[13]R. Armenteros et al., Phys. Letters 24B, 198 (1967).

[14]From a consideration of isospin and corrections for neutral decay modes, one obtains $\Xi^-\pi^+:\Sigma^0\bar{K}^0:\Lambda^0\bar{K}^0=6:1:3$. The additional factors come from the SU(3) Clebsch-Gordan coefficients with $\alpha=0.12$.

STUDY OF $Y_1^*(1660)^\pm \to \Sigma^0\pi^\pm$ (AND $\Lambda\pi^\pm$)*

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Large samples of $Y^*(1660)^\pm \to \Sigma^0\pi^\pm$ have been analyzed. Little $\Lambda\pi$ decay is observed, but $\Sigma\pi$ and $Y_0^*(1405)\pi$ modes are comparable. The spin and parity conclusion from $\Sigma^0\pi$ study is $\frac{3}{2}^-$.

Many conflicting results have been obtained for the decay branching ratios and the spin and parity assignment of the $Y_1^*(1660)$. First indications of its existence, its spin, and its SU(3) classification were all presented in three simultaneous reports made about five years ago[1]; however, subsequent studies yielded very confusing results.[2]

The inconsistencies were partially resolved recently when three separate analyses demonstrated the existence of a new $Y_1^*(1695)$ decaying predominantly into $\Lambda\pi$.[3,4] The report of Primer et al. shows [from inspection of about 250 $\Sigma^0\pi^+\pi^-$, 800 $\Lambda\pi^+\pi^-$, and 180 $Y_0^*(1405)\pi^+\pi^-$ events] that the $Y_1^*(1660)$ has branching ratios of about 60% into $\Sigma\pi$ and 40% into $Y_0^*(1405)\pi$, whereas the $Y_1^*(1695)$ decays predominantly into $\Lambda\pi$.[4]

This article presents information on K^- interactions at 1.7 BeV/c:

$$K^- + p \to \Sigma^0 + \pi^+ + \pi^- \quad \text{(990 events)}, \tag{1}$$

$$K^- + p \to \Lambda + \pi^+ + \pi^- \quad \text{(1538 events)}. \tag{2}$$

Data on $\Sigma^0\pi^+\pi^-$(1346 events) at 2.1 BeV/c are also discussed.

At 1.7 BeV/c a strong $Y_1^*(1660)$ enhancement exists in both the $\Sigma^0\pi^+$ and $\Sigma^0\pi^-$ systems in Reaction (1); a questionable peak is seen near 1660 MeV in the $\Lambda\pi^+$ system of Reaction (2). The $\Lambda\pi$ spectra show no evidence of $Y_1^*(1695)$ production.

Comparison is made of the $\Sigma^0\pi$ data at 2.1 BeV/c with published results on $Y_0^*(1405)\pi$ at this momentum.[5] The branching ratios obtained are in agreement with those of Ref. 4.

Spin and parity analysis of the decay sequence $Y_1^*(1660) \to \Sigma^0\pi$, $\Sigma^0 \to \Lambda + \gamma$, and $\Lambda \to p + \pi^-$ yields a $\frac{3}{2}^-$ assignment, in support of the conclusion of Eberhard, Pripstein, and Shively from $Y_1^*(1660) \to Y_0^*\pi$.[5] This lends further validity to the Primer et al. designation of $\Sigma\pi$ as a significant decay mode of the $Y_1^*(1660)$. (Alternatively, this study supports positive Σ^0 parity.)

In 1965 realignment of the "K-63" beam channel at the Bevatron was carried out in collaboration with Joseph J. Murray to obtain a 1.7-BeV/c K^- beam and an exposure of 3500 events/mb in the 72-in. bubble chamber. The primary purpose was to obtain a relatively clean, large sample of events containing the $Y^*(1660)$ as a final-state resonance of $\Sigma^0\pi$. The earlier "K-72" data (1.2-1.7 BeV/c) had yielded a very impressive peak near 1660 MeV in the $\Sigma^0\pi^+$ mass spectrum[6]; however, spin and parity analysis produced inconclusive results.

