The Development of Particle Physics

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CP violation

- Charge conjugation and time reversal symmetries.
- CPT theorem.
- Neutral kaon system.
- CP violation in neutral kaon system.
- Experimental evidence for CP violation in neutral kaon system.
  - Experiment
  - Data analysis
  - Results and outcomes
- Other possible examples of CP violation.
- Summary and conclusions.

Charge conjugation

- **C operation - interchange of particle with its antiparticle.**
- C symmetry in classical physics - invariance of Maxwell's equations under change in sign of the charge, electric and magnetic fields.
- C symmetry in particle physics - the same laws for a set of particles and their antiparticles: collisions between electrons and protons are described in the same way as collisions between positrons and antiprotons. The symmetry also applies to neutral particles.
- **$C\psi = \pm \psi$: even or odd symmetry.**
- Example: particle decay into two photons, for example $\pi^0 \rightarrow 2\gamma$, by the electromagnetic force. Photon is odd under C symmetry; two photon state gives a product $(-1)^2$ and is even. So, if symmetry is exact, then 3 photon decay is forbidden. In fact it has not been observed.
- **C symmetry holds in strong and electromagnetic interactions.**

Charge conjugation and time reversal.

- As we saw, C invariance was violated in weak interactions because parity was violated, if CP symmetry was assumed to be preserved.
- Under C operation left-handed neutrinos should transform into left-handed antineutrino, which was not found in nature. However, the combined CP operation transforms left-handed neutrino into right-handed antineutrino, which exists.
- **T operation - connect a process with that obtained by running backwards in time: reverses the directions of motion within the system.**
- **T symmetry: "initial state → final state" can be converted to "final state → initial state" by reversing the directions of motion of all components of the system.**

CPT theorem

- It is possible to define product symmetries, like CP (parity and charge conjugation simultaneously to reveal a system of antiparticles in the reverse-handed coordinate system) or CPT symmetry.
- **Combined CPT symmetry is absolutely exact**: for any process, its mirror image with antiparticles and time-reversal process should look exactly as the original - CPT theorem.
- **Consequences: the same masses, lifetimes, electric charges (with opposite signs) and magnetic moments for particles and antiparticles.**
- If any one individual (or pair) of the symmetries is broken, there must be a compensating asymmetry in the remaining operation(s) to ensure exact symmetry under CPT operation.
- The CPT symmetry was checked through the possible difference in masses, lifetimes, electric charges and magnetic moments of particle and antiparticles and was found to be **exact down 10^{-19}** (relative difference in masses).

Neutral kaon system

- Two isospin doublets (I_3=±1/2, S=±1): $K^+(u\underline{s})$ and $K^0\,(d\underline{s})$ with S=+1 and $K^-\,(s\underline{u})$ and $\underline{K}^0\,(s\underline{d})$ with S=-1.
- K^0 and $\underline{K}^0$ are produced in strong interactions and are eigenstates of strong interactions as in strong interactions the third projection of isospin and strangeness are conserved (definite assignment of I_3 and S).
- However, they are not eigenstates of the CP operation. The linear combinations of these particles can be formed to identify the eigenstates of the CP:
  - $\boldsymbol{K^0_1 = (K^0 + \underline{K}^0) / \sqrt{2}}$ with even CP symmetry: $\boldsymbol{CP\, K^0_1 = + K^0_1}$
  - $\boldsymbol{K^0_2 = (K^0 - \underline{K}^0) / \sqrt{2}}$ with odd CP symmetry: $\boldsymbol{CP\, K^0_2 = - K^0_2}$
- The weak interaction acts on the states K^0_1 and K^0_2, so the particles, which decay, are K^0_1 and K^0_2 without well-defined strangeness.

Neutral kaon system

- The proof of the identity of $K^0{}_1$ and $K^0{}_2$ comes from their decays. Assume that CP is preserved in weak interactions. As $K^0{}_1$ is even under CP operation, it can decay only to states which are also even, for example 2π. $K^0{}_2$ is odd under CP operation and can decay only to states which are also odd, for example 3π.
- The difference in the decay modes results in the significant difference in the lifetimes:

$$\boldsymbol{K^0{}_1 \rightarrow 2\pi}, \quad \tau = 8.93\times10^{-11}\ \mathrm{s}$$

$$\boldsymbol{K^0{}_2 \rightarrow 3\pi}, \quad \tau = 5.17\times10^{-8}\ \mathrm{s}$$

- Long-lived $\boldsymbol{K^0{}_2}$ was first observed by Lande et al. using a 3-GeV beam from the Brookhaven Cosmotron.

