PHYSICS AT DAΦNE

by PAULA FRANZINI & JULIET-LEE FRANZINI

A mother-daughter team describe the fundamental symmetries of nature that will be studied at the first particle "factory" being built at Frascati in Italy.

IN 1801 Thomas Young discovered that the pattern obtained by shining light onto two fine slits was different from the mere superposition of the two patterns obtained from light shining onto each slit individually. This could not be explained by understanding light as composed of independent bits of matter, but it made sense if light was understood as a wave-producing interference, or beat phenomenon. In modern physics, we understand that all particles—whether the photons of light, the electrons and nucleons that compose all matter, or the myriad unstable particles such as mesons that exist only in cosmic rays, high energy accelerator collisions, and the early universe—must be understood in terms of a wave-particle duality. However, interference patterns have never been seen for the case of two particles flying in opposite directions. In 1996, in Frascati, Italy, a new accelerator, DAΦNE, with a dedicated experiment KLOE, will observe such patterns for the first time, for K meson pairs, and at the same time it will make measurements of *CP* and *CPT* violation with ground-breaking precision.

FOR FIFTY YEARS experiments involving the K mesons have contributed much to the construction of the present theory of elementary particles and their interactions, the so-called Standard Model of particle physics. In this model matter is made of two sets of particles and their antiparticles, quarks, which make up the proton, and leptons (the electron, e^-, is an example). Forces are transmitted by another set of particles, the gauge bosons—the photon for the electromagnetic force, gluons for the strong force (a short range force, holding the nuclei together), and W and Z particles for the weak force (an even shorter range, weaker force, accounting for the decay of the neutron). In the Standard Model particles undergo strong, electromagnetic, and weak interactions. (For greater understanding of the Standard Model, refer to Patricia Burchat's article "A People's Guide to the Standard Model," in the Summer 1993 issue of the *Beam Line*, Vol. 23, No. 2.)

The quarks come in six flavors. In order of increasing mass they are u (up), d (down), s (strange), c (charm), b (beauty or bottom), and the recently discovered t or top quark (see "Discovery of the Top Quark" by Bill Carithers and Paul Grannis in the last issue of *Beam Line*, Vol 25, No. 3). Only u and d quarks occur in ordinary matter, making up the proton and the neutron; the heavier quarks are short-lived and form particles that are only seen in accelerators or cosmic rays and presumably in the very, very early universe. K mesons, in particular, consist of a u or d quark combined with an s antiquark. B mesons, to be studied at the Stanford Linear Accelerator Center (SLAC) en masse in a few years, are a similar combination with s replaced by b.

The threefold combination of symmetries, CPT, described on page 30 of the previous article requires that particles and antiparticles should have the same masses and lifetimes. It is in the K-meson system that this test can be carried out to its ultimate accuracy (see section on page 38).

CP VIOLATION'S cradle and, so far, only home is the neutral K system. Of course evidence for it in other systems, for example, the neutral B mesons, is also eagerly awaited. This is in fact the mission of the SLAC B-Factory.

For the strong and electromagnetic interactions, the K^0 (a d plus a $\bar{s}$) and the $\bar{K}^0$ ($\bar{d}\,s$) are distinct particles, protected by the C symmetry from changing into each other. The weak interaction, however, violating C, allows both these particles to decay, for example, into two π mesons (a combination of two u or d quarks and their antiquarks), and therefore, at second-order, to change into each other. Thus, we speak of K^0 and $\bar{K}^0$ as distinct particles because they are produced by the strong interaction, but when it comes to their decay by the weak interaction, it no longer makes sense to speak of them as distinct.