The "K-63" film yielded some 990 events fitting Reaction (1) rather well; i.e., the confidence level for this hypothesis was ≥ 0.005 and was at least three times greater than that for any competing hypothesis ($\Lambda\pi^+\pi^-$ or $\Lambda\pi^+\pi^-\pi^0$). However, to obtain a very pure sample of $\Sigma^0\pi^+\pi^-$ the author imposed more stringent conditions, namely, that the confidence level be ≥ 0.20. (The distribution in the $\Sigma^0\pi\pi$ confidence level showed considerable peaking below about 0.10, but was flat above 0.20.) To check possible bias, spin and parity analysis was carried out with a confidence-level minimum of 0.05; parameters obtained were quite similar to those found with a minimum of 0.20.

The number of events at 1.7 BeV/c which fitted $\Sigma^0\pi^+\pi^-$ production with a confidence level ≥ 0.20 was 613. Figure 1 shows the Dalitz plot and mass projections. The $Y^*(1660)^\pm$ resonance bands overlap near the center of the Dalitz plot. It would have been difficult to describe the production mechanism at 1.7 BeV/c completely. Therefore the $Y^*(1660)^-$ resonant band, as well

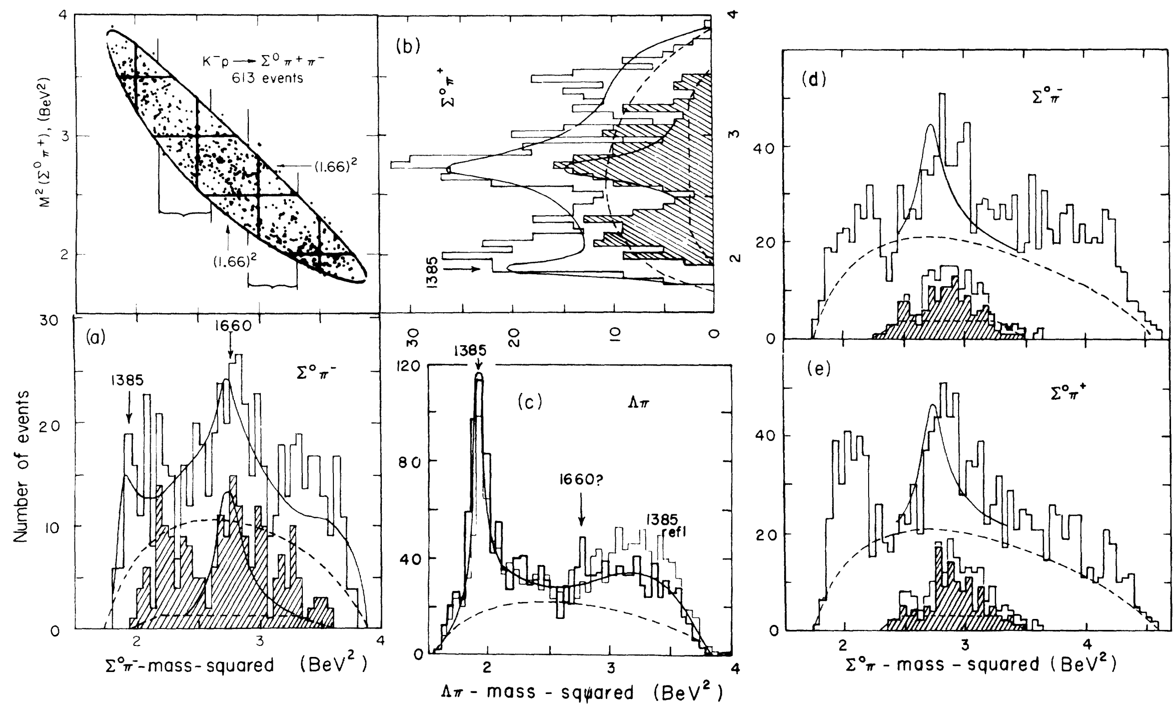

FIG. 1. Dalitz plot for Reaction (1) at 1.7 BeV/c, mass spectra for Reactions (1) and (2) at 1.7 BeV/c [(a), (b), and (c)], and mass spectra for (1) at 2.1 BeV/c [(d) and (e)]. Noninterference events are crosshatched. The heavy histogram in (c) represents the $\Lambda\pi^+$ mass spectrum; the light histogram, the $\Lambda\pi^-$ mass spectrum. With incoherent superposition of phase space plus resonances, fits were made simultaneously for the $\Sigma^0\pi^\pm$ data of (a) and (b), and for the $\Lambda\pi^\pm$ data of (c). In (d) and (e) the peaks represent the $Y^*(1660)$; the lower histograms present the noninterference events in a "nonresonant" $\Sigma\pi$ band from 2.92 to 3.32 BeV^2 and in a cleaner nonresonant band from 3.03 to 3.32 BeV^2 (crosshatched). Dashed lines represent phase space.

