Testing discrete symmetries in K decays

P. DEBU – CEA Saclay – France
February 7, 2000

Discrete symmetries, P and C

When physicists try to lay down the laws that govern the processes they are studying, they use as a first guidance the most general properties of the system.

There are fundamental and universal examples. The laws of Nature are believed to be independent of the position of the observer, or of his orientation. One says that they are invariant by translation and rotation.

Consider now a simple experiment, like playing billiards. Imagine you are looking at the image of the game in a large mirror instead of looking directly at the billiard table. Would you be able to tell from the moves of the balls that you are looking at a virtual image? The answer is no. Laws of classical mechanics are obeyed by the mirror experiment. They are invariant under the transformation called Parity (P), which consists in changing the sign of spatial coordinates.

We say that classical mechanics respect the P symmetry.

Imagine that instead of looking at the billiards game in a mirror, you replace every piece of matter by antimatter. Could you tell the difference from the moves ? The answer is again no. Laws of classical mechanics apply to antimatter. The operation which consists in replacing a particle by its antiparticle is called Charge Conjugation (C).

Classical mechanics respect the C symmetry.

Every particle has its corresponding antiparticle, which has the same mass but the opposite charge. This is the origin of the name Charge Conjugation. The antiparticle of the electron e^- is the positron e^+. The antiparticle of the proton p is the antiproton $\bar{p}$. The proton is made of 3 quarks, 2 u quarks and 1 d quark. The antiproton is made of 3 antiquarks, 2 $\bar{u}$ and 1 $\bar{d}$. The neutron is made of 3 quarks, 2 d quarks and 1 u quark. The antineutron is made of 2 $\bar{d}$ and 1 $\bar{u}$. One can imagine building an antiworld from these elementary pieces. If the laws of Nature would be C symmetric, this antiworld could not be distinguished from the world we know. But they are not.

Weak interactions and violation of P and C symmetries

There are four known fundamental interactions between elementary particles. Gravitation is felt by all particles. Charged particles undergo electromagnetic interactions. The protons and the neutron are bound in nuclei by the strong interaction. Weak interactions transform quarks into one another and cause the β decays of unstable nuclei.

It was assumed for a long time that the fundamental interactions respect both P and C symmetries, but experimental observations led two theoreticians, T.D. Lee and C.N. Yang, to suggest in 1956 that P and C symmetries might be violated by the weak interactions. One year later, an experiment led by C.S. Wu, a detailed study of the β decay of Co^{60} in a magnetic field, brought indeed the proof that P symmetry was violated by weak interactions. Additional theoretical work showed that at the same time, the C symmetry was violated. However, it was also realized that the observed processes do respect the CP transformation, the one obtained by applying both the C and the P transformations. In other words, the virtual experiment obtained by looking at the original process in a mirror AND by replacing all particles by their antipartners would obey the known properties of weak interactions.

This was a very important observation.

Time reversal and CPT symmetry

There is a fundamental reason why CP symmetry plays a crucial role. It is indeed linked to the Time Reversal transformation (T).

This transformation consists in "looking" at an experiment backwards in time, like playing a movie backwards. Although, at the macroscopic level, one can immediately distinguish which is the real experiment and which is the reversed movie, this is not a priori the case at the microscopic level. Indeed, the laws of classical mechanics remain valid after Time Reversal.

Classical mechanics is an example of a very successful theory for physics phenomena, valid for many human applications. What about the symmetry properties of the other theories? There is an important theorem, known as the CPT theorem, which states that, under very general assumptions, any theory of microscopic interactions must respect the CPT symmetry.

This means that in the present day theoretical framework of particle physics, it is believed that the laws of physics are invariant under CPT.

As a consequence, CP symmetry implies T symmetry, and vice-versa, because any CP violation should be compensated by some T violation to follow the CPT theorem.

The 1957 observation that CP symmetry still holds could be seen as a necessary consequence that microscopic phenomena obey the T symmetry.

CP violation

CP violation was discovered in 1964 in an experiment dedicated to the study of K^0 and $\bar{K}^0$ mesons. It was performed by J.H. Christenson, J.W. Cronin, V.L. Fitch and R. Turlay.

