EVIDENCE FOR CONSTRUCTIVE INTERFERENCE BETWEEN COHERENTLY REGENERATED AND CP-NONCONSERVING AMPLITUDES*

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We report here some preliminary results from an experiment designed to measure the phase of the CP-nonconserving component in a long-lived neutral K-meson beam.[1] While the results are preliminary in that only a small fraction of the total data have been analyzed, we believe the main conclusion drawn at this time is clear.

As concluded in reference 1, the long-lived neutral K_L^0 meson with a unique lifetime and mass is not a pure eigenstate of CP but is a mixture given by $K_L^0 = K_2^0 + \epsilon K_1^0$, where K_1^0 and K_2^0 are the eigenstates with eigenvalues +1 and −1, respectively, and where $|\epsilon| \cong 2\times10^{-3}$. A change in this mixture of states occurs when the K_L^0 beam is passed through a scattering medium. The difference in the K^0 and $\bar{K}^0$ forward-scattering amplitudes, $f(0)$ and $\bar{f}(0)$, produces a coherent conversion of the K_2^0 component to K_1^0 (the reverse process is negligible). The wave becomes $\psi = K_2^0 + (\epsilon + A_r)K_1^0$, where A_r is the coherent regeneration amplitude given, at equilibrium, by

$$A_r = \frac{2\pi i[f_{21}(0)/k]N_r\Lambda_S}{i\delta + \frac{1}{2}}, \qquad (1)$$

with $f_{21}(0) = \frac{1}{2}[\bar{f}(0) - f(0)]$; k is the wave number; δ is the mass difference, $m_S - m_L$, in units of the decay rate of the short-life component K_S^0; N_r is the number of scattering centers per cm^3; and Λ_S is the mean decay length of the K_S^0.

The branching ratio for 2π decay[2] in material is proportional to $|\epsilon + A_r|^2$. Of course ϵ and A_r should have equal magnitudes for a maximum interference effect. In solid material, however, $A_r \gg \epsilon$, the interference effects are small, and A_r can be separately determined. Neglecting attenuation and interference effects to keep the formulas perspicuous, the coherently regenerated K_S^0 intensity immediately behind a piece of solid material of thickness l (measured in units of Λ_S) and nuclei density N_S is

$$I_S = 4\pi^2 N_S^2 \Lambda_S^2 |[f_{21}(0)/k] \times [1 - \exp(-i\delta l - l/2)](i\delta + \tfrac{1}{2})^{-1}|^2 \qquad (2a)$$

$$= |A_r|^2 (N_S/N_r)^2 \times [1 + \exp(-l) - 2\exp(-l/2)\cos\delta l]. \qquad (2b)$$

The experimental procedure was to determine $|A_r|$ for an arbitrary density N_r by using Eq. (2b) and measuring I_S. The intensity, I_a, of 2π decays over a length L was measured with no material present and is proportional to $|\epsilon|^2$. Finally, diffusely distributed material of a density such that $|\epsilon| \sim |A_r|$ was placed in the decay volume and the intensity, I_d, of 2π decays in the same length L was measured. In terms of directly determined quantities the phase angle α between A_r and ϵ is given by

$$\cos\alpha = \frac{(I_d - I_a - I_p)}{2(I_a I_p)^{1/2}}, \qquad (3)$$

where $I_p = |A_r|^2 L/\Lambda_S$.

The experiment was performed at the Brookhaven National Laboratory AGS. The K_L^0 beam, produced by 28-BeV protons in a Be target, is similar to that described in reference 1, except that (a) the beam was at +30° instead of −30° relative to the circulating protons, (b) the detection apparatus was ~82 ft from the target, and (c) the collimation system defined a solid angle of 22 μ sr at the target in the accelerator. The vector momenta of the charged secondaries from K^0 decay were measured in a spectrometer comprised of spark chambers before and after a magnetic field. A plan view, which is a composite of a drawing and spark-chamber photographs of an actual event, is shown in Fig. 1. Most features are evident in the figure. Triggering required a five-fold coincidence between scintillation counters C_1, C_2, C_3, C_4, and C_5. All chamber plates are of 0.001-in. Al except the last six plates in the chamber behind the magnet, which together contained three radiation lengths of Pb to detect electrons from the K_{e3} decay mode. The extra spark images along the central tracks come from mirrors placed to give depth information. We emphasize a particularly useful feature of the apparatus; namely, the trajectories of the secondaries from a two-body decay, in the projection along the magnetic field,

