Possible Anisotropies in the Production and Decay Correlations of the η' (958)†

G. R. Kalbfleisch, S. R. Borenstein,* J. S. Danburg,‡ R. C. Strand, and V. Vanderburg
Brookhaven National Laboratory, Upton, New York 11973

and

J. W. Chapman, R. K. Kiang,§ and J. Lys‖
University of Michigan, Ann Arbor, Michigan 48104

and

A. Rittenberg
Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720
(Received 6 June 1973)

The spin and parity analysis of the $\eta'(958)$ from the distribution of events on the $\pi^+\pi^-\eta$ and the $\pi^+\pi^-\gamma$ Dalitz plots has been shown to favor $J^P=0^-$ over 2^-, but not conclusively. The Brookhaven National Laboratory–University of Michigan data reported here indicate anisotropies in the production and decay correlation angular distributions. Earlier Lawrence Berkeley Laboratory data dilute these effects. The observed anisotropies weaken the evidence for a $J^P=0^-$ assignment for the $\eta'(958)$.

The conclusion that $J^P=0^-$ for the $\eta'(958)$ is supported by two observations. Firstly, the standard Dalitz-plot analysis of the $\eta'(958)$ decay into $\pi^+\pi^-\eta(549)$ and $\rho^0\gamma$ favor $J^P=0^-$ over $J^P=2^-$, but not conclusively.[1,2] Secondly, no significant correlations between the η' production and decay angles have been observed when averaged over all production angles in experiments at various energies.[1-4] Ogievetsky, Tybor, and Zaslavsky,[5] proponents for a $J^P=2^-$ η' meson, have emphasized that the production-decay correlations should be studied for η' mesons produced in the extreme forward direction. They and Klosinski, Rembielinski, and Tybor[6] point out that production-decay correlations must exist for the very forward η', if indeed $J^P=2^-$. The Brookhaven National Laboratory (BNL)–University of Michigan data[2] at 2.18 GeV/c show anisotropies for the very forward produced η'. The earlier Lawrence Berkeley Laboratory (LBL) data[1] spanning a range of incident K^- momenta from 2.1 to 2.65 GeV/c do not show such anisotropies averaged over all energies. Both the separate and combined data of these two experiments are reported here. The difficulty of determining between J^P assignments with $\Delta J=2$, pointed out by Zemach,[7] is clearly illustrated in these data.

The BNL–University of Michigan data[2] of 1400 $\eta'(958)$ events in all decay modes come from the reaction $K^-p\to\Lambda\eta'(958)$ at 2.18 GeV/c. The LBL data[1] consist of 800 events from the same reaction at 2.1, 2.47, and 2.65 GeV/c, with the bulk of the data coming from 2.1 and 2.65 GeV/c.

Various production and decay angular correlations can be examined which should all be isotropic if $J=0$.

For the $\pi^+\pi^-\eta$ decay mode, the distribution of the decay-plane normal, $\hat{n}$, with respect to the incident beam, $\hat{K}$, was calculated in the η' rest frame. For the $\rho^0\gamma$ decay, the γ direction $\hat{\gamma}$ relative to the beam $\hat{K}$ was used. The distributions $\hat{n}\cdot\hat{K}$ and $\hat{\gamma}\cdot\hat{K}$ are each presented as a polar-equatorial ratio, P/E, because of the severe statistical limitation imposed by the "very forward" cut. The P/E ratios are presented in Table I for various production angle cuts on $\cos\theta^*=(\hat{K}\cdot\eta')$ in the K^-p c.m. system. Isotropic distributions are characterized by $P/E=1$. Anisotropies should appear for events with $\cos\theta^*$ near 1 if $J=2$. The standard prescription that $\theta^*<(kr)^{-1}$ implies $\langle\theta^*\rangle\simeq 0.1$, so $\theta^*<0.2$ rad should suffice,[6] i.e., $\cos\theta^*>0.98$. However, only 7% of all data survives such a cut (166 events in the combined sample in both decay modes). The P/E ratios for $\cos\theta^*>0.98$ in the BNL–University of Michigan data are $P/E(\hat{n}\cdot\hat{K})=\frac{23}{43}=0.54\pm0.14$ and $P/E(\hat{\gamma}\cdot\hat{K})=0.35\pm0.31$, both deviating from unity. The $P/E(\hat{n}\cdot\hat{K})=\frac{23}{43}$ observed is, e.g., 2.5 standard deviations from an assumed isotropic $J^P=0^-$ expectation of $(33\pm4)/(33\pm4)$. The LBL data averaged over energy show consistency with isotropy. The LBL 2.1-GeV/c data give indications of deviating from isotropy (see footnotes to Table I); with larger statistics than those available here, tighter $\cos\theta^*$ cuts can be made at higher energy in order to check for the necessary anisotropies