The K^0 is a particle made of an anti s quark ($\bar{s}$) and a d quark. Because weak interactions can change a strange quark into a non strange quark, both K^0 and $\bar{K}^0$ mesons can decay into the same final state of 2 pions, and moreover, by a succession of two weak processes, the K^0 can become a $\bar{K}^0$ and vice-versa!

During the propagation of the K mesons, a continuous $K^0 \leftrightarrow \bar{K}^0$ oscillation occurs. Were CP conserved, the propagating states would be the symmetric and antisymmetric states superpositions $K_1 = (K^0 + \bar{K}^0)/\sqrt{2}$ and $K_2 = (K^0 - \bar{K}^0)/\sqrt{2}$. The 2 pion state issued of a K decay being a CP even state, this decay would be allowed for the K_1 which is also a CP even state, and forbidden for the K_2, which is CP odd.

Indeed, physicists observed both a short lived K meson, called K_S, decaying into 2 pions, and a 500 times longer lived K_L which could only undergo three body decays. The whole picture seemed consistent with the previous description.

The 1964 experimental demonstration of CP violation was the detection of K_L decays into 2 charged pions. Although this happened only rarely, about twice every thousand decays, it was a clear sign of CP violation in microscopic processes.

This came as a big surprise, but it was also soon realized, in 1967, by A. Sakharov, that CP violation is one of the necessary

Article available at http://www.europhysicsnews.org or http://dx.doi.org/10.1051/epn:2000301

conditions to explain why our universe is almost exclusively made of matter, although it starts from a symmetric state after the Big-Bang model.

This made CP violation even more fascinating.

At that time, it was necessary to introduce new types of interactions to implement CP violation in the theoretical framework. One very popular model was proposed by L. Wolfenstein in 1964. He introduced a so called superweak interaction, the strength and properties of which were such that CP violation was a small effect which could only be seen with the K mesons, and came solely through the $K^0 \leftrightarrow \bar{K}^0$ oscillation.

In 1973, M. Kobayashi and T. Maskawa showed that CP violation could also occur in weak interactions under the condition that at least 3 families of 2 quarks exist. Today, the existence of 6 quarks is established (the heaviest one, the t quark, has been discovered in 1995), but at that time, only the existence of 3 quarks was postulated. This is a noticeable theoretical insight.

The presence of three families of quarks allows the introduction of one single parameter in the theory which causes CP violation. The test of such a model requires several independent observations of CP violation.

Direct CP violation

CP violation seen with the K mesons can occur in 2 different ways.

It has been established that the K_L state is not the pure antisymmetric state K_2, but rather an admixture of K_1 and K_2:

$$K_L = K_2 + \epsilon K_1$$

This small impurity ($\epsilon \simeq 2\ 10^{-3}$) allows the K_L to decay into 2 pions. This is referred to as CP violation in the mixing. While the introduction of this ϵ parameter allows a proper phenomenological description of the observations, it brings no understanding of the origin of CP violation.

However, in the standard model of weak interactions with 3 families, CP violation can also occur directly in the decay of the K_2 itself. This is called CP violation in the decay, or direct CP violation. Contrarily, the superweak model of L. Wolfenstein does not allow such a decay.

Many experiments have been launched already in the late 60's to search for direct CP violation. It can be detected through a tiny difference between decays in 2 charged pions and 2 neutral pions. This difference is parametrized by a very small quantity ϵ', which can be measured by using the very simple relation :

$$\frac{\text{decay rate of } K_L \to \pi^+\pi^-}{\text{decay rate of } K_S \to \pi^+\pi^-} \Big/ \frac{\text{decay rate of } K_L \to \pi^0\pi^0}{\text{decay rate of } K_S \to \pi^0\pi^0} \simeq 1 - 6\,\epsilon'/\epsilon$$

Although it is in principle possible to compute the value of ϵ'/ϵ in the standard model, it is in practice a very difficult task. Most theorists give estimates in the range of a few 10^{-4} for the ratio ϵ'/ϵ.

In 1988, a first evidence for the existence of direct CP violation was published by the NA31 collaboration at CERN [1] :

$$\epsilon'/\epsilon = (3.3 \pm 1.1)\ 10^{-3}$$

Later, their american competitors, E731 at FNAL, published [2]:

$$\epsilon'/\epsilon = (7.4 \pm 5.9)\ 10^{-4}$$

The NA31 completed their experiment and obtained in 1993 [3] :

$$\epsilon'/\epsilon = (2.3 \pm .65)\ 10^{-3}$$

This experimental situation, two results hardly compatible, did not allow to conclude. This led the two groups to launch more precise experiments, E832 at FNAL and NA48 at CERN.

