Kaons — A Micro-Physics Laboratory

—— *"Will You Still Need Me When I'm 64?" (The Beatles)* ——

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I explore the essential role that kaons have played in revealing the nature of the micro-physics world of elementary particle physics.

§1. Discovery

Sixty-four years ago marked a remarkable year of discovery in elementary particle physics. In 1947, Yukawa's mesotron was finally discovered in high altitude cosmic ray data by the Powell and Bristol Group[1] using photographic emulsions and later observed as pions artificially produced at accelerators by Gardner and Lattes[2] in 1948. The neutral pion was later discovered in its two-photon mode in 1950 by Steinberger, Panofsky and Steller.[3] These discoveries confirmed the two-meson picture proposed by S. Sakata and K. Inoue in 1942 and published following the war.[4)–6)] Sakata had argued that the particle previously observed in cosmic ray studies (the muon) was weakly interacting and could not be identified as the particle proposed by Yukawa in 1935 to mediate the strong nuclear force. A new particle was therefore required with the correct properties and the pion discoveries of 1947 confirmed these conjectures.

The pion was not the only discovery made in 1947. Two unusual cosmic ray events were seen in a cloud chamber experiment by Rochester and Butler[7] having a characteristic V shape. The discovery of these V-particles signaled the first observation of kaons. In 1948, an emulsion event of a three pion decay was also observed by Brown and the Bristol Group.[8]

The early 1950's brought new detection techniques (precision emulsions and bubble chambers) and new accelerators (Bevatron and Cosmotron). The copious production of the new mesons and associated hyperons indicated that the strong interactions were responsible for generating the new states. However, the long lifetimes of the new particles suggested weak processes were responsible for their decays. New concepts, such as associated production, and new symmetries, such as V-parity, were proposed by Nambu, Nishijima, Pais and others[9)–12)] to understand these novel phenomena. Careful analysis of the production of these new states led to the concepts of charge independence, isospin and strangeness. Nakano and Nishijima[13] and Gell-Mann[14] argued that the data required a new additive quantum number, strangeness, that is conserved in the strong production processes but violated in the weak decays of the new particles. The new mesons could be classified as distinct doublets with isospin one-half.

Gell-Mann and Pais[15] observed the possibility of neutral particle mixing and that the mass eigenstates of these neutral states would be expected to be odd or

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even under charge conjugation, C — later CP, with different lifetimes for the two states, K_1 and K_2. The longer-lived meson was soon observed at the Cosmotron in 1955. New analysis techniques were developed to explore the novel physics of strange particles. Dalitz[16] advocated the study of kinematic distributions and developed the famous Dalitz plot to search for structure in three body decays of the new states. He has also argued that parity violation could have been independently discovered in kaon decays using these methods with sufficient statistics.

§2. Symmetries

Symmetries have played an essential role in revealing the nature of elementary particles and their dynamical interactions. Charge independence of the nuclear force led to the concept of strong isospin, and we have seen that the structure of the production and decays of the new states discovered in the revolution of 1947 led to establishment of a new quantum number, strangeness, which was thought to be an exact symmetry of the strong interactions.

The idea that some states might be viewed as composite states and not as fundamental particles has a long history. The Fermi-Yang model[17] suggested that the pions could be viewed as strongly bound states of neutrons and protons with their antiparticles. Sakata[18] extended these concepts to include strangeness and developed the famous Sakata Model where the three fundamental constituents were the baryons (P, N, Λ). All strongly interacting particles could now be classified under the $SU(3)$ symmetry of these fundamental constituents. The mesons and some hyperons were taken to be composite states built from these constituents. This new theory seemed to give a very successful description of mesons but had increasing difficulty interpreting the structure of baryons and hyperons.

An alternative composite picture of mesons and baryons was developed by Ne'eman,[19] Gell-Mann[20] and Okubo[21] who invoked a different application of $SU(3)$ and "the eightfold way". In their picture, the mesons were identified in octet representations of the $SU(3)$ symmetry, as in the Sakata Model, but differed by also identifying the baryons and hyperons with octet and decuplet representations of $SU(3)$. In this new picture, the fundamental triplet representation did not play a direct role. Based on these new classifications, successful predictions were made for the mass relations and decay patterns of the strongly interacting particles.