TABLE I. Polar-equatorial ratios (P/E) as a function of the c.m. production $\cos\theta^* = (\hat{K}\cdot\hat{\eta}')$ for the reaction $K^-p \to \Lambda\eta'(958)$. $\hat{n}\cdot\hat{K}$ is the cosine of the polar angle of the normal to the $\pi^+\pi^-\eta(548)$ decay plane relative to the incident K beam in the η' rest frame; $\hat{\gamma}\cdot\hat{K}$ is that of the γ in the $\eta' \to \rho^0\gamma$ decay. A background subtraction has been performed for the $\eta' \to \rho^0\gamma$ decays. The background region is 900–930 and 990–1020 MeV, respectively, and the η' region is 930–990 MeV. P is the number of events with $|\hat{n}\cdot\hat{K}|$ (or $|\hat{\gamma}\cdot\hat{K}|$) >0.5; E is the number of events with $|\hat{n}\cdot\hat{K}|$ (or $|\hat{\gamma}\cdot\hat{K}|$) <0.5. The columns labeled BNL–Michigan and LBL are for BNL–University of Michigan data at 2.18 GeV/c, and the LBL data for 2.1, 2.47, and 2.65 GeV/c, respectively.

	$P/E\ (\hat{n}\cdot\hat{K})$		$P/E\ (\hat{\gamma}\cdot\hat{K})_{\text{Subtracted}}$	
	BNL–Michigan	LBL	BNL–Michigan	LBL
$0.6 < \cos\theta^* < 0.8$	0.93 ± 0.14	1.04 ± 0.20	1.00 ± 0.43	0.76 ± 0.46
$0.8 < \cos\theta^* < 0.9$	0.88 ± 0.12	0.80 ± 0.15	1.29 ± 0.63	1.33 ± 0.60
$0.9 < \cos\theta^* < 1.0$	0.79 ± 0.09	0.97 ± 0.13[a]	0.66 ± 0.21	1.17 ± 0.31[b]
$0.9 < \cos\theta^* < 0.98$	0.87 ± 0.11	0.93 ± 0.14	0.78 ± 0.27	1.17 ± 0.39
$0.98 < \cos\theta^* < 1.$	0.54 ± 0.14	1.14 ± 0.33	0.35 ± 0.31	1.2 ± 0.5
$0.6 < \cos\theta^* < .98$	0.89 ± 0.07	0.92 ± 0.09	0.97 ± 0.23	1.12 ± 0.24
	BNL–Michigan + LBL		BNL–Michigan + LBL	
$0.6 < \cos\theta^* < .98$	$499/554 = 0.90 \pm 0.06$		$(190\pm24)/(187\pm22) = 1.02 \pm 0.18$	
$0.9 < \cos\theta^* < 1.0$	$251/292 = 0.86 \pm 0.07$		$(97\pm15)/(115\pm15) = 0.84 \pm 0.17$	
$0.98 < \cos\theta^* < 1.0$	$48/65 = 0.74 \pm 0.14$		$(21\pm7)/(32\pm7) = 0.66 \pm 0.27$	

[a]LBL 2.1-GeV/c data only, 0.69 ± 0.17.
[b]LBL 2.1-GeV/c data only, 0.60 ± 0.32.