as the $Y^*(1385)^\pm$ bands, was eliminated for study of the $Y^*(1660)^+$ decay, and vice versa. The remaining "noninterference zones" of the Dalitz plot are indicated by horizontal curly brackets (for Y^{*+} study) in Fig. 1; these extend from 2.2 to 2.6 BeV^2 and from 2.92 to 3.32 BeV^2.[7] With $1580 \leq M(\Sigma\pi) \leq 1740$ MeV for the $Y^*(1660)$, 101 Y^{*+}, and 87 Y^{*-} are found among the noninterference events (crosshatched mass spectra). The Y^{*+} are peaked backward, whereas the Y^{*-} show only slight polar peaking.

The $\Sigma^0\pi$ curves of Figs. 1(a) and 1(b) represent incoherent superpositions of phase space, $Y^*(1385)^\pm$, and $Y^*(1660)^\pm$ calculated with the program OWL,[8] a P-wave resonance form ($\Gamma = 38$ MeV) being utilized for the $Y^*(1385)$ and a D-wave form ($\Gamma = 72$ MeV) for the $Y^*(1660)$. A variation of the width of the $Y^*(1660)$ in fitting the noninterference $\Sigma^0\pi$ data indicated a best value of about 75 ± 15 MeV. Figures 1(d) and 1(e) present mass spectra of the $\Sigma^0\pi^\pm$ at 2.1 BeV/c.

In the $\Lambda\pi^+$ spectrum [Fig. 1(c)] there is a slight enhancement of 33 ± 15 events in a narrow region near (1660 MeV)^2. This may be compared with the figure of 150 ± 31 $Y^*(1660)^+ \to \Sigma^0\pi^+$ events. The latter is obtained from Fig. 1(b) by observing that 220 ± 15 events exist in the region 2.50-3.03 BeV^2, with a phase-space background of 111 ± 10 and a $Y^*(1660)^-$ reflection of about 17; and by observing that the noninterference events number 104 ± 10 in the same region with a background of about 25. The former gives a net resonant contribution of 92 ± 18 and the latter a net (after correction for Dalitz-plot area) of 142 ± 20. A compromise between these two values may be taken as 120 ± 25 events. Correction for the confidence-level cut yields 150 ± 31. The relative branching ratio thus is[9]

$$[Y^*(1660)^+ \to \Sigma^0\pi^+]/(Y^{*+} \to \Lambda\pi^+) = 4.5 \pm 2.3 = 1/(0.22 \pm 0.11). \quad (3)$$

The branching ratio can also be obtained from the $Y^*(1660)^-$, as a limit. No enhancement is visible in the $\Lambda\pi^-$ histogram of Fig. 1(c) at (1660 MeV)^2; and the number of $Y^{*-} \to \Lambda\pi^-$ is taken as

<15 events. By the same procedure as for the $Y^*(1660)^+$ above, the ratio is found to be

$$[Y^*(1660)^- \to \Sigma^0\pi^-]/(Y^{*-} \to \Lambda\pi^-) > 10, \text{ or } > 1/0.10. \quad (4)$$

The value obtained by Huwe was[6]

$$[Y^*(1660)^+ \to \Sigma^0\pi^+]/(Y^{*+} \to \Lambda\pi^+) = 3.4 \pm 1.5 = 1/(0.29 \pm 0.13). \quad (5)$$

