EXPERIMENTAL VERIFICATION OF THE $\Delta I = \frac{1}{2}$ SELECTION RULE IN THE LEPTONIC DECAY OF KAONS

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The relative probability for the decays $K_2^0 \to e^\pm + \pi^\mp + \nu$ has been measured with a cloud chamber containing a lead plate; these decays comprise 46 ± 11% of all decays with charged products. Four electron-positron pairs with large divergence angles were found and analyzed. It is shown that these events should be considered to be direct experimental evidence for the existence of the hitherto unobserved decay mode $K_2^0 \to 3\pi^0$. The value of the absolute probability for the decays $K_2^0 \to e^\pm + \pi^\mp + \nu$ determined from the mean life of the K_2^0 meson (with the $K_2^0 \to 3\pi^0$ mode taken into account) is consistent, within the experimental error, with twice the absolute probability for the decay $K^+ \to e^+ + \pi^0 + \nu$; this is evidence that the $\Delta I = \frac{1}{2}$ selection rule can be extended to leptonic K decays. An estimate of the absolute probability for $K_{\mu 3}^0$ decay is also consistent with the $\Delta I = \frac{1}{2}$ rule.

THE first isospin selection rule for hyperon and kaon decay processes was stated by Gell-Mann and Pais,[1] who proposed that the magnitude of the isospin could change by $\frac{1}{2}$ in non-leptonic decays. Further work showed that, within the experimental accuracies, all decays involving only strongly interacting particles are satisfactorily described by the $\Delta I = \frac{1}{2}$ selection rule (see, for example, the review article by Okonov[2]).

More recently Okun'[3] considered this rule within the framework of the composite model of elementary particles proposed by Sakata;[4] in this model the nucleon and Λ^0 are taken to be the fundamental particles. Okun' showed that if only four-Fermion interactions are considered, then the basic decay is $\Lambda^0 \to p + e^-(\mu^-) + \nu$, in which the isospin of the strongly interacting particles changes by $\frac{1}{2}$. In the framework of the Sakata model, all other leptonic decays of strange particles can be described as proceeding via this basic decay. It follows that the $\Delta I = \frac{1}{2}$ rule can be extended to K_{e3} and $K_{\mu 3}$ decays, with resultant expressions for the absolute decay probabilities

$$W(K_{e3}^0) = 2W(K_{e3}^+) \quad (1)$$

$$W(K_{\mu 3}^0) = 2W(K_{\mu 3}^+). \quad (2)$$

Marshak et al.[5] arrived at the same conclusion making the more general assumptions that the transformation properties in isospin space are the same for weak interactions of strange particles with and without lepton participation.

The first steps toward the verification of the $\Delta I = \frac{1}{2}$ rule for both leptonic and nonleptonic K decays were taken by Kobzarev and Okun'[6] and Okubo et al.,[7] who calculated the mean life of K_2^0 from experimental data on K^+ decay. The calculated value differed little from the experimental value.

However, a direct comparison of the absolute probabilities for leptonic decay of kaons [a check of the validity of Eqs. (1) and (2)] has not yet been made* for lack of experimental data on K_2^0 decay. In the cloud-chamber experiment of Bardon et al.,[9] several cases of K_{e3} and $K_{\mu 3}$ decay of K_2^0 were identified by the kinematics of the V^0 event and ionization measurements. However, as these authors themselves point out, they were not able to estimate with any accuracy the relative probabilities for these decays.

The present experiment is part of an investigation† of the properties of K_2^0 mesons with a cloud chamber and was performed with the proton synchrotron of the Joint Institute for Nuclear Research. Its purpose was the determination of the absolute probability for the decays $K_2^0 \to e^\pm + \pi^\mp + \nu$ and an estimate of the $K_{\mu 3}^0$ decay probability.

*An attempt at an experimental determination of the total probability for leptonic decay of K_2^0 was made by Crawford et al.[8]; in all, eight leptonic decays of K_1^0 and K_2^0 were observed.

†Partial results of this investigation have been published[10] and reported to the Rochester conference.[11] It should be mentioned that our communication was published in a strongly distorted form in the Proceedings of the Rochester Conference.