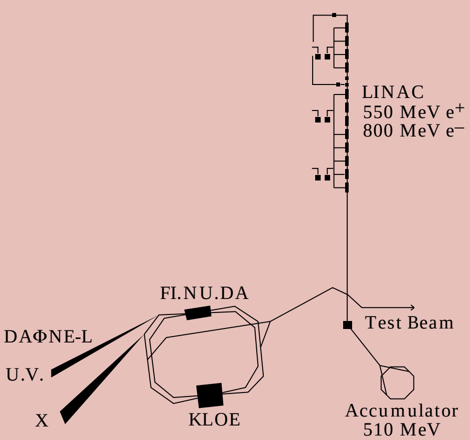
If CP were a perfect symmetry, the physical particles would be the symmetric and antisymmetric combinations of K^0 and $\bar{K}^0$. These, called K_1 and K_2, are respectively even and odd under CP, and as a result must decay respectively to two and three pions. Since the mass of three pions is very close to the K mass, there is a lack of what is called phase space, and the K_2 is thus much longer lived. K^0 mesons of two very different lifetimes were observed in 1956; in 1964 the observation that the K^0 with a long lifetime decays a minute fraction of the time to two pions proved unambiguously that CP also is violated. Instead of K_1 and K_2, the physical states are now K_S and K_L, where K_S is K_1 with a small admixture of K_2, and K_L is K_2 with a small admixture of K_1. The amount of this admixture is parametrized by the CP violation parameter ε, which has the measured value $|\varepsilon| = (2.259\pm0.018)\times10^{-3}$.

The story of CP violation has a final twist. In addition to the well-measured CP violation just described, coming from the admixture of K_1 in K_L, there is the possibility of direct CP violation in the decay of K_2. Physically it turns out that this can be measured in the difference of the CP violation in the neutral and charged π decays of the K's. This direct CP violation is parametrized by the quantity ε'. Thirty years of measurements of ε' have not been able to determine if ε' is zero or not, but have found that it is much smaller than even ε. Increasingly accurate measurements have only chased it closer and closer to zero. Currently it is known to be between zero and three thousandths of ε. DAΦNE is being built to reduce the uncertainty by another factor of ten. This precision measurement of ε' will give us an important clue as to whether the Standard Model, which predicts its value to be on the order of a few parts in ten thousand, is sufficient or whether it requires modifications.

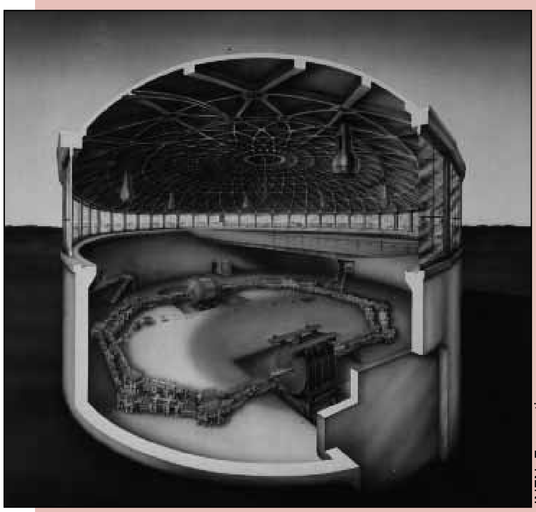
The How of DaΦne

WHAT MAKES A FACTORY? The luminosity of a collider is given by $\mathcal{L} = fnN_1 N_2/A$. Here n is the number of bunches (rather than being uniformly distributed, the particles in DAΦNE are gathered into several (30–120) flat (3 centimeters long by 3 millimeters wide by 0.02 millimeters high) bunches spaced at roughly one meter intervals); f the revolution frequency (how many times around the collider the bunches go per second); N_i the number of particles per bunch for each species of particle, and A the area of the beams (for fully overlapping beams). Thus, many bunches of many particles going around at a high frequency, focussed tightly into beams of a very small area, produce a high luminosity. Nonetheless, if these parameters are modified to produce a larger luminosity, without radically new technology, the luminosity in a single ring machine will be limited by what is known as beam-beam interactions to be about that of current colliders. The beams get disrupted and thus the small bunch size needed for high luminosity is destroyed; bunches containing more particles lead to stronger disruption. Multiple bunches in a single ring do not help; each bunch sees all of its counterparts and gets successively more and more perturbed.

