Title
SIGN OF THE Ko - Ko MASS DIFFERENCE

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ABSTRACT

Evidence is presented that the long-lived neutral K is heavier than the short-lived.

We have performed an experiment to measure the sign of $m_1 - m_2$ using the method suggested by Camerini et al.[1] We find K_2^0 to be heavier than K_1^0. Our statistical confidence level depends on the unresolved Fermi-Yang - type (F-Y) ambiguity that exists at present in the KN (strangeness $S = +1$) phase shifts in isotopic spin state $I = 0$. If the F solution (large positive $p_{3/2}$ phase shift) is the correct solution, we obtain Monte Carlo betting odds of 45 to 1 for $m_2 > m_1$, assuming $|m_1 - m_2| = 0.57\ \tau_1^{-1}$. If instead the Y solution (large positive $p_{\frac{1}{2}}$ phase shift) is correct, our betting odds for $m_2 > m_1$ are 5 to 1.[2] We have not resolved the F-Y ambiguity.[3]

The experiment uses 6040 K^0 mesons produced in the Alvarez 72-in. hydrogen bubble chamber via the reactions

$$\pi^- + p \rightarrow \Lambda + K^0 \text{ (4771 events)} \tag{1}$$

and

$$\pi^- + p \rightarrow \Sigma^0 + K^0,\ \Sigma^0 \rightarrow \Lambda + \gamma \text{ (1269 events)}, \tag{2}$$

where the Λ decays visibly via $\Lambda \rightarrow p + \pi^-$. This is the same sample of K^0 we used in a previous experiment to determine $|m_1 - m_2|$ by means of secondary hyperon production,[4] except that in the present experiment we discard K^0 with momentum greater than 600 MeV/c, because of present lack of information on the $I = 1$, $\overline{K}N$ ($S = -1$) scattering amplitudes above 600 MeV/c.

The predicted K^0 direction from reaction (1) is known to within about ± 0.5 deg; that from reaction (2) is known to within about ±20 deg. In the case of reaction (1), we scan along this predicted direction, within a cone ±5 deg wide; for reaction (2), we scan within the entire volume downstream from the vertex. We look for elastic scatters

$$K_{neutral} + p \rightarrow K_1^0 + p \,, \qquad (3)$$

where the final K_1^0 is detected by its visible decay $K_1^0 \rightarrow \pi^+\pi^-$ (double-vee events). There is no cutoff on the length of the recoil proton. We find 23 double-vee events with initial K^0 momentum $P_K < 600$ MeV/c; these are summarized in Table I. Six similar events with $P_K > 600$ MeV/c are not used. Our demand for a visible Λ decay gives us essentially 100% detection efficiency for finding double-vee events. There are no ambiguous events and no background.

We also find 13 single-vee events corresponding to K^0 production via reaction (1), with a visible Λ decay, and with an associated recoil proton from elastic K-p scattering without a subsequent visible K_1^0 decay. For single-vee events we impose a 1.5-cm minimum-length cutoff on the recoil proton, thus reducing our background due to random proton recoils to an estimated 0.2 events. The absence of a visible K_1^0 decay can correspond either to $K_1^0 \rightarrow 2\pi^0$ or to K_2^0 leaving the chamber without decaying. This ambiguity leads to a washing out of information on the sign of $m_1 - m_2$, and we therefore do not use these 13 events in determining $m_1 - m_2$. We do include them in tests (described below) of the predictions made by the various sets of phase shifts.

For a K^0 produced at $t = 0$ with c.m. momentum $\hbar k$, the probability $P(x)dx$ that an elastic scatter of type (3) will occur at proper time t in lab distance interval dx and with c.m. scattering angle θ (of the outgoing K with respect to the incident direction) in differential solid angle $d\Omega$ is given by

$$P(x)dx = \tfrac{1}{2}\,\eta(t) I(t, \theta, k) n dx d\Omega \,. \qquad (4)$$

Here n is the number of protons per unit volume, and x lies between 0 and x_{max}, with x_{max} determined for each event by the fiducial volume. The factor $\eta(t)$ is an escape correction factor given by $\eta = 1-\exp(-\lambda_1 T')$, where T' is the escape time of the scattered K_1^0, and is a known function of t for each event. (For most events $\eta(t)$ is approximately 1 except near $t = t_{max} \equiv T$.) The remaining factor is