The $\Sigma^0\pi^+\pi^-$ events at 2.1 BeV/c were obtained from the same (K-63) run that yielded the lowest momentum sample of $\Sigma^\pm\pi^\mp\pi^+\pi^-$ presented by Eberhard, Pripstein, and Shively.[5] Examination of the $\Sigma\pi\pi\pi$ report shows that the number of $Y^*(1660)$ plus background events produced with $\cos\theta^* < -0.8$ was 323 for the several momentum samples from 2.45 to 2.7 BeV/c and 463 with the data at 2.1 BeV/c ($\cos\theta^* < -0.7$) added to the 2.45-2.7 BeV/c data, and hence that the number of $Y^*(1660)$ plus background events at 2.1 BeV/c, with $\cos\theta^* < -0.7$, was 140 ± 28. [The number of events was corrected for scanning biases; the mass range accepted for the $Y^*(1660)^+$ was 1580 to 1740 MeV.] Subtraction of background yields 112 ± 29 $Y^*(1660)^+ \to Y_0^*\pi^+$ events.[10]

In the 2.1-BeV/c data on $\Sigma^0\pi^+\pi^-$ we find 387 events with a $\Sigma^0\pi^+$ mass between 1580 and 1740 MeV [Fig. 1(e), upper histogram]; $\Sigma^0\pi^+\pi^-$ fits having confidence levels as low as 0.005 were accepted.[11] We can also use the noninterference data [crosshatched histogram of Fig. 1(e)] to estimate the number of $Y^*(1660)^+$. With correction for the Dalitz-plot area (0.32×total) and for the confidence-level restriction (0.8×total), the result is 324 ± 36 events.

Subtraction of background and $Y^*(1660)^-$ reflection yields (387−217−22) or 148 ± 25 events for the total-plot estimate and (324−125) or 199 ± 40 events for the noninterference estimate. From these two figures 180 ± 35 seems reasonable. This must be corrected for the decay Λ branching ratio ($\frac{2}{3}$), for the fraction of data processed (0.85), and for scanning efficiency (0.90). To compare with Eberhard, Pripstein, and Shively we use only those events with Y^* production $\cos\theta^* < -0.7$, which constitute 0.25 ± 0.05 of our data. We thus find the number of $Y^{*+} \to \Sigma^0\pi^+$ events is 89 ± 25.

We wish to consider all charge states; correction of the $Y_0^*\pi^+$ number for the absence of $\Sigma^0\pi^0\pi^+$ gives 168 ± 44 and of our $\Sigma\pi$ number for the absence of $\Sigma^+\pi^0$ yields 178 ± 50. Our final branching ratios (including the Eberhard, Pripstein, and Shively data) are thus[12]

$$[Y^*(1660) \to \Sigma\pi]/\text{total}, \ 0.51 \pm 0.10;$$

$$[Y^*(1660) \to Y_0^*\pi]/\text{total}, \ 0.49 \pm 0.10. \quad (6)$$

Primer et al. obtained 0.63 ± 0.20 for $\Sigma\pi$ and 0.37 ± 0.15 for $Y_0^*\pi$.

The spin and parity hypotheses $\frac{3}{2}^+$ and $\frac{3}{2}^-$ were considered for the $Y^*(1660) \to \Sigma^0\pi^\pm$ by analyzing noninterference resonant events with a maximum-likelihood technique utilizing Byers-Fenster parametrization.[13,14] (Likelihood treatment yields good analyzability in the decay $\Sigma^0 \to \Lambda + \gamma$ and more readily accommodates cuts in the resonant bands than a moment analysis.[15]) The distributions for the Σ^0 from the $Y^*(1660)$ decay, i.e., the angular distribution $I(\theta, \varphi)$ and the polarization distributions ($I\vec{P}_\Sigma \cdot \hat{\Sigma}$, $I\vec{P}_\Sigma \cdot \hat{x}$, and $I\vec{P}_\Sigma \cdot \hat{y}$), may all be represented as sums of orthogonal functions having coefficients t_{LM} (characterizing the Y^* spin state). Parity discrimination results solely from the sign of the coefficients of the transverse-polarization distributions relative to those of the longitudinal-polarization distribution; this sign gives γ, which is defined as $(|p|^2 - |d|^2)/(|p|^2 + |d|^2)$, with p the $l=1$ amplitude and d the $l=2$ amplitude in spin-$\frac{3}{2}$ $\to$ spin-$\frac{1}{2}$ decay.