if $J^P = 2^-$. The data are combined in the bottom part of Table I, and we see that for $0.6 < \cos\theta^* < 0.98$, $P/E(\hat{n}\cdot\hat{K}) = 0.90 \pm 0.06$ deviates by almost 2 standard deviations from 1; and that for $\cos\theta^* > 0.98$, $P/E(\hat{n}\cdot\hat{K}) = 0.74 \pm 0.14$ and $P/E(\hat{\gamma}\cdot\hat{K}) = 0.66 \pm 0.27$. These three numbers have a probability (in a χ^2 sense) of a few percent to be in agreement with isotropy, as compared to a small fraction of a percent for the same three numbers from the BNL–University of Michigan data alone. The angular distributions for $\cos\theta^* > 0.98$ are presented in Fig. 1 with theoretical curves[6] for $\rho_{00} = 0.5$. These data give as much evidence for $J = 2$ as the Dalitz plots do for $J = 0$; that is, the confidence level for $J = 0$ is less than that for $J = 2$ from the production and decay correlations, whereas $J = 2$ is less probable than $J = 0$ from the Dalitz-plot analysis. Thus, $J = 0$ or 2 are both tenable.

Several Monte Carlo studies were undertaken to verify that the observed asymmetries were not introduced into a 0^- η' decay by any known bias. No effects in the P/E ratios of greater than 1% were discovered. The following biases were eliminated as possible causes of the observed asymmetry:

(1) A systematic shift in the beam momentum leading to a fore/aft shift of the neutral momentum (η or γ) in fitting.

(2) A smaller than realistic beam-momentum error in fitting, leading to a fore/aft shift of the neutral momentum in fitting. This effect is observable as a depletion of the very polar normals but results in few normals crossing the polar-equatorial boundary.

(3) A loss of events with a high-momentum track near zero degrees relative to the beam. The data were measured on a flying-spot scanner for which overlaying beam track confusion could lead to an event loss.

(4) Confusion as to whether the $\pi^+\pi^-$ selected as the primary decay products of the η' are actually from the subsequent decay of the η. Misassignment of this type is small for the $\pi^+\pi^-\eta$, $\eta \to$ neutrals decay because of the favorable decay branching ratios involved. For the $\pi^+\pi^-\eta$, $\eta \to \pi^+\pi^-\pi^0$ (or γ) the misassignment is greater, but no asymmetry results from misassigned events.

Since the experimental situation regarding the Dalitz plot and production-decay correlations is inconclusive, it is important to look into what

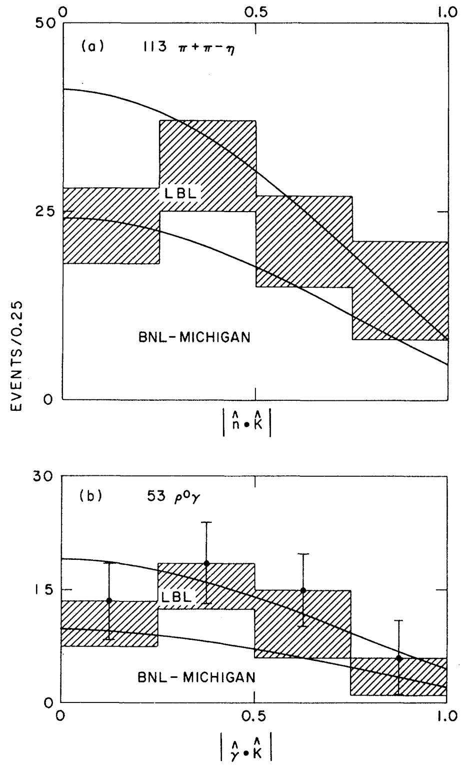

FIG. 1. The production and decay correlation ($\hat{n}\cdot\hat{K}$ and $\hat{\gamma}\cdot\hat{K}$) distributions for events with $\cos\theta^* > 0.98$ (see text). (a) $|\hat{n}\cdot\hat{K}|$ for $\eta'\to\pi^+\pi^-\eta$. (b) $|\hat{\gamma}\cdot\hat{K}|$ for $\eta'\to\rho^0\gamma$ with background subtracted (see Table I). The errors on the total $\rho^0\gamma$ data are shown since they are greater than $N^{1/2}$ because of the background subtraction. The solid curves are the predictions of Ref. 6 for an arbitrary "middle" value of $\rho_{00}=0.5$ and for ($\pi^+\pi^-\eta$) B_0:B_1:B_2 $=1$:0:3.72 and for ($\rho^0\gamma$) C_1:C_2:$C_3=1$:$-$ 0.5:1. The two curves in each figure are normalized to the BNL–University of Michigan data alone and to all the data, respectively. No curves are shown for the isotropic assignment since they can be easily visualized. The predicted P/E ratios (Ref. 6) vary from 0.75 to 0.35 for both $|\hat{n}\cdot\hat{K}|$ and $|\hat{\gamma}\cdot\hat{K}|$ for a variation of ρ_{00} from 0 to 1, respectively.

other information might shed light on the problem.