$$I(t, \theta, k) = \left|f_{11} \exp(-i\omega_1 t) + f_{12} \exp(-i\omega_2 t)\right|^2$$

$$+ \left|g_{11} \exp(-i\omega_1 t) + g_{12} \exp(-i\omega_2 t)\right|^2, \qquad (5)$$

with $\omega_1 = m_1 - \frac{1}{2} i\lambda_1$ and $\omega_2 = m_2 - \frac{1}{2} i\lambda_2$, where λ_1 and λ_2 are the inverse lifetimes of K_1^0 and K_2^0. Amplitudes f_{11} and g_{11} correspond respectively to non-spin-flip and spin-flip scattering amplitudes for $K_1^0 p \to K_1^0 p$; f_{12} and g_{12} are non-spin-flip and spin-flip amplitudes for $K_2^0 p \to K_1^0 p$. Thus $f_{11} = \frac{1}{2}(f + \bar{f})$, $g_{11} = \frac{1}{2}(g + \bar{g})$, $f_{12} = \frac{1}{2}(f - \bar{f})$, and $g_{12} = \frac{1}{2}(g - \bar{g})$, where f and g are non-spin-flip and spin-flip amplitudes for $K^0 p \to K^0 p$, and $\bar{f}$ and $\bar{g}$ are those for $\bar{K}^0 p \to \bar{K}^0 p$. One can show that the terms in Eq. (5) that are proportional to $\sin(m_1 - m_2)t$, and hence that give the sign of $m_1 - m_2$, are proportional to $\mathrm{Im}(f^* \bar{f} + g^* \bar{g})$. For $\bar{K}^0$-p scattering we have $I = 1$, so that $\bar{f} = \bar{f}_1$ (single subscript now refers to I-spin state) and $\bar{g} = \bar{g}_1$. For K^0-p scattering we have both $I = 0$ and $I = 1$; thus, $f = \frac{1}{2}(f_0 + f_1)$ and $g = \frac{1}{2}(g_0 + g_1)$. We write f_I and g_I (where $I = 0$ or 1) in the partial-wave expansion

$$f_I = k^{-1} \sum_L \left[(L+1)\, T_{I,L+} + L\, T_{I,L-}\right] P_L(\cos\theta)$$

$$g_I = k^{-1} \sum_L \left[T_{I,L+} - T_{I,L-}\right] P_L^1(\cos\theta), \qquad (6)$$

where the sum is over $L = 0, 1,$ and 2, and L+ and L- refer to $J = L + \frac{1}{2}$ and $L - \frac{1}{2}$. Expressions analogous to Eq. (6) also hold for $\bar{f}_1$ and $\bar{g}_1$. The phase shifts δ are given by $T = e^{i\delta}\sin\delta$, with appropriate subscripts.

To obtain the $S = +1$ phase shifts we use the SPD solutions of Stenger et al.[5] The $I = 1$ phase shifts are well determined, but the $I = 0$ phase shifts contain the F-Y ambiguity. To obtain a smooth dependence on k (necessary because each of our events has its own K^0 momentum), we fit these phase shifts to a two-parameter effective-range expansion $k^{2L+1}\cot\delta = A^{-1} + \frac{1}{2} rk^2$. The results are in footnote 6.

For $S = -1$ amplitudes we draw on several published K^--p interaction experiments,[7, 8, 9, 10] on recent K_2^0-p interaction results,[11] and on parts of our own data. The partial-wave amplitudes are given by $T = k^{2L+1}\bar{A}/(1-ik^{2L+1}\bar{A})$, where $\bar{A}$ is a complex scattering length (we suppress indices). We have examined all available solutions. (These and other details will be published elsewhere.) We describe here three sets of solutions which we label T(Tripp), KT (Kim-Tripp) and KT'. Solution T is solution I of Watson et al.[8] Solution KT consists of solution I of Kim[10] for $L = 0$, $I = 1$, and solution I of Watson et al.[8] for $L = 1$ and 2, $I = 1$. Our preference for Kim's S-wave scattering length is based partly on recent results of Kadyk et al.[11] for the ratio $R \equiv \sigma(K_2^0 p \to K_1^0 p)/[\sigma(K_2^0 p \to \Lambda\pi^+) + 2\sigma(K_2^0 p \to \Sigma^0\pi^+)]$, and partly on our own data.

