these figures are shown as Figs. 1 and 2.

Figure 1 is a simple count of the number of meson resonances listed in the Tables, categorized as those "understood" -- i.e., all quantum numbers are believed known -- and those simply "listed". A rapid recent increase in both of these categories occurred because of the discovery of the J/ψ and related particles.

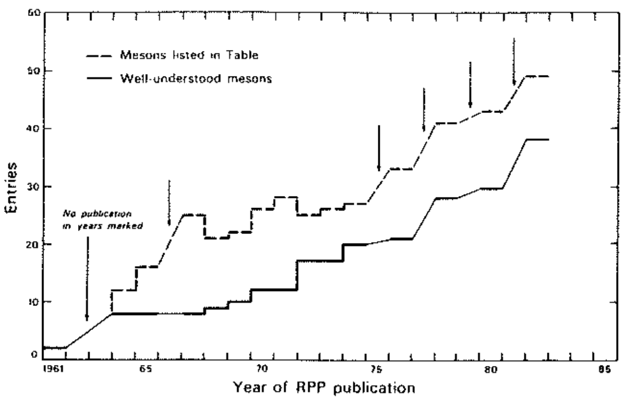


Fig. 1. Number of meson resonances listed in the Tables (dashed line) and those for which all quantum numbers are known (solid line), as a function of year of publication of the Review of Particle Properties.

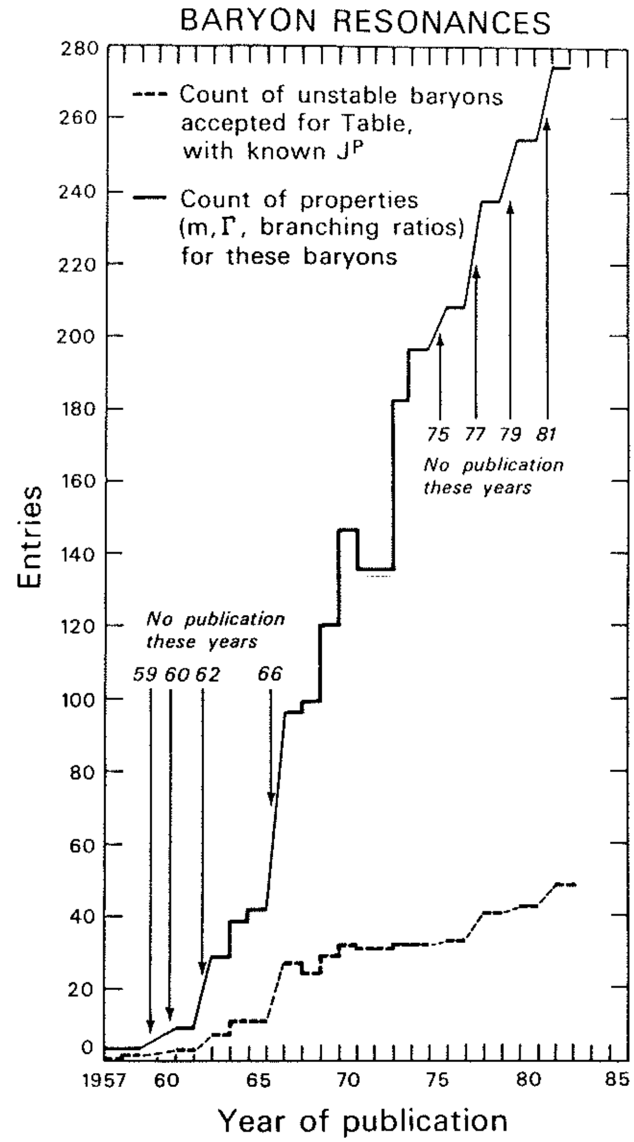


Fig. 2. Total amount of information (mass + width + branching ratios) on baryon resonances listed in the Tables, restricted to those with well-established J^P (solid line). Dashed line shows numbers of such resonances listed. Abscissa shows year of publication of Review of Particle Properties.

In Figure 2 we present similar information for the baryon resonances, but concentrate here on the "growth of understanding". That is, the *number* of known baryons (we include for this figure only those with known J^P) has grown only very slowly with time (dashed line); the real progress has been in the measurement of the *properties* of those baryons. Therefore we show as the solid line a count of the number of baryonic properties -- mass, width, and branching ratios. Most of these results are from partial-wave analyses.

A history of the values of some of the constants in the Review of Particle Properties is presented in Figs. 3-7. It may be said that one can estimate the age of a high energy physicist by asking him or her the mass of the Λ. If the answer is 1115.44 MeV, he probably was deep into his graduate training in 1965.

A history of this sort has more than whimsical value. We may use it as a guide to develop a "feel" for the reliability of current values. In Fig. 3 we show how the generally accepted values for the speed of light and a couple of other constants have changed with time. The "generally accepted value" is usually an average over several experiments, performed by a compiler (in Fig. 3, the compiler is other than the Particle Data Group in all cases, although we do quote the compiled results). The abscissa on all these figures is the date of publication of the value shown. Clearly there is a general progression toward better understanding -- at least as measured by the size of the error bars. However, the size of the error bars does not tell the full story, as we can see by the frequency with which the "best" value has changed by more than one standard deviation. Changes in these values can come from several sources: a new experimental measurement, re-evaluation of an old measurement (which can come about if a previously unrecognized source of bias is discovered and corrected, or if a new value for one of the input constants, e.g. the electric charge, is available), or a change in the averaging procedure.

In Fig. 4 we show the history of some masses (including the Λ, for radioactive Λ dating of your colleagues), based on averages which we ourselves performed. These are adapted from those originally presented by Rosenfeld[1] in 1975. The publication date refers to the publication of the Review of Particle Properties.