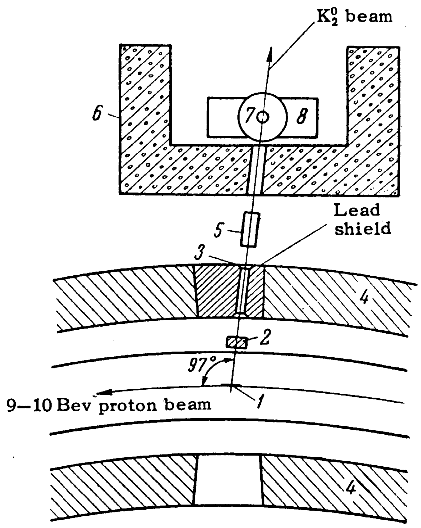

FIG. 1

In order to identify the decays, we placed in the chamber a 5.8 g/cm^2 lead plate perpendicular to the K_2^0 beam. The K_{e3}^0 decays were selected by measuring the momentum loss of the decay product on traversing the plate, since an electron has a high probability for a large energy loss by radiation in the plate. For example, the probability of loss by radiation of more than 30% of the electron's initial energy is 0.86.

The experimental arrangement is shown in Fig. 1. The source of the K_2^0 mesons was an internal 20 × 25 × 70 mm lead target placed in the beam of 9 — 10 Bev protons. The particles which come out of the target at an angle of 97° with the proton beam pass through a window in the wall of the accelerator vacuum chamber, through a 50 — 100 g/cm^2 lead converter, 2, and through a 30 × 120 mm lead collimator 1.5 m long, 3, set in an aperture, 4, in the iron yoke of the proton synchrotron magnet. Then the particle beam passes between the polepieces of a beam-purifying SP-63 magnet, 5, with a 10,000 oe field. Further on, the beam passes through a second lead collimator 1.5 m long with a 50 × 200 mm rectangular cross section set in the concrete shield, 6, and then into the cloud chamber, 7, which is in the field of an MS-4 electromagnet, 8.

The distance from the last collimator slit to the chamber was over 1 m, so that all K_1^0 particles produced in the collimator walls would decay on the way to the chamber. The cloud chamber was 8 m from the internal target. The chamber used has been described in detail in a previous paper.[12]