We test a set of solutions by comparing the predicted with the observed number of events produced by our sample of neutral kaons for each of the following six categories: charge-exchange production of K^+;

inelastic scattering of $\overline{K}^0$ (hyperon production), and forward- and backward-scattered neutral kaons in double-vee and single-vee events. In using various sets of scattering amplitudes to make predictions for the elastic scattering, we first integrate Eq. (4) over x from zero to x_{max} for each K^0 from reactions (1) and (2) and sum the results. Oscillatory terms from the integrand then average essentially to zero. This fact plus the fact that the potential path is usually large compared to the mean K_1^0 decay path length (the median potential proper time is about 15×10^{-10} sec) lead to predictions that are insensitive to the magnitude and sign of $m_1 - m_2$. We can therefore test the scattering amplitudes before using them to determine $m_1 - m_2$. The results are given in Table II. For the solutions T + F and T + Y we obtain $\chi^2 = 46.7$ and 20.0, respectively. For KT + F and KT + Y we find $\chi^2 = 28.8$ and 15.0, which, although an improvement, is still a poor fit for both solutions.

We have searched for solutions that give better predictions for our six mass-independent data. We arbitrarily leave the $S = +1$ solutions untouched, and vary the $S = -1$ amplitudes. Our present best solution of this kind we call KT', which is solution KT modified by changing the real part of the $p_{3/2}$ scattering length from +0.0409 to -0.0409, and by changing the $p_{\frac{1}{2}}$ scattering length from -0.042 + i0.0092 to -0.1 - i0.015. We then obtain $\chi^2 = 10.4$ for solution KT'+F, and 7.0 for KT' + Y. When solution KT' is compared with the data of Watson et al. (replacing T) we find that the major effect is to increase their χ^2 for $d\sigma/d\Omega$ for K^--p elastic scattering at 390 MeV/c from 35 to 53 ($\langle\chi^2\rangle = 18$), and for charge-exchange scattering from 14 to 25 ($\langle\chi^2\rangle = 9$).

We find that it makes very little difference to our subsequent time-dependence analysis (to find $m_1 - m_2$) whether we use solutions T, KT, or KT'. We proceed as follows. For a given event i we form a normalized probability distribution function $p_i(t) = I_i(t)\eta_i(t)/\int I_i(t)\eta_i(t)dt$, where the integral is from t = 0 to T_i and where $I_i(t) = I(t,\theta_i,k_i)$ from Eqs. (5) and (6), with a given set of phase shifts and with a choice for $m_1 - m_2$. To compare graphically the predicted and observed time distributions, we sum $p_i(t)$ over the 23 events and plot the result in Fig. 1 for the four cases corresponding to KT + F and to KT + Y, each with $m_1 - m_2 = +0.57$ and -0.57 (in units of τ_1^{-1}, assuming $\tau_1 = 0.88 \times 10^{-10}$ sec).[12] The observed time distribution exhibits an enhancement in the first 2×10^{-10} sec and favors negative $m_1 - m_2$.

To use all of the information, we form a likelihood function $\mathcal{L}(m_1 - m_2)$ by setting $t = t_i$ in $p_i(t)$ and taking the product over the 23 events, $\mathcal{L} = \prod_i 50\, p_i(t_i)$, for a given set of scattering amplitudes. (The factor 50 is a convenient normalization factor.) The results for solutions KT + F and KT + Y are shown in Fig. 2. (Those using KT' are very similar and are not shown.) The fact that $\mathcal{L}(m_1 - m_2)$ does not have its maximum value near the known magnitude $|m_1 - m_2| \approx 0.57$ has given us concern. We find that varying the phase shifts or scattering lengths within reasonable limits has little effect on the shape of $\mathcal{L}(m_1 - m_2)$. Monte Carlo studies have convinced us that, with only 23 events, we have suffered a reasonable statistical fluctuation; for a "true" value of $m_1 - m_2 = -0.57$ we find that the probability that $\mathcal{L}$ will have a maximum somewhere between $m_1 - m_2 = -1$ and $+1$ is only about 33%.

