EXPERIMENTAL TEST OF THE SELECTION RULE $\Delta S = \Delta Q$*

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An experiment has been conducted to test the selection rule $\Delta Q = \Delta S$ by means of leptonic decays of neutral K mesons, which is based on a straightforward extension of the method proposed by Treiman and Sachs[1] for determining the $K_1{}^0$-$K_2{}^0$ mass difference. The selection rule, which has had no previous experimental tests, is crucial in understanding the strangeness-nonconserving weak interactions.

The selection rule $\Delta Q = \Delta S$ suggested by Feynman and Gell-Mann,[2] which is related to the weak interaction current, implies that leptonic decays of strange particles are allowed only when the difference in charge between the initial and final strongly interacting particles in the decay is equal to the difference in strangeness.

From the $\Delta Q = \Delta S$ selection rule, it follows that the processes,

$$K^0 \to e^- + \pi^+ + \bar{\nu}, \tag{1a}$$

$$\bar{K}^0 \to e^+ + \pi^- + \nu, \tag{1b}$$

are forbidden, whereas the processes,

$$K^0 \to e^+ + \pi^- + \nu, \tag{2a}$$

$$\bar{K}^0 \to e^- + \pi^+ + \bar{\nu}, \tag{2b}$$

are allowed.

One can check the $\Delta Q = \Delta S$ selection rule by verifying the absence of (1a) and (1b). In practice, however, it is impossible to obtain a pure K^0 beam independent of time and hence one must look at the rates of the decays $e^+\pi^-\nu$ and $e^-\pi^+\bar{\nu}$ and compare them with K^0 and $\bar{K}^0$ states as a function of time; and in addition, study the time dependence of the sum of both decays, which is independent of the $K_1{}^0$ and $K_2{}^0$ mass difference.

If one starts with a pure K^0 beam, then the ratio of intensities of the K^0 to $\bar{K}^0$ states is equal to

$$\frac{I_{K^0}(t)}{I_{\bar{K}^0}(t)} = \frac{\exp(-\lambda_1 t) + \exp(-\lambda_2 t) + 2[\exp(-\lambda_1 - \lambda_2)t/2]\cos\Delta\omega t}{\exp(-\lambda_1 t) + \exp(-\lambda_2 t) - 2[\exp(-\lambda_1 - \lambda_2)t/2]\cos\Delta\omega t}, \tag{3}$$

where $\Delta\omega$ is the $K_1{}^0, K_2{}^0$ mass difference, $(\Delta m)c^2$, in units of $\hbar/\tau_1$, and λ_1, λ_2 are the decay rates of the $K_1{}^0$ and $K_2{}^0$, respectively. (The absorption of the beam is neglected.)

The ratio $R(t)$,

$$R(t) = \frac{N^+(t)}{N^-(t)} = \frac{\text{number of decays } e^+\pi^-\nu}{\text{number of decays } e^-\pi^+\bar{\nu}}, \tag{4}$$

is equal to the ratio of K to $\bar{K}$ [Eq. (3)] if $\Delta S = \Delta Q$ is assumed, and the total rate is

$$N^+(t) + N^-(t) = C[\exp(-\lambda_1 t) + \exp(-\lambda_2 t)], \tag{5}$$

which shows that the partial leptonic rate of the $K_1{}^0$ is equal to that of the $K_2{}^0$.

If the selection rule $\Delta Q = \Delta S$ is not valid, then the decay modes (1a) and (1b) are allowed and hence $N^+(t)$ and $N^-(t)$ depend on both the K^0 and $\bar{K}^0$ amplitudes,

$$A^+(t) = K[A_{K^0}(t) + xA_{\bar{K}^0}](t),$$
$$A^-(t) = K[xA_{K^0}(t) + A_{\bar{K}^0}](t). \tag{6}$$

In deriving the relationship between the amplitudes $A^+(t)$ and $A^-(t)$ in Eq. (6), invariance under CPT is assumed.[3] The parameter x, which is real because of time reversal invariance, measures the degree of violation of the selection rule $\Delta Q = \Delta S$ (if $\Delta Q = \Delta S$, $x = 0$).

