Kaons - A Micro-physics Laboratory

"Will you still need me when I'm 64?" (The Beatles)

William A. Bardeen

Guest Scientist Retired

Fermilab

- Outline

-Discovery

-Symmetries

-Quarks

-Weak Matrix Elements

-Future Prospects

- Pion Discovery - 1947

Yukawa's mesotron is discovered in 1947 in high altitude cosmic ray emulsions and later as pions produced artificially by accelerators in 1948.

- C. Lattes, H. Muirhead, G. Occhialini and C. Powell, Nature 159:694(1947)
- E. Gardner and C. Lattes, Science 107:270(1948)

Confirms two meson conjecture.

- S. Sakata and K. Inouye (1942), Prog.Theor. Phys. 1:143(1946)
- Y. Tanikawa, Prog.Theor.Phys. 2:220(1947)
- R.E. Marshak and H.A. Bethe, Phys.Rev. 72(1947)506

The neutral pion was also discovered in its two photon mode at accelerators in 1950.

- J. Steinberger, W. Panofsky and J. Steller, Phys.Rev. 78:802(1950)

• V-particle Discovery - 1947

Two unusual cosmic ray events seen in a cloud chamber experiment with a characteristic V shape.

• G.D. Rochester and C.C. Butler, Nature 160(1947)855

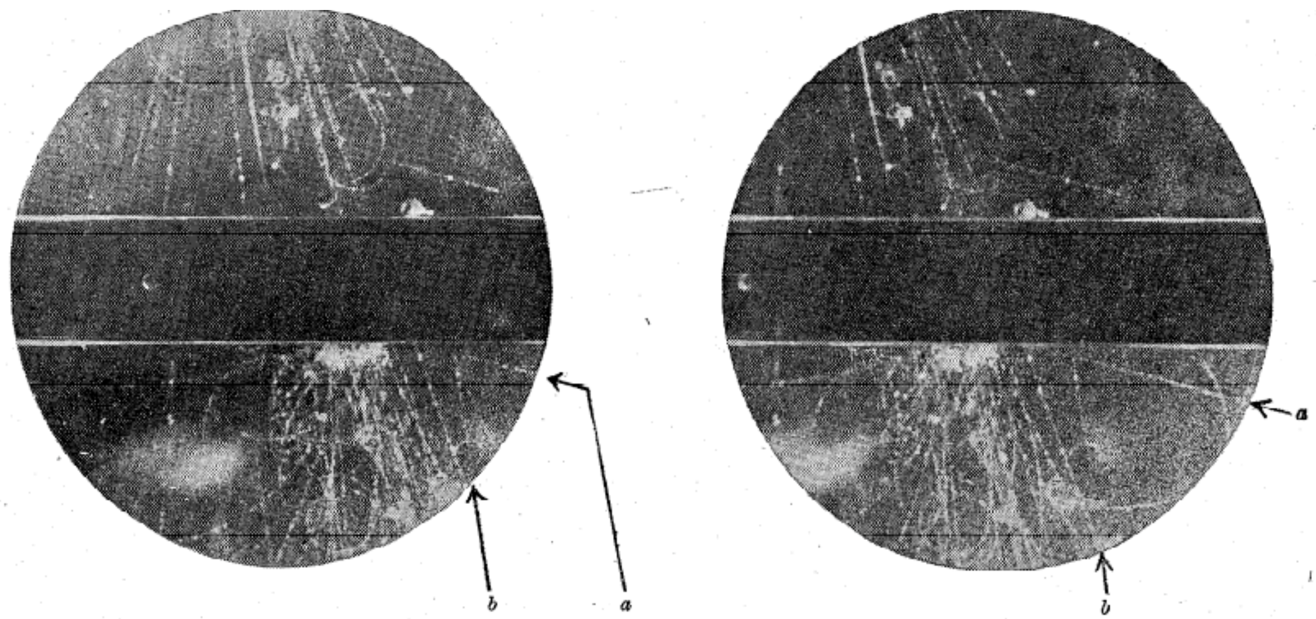


Fig. 1. STEREOSCOPIC PHOTOGRAPHS SHOWING AN UNUSUAL FORK (a b) IN THE GAS. THE DIRECTION OF THE MAGNETIC FIELD IS SUCH THAT A POSITIVE PARTICLE COMING DOWNWARDS IS DEVIATED IN AN ANTICLOCKWISE DIRECTION

• V-particle Discovery

An emulsion picture of a three pion event (1948).