In Fig. 5 we show the best estimates for the lifetimes of some of the particles stable against strong decay. These and subsequent figures have been compiled since publication of the Rosenfeld article.[1] In Fig. 6 we show the widths of some of the resonances, and in Fig. 7, the values of some of the branching fractions. All values are taken from the Tables. Before 1964, very few branching fractions were listed in the Tables. In all cases, a representative sample is chosen, usually from those with a lot of activity (a limited number of special requests for a more complete set of such figures may be honored, for those seriously interested in the history of the "best" values of physical constants). In each figure, the heavy inner error bar represents the statistical error computed in the averaging procedure, and the thin outer error bars, when present, indicate the increase in the error due to the "scale factor". The scale factor is described in the introductory text, Sec. VII. It represents an attempt to quantify the increase in the uncertainty which is present in the case of experiments which disagree by more than a certain amount. In the case where the error represents an "educated guess," rather than a calculation, the inner error bar is absent.

On the whole, the number of times the values have changed by more than one standard deviation over the years is remarkably few. Even those branching fractions which involve rare decays and which are therefore presumably difficult to measure (Fig. 7) are, for the most part, within one or two standard deviations in 1978 of their value in any year since 1960. This is in spite of the vast amount of new experimental input, and indicates the general reliability of the results.

Of course, the data points for a given quantity are hardly independent of each other, but those differing by several years frequently have quite different experimental input. The relative lack of change is a comment both on the experiments and on the averaging procedures. We, of course, are responsible only for the averages (except Fig. 3). These averages entail considerable exercise of judgment: there are conflicting experiments, experiments with impossibly small errors, "preliminary" results, and so forth. Statistical procedures will tell us that two experiments do not agree; they do not give a clue as to which (if either) is a good representation of the truth. Major decisions, and their motivations, are usually discussed on a case-by-case basis in the Data Card Listings; general comments may be found in Sec. II of the text and in Rosenfeld[1]. Note that, occasionally, the error bars increase from one publication to the next. This is usually the result of decision making by the compiler, e.g., to cease using a particular result, or because of new results in poor agreement with the old results.

We show these figures not only to demonstrate that there is not much change in these averages in the usual case, but also to show that there exist cases with relatively large changes. There is a psychological danger in preparing tables of "right" answers. The old joke about the experimenter who fights the systematics until he or she gets the "right" answer (read "agrees with previous experiments"), and then publishes, contains a germ of truth (presumably, those who compile and average experimental results are also not immune to this disease). A result can disagree with the average of all previous experiments by five standard deviations, and still be right. Hence, perhaps it is of value to show that large changes can (and do) sometimes occur.

Reference

1. A. H. Rosenfeld, Ann. Rev. Nucl. Sci. **25**, 555 (1975).

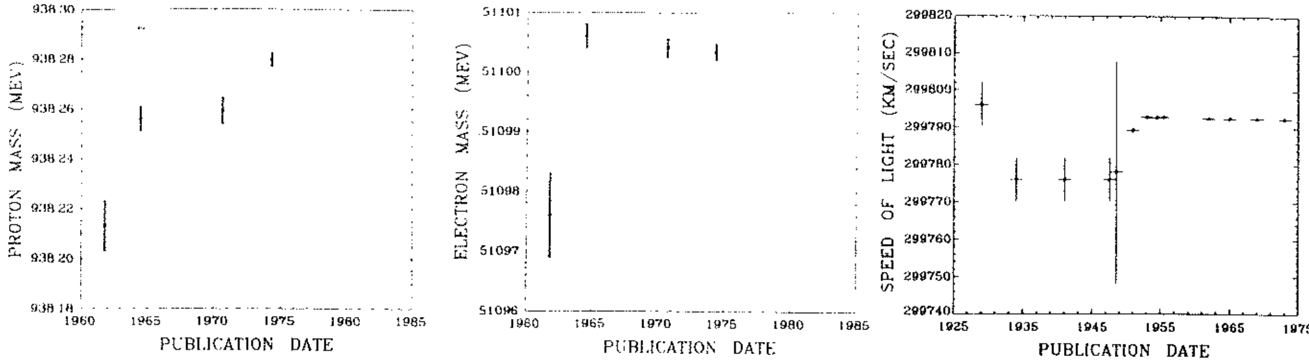


Fig. 3. The "generally accepted values" of the proton mass, the electron mass, and the speed of light, as a function of the publication date of the compilation used (not done by the Particle Data Group). Data for the speed of light plot courtesy of E. R. Cohen, Rockwell International Science Center. See the Stable Particle Data Card Listings for references on proton and electron masses.

