Measurement of CP Violation in Neutral Kaon Decays via a Compact Beamline Experiment

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Introduction and Motivation

I propose to measure the semileptonic charge asymmetry in neutral kaon (K^0) decays as a novel test of CP violation under experimental conditions that have never been previously explored. The objective is to determine the asymmetry parameter, δ_L, defined by

$$\delta_L = \frac{\Gamma(K_L \to \pi^- \ell^+ \nu) - \Gamma(K_L \to \pi^+ \ell^- \bar{\nu})}{\Gamma(K_L \to \pi^- \ell^+ \nu) + \Gamma(K_L \to \pi^+ \ell^- \bar{\nu})},$$

where ℓ represents an electron or a muon. Although CP violation in kaon decays is well known, no published experiment has measured δ_L using a small-scale, low-energy beamline setup that utilizes a charge-exchange method to produce a predominantly pure neutral kaon beam.(Or I missed it during my research)

What is the idea of the experiment?
I intend to generate a neutral kaon beam via the charge-exchange reaction:

$$K^+ + n \to K^0 + p\,.$$

A K^+ beam, produced by a primary high-energy proton beam impinging on a target, will be momentum selected and then directed onto a thin, hydrogen-rich target (such as polyethylene) to induce the charge exchange. The resulting neutral kaon beam, after a short distance, will be dominated by the long-lived K_L state. By measuring the decay products in semileptonic decays, I will compare the number of electrons versus positrons to quantify CP violation.

What is new about it?
The novelty of this approach lies in:

1. **Experimental Regime:** Utilizing a compact, low-energy beamline setup rather than large-scale detectors.

2. **Charge-Exchange Production:** Producing a neutral kaon beam by converting a charged kaon beam via a thin target, thereby yielding an initially pure K^0 or $\bar{K}^0$ beam.

3. **Measurement Conditions:** Focusing on the semileptonic asymmetry δ_L under experimental conditions that have not been previously published.

Why has no one made an experiment before?
Historically, the measurement of CP violation in kaon decays demanded very high statistics and extremely sensitive detectors to resolve an asymmetry on the order of 10^{-3}. Such experiments required large, expensive setups (e.g., those at CERN or Fermilab). This approach leverages recent advances in detector technology and simulation, allowing us to design a compact apparatus that can achieve the necessary resolution within a modest budget.

Why is it at least partially useful (scientific usefulness only)?
A precise measurement of δ_L in a new experimental regime offers an independent cross-check of the Standard Model prediction for CP violation. If our measurement agrees with established values (approximately 3×10^{-3}), it reinforces the universality of CP violation. Conversely, any deviation—however slight—might hint at physics beyond the Standard Model. Furthermore, the novel experimental techniques we develop may inspire similar low-cost, high-precision experiments in the future.

What is the main physical idea behind the experiment?
The experiment exploits the fact that neutral kaons, initially produced as pure K^0, evolve into a mixture of the short-lived K_S and long-lived K_L states. The CP violation manifests in the K_L decays, where a small asymmetry in the semileptonic channels occurs due to the $\Delta S = \Delta Q$ rule. This rule implies that a K^0 decays into $\pi^- \ell^+ \nu$, while $\bar{K}^0$ decays into $\pi^+ \ell^- \bar{\nu}$. Our measurement will focus on detecting this asymmetry, which is a direct signal of CP violation.

Experimental Setup

Beamline and Kaon Production:

The experiment will be conducted on a CERN secondary beamline. The setup is as follows:

- **Primary Production:** A high-energy proton beam strikes a primary target, producing a secondary beam containing various particles, including a significant flux of K^+ mesons.
- **Beam Selection:** Standard beamline magnets will be used to select a momentum band for the K^+ mesons (e.g., 5–10 GeV/c).
- **Charge-Exchange Target:** A thin hydrogen-rich target (such as polyethylene or a small liquid hydrogen cell) is placed in the path of the K^+ beam. Here, the reaction

  $$K^+ + n \to K^0 + p$$

  converts a fraction of the K^+ into neutral K^0.
- **Neutral Beam Formation:** Downstream of the target, a dipole magnet sweeps away remaining charged particles. A collimator further defines the neutral beam, resulting in a beam predominantly composed of neutral kaons.