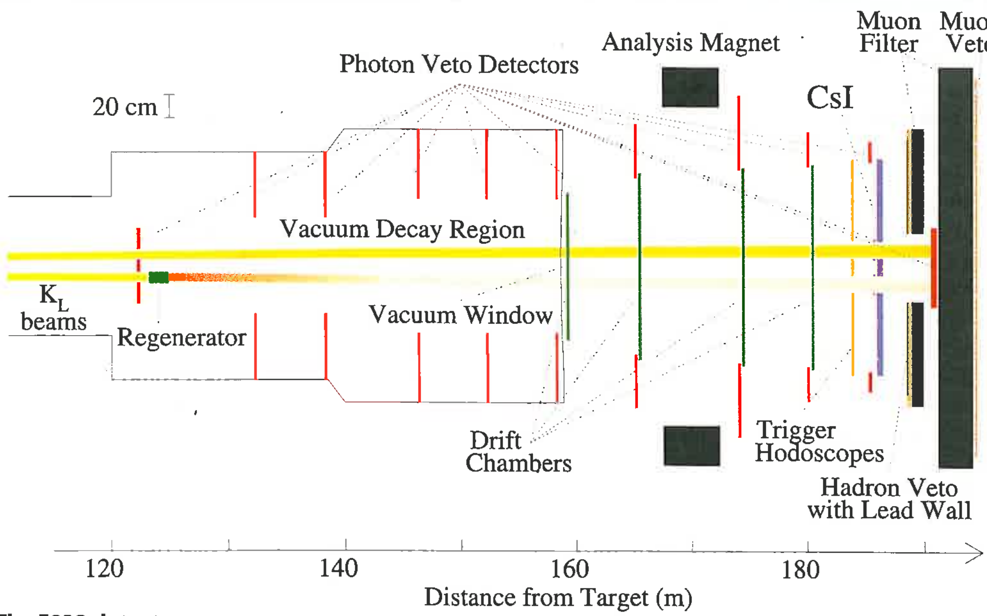

Fig 1 The E832 detector

An experimental challenge

The smallness of the quantity to be measured implies very stringent constraints on the experiments. In excess of ten millions of K to 2 pion decays must be recorded to reach an accuracy of less than 10^{-4} on ϵ'/ϵ, which is necessary to match the predicted range of values.

Intense beams of neutral particles need to be produced. Both types of mesons, K_L and K_S, must be produced and identified, and both types of decays, $\pi^+\pi^-$ and $\pi^0\pi^0$, reconstructed. Detectors must stand a flux of several hundreds kHz of particles during several months. A very powerful selection of the few percent of interesting decays must be applied to reduce the amount of data to be recorded.

The major difference between the american and the european experiment is the production and the identification of the K mesons. In the former (fig. 1), high energy protons hit a single target, and collimators are used to define 2 beams of neutral particles. One of the beams is intercepted by a block of matter which allows the production of short lived K mesons near the detector, while long lived mesons remain in the matter free beam. In the latter (fig. 2), two targets are used to produce the K mesons. One is situated about 200m upstream of the detector, so that only K_L decays can reach the detector. The second target is 100m downstream, and from which accepted K_S decays are dominant.

The most difficult decay to detect, reconstruct and disentangle from background events is the $K_L \to 2\pi^0$ decay. Both π^0 decay immediately into 2 gamma rays, so that the final state only consists in 4 neutral particles. The master piece of both the american and the european detectors is the electromagnetic calorimeter, dedicated to the detection and measurement of the energy and position of the gamma rays.

The American calorimeter (fig. 3) is an assembly of about 3100 pure CsI crystals. Showers of particles are created by the interactions initiated by the incident gamma rays, and these particles produce Cerenkov light in the crystals. The amount of light detected is a measure of the deposited energy.

The NA48 collaboration built a liquid krypton calorimeter, a tank of about 10m^3 embedded in a cryostat to keep the krypton liquid. In this case, this is the ionisation of krypton atoms induced by the showers of particles which is detected by applying a high voltage between immersed electrodes. The electrode structure has a useful aperture of about 2.4m and consists in about 26000 CuBe ribbons very precisely positioned, which define 13000 readout cells (fig. 4).