From Eq. (6) it follows that the ratio R is given by

$$R(t) = \frac{N^+(t)}{N^-(t)} = \frac{(1+x)^2 \exp(-\lambda_1 t) + (1-x)^2 \exp(-\lambda_2 t) + 2(1-x^2)[\exp(-\lambda_1 - \lambda_2)t/2] \cos\Delta\omega t}{(1+x)^2 \exp(-\lambda_1 t) + (1-x)^2 \exp(-\lambda_2 t) - 2(1-x^2)[\exp(-\lambda_1 - \lambda_2)t/2] \cos\Delta\omega t}. \quad (7)$$

In this notation $(1+x)^2$ and $(1-x)^2$ are proportional to the partial leptonic decay rates of K_1^0 and K_2^0, respectively. The total decay rate becomes

$$N^+(t) + N^-(t) = C[(1+x)^2 \exp(-\lambda_1 t) + (1-x)^2 \exp(-\lambda_2 t)]. \quad (8)$$

For $x = 0$, $\Delta Q = \Delta S$, Eq. (7) reduces to Eq. (3) and Eq. (8) to Eq. (5).

The 30-inch Berkeley propane bubble chamber was exposed in a separated K^+ beam of momentum 790 Mev/c, from the Berkeley bevatron. About 1.5×10^5 frames were scanned for "V's," which could be interpreted as leptonic decays of neutral K mesons from the charge exchange in propane of the incoming K^+. Only leptonic decays were accepted where (a) the electron was identified by curvature-range measurements, and (b) the Q of the decay was found to be within 20% of the expected value.

Since the Q value is sensitive to the direction of the neutral K meson, spurious origins are quite unlikely. Five events were eliminated by this method, one of which gives a correct Q value if it came from the window.

Events found by other methods of identification of the electron, such as knock-on δ rays and bremsstrahlung, were not accepted because of the difference in the cross section of e^+ and e^- which would introduce a charge bias into the results. Leptonic decays into μ mesons were not accepted because of charge bias in the recognition.

Several types of phenomena can produce events which superficially can appear to be a leptonic decay and attributed to an unrelated charge-exchange origin, namely:

(A) K_1^0 decays with two π^0's, with one π^0 decaying into two electrons and a γ. Occasionally one of the electrons may be identified as a lepton and the other electron incorrectly assumed to be a pion. By assuming that both tracks from the V are electrons, it is possible to calculate the virtual mass of the γ ray which decayed into the electrons. The probability as a function of the ratio of this mass to the pion mass (χ/μ) has been checked experimentally.[4] If events are accepted with virtual mass greater than 50 Mev, then the expected contamination for the entire run is about 1 event using the above probability.[5] Furthermore, the number which will have the correct Q value will be less than 0.1. These events with virtual mass less than that of the pion have the χ/μ value listed in Table I.

(B) Occasionally a K^+ from the beam will backscatter from the bottom wall and decay in flight into a lepton. This "V" may be mistaken for a leptonic decay by incorrectly assuming that the backscattered K^+ is a negative particle leaving the chamber. Note that this type of background will lead to "V's" with positively charged leptons. The number of backward K's has been determined from τ decays in flight of backward K^+. Knowing the leptonic decay rate of K^+, the number of spurious neutral V's from this source is estimated to be of the order of or less than 18 events for the entire run. Less than 10^{-3} of these events will have the electron identified and will both fit the Q of the K^0 leptonic decay and lie within the first five K_1^0 lifetimes.

(C) A large-angle scattering in propane of a high-energy electron can simulate a neutral "V." The number of electrons of energy larger than 50 Mev entering the chamber was determined and found to be 2×10^{-2} electron per frame. Using the scattering cross section, the number of V's from this source was found to be 10^{-3} for the entire run.