Regeneration of K^0_1

- Pure K^0_2 beam passing through matter would regenerate a K^0_1 component.
- $K^0 = (K^0_1 + K^0_2) / \sqrt{2}, \quad \underline{K}^0 = (K^0_1 - K^0_2) / \sqrt{2}$
- Suppose we start with K^0 beam, which is a combination of K^0_1 and K^0_2.
- K^0_1 decay quickly and only K^0_2 remain. K^0_2 is a combination of K^0 and $\underline{K}^0$ in equal proportion.
- K^0 and $\underline{K}^0$ interact differently with matter. For example, the process $\underline{K}^0 + p \rightarrow \pi^+ + \Lambda$ is allowed, while $K^0 + p \rightarrow \pi^+ + \Lambda$ is forbidden.
- So, after some thickness of matter the transformation will be:

$$K^0_2 = (K^0 - \underline{K}^0) / \sqrt{2} \rightarrow (f K^0 - \underline{f}\, \underline{K}^0) / \sqrt{2} = (f + \underline{f})\, K^0_2 /2 + (f - \underline{f})\, K^0_1 /2$$

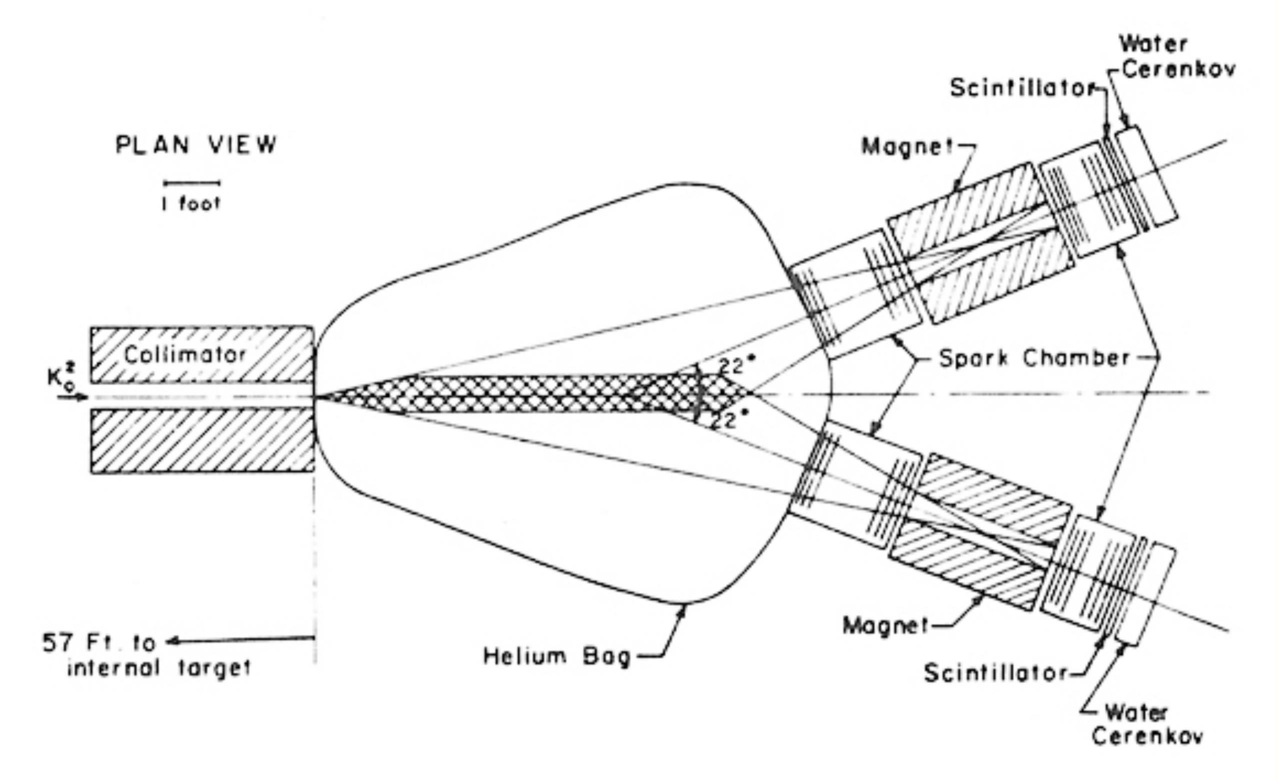
- As $f \neq \underline{f}$, the fraction of K^0_1 is not zero anymore.
- ***Regeneration*** of K^0_1 in K^0_2 beam passing through matter, predicted by Pais and Piccioni, was observed by Muller et al. at the Bevatron. This allowed to determine a tiny difference in masses of K^0_1 and K^0_2: $\Delta m/m = 7\times10^{-15}$.