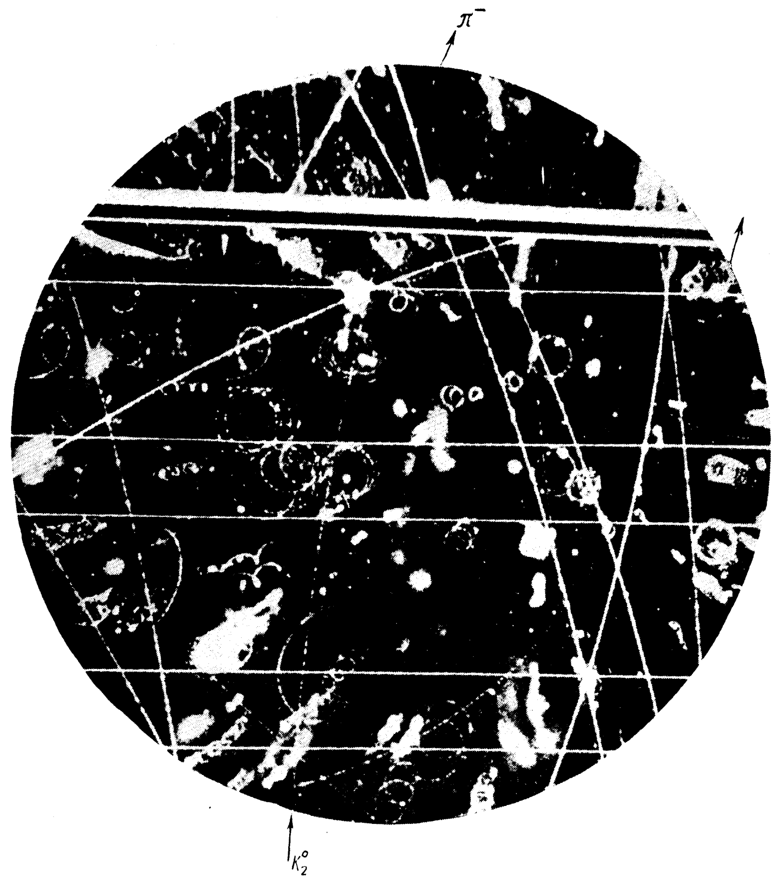

FIG. 2

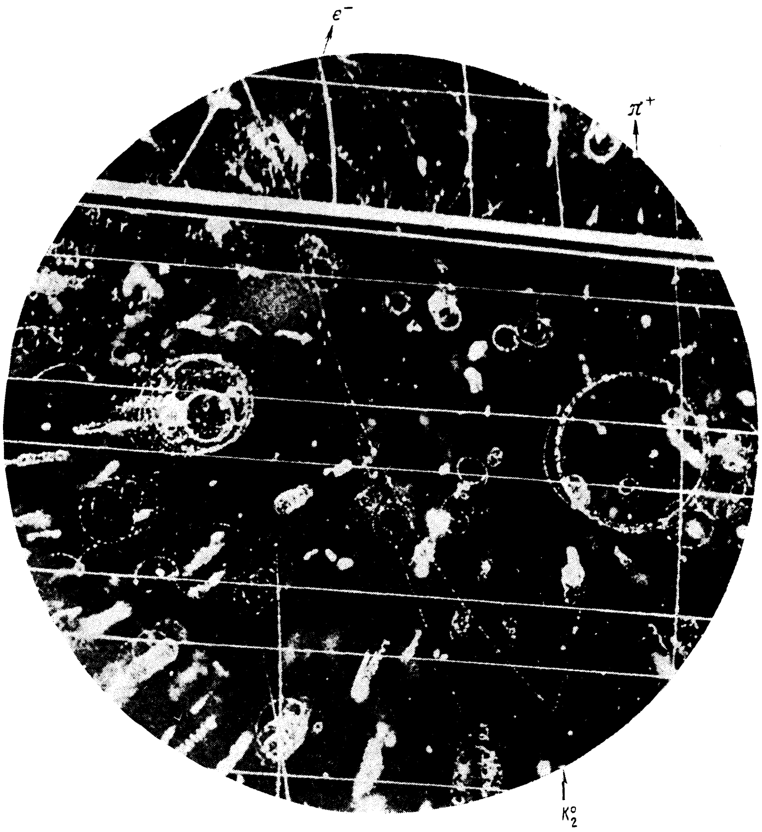

FIG. 3

In the present arrangement, the height of the illuminated region of the chamber was increased to 90 mm by enlarging the gap between the windings of the MS-4 magnet. The average magnetic field in the illuminated region was 15,000 oe with field inhomogeneity not exceeding 4%. The cylindrical glass wall of the chamber was 2 g/cm^2 thick.

EXPERIMENTAL RESULTS

In all, about 12,000 stereo pictures were made; they registered 670 V^0 decays and one four-prong event. About 40 events were identified as decays of Λ^0 particles produced by K_2^0 mesons in the lead plate and in the chamber walls. The remaining events were K_2^0 decays. With an average intensity of 5×10^8 accelerated protons per pulse, each picture showed about 10 protons knocked out of the chamber walls. The number of electron pairs detected was about a third of the number of V^0 events; only four pairs made large angles with the direction of the K_2^0 beam. The latter figure shows that the noise from uncollimated γ rays was very small in our apparatus; this allowed neutral $K_{3\pi}$ decays to be detected by their Dalitz pairs (pairs from the decay $\pi^0 \rightarrow \gamma + e^+ + e^-$).

Among the 440 K_2^0 decays detected in the chamber with the lead plate, 114 cases were observed in which charged decay products penetrated the plate; in each of these cases, because of the mode of illumination of the chamber, the particle would necessarily be observed after traversing the plate. Examples of cases in which such particles (π^- and e^-) traverse the plate are shown in Figs. 2 and 3. In all cases, the following were measured: momenta* of the decay product before and after passing through the lead plate, the angles at which the particle entered and left the plate, and also the momentum of the second decay product. In all, 24 cases of plate penetration were found in which the particle lost more than 30% of its momentum (18 cases) or stopped in the plate (5 cases) or made a star (1 case). In each case, as can be seen from Table I, the observed energy loss or stopping cannot be due to ionization loss.

In six cases of penetration, showers of two or three electrons were observed. For these, the average momentum of the shower particles is shown in the second column of the table. Clearly,

*The error of the momentum measurement did not exceed 10%.

Table I

Particle momentum, Mev/c		Momentum loss, %	Lead thickness g/cm²	Momentum of second particle, Mev/c
before penetration	after penetration			
279	Star	—	6.5	148
209	Stopped	—	7.1	68
225	137 shower	39	6.0	—
270	63 "	77	6.0	193
135	45 "	67	5.9	68
202	32	84	5.9	36
229	59 shower	74	5.8	301
290	144	51	6.1	99
126	27 shower	79	5.9	248
310	144	54	5.8	252
150	9	94	8.8	—
189	18	90	8.8	234
117	22	81	6.2	158
283	54	81	5.9	166
351	225	36	7.1	99
193	113	41	6.3	—
144	77	47	5.9	410
113	50	56	6.2	207
144	Stopped	—	8.4	148
148	16 shower	89	6.5	135
218	140	36	7.1	50
236	Stopped	—	5.9	92
180	"	—	10.0	—
—	"	—	6.0	270

all of the penetrations with momentum loss greater than 30% must be identified as electron penetrations. The five particles that stopped may be electrons or pions that produce prongless stars. In order to find the true number of electron plate penetrations it is necessary to correct first for the cases of penetration in which the momentum loss is less than 30% and then subtract the number of pions that produce prongless stars from the total number of stopped particles.