The detection and reconstruction of K decays into charged particles is made with a spectrometer consisting of 4 drift chambers and a dipole magnet. Additional counters and detector elements are used for fast detection purposes and background rejection.

Even after the online filtering of K decays by a farm of processors, both experiments have to record about 100 TByte per year at a sustained rate of a few Mbyte/s during several months !

Both teams have announced their first result obtained with a partial data set [4, 5]:

$$E832: \epsilon'/\epsilon = (28.0 \pm 4.1)\ 10^{-4}$$
$$NA48: \epsilon'/\epsilon = (14.0 \pm 74.3)\ 10^{-4}$$

The american result is surprisingly high in view of the previous results. Taken all together, the NA31, E731, E832 and NA48 measurements lead to the average: $\epsilon'/\epsilon = (19.2 \pm 2.5)\ 10^{-4}$.

While this set of results demonstrates the existence of direct CP violation, this spread of values is uncomfortable.

The additional data of E832 and NA48 should bring extremely valuable information. Moreover, a new experiment, KLOE at Frascati in Italy, has just started. It should produce another measurement of ϵ'/ϵ using a completely different technique.

If a high value of ϵ'/ϵ is confirmed, this might be an indication for sources of CP violation outside the standard model.

T violation and CPT tests with K mesons

As was mentioned in the introduction, K mesons are a superposition of K^0 and $\bar{K}^0$ which transform into each other during propagation.

The CPLEAR experiment at CERN was able to measure a tiny difference between the probability of a K^0 to become a $\bar{K}^0$ at a time t and that of the reversed process.

In this experiment, K^0 and $\bar{K}^0$ are produced through the reactions $p\bar{p} \to \pi^- K^+ K^0$ and $p\bar{p} \to \pi^- K^- K^0$. The antiprotons are extracted from the Low Energy Antiproton Ring at CERN, and stopped in a hydrogen target at the center of the detector. Detecting the K^+ (resp. K^-) identifies the K^0 (resp. $\bar{K}^0$) production. The decays $K^0 \to \pi^- e^+ \nu_e$ and $\bar{K}^0 \to \pi^+ e^- \bar{\nu}_e$ allow the identification of the decaying K meson with the sign of the emitted electron. It is observed that the probability that a K^0 is produced initially and oscil-

NEWS FROM EUROPHYSICS LETTERS

Appearing soon

Papers accepted up to 8 February to appear in forthcoming issues

Intrinsic non-exponential relaxation near the glass transition of an orientationally disordered crystal – *M. Winterlich and R. Böhmer*

Ripple topography of ion beam eroded graphite: A key to ion-beam-induced damage tracks – *S. Habenicht, W. Bolse, H. Feldermann, U. Geyer, H. Hofsäss, K. P. Lieb and F. Roccaforte*

The Mott-Hubbard transition and the paramagnetic insulating state in the two-dimensional Hubbard model – *F. Mancini*

Distinct roles of the triplicated Zn Cl_4 tetrahedra in phase soliton formation and residual commensurations in K_2 Zn Cl_4 – *Dong Keun Oh, Young Man Kwon, Cheol Eui Lee and S. Y. Jeong*

Single-particle mean kinetic energy in low-density supercritical ^{4}He – *D. Colognesi, C. Andreani and R. Senesi*

Polycontinuous morphologies and interwoven helical networks –*S. T. Hyde and S. Ramsden*

Pseudo-contact angle due to superfluid vortices in ^{4}He – *R. Luusalo, A. Husmann, J. Kopu and P. J. Hakonen*

Collapse of cavitation bubbles in blood – *E. A. Brujan*

Comment on "Propagator of the Fokker-Planck equation with a linear force—Lie-algebraic approach" by C. F. Lo – *P. Demo, A. M. Sveshnikov and Z. Kozísek*

Nucleation and growth in order-to-order transitions of a block copolymer – *G. Floudas, R. Ulrich, U. Wiesner and B. Chu*

Statistical mechanics of point particles with a gravitational interaction – *M.-L. Chabanol, F. Corson and Y. Pomeau*