Decay Volume and Detection Region:
A decay volume (approximately 5–10 meters in length) is installed where the neutral kaons can decay. Since K_S decays rapidly (lifetime ≈ 0.09 ns), after a few meters the beam will be essentially pure K_L. Detectors surrounding this decay volume will capture the decay products for analysis.

Detector Components and Design

Required Components:

- **Trigger Scintillators:** Fast plastic scintillators to register incoming beam particles and trigger on decay events.
- **Tracking Detectors:** Wire chambers or drift chambers to reconstruct charged particle trajectories and locate decay vertices.
- **Spectrometer Magnet:** A dipole magnet is used to bend charged particles for momentum analysis and charge separation.
- **Particle Identification (PID):**
  - **Cherenkov Detectors:** Threshold Cherenkov counters to distinguish electrons (or positrons) from pions based on velocity.

- **Electromagnetic Calorimeter:** A compact calorimeter (such as a lead-glass detector) to measure energy deposition and assist in particle identification.

- **Optional Muon Detector:** A simple muon filter (using a few tens of cm of iron followed by a scintillator) to reject muon-induced background. If you've noticed this, it means you're truly reading through my entire document—how kind of you! Take a short break and send me a smiley face in a personal message for a little Karma boost. (:

Detector Layout and Design:
The detector system is designed symmetrically with two identical arms placed after the spectrometer magnet. Each arm contains:

1. A Cherenkov counter optimized to trigger on ultrarelativistic electrons/positrons.

2. An electromagnetic calorimeter module to measure energy deposition.

This dual detection module, which we plan to prototype within a \$2000 budget, ensures that the charge-identification efficiency is extremely high and symmetric between e^+ and e^-. Our design target is to achieve a relative efficiency difference below 10^{-4} so that the detector's intrinsic accuracy exceeds the precision required to measure a $\sim 10^{-3}$ asymmetry.

Projected Accuracy and Requirements

To resolve an asymmetry on the order of 10^{-3}, the statistical precision of the measurement must be better than 0.1–0.2%. This requires:

- Collecting on the order of 10^5 to 10^6 K_L decay events.

- Achieving detector momentum resolution of approximately $\Delta p/p \sim 5\%$ or better, which is attainable with our proposed dipole magnet and tracking detectors.

- Calibrating the Cherenkov and calorimeter systems to ensure that any difference in the detection efficiency for electrons versus positrons is below the targeted asymmetry.

Monte Carlo simulations (using GEANT4) will be used to optimize detector geometry and confirm that the statistical and systematic uncertainties remain within acceptable bounds.

Feasibility and CERN Support

Our experimental design leverages much of CERN's existing beamline infrastructure:

- The primary and secondary beamlines, as well as basic tracking detectors and magnets, are available as part of the Beamline for Schools (BL4S) program.
- Our custom-built detector module (dual Cherenkov-calorimeter) is the primary additional component and is designed to be built within a $2000 budget.
- Previous BL4S experiments have demonstrated that compact, innovative setups can be integrated successfully at CERN. The operational overhead for our experiment is minimal compared to the resources already provided by CERN.

Given that our experiment requires little new infrastructure and aims to measure a fundamental physics parameter under new conditions, it is highly likely that CERN will support our proposal based on past winners' experiences.

Prototype Development (Team-Built Component)

I plan to develop a prototype for a dual-function Cherenkov-calorimeter module that will:

- Serve as a threshold Cherenkov detector for PID by using an acrylic or quartz radiator coupled to SiPMs or a small PMT.
- Incorporate a compact calorimetric section (e.g., a small lead-glass block or a sampling calorimeter using lead and plastic scintillator) to measure the energy deposition.

The design goal is to build two identical modules (one for each arm) within a total cost of $2000. The estimated cost breakdown is as follows:

- Radiator material and photosensors: $300–$500.
- Calorimeter components: $300.
- Readout electronics (PCB, ADC, amplification circuitry): $300.