• R. Brown et al (Bristol Group), Nature 60(1949)855

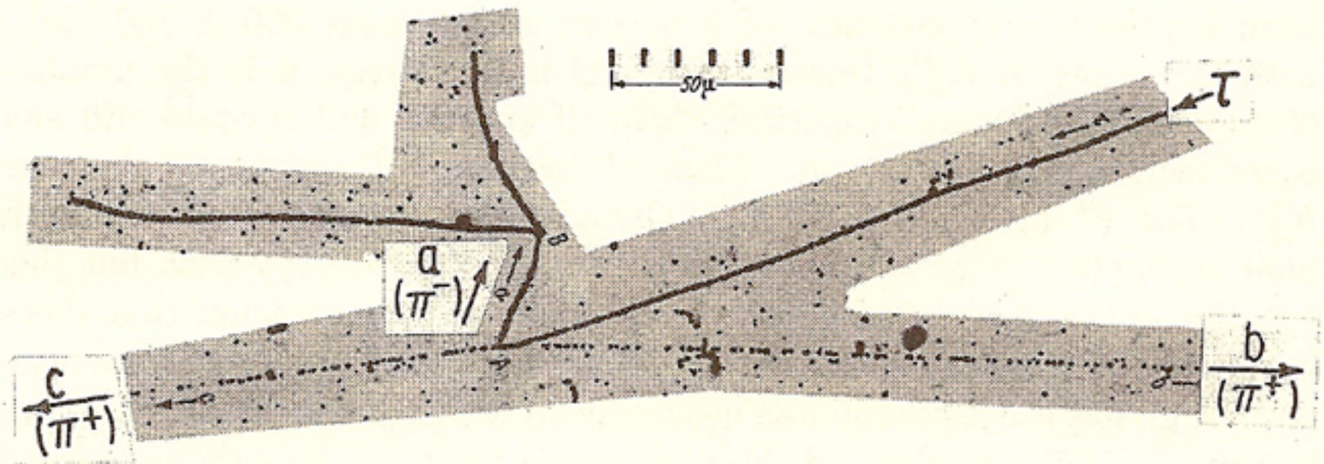


Figure 1.2: First τ^+ event. See text for explanation of tracks.

- V-particle Discovery

New techniques - precision emulsions, bubble chambers
New accelerators - Bevatron, Cosmotron

Copious production of new mesons and hyperons indicating strong production but with long lifetimes indicating weak decays.

Associated production of new particles - V-parity?

- Y. Nambu, K. Nishijima and Y. Yamaguchi, Prog.Theor.Phys. 6(1951)615,619
- H. Miyazawa, Prog.Theor.Phys. 6(1951)631
- S. Oneda, Prog.Theor.Phys. 6(1951)633
- A. Pais, Phys.Rev. 86(1952)663

- V-particle Discovery

Charge independence, isospin and strangeness

Mesons are distinct doublets with isospin 1/2. New additive quantum number, strangeness (not V-parity), is conserved in the strong production process.

- T. Nakano and K. Nishijima, Prog.Theor.Phys. 10(1953)581
- M. Gell-Mann, Phys.Rev. 92(1953)833

Neutral Particle Mixing and Charge Conjugation

Neutral Meson Mass eigenstates are odd or even under C (later CP) but with different lifetimes, K_1 and K_2

- M. Gell-Mann and A. Pais, Phys.Rev. 97(1954)1387

\- Longer lived meson observed at Cosmotron (1955).

