# EVIDENCE FOR THE $2\pi$ DECAY OF THE $K_2^0$ MESON*†

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(Received 10 July 1964)

This Letter reports the results of experimental studies designed to search for the $2\pi$ decay of the $K_2^0$ meson. Several previous experiments have served[1,2] to set an upper limit of 1/300 for the fraction of $K_2^0$'s which decay into two charged pions. The present experiment, using spark chamber techniques, proposed to extend this limit.

In this measurement, $K_2^0$ mesons were produced at the Brookhaven AGS in an internal Be target bombarded by 30-BeV protons. A neutral beam was defined at 30 degrees relative to the circulating protons by a $1\frac{1}{2}$-in.$\times 1\frac{1}{2}$-in.$\times$48-in. collimator at an average distance of 14.5 ft. from the internal target. This collimator was followed by a sweeping magnet of 512 kG-in. at ~20 ft. and a 6-in.$\times$6-in.$\times$48-in. collimator at 55 ft. A $1\frac{1}{2}$-in. thickness of Pb was placed in front of the first collimator to attenuate the gamma rays in the beam.

The experimental layout is shown in relation to the beam in Fig. 1. The detector for the decay products consisted of two spectrometers each composed of two spark chambers for track delineation separated by a magnetic field of 178 kG-in. The axis of each spectrometer was in the horizontal plane and each subtended an average solid angle of $0.7\times 10^{-2}$ steradians. The spark chambers were triggered on a coincidence between water Cherenkov and scintillation counters positioned immediately behind the spectrometers. When coherent $K_1^0$ regeneration in solid materials was being studied, an anticoincidence counter was placed immediately behind the regenerator. To minimize interactions $K_2^0$ decays were observed from a volume of He gas at nearly STP.

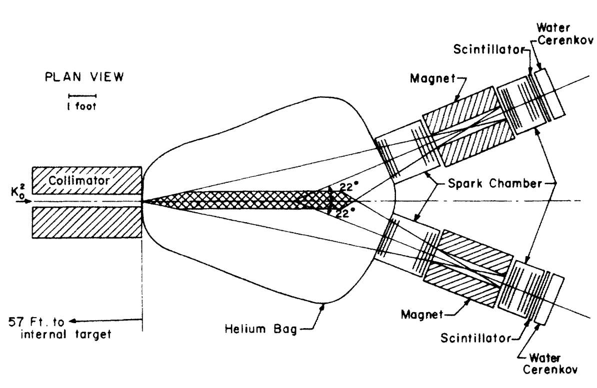


FIG. 1. Plan view of the detector arrangement.

The analysis program computed the vector momentum of each charged particle observed in the decay and the invariant mass, $m^*$, assuming each charged particle had the mass of the charged pion. In this detector the $K_{e3}$ decay leads to a distribution in $m^*$ ranging from 280 MeV to ~536 MeV; the $K_{\mu 3}$, from 280 to ~516; and the $K_{\pi 3}$, from 280 to 363 MeV. We emphasize that $m^*$ equal to the $K^0$ mass is not a preferred result when the three-body decays are analyzed in this way. In addition, the vector sum of the two momenta and the angle, $\theta$, between it and the direction of the $K_2^0$ beam were determined. This angle should be zero for two-body decay and is, in general, different from zero for three-body decays.

An important calibration of the apparatus and data reduction system was afforded by observing the decays of $K_1^0$ mesons produced by coherent regeneration in 43 gm/cm$^2$ of tungsten. Since the $K_1^0$ mesons produced by coherent regeneration have the same momentum and direction as the $K_2^0$ beam, the $K_1^0$ decay simulates the direct decay of the $K_2^0$ into two pions. The regenerator was successively placed at intervals of 11 in. along the region of the beam sensed by the detector to approximate the spatial distribution of the $K_2^0$'s. The $K_1^0$ vector momenta peaked about the forward direction with a standard deviation of $3.4\pm 0.3$ milliradians. The mass distribution of these events was fitted to a Gaussian with an average mass $498.1\pm 0.4$ MeV and standard deviation of $3.6\pm 0.2$ MeV. The mean momentum of the $K_1^0$ decays was found to be 1100 MeV/$c$. At this momentum the beam region sensed by the detector was 300 $K_1^0$ decay lengths from the target.