Given the magnitude $\delta \equiv |m_1 - m_2|$, we summarize our data by giving the likelihood ratio $\mathcal{L}(-\delta)/\mathcal{L}(+\delta) \equiv R(\delta)$, which is expected to be greater (less) than 1.0 for K_2^0 heavier (lighter) than K_1^0. For solutions KT + F and KT + Y we obtain R(0.57) = 95.1 and 7.4 respectively. These likelihood ratios cannot be immediately interpreted as statistical "betting odds." To understand their statistical significance we use a Monte Carlo (MC) method. We simulate many "experiments" of 23 events each. In each MC experiment, each of the 23 events has the same values of momentum k_i, scattering angle θ_i, and potential time T_i as one of the 23 events of the real experiment, but the time of the scatter, t_i, is chosen according to the a priori probability function $p_i(t)$ for that real event.[13] For a given value of δ we generate 1000 MC experiments with the t_i chosen according to $m_1 - m_2 = +\delta$, and 1000 according to $m_1 - m_2 = -\delta$. For each MC experiment we calculate $\mathcal{L}(m_1 - m_2)$ as a function of $m_1 - m_2$ (for a given set of scattering amplitudes). Using the set of amplitudes KT + Y, we find that the 1000 MC experiments generated assuming $m_1 - m_2 = -0.57$ give five times as many experiments with R(0.57) = 7.4 (within a small interval ΔR) as do the 1000 experiments generated assuming $m_1 - m_2 = +0.57$. We therefore assign MC betting odds of 5 to 1 for K_2^0 heavier than K_1^0, assuming KT + Y. The corresponding MC betting odds using KT + F are 45 to 1 for K_2 heavier than K_1. (We obtain essentially the same MC betting odds if we use S = -1 solution KT' instead of KT.)

We also use the MC experiments to estimate the "goodness of fit" in a manner entirely analogous to the χ^2 tests that one can use with a larger sample of events. For phase-shift set KT + Y (KT + F) the real experiment gives $\log_{10}\mathcal{L}(-0.57) = 9.58$ (10.00). The result of the MC experiments is that if the hypothesis $m_1 - m_2 = -0.57$ is correct, then the most probable value for $\log_{10}\mathcal{L}(-0.57)$ is 9.85 (9.80), with 2/3 of the MC experiments giving values between 9.20 and 10.55 (9.25 and 10.50). Thus the fit of the data to the hypothesis $m_1 - m_2 = -0.57$ is good. Similarly, the real experiment gives $\log_{10}\mathcal{L}(+0.57) = 8.72$ (8.02). The MC result is that if the hypothesis $m_1 - m_2 = +0.57$ is correct, then the most probable value for $\log_{10}\mathcal{L}(+0.57)$ is 9.9 (10.2), and the probability of getting $\log_{10}\mathcal{L}(+0.57)$ as low or lower than our observed value of 8.72 (8.02) is only 0.027 (0.001). Thus the fit is poor for the hypothesis $m_1 - m_2 = +0.57$.

Two other experiments, both based on coherent regeneration, have also reported evidence for K_2^0 heavier than K_1^0.[14,15]

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FOOTNOTES AND REFERENCES

*This work was done under the auspices of the U. S. Atomic Energy Commission.

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2. A preliminary result was given by G. W. Meisner, R. L. Golden, B. B. Crawford, and F. S. Crawford, Jr. in Proceedings of the International Conference on Fundamental Aspects of Weak Interactions, Brookhaven National Laboratory Report BNL-837 (1963), p. 66 (unpublished). The large betting odds quoted there were based on the assumption $|m_1 - m_2| = 1.5\,\tau_1^{-1}$.

3. The Yang-type phase shifts are favored by SU(3) invariance, according to R. L. Warnock and G. Frye, Phys. Rev. 138, B947 (1965).