The leptonic decays of strongly interacting particles also played an essential role in developing our understanding of symmetries and the nature of the weak force. Using evidence based on the leptonic decays of baryons and hyperons, the weak currents could be identified as belonging to octets of the eightfold way. By careful study of the pattern of the weak decays, Cabbibo[22] conjectured that the strangeness-changing weak currents are generated by an $SU(3)$ rotation of the weak isospin current and introduced the Cabbibo angle, θ, as a fundamental parameter describing this rotation.

$$J_\mu = \cos\theta\big(J_\mu^{(0)} + g_\mu^{(0)}\big) + \sin\theta\big(J_\mu^{(1)} + g_\mu^{(1)}\big), \quad \theta \sim 0.26. \tag{2·1}$$

Dualities between the weak mixing of leptonic currents and the structure of the

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hadronic weak currents played an essential role in improving our understanding of both the weak and the strong interactions as emphasized by Maki, Nakagawa and Sakata.[23)]

The observation of partiy violation in the weak interaction processes stimulated V. Fitch and J. Cronin to explore what other symmetries might be broken in rare processes. Again, kaons provided a unique laboratory for exploring the possibility that the CP symmetry might also be violated. They realized that CP violation would imply that the neutral kaons would not remain in CP mass eigenstates and a small mixing could be generated. A clever use of coherent regeneration allowed them to observe this mixing in the two pion decays of the K_2 meson,[24)]

$$\mathrm{K}_2^0 = \frac{1}{\sqrt{2}}\left(\left(K_0 - \overline{K}_0\right) + \varepsilon\left(K_0 + \overline{K}_0\right)\right), \tag{2·2}$$

where the mixing parameter, $\varepsilon \sim 2.3 \times 10^{-3}$, measures the strength of the CP violation.

§3. Quarks

Kaon physics has inspired four of the six known quarks. In 1964, Gell-Mann (quarks)[25)] and Zweig (aces)[26)] propose hadronic constituents (u, d, s) with fractional baryon number $\mathrm{B} = 1/3$. Baryons are three quark states, and mesons are quark-antiquark states. Their proposal is similar to the Sakata triplet model but with fundamentally different physics implications. Kaon physics requires the existence of the strange quark (s) and provides substantial motivation for this composite picture of hadrons

The quark theory also has implications for the weak interactions. In Cabbibo theory, the weak current involves only the quark combination $(d\cdot\cos\theta + s\cdot\sin\theta)_L$ and the orthogonal combination $(-d\cdot\sin\theta + s\cdot\cos\theta)_L$ remains uncoupled. This generic behavior of the weak interactions would normally be expected to imply the existence of flavor-changing neutral current processes. In a remarkable paper, Glashow, Iliopoulos and Maiani[27)] 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. They further suggest a role for a new charm quark[28)] that couples to the orthogonal (d, s) combination in the weak current. The natural suppression of neutral current processes occurs from cancellations between the up and charm quark contributions to higher order processes. However, this requires that the charm quark cannot be heavier than a few GeV. This prediction was confirmed with the discovery of mesons and baryons containing the charm quark.

In 1972, Kobayashi and Maskawa[29)] explored the possible sources of the CP violation responsible for the K_1 K_2 mixing observed by Fitch and Cronin in 1964.[24)] They argue that the four-quark GIM model cannot produce the observed 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, $\{\mathrm{V}_{CKM}\}$, contains three angles and one new CP violating phase. Therefore, three

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extra quarks would be required to exist beyond the three u, d, s quarks known in 1972. The charm, bottom and top quarks have all been subsequently discovered and provide the foundation of the present Standard Model of elementary particle physics.