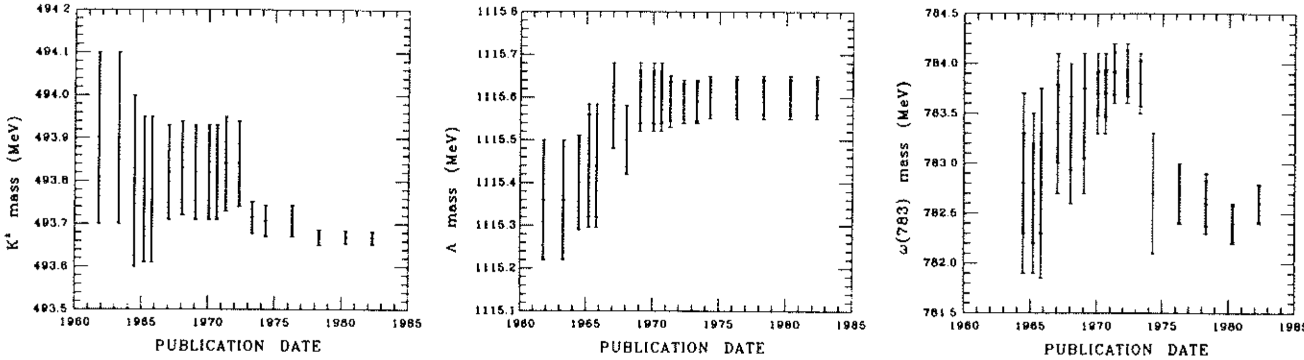


Fig. 4. Particle Data Group averages of the masses of various particles, as a function of date of publication of Review of Particle Properties (Adapted, with permission, from *Annual Review of Nuclear Science,* Volume 25. Copyright 1975 by Annual Reviews, Inc. All rights reserved). Full error bar indicates quoted error; thick-lined portion indicates quoted error with "scale factor" removed (see Sec. VII of introductory text).

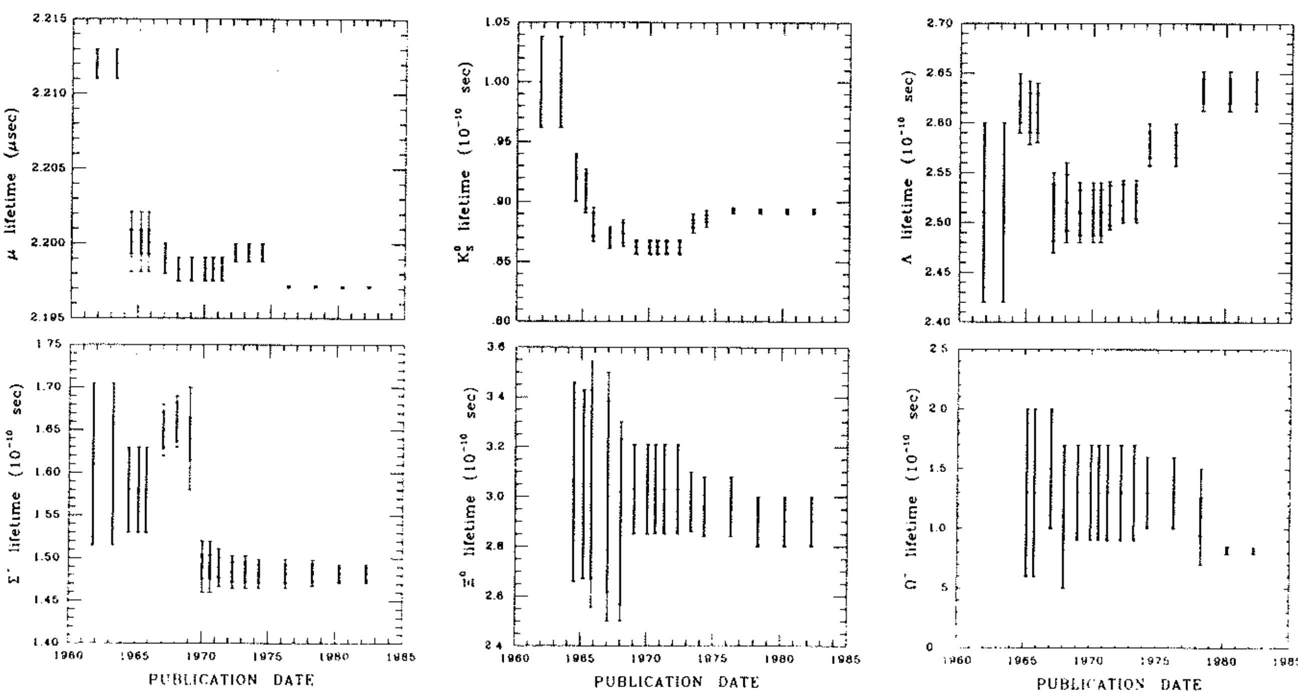


Fig. 5. Particle Data Group averages of the lifetimes of various particles, as a function of publication date of RPP.