For the $K_2^0$ decays in He gas, the experimental distribution in $m^*$ is shown in Fig. 2(a). It is compared in the figure with the results of a Monte Carlo calculation which takes into account the nature of the interaction and the form factors involved in the decay, coupled with the detection efficiency of the apparatus. The computed curve shown in Fig. 2(a) is for a vector interaction, form-factor ratio $f^-/f^+=0.5$, and relative abundance 0.47, 0.37, and 0.16 for the $K_{e3}$, $K_{\mu 3}$, and $K_{\pi 3}$, respectively.[3] The scalar interaction has been computed as well as the vector interaction

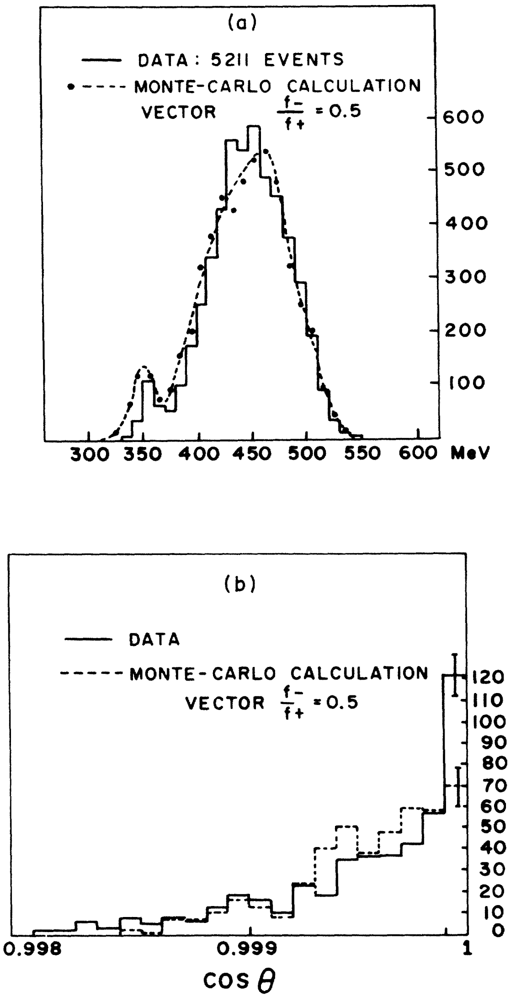


FIG. 2. (a) Experimental distribution in $m^*$ compared with Monte Carlo calculation. The calculated distribution is normalized to the total number of observed events. (b) Angular distribution of those events in the range $490 < m^* < 510$ MeV. The calculated curve is normalized to the number of events in the complete sample.

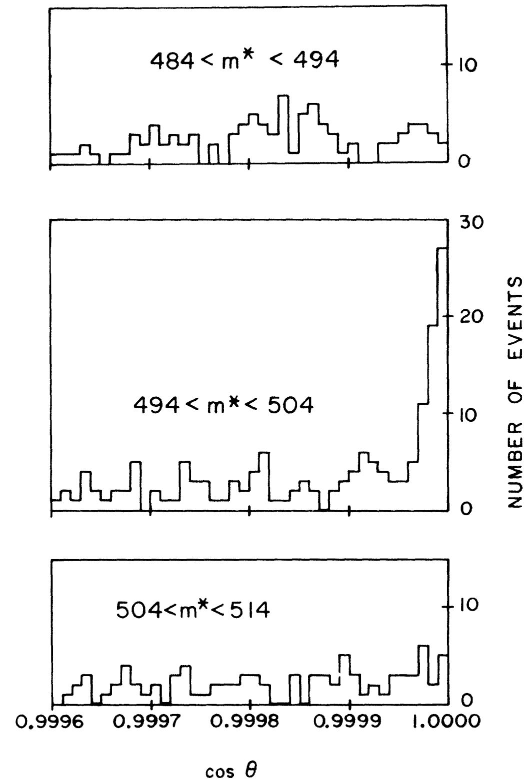


FIG. 3. Angular distribution in three mass ranges for events with $\cos\theta > 0.9995$.

with a form-factor ratio $f^-/f^+ = -6.6$. The data are not sensitive to the choice of form factors but do discriminate against the scalar interaction.

Figure 2(b) shows the distribution in $\cos\theta$ for those events which fall in the mass range from 490 to 510 MeV together with the corresponding result from the Monte Carlo calculation. Those events within a restricted angular range ($\cos\theta > 0.9995$) were remeasured on a somewhat more precise measuring machine and recomputed using an independent computer program. The results of these two analyses are the same within the respective resolutions. Figure 3 shows the results from the more accurate measuring machine. The angular distribution from three mass ranges are shown; one above, one below, and one encompassing the mass of the neutral $K$ meson.