While inspired by the CP violation in the weak mixing of the CP eigenstates, as measured by the ε parameter, the KM theory predicts that there should also be direct CP violation in the kaon decay amplitudes as measured by the parameter, ε'/ε.

$$\eta_{+-} = \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} = \varepsilon + \varepsilon', \tag{3·1}$$

$$\eta_{00} = \frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)} = \varepsilon - 2\varepsilon', \tag{3·2}$$

$$\frac{\Gamma(K_L \to \pi^+\pi^-)}{\Gamma(K_S \to \pi^+\pi^-)} \Bigg/ \frac{\Gamma(K_L \to \pi^0\pi^0)}{\Gamma(K_S \to \pi^0\pi^0)} = 1 + 6\mathrm{Re}(\varepsilon'/\varepsilon). \tag{3·3}$$

$\mathrm{Re}(\varepsilon'/\varepsilon)$ has been measured precisely in a remarkable series of experiments by NA48 at CERN and by KTeV at Fermilab with the results,

$$(\varepsilon'/\varepsilon) = (14.7 \pm 2.2) \times 10^{-4} \ - \ \mathrm{NA48}^{30)} \tag{3·4}$$

and

$$(\varepsilon'/\varepsilon) = (19.2 \pm 2.1) \times 10^{-4} \ - \ \mathrm{KTeV}.^{31)} \tag{3·5}$$

Theoretical estimates for $\mathrm{Re}(\varepsilon'/\varepsilon)$ are in rough agreement with these observations.[32)] However, the detailed comparison of these results with the predictions of the Kobayashi-Maskawa theory is hampered by our inability to compute precisely the relevant weak matrix elements.

CP violation is highly suppressed in the kaon system but this also makes it a sensitive place to search for the effects of new physics. The CP violation effects are much larger in systems involving the b-quark, and a remarkable array of B-physics results of the past two decades has firmly established the CKM paradigm of the six known quark and their mixing through the weak interaction processes.

§4. Weak matrix elements

Probing the weak interactions at low energies requires a deep understanding of weak matrix elements. Weak interaction processes in involving virtual W and Z bosons occur at short distance due to their heavy masses. In the Standard Model, the strong interactions that bind the quarks and gluons into hadrons is described by quantum chromodynamics. Due to asymptotic freedom, we can describe the short distance effects of the strong interactions using perturbation theory but the long distance physics requires a nonperturbative knowledge of the strong force.

The nonperturbative evaluation of hadronic weak matrix elements involves the factorization of the short distance physics using the operator product expansion. The effective weak Hamiltonian has the following structure,

$$\mathrm{H_{wk}} = \frac{G_F}{\sqrt{2}} \sum_i V^i_{CKM} C_i(\mu) Q_i(\mu), \tag{4·1}$$

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$$A(M \to F) = \langle F| \mathrm{H_{wk}} |M\rangle = \frac{G_F}{\sqrt{2}} \sum_i V^i_{CKM} C_i(\mu) \langle F| Q_i(\mu) |M\rangle \,, \qquad (4{\cdot}2)$$

where the coefficient function, $C_i(\mu)$, contains the contributions of the perturbative short distance physics and $\langle Q_j(\mu)\rangle$, describes the nonperturbative matrix elements of universal light quark operators. The current status of using these methods to describe weak mixing and decays at NLO and NNLO is given in a review by Buras[33] and the specific application to kaon decays in a review by Cirigliano et al.[34]

There are many different approaches to evaluating the long distance contributions to the matrix elements of the universal light quark operators including chiral peturturbation theory, large Nc expansions, lattice field theory, quark effective field theories, meson effective field theories, hidden local symmetries and methods based on the new techniques of the ADS/CFT correspondence. Chiral perturbation theory and the large Nc methods are systematic at leading orders but it is difficult to control the higher order terms in their respective expansions. Theories based on models such as the effective field theories and the ADS/CFT method involve approximations or model dependence whose systematic errors are difficult to assess. The lattice field theory methods are systematic and have controlled expansions but require large computing resources to obtain high precision results.

