CP, CPT Study at Jefferson Laboratory

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1 Physics Motivation

ϕ-meson, as many times discussed (see. [?]) is a good source of correlated pairs of neutral kaons because it decays into correlated K_SK_L pairs 32% of the time. By studying the equal decay modes of K_L and K_S quantum mechanics correlation can be seen in 0-8 K_S lifetime region (cτ_S=2.676cm). Final states can be the same due to CP-violating decay of K_L into $\pi^0\pi^0$ or $\pi^+\pi^-$ with 2×10^{-3} branching ratio but as for K_S they are main decay modes. Semileptonic dacays also can be used for this interferometery, but B($K_S \to \pi l \nu_l$) is expected at the level of 5×10^{-4}.

The idea of experiments discussed for ϕ-factories is in simultanious detection of K_SK_L decays in $\pi^+\pi^-\pi^0\pi^0$ state and reconstruction of their decay points with accuracy better than one K_S decay length. Due to fully asymmetric final state ($J^{PC} = 1^{--}$) quantum mechanics prohibits decay of both kaons at the same distance from originated ϕ if they have the same decay mode.

In addition to this very exciting quantum mechanics test at macroscopic distances this interferometry can be used for a study of direct CP violation in K_L decays (ϵ'/ϵ) and for precision CPT tests. For these purposes one should measure the difference in number of events when $\pi^+\pi^-$ pair appeares before $\pi^0\pi^0$ (N_{+-}) with those when $\pi^0\pi^0$ pair is first (N_{00}).

$$A(t_{+-} - t_{00}) = (N_{+-} - N_{00})/(N_{+-} + N_{00}),$$

where t_{+-}, t_{00} are times (or decay lengths) from ϕ to decay point of kaon with neutral or charged pions.
This asymmetry integrated over all K_L decay lengths (less acceptance gives less accuracy) is related as A=$3 \cdot Re(\epsilon'/\epsilon)$ with direct CP violation parameter.

The evaluation of this asymmetry in the interference region ($t_{+-} - t_{00} = 1 - 5\ \tau_S$) gives an information about imaginary part of ϵ'/ϵ and CPT conservation.

As it was shown in [?] with the 10^{11} produced ϕ's and reasonable detector acceptance (20% of K_L decay length, cτ_L=15.49 m and $\beta = 0.22$ in case of $e^+e^- \to \phi$) the ϵ'/ϵ value can be measured with about 10^{-4} accuracy. DAFNE claimes to have 50% acceptance for K_L decays with a 4 m diameter of drift chamber.

If photon detector can reconstruct $\pi^0\pi^0$ vertex with accuracy better τ_S the interferometry test would give accuracy in CPT test parameter $\Delta\Phi = \Phi_{+-} - \Phi_{00}$ about 0.1 degree with a present limit about 1 degree.

By using K_L decay or nuclear interaction in the forward system as a tag K_S rare decays can be studied, including first observation of CP violated $K_S \to \pi^0\pi^0\pi^0$ and $K_S \to \pi^+\pi^-\pi^0$ modes, which are predicted at the level of 2×10^{-9}.

The electroproduction of ϕ at CEBAF also can be a source of correlated $K_S K_L$ pairs and below some preliminary analysis of posibility to perform similar experimets is presented.

2 Photon Flux

For estimation the total number of produced ϕ's was chosen $N_\phi = 10^{11}$. For a year experimental time 10^7 s the corresponding ϕ production rate should be 10^4/s. This rate is equivalent to 3×10^{33} luminosity of e^+e^- collider which is a goal for ϕ-factories.

As an example 2.5 cm of Be taget was chosen (7% rad.length, 4.6 g/cm^2) the same as was using in RadPhi experiment at CEBAF.

The total hadron production cross section for 4-6 GeV photons is 150 μb/nucleon and for ϕ production it is 0.5 μb/nucleon.

All together give a flux $7 \cdot 10^9$ photons/s for a ϕ rate of 10^4/s.

To be able to reconstruct decay length in terms of life time units with accuracy better than one τ_S and for constrained purpose, about 2% uncertainty in photon energy is required. Existing tagging system is not capable to work with this flux but Pestov counters with 25 ps resolution could help.

For that value of photon flux and desired photon energy spread the coherent bremsstrahlung system, reported by Richard Jones (UConn) at Bloomington workshop can be used. With 8 GeV initial electrons it can produce 6 GeV photons with about 2% energy spread with intensity about 3×10^8 (plus about 2×10^8 of 5 and 4 GeV) For CPT study it should be 20 times more intensive photon beam.

Questions: Is 10^{10} flux achievable with tagged photons by 25 ps Pestov counters? Or by coherent bremsstrahlung system? With higher electron energy (16-20 GeV) may be it is posible to get this rate for 4-5 GeV photons. What is lifetime of the diamond crystal at that intensity? What is the physical limit of intensity?