The first correction was found for each case of penetration by using the Eyges formulas[13] for the probability distribution of the total electron energy loss due to radiation and ionization. This method yielded an addition of three events. The second correction was taken to be equal to the number of nuclear interactions with the lead nuclei that would be produced by all the decay products that penetrated the plate (excluding electrons and muons) if the cross section were geometrical.* The correction was three events. Thus, the true number of electron penetrations is 24.

In order to determine the relative probability of K_{e3} decay, a correction must be made for the motion of the decaying K_2^0. It can easily be shown that the motion of the K_2^0 leads to an increase in the number of heavy decay products (pions and muons) penetrating the plate as compared to the number of penetrations of light decay products (electrons and neutrinos). Obviously, this correction is equal to the ratio of the solid angles (in the center-of-mass system of the K_2^0) within which the emitted pions or electrons penetrate the plate. In calculating this correction we used a value of about 120 Mev for the average energy of the decaying K_2^0 particles; this value was determined from the momentum measurements (Table I) with the assumption that the energy spectra of electrons and neutrinos are identical in K_{e3} decay. The result was that the number of electron penetrations of the plate should be multiplied by a factor of 1.1 to correct for the motion of the K_2^0 particles.

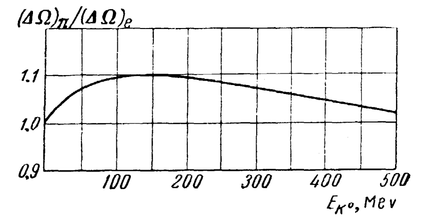

FIG. 4

Figure 4 shows the dependence of this correction on the K_2^0 energy. From the curve it is clear that we do not make a significant error by using an average energy of the K_2^0 particles* (100 Mev) to determine this correction

Our final result is that the corrected number of electron penetrations is 26. This corresponds to a K_{e3} decay probability $q = 0.46 \pm 0.11$ relative to all decays with charged products. The error is a mean square composed of the statistical error and the errors in the selection of events and in the corrections.

*The number of muons that penetrated the plate is roughly estimated at 25. The correction for possible stoppings of elastically scattered pions is negligibly small.

*Our estimate of the average K_2^0 energy is somewhat too high.

The four observed electron-positron pairs, interpreted as Dalitz pairs from the decay $K_2^0 \rightarrow 3\pi^0$ (and discussed below), make it possible to evaluate the relative probability for this decay mode (under our conditions, the calculated efficiency for detection of Dalitz pairs was about 75%). Our value for the relative probability is $w(K_2^0 \rightarrow 3\pi^0)/\Sigma w = 0.18 \pm 0.09$.* From this we can now determine the probability for the decay $K_2^0 \rightarrow e^\pm + \pi^\mp + \nu$ relative to all K_2^0 decays (0.38 ± 0.10), and, from the lifetime of the K_2^0

$$\tau(K_2^0) = \left(6.1\ {}^{+1.6}_{-1.1}\right) 10^{-8}\ \text{sec},$$

we can find the absolute probability for K_{e3}^0 decay; the latter is $w(K_{e3}^0) = (6.2 \pm 2.0) \times 10^6\ \text{sec}^{-1}$.

The fraction of $K_2^0 \rightarrow 3\pi^0$ decays can also be estimated under the assumption that the $\Delta I = \frac{1}{2}$ rule holds for $K \rightarrow 3\pi$ decays; from this assumption it follows that the $K^+ \rightarrow 3\pi$ and $K_2^0 \rightarrow 3\pi$ absolute probabilities are equal and also that $K_2^0 \rightarrow \pi^+ + \pi^- + \pi^0$ and $K_2^0 \rightarrow 3\pi^0$ are related.[6,7] Using this assumption and the experimental values for the $K^+ \rightarrow 3\pi$ branching ratio (7.7 ± 0.7)%[14] and mean life $(1.21 \pm 0.01) \times 10^{-8}$ sec, we find the relative probability for $K_2^0 \rightarrow 3\pi^0$ to be 0.30 ± 0.03 and the absolute probability for $K_2^0 \rightarrow e^\pm + \pi^\mp + \nu$ to be $(5.8 \pm 1.8) \times 10^6\ \text{sec}^{-1}$.