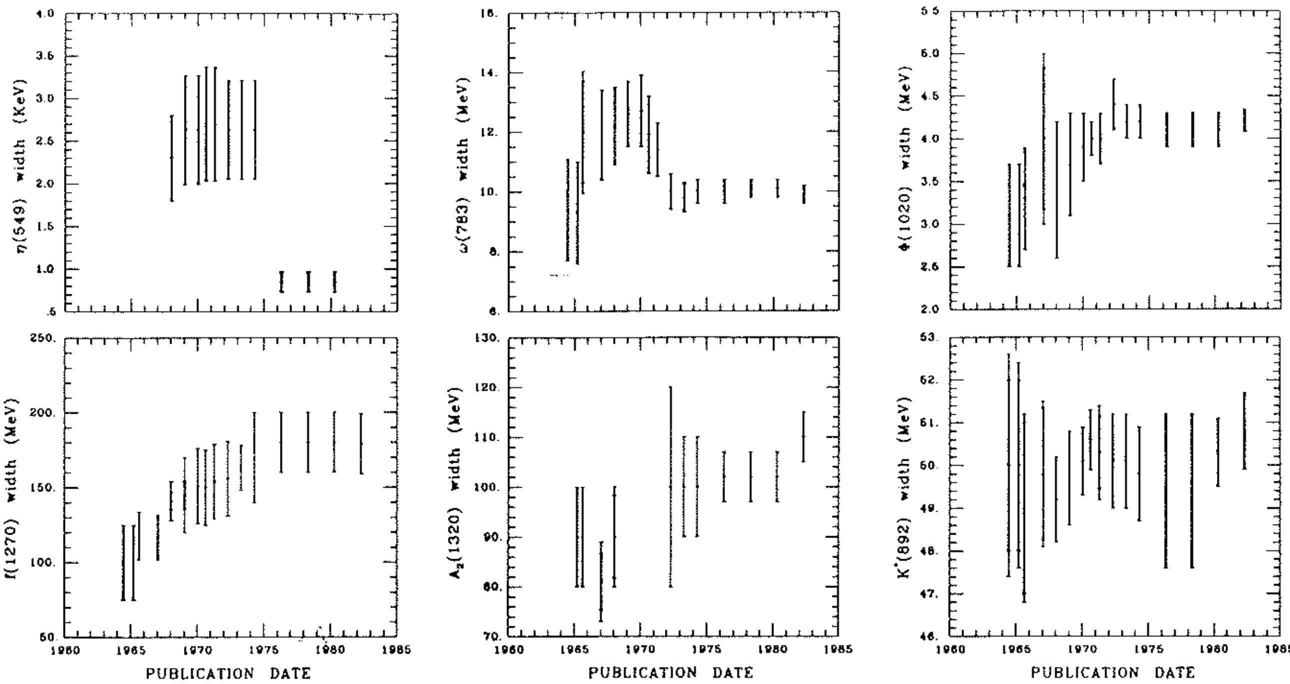


Fig. 6. Particle Data Group averages of the widths of various resonances, as a function of date of publication of RPP. The gap in the A_2 data indicates the years when the A_2 was thought to be split.

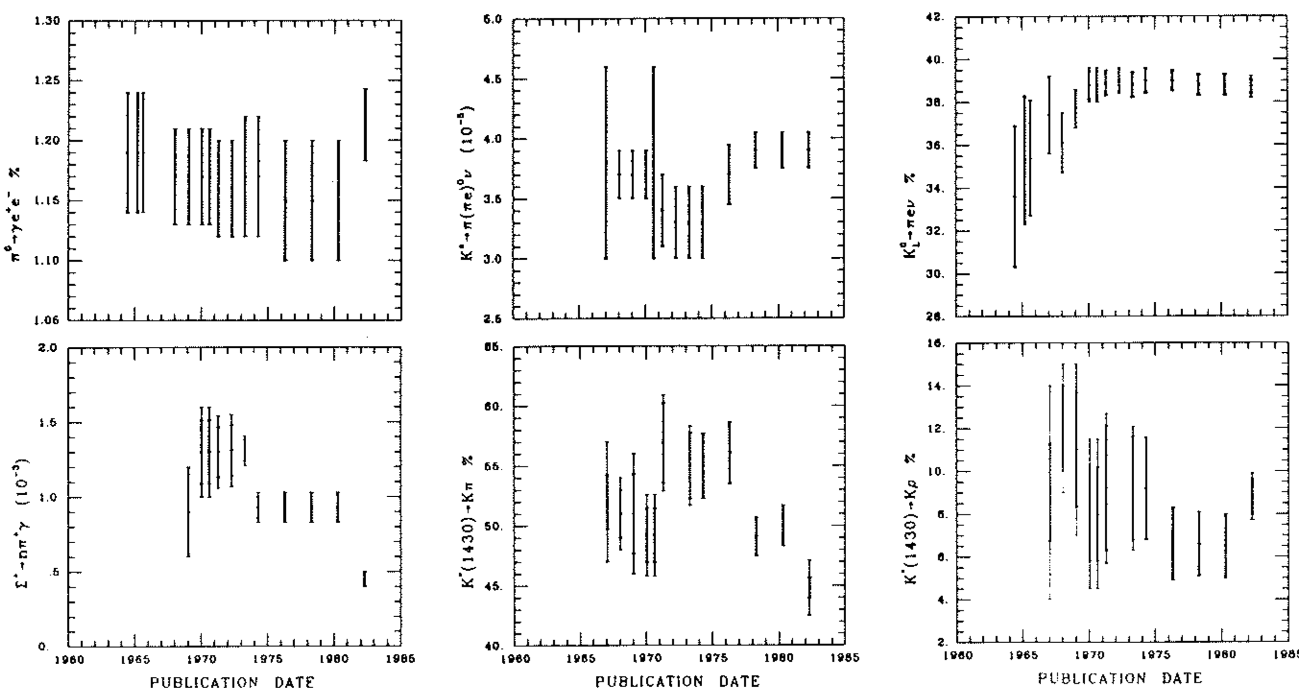


Fig. 7. Particle Data Group averages of various branching fractions, as a function of date of publication of RPP.

THE FUNDAMENTAL INTERACTIONS AND PARTICLES

THE PARTICLES OF THE MICROWORLD INTERACT VIA 4 KNOWN FORCES:

1. GRAVITY
2. ELECTROMAGNETISM

} LONG RANGE

3. STRONG FORCE
4. WEAK FORCE

} SHORT RANGE

IN AN ELEMENTARY INTERACTION, SUCH AS $a+b \to c+d$, WE SAY THAT THE INTERACTION TAKES PLACE DUE TO THE EXCHANGE OF A QUANTUM OF THE CORRESPONDING FORCE FIELD. ALL OF THESE QUANTA ARE BOSONS.

GRAVITY	$\longrightarrow$ GRAVITON	(SPIN 2, MASSLESS)	NOT YET OBSERVED
E & M	$\longrightarrow$ PHOTON	(SPIN 1, MASSLESS)	WELL KNOWN
STRONG FORCE	$\rightarrow$ GLUON	(SPIN 1, MASSLESS)	INDIRECTLY OBSERVED
WEAK FORCE	$\rightarrow$ $W^{\pm}, Z^0$	(SPIN 1, HEAVY)	OBSERVED IN 1982, 1983

THE FUNDAMENTAL PARTICLES WHICH INTERACT ARE NOW CATEGORIZED AS QUARKS AND LEPTONS, WHICH ARE ALL SPIN $1/2$ FERMIONS. TO EACH SUCH PARTICLE THERE IS A CORRESPONDING ANTI-PARTICLE. THESE PARTICLES HAVE VARIOUS INTERNAL QUANTUM NUMBERS WHICH ARE CONSERVED IN SOME OR ALL INTERACTIONS.

