ample.

[13]About 8 events have been misidentified because of the Λ^0-Σ^0 ambiguity.

[14]For this purpose, the mass of the K^* was taken to be between 840 and 940 MeV/c^2.

[15]Due to the difference of 80 MeV/c^2 in mass, we do not believe that this enhancement is related to that observed by a CERN group at 1420 MeV/c^2; R. Armenteros et al., in Proceedings of the Sienna International Conference on Elementary Particles (Società Italiana di Fisica, Bologna, Italy, 1963).

[16]The true mass of the resonance probably lies above 1500 MeV/c^2 due to the change in the Q value across the broad resonance. See J. D. Jackson, Nuovo Cimento 34, 1644 (1964). The estimate of the width is obtained from the K_1K_1 mass plot.

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[18]L. M. Hardy et al., Phys. Rev. Letters 14, 401 (1965).

[19]G. Goldhaber et al., Phys. Rev. Letters 12, 336 (1964); S. U. Chung et al., Phys. Rev. Letters 12, 621 (1964); Aachen-Berlin-Birmingham-Bonn-Hamburg-London (I.C.)-München Collaboration, Phys. Letters 10, 226 (1964).

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[21]M. Gell-Mann and Y. Ne'eman, The Eightfold Way (W. A. Benjamin, Inc., New York, 1964), p. 11; J. J. Sakurai, Phys. Rev. Letters 9, 472 (1962); S. Okubo, in Proceedings of the Athens Topical Conference on Recently Discovered Resonant Particles, Ohio University, Athens, Ohio, 1963, edited by B. A. Munir and L. J. Gallahar (Ohio University Physics Department, Miami, Ohio, 1963), p. 193.

[22]After this paper was completed, we received a preprint in which similar but more extensive calculations concerning this 2^+ nonet are carried out. See S. Glashow and R. Socolow, following Letter [Phys. Rev. Letters 15, 329 (1965)].

BRANCHING RATIOS FOR DECAYS OF THE f^0, A_2, AND $K^*(1400)$ MESONS*

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(Received 12 July 1965)

Thus far, it has been possible to associate the low-mass baryon and meson resonances with SU(3) multiplets. In addition to providing a mass relation for members of a multiplet, the symmetry model relates their partial widths for decay into lower mass multiplets.[1] With the discovery of the $f'(1500)$,[2] it appears likely that the sequence[3] $f^0(M=1253\pm10$ MeV; $\Gamma=100\pm25$ MeV), $A_2(M=1320\pm15$ MeV; $\Gamma=85\pm10$ MeV), $K^*(M=1410\pm10$ MeV; $\Gamma=100\pm20$ MeV), and $f'(M=1500\pm20$ MeV; $\Gamma=100\pm25$ MeV) represents a nonet of $J^P=2^+$ mesons. Because of the variety of decay modes accessible to these states, a comparison of available experimental data with the predictions based on SU(3) is of interest. Details of the calculations as well as references to other theoretical work on $J^P=2^+$ mesons are given by Glashow and Socolow.[4]

To estimate the branching ratios for the f^0 and A_2, we used events produced in π^-+p interactions at 3.2 BeV/c. Since this momentum is near threshold for $Y+K^*(1400)$, we obtained the branching ratios for $K^*(1400)$, using events produced at 3.9 and 4.2 BeV/c. The quantity of film used at each momentum is shown in Table I. Results on the branching fractions and cross sections are summarized in Table II. To facilitate comparison with other experiments, we indicate briefly the procedure used in the analysis; details will be published elsewhere.

The number of events corresponding to each decay mode and seen in our sample was estimated. (In most cases a smooth curve was drawn over the mass spectrum of the decay products to represent the background; the number of events above the curve and near the mass of the decaying particle was used.) This number was corrected for detection efficiency[5] (column 4 in Table II), and converted into cross-section units, by means of Table I. These values can then be directly compared to find the desired branching ratios.

Since the f^0, A_2, and $K^*(1400)$ are all produced peripherally in π^-+p interactions, the low Δ^2 (four-momentum transfer squared) events

Table I. Summary of measured film used in estimating branching ratios.

Final state	Beam momentum (BeV/c)	Sample size (events/μb)
2 prongs	3.2	0.36
4 prongs	3.2	1.1
Events involving strange particles	3.2	8.0
Events involving strange particles	3.9 to 4.2	4.5

Table II. Cross sections and branching fractions for the f^0, A_2, and $K^*(1400)$.