Both of the above absolute probabilities for K_{e3}^0 decay agree within experimental error with twice the probability of the corresponding K decay:[14,15] $2w(K_{e3}^+) = (8.4 \pm 1.2) \times 10^6\ \text{sec}^{-1}$. This agreement is evidence that the $\Delta I = \frac{1}{2}$ rule may be extended to leptonic K decays. However, final confirmation of this rule awaits more accurate determinations of both the K_{e3} relative probability and the K_2^0 mean life.[7]

Table II

Case No.	Momentum, Mev/c +	Momentum, Mev/c −	Angle with beam, deg	Divergence angle, deg
1	55	42	7 — 9	65
2	10	43	99	50
3	111	103	19	70
4	26	79	25	10

It should be noted that the detection of one four-prong decay and four electron pairs with large divergence angles allows a rough experimental determination of the fraction of K_2^0 particles that decay into three pions. If all four pairs, with parameters shown in Table II, are taken to be Dalitz pairs from $K_2^0 \rightarrow 3\pi^0$, then we find that the total number of $K_{3\pi}$ decays is about 30 per cent of the total number of K_2^0 decays. This is not in disagreement with the $\Delta I = \frac{1}{2}$ rule, which predicts equality of the absolute probabilities for $K^+ \rightarrow 3\pi$ and $K_2^0 \rightarrow 3\pi$. The absolute probability for $K_2^0 \rightarrow \mu^\pm + \pi^\mp + \nu$ determined from the experimental values of the K_{e3}^0 and $K_{3\pi}^0$ branching ratios is $(5.6 \pm 3.0) \times 10^6\ \text{sec}^{-1}$, and agrees within experimental error with twice the $K_{\mu3}^+$ probability $(6.8 \pm 0.8) \times 10^6\ \text{sec}^{-1}$.

The analysis of the large-angle electron pairs is of interest as a proof of the existence of the $K_2^0 \rightarrow 3\pi^0$ decay mode. There is uncertainty in the identification of only the third of the four pairs shown in Table II; because of the background, sufficiently accurate ionization measurements could not be made on the decay products. In the remaining cases, the identification is beyond doubt.

What is the nature of these pairs? The fourth could be, in principle, the result of conversion of a "beam" γ ray by the chamber gas, since the probability that one of the electron pairs observed in the direction of the incident beam have a divergence angle greater than 20 — 25° is 0.6.* Because of their large angles with the incident beam, the first two pairs cannot be attributed to this process. Nor can they be attributed to conversion of non-collinear rays, since in that case several hundred pairs with smaller divergence angles would have been observed. The electron-positron pairs we detected cannot be Dalitz pairs from the decay of π^0's created by "beam" neutrons striking the nuclei in the chamber gas, since not a single star with an electron-positron pair was detected. Moreover, an estimate made on the basis of the observed production of charged pions shows that the probability of observation of a single Dalitz pair from the decay of a π^0 produced in a prongless star is less than 10^{-2}. At the same time, the decay of a K_2^0 into π^0 mesons accounts very well for all the features of the observed Dalitz pairs.

Since we did not detect a single decay of the long-lived K^0 into π^+ and π^-, the decay $K_2^0 \rightarrow 2\pi^0$ is extremely improbable. The probabilities of other K_2^0 decays involving π^0 mesons and other neutrals (for example, $K_2^0 \rightarrow 2\pi^0 + \gamma$) are also very small.

Thus, there is every reason to ascribe the observed Dalitz pairs to the decay $K_2^0 \rightarrow 3\pi^0$. Therefore, the very fact that they are observed must be considered as direct experimental evidence for

*As will be evident from the discussion of the properties of these pairs, this value may be too high.

*This probability was determined from the distribution calculated by Borsellino.[16]

this decay. The ratio of the number of single Dalitz pairs and the number of four-prong events due to the $K_2^0 \to \pi^+ + \pi^- + \pi^0$ decay with a Dalitz pair is also evidence in favor of this interpretation.[10*]

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*The $\Delta I = 1/2$ rule gives 2 for the ratio of $K_2^0 \to 3\pi^0$ to $K_2^0 \to \pi^+ + \pi^- + \pi^0$.

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