π-shifted magnetoconductance oscillations in mesoscopic superconducting-normal-heterostructures – *V. N. Antonov, H. Takayanagi, F. K. Wilhelm and A. D. Zaikin*

Transmission and reflection of waves by an anharmonic interface – *Z. Odziana and P. Zielinski*

Plasmon and charge quantization effects in a double-barrier quantum wire – *A. Braggio, M. Grifoni, M. Sassetti and F. Napoli*

Phonon-like and single-particle dynamics in liquid lithium – *T. Scopigno, U. Balucani, A. Cunsolo, C. Masciovecchio, G. Ruocco, F. Sette and R. Verbeni*

Note on irreducible approach to reducible second-class constraints – *C. Bizdadea, A. Constantin and S. O. Saliu*

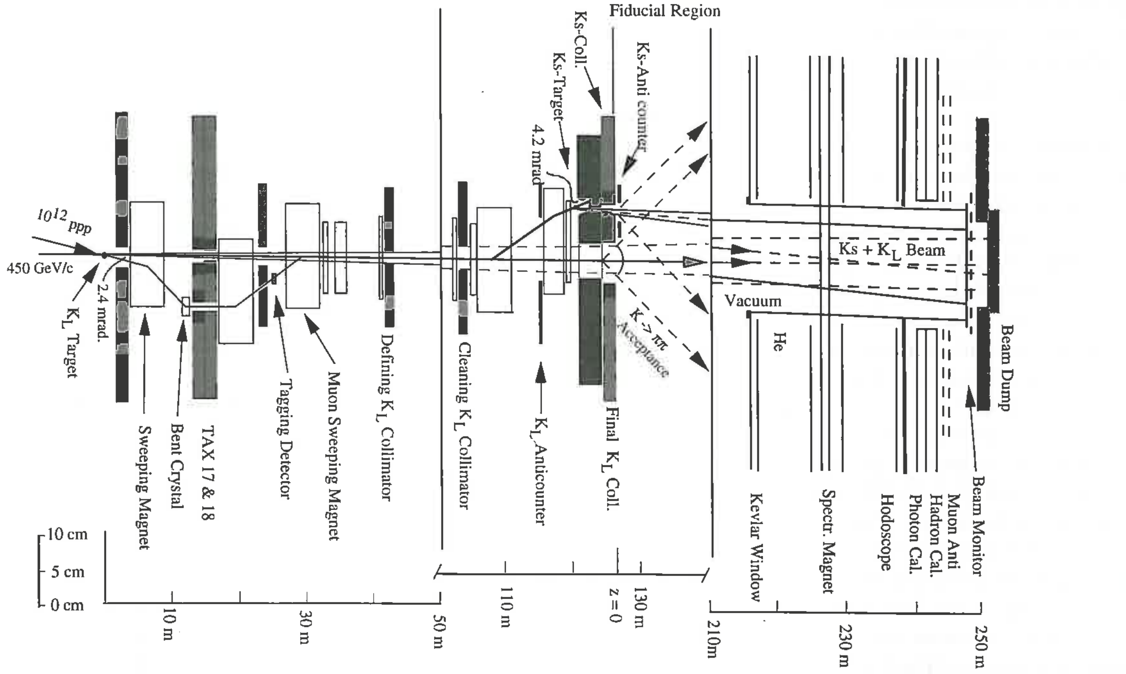

Fig 2 **Schematic layout of the NA48 experiment**

lates into a $\bar{K}^0$ decaying by emitting an electron is different from that of the process where the K^0 and $\bar{K}^0$ are exchanged (a positron being emitted in that case).

The relative difference is small, (6.6 ± 1.6) 10^{-3} [6], but significant. This is a direct evidence for a microscopic violation of the Time Reversal symmetry.

Another outstanding result of CPLEAR is a comparison between the masses of the K^0 and the $\bar{K}^0$, $\Delta m/m$ = (-3 ± 4) 10^{-18} [7]. This is the most precise test of the CPT symmetry, which implies that particles and antiparticles should have the same mass.

These recent results show that the K meson system provides an invaluable opportunity to test the fundamental properties of physics laws.