(D) μ mesons entering the chamber and subsequently decaying in flight can simulate a leptonic decay. There is about 0.5 μ^+ meson per frame entering the chamber from one side. There is a strong correlation of the angle with which they enter the chamber with their momentum. The number of spurious neutral V's within five lifetimes of a K^0 origin, and which might accidentally fit the Q of a K^0 leptonic decay, is about 0.1.

(E) A study of the characteristics and frequency of neutron stars has shown that the number of spurious neutral V's from this source is negligible. The frequency of Λ interactions is known and the production of spurious events is unim-

Table I. Details of leptonic decay events.

Event number	Lepton charge	Time in τ_1	P_{K^0} (Mev/c)	Laboratory system P_π	P_ν	P_e	P in Mev/c (from range) assuming lepton to be pion	Observed range of lepton in cm	Remarks
2586	e^-	1.4	175 ± 55	300 ± 30	109 ± 12	85 ± 6	130	17	
4486	e^+	13.5	627 ± 84	210 ± 25	483 ± 50	64 ± 7	105	12	
4508	e^+	6.2	259 ± 26	145 ± 7	292 ± 17	66 ± 4	190	60	π and e stop
18 262	e^-	3.7	414 ± 120	312 ± 13	269 ± 77	35 ± 4	140	25	
27 642	e^+	0.8	453 ± 128	296 ± 12	192 ± 77	151 ± 4	164	39	
35 335	e^+	5.5	396 ± 40	192 ± 20	331 ± 30	67 ± 7	160	40	e stops
36 353	e^+	~ 0.04	373 ± 100	172 ± 9	365 ± 62	35 ± 6	85	6.1	
36 709	e^-	1.9	491 ± 150	406 ± 25	256 ± 80	14 ± 4	75	4	
41 600	e^-	~ 0.05	400 ± 100	291 ± 65		29 ± 3	80	5	K^0 vertex not well resolved
42 096	e^+	~ 0.02	450 ± 100	258		51 ± 7			K^0 direction not measurable
57 281	e^+	6.6	464 ± 120	519 ± 100	66 ± 14	76 ± 5	130	21	
57 397	e^+	<0.05	400 ± 120	316 ± 22		73 ± 6	150	30	K^0 direction not measured
66 061	e^+	0.12	416 ± 120	313 ± 45	193 ± 100	110 ± 16	97	9	
66 695	e^+	0.4	350 ± 110	95 ± 40		48 ± 4	160	40	e stops
72685	e^+	1.6	364 ± 50	169 ± 7	287 ± 85	109 ± 6	160	36	
89 184	e^+	0.3	339 ± 50	150 ± 14	380 ± 38	17 ± 4	105	12	e stops
100 512	e^-	2.6	400 ± 100	300 ± 60	260 ± 100	80 ± 10			
114 287	e^+	0.6	449 ± 40	150 ± 6	449 ± 27	17 ± 4	110	14	e stops
119 671	e^+	1.5	615 ± 80	243 ± 13	414 ± 80	96 ± 8	150	32	
120 115	e^-	0.6	445 ± 45	487 ± 40	69 ± 10	90 ± 6	125	20	
123 971	e^-	2.7	411 ± 130	269 ± 20	326 ± 100	15 ± 4	90	7	e stops
125 135	e^+	0.4	441 ± 70	150 ± 17	410 ± 60	48 ± 4	125	17	$\chi/\mu^{a} = 0.45$
125 721	e^-	0.9	430 ± 130			118 ± 6	140	23	π interacts
136 420	e^-	0.9	430 ± 130			91 ± 6	130	22	π track short
140 722	e^-	5.3	255 ± 26	64 ± 5	300 ± 20	104 ± 5	170	42	π^+ stops
012 021	e^+	1.5	360 ± 90	166		60 ± 8			π^- interacts
202 941	e^+	0.4	285 ± 70	185		80 ± 10			
021 893	e^-	0.13	390 ± 100	90		34 ± 10			π^+ decays

[a] χ/μ is ratio of virtual mass to pion mass in electron pair analysis.

portant.