The ninth pseudoscalar meson.—The spin and parity of the $E(1430)$ meson[8] is in a similar situation, that is, $J^P=0^-$ or 1^+. Therefore, neither the η' nor the E can be assigned as the *ninth* 0^- nonet member yet, although Schwinger[9] argues that the ninth member should have a mass near 1500 MeV.

Width of $\eta'(958)$.—Our estimate of the true upper limit obtained by Binnie and co-workers[10,11] is $\Gamma < 2.8$ MeV (95% confidence level). If a width $\Gamma\sim 1$ MeV were found, then $J=0$ would be favored.[12] However, if $\Gamma<0.1$ MeV, then either $J=0$ or 2 would be possible. A width $\Gamma\sim 50$ keV for a $J=0$ η' is expected using a Duffin-Kemmer-Petiau description,[13] as opposed to the ~1-MeV value from a Klein-Gordon description, whereas for $J=2$, $\Gamma\sim 5$ keV is expected.[5]

$\pi^+\pi^-\eta/\pi^+\pi^-\gamma$ branching ratio.—The observed ratio of about 2 is perhaps low for a strong $\pi^+\pi^-\eta$ decay with $J=0$. This value is about a factor of 30 low according to Fischbach *et al.*[13] This ratio was expected to be about 10 according to Brown and Faier.[12] A $J=2$ η' would have angular momentum barriers in the $\pi^+\pi^-\eta$ mode to help with this problem.

Linear matrix element for $\eta'\to\pi^+\pi^-\eta$.—The $\eta'\to\pi^+\pi^-\eta$ Dalitz plot for $J^P=0^-$ can be modified by the addition of the factor $1+\alpha Y$ to a matrix element, where α is a parameter and

$$Y=(m_\eta+2m_\pi)(T_\eta/m_\pi Q)-1,$$

and m_η, m_π, T_η are the η and pion masses and the η kinetic energy, and Q is the energy release in the decay.[14] For $\eta(549)$ and K^0 decay to three pions, the corresponding parameter is $\alpha'\simeq-0.5$.[15] Charged decay modes of the kaon have different large values[11] for α. For η' decay the parameter α has been found to be -0.11 ± 0.05 by Rittenberg,[1] -0.05 ± 0.04 by Danburg *et al.*,[2] and -0.28 ± 0.06 by Dufey *et al.*[16] Schwinger[17] proposed that α be $-\frac{7}{17}=-0.41$. Dolgov, Vainshtein, and Zakharov[18] give a value of -0.43.[19] The near-zero α parameter observed for the η' decay may prove troublesome for a $J^P=0^-$ assignment.

The decays $A_2\to\pi\eta(549)$ and $A_2\to\pi\eta'(958)$.—The decay modes $A_2\to\pi\eta(549)$ and $A_2\to\pi\eta'(958)$ are ~16% and $\lesssim 3\%$, respectively.[11] For the currently assumed pseudoscalar nonet, the η is mostly octet and the η' mostly singlet. Thus the small $\pi\eta'/\pi\eta$ ratio implies that the singlet/octet coupling ratio must be small. If $J^P(\eta')=2^-$ then two different couplings are also needed. If a $J^P=2^-$ η' were to be the Regge recurrence of the η, then the coupling must vary as a function of position on the trajectory. The case of a $J^P=2^-$ η' on its own trajectory[20] would modify calculations in the $\pi^\pm p\to pA_2^\pm$ reaction, since exchange of both the ρ and η' trajectories might be of comparable importance.

The reaction $pd\to He^3X^0$.—If the $X^0(953)$[21] observed in this reaction is indeed the η', as discussed by Brody,[22] then the He^3 form factor gives some evidence for $J=0$ for the η'.