These opportunities are far from being exhausted. The previously mentioned KLOE experiment will pursue very detailed tests of quantum mechanics and discrete symmetries. In a longer term, experiments are proposed at BNL (Brookhaven National Laboratory), FNAL (Fermi National Laboratory near Chicago), KEK (High Energy Physics Laboratory in Japan) and CERN (European Laboratory for Particle Physics) to study rare K decays to allow very stringent tests of CP violation and the standard model framework. Sensitivities to decay probabilities well below 10^{-10} are considered.

CP violation and B mesons

B mesons are similar to K mesons, but the b quark plays the role of the s quark. In the Standard Model, there are three families of 2 quarks : (u,d), (c,s), (t,b). Weak interactions allow transitions between up type quarks (u,c,t) and down type quarks (d,s,b). There are very precise relations between these transitions if indeed only 3 families of quarks exist. As a consequence, and because in the Standard Model CP violation arises from these transitions, CP violation processes in the K system translate into CP violation processes in the B system. This is a very strong prediction of the theory, which must be tested.

Two dedicated experiments have just started : BABAR at SLAC (Stanford Linear Accelerator Center, USA), and BELLE at KEK.

There is one big difference between B mesons and K mesons, which makes their study more difficult. The B mesons are about 10 times heavier, and thus can decay into many different channels and have a very short life time (about 10^{-12} s !). The observation of $B \leftrightarrow \bar{B}$ oscillation and decay is quite hard. B's must be produced with sufficient energy so that the relativistic expansion of their life time let them travel for several hundred of micrometer before decaying.

The BABAR and BELLE detectors are attached to asymmetric e^+e^- colliders. The positron and electron beams have different energies. A resonant $b\bar{b}$ state is produced and decays into a pair of B mesons.

CP violation in the B system is expected to be observed in many different ways, either directly or via the $B \leftrightarrow \bar{B}$ oscillation.

Although all decay modes are rare, the expected CP violation effects can be large. A popular example is the decay $B \rightarrow J/\Psi K_S$, for which the asymmetry between B and $\bar{B}$ oscillation and decay rate could be of order 60%.

B meson production is much higher with hadronic colliders, but the selection and reconstruction of interesting decays is much more efficient at an e^+e^- collider. About thirty millions $b\bar{b}$ could be produced per year at SLAC or KEK for BABAR and BELLE, to be compared with two hundreds billions at the $p\bar{p}$ FNAL collider for each of the 2 experiments called CdF (Collider Detector at Fermilab) and D^0. However, about one thousand