THERE ARE 5 KNOWN QUARKS, AND A 6TH IS COMMONLY BELIEVED TO EXIST, BUT AWAITS ACTUAL DISCOVERY.

TYPE	FLAVOR	CHARGE	APPROXIMATE MASS (MeV)
u	UP	$+2/3$	300
d	DOWN	$-1/3$	300
s	STRANGE	$-1/3$	500
c	CHARM	$+2/3$	1600
b	BOTTOM	$-1/3$	4800
t	TOP	$+2/3$	NOT YET KNOWN, MAYBE $\sim$ 50,000

THE QUARKS HAVE AN ADDITIONAL QUANTUM NUMBER, COLOR, WHICH PLAYS THE ROLE OF CHARGE FOR THE STRONG FORCE. EACH QUARK CAN HAVE 3 KINDS OF COLOR CHARGE, RED, GREEN, OR BLUE, COMPARED TO ONLY 1 KIND OF ELECTRIC CHARGE. ANTI-QUARKS HAVE ANTI-COLOR.

FOR AS YET UNEXPLAINED REASONS, THE COLOR FORCES SEEM TO OBEY CONFINEMENT - INDIVIDUAL COLORS ARE NOT DIRECTLY OBSERVABLE ($\Rightarrow$ INDIVIDUAL QUARKS NOT OBSERVABLE). INSTEAD, ALL KNOWN QUARK COMBINATIONS ARE COLOR SINGLETS - ANTI-SYMMETRIC COMBINATIONS OF THE VARIOUS COLORS WHICH HAVE NET COLOR ZERO.

UNLIKE PHOTONS WHICH CARRY NO ELECTRIC CHARGE, THE GLUONS CARRY COLOR (OR MORE PRECISELY, A COLOR AND AN ANTI-COLOR) SO THAT GLUONS CAN INTERACT DIRECTLY WITH OTHER GLUONS. IN PRINCIPLE 2 GLUONS COULD COMBINE TO FORM A BOUND STATE = "GLUEBALL"

AS THE STRONG GLUON FIELD CAN INTERACT WITH ITSELF, THE SUPERPOSITION PRINCIPLE DOES NOT HOLD, AND THE THEORY OF THE STRONG FORCE IS NON-LINEAR. GRAVITY ALSO IS A NON-LINEAR FORCE, AS GRAVITONS CAN INTERACT WITH GRAVITONS AS WELL AS OTHER FORMS OF MATTER.

THE COLOR FORCES APPEAR TO FAVOR ONLY 2 ARRANGEMENTS OF QUARKS:

TRIPLETS qqq AND QUARK-ANTIQUARK DOUBLETS $q\bar{q}$

THE TRIPLETS ARE CALLED <u>BARYONS</u> AND THE DOUBLETS <u>MESONS</u>

THE PATTERNS OF ARRANGEMENT OF QUARKS INTO HADRONS AND MESONS ARE GOVERNED IN SOME WAY BY GROUP THEORY. IF WE CONSIDER ONLY 3 QUARK, $u, d,$ AND s, AS INGREDIENTS, THE SU(3) ALGEBRA HOLDS.

BARYONS:

	n udd		p uud			
Σ^- dds	Λ, Σ^0 uds		Σ^+ uus			
	Ξ^- dss		Ξ^0 uss			

SPIN 1/2

<u>FLAVOR</u> <u>OCTET</u>

Δ^- ddd	Δ^0 udd	Δ^+ uud	Δ^{++} uuu
Σ^{*-} dds	Σ^{*0} uds	Σ^{*+} uus	
Ξ^{*-} dss	Ξ^{*0} uss		
Ω^- sss			

SPIN 3/2

<u>DECUPLET</u>

MESONS:

K^0 $d\bar{s}$		K^+ $u\bar{s}$
π^- $d\bar{u}$	η, π^0 $u\bar{u}, d\bar{d}$ $s\bar{s}$	π^+ $u\bar{d}$
K^- $s\bar{u}$		$\bar{K}^0$ $s\bar{d}$

SPIN 0

K^{*0} $d\bar{s}$		K^{*+} $u\bar{s}$
ρ^- $d\bar{u}$	ω, ρ^0 $u\bar{u}, d\bar{d}$ $s\bar{s}$	ρ^+ $u\bar{d}$
K^{*-} $s\bar{u}$		$\bar{K}^{*0}$ $s\bar{d}$

SPIN 1

ALSO A SPIN 1 SINGLET : $\phi = \frac{1}{\sqrt{3}}\left(u\bar{u} + d\bar{d} + s\bar{s}\right)$

ANY PARTICLE CONTAINING QUARKS IS CALLED A <u>HADRON</u>.

THE LEPTONS HAVE NO COLOR CHARGE, AND SO DO NOT INTERACT STRONGLY. THERE ARE 3 KNOWN PAIRS OF LEPTONS

$$\begin{pmatrix} e^- \\ \nu_e \end{pmatrix} \qquad \begin{pmatrix} \mu^- \\ \nu_\mu \end{pmatrix} \qquad \begin{pmatrix} \tau^- \\ \nu_\tau \end{pmatrix}$$

$$M_e = .5\,\text{MeV} \qquad M_\mu = 105 \qquad M_\tau \simeq 1872$$

THE NEUTRINOS ν_e, ν_μ, ν_τ HAVE NO ELECTRIC CHARGE, AND NO MAGNETIC MOMENT, SO THEY DO NOT INTERACT ELECTROMAGNETICALLY EITHER.