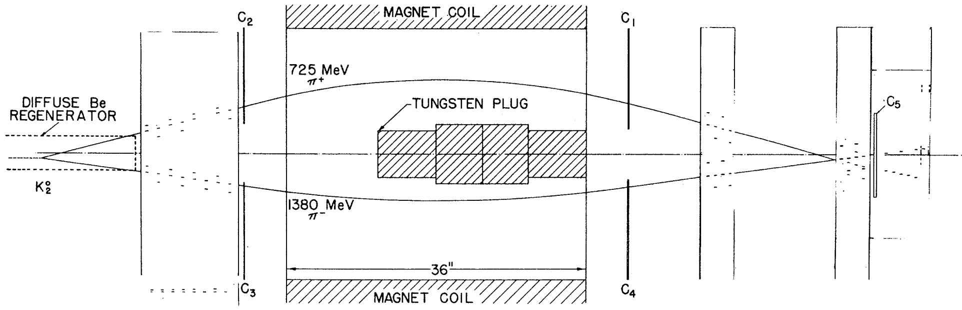

FIG. 1. Plan view of detection equipment with a sample event superimposed.

cross over at a point which is, to a good approximation, on the extrapolated line of flight of the decaying particle. The beam was monitored by two separate neutron counters placed 17 ft upstream from the K_L^0-decay region.

From the vector momenta of the two charged particles the invariant mass of each event is calculated assuming the two secondaries are π mesons. In addition, the angle θ between the vector sum of the two momenta and the beam direction is computed. We obtain the number of 2π events in a sample of data by plotting a $\cos\theta$ distribution of those events in a mass range encompassing the K^0 mass and determine the number that lie in the forward peak above the background.

Beryllium was selected as the regeneration material to minimize the multiple coulomb scattering of the charged decay products. To attain low density, $4\times7\times0.022$-in. Be plates were arranged at intervals of 0.400-in. Granularity effects in such an array are negligible if the element spacing is small compared with the K_S^0 decay length (~3 in. in this experiment) and small compared with the wavelength of the oscillation associated with the K_S^0–K_L^0 mass difference (~36 in. for $\delta = 0.5$). The whole assembly was 39.6 in. long. Equation (2) applies to the equilibrium case, and we retain its applicability by using in the final sample only those events which originated in the last 18 in. of the assembly. Solid Be 3.125 in. thick was used to obtain I_S. Spatial effects were averaged out by moving the solid Be in 3-in. steps along the beam and summing those data originating in the pertinent 18 inches.

The angular distributions for those events which have been obtained in the three experimental configurations with the corresponding monitor readings are shown in Fig. 2. The mass has been restricted to $485 < m^* < 505$ MeV.

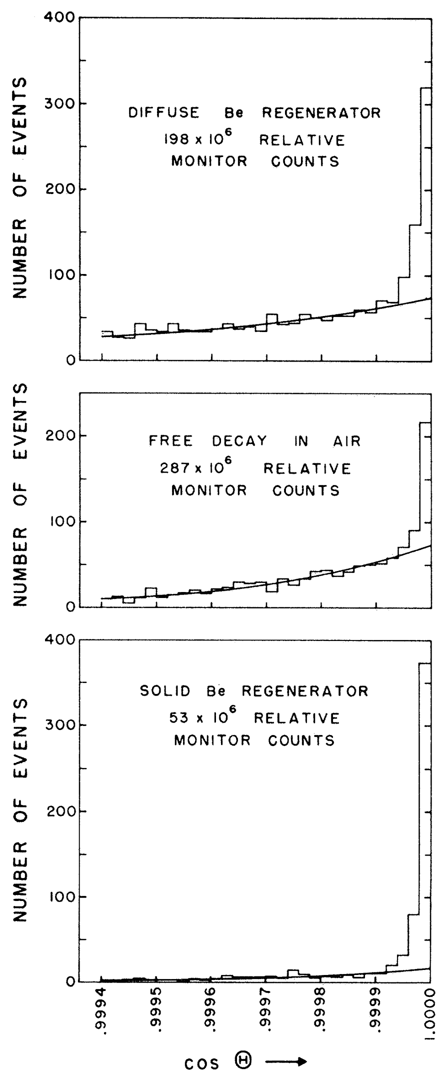

FIG. 2. Data obtained in the three experimental configurations. The solid lines represent best fits to the background.