Summarizing, we believe that the events arise from the leptonic decays of neutral K mesons from the charge exchange of K^+ in the propane.

A total of 28 events were found where the electron was identified by range curvature and 4 additional events by δ rays and bremsstrahlung. Of the 28 events, 17 are $e^+\pi^-\nu$ and 11 are $e^-\pi^+\bar{\nu}$. Six decays of the type $\pi^- + \mu^+ + \nu$ were found, but since there is a strong charge bias in detecting this kind of decay, they were not included. The details of the events accepted are given in Table I.

In order to evaluate the Q of the decay and to determine the time of flight of the K^0 meson, it is necessary to determine the momentum of the K^0. This was accomplished by measuring the momentum on 501 K_1^0 decays and determining the dependence of the momentum of the angle between the incoming K^+ and the K^0; this is necessary because the charge-exchange interactions occur in carbon.

The distribution at all angles has a half-width of about 25%. The mean momentum as a function of the angle between the K^+ and K^0 was used to find the time of flight and also to calculate the Q of the leptonic decay.

Due to the size of the chamber, a substantial correction must be made for the events which escape. This correction factor has been estimated in two ways: (1) from simple geometry, and (2) by the time distribution of 543 K_1^0 decays and their departure from the expected ex-

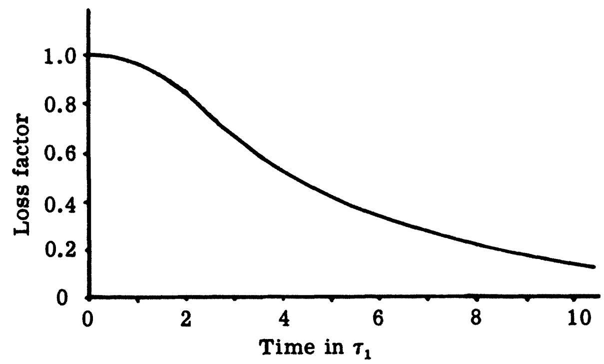

FIG. 1. Loss factor as a function of time.

ponential curve. The geometrical loss curve is shown in Fig. 1.

The time distribution of the events $e^+ + \pi^- + \nu$; $e^- + \pi^+ + \bar{\nu}$ and their sums are shown in Figs. 2(a) and 2(b).

The momentum of the neutral K^0 of each event, and its error, given in Table I, were found by the best constrained fit to the Q value as well as the momentum distribution for K_1^0 decays.

The ratio $R(t)$ expressed by Eqs. (3) and (4) could explain the observed behavior of $N^+(t)/N^-(t)$ only if values of Δm larger than 5 are assumed. Such values of Δm are in disagreement with those found in measurements of Δm in other experiments.[6-8] On the other hand, if one assumes the value $\Delta m = 1.6$,[8] the ratio of the likelihood that the observed distribution $R(t)$ originates from Eqs. (3) and (4) to the likelihood that it originates from Eq. (7) is smaller than 0.01.

A further test for the $\Delta Q = \Delta S$ selection rule validity is the comparison of the total experimental decay rate $N^+(t) + N^-(t)$ with the one expected from Eq. (5). The ratio of the likelihood that the time distribution (disregarding the charge distribution) originates from Eq. (5) to the likelihood that it originates from (7) is less than 0.02.

Furthermore, because the ratio $R(t)$ is very sensitive only in the region of very small time intervals, where the number of events is small and the measurements on the events are more difficult, a comparison has been made between the time distribution of the $\pi^+ e^- \bar{\nu}$ decays with the $\bar{K}^0$ interactions which produce Λ^0 $[N_{\bar{K}^0}(t)]$. Since, in the $\Delta Q = \Delta S$ hypothesis, both processes are proportional to the intensity of the $\bar{K}^0$ component and independent of the mass difference, the ratio $N^-(t)/N_{\bar{K}^0}(t)$ is expected to be a constant in time. The geometrical loss factor is essentially the same for the leptonic decays and $\bar{K}^0$ interactions, and hence a knowledge of this value of the loss factor is not needed. A comparison of 140 $\bar{K}^0$ interaction events and the $e^-\pi^+\bar{\nu}$ events can be made from the data in Table II. Even though the number of events is rather small, the ratio $N^-(t)/N_{\bar{K}^0}(t)$ is not a constant and suggests that the rule $\Delta Q = \Delta S$ is probably not valid.