THE NEUTRINOS ARE VERY NEARLY, IF NOT EXACTLY, MASSLESS. ALTHOUGH THEY ARE SPIN ½ PARTICLES THEY APPEAR TO HAVE ONLY 1 POSSIBLE SPIN ORIENTATION: SPIN OPPOSITE TO THE DIRECTION OF MOTION ≡ LEFT HANDED HELICITY

$$\nu \;\; \xrightarrow[\text{MOTION}]{\overset{\text{SPIN}}{\longleftarrow}}$$

ANTI-NEUTRINOS HAVE RIGHT HANDED HELICITY.

THE CONVENTION IS THAT NEGATIVELY CHARGED LEPTONS ARE PARTICLES, WHILE POSITIVELY CHARGED LEPTONS ARE ANTIPARTICLES.

FOR THE HADRONS, THE QUARK TRIPLETS ARE PARTICLES, ANTI QUARK TRIPLETS ARE ANTIPARTICLES. FOR THE MESONS THERE IS NO CLEAR RULE AS TO WHICH IS A PARTICLE OR ANTIPARTICLE; FOR EXAMPLE, THE π^0 IS ITS OWN ANTIPARTICLE!

YUKAWA'S IDEA - MESON THEORY

YUKAWA HAD THE VISION THAT THE NUCLEAR FORCE MIGHT BE SOMETHING LIKE ELECTROMAGNETISM, BUT THAT THE QUANTUM OF THE FORCE FIELD - THE MESON - HAS NON-ZERO MASS. THE BASIC FEATURES OF HIS ARGUMENT CAN BE UNDERSTOOD SEMI-CLASSICALLY.

THE ELECTROMAGNETIC POTENTIAL OBEYS A WAVE EQUATION

$$\nabla^2 \varphi - \frac{1}{c^2}\frac{\partial^2 \varphi}{\partial t^2} = 0$$ IN FREE SPACE. PLANE WAVE SOLUTIONS

HAVE THE FORM $\varphi = e^{i(\omega t - \vec{k}\cdot\vec{r})}$ WITH $\omega = kc$.

THE STATIC POTENTIAL DUE TO A POINT CHARGE AT REST SATISFIES

$$\nabla^2 \varphi = 4\pi e\, \delta(\vec{r}) \qquad \text{OR} \qquad \varphi = e/r$$

YUKAWA ASKS US TO CONSIDER THE MODIFICATIONS:

$$\nabla^2\varphi - \frac{1}{c^2}\frac{\partial^2\varphi}{\partial t^2} = \mu^2\varphi$$ FOR WAVES, & $$\nabla^2\varphi - \mu^2\varphi = 4\pi g\,\delta(\vec{r})$$ FOR A POINT 'CHARGE' g. A TRIAL PLANE WAVE SOLUTION $e^{i(\omega t - \vec{k}\cdot\vec{r})}$

LEADS TO THE DISPERSION RELATION $\frac{\omega^2}{c^2} = k^2 + \mu^2$

INVOKING THE DE BROGLIE RELATIONS $E = \hbar\omega$, $p = \hbar k$, WE HAVE

$E^2 = p^2c^2 + \hbar^2\mu^2c^2$. THUS WE IDENTIFY THE MASS OF THE WAVES AS $M = \frac{\hbar\mu}{c}$. (IN THIS SENSE A PHOTON INSIDE A DIELECTRIC MEDIUM HAS A MASS!)

FOR THE STATIC SOLUTION WE EXPECT A SPHERICALLY SYMMETRIC POTENTIAL SO $\nabla^2\varphi \Rightarrow \frac{1}{r}\frac{\partial^2}{\partial r^2}(r\varphi)$. OUTSIDE THE ORIGIN, THEN,

$\frac{\partial^2}{\partial r^2}(r\varphi) = \mu^2(r\varphi) \Rightarrow r\varphi = K e^{\pm\mu r}$. CLEARLY $\varphi = K\frac{e^{-\mu r}}{r}$ ONLY.

BY CONSIDERING A SMALL SPHERE ABOUT THE ORIGIN AND USING GAUSS' LAW WE FIND $\varphi = \frac{g}{r}e^{-\mu r}$

THIS IS A SHORT RANGE POTENTIAL, OF CHARACTERISTIC LENGTH

$$r \sim \frac{1}{\mu} = \frac{\hbar}{Mc}$$ ($\equiv$ COMPTON WAVELENGTH OF THE MESON)

IF THE MESON POTENTIAL HOLDS NUCLEI TOGETHER, THEN WE EXPECT $r \sim$ SIZE OF DEUTERON, KNOWN TO BE ABOUT 1.5 FERMIS FROM EXPERIMENTS OF RUTHERFORD ET AL. HENCE

$$M \sim \frac{1}{1.5\text{ FERMIS}} = \frac{197\text{ MeV FERMI}}{1.5\text{ FERMI}} = 132\text{ MeV}$$

IN 1947 THE $\pi^\pm$ MESONS WERE FOUND IN COSMIC RAYS, WITH MASS 140 MeV. PERKINS WAS THE FIRST TO SHOW THAT THESE MESONS INTERACT STRONGLY, AND SO APPEAR TO AGREE RATHER WELL WITH YUKAWA'S IDEA!