The solution generally found in "factories" is to have two separate rings (hence the DA in DAΦNE, for Double Annular), which cross each other at a small but non-zero crossing angle (about 1 degree for DAΦNE). This crossing angle is needed, even though head-on collisions are less disruptive to the beam, because if the two beams were parallel even for a few meters, each bunch would then pass several of its counterparts in a small machine like DAΦNE, where there will eventually be more than one bunch per meter.



The DAΦNE collider complex.



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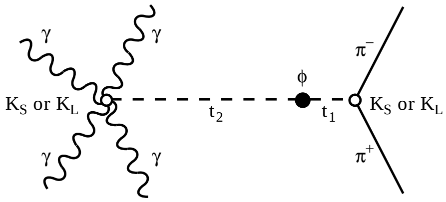
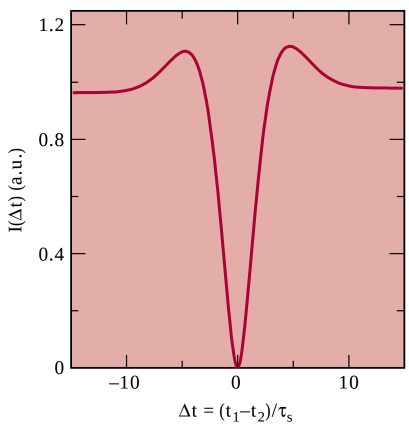
An artist's view of the two rings of the DAΦNE complex showing the magnet layout and the two detectors, KLOE for particle physics on the right and FINUDA for nuclear physics on the left.

TO REACH the desired accuracy in ε' requires the observation of five million $K_L \rightarrow 2\pi$ decays among five billion K_L decays. One way to obtain these astronomical numbers of K_L is to build a particle "factory" which produces a known particle of approximately twice the K-mesons' mass, the phi (ϕ). The ϕ is the lightest vector meson composed of a strange quark and an anti-strange quark, making it the lightest copiously producible particle decaying into two kaons. In June 1990 the first particle factory project, DAΦNE, was funded by the Istituto Nazionale di Fisica Nucleare, INFN, of Italy, and was christened DAΦNE, for Double Annular Φ-factory for Nice Experiments. DAΦNE is an e^+e^- collider, where electrons and positrons of 510 million electron volts (MeV) are hurled at each other head on. At this total energy of 1019.4 MeV, the cross section (the effective target area displayed by the electrons and positrons to each other) for producing a ϕ is very large, approximately 5×10^{-30} cm^2, with negligible accompanying background. DAΦNE's target luminosity, a measure of the collision frequency per unit cross section, is $\mathcal{L} = 10^{33}\text{cm}^{-2}\text{s}^{-1}$, which means 5000 ϕ's are produced per second. Using the canonical high energy physics definition of one physics year equals ten million seconds (one third of an actual year, to account for such things as down time, maintenance, fine tuning), this means fifty billion ϕ's per year!

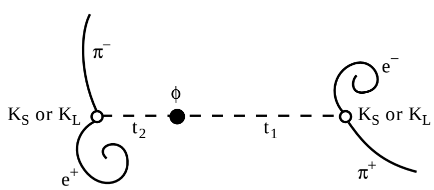
The ϕ decays into charged kaon pairs about half of the time. These kaons move at a quarter of the speed of light (c), and on average travel about one meter before they in their



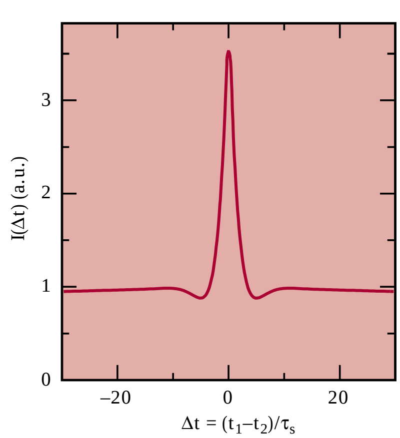
A ϕ (the black dot) decaying to two K's (the white dots) in turn decaying at times t_1 and t_2 to the final states $f_1 = \pi^+\pi^-$ and $f_2 = \pi^0\pi^0$ (each π^0 decays finally to two photons).



