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Test of the Quantum Theoretical Behavior of the K^0-$\bar{K}^0$ System

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ABSTRACT

As a test of the conventional quantum theoretical description of the K^0-$\bar{K}^0$ system, the amplitude of the K_S-K_L interference term has been determined in the decay $K_{S,L} \rightarrow \pi^+\pi^-$, employing a K_L^0 beam incident on a regenerator. The data at each momentum are consistent with the general expectations of quantum theory and with the conventional phenomenology of CP violation. The ratio k of the measured amplitude of the interference to its predicted value is found to be $k = 0.95 \pm 0.034$ when averaged over our data at all momenta, and 0.97 ± 0.02 when additional information is used from other experiments.

In conventional formulations of the quantum theory, a system in an initially pure state will remain in a pure state if totally isolated from external pertubations. Although tests of this and other fundamental aspects of conventional quantum theory (CQT) have exhibited no contradictory evidence, these tests have mostly been confined to the domain of atomic physics[1] and very few at higher energies.[2] It is of interest therefore, to examine those processes in high energy physics and in weak interactions, which could provide a test of the CQT framework.

There are different ways in which CQT could be extended.[3-7] One possibility is the time evolution of an initially pure state into an incoherent mixture of states.[5,6] The predictions based on unitarity would then be violated, i.e., the time evolution of the system's density matrix would not be represented by a unitary transformation, although probability would still be conserved.[8] For example, according to the conventional description of the $K^0-\bar{K}^0$ system, the K^0 particles that survive after a long path from the production target are supposed to be in a pure state, K^0_L, and they remain in a pure[9] state after regeneration in the exact forward direction and after further propagation. The amplitude of the interference term is characteristic of a pure state, i.e. maximum. A dilution of the interference would indicate either a violation of CQT in the regeneration process due to strong interactions, or in the decay due to weak interactions,[3,5,6] or the necessity to consider the long lived K^0's as a mixed state.[10] If the interference term is found to have the correct amplitude, it is an implicit test of our quantum theoretical description with respect to those three possible deviations mentioned above.

This article describes a study of the $K_{S,L} \rightarrow \pi^+\pi^-$ decay, in which the data have been analyzed to search for just such a dilution. No significant dilution is found; the results are compatible with the expectations of CQT.

After correction for the overall detection efficiency of the apparatus and data analysis, $\varepsilon(\tau,p)$, the intensity $I(\tau,p)$ of the $K_{S,L} \rightarrow \pi^+\pi^-$ decays in the beam direction (transmission regeneration) for an initially pure K_L beam incident on a regenerator can be written as

$$I(\tau,p) = \frac{N(\tau,p)}{\varepsilon(\tau,p)} = S(p) \left[A\, e^{-\Gamma_S \tau} + B\, e^{-\Gamma_L \tau} + 2k\sqrt{AB}\, e^{-(\Gamma_S+\Gamma_L)\tau/2} \cos(\Delta m \tau + \phi) \right]. \quad (1)$$

Here τ is the proper time measured from the exit face of the regenerator, p is the K^0 momentum, $N(\tau,p)$ the number of K^0 decays observed per unit of p and of τ, $S(p)$ is the momentum spectrum, $\Gamma_S(\Gamma_L)$ is the total $K_S(K_L)$ decay rate, and Δm is the K_L-K_S mass difference. A and B are proportional to the product of the square of the amplitudes of K_S and K_L and their decay rates into $\pi^+\pi^-$. The angle ϕ is the phase difference between the two K_S and K_L decay amplitudes.[11]

The prediction of CQT is that k = 1. Therefore, the parameter k measures the ratio of the observed interference term to that expected from CQT.[12] The existence of a large interference phenomenon was first observed 10 years ago.[13] Measurements of the parameter k have been reported.[14,15] For ref. 14, k = 1.20 ± 0.14, compatible with 1. In ref. 15, measured values of k are reported as a function of K^0 momentum and these values are shown on fig. 1. Taking their indicated errors at face value and ignoring possible correlations between the different momenta, the χ^2 for the hypothesis k = 1 is 16.5 for 7 degrees of freedom whereas, if a linear dependence of k as a function of momentum is assumed (dotted line on fig. 1), the χ^2 is 4.9 for 5 degrees of

freedom. The difference of 11.6 in χ^2 for two additional degrees of freedom (confidence level of about 0.5%) shows either that other errors have to be added to the errors shown in ref. 15 or that a momentum dependent violation of CQT is indicated by their data.