Production reaction	Decay mode	Charge state observed	(Charge state observed / All charge states)	Events in peak Total	Events in peak Peripheral[a]	Cross section[b] (μb)	Branching[b] fraction
$\pi^-+p\to f^0+n$	$f^0\to 2\pi$	$\pi^+\pi^-$	2/3	110 ± 30	85 ± 20	465 ± 130	≈ 1.0
	$f^0\to K+\bar{K}$	$K_1^0K_1^0$ [c]	1/9		4 ± 8		<0.04
	$f^0\to 2\pi^++2\pi^-$	$2\pi^+2\pi^-$	1		5 ± 6		<0.04
$\pi^-+p\to A_2^-+p$	$A_2\to\rho+\pi$	$\rho^0+\pi^-\to\pi^++\pi^-+\pi^-$	1/2	165 ± 45	97 ± 22	330 ± 60	$0.91_{-0.10}^{+0.04}$
		$\rho^-+\pi^0\to\pi^-+\pi^0+\pi^0$	1/2	64_{-15}^{+30}	34 ± 8		
	$A_2\to\eta+\pi$	$\eta_c\pi^-$ [d]	1/3	4 ± 4	4 ± 3	12 ± 12	0.03 ± 0.03
		$\eta_n\pi^-$ [d]	2/3	4 ± 6	3 ± 4		
	$A_2\to K+\bar{K}$	$K^-K_1^0$ [c]	1/3	53 ± 10	36 ± 9	20 ± 5	0.055 ± 0.015
	$A_2\to X^0+\pi$	$(\eta_n\pi^+\pi^-)\pi^-$ [d, e]	2/5		0 ± 5		<0.10
$\pi^-+p\to K^{*0}(1400)+\Lambda$	$K^*(1400)\to K+\pi$	$K^+\pi^-$ [f]	4/9	14 ± 3	13 ± 3	7 ± 2	f[g]
		$K_1^0\pi^0$ [c, f]	2/27		-1 ± 3		
	$K^*(1400)\to K+\eta$	$K_1^0\eta_c$ [c, d, f]	2/27		0 ± 1		<1/2
		$K_1^0\eta_n$ [c, d, f]	4/27		1 ± 1		
	$K^*(1400)\to K+\omega$	$K_1^0\omega_c$ [c, f, h]	1/5		0 ± 1		<1/3
	$K^*(1400)\to K^*(890)+\pi$	$K^{*+}(890)+\pi^-\to K^++\pi^-+\pi^0$ [f]	4/27		1 ± 3		$1/3\pm 1/3$
		$\to K^0+\pi^++\pi^-$ [h]	28/81		3 ± 3		
		$K^{*0}(890)+\pi^0\to K^++\pi^-+\pi^0$ [f]	4/27		2 ± 3		
	$K^*(1400)\to K+\rho$	$K^++\rho^-\to K^++\pi^-+\pi^0$ [f]	4/9		-6 ± 4		<1/12
		$K^0+\rho^0\to K^0+\pi^++\pi^-$ [i]	7/27		-3 ± 3		

[a]For the f^0n and A_2^-p final states, "peripheral" stands for $\Delta^2<0.65$ (BeV/c)^2. For the $K^{*0}(1400)\Lambda$ final state, "peripheral" stands for $\Delta^2<1.2$ (BeV/c)^2.
[b]Including unobserved charge states.
[c]$K_1^0\to\pi^++\pi^-$ decay required.
[d]Here η_c stands for $\eta\to\pi^++\pi^-+\pi^0$ or $\pi^++\pi^-+\gamma$ decay; and η_n stands for $\eta\to$ neutrals. We assume $\Gamma(\eta\to\eta_c)/\Gamma(\eta)\approx\frac{1}{3}$ and $\Gamma(\eta\to\eta_n)/\Gamma(\eta)\approx\frac{2}{3}$.
[e]We assume $\Gamma(X^0\to\eta_n+\pi^++\pi^-)/\Gamma(X^0)\approx\frac{2}{5}$.
[f]$\Lambda\to p+\pi^-$ decay required.
[g]We set the "branching fraction" for $K^*(1400)\to K+\pi$ equal to 1 and compare its other decay modes with this arbitrary standard.
[h]ω_c stands for $\omega\to\pi^++\pi^-+\pi^0$. We assume $\Gamma(\omega\to\omega_c)/\Gamma(\omega)\approx 9/10$.
[i]Either $\Lambda\to p+\pi^-$ or $K_1^0\to\pi^++\pi^-$ decay required.

were considered separately to reduce background. In those cases where the peripheral sample did not show evidence for a particular decay mode, an upper limit for the branching fraction is given. The removal of the corresponding number of events from this sample would leave a depression of one standard deviation in the background.