3 $K_S K_L$ Pair Rate

The rate of 10^4/s of ϕ is taken. It should be mentioned, that the total hadronic rate in this case will be an order of 3×10^6. The $K_S K_L$ pair rate from ϕ decays is 3×10^3. Few types of experiments can be set:

1. Tagged K_S. With the near 100% detection efficiency of K_L (by decay in flight and by nuclear interaction in the forward calorimeter) and with constrained from initial ϕ energy and momentum this rate can be used for study of rare decays of K_S: $K_S \to \gamma\gamma$ and CP-violation decays $K_S \to \pi^0\pi^0\pi^0, \pi^+\pi^-\pi^0$ predicted at the level of 2×10^{-9}. With 10^7 s of running time proposed $K_S K_L$ pair rate gives 60 events of that kind.

2. Direct CP violation studies. To have reasonable acceptance for detection of K_L decays in flight with full reconstruction and event selection seems to be difficult

experimentally - detector becomes too long: $\gamma\beta\ c\tau_L = 100$ m. So I do not propose to perform measurement of ϵ'/ϵ.

3. For the interferometry only about 8-10 K_S decay lenghts are needed. With 3 GeV/c kaon momenta the K_S decay length is $\gamma\beta\ c\tau_S = 15$cm, so about 1.2-1.5 m decay volume is needed.

In this case usefull rate will be $3 \cdot 10^3 \times 10 \cdot \tau_S/\tau_L \times$ (detector acceptance). Assuming 4π detector it gives about 50 detected $K_S K_L$ pairs/s. But only 0.2% of them are with $\pi^+\pi^-\pi^0\pi^0$ final state. So, CP rate is 0.1/s. With 10^7 running time 10^6 such events can be expected, what can give few$\times 10^{-3}$ accuracy in the asymmetry. For the CPT test the most sensitive region is $\Delta t = 1 - 4\ \tau_S$, where intensity is dropping down due to QM. But remain number of events could be enough for CPT test at the level $\Delta\Phi < 0.1^0$.

All above estimations were performed in [?], where other ϕ decay physics was discussed and which could be performed at CEBAF with less photon flux. It includes radiative and other rare decays of ϕ as well as η, η' decays when ϕ can be considered as source of tagged (with photon) η and η' via $\phi \to \eta\gamma$ or $\phi \to \eta'\gamma$.

4 Target and Recoil System

The recoil system should measure the proton momentum and its output angle with sufficient accuracy to predict ϕ total energy and momentum direction to be used as a constraint in $K_S K_L$ reconstruction. This determination should be better than the overall detector resolution to be effectively used and should be an order of few percent.

Two obvious disadvantages of Be taget are: Fermi motion of nuclei in the Be atom what leads to about 200 MeV additional energy spread of secondary particles; and recoil proton should go through condense Be matiarial to be detected in the recoil system. These DE/DX losses can be minimized by making cylindrical target with small diameter.

As an alternative to Be target liquid hydrogen can be used. With density of 0.07 g/cm^3 the 70 cm length of LH_2 is needed for the same ϕ rate (8% rad.length). The transverse dimention can be made relatively smaller, than for Be taget and no effect from Fermi motion is expected.

5 Regeneration

The crucial point for all above can be nuclear interaction of kaons with the target nuclei. This is the main difference of target experiments with colliding beams ones.

The total nuclear cross section for 2-3 GeV kaons is about 20 mb/nucleon including about 1 mb/nucleon (should be checked) regeneration of K_L into K_S. For average pass of kaon through half of the target length the total hadronic interaction rate for $3 \cdot 10^3$ kaons is 15/s (88/s ?!! should be checked!) what should be compared with 50/s of usefull $K_S K_L$ pair rate. But only about 3/s (17/s ?!!) are $\Sigma\pi$ or $\Lambda\pi$ which can give similar signature as kaon decay. But they can be rejected by missing mass analysis and looking for recoil proton. So nuclear interaction wont give too much background to correlated kaon pairs.

More complicated with regeneration. The above cross section gives 0.7/s of regenerated K_L compare with 0.1/s of usefull CP decays. The regenerated K_S has different angular and momentum distribution than original K_S or K_L and constrained fit for $\pi^+\pi^-\pi^0\pi^0$ final state could remove most of them.

Question: how many? There is approved by INTASS grand for study of this effect in KLOE drift chamber (Frascati(J.Franzini)-Novosibirsk(E.Solodov)), where regeneration is smaller, but still 100 times higher than signal from direct CP violation.

It should be mentioned, that regeneration itself will not give an asymmetry, because in final state one has $K_S K_S$. Regeneration reduces sensitivity of the asymmetry measurement (10% for KLOE, 7 times for CEBAF?!). But if one rejects regenerated events by constrained fit, it becomes dangerous, because constrained fit can remove more $\pi^+\pi^-$ than $\pi^0\pi^0$ due to better resolution and immediately gives asymmetry. It should be under control at the level of 10^{-3} or better.