THE MESON THEORY WAS SOON APPLIED TO A MODEL OF THE PROTON AND NEUTRON. THE PROTON IS VIEWED NOT AS A STATIC OBJECT, BUT CONTINUALLY UNDERGOING SUCH TRANSFORMATIONS AS

$$p \leftrightarrow n + \pi^+ \qquad p \leftrightarrow p + \pi^0$$

SIMILARLY $\quad n \leftrightarrow p + \pi^- \qquad n \leftrightarrow n + \pi^0$

THESE QUANTUM FLUCTUATIONS, OF COURSE, CANNOT LAST VERY LONG, GOVERNED BY $\Delta E \, \Delta t \sim \hbar$, SO $\Delta t \sim \hbar / 130\,\mathrm{MeV} \sim \frac{1.5\ \mathrm{FERMI}}{c} \sim 10^{-23}$ SEC.

PEOPLE SOMETIMES TALK OF THE PION CLOUD SURROUNDING THE PROTON. IN THIS VIEW THE SIZE OF THE PROTON IS REALLY THE SIZE OF THE PION CLOUD.

WE CAN ESTIMATE THE MESON COUPLING CONSTANT g, AS FOLLOWS.

SCATTERING OF π-MESONS OFF PROTONS IS THE ANALOGUE OF SCATTERING PHOTONS OFF ELECTRONS. J.J. THOMSON TELLS US (VIA CLASSICAL E&M) THAT FOR THE LATTER:

$$\sigma_{\text{THOMSON}} = \frac{8\pi}{3}\left(\frac{e^2}{m_e c^2}\right)^2 = \frac{8\pi}{3}\left(\frac{e^2}{\hbar c}\right)^2\left(\frac{\hbar}{m_e c}\right)^2$$

"CLASSICAL ELECTRON RADIUS"

FOR π-P SCATTERING THE ANALOGUE OF $e^2/\hbar c$ IS $\dfrac{g^2}{\hbar c} \equiv \alpha_{\text{STRONG}}$

WE MIGHT THINK TO REPLACE m_e BY M_p, BUT IN THE PION CLOUD VIEW OF THE PROTON, THE π-MESONS WILL SCATTER OFF THE CLOUD (THE QUANTUM-QUANTUM SCATTERING NOT ALLOWED IN E&M) AND SO M_π IS THE APPROPRIATE MASS.

$$\text{So} \quad \sigma_{\pi p} \sim 4\pi \left(\frac{g}{\hbar c}\right)^2 \left(\frac{\hbar}{M_\pi c}\right)^2$$

WE USE 4π RATHER THAN $\frac{8\pi}{3} = \frac{2}{3} \cdot 4\pi$ AS A PHOTON HAS ONLY 2 OF THE POSSIBLE 3 SPIN STATES OF A SPIN 1 PARTICLE, AND THE CROSS-SECTION IS CORRESPONDING REDUCED.

EXPERIMENTALLY, $\sigma_{\pi p_{\text{ELASTIC}}} \sim 3$ MILLIBARNS (ABOVE THE RESONANCE REGION) (SEE DATA ON P.25)

$$\text{So} \quad 3 \times 10^{-27}\ \mathrm{cm}^2 = 4\pi\, \alpha_s^2\, (1.5 \times 10^{-13})^2$$

$\Rightarrow \alpha_s \sim 0.1$

A REASONABLE ESTIMATE FOR STRONG INTERACTIONS AT C.M. ENERGIES 2–10 GeV.

ANOTHER ASPECT OF MESON THEORY WAS A MODEL OF THE PION DUE TO FERMI & YANG (1949). IN THIS, A PION IS MADE OF A NUCLEON-ANTINUCLEON PAIR:

$$\pi^+ \leftrightarrow p\bar{n}$$

$$\pi^0 \leftrightarrow \frac{1}{\sqrt{2}}(p\bar{p} - n\bar{n})$$

$$\pi^- \leftrightarrow n\bar{p}$$

RECALL THAT A PROTON IS ALSO THOUGHT OF AS $p \leftrightarrow n\pi^+$ or $p\pi^0$. SO WE HAVE A KIND OF CIRCULARITY. THIS IDEA WAS POPULAR FOR QUITE A WHILE AND HAS A CERTAIN PHILOSOPHICAL APPEAL. ALL ELEMENTARY PARTICLES ARE MADE OUT OF ALL OTHERS: THE BOOTSTRAP IDEA. THIS NOTION VERY NEATLY PUTS AN END TO THE QUEST FOR FINER AND FINER SUBDIVISION OF MATTER.

HOWEVER THE QUARK MODEL OF MESON AND NUCLEON STRUCTURE HAS TRIUMPHED OVER THE BOOTSTRAP MODEL, FOR NOW AT LEAST.

AS AN EXAMPLE OF A SIMPLE FACT BETTER PREDICTED BY THE QUARK MODEL THAN MESON THEORY, CONSIDER THE TOTAL CROSS SECTIONS AT HIGH ENERGY

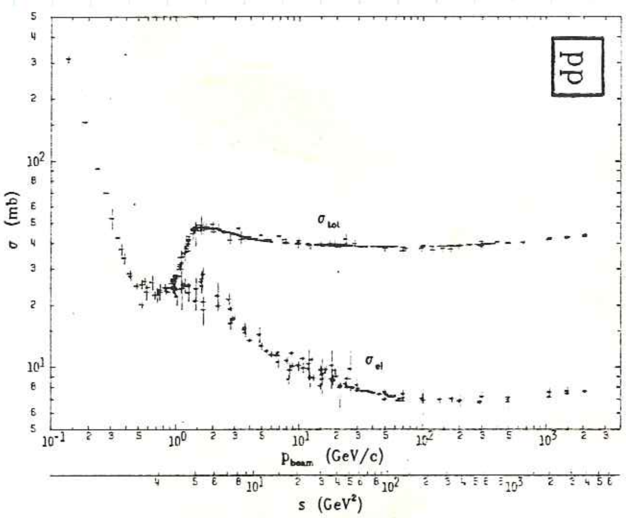
$\sigma_{\pi^- p} \sim \sigma_{K^- p} \sim 25\,\text{mb}$ while $\sigma_{pp} \sim 40\,\text{mb}$.