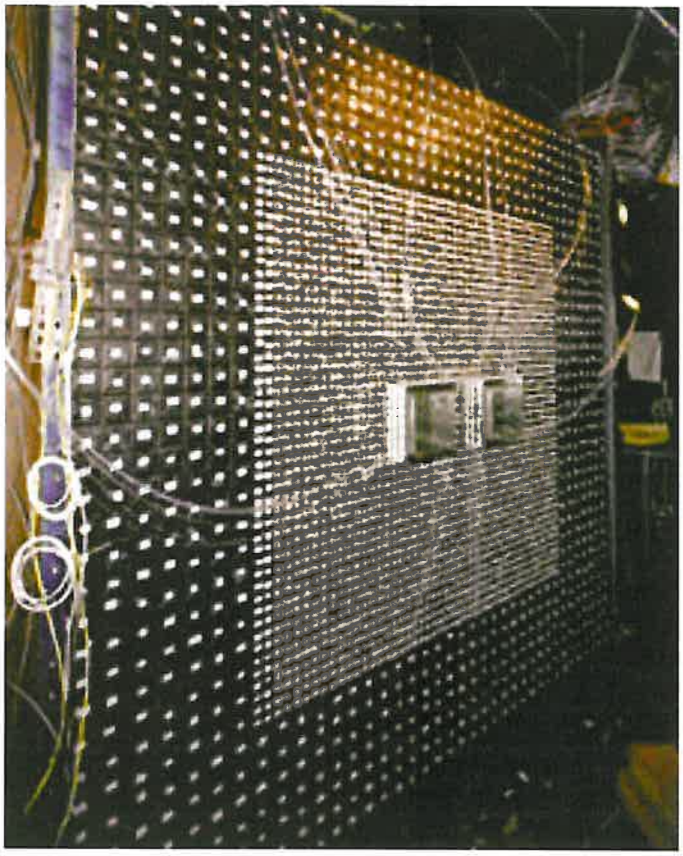

Fig 3 **The E832 CsI calorimeter front face**

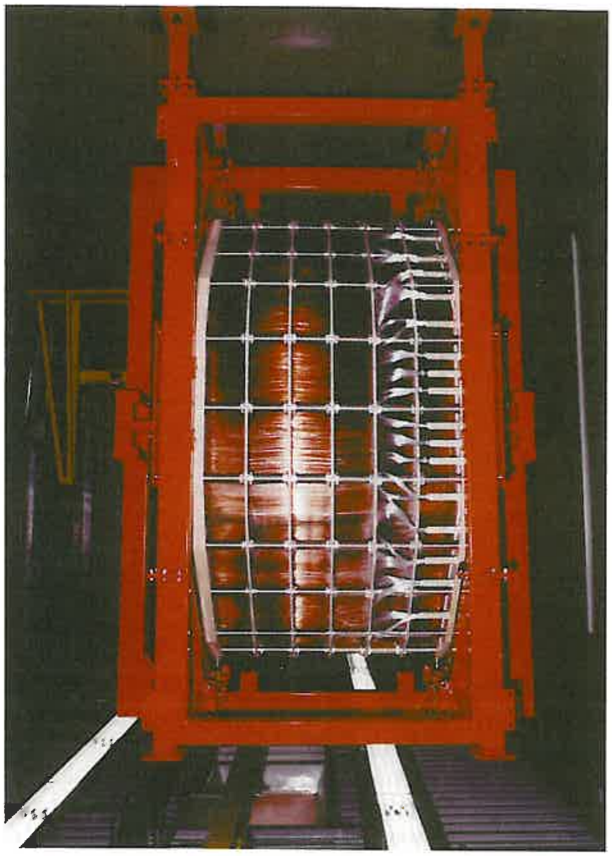

Fig 4 **The electrode structure of the NA48 liquid krypton calorimeter**

$B \to J/\Psi K_S$ decays can be used for analysis in the former case, and only fifteen thousands in the latter, which is relatively much less.

In spite of the very difficult extraction of interesting events, CdF has already attempted a measurement of one CP violation parameter in the B system. However, the uncertainty is too large to draw any conclusion yet. An experiment at DESY (high energy physics laboratory near Hamburg), HERA-b, is about to start, and is one of the competitors in this opening field.

In the long term, extensive studies of B physics will be performed by experiments in preparation for the Large Hadron Collider in construction at CERN, and at the BTEV dedicated program at FNAL, if it is accepted.

Conclusion

A very important experimental step has been recently reached with the demonstration of direct CP violation in K decays, as expected in the Standard Model of particle physics.

The next step is to challenge this model with the B system. First results will come very soon and with increasing precision in th following years.

In a longer term, extremely K decays could provide additional theoretically very clear tests of the standard model paradigm for CP violation and one hopes to reveal surprising effects.

In parallel with this program of refining the Standard Model confrontation with experiment, another path must be followed. Indeed, it is widely accepted that the standard explanation for the CP symmetries seen with K mesons is not at all sufficient to allow for the observed matter-antimatter asymmetry in the universe. As a consequence, one should also look for CP violation in places where it is not expected or expected to be very small. Examples are the study of charmed mesons (mesons similar to K's and B's but with a c quark instead of the s or b quark) and Λ hyperons decays, the measurement of the electric dipole moment of the neutron, the spectroscopy of the antihydrogen atom.

Each of these fascinating experimental challenges offers strong perspectives to deepen our understanding of fundamental (a)symmetries of Nature.

References

[1] H. Burhardt et al., Phys. Lett. B 206 (1988) 169

[2] L.K. Gibbons et al., Phys. Rev. Lett. 70 (1993) 1199

[3] G.D. Barr et al., Phys. Lett. B 317 (1993) 233

[4] A. Alavi-Harati et al. Phys. Rev. Lett. 83 (1999) 22

[5] This is a combination of the result obtained with data taken in 1997, V. Fanti et al., Phys. Lett. B 465 (1999) 335, and the preliminary result from 1998 data, A. Ceccucci, CERN seminar February 29th 2000

[6] A. Angelopoulos et al., Phys. Lett. B 444 (1998) 43

[7] A. Angelopoulos et al., CERN-EP/99-150, submitted to Phys. Lett. B