Observation of $K^0_2 \rightarrow 2\pi$

- **If *CP* is a good symmetry, then $K^0_2 \rightarrow \pi^+ + \pi^-$ decay is strictly forbidden.**
- Christenson et al. set up an experiment to check this. Actually, the objective of the experiment was to extend the limit on the fraction of K^0_2, which decay into two pions.
- Alternating Gradient Synchrotron (AGS) at Brookhaven.
  - 30 GeV proton beam.
  - Be target.
  - Neutral kaons were produced in $p + Be$ collisions.
  - K^0_2 beam - at 30° relative to circulating protons.
  - Collimator at 4.5 m from the target, magnet at 6.5 m, 2nd collimator at 18 m.
- K^0_1 (short-lived) decayed before reaching the 2nd collimator.

Observation of $K^0_2 \rightarrow 2\pi$

- Two spectrometers:
  - Spark chamber,
  - Magnet,
  - Scintillator,
  - Water Cherenkov counter.
- Spark chambers were triggered on a coincidence between water Cherenkov ($v > 0.75\ c$ - pions) and scintillation counters. This removed most slow particles produced in collisions of neutrons.

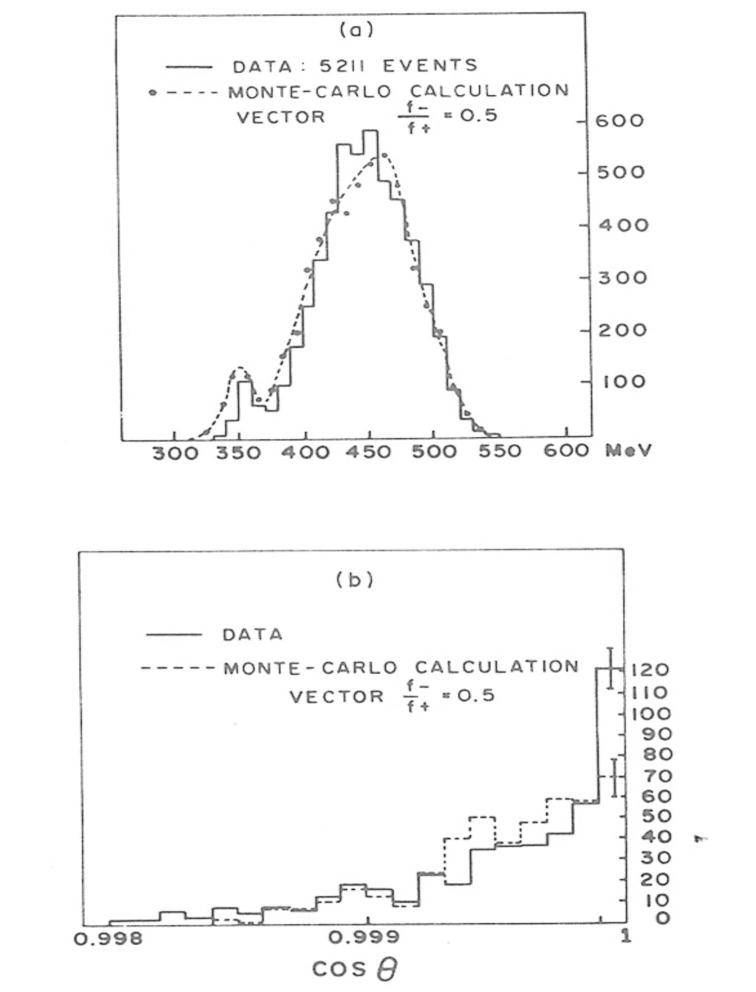


Data analysis

- Signal events:
  - pair of particles (one particle in each spectrometer) with opposite charges;
  - invariant mass $M_{12}^2=(p_1+p_2)^2=(\boldsymbol{p}_1+\boldsymbol{p}_2)^2-(E_1+E_2)^2$ should correspond to $\boldsymbol{K^0_2}$ mass (498 MeV);
  - momenta should lie in the direction of $\boldsymbol{K^0_2}$ beam.
- Background events:
  - $\boldsymbol{K^0_2 \to 3\pi}$, invariant mass of two particle system assuming each charged particle has the mass of the charged pion: 280-363 MeV,
  - $\boldsymbol{K^0_2 \to \pi \mu \nu}$ (280-516 MeV),
  - $\boldsymbol{K^0_2 \to \pi e \nu}$ (280-536 MeV).
- Analysis program:
  - momenta of the two detected charged particles,
  - their invariant mass assuming detected particles are charged pions,
  - the angle θ between the vector sum of the two momenta and the direction of the $\boldsymbol{K^0_2}$ beam (zero for two-pion decay, non-zero for three-particle decay with only two particles detected).