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6. For $A^I_{L,2J}$ in units of f^{2L+1} and $r^I_{L,2J}$ in f^{1-2L} we obtain $A^1_{01} = -0.29$, $r^1_{01} = 0.5$; $A^0_{01} = 0.04$, $r^0_{01} = 0.0$. For the Y (large $p_{\frac{1}{2}}$) solution we obtain $A^0_{11} = 0.11$, $r^0_{11} = 0.0$; $A^0_{13} = -0.05$, $r^0_{13} = 102.0$; $A^0_{23} = 0.06$, $r^0_{23} = -65.0$; $A^0_{25} = 1.0$, $r^0_{25} = -320.5$. For the F(large $p_{3/2}$) solution we obtain $A^0_{11} = -0.30$, $r^0_{11} = -61.0$; $A^0_{13} = 0.12$, $r^0_{13} = 4.1$; $A^0_{23} = 0.0$, $r^0_{23} = 0.0$; $A^0_{25} = 0.15$, $r^0_{25} = -64.0$. We make no physical interpretation of the values of these parameters; they give good fits to the phase-shift data.

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12. We take $|m_1 - m_2| \doteq 0.57\ \tau_1^{-1}$ (assuming $\tau_1 = 0.88 \times 10^{-10}$ sec) as an average of the results listed in Ref. 4, plus the more recent results of C. Alff-Steinberger, W. Heurr, K. Kleinknecht, C. Rubbia, A. Scribano, J. Steinberger, M. J. Tanneubaum, and K. Tittel, Phys. Letters 20, 207 (1966); of M. Bott-Bodenhausen, X. De Bonard, D. G. Cassel, D. Dekkers, R. Felst, R. Mermod, I. Savin, P. Scharff, M. Vivargent, T. R. Willitts, and K. Winter,

Phys. Letters 20, 212 (1966); and of R. March, U. Camerini, D. Cline, W. Fry, W. Fischbein, J. Gaidos, R. Hantman, and R. Stark, Bull. Am. Phys. Soc. 11, 326 (1966).

13. Even if we had very many events with known k_i and θ_i but not t_i, we would have essentially no information useful for finding the sign of $m_1 - m_2$. Therefore, we do not generate random values of k_i and θ_i in the MC experiments, but instead confine ourselves to generating t_i, thus avoiding irrelevant fluctuations that would arise from MC-generated k_i and θ_i.

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Table I. Summary of 23 events. t and T are the actual and potential proper times for the elastic scatters, in units of 10^{-10} sec, P_K is the K^0 laboratory momentum in MeV/c, and θ is the angle between the incident and outgoing K in the K-p center of mass.

Event	t	T	P_K	Cos θ
528328	0.55	11.74	490.5±6.4	0.02
533615	21.63	28.51	600.7±4.8	-0.33
557391	42.79	53.17	322.9±5.5	-0.65
562253	0.41	11.43	413.7±7.0	-0.62
583074	2.36	4.15	546.6±9.1	-0.08
591424	1.95	19.68	563.1±5.1	-0.91
602450	12.33	16.21	539.1±4.8	-0.96
683243	14.25	20.94	558.7±7.5	-0.97
691160	0.87	14.08	546.4±8.7	-0.95
773436	1.27	9.27	299.5±1.1	0.03
778118	4.27	25.76	260.5±3.2	-0.37
826368	13.58	15.94	349.4±7.2	-0.91
828583	30.89	57.71	305.3±1.6	-0.17
837477	16.46	29.63	408.6±2.4	0.39
1363048	4.33	8.18	195.6±3.4	-0.68
1479538	8.34	20.54	597.9±3.1	0.91
1738296	9.39	46.56	325.0±4.3	-0.61
1760182	11.06	16.83	454.8±3.0	0.73
1815424	24.42	27.09	392.2±4.1	-0.83
1867430	3.12	8.65	431.3±5.2	0.39
1882600	0.85	18.48	491.1±8.4	-0.14
1884143	6.63	32.83	329.5±1.4	-0.28
1886184	32.01	43.66	274.9±1.4	-0.08

Table II. Comparison of observed with predicted counts in six categories for six sets of phase shifts. The only significant discrepancies are in categories iv and vi. For a good hypothesis $\langle \chi^2 \rangle$ is 6.