Interference pattern for $f_1 = \pi^+\pi^-$, $f_2 = \pi^0\pi^0$.



A ϕ (the black dot) decaying to two K's (the white dots) in turn decaying at times t_1 and t_2 to the final states $f_1 = \pi^+e^-\bar{\nu}$, $f_2 = \pi^-e^+\nu$. Note that the neutrinos are not depicted because they are "invisible" particles.



Interference pattern for $f_1 = \pi^+e^-\bar{\nu}$, $f_2 = \pi^-e^+\nu$.

turn decay. In one physics year, 25 billion pairs are produced. Another third of the time, the ϕ decays into a pair of neutral kaons, moving at 1/5 *c*. Moreover, the kaons produced at DAΦNE are not just any kaons, but kaons in a well-defined quantum-mechanical and kinematic state: one of them is always a K_S traveling on average 6 millimeters. The other kaon is always a K_L, traveling on average 3.5 meters. In a physics year, 15 billion K_SK_L pairs are produced.

DAΦNE is shown schematically in the box on the preceding page. There are two interaction areas for the two experiments KLOE (particle physics) and FINUDA (nuclear physics) and also the possibility for lower energy and medical research with the ultraviolet and X-ray beams of the DAΦNE-L(ight) facility. The DAΦNE main rings are 98 meters in perimeter, in a roughly rectangular shape of 32 by 23 meters. When DAΦNE starts up, at one tenth of its final luminosity, it will already have about the same number of particles in its 98 meter ring as the Large Electron Positron (LEP) at CERN in Geneva, Switzerland, currently has in its 27 kilometer ring.

AT DAΦNE neutral *K*-meson pairs from ϕ decays are produced in a pure *C*-odd quantum state. It turns out that this means the observation of a K_S (K_L) signals and guarantees the presence of K_L (K_S) of opposite momentum; in other words, we will never have a decay with two K_S or two K_L. This gives DAΦNE unique advantages for the study of *CP* and *CPT* violation—because of the quantum mechanical coherence of the initial two kaons state, interference phenomena can be observed without identification of K_S's or K_L's. One can understand this by analogy with the classical experiment of shining a light onto two slits and observing the spatial pattern on a screen beyond, without knowing from which slit the photons came. One notes that the pattern observed when both holes are open is not the mere superposition of that obtained when one hole alone is open added to that obtained when only the other hole is opened. Because of the phase relationship between the waves, one gets a complex pattern. In a similar way at DAΦNE, the intensity distribution one observes depends on which final states are involved, as described below. In short, one can perform a whole spectrum of precision *K*-meson interferometry experiments by measuring the decay intensity distributions of the *K*-meson pair as a function of the distance between the two decay vertices for appropriate choices of the two final states.

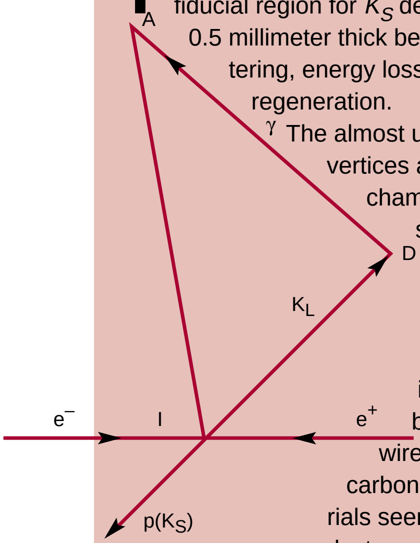
If we label the final state of one *K* by f_1, and the time at which the decay occurs by t_1, and similarly f_2 and t_2 for the other *K*, by varying the time difference t_1–t_2 and the final states examined, it is possible to measure many different parameters describing *CP* and *CPT* violation. The interference term is sensitive to the mass difference between K_S and K_L. For example, with $f_1 = \pi^+\pi^-$, $f_2 = \pi^0\pi^0$, as illustrated in the top illustration on this page, one measures the real part of ε' at large time differences, and the imaginary part of ε' at short time differences. The next illustration on the left shows the destructive interference pattern for this case.