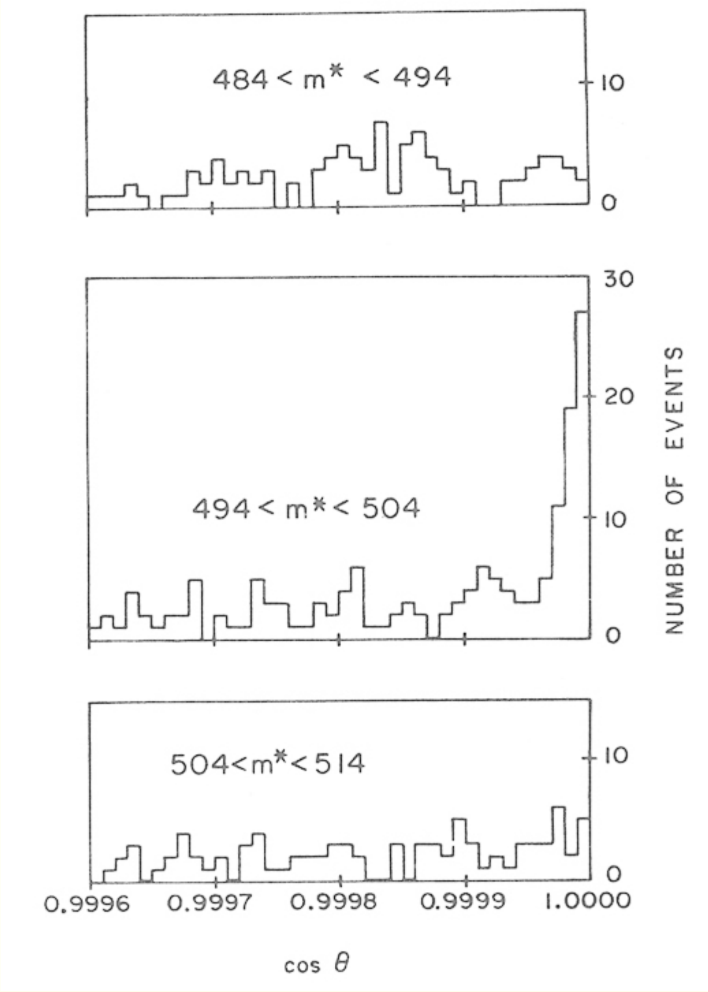
Results

- Calibration: decays of K^0_1 (into two pions) produced by regeneration in tungsten.
- Distribution in the invariant mass for all K^0_2 decays (top figure).
- Angular distribution of events in the range of invariant masses from 490 to 510 MeV (expected 498 MeV): measurements and calculations for background events (bottom figure).
- Clear excess of events at small θ.



Results

- Angular distributions of events in three invariant mass ranges: peak at $\theta = 0$ is seen only for masses similar to the kaon mass (498 MeV). 45 events in the forward peak after background subtraction.
- The mass of $\boldsymbol{K^0_2}$ was found from the measurements of invariant mass as 499.1±0.8 MeV. Not much different from the mass of $\boldsymbol{K^0_1}$ found from calibration regeneration experiment (498.1±0.4 MeV).



Results and outcomes

- Branching ratio: $\boldsymbol{R = (K^0{}_2 \to \pi^+ + \pi^-)/(K^0{}_2 \to \textit{all charged modes}) =}$ **(2.0±0.4)×10^{-3}**.
- **$K^0{}_1$ and $K^0{}_2$ (in our previous definition) are not exact eigenstates of CP symmetry and are not quite particles seen by the weak interactions.** Instead, the true eigenstates of CP have a small admixture of another particle and a new scheme has been adopted:

$$K_L^0 = \frac{1}{\sqrt{1+\varepsilon^2}}(K_2^0 + \varepsilon K_1^0)$$

$$K_S^0 = \frac{1}{\sqrt{1+\varepsilon^2}}(K_1^0 - \varepsilon K_2^0)$$

  $\boldsymbol{\varepsilon}$ is the parameter quantifying CP violation (admixture of the 2nd particle or 'wrong' CP eigenstate). It is measured as **2.3×10^{-3}**.
- Similar branching ratio was found for $\boldsymbol{K^0{}_L \to \pi^0 + \pi^0}$ decay (**9.1×10^{-4}**).