None of the above additional factors is decisive, however. Thus, in conclusion, $J^P = 0^-$ or 2^- for the η' are both possible. Further observations of anisotropies in η' production and decay correlations as presented here would revise our present assignment of $[\pi, K, \eta, \eta'(958)]$ mesons as comprising the pseudoscalar nonet.

Thanks are due to Professor E. Fischbach and Professor L. Balazs for helpful discussions, and to Purdue University, where some of this work was done, for their hospitality to one of us (G.R.K.).

†Work supported by the U. S. Atomic Energy Commission.

*Permanent address: York College, City University of New York, Flushing, N.Y. 11365.

‡Present address: Geophysics Department, Shell Development Company, Houston, Tex. 77001.

§Present address: 370 First Avenue, New York, N.Y. 10010.

‖Present address: Flat 221, Avoca Street, Randwick, N.S.W. 2031, Australia.

[1]A. Rittenberg, Ph.D. thesis, UCRL Report No. UCRL-18863, 1969 (unpublished).

[2]J. S. Danburg *et al.*, in *Experimental Meson Spectroscopy—1972,* AIP Conference Proceedings No. 8, edited by A. H. Rosenfeld and K.-W. Lai (American Institute of Physics, New York, 1973), p. 91.

[3]P. M. Dauber *et al.*, Phys. Rev. Lett. 13, 449 (1964).

[4]M. Aguilar-Benitez *et al.*, Phys. Rev. D 6, 29 (1972).

[5]V. I. Ogievetsky, W. Tybor, and A. N. Zaslavsky, Phys. Lett. 35B, 69 (1971).

[6]J. Klosinski, J. Rembielinski, and W. Tybor, Acta Phys. Pol. B1, 359 (1970); V. I. Ogievetsky, W. Tybor, and A. N. Zaslavsky, private communications.

[7]C. Zemach, Phys. Rev. 133, B1202 (1964).

[8]P. Baillon *et al.*, Nuovo Cimento 50A, 393 (1967); note that $J^P = 2^-$ is not conclusively ruled out either.

[9]J. Schwinger, Phys. Rev. Lett. 12, 237 (1964).

[10]D. M. Binnie *et al.*, Phys. Lett. 39B, 275 (1972); since the true width can only be measured if the resolution is less than or equal to it, an upper limit must be quoted using the variance of the χ^2 function. Thus, instead of adding 4 to the χ^2 to get the 95% confidence level upper limit, $2(2)^{1/2} \times$(No. degrees of freedom)$^{1/2}$ must be added [see, e.g., P. Söding *et al.*, Phys. Lett. 39B, 1 (1972); or T. A. Lasinski *et al.*, Rev. Mod. Phys. 45, S1 (1973)], which is $2(2 \cdot 8)^{1/2} = 8$. This gives, via their Table I, $\Gamma(\eta') < 2.8$ MeV (95% confidence level).

[11]Söding *et al.*, Ref. 10; Lasinski *et al.*, Ref. 10.

[12]L. M. Brown and H. Faier, Phys. Rev. Lett. 13, 73 (1964).

[13]E. Fischbach *et al.*, Phys. Rev. Lett. 29, 1046 (1972).

[14]R. H. Dalitz, Phil. Mag. 44, 1068 (1953).

[15]D. W. Carpenter *et al.*, Phys. Rev. D 1, 1303 (1970), and references given therein.

[16]J. P. Dufey *et al.*, Phys. Lett. 29B, 605 (1969); the value of α was obtained after correction for the acceptance of the apparatus; most of the discrepancy of this value of α and that of the bubble-chamber experiments (see Refs. 1 and 2) is due to this correction.

[17]J. Schwinger, Phys. Rev. 167, 1432 (1968).

[18]A. D. Dolgov, A. I. Vainshtein, and V. I. Zakharov, Phys. Lett. 24B, 425 (1967).

[19]This value of $\alpha(\eta')$ is not necessarily predictable (see Ref. 5).

[20]Such an η' trajectory is discussed in A. Bujak, A. A. Filippov, V. Ogievetsky, and A. Zaslavsky, Joint Institute for Nuclear Research, Dubna, Report No. E2-6847, 1972 (to be published).

[21]B. Maglich *et al.*, Phys. Rev. Lett. 27, 1479 (1971).

[22]H. Brody, Phys. Rev. Lett. 28, 1217, 1497(E) (1972).