With $f_1 = \pi^+e^-\bar{\nu}$ and $f_2 = \pi^-e^+\nu$, as illustrated in the third and bottom illustrations on the left on the preceding page, one can measure the *CPT*-violation parameter, in other words, test whether *CPT* is violated, and in fact weigh the relative masses of the K^0 and $\bar{K}^0$, to one part in a quintillion (10^{18}). The bottom illustration shows the constructive interference pattern for this case.

Many other patterns result from choosing different decay channels; from them we can learn all about the neutral *K*-meson system, that is, determine the total set of 16 parameters which define the system. No other experiment at any other high energy accelerator can do this.

THE KLOE detector's main mission is to study ε' with a sensitivity of the order of one part in ten thousand via traditional branching ratio methods as well as through a whole host of quantum interferometry measurements. It is also fully capable of investigating a whole range of other physics. The scale of KLOE is driven by a fundamental parameter, the average distance the K_L goes before decaying (3.5 meters). A practical compromise is to detect K_L decays in a big, cylindrical chamber of radius

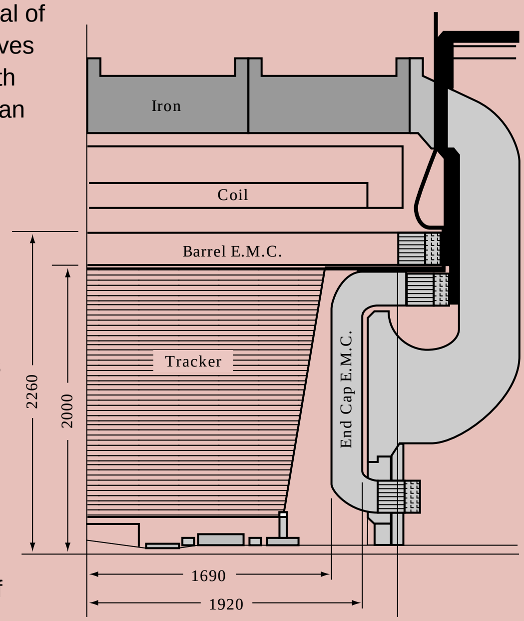
The How of KLOE



THE RADIUS of the beam pipe around the luminous point is 10 centimeters. This allows the definition of a clean fiducial region for K_S decays. The beam pipe is made of 0.5 millimeter thick beryllium to minimize multiple scattering, energy loss for charged kaons and K_L to K_S regeneration.

The almost uniform distribution of K_L decay vertices and secondary tracks in the chamber volume requires a constant size drift cell. This is achieved by using only alternating stereo layers, with constant inward radial displacement at the chamber center. The total number of cells is about 12,000. We use helium-based gas mixtures, aluminum wires, as well as spherically shaped carbon fiber endwalls to minimize materials seen by the photons entering the electromagnetic calorimeter.

Unique to the KLOE experiment is the method of determining the flight path of K_L (the segment ID in the illustration above) by time measurements. *I* is the phi decay point, the direction of ID is given by $-pK_S$, and *A* is the photon conversion apex in the calorimeter. As illustrated, the flight time measurements for even a single photon of the four from $\pi^0\pi^0$ allow the determination of the K_L decay path. The time-of-arrival of a photon gives the flight path of the K^0 to an accuracy $\delta l = \beta_K c \delta t \sim 6{\times}10^{-3}$cm $\times\ \delta t$ (picoseconds). For a 510 MeV K^0, one expects a time resolution of approximately 100 picoseconds and a path resolution of 0.6 centimeters.



KLOE cross section along the beam axis.