For the new CEBAF detector it may be reasonable to consider 10 times shorter target with 10 times more photon flux (10^{11}/s !). Or it may be a compromize - shorter target - longer running time.

The LH_2 target has some advantage. Because K_S decay length is shorter, than target length, the regeneration (and nuclear interactions) is not integrated over full length of the target as for Be case. It could give factor of 2-3 in signal/background ratio.

We should think how to reduce this background.

Also regeneration can bring us a new interesting physics. The coherent fraction of regenerated K_S's (it is a question how many?) will interfere with original K_S's and in general should be canceled. Or it may give another interesting effects.

Note: Numbers of this sections are very preliminary and because of importance should be carefully checked.

6 Detector Requirements

Some detector features were discussed at Bloomington Workshop July 14-16, 1997 and were summarized in A. Dzierba letter to participants. It was agreed, that detector should be designed employing state-of-art detector technology. I would suggest to consider 4π detector with equivalent systems to be able to perform complete analysis for all particles in backward and forward directions (momentum, energy, angular resolution, particle ID ...). As it is seen from above, CP,CPT study gives good example about quality of the detector. It should include:

- good tracking in all directions with momentum measurement to reconstruct kaon mass and predict the direction and momentum of another kaon, decaying into photons.

- good segmented 4π calorimeter to reconstruct effective kaon mass and remove background from $K_L \to \pi^0\pi^0\pi^0$ decay. It should be able to reconstruct decay point with accuracy better than one τ_S.

- good particle ID. For CP study the main background decay into two charged pions is $K_L \to \pi\mu\nu_\mu$ decay, when neutrino is soft and muon can be selected as pion. Boost can give some advantage compare to colliding beams experiments, when pions and muons are soft and muon range system cannot be used.

- good timing

Beam line should prevent detector from direct exposition of huge initial flux of electrons and photons.

The target and recoil proton region should have about 1.5m length surrounded by cylindrical drift chamber and cylindrical calorimeter covering polar angles from about 20 to 180 degrees with no holes. This recoil region should be instrumented with all above systems. Good example with similar dementions and resolutions is CMD-2 detector. CsI crystals (pure, with good timing) can be used. (After producing about 10 tons of crystals for KEK, Novosibirsk can do another similar job for TJNAL) Recoil proton has 200-700 MeV/c momentum and also will be clearly seen in the same detector.

But for the trigger one should use fast timing (with DE/DX recognition). Full hadronic rate is expected at the level of 10^6 and trigger system should reduce this rate to about 10^3 or so to be able to record data. So fast (scintillators?) counters should be set before DC with amplitude analysis for DE/DX of protons. (May be after DC? Or crystals are fast enough?)

The forward going system should cover $\pm 20(?)$ degrees with uniform acceptance. One dipole magnet will not give this uniformity, but two in perpendicular direction could do. Torroidal magnetic spectrometer can also be considered. By detecting charged particle in forward direction, it should be posibility to reconstruct decay point in the decay region with accuracy about few cm.

Good segmented calorimeter with excelent spatial resolution is required. With four detected photons from two neutral pions one should be able to reconstruct kaon decay point with about 10 cm accuracy or better. It may be crystal calorimeter or liquid Krypton as in CERN NA48 or in KEDR detector in Novosibirsk.

For CP study it is not nesessery to select kaons, so Cerenkov counters are not needed, but muon range system should be used. But Cerenkov counters will be usefull for identifying charged kaons from other decays. About 50% of ϕ decays give K^+K^- pairs and rare decays and interactions of tagged charged kaons can be studied. CP-violation in asymmetry in $K^\pm \to \pi^\pm\pi^+\pi^-$ rates can be searched.

The trigger rate should be an order of 1 MHz and with sofisticated trigger processors the rate should be reduced to about 1 kHz to be able to record to tapes only interesting events. (Remember we expect $10^4\phi$/s.)

7 Conclusion

The continuous electron beam at Jefferson Laboratory can provide photon beam with necessary intensity for production of $10^4\phi$/s. This rate is the same as the goal intensity of ϕ-factories, which are under construction in Frascati and Novosibirsk. The very exiting experiments for CP-CPT study can be performed with this number of ϕ-mesons with different experimental approach to systematic errors.

Detector, designed for CP-CPT study automaticaly becomes a general purpose detector with excellent resolutions, particle identification and sophisticated triggers.

The photon and secondary particles rate proposed for CP-CPT study is not extremely high. For example LHC-B experiment at CERN plans to work with much higher rate.

The CP-CPT measurements should be consider as posible program for a new generation of the detectors in Jefferson Laboratory.

References

[1] S. Eidelman, E. Solodov, and J. Thompson, Nuclear Physics B (Proceedings Supplement) **24A** (1991) 174.