	Category[a]						
	i	ii	iii	iv	v	vi	χ^2
Observed[b]	9+1.3	44+3.5	5	15	10+0.6	3+0.6	——
T + Y	9.4	45.6	4.3	5.7	8.1	9.6	20.0
T + F	9.4	45.6	3.4	3.4	8.7	11.9	46.7
KT + Y	9.4	50.8	6.2	7.3	10.8	12.5	15.0
KT + F	9.4	50.8	5.3	5.0	11.4	14.8	28.8
KT' + Y	9.4	43.4	6.9	12.5	13.2	11.8	7.0
KT' + F	9.4	43.4	6.2	10.6	13.4	13.5	10.4

a. The categories are (i) $K^0p \rightarrow K^+n$, (ii) $\overline{K}^0p \rightarrow$ hyperon, (iii) double-vee events with K scattered forwards (in c.m.), (iv) double-vee events with K scattered backwards, (v) single-vee events with K scattered forwards, and (vi) single-vee events with K scattered backwards.

b. Nonintegers are prorated contributions from six ambiguous events.

FIGURE CAPTIONS

Fig. 1. Time distribution of 23 events. (One event with $t > 40 \times 10^{-10}$ sec is not shown.) Labels F and Y on the curves refer to phase-shift solutions KT + F and KT + Y, with superscripts + and - referring to $m_1 - m_2 = +0.57$ and -0.57. The curves are constructed by summing $p_i(t)$ over the 23 events; therefore a discontinuity occurs at each time $t = T_i$ (potential proper time for ith event). The individual events are shown as vertical bars. The histogram gives counts per 10^{-10} sec in the indicated interval. The detection efficiency $\epsilon(t)$ is the fraction of the 6040 K^0 mesons having potential time $T > t$.

Fig. 2. Likelihood function $\mathcal{L}(m_1 - m_2)$ for 23 events.

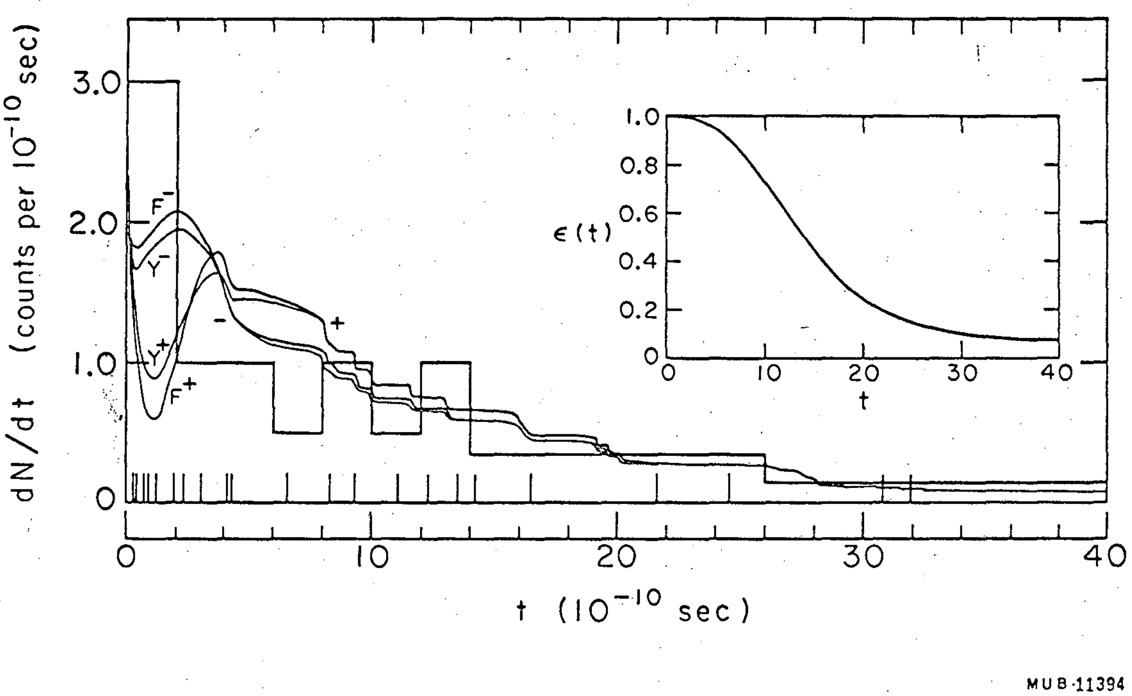
dN/dt (counts per 10^{-10} sec)
3.0
2.0
1.0
0
F⁻
Y⁻
Y⁺
F⁺
-
+
1.0
0.8
0.6
0.4
0.2
0
ε(t)
0
10
20
30
40
t
0
10
20
30
40
t (10^{-10} sec)
MUB-11394