The expression for Λ polarization in $\Sigma^0 \to \Lambda + \gamma$, $\vec{P}_\Lambda = -(\vec{P}_\Sigma \cdot \hat{\Lambda})\hat{\Lambda}$, is incorporated into the usual distribution function for Λ decay to give

$$Z = I - \alpha_\Lambda [(I\vec{P}_\Sigma \cdot \hat{\Sigma})(\hat{\Sigma} \cdot \hat{\Lambda}) + (I\vec{P}_\Sigma \cdot \hat{x})(\hat{x} \cdot \Lambda) + (I\vec{P}_\Sigma \cdot \hat{y})(\hat{y} \cdot \Lambda)](\hat{\Lambda} \cdot \hat{p}). \quad (7)$$

The likelihood $\mathcal{L}$ is found from

$$\ln\mathcal{L} = \sum_{i=1}^{n} \ln Z(i), \quad (8)$$

where Z is evaluated by putting in I and $I\vec{P}_\Sigma$ calculated from assumed Y^* spin, parity, and t_{LM}, and from observed direction cosines of the Σ^0, Λ, and p of the ith event.

The omission of the interference region is accommodated by normalizing the distribution function Z; thus the log of the likelihood function is

$$\ln\mathcal{L} = \sum_{i=1}^{n} \ln[Z(i)/N(i)], \quad (9)$$

where the sum is taken over events 1 through n

Table I. Likelihood results for spin $\frac{3}{2}$ and parity $\pm$ ($\gamma = \pm 1$).

Sample	Incident momentum (BeV/c)	Resonance	Special condition	Production angle	No. of events	ln$\mathcal{L}$ $\gamma=+1$	ln$\mathcal{L}$ $\gamma=-1$	Equiv. χ^2	Confidence level ($3/2^+$)
1	1.7	Y^*(1660)	$t_{22}=0$	B[a]	106	138.98	143.24	8.52	0.0035
2			$t_{22}=0$	F	82	105.96	106.42	0.92	0.35
3				B	106	144.51	148.94	8.86	0.0030
4				F	82	111.64	112.44	1.60	0.20
5	2.1	Y^*(1660)		B	159	270.91	271.13	0.44	0.50
6				F	83	138.49	139.44	1.90	0.16
7	1.7	Y^*(1385)		F	122	184.21	183.35	(1.72)[b]	(0.18)[b]
8				B	76	116.19	116.70	1.02	0.31
9	1.7	Y^*(1660)	$\hat{\Sigma}\cdot\hat{Y}^* \geq 0$	all	62	72.20[c]	72.09	----	----
10	1.7	Y^*(1385)	$\hat{\Sigma}\cdot\hat{Y}^* \geq 0$	F[d]	46	73.95	73.35	(1.20)[b]	(0.26)[b]

[a]The symbols "B" and "F" mean "backward" and "forward," respectively.
[b]Parentheses indicate $\frac{3}{2}^+$ is favored over $\frac{3}{2}^-$.
[c]For this solution t_{10} was pushed beyond its (spin-$\frac{3}{2}$) limit to 0.95; with t_{10} restricted to about 0.75, ln$\mathcal{L}$ was approximately 71.9.
[d]Backward events are not listed here, as solutions were poor. [The $Y^*(1385)$ was peaked forward.]

and where

$$N(i) \equiv \int_{-1}^{1}\int_0^{2\pi}\left[\int_{-1}^{\cos\psi_1(i)} Z d\cos\psi + \int_{\cos\psi_2(i)}^{1} Z d\cos\psi\right] d\zeta d(\hat{\Lambda}\cdot\hat{p}). \qquad (10)$$

Here $\cos\psi$ represents $\hat{\Sigma}\cdot\hat{Y}^*$ and ζ is the corresponding azimuthal angle. The $\cos\psi_1$ and $\cos\psi_2$ represent the boundaries at fixed nonresonant $\Sigma\pi$ mass. The variable parameters in maximizing ln$\mathcal{L}$ for the $Y^* \to \Sigma^0 \to \Lambda \to p$ decay sequence are the t_{LM}. For spin $\frac{3}{2}$ these are t_{20}, Ret_{22}, and Imt_{22} for the angular distribution, and t_{10}, t_{30}, Ret_{32}, and Imt_{32} for the polarization angular dependence.[16]

Table I represents the likelihood results for the various samples or combinations of samples. Because the computer search was more efficient with Ret_{22} = Imt_{22} = 0, some results with the restriction are presented; results without it are very similar. In all cases except sample 9 the final t_{LM} values obtained by maximizing the likelihood function were well below their maximum possible values for $J=\frac{3}{2}$.