The experiment reported here was performed at the Brookhaven National Laboratory Alternating Gradient Synchrotron. K_L produced at an internal target impinged upon a carbon regenerator 81.3 cm long. The K_S flux from the target has decayed by a minimum of 100 lifetimes at the entrance face of the regenerator. Results of an analysis of the data emphasizing the determination of ϕ have been previously reported, to which the interested reader is referred for further experimental details.[16] Although the data employed in reference 16 and the present case are identical, the treatment here is optimized for the determination of k and therefore somewhat different. For clarity, however, we include here some of the aspects which are common to both analyses.

The decay mode $K_{S,L} \rightarrow \pi^+\pi^-$ was identified by requiring an invariant mass $M(\pi\pi)$ within two standard deviations of the K^0 mass, and the absence of veto, Čerenkov and muon counter signals. Various fiducial and secondary momentum cuts were imposed, leaving mainly $K \rightarrow \pi^+\pi^-$ and a small contribution of $K^0_{\mu 3}$ decays in which the muon was undetected. Approximately 2×10^6 events survived. The events between 4 and 10 GeV/c were binned in 1 GeV/c momentum intervals and 0.05×10^{-9} second proper time intervals. The residual $K^0_{\mu 3}$ decays and the incoherently regenerated $K_S \rightarrow \pi^+\pi^-$ events were eliminated by subtractions in angle for every proper time bin.[17] The efficiency $\varepsilon(\tau,p)$ was evaluated by a Monte Carlo technique.

Using a minimum χ^2 technique, fits of the data were made to equation (1) allowing Γ_S, Δm, and, for each momentum interval, a different set of parameters A, B, and ϕ, to vary. Γ_L was fixed at the value 1.931×10^7 sec^{-1} as given by ref. 18 but our results were quite insensitive to the value of Γ_L used. We present here several fits to the data.[19] In the first fit, k was constrained to be 1 as expected from CQT. In the second fit, k was allowed to vary, but was constrained to be the same at all momenta. The results of both fits are given in the first two columns of Table I. The difference in χ^2 is sufficiently small that the conclusion can be drawn that this test, using only our data, is consistent with CQT, yielding for k the value 0.947 ± 0.034.

However, due to the correlations between k, Γ_S and Δm, the determination of k can be improved by better knowledge of Γ_S and Δm. Accordingly we present a third fit using two additional data points corresponding to the values of Γ_S and Δm and their errors as given by the Particle Data Group compilation.[18] The result of this fit, shown in column 3 of Table I, is also consistent with CQT, with a slightly reduced error for k.

In the compilation of reference 18, the error given for Γ_S is larger than some of the input data. This is due to substantial inconsistencies between recent measurements and two older determinations, both using the same technique.[20] In the fourth fit, we have chosen to reject the older results, and have selected experiments[21-24] that measured Γ_S or Δm with high accuracy, and that were not vulnerable to uncertain corrections due to the recent controversy on the magnitude of the CP violation parameter η_{+-}. With our data and these values as additional data points, the fourth fit gave the results shown in column 4 of Table I. The value of k obtained with this less conservative viewpoint is 0.97 ± 0.02, also in good agreement with the expectations of CQT. In our judgment, the reliability of the input data used in the fourth fit is sufficiently high that we prefer to quote this value of k as our best result.

Other fits of the data were performed, still using the results from ref. 21 to 24

as additional data points. If k is constrained to be 1, the χ^2 is 108.1; if k is allowed to have a linear dependence as a function of momentum (two degrees of freedom for k), the χ^2 is 105.5 and the best fit is represented by the solid line on fig. 1; if k is allowed to take a different value at each momentum (6 degrees of freedom for k), the χ^2 is 104.2 and the values of k are represented by the dots on fig. 1. The differences in χ^2, 2.6 for two degrees of freedom and 3.9 for 6 degrees of freedom, show that our data are compatible with the CQT prediction k = 1. To further illustrate the quality of the fits with k = 1, an interference term was extracted from the data and is shown in Fig. 2, along with the corresponding fitted values, for each momentum interval.