The background consists of incoherent regeneration and/or three-body decay events, depending on the sample of data, and in each case an exponential gives an excellent fit to the background distribution over the range $0.9994 < \cos\theta < 0.9999$. The background under the peaks in Fig. 2 is then evaluated with good accuracy by extrapolation of the fitted curve to zero angle. The momentum band of the detected K meson is 1.55 ± 0.30 BeV/c.

The data are corrected for attenuation in the Be and for small end effects arising from the fact that the diffuse regenerator is not of infinite extent. Also, a correction for interference in the regeneration in solid Be is made using an iterative procedure, starting from the value of α obtained with no correction to the solid-Be data. Because the thickness of the solid Be was approximately one K_S^0 decay length, I_S is insensitive to the mass difference δ. However, as noted in Eq. (2), the equilibrium regeneration amplitude in the diffuse regenerator is sensitive to δ. For this reason, $\cos\alpha$ calculated from the data is a function of the assumed mass difference. The results are shown in Fig. 3, with the central values of the most recent measurements[3,4] of δ indicated by arrows. The correction for interference in the case of the solid Be depends on the relative sign of α and δ and causes the $\cos\alpha$ vs δ curve to be double valued.

Figure 3 shows clear evidence for constructive interference between ϵ and A_γ. From this constructive interference we conclude that the

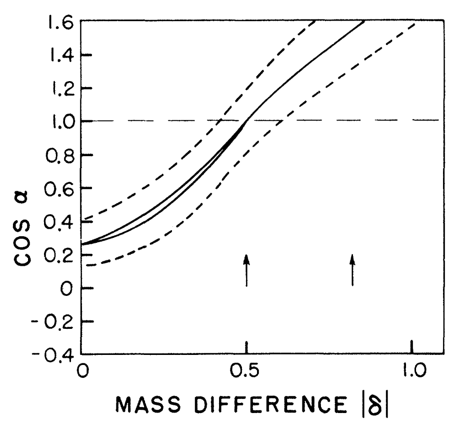

FIG. 3. $\cos\alpha$ computed from the data versus assumed mass difference. The dotted lines give the one-standard-deviation error limits. Because of the associated errors the computed values of $\cos\alpha$ are extended beyond unity.

CP-nonconserving component in the K_L^0 beam is precisely the same state as is produced in the regeneration—that new particles cannot be invoked to explain the effect in reference 1. Furthermore, for mass differences in the region of 0.5 to 0.8, the interference appears to be a maximum. The data strongly reject higher mass differences.

The absolute phase of ϵ depends on knowledge of the phase of A_γ, for which we rely on optical-model calculations at the present time. We use as input data the total cross sections for charged K's on neutrons and protons and assume charge independence to obtain the imaginary parts of the K-nucleon amplitudes. We have taken the real amplitude, relative to the imaginary, to be (0, 0), (−0.4, −0.25), and (−0.4, −0.40) for plus and minus strangeness, respectively. In all cases, the computed regeneration amplitude $f_{21}(0)$ is pure imaginary to within 15° over the momentum band involved in this experiment. As pointed out by Wu and Yang,[5] if the $\Delta I = \frac{1}{2}$ rule is valid in $K_L^0 \rightarrow 2\pi$ decay, then

$$\epsilon \cong (-M_i + iy)/(i\delta + \tfrac{1}{2}), \qquad (4)$$

where all quantities are in units of the K_S^0-decay rate. The numerator contains all possible CP-nonconserving elements; M_i is the imaginary (off the energy shell) mass contribution, and y is the imaginary off-diagonal component of the lepton and 3π transition rates. A nicety of the present experiment is that the denominator cancels out in any comparison of ϵ and A_γ. Moreover, if the $\Delta I = \frac{1}{2}$ rule is valid, a nearly pure imaginary $f_{21}(0)$ coupled with the highly constructive interference observed in this experiment indicates that, within the framework of CPT invariance, a large part, if not all, of the ϵ arises from M_i, a possibility anticipated by Sachs and Treiman.[6]