The average of the distribution of masses of those events in Fig. 3 with $\cos\theta > 0.999\,99$ is found to be $499.1 \pm 0.8$ MeV. A corresponding calculation has been made for the tungsten data resulting in a mean mass of $498.1 \pm 0.4$. The difference is $1.0 \pm 0.9$ MeV. Alternately we may take the mass of the $K^0$ to be known and compute the mass of the secondaries for two-body decay. Again restricting our attention to those events with $\cos\theta > 0.999\,99$ and assuming one of the secondaries to be a pion, the mass of the other particle is determined to be $137.4 \pm 1.8$. Fitted to a Gaussian shape the forward peak in Fig. 3 has a standard deviation of $4.0 \pm 0.7$ milliradians to be compared with $3.4 \pm 0.3$ milliradians for the tungsten. The events from the He gas appear identical with those from the coherent regeneration in tungsten in both mass and angular spread.

The relative efficiency for detection of the three-body $K_2^0$ decays compared to that for decay to two pions is 0.23. We obtain $45 \pm 9$ events in the forward peak after subtraction of background out of a total corrected sample of 22 700 $K_2^0$ decays.

Data taken with a hydrogen target in the beam also show evidence of a forward peak in the $\cos\theta$ distribution. After subtraction of background, $45 \pm 10$ events are observed in the forward peak at the $K^0$ mass. We estimate that ~10 events can be expected from coherent regeneration. The number of events remaining (35) is entirely consistent with the decay data when the relative target volumes and integrated beam intensities are taken into account. This number is substantially smaller (by more than a factor of 15) than one would expect on the basis of the data of Adair et al.[4]

We have examined many possibilities which might lead to a pronounced forward peak in the angular distribution at the $K^0$ mass. These include the following:

(i) $K_1^0$ coherent regeneration. In the He gas it is computed to be too small by a factor of $\sim 10^6$ to account for the effect observed, assuming reasonable scattering amplitudes. Anomalously large scattering amplitudes would presumably lead to exaggerated effects in liquid $H_2$ which are not observed. The walls of the He bag are outside the sensitive volume of the detector. The spatial distribution of the forward events is the same as that for the regular $K_2^0$ decays which eliminates the possibility of regeneration having occurred in the collimator.

(ii) $K_{\mu 3}$ or $K_{e3}$ decay. A spectrum can be constructed to reproduce the observed data. It requires the preferential emission of the neutrino within a narrow band of energy, ±4 MeV, centered at $17 \pm 2$ MeV ($K_{\mu 3}$) or $39 \pm 2$ MeV ($K_{e3}$). This must be coupled with an appropriate angular correlation to produce the forward peak. There appears to be no reasonable mechanism which can produce such a spectrum.

(iii) Decay into $\pi^+\pi^-\gamma$. To produce the highly singular behavior shown in Fig. 3 it would be necessary for the $\gamma$ ray to have an average energy of less than 1 MeV with the available energy extending to 209 MeV. We know of no physical process which would accomplish this.

We would conclude therefore that $K_2^0$ decays to two pions with a branching ratio $R = (K_2 \to \pi^+ + \pi^-)/(K_2^0 \to \text{all charged modes}) = (2.0 \pm 0.4) \times 10^{-3}$ where the error is the standard deviation. As emphasized above, any alternate explanation of the effect requires highly nonphysical behavior of the three-body decays of the $K_2^0$. The presence of a two-pion decay mode implies that the $K_2^0$ meson is not a pure eigenstate of $CP$. Expressed as $K_2^0 = 2^{-1/2}[(K_0 - \bar{K}_0) + \epsilon(K_0 + \bar{K}_0)]$ then $|\epsilon|^2 \cong R_T \tau_1 \tau_2$ where $\tau_1$ and $\tau_2$ are the $K_1^0$ and $K_2^0$ mean lives and $R_T$ is the branching ratio including decay to two $\pi^0$. Using $R_T = \frac{3}{2}R$ and the branching ratio quoted above, $|\epsilon| \cong 2.3 \times 10^{-3}$.

We are grateful for the full cooperation of the staff of the Brookhaven National Laboratory. We wish to thank Alan Clark for one of the computer analysis programs. R. Turlay wishes to thank the Elementary Particles Laboratory at Princeton University for its hospitality.

*Work supported by the U. S. Office of Naval Research.

†This work made use of computer facilities supported in part by National Science Foundation grant.

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