The possibility of distortion of the experimental $Y^*(1660)$ distributions by interference from the ρ resonance in the π-π system was investigated. The band would be centered in the lower left half of the Dalitz plot (at 1.7 BeV/c), which ranged in π-π mass from 885 to 650 MeV. Since it was difficult to determine the extent of the ρ contribution, the lower part of the plot was simply eliminated ($\hat{\Sigma}\cdot\hat{Y}^* \geq 0$) and the data reprocessed (Table I).

The same techniques of analysis were also applied to the $Y_1^*(1385)^\pm \to \Sigma^0\pi^\pm$ events in the 1.7-BeV/c data. As expected, the $Y^*(1385)$ was found to have positive parity, although the odds were not convincing (Table I).

The $Y^*(1660)$ data produced by 2.1-BeV/c K^- were also analyzed as above. More background and interference effects for these data are probably responsible for somewhat weak results (Table I).

Conclusions may be drawn from the data discussed above by interpreting the decrease in ln$\mathcal{L}$ from the better to the poorer parity hypothesis as $\frac{1}{2}\chi^2$, where the number of degrees of freedom is one. The final column in Table I indicates the confidence level for the poorer hypothesis. Best discrimination between parity hypotheses for the $Y^*(1660)$ is obtained with a combination of samples 3, 4, 5, and 6; the spin and parity assignment of $\frac{3}{2}^-$ is much preferred over that of $\frac{3}{2}^+$, with an equivalent χ^2 of 12.80 for $\frac{3}{2}^+$ (or a confidence level of 0.0003). Figure 2 presents graphically some of the sample 1 results.

A spin of $\frac{3}{2}$ (or greater) is supported for the data in that three of the six t_{2M} and t_{3M} quantities are 2.3 to 2.9 standard deviations away from zero for the cleanest sample, the backward $Y^*(1660)$ at 1.7 BeV/c, and the Ret_{22} is nearly 4

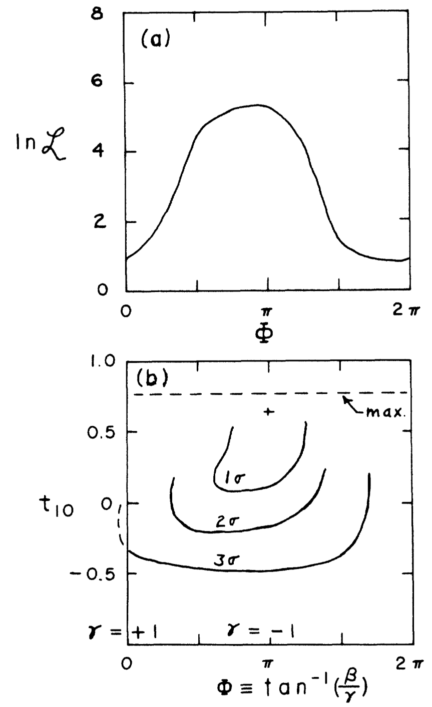

FIG. 2. The plots in (a) and (b) represent spin and parity results from just one data sample (sample 1). In (a), lnℒ is arbitrarily normalized; in (b), contours of constant ℒ are labeled by the equivalent number of standard deviations. (All parameters not shown were optimized.) The Φ variable, defined in terms of the continuous parameters β and γ used for weak decay, is equal to 0 ($\gamma=+1$) for positive parity or to π ($\gamma=-1$) for negative parity.

standard deviations from zero for the backward $Y^*(1660)$ at 2.1 BeV/c.

The $\frac{3}{2}^-$ assignment for the $Y^*(1660)$ makes it reasonable to associate this resonance with the $N^*(1518)$ and the $\Xi^*(1820)$ in a $\frac{3}{2}^-$ ($D_{3/2}$) octet, the octet having Y_0^* state that mixes with a singlet state to produce the observed $Y_0^*(1700)$ and the $Y_0^*(1518)$.[17]

We are grateful for the assistance of Shu-Bon Chan (University of Massachusetts) in fitting mass spectra and in reading the manuscript. Contributions from the 72-in. bubble-chamber crew, encouragement from Joseph J. Murray, and support from Luis W. Alvarez have been appreciated. Discussions of the likelihood method with Frank Solmitz and Gerald Lynch were helpful.