- V-particle Discovery

Kinematic Distributions - The Dalitz Plot for τ+ decay
- Search for structure, evidence for parity violation.
- R.H. Dalitz, Phys.Rev. 94(1954)1046, Rep.Prog.Phys. <u>20</u>(1957)

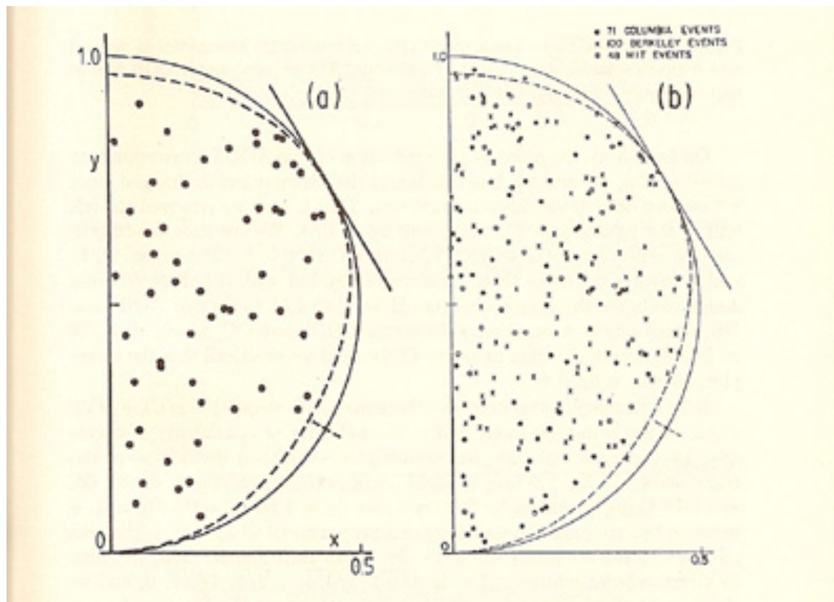


Figure 1.5: Phase space plots for τ^+ decays. (a) 58 cosmic ray events in 1955; (b) 219 Bevatron events in 1956.

• Symmetries

Sakata Model of fundamental constituents (P,N,Λ)
-Mesons and some hyperons as composite states
-Extension of the Fermi-Yang model
-Success in describing properties of mesons but difficulty interpreting baryons

• S. Sakata, Prog.Theor.Phys. 16(1956)

SU(3) and the eightfold way

• Y. Ne'eman, Nucl.Phys. 26(1961)1067
• M. Gell-Mann, Phys.Rev. 125(1962)1067
• S. Okubo, Prog.Theor.Phys. 27(1962)949

Meson octets, baryon octet and decuplet, mass relations and decay patterns

- Symmetries

Leptonic decays probe structure of hadronic weak currents

-Currents are also octets of the eightfold way.
-Evidence based on leptonic decays of hyperons.
-Strangeness changing currents are generated by SU(3) rotation of the weak isospin current - the Cabbibo angle.

- N. Cabbibo, Phys.Rev.Lett. 10(1963)531

$$J_\mu = \cos\theta(J_\mu^{(0)} + g_\mu^{(0)}) + \sin\theta(J_\mu^{(1)} + g_\mu^{(1)}), \ \theta \sim 0.26$$

-Dualities with weak mixing of leptonic currents

- Z. Maki, M. Nakagawa and S. Sakata, Prog.Theor.Phys. 28(1962)870

• Symmetries

Observation CP Violation in Kaon decays

• J.H. Christenson, J.W. Cronin, V.L. Fitch and R. Turlay, Phys.Rev. Lett. 13(1964)138

Clever use of coherent regeneration allows observation of CP violation in the two pion decays of the K_2 meson.

$$\mathrm{K}_2^o = \frac{1}{\sqrt{2}}\left(\left(K_o - \overline{K}_o\right) + \varepsilon\left(K_o + \overline{K}_o\right)\right)$$

Small mixing parameter: $\varepsilon \sim 2.3\times10^{-3}$

• Quarks

Kaon physics has inspired four of the six known quarks.

Gell-Mann (quarks) and Zweig (aces) propose hadronic constituents (u,d,s) with fractional baryon number, B=1/3. Baryons are qqq states. Similar to Sakata triplet model but with fundamentally different physics implications.

- M. Gell-Mann, Phys.Lett. 8(1964)214
- G. Zweig, CERN-8182-TH-401 (1964), CERN-8419-TH-412 (1964)

In Cabbibo theory, the weak current involves only the quark combination $(d\cos\theta+s\sin\theta)_L$ and the orthogonal combination $(-d\sin\theta+s\cos\theta)_L$ is uncoupled.