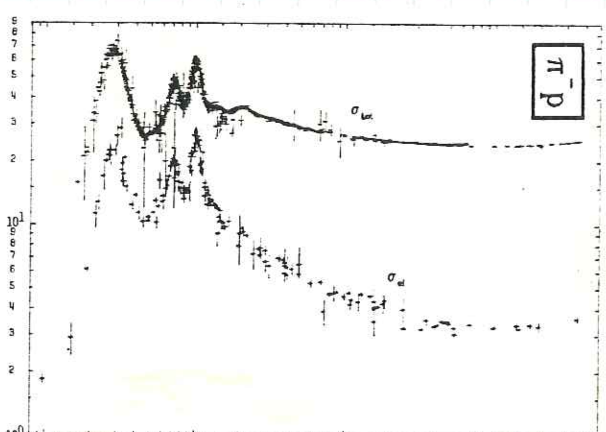
THE INTERACTION AMONG ALL QUARK FLAVORS IS OF EQUAL STRENGTH, SO

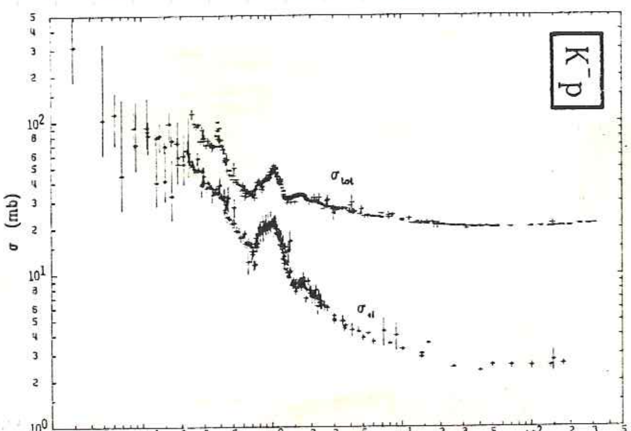
$\sigma_{\text{MESON-HADRON}} \sim 2 \times 3 = 6$ UNITS

$\sigma_{\text{HADRON-HADRON}} \sim 3 \times 3 = 9$ UNITS

THE UNIT, $\sigma_{\text{QUARK-QUARK}} \sim 4\,\text{mb}$







Dec. 10, 1983

ALBERT O. ROBERTS
216 LATTA RD. DURHAM, N.C. 27712
PHONE 919-477-4289

Dr. C. Quigg
Fermi Nat'l Lab.
Batavia, Illinois
60510

N U C L E O N S

Believe it or not! Ignore it at your own risk!

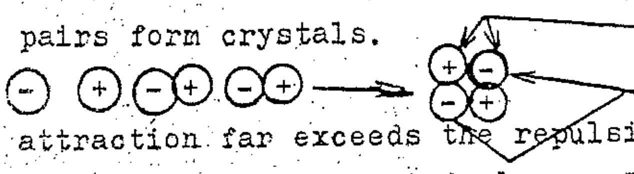
"Nucleons are made of Electrons(e^-) and Positrons (e^+)."

We put e^- and e^+ and nothing else into the vacuum of an accelerator and Nucleons come out. This is proof enough of this beautiful, simple truth, but there is much more evidence.

Nucleons in collision break up into Mesons. Some of these are positive, some negative, some neutral. This proves that there were many e^- and e^+ within the Nucleons. Mesons decay very quickly and the end product is e^- and e^+.

These facts are irrefutable. Rejoice with me, the problem is solved. Lets file the quarks away with the old phlogiston and get on with science.

The method nature uses to assemble e^- and e^+ into Nucleons is crystallization as it is in all dense materials. Collisions of e^- and e^+ form pairs $(e^-e^+)^o$, and pairs form crystals.



Unlike particles are close together.
Like particles are separated, so the coulomb attraction far exceeds the repulsion. These forces hold things together, so we dont need the postulated gluons. The repulsive forces prevent black holes. This diagram shows the begining of a nucleon crystal. The pattern is the cubic lattice.

The neutral nucleon, or neutron, has a balanced charge. It has the same number of e^- as e^+. By mass ratio, it has 919 e^- and 919 e^+. The positive nucleon, or proton has one unmatched e^+. The neutron often changes into a proton by emiting one e^- and one pair $(e^-e^+)^o$ which we call a neutrino. So the proton has 917 e^- and 918 e^+.

The 2 and only primordial elementary particles are e^- and e^+. Neither is an antiparticle. They join to form neutral pairs $(e^-e^+)^o$ which is the ubiquitous positronium. This is almost undetectable, so it seems to annihilate. Here is the missing mass. Nucleons are the solid state of positronium. Our great storehouse of mass and energy is a universe filled with positronium $(e^-e^+)^o$. To make electricity, we pull these pairs apart in magnetic fields.

If we cannot believe what our accelerators are telling us, why should we keep spending billions on larger and larger accelerators? I hope that some good scientists will recognize this viewpoint as a possible breakthrough, and will publish reviews on this paper and/or my book The Nucleon Simplified. I am now 87, so this may be my last effort to get this important matter before the forum.

Albert O. Roberts

PS This is the science of the **future**. You can help introduce this simple, beautiful truth. Will you ride up front, or follow in the rear?