Through a large variety of efforts throughout the world, lattice field theory is now able to make some rather precise predictions for some of the relevant weak processes. The following results are taken from the compilation at latticeaverages.org.[35]

$$\begin{array}{lrl} f_\pi & 129.5 \pm 1.7 \text{ MeV} & 1.3\%, \\ f_K & 156.0 \pm 1.1 \text{ MeV} & 0.7\%, \\ f_K/f_\pi & 1.1931 \pm 0.0053 & 0.6\%, \\ B_K & 0.734 \pm 0.020 & 1.5\%, \\ F_+^{K\pi}(0) & 0.9584 \pm 0.0044 & 0.5\%. \end{array} \qquad (4{\cdot}3)$$

The K$\pi\pi$ decay amplitudes are more difficult to evaluate on the lattice. Mawhinney et al.[36] have recently reported encouraging results for the ΔI=3/2 amplitudes.

$$\begin{aligned} \mathrm{Re}(A_2) &= (1.40 \pm 0.08_{stat} \pm 0.12_{NPR} \pm 0.14_{sys}) \times 10^{-8} \text{ GeV}, \\ \mathrm{Im}(A_2) &= -(5.65 \pm 0.31_{stat} \pm 0.37_{NPR} \pm 0.60_{sys}) \times 10^{-13} \text{ GeV}, \\ \mathrm{Re}(A_2) &= 1.484 \times 10^{-8} \text{ GeV (experiment)}. \end{aligned} \qquad (4{\cdot}4)$$

Lattice computations for the ΔI = 1/2 K$\pi\pi$ decay amplitude and Re(ε'/ε) are still unable to provide precise results.

§5. Future prospects

Kaon physics has a remarkably bright future. Weak decays and weak mixing are sensitive to a wide range of new physics. The strong suppression of flavor-changing neutral current processes in the kaon system make it a unique laboratory for exploring new physics, particularly in those processes where the Standard Model contributions can be precisely evaluated.

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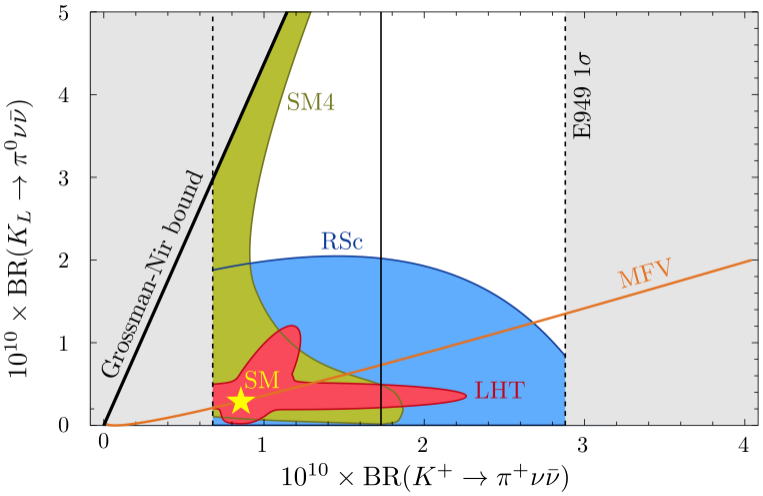

Fig. 1. Correlation between the branching ratios of $K_L \to \pi^0 \nu\overline{\nu}$ and $K^+ \to \pi^+ \nu\overline{\nu}$ in MFV and three concrete NP models. The gray area is ruled out experimentally or model independently by the GN bound. The SM point is marked by a star.

Many authors have emphasized the importance of observing the "Golden Modes" of semileptonic kaon decays. The two neutrino semileptonic decays of the charged and neutral kaon decays are highly suppressed and can be predicted with a few percent precision in the Standard Model. The current predictions[37] for the branching ratios are

$$\begin{aligned} K^+ \to \pi^+ \nu\nu \quad & (7.81 \pm 0.67 \pm 0.33 \pm 0.26 \pm 0.08) \times 10^{-11}, \\ K_L \to \pi\nu\nu \quad & (2.43 \pm 0.38 \pm 0.09 \pm 0.05 \pm 0.03) \times 10^{-11}, \end{aligned} \tag{5·1}$$

where the dominant errors are presently due to current uncertainties in the CKM matrix and other standard model input parameters. The irreducible theory errors are at the percent level.

At present, the BNL experiment, E949, reports the observation of seven events for the charged decay mode representing a measurement of the branching ratio of $(1.73 + 1.15 - 1.05) \times 10^{-10}$,[38] consistent with the Standard Model prediction but with a central value of twice the expected rate. The KEK experiment, E391a, has reported an upper limit on the neutral decay mode of 6.7×10^{-8} (90% CL),[39] which is much larger than the expected Standard Model rate leaving considerable room for the discovery of new physics in future experiments.