Finally, fits were also performed replacing the constant k in equation (1) by the function $Qe^{-R\tau}$ of τ, identical at all momenta, and allowing the parameters Q and R to vary (two degrees of freedom). This particular parameterization was inspired by the extension of CQT described in ref. 6, where the constant in the exponential of the interference term of equation (1) is allowed to be different from $1/2(\Gamma_S + \Gamma_L)$. The best value for Q was 0.99 ± .07, for R it was 0.003 ± .01, and the χ^2 was 106.3, i.e. 1.8 less than the χ^2 for the hypothesis k = 1. Therefore our results are still compatible with CQT.

In conclusion, the amplitude of the interference is found to be consistent with CQT; it is measured to be equal to 0.97 ± 0.02 when averaged over all momenta. These results limit the possible extensions of quantum theory.[5,6] The conjectures[10,25] proposed to explain the long life $\pi^+\pi^-$ decay mode of the K^0 meson without CP violation require a large reduction of the interference term. Our result reinforces the result of ref. 14 and 15 that already ruled out such hypotheses.

We wish to thank the staff of Nevis Laboratories, and in particular Bill Sippach and Yin Au, for their contributions to the success of the experimental program. We wish also to thank the staff of the Brookhaven National Laboratory AGS, especially Drs. David Berley and Satoshi Ozaki for their continued support during the course of the experiment. We are indebted to Prof. E.H. Wichmann for a fruitful discussion. Finally, we wish to acknowledge the contributions of Prof. Jack Steinberger in the conception and early stages of the experiments.

TABLE I

Results of the Fits

Constraint of k = 1 Other experimental data used	Used None	Not Used None	Not Used Ref. 18	Not Used Ref. 21-24
k Γ_s in 10^{10} s^{-1} Δm in 10^{10} s^{-1}	1 1.133 ±0.0053 0.566 ±0.015	0.947 ±0.034 1.125 ±0.007 0.577 ±0.017	0.988 ±0.030 1.124 ±0.006 0.542 ±0.0034	0.972 ±0.021 1.118 ±0.004 0.535 ±0.002
Correlation between k and Γ_s Correlation between k and Δm Correlation between Γ_s and Δm	-- -- 0.83	0.68 -0.40 0.27	0.86 -0.13 0.05	0.72 -0.12 0.02
χ^2 Number of degrees of freedom	101.0 126	98.8 125	103.5 127	106.4 129
Change of χ^2 when unitarity constraint is relaxed	--	2.2 [a]	0.2 [a]	1.7 [a]
Confidence level for that change of χ^2	--	14%	65%	19%

(a) This is the difference in χ^2 between fits made with and without the constraint k = 1, for a difference of 1 between the degrees of freedom. Column 2 is to be compared with column 1, while columns 3 and 4 are compared to fits with k = 1 (not shown here).