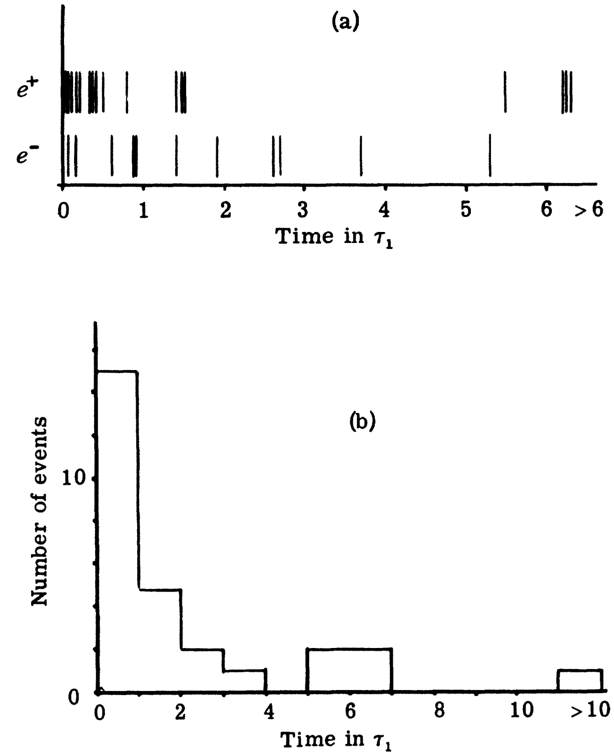

FIG. 2. (a) Time distribution of leptonic decays. (b) Time distribution of events regardless of the sign of the charge of the lepton.

The violation parameter "x," which represents the ratio between the amplitudes $(T_3 = 3/2)/(T_3 = 1/2)$ in the strangeness-nonconserving current, can be

Table II. Comparison of $N^-(t)$ with $\bar{K}^0$ interactions.

Interval of time in units of τ_1	$N^-(t)$	$N_{\bar{K}^0}(t)$	$N^-(t)/N_{\bar{K}^0}(t)$
0-1	5	3	1.65 ±1.2
1-2	2(1)[a]	28	0.1 ±0.06
>2	4(2)[a]	109	0.05 ±0.002

[a]The numbers in parentheses are additional events which were recognized by δ rays and bremsstrahlung.

determined by a combined analysis on the behavior of the total decay rate and the charge ratio. A maximum likelihood calculation has been made for the $N^+(t)+N^-(t)$ decay rate using Eq. (8), where $[(1+x)/(1-x)]^2$ represents the ratio between the partial rates of the K_1^0 and K_2^0 in the $e^{\pm}+\pi^{\mp}+\nu$ channel. The value found for $(1+x)/(1-x)$ is 3.5 ± 1.0 ($\Gamma_1/\Gamma_2=12^{+8}_{-6}$). This leads to two possible values for x, namely, $x=0.55$ and $x=1.86$. Only the value $x=0.55^{+0.08}_{-0.12}$ is consistent with the measured $R(t)$ distribution.

We have performed the likelihood calculations with various values of ΔM (in the interval $1\leq\Delta m\leq2$) and with geometrical loss factors changed by as much as ±20%. The results quoted above are essentially unaffected by these changes.

We have changed the important parameters of our analysis, such as the geometrical correction, momentum spread, selection of events, etc. We found that the likelihood ratio was never larger than 0.01. We therefore conclude that the $\Delta Q=\Delta S$ selection rule is not valid.

Due to the recognition of the lepton by the range-curvature method, there is a preferential selection of low-energy electrons. Since x may be dependent on the energy of the lepton, the value obtained by using the entire electron spectrum may be different.

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