Results and outcomes

- At present the degree of CP violation is usually quoted as the amplitude ratio of processes:

$$|\eta_{+-}| = \frac{ampl(K_L^0 \to \pi^+\pi^-)}{ampl(K_S^0 \to \pi^+\pi^-)} = (2.29 \pm 0.02) \times 10^{-3}$$

$$|\eta_{00}| = \frac{ampl(K_L^0 \to \pi^0\pi^0)}{ampl(K_S^0 \to \pi^0\pi^0)} = (2.28 \pm 0.02) \times 10^{-3}$$

- CP violation was also demonstrated in the leptonic modes of K^0_L decay

$K^0_L \to \pi^- + e^+ + \nu_e$, $K^0_L \to \pi^+ + e^- + \underline{\nu}_e$ with the asymmetry:

$$\Delta = \frac{rate(K_L^0 \to \pi^- e^+ \nu_e) - rate(K_L^0 \to \pi^+ e^- \overline{\nu}_e)}{rate(K_L^0 \to \pi^- e^+ \nu_e) + rate(K_L^0 \to \pi^+ e^- \overline{\nu}_e)} = (3.27 \pm 0.012) \times 10^{-3}$$

- CP violation provides a definition of matter and antimatter: positron (antimatter) is defined as the lepton which is produced more often in K^0_L leptonic decay. Can also separate left from right using neutrinos in K^0_L decay.

Direct and indirect CP violation

- **Indirect CP violation: the CP-forbidden K^0_1** component in K^0_L decays via **the CP-allowed process** with a probability $|\varepsilon|^2/(1+|\varepsilon|^2)\approx|\varepsilon|^2$ of finding a K^0_1 component in K^0_L - process described as an admixture of the 'wrong' CP eigenstate.
- **Direct CP violation: the CP-allowed K^0_2** component in K^0_L decays via the **CP-forbidden process: $K^0_2 \rightarrow 2\pi$** .
- A detailed analysis of data showed that the former process dominates.
- Several experiments at CERN and Fermilab found a contribution of direct CP violation as $\varepsilon'/\varepsilon=(1.8\pm0.4)\times10^{-3}$. If this results is correct, then direct CP violation is found.
- 'Superweak' force, proposed by Wolfenstein, responsible for interactions with $\Delta S=2$. This predicts $\varepsilon'=0$.

Other possible examples of CP violation

- Other possible neutral particle systems with CP violation effects:
  - D^0-$\underline{D}^0$ - calculated to be very small and possibly unobservable.
  - B^0-$\underline{B}^0$ - direct CP violation should dominate, ideal for its search, but many decay modes, low branching ratio to decay modes common for both B^0 and $\underline{B}^0$, about 10^{10} B-meson decays are needed to measure CP violation.
  - In fact CP-violation in B-meson decays has been recently observed in several experiments.
- Cosmological CP violation is necessary to generate a cosmological matter-antimatter asymmetry:
  - To distinguish unambiguously matter from antimatter on a cosmic scale.
  - It provides difference in rate of decays of supermassive bosons X and Y into baryons and antibaryons (this asymmetry requires also non-conservation of baryon number).

Summary and conclusions

- Kaon system provided the first evidence for CP violation in nature.
- CPT is an exact symmetry.
- Indirect CP violation dominates with a degree of 2.3×10^{-3}, but direct CP violation is also present.
- CP violation provides a definition of matter and antimatter.
- CP violation is required to generate cosmological matter-antimatter asymmetry.
- Big efforts are applied to find CP violation (direct violation in particular) in other systems (B^0 - $\underline{B}^0$). The results show the presence of CP violation in agreement with Standard Model predictions.

References

- Recommended textbooks.
- J. H. Christenson et al. "Evidence for the 2π decay of the $K^0{}_2$ meson", *Phys. Rev. Lett.* **13** (1964) 138.
- S. Bennett et al. "Measurement of the charge asymmetry in the decay $K^0{}_L \rightarrow \pi^\pm + e^\pm + \nu$", *Phys. Rev. Lett.* **19** (1967) 993.