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[1]L. W. Alvarez et al., Phys. Rev. Letters 10, 184 (1963); P. L. Bastien and J. P. Berge, Phys. Rev. Letters 10, 188 (1963); and S. L. Glashow and A. H. Rosenfeld, Phys. Rev. Letters 10, 192 (1963).

[2]See the review articles by C. Peyrou, in Proceedings of the Oxford International Conference on Elementary Particles, 1965 (Rutherford High Energy Laboratory, Chilton, Berkshire, England, 1966); and by M. Ferro-Luzzi, in Proceedings of the Thirteenth International Conference on High Energy Physics, 1966 (University of California Press, Berkeley, Calif., 1967).

[3]M. Derrick et al., Phys. Rev. Letters 18, 266 (1967); and D. C. Colley et al., Phys. Letters 24B, 489 (1967).

[4]M. Primer et al., Phys. Rev. Letters 20, 610 (1968).

[5]P. Eberhard, M. Pripstein, and F. T. Shively, Phys. Rev. 163, 1446 (1967).

[6]D. O. Huwe, University of California Radiation Laboratory Report No. UCRL-11291, 1964 (unpublished).

[7]The width of the $Y^*(1660)$ is given as 50 MeV in the report of A. H. Rosenfeld et al., Rev. Mod. Phys. 40, 77 (1968). The widths reported by Eberhard, Pripstein, and Shively (Ref. 5) and Primer et al. (Ref. 4) are 75 ± 10 and 60 ± 20 MeV, respectively.

[8]A CDC 6600 "Monte Carlo Phase-Space Program" written by Gerald Lynch (Alvarez Programming Note No. P-162, Lawrence Radiation Laboratory, Berkeley, unpublished).

[9]The error should be interpreted with care, since a ratio of two normally distributed quantities is not itself normally distributed. The 0.22 ± 0.11 value is closer to having a standard deviation error in the usual sense.

[10]The "weights" of Eberhard, Pripstein, and Shively (Ref. 5) gave correct relative values, but should not be taken too seriously for absolute values (P. Eberhard, private communication). Thus the errors in Eq. 6 should perhaps be increased to ≈ 0.15.

[11]We observe some $Y^*(1660)^-$ in the $\Sigma^0\pi^-$ spectrum, Fig. 2, whereas Eberhard, Pripstein, and Shively apparently see no $Y^*(1660)^-$. Evidently isospin restrictions cause different interferences for $Y_0^*\pi^\pm$ compared with $\Sigma^0\pi^\pm$.

[12]This assumes no $\bar{K}^0p$ final state, "total" being $\Sigma\pi$ plus $Y_0^*\pi$. Also, footnote 9 again applies.

[13]N. Byers and S. Fenster, Phys. Rev. Letters 11, 52 (1963).

[14]J. Button-Shafer, Alvarez Group Physics Memo No. 533, Lawrence Radiation Laboratory, University of California, Berkeley, 1964 (unpublished).

[15]See F. S. Crawford, Alvarez Group Physics Memo No. 433, Lawrence Radiation Laboratory, Berkeley, 1964 (unpublished). This indicates an equivalent analyzability for $\Sigma^0 \rightarrow \Lambda + \gamma$ of about 0.60.

[16]The Σ^0 direction ($\hat{\Sigma}$) is found in the Y^* rest frame, $\hat{\Lambda}$ in the Σ^0 rest frame, and $\hat{p}$ in the Λ rest frame, all frames being connected by "parallel-axis" Lorentz transformations. The odd-M t_{LM} are zero if the Y^* production normal is chosen as z axis. The only terms in Z contributing to $N(i)$ are a constant and a $t_{20}'P_{20}(\cos\psi)$

term, where $t_{20}' = \sum_M \mathfrak{D}_{0M}^{2*}(\varphi^Y, \theta^Y, -\varphi^Y) t_{2M}$, with θ^Y and φ^Y giving the Y^* direction in the original coordinate system.

[17]R. H. Dalitz, in Proceedings of the Oxford International Conference on Elementary Particles, 1965 (Rutherford High Energy Laboratory, Chilton, Berkshire, England, 1966), and in Proceedings of the Thirteenth International Conference on High Energy Physics, 1966 (University of California Press, Berkeley, Calif., 1967); and N. Masuda and S. Mikamo, Phys. Rev. 162, 1517 (1967). These articles indicate a problem, namely, that $\Xi^*(1820) \to \Sigma\bar{K}$ is not observed.