- Quarks

Glashow, Iliopoulos and Maiani argue that the strong suppression of the neutral current decays of the K_2 and K^+ mesons requires a remarkably low cutoff of 3-4 GeV for higher order weak processes.

- S.L. Glashow, J. Iliopoulos and L. Maiani, Phys.Rev. D2(1970)1285

They suggest the existence of a new charm quark coupled to the orthogonal d,s quark combination. The natural suppression of neutral current processes occurs from the cancellations between up and charm quark contributions to higher order processes.

The charm quark can not be heavier than a few GeV.

• Quarks

In 1972, Kobayashi and Maskawa study the possible source of the CP violation responsible for K_1K_2 mixing observed by Fitch and Cronin in 1964. They argue that the four quark GIM model can not produce CP violation within the framework of the new renormalizable standard model of the electroweak interactions.

-The minimal model with CP violation requires six quarks in three weak doublets. The weak mixing matrix for charged current interactions contains three angles and one new CP violating phase, V_{CKM}.

-The charm, bottom and top quarks have all been subsequently discovered.

•M. Kobayashi and T. Maskawa, Prog.Theor.Phys. 49(1973)652

• Direct CP Violation

CP violation can occur indirectly through mixing of the CP eigenstates, K_1 and K_2, measured by ε, or through direct CP violation in the decay amplitudes as measured by ε'/ε.

$$\eta_{+-} = \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} = \varepsilon + \varepsilon', \quad \eta_{oo} = \frac{A(K_L \to \pi^o\pi^o)}{A(K_S \to \pi^o\pi^o)} = \varepsilon - 2\varepsilon'$$

$$\frac{\Gamma(K_L \to \pi^+\pi^-)}{\Gamma(K_S \to \pi^+\pi^-)} / \frac{\Gamma(K_L \to \pi^o\pi^o)}{\Gamma(K_S \to \pi^o\pi^o)} = 1 + 6\mathrm{Re}(\varepsilon'/\varepsilon)$$

$\mathrm{Re}(\varepsilon'/\varepsilon)$ measured precisely by NA48 and KTeV

-NA48(2001): $(14.7 \pm 2.2) \times 10^{-4}$

-KTeV(2011): $(19.2 \pm 2.1) \times 10^{-4}$

• Weak Matrix Elements

Testing the standard model and the CKM paradigm in weak interaction processes.

Nonperturbative evaluation of hadronic weak matrix elements.

Factorization of short distance physics using the operator product expansion.

The effective weak Hamiltonian:

$$\mathrm{H}_{\mathrm{wk}} = \frac{G_F}{\sqrt{2}} \sum_i V_{CKM}^i C_i(\mu) Q_i(\mu)$$

$$A(M \to F) = \langle F | \mathrm{H}_{\mathrm{wk}} | M \rangle = \frac{G_F}{\sqrt{2}} \sum_i V_{CKM}^i C_i(\mu) \langle F | Q_i(\mu) | M \rangle$$

$C_i(\mu)$ - perturbative short distance physics
$\langle Q_i(\mu)\rangle$ - nonperturbative operator matrix elements

• Weak Matrix Elements

Approaches to computing operator matrix elements

-Chiral perturbation theory
-Large Nc expansions
-Lattice field theory
-Quark effective field theories
-Meson effective field theories
-Hidden local symmetry
-ADS/CFT

- Weak Matrix Elements

Precision lattice results. (latticeaverages.org)

f_π	129.5±1.7 MeV	1.3%
f_K	156.0±1.1 MeV	0.7%
f_K/f_π	1.1931±0.0053	0.6%
B_K	0.734±0.020	1.5%
$f_+^{K\pi}(0)$	0.9584±0.0044	0.5%

$K\pi\pi$ Amplitudes, $\Delta I=3/2$ (Mahwinney, Lattice 2011)

$$\mathrm{Re}(A_2) = (1.40 \pm 0.08_{stat} \pm 0.12_{NPR} \pm 0.14_{sys}) \times 10^{-8} GeV$$

$$\mathrm{Im}(A_2) = -(5.65 \pm 0.31_{stat} \pm 0.37_{NPR} \pm 0.60_{sys}) \times 10^{-13} GeV$$

$$\mathrm{Re}(A_2) = 1.484 \times 10^{-8} GeV \ \text{(experiment)}$$

$K\pi\pi$ Amplitudes, $\Delta I=1/2$, ε'/ε - not yet

• Future Prospects

Golden Modes:

P. Valente (2008)

	Short-distance contribution (Γ_{sd}/Γ)	Irreducible theory error on amplitude	**Total SM BR**
$K^0_L \to \pi^0 \nu \nu$	**>99%**	**1%**	**3×10^{-11}**
$K^+ \to \pi^+ \nu \nu$	88%	3%	**8×10^{-11}**
$K^0_L \to \pi^0 e^+ e^-$	38%	15%	**3.5×10^{-11}**
$K^0_L \to \pi^0 \mu^+ \mu^-$	28%	30%	**1.5×10^{-11}**

• Future Prospects

New Physics in K->$\pi\nu\underline{\nu}$

K. Staub (2011)

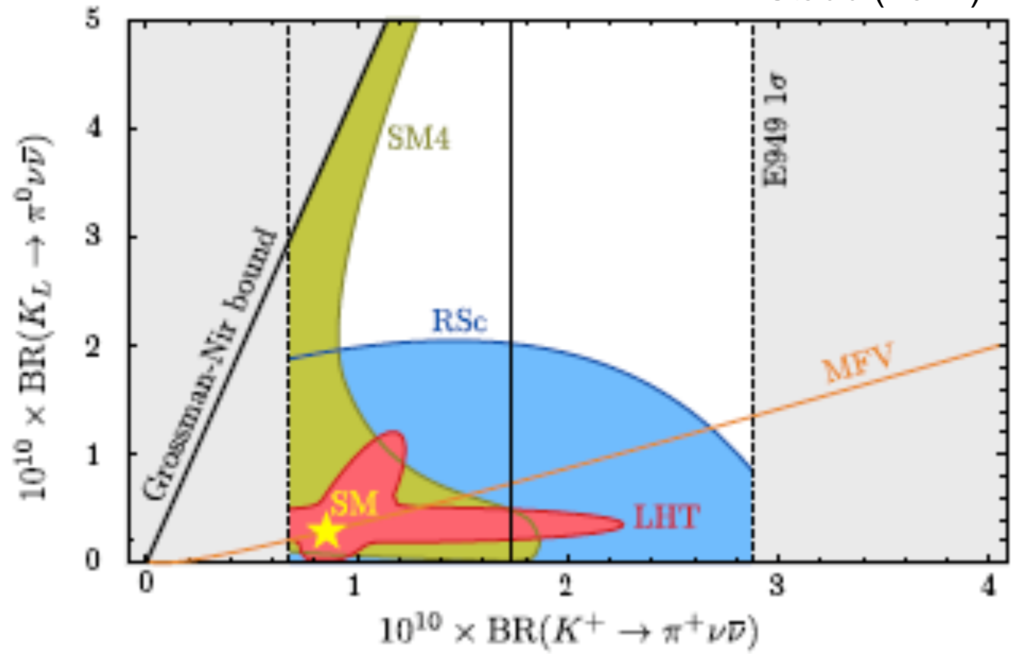


Figure 1: Correlation between the branching ratios of $K_L \to \pi^0 \nu\bar{\nu}$ and $K^+ \to \pi^+ \nu\bar{\nu}$ in MFV and three concrete NP models. The gray area is ruled out experimentally or model-independently by the GN bound. The SM point is marked by a star.

- Future Prospects

CERN (2012-2013)
- NA62: $K^+ \to \pi^+ \nu \underline{\nu}$ ~100 SM events
- Upgrades possible to ~1000 event level