REFERENCES

1. For instance, see C.A. Kocher and E.D. Commins. Phys. Rev. Lett. 18, 575 (1967). S.J. Freedman and J.F. Clauser. Phys. Rev. Lett. 28, 938 (1972).
2. For instance, see L.R. Kasday, J. Ullman and C.S. Wu. Bull. Am., Phys. Soc. 15, 586 (1970) and Columbia University Report LE 350. P.H. Eberhard et.al., Phys. Lett. 53B, 121 (1974).
3. M. Roos. Communications Physics - Mathematics 33, 3 (1966).
4. L. Lanz, L.A. Lugiato and G. Ramella. Physics 54, 94 (1971).
5. P.H. Eberhard. CERN 72-1 (1972) unpublished.
6. M.S. Marinov. JETP Letters 15, 677 (1972).
7. M. Kupczinski, International Center for Theoretical Physics, Trieste, Report IC/73/51 (1973) and Warsaw University Report IFT/74/7 (1974), unpublished.
8. As in ref. 5, the CQT time evolution of the density matrix according to a unitary transformation is called unitarity and the conservation of its trace is called conservation of probability. These definitions are not accepted everywhere. In ref. 6, unitarity and probability conservation both refer to the trace condition only, and "unitarity" is declared good even when the evolution is not described by a unitary matrix. This ambiguity about the significance of the word unitarity may lead to some confusion.
9. The word "pure" is meant in the quantum theoretical sense of a state that can be described by a single wave function.
10. P.K. Kabir and R.R. Lewis, Phys. Rev. Letters, 15, 306 (1965).
11. The quantity $\sqrt{A/B}\, e^{i\phi}$ is equal to the ratio of the K_S^0 regeneration amplitude ρ to the CP violation parameter η_{+-}, describing K_L^0 decay into $\pi^+\pi^-$.
12. The parameter η of ref. 5 is related to k by the relation $\eta = k^2$.
13. V.L. Fitch, R.F. Roth, J.S. Russ and W. Vernon, Phys Rev. Lett. 15, 73 (1965).
14. C. Alff Steinberger et al., Physics Lett. 21, 595 (1966).
15. P. Darriulat, J.P. Deutsch, K. Kleinknecht, C. Rubbia, and K. Tittel, Phys. Lett. 29, 132 (1969).
16. W.C. Carithers et al., Phys. Rev. Lett. 34, 1240 (1975) and W.C. Carithers et al., Phys. Rev. Lett. 34, 1244 (1975).
17. A careful subtraction of the scattered events was necessary because they would have a substantially different $K_{S,L}$ interference pattern from the coherently regenerated events.
18. V. Chaloupka et al., Review of Particle Properties, Phys. Lett. 50B, 1 (1974). $\Gamma_S = (1.1284 \pm 0.0091)\ 10^{10}s^{-1}$, $\Gamma_L = (0.001931 \pm 0.000015)\ 10^{10}s^{-1}$, $\Delta m = (0.5403 \pm 0.0035)\ 10^{10}s^{-1}$.
19. As a check of consistency, some fits were made using slightly different χ^2 parameterization and different fitting programs. One was Optime (Computer Phys. Commun. 3, 296, 1972 and 5, 163, 1973) and the second one was Minuit (F. James and M. Roos, CERN Computer 6000 Series Program Library D506-D516). They gave equivalent results.
20. L. Kirsch et al., Phys. Rev. 147, 939 (1966) and R.A. Donald et al., Phys. Lett. 27B, 58 (1968).
21. O. Skjeggestad et al., Nucl. Phys. 48B, 343 (1972). $\Gamma_S = (1.116 \pm 0.006)\ 10^{10}s^{-1}$.
22. C. Geweniger et al., Phys. Lett. 48B, 483 (1974). $\Gamma_S = (1.119 \pm 0.006)\ 10^{10}s^{-1}$.

23. M. Cullen et al., Phys. Lett. 32B, 523 (1970). $\Delta m = (0.542 \pm 0.006)\ 10^{10} s^{-1}$.
24. Combined result of two experiments, C. Geweniger et al., Phys. Lett. 52B, 108 (1974) and S. Gjesdal et al., Phys. Lett. 52B, 113 (1974). $\Delta m = (0.5338 \pm 0.0022)\ 10^{10} s^{-1}$.
25. B. Laurent and M. Roos, Phys. Lett. 13, 269 (1964) Errata Phys. Lett. 15, 104 (1965).

Figure Captions

Fig. 1 The parameter k as a function of K^0 momentum. Triangles are results from ref. 15 and the dotted line is the best fit of this data to a straight line. Dots are results from this experiment and the solid line is the corresponding best fit to a straight line.

Fig. 2 The extracted interference term for each 1 GeV/c momentum interval from 4-10 GeV/c. The fit of Eq. 1 to the data assumed k = 1. The interference term was isolated by subtracting the first two (non-interference) terms from the efficiency-corrected data, and then dividing by the multiplicative factor of the cosine (interference) term, $2\sqrt{AB}\, e^{-(\Gamma_s + \Gamma_L)\tau/2}$.