TIME REVERSAL AND THE K^0 MESON DECAYS

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We show that T is not conserved in the CP-nonconserving $K^0 \to 2\pi$ decays by direct data analysis (rather than inferentially via CPT) over a considerable range of values for the Wu-Yang parameters within the span of existent data. In particular, if $|\eta_{00}|/|\eta_{+-}| \leq 1.0$, then T is broken. This result is independent of the final state $\pi\pi$ interaction.

Since the discovery of CP nonconservation in the decay of a neutral kaon into two pions,[1] a concomitant breakdown of time-reversal symmetry has been inferred by application of the fundamental CPT theorem. The experimental validity of this theorem was assumed by Lee, Oehme, and Yang[2] and by Wu and Yang[3] in their analyses of K^0 interference[4] phenomena. Although the possibility of CPT asymmetry has been considered[5] and transitory difficulties in closing the Wu-Yang diagram have occurred,[6] the present K^0 experimental situation is sufficiently fluid that one may reasonably assume that CPT symmetry remains a valid principle.[7] Nevertheless, microscopic time-reversal symmetry and its breaking are of sufficient intrinsic interest that it seems worth analyzing the data on K^0 decay to test the two-pion mode for T nonconservation directly, rather than inferentially via CPT and CP. We report here on the results of such an analysis, where T invariance is assumed at the outset and T nonconservation is established by contradiction over a fairly wide range of values for the relevant parameters within the span of present experimental data.[8]

Consider the amplitude ratios discussed by Wu and Yang[3]:

$$\eta_{+-} \equiv (K_L \to \pi^+\pi^-)/(K_S \to \pi^+\pi^-) \tag{1}$$

$$\eta_{00} \equiv (K_L \to \pi^0\pi^0)/(K_S \to \pi^0\pi^0), \tag{2}$$

where K_S and K_L are the short- and long-lived neutral kaons. The assumption of T invariance implies

$$\eta_{+-} = \bar{\epsilon} + \bar{\epsilon}' \tag{3}$$

$$\eta_{00} = \bar{\epsilon} - 2\bar{\epsilon}', \tag{4}$$

where

$$\theta_{\bar{\epsilon}} = \tan^{-1}[2(m_L - m_S)/(\gamma_S - \gamma_L)] - 90° \tag{5}$$

$$\theta_{\bar{\epsilon}'} = -(\delta_0 - \delta_2) \text{ or } -(\delta_0 - \delta_2) + 180°. \tag{6}$$

In the above $\theta_z \equiv \arg z$, where $z = \bar{\epsilon}$ or $\bar{\epsilon}'$, m_S (m_L) and γ_S (γ_L) are the mass and decay rate of K_S (K_L), and δ_I are the s-wave phase shifts due to the strong final-state pion interactions with isospin $I = 0, 2$. That is, the assumption of T invariance again leads to a Wu-Yang diagram [cf. Eqs. (3) and (4), and the inset of Fig. 1]. The parametrization differs from that when one assumes CPT invariance only in that the T-invariant phase angles $\theta_{\bar{\epsilon}}$ and $\theta_{\bar{\epsilon}'}$ differ by 90° from the corresponding CPT-invariant phases $\theta_{\bar{\epsilon}}$ and $\theta_{\bar{\epsilon}'}$. In obtaining Eq. (5) we have neglected contributions to $\theta_{\bar{\epsilon}}$ from the leptonic and 3π CP-nonconserving terms in the decay matrix as well as terms $O(|A_2/A_0| \times |\bar{\epsilon}'|)$ and $O([A_2/A_0]^2 |\bar{\epsilon}|)$. Here A_I are the $I = 0$ and $I = 2$ standing-wave amplitudes, real by the assumption of T invariance. Our second assumption, consistent with existent data but subject to further experimental test, is that the error $\Delta\theta_{\bar{\epsilon}}$, introduced by the neglect of these terms, satisfies[9]

$$|\Delta\theta_{\bar{\epsilon}}| \leq 10°. \tag{7}$$

Since we make no further approximations and re-