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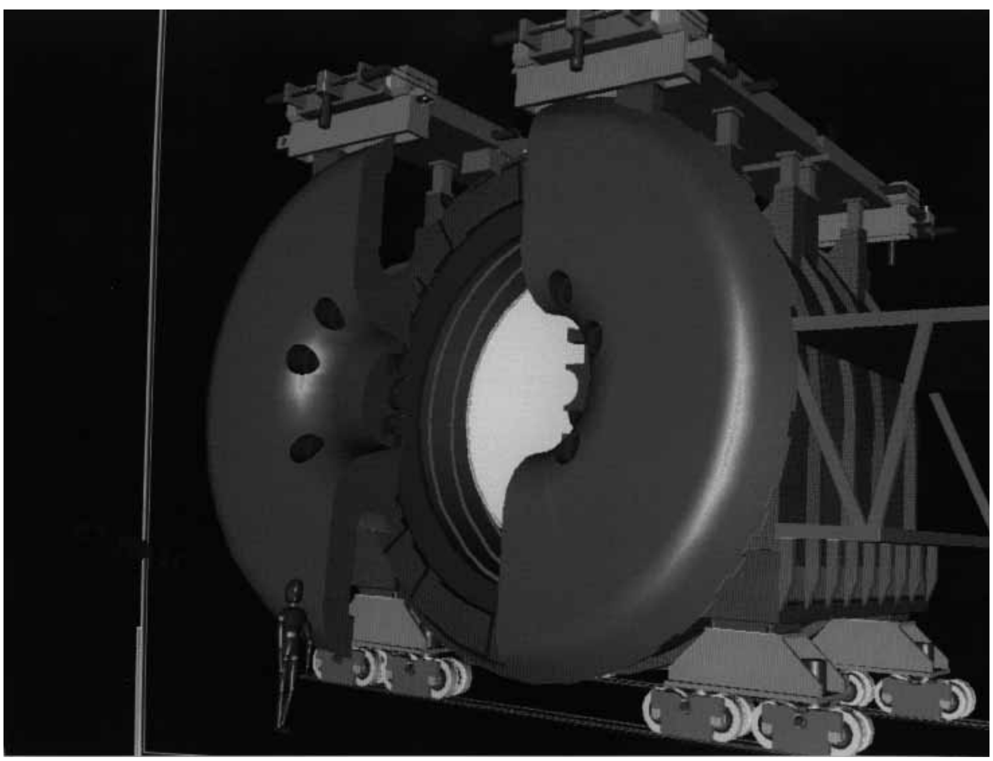
The site and the buildings that will house DAΦNE and its detectors. The ferro-concrete single span dome, designed by Pier Luigi Nervi, a famous Italian architect, is a national landmark.



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An artist's conception of KLOE.

approximately 2 meters and length 370 centimeters. The KLOE cross section is shown in the box on page 39. Detector requirements are to collect statistics; to measure the path length of the K_S, K_L decays to the required accuracy; to reject backgrounds at the desired level; and to be self-calibrating. Thus, the experimental apparatus must be able to track charged particles of momenta between 50 and 250 MeV/c. It must also detect with very high efficiency (low failure rate) photons with energy as low as 20 MeV, measure their energies with a fractional resolution of 15 percent at 100 MeV, and provide the space coordinates of the photon conversion point, where the daughter photons from a π^0 became an electron-positron pair. A largely empty space, with a special gas and fifty thousand fine wires, lets us see where the charged particles went. The photon measurements are done in a lead-scintillating fiber sampling electromagnetic calorimeter with exceptional timing abilities that surrounds the tracking chamber. It is in turn surrounded by a superconducting coil providing a solenoidal field of 0.6 tesla.

SINCE DAΦNE is also a prolific source of charged *K*-mesons, not only can *CP* studies be pursued there too, but one can also further the knowledge of the low energy meson theory known as chiral perturbation theory. It also is a perfect laboratory for light meson spectroscopy and nuclear physics. Still, for the KLOE experimenters the thrill is really the opportunity to perform the most accurate tests and measurements in particle physics while being able to observe beautiful interference patterns in a quantum mechanical system.