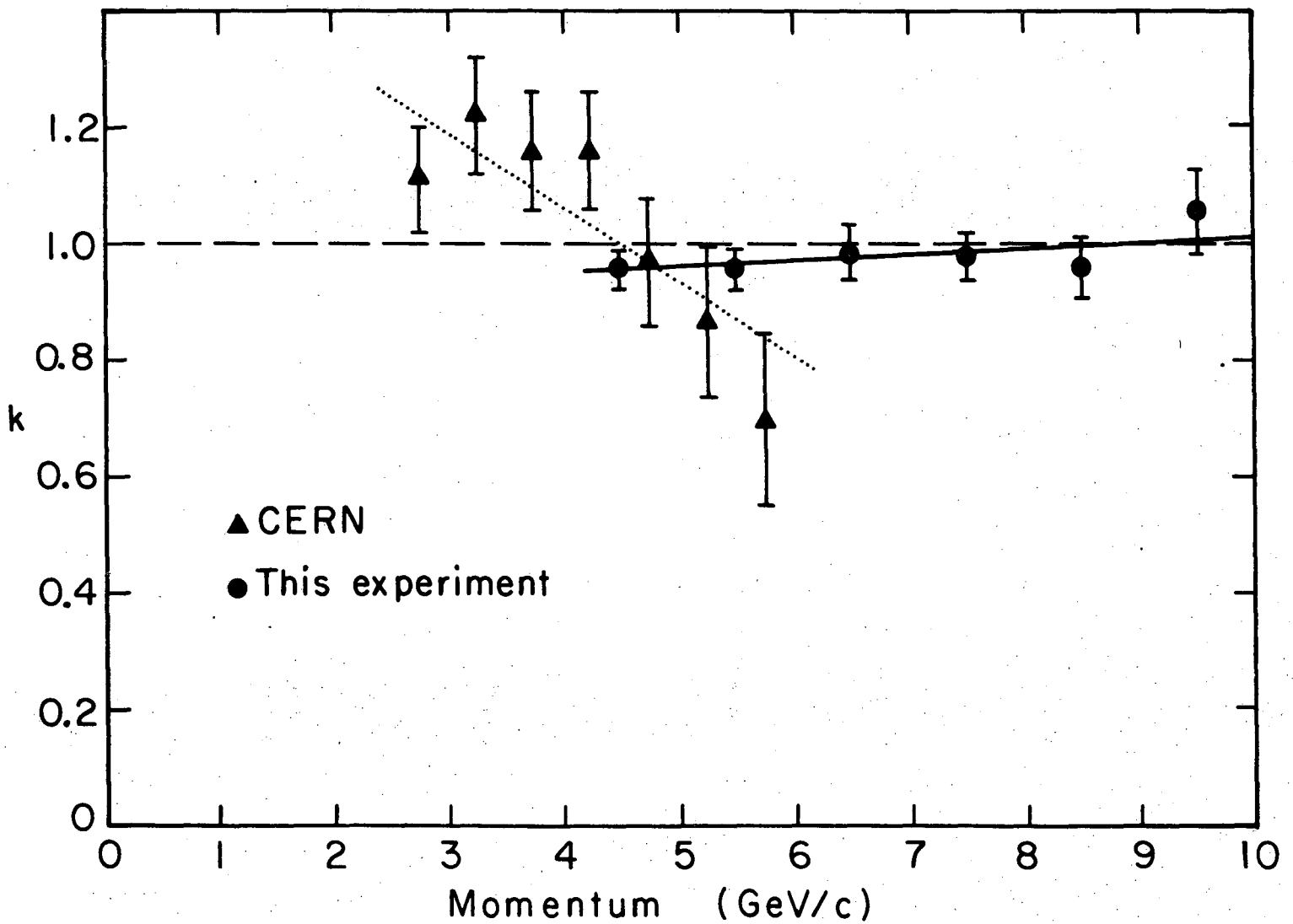

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Fig. 1

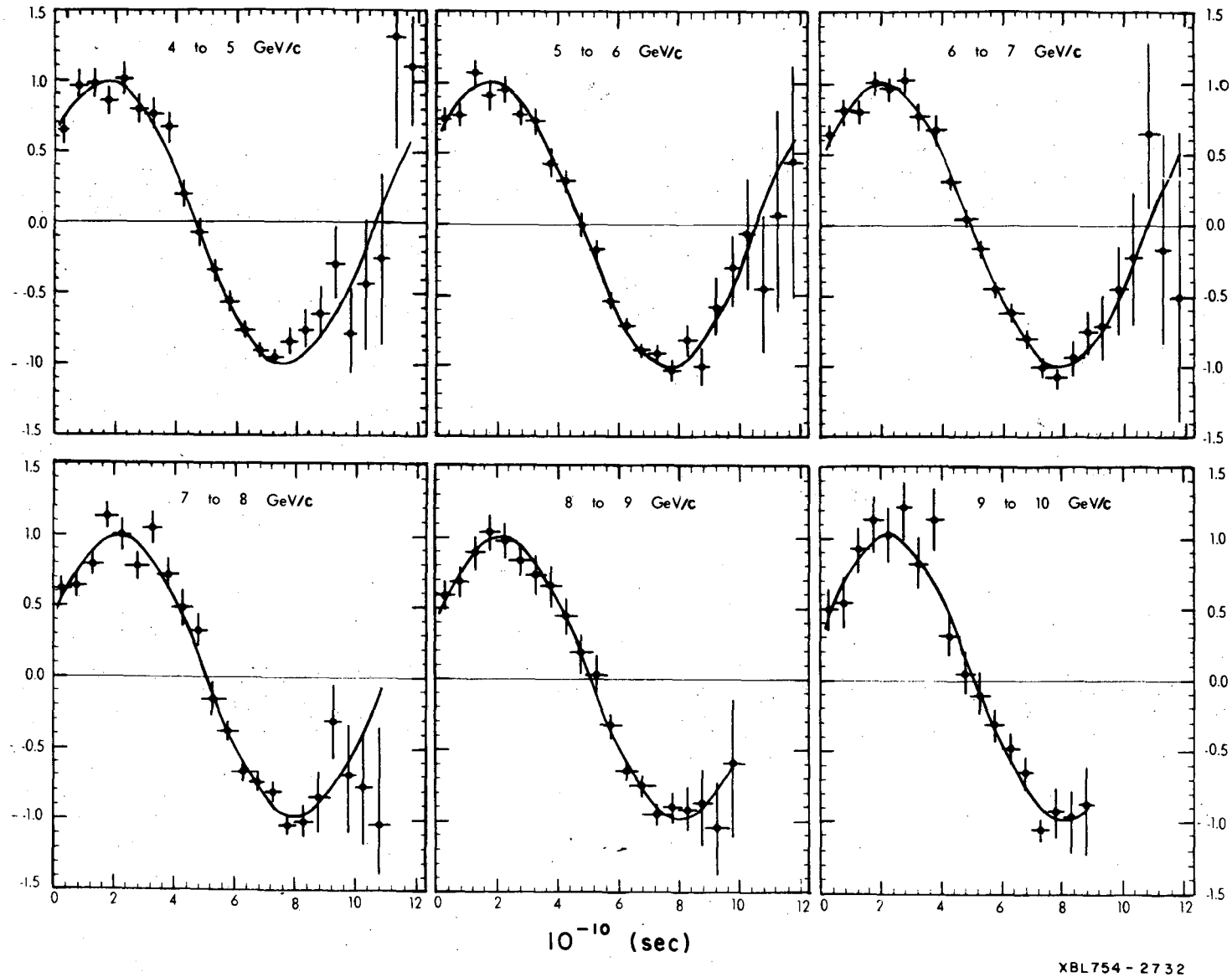
4 to 5 GeV/c
5 to 6 GeV/c
6 to 7 GeV/c
7 to 8 GeV/c
8 to 9 GeV/c
9 to 10 GeV/c
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
0
2
4
6
8
10
12
10^{-10} (sec)
XBL754-2732

Fig. 2

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