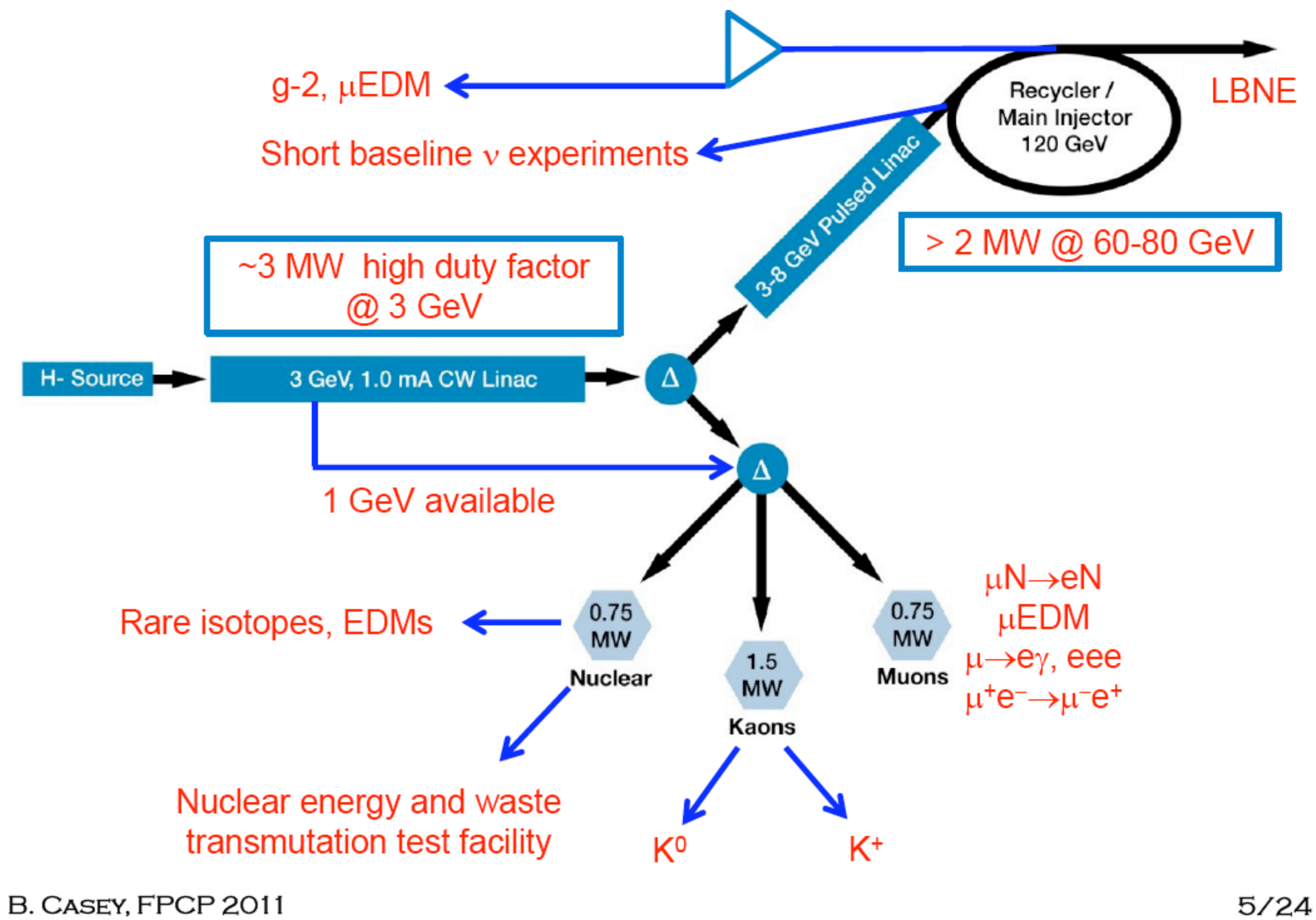
J-Parc (2013-2015)
- KOTO: $K_L \to \pi^0 \nu \underline{\nu}$ few SM events in 3yr
- TREK: $K^+ \to \pi^0 \mu^+ \nu$, T-violation, $\delta P_T \sim 10^{-4}$, SM $\sim 10^{-7}$

KLOE and KLOE-2 (2013-15) 20fb^{-1}
- $K \to \pi l \nu$: $f_+(0)V_{us}$, $K \to 3\pi$, interferometry

Fermilab (2020-)
- Project X: Intense charged and neutral Kaon beams

- Future Prospects

Project X - Proposed Beamlines



Happy Birthday!

Kaons at 100_8

Shoichi Sakata at 100_{10}

Yes, we do still need you.