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[2]Both ϵ and A_γ are the amplitudes for only the $\pi^+\pi^-$ decay mode, making the results independent of the $\Delta I = \frac{1}{2}$ rule.

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R. Turlay, Proceedings of the International Conference on Fundamental Aspects of Weak Interactions (Brookhaven National Laboratory, Upton, New York, 1964); and to be published. Using the "gap" method, which gives a result independent of all nuclear scattering parameters, these authors obtain $\delta = 0.5 \pm 0.1$ not corrected for interference. Incorporating the results of the present experiment, the corrected central value is approximately 0.55.

[4]T. Fujii, J. V. Jovanovich, F. Turkot, and G. T. Zorn, Phys. Rev. Letters 13, 253 (1964). These authors obtain $\delta = 0.82 \pm 0.12$ uncorrected for interference effects.

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[6]R. G. Sachs and S. B. Treiman, Phys. Rev. Letters 8, 137 (1962).

QUANTIZED GRAVITATIONAL THEORY AND INTERNAL SYMMETRIES*

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The purpose of this note is to report on some consequences for internal symmetries of elementary particles which are now indicated by a careful investigation of the program to construct a general relativistic quantum theory of gravitation. We shall attempt to outline briefly the reasoning which led us to the consideration of a very specific group for the internal symmetries. The fact that the group which we obtained is an infinite group, rather than a Lie group, was at first regarded as a serious impediment. However, in view of a recent paper by O'Raifeartaigh[1] which questions the desirability of Lie groups in view of their inability to yield a mass splitting, we are encouraged to present our considerations at this time.

A customary procedure for quantizing a given classical theory is to obtain the Poisson brackets of the dynamical variables of the classical theory, and then to preserve a judiciously chosen subset of these commutation relations as commutators of the corresponding Hermitian operators (up to the ubiquitous factor $i\hbar$) in the quantum theory. That we do not preserve all the commutation relations in the transition to quantum theory is evident from the fact that the classical canonical group and the corresponding quantum unitary group are not homomorphic. The usual procedure of preserving the commutation relations of the "fundamental" dynamical variables x_i and p_i (or their field-theoretic counterparts) is less than candid in view of our ability to perform canonical transformations to new canonical variables $\bar{x}_i$ and $\bar{p}_i$ before making the transition to quantum theory. A simple consideration of the effect of such a procedure when the canonical transformation is the point transformation from rectangular to polar coordinates demonstrates that, in general, the quantum theories so obtained are inequivalent. Upon reflection, in order to obtain a Lorentz-covariant quantization of a Lorentz-covariant classical field theory, the criterion for determining the preferred subset of the commutation relations which are to be preserved is evidently to select the Lie algebra of the inhomogeneous Lorentz (i.e., Poincaré) subgroup of the classical canonical group. The important epistomological reasons for such a choice will be discussed elsewhere.

When we turn to the general theory of relativity, the preferred subgroup of the canonical group is no longer the Poincaré group, but rather the group of general coordinate transformations (i.e., Einstein group). At first sight it would thus appear that the program for a generally covariant quantization would be to employ the dynamical variables of general relativity in order to construct a realization of the Lie algebra of the Einstein group, and then to preserve this subalgebra of the canonical group of the classical theory in the transition to the unitary group of the quantized theory. However, such a program cannot possibly work! This is due to the fact that the Einstein group is a function group, a consequence being that the generators of infinitesimal coordinate transformations are necessarily constraints of the theory. All observable dynamical variables must commute with all the constraints and are therefore space-time invariants. (Analogously, in Maxwell theory we do not realize the gauge group by means of observables. The observables must be gauge invariant.) In view of the fact that the Einstein group is simple,