- Ancillary components (optical coupling materials, housings, wiring, etc.): $100–$200.

The prototype will be thoroughly tested with cosmic rays and beta sources to validate performance. This includes calibrating the Cherenkov threshold and ensuring energy resolution is sufficient for robust electron identification.

Competitive Advantages of Our Proposal

The competitive strengths of this proposal include:

1. **Unique Physics Objective:** Measuring the semileptonic asymmetry δ_L in a compact, low-energy beamline is unprecedented.

2. **Innovative Experimental Approach:** Using a charge-exchange reaction to produce a pure neutral kaon beam and a dual-function detector module is novel.

3. **Cost-Effectiveness:** By leveraging existing CERN beamline infrastructure and keeping our custom build under $2000, we maximize scientific output while minimizing cost.

4. **Comprehensive Work Plan:** Our proposal integrates theoretical studies, detailed simulations, prototype development, and data analysis, ensuring a high likelihood of success.

5. **Potential Scientific Impact:** A precise measurement of δ_L in a new regime could provide valuable confirmation of CP violation under alternative experimental conditions and possibly reveal subtle new physics effects.

Work Plan (Project Roadmap)

1. **Background Research and Theory:**

    - Study the theoretical framework of CP violation in the neutral kaon system, including a review of classical experiments (Cronin-Fitch, CPLEAR, KTeV).(Done.)
    - Calculate the expected semileptonic asymmetry and determine statistical requirements.(Done.)

2. **Simulation and Feasibility Analysis:**

    - Develop a Monte Carlo simulation (using GEANT4 or similar) to model the entire experimental setup: beamline, charge-exchange process, kaon decay, and detector response.(Think we would need a processing cluster.)
    - Optimize the decay volume length, detector placements, and magnet settings to maximize event rates and minimize systematic uncertainties.(A lot of theoretical work, the next think I will do.)

3. **Prototype Construction:**

    - Design and build the dual Cherenkov-calorimeter module within a $2000 budget.(Work for a good engineer, I can not do this on my own. Need help.)
    - Source materials (acrylic/quartz radiator, SiPMs/PMTs, lead glass/scintillator layers) and assemble the module.
    - Test the prototype using cosmic rays and radioactive beta sources to ensure correct threshold behavior and energy resolution.

4. **Calibration and Data Analysis Pipeline:**

    - Develop data acquisition software and analysis routines using CERN's ROOT framework.
    - Calibrate detector efficiencies and verify symmetric charge response via simulation and laboratory tests.
    - Define selection criteria for clean semileptonic decay events and determine the statistical sensitivity to δ_L.

5. **(In case we win.)CERN Integration and Final Setup:**

    - Collaborate with CERN staff to integrate our custom-built module into the beamline.
    - Align our detector with existing tracking detectors, magnets, and trigger systems.
    - Finalize the trigger configuration and perform system tests with a low-intensity beam.

6. **Experiment Execution at CERN:**

    - Collect data during allocated beam time, ensuring that calibration runs and systematic checks (such as reversing magnet polarity) are performed.
    - Monitor real-time data quality and adjust parameters if necessary.

7. **Data Analysis and Interpretation:**

    - Process the collected data to identify semileptonic K_L decays and count e^+ versus e^- events.
    - Correct for detector efficiencies and systematic biases.
    - Compare the measured δ_L with theoretical predictions and previously published values.

Conclusion

This proposal outlines a novel, cost-effective approach to measure CP violation in neutral kaon decays under experimental conditions that have not been previously published. By producing a neutral kaon beam through charge exchange and developing a dual-function Cherenkov-calorimeter module within a \$2000 prototype budget, we aim to achieve the precision necessary to measure the semileptonic asymmetry δ_L. Our comprehensive work plan—from theoretical groundwork and simulation through prototype construction and data analysis—ensures that the experiment is both feasible and scientifically valuable. I would greatly appreciate any feedback on this proposal. While I have presented the core ideas concisely, many details have been omitted for the sake of readability. If you have any questions, suggestions, or corrections, please feel free to reach out.