Fig. 1

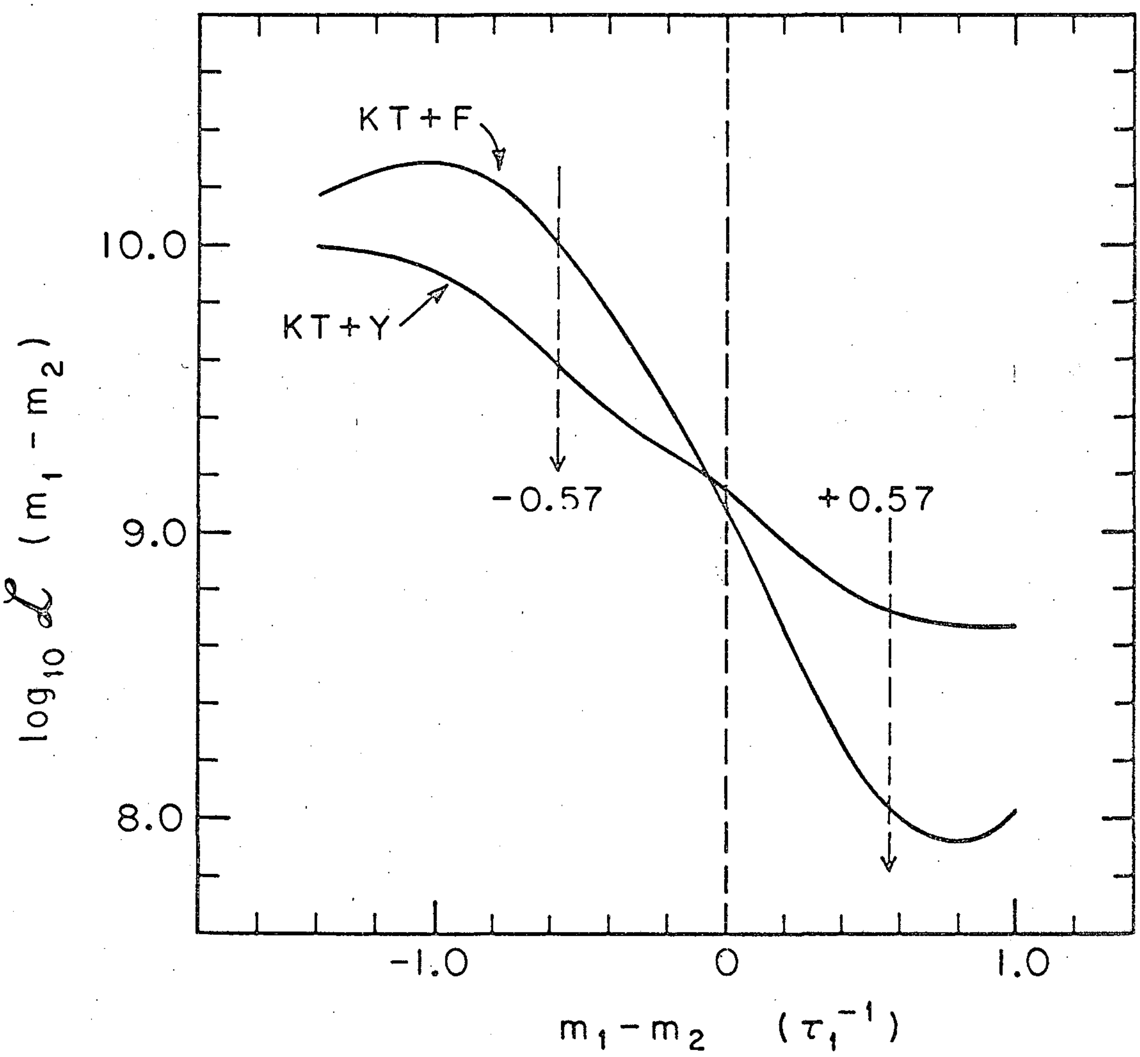

Fig. 2

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