Given the small theoretical errors for these processes, precise measurements could be sensitive to a wide range of new physics phenomena. Some of these predictions are summarized in a plot taken from a paper by Straub.[40] They include minimal flavor violation (MFV), little Higgs models (LHT), Randall-Sundrum models (RSc), and a fourth generation in the Standard Model (SM4).

New experiments have been proposed to make more precise measurements of these Golden Modes. At CERN, the NA62 Collaboration[41] will study the charged decay mode beginning in 2012 with the goal of achieving $\sim$ 100 SM events. At

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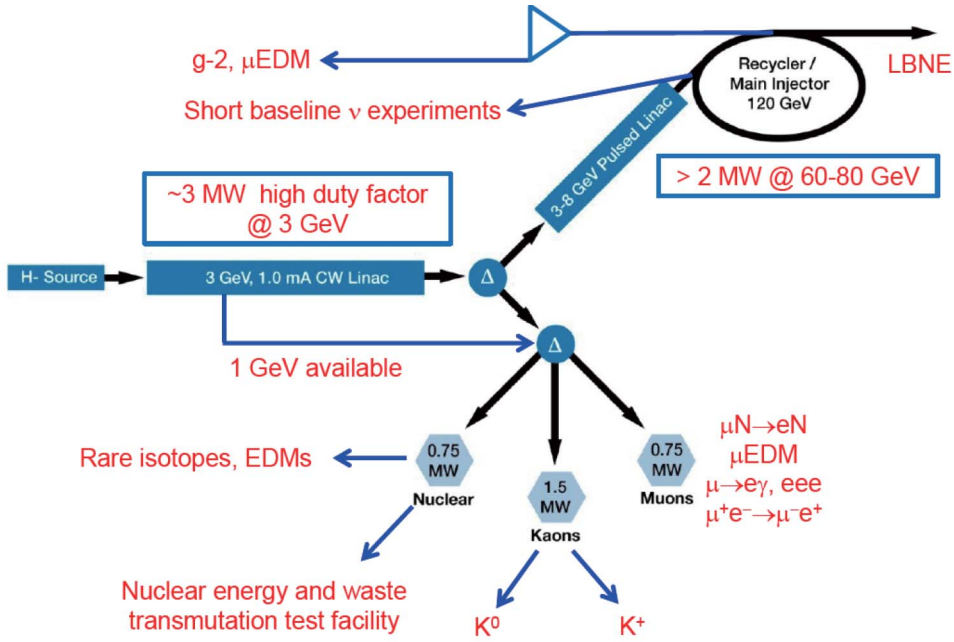

Fig. 2. (Color online) Proposed Project X Facilities at Fermilab.

J-PARC, the KOTO Collaboration[42)] has proposed to measure the neutral mode with the expectation of observing a few events at the Standard Model rate in a run beginning in 2013. At Frascati, KLOE-2[43)] will have large samples of kaons to study a variety of rare kaon processes.

Fermilab also has also announced prospects for future kaon experiments to study rare kaon physics including the Golden Modes. The ORKA Collaboration, P1021, proposes an experiment using a Main Injector kaon source that could produce about 210 events/yr in the charged Golden Mode and a precise measurement of any deviations from the predictions of the Standard Model. Finally, the development of a new accelerator complex at Fermilab, Project X, would provide high intensity beams for the precision measurements of many rare processes including charged and neutral kaon beams.

§6. Summary

Kaons have provided a unique laboratory for revealing the secrets of the Standard Model of elementary particle physics. They have inspired the discovery of four of the six known quarks. They have allowed sensitive probes of fundamental symmetries that have played such an important role in our understanding of physics at the smallest distances. Future kaon experiments will be sensitive to physics beyond the scales currently being directly probed by the experiments at the Large Hadron Collider at CERN.

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HAPPY BIRTHDAY!

Kaons at 100_8

Shoichi Sakata at 100_{10}

And yes, we do still need you.

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