$\underline{f^0}$.—The number of $f^0 \to \pi^+ + \pi^-$ events was estimated by comparing di-pion–mass spectra from the reactions

$$\pi^- + p \to \pi^- + \pi^+ + n, \tag{1a}$$

and

$$\pi^- + p \to \pi^- + \pi^0 + p. \tag{1b}$$

To remove background in Eq. (1a), the $\pi^-\pi^0$ mass distribution beyond 1350 MeV was normalized to the corresponding region in the $\pi^-\pi^+$ distribution and subtracted. The difference shows a peak of 110 ± 30 events centered at 1250 MeV, with a width $\Gamma = 100$ to 120 MeV.

Decays into $K\bar{K}$ pairs were studied in the reactions

$$\pi^- + p \to K_1 + K_1 + n, \tag{2a}$$

and

$$\pi^- + p \to K_1 + K^- + p. \tag{2b}$$

Both $K\bar{K}$ mass distributions show strong peaks at 1310 MeV, so that the K_1K_2 events of Reaction (2a) in the f^0 region are strongly contaminated by $A_2^0 \to K_1 + K_1$ decays. Therefore, the 10 ± 4 events above background in the 1200- to 1300-MeV interval is an upper limit to the number of $f^0 \to K_1 + K_1$ decays, corresponding to a branching fraction[6] $\Gamma(f^0 \to K + \bar{K})/\Gamma(f^0) \lesssim 0.03$. A consistent result is obtained when events with $\Delta^2 < 0.65$ $(\mathrm{BeV}/c)^2$ are examined separately; in this case a comparison of $K\bar{K}$ spectra from Reactions (2a) and (2b) suggests that at most 4 ± 8 K_1K_1 events result from f^0 decay.[7]

$\underline{A_2}$.—Evidence for the decay modes $A_2 \to \pi + \rho$, $A_2 \to \pi + \eta$, and $A_2 \to K + \bar{K}$ has been reported by several groups.[8] In the present experiment, the decays[9] $A_2^- \to \pi^- + \rho^0$ and $A_2^- \to \pi^0 + \rho^-$ were studied in the reactions

$$\pi^- + p \to \pi^- + \pi^- + \pi^+ + p, \tag{3a}$$

and

$$\pi^- + p \to \pi^- + p + MM, \tag{3b}$$

where MM stands for the mass of unobserved neutral systems; in (3b) we require $MM \gtrsim 2m_{\pi^0}$. Because of large backgrounds associated with these reactions, there is some uncertainty in estimating the number of A_2 events. The decay mode $A_2^- \to \eta + \pi^-$ also contributes to the A_2 peak in the $\pi^- + MM$ spectrum of Reaction (3b). To estimate this contribution, the MM distribution was plotted separately for the $\pi^- + MM$ combinations in the 1250- to 1390-MeV interval. Although no clear evidence for an η peak is observed, the MM distribution is consistent with the presence of at most $10 \pm 10\%$ $\eta\pi^-$ decays in the A_2 peak. Consequently, almost all the 68^{+30}_{-15} events above background in the $\pi^- + MM$ distribution must be attributed to the decay $A_2^- \to \pi^0 + \rho^-$. In the $\pi^-\pi^-\pi^+$ mass spectrum from Reaction (3a), an A_2 peak of 165 ± 45 events is observed. A consistent number of events is found in the peak when at least one $\pi^-\pi^+$ pair is required to be in the ρ^0 interval. Despite the marked differences in background in Reactions (3a) and (3b), the relative size of the observed peaks is consistent with the equality of the rates $\Gamma(A_2^- \to \pi^- + \rho^0)$ and $\Gamma(A_2^- \to \pi^0 + \rho^-)$.

The reaction

$$\pi^- + p \to \pi^- + \pi^- + \pi^+ + p + MM \tag{3c}$$

was used in the study of the sequence $A_2^- \to \pi^- + \eta$, with $\eta \to \pi^+ + \pi^- + \pi^0$ or $\eta \to \pi^+ + \pi^- + \gamma$. Near 1320 MeV 4 ± 3 peripheral events were found above background, and the total sample gives no additional evidence for this decay mode. This implies that the branching fraction $\Gamma(A_2^- \to \pi^- + \eta)/\Gamma(A_2^-)$ is equal to 0.03 ± 0.03.[10]

The decay $A_2^- \to X^0(959) + \pi^-$ is also allowed to proceed via strong interactions. No evidence for the sequence $A_2^- \to X^0 + \pi^- \to \pi^- + \pi^- + \pi^+ + \eta \to \pi^- + \pi^- + \pi^+ + MM$ was observed when events in (3c) were used. The branching fraction[11] $\Gamma(X^0 \to \pi^- + \pi^+ + \eta$ with $\eta \to MM)/\Gamma(X^0) \approx \frac{2}{5}$ was used to obtain the upper limit $\Gamma(A_2^- \to \pi^- + X^0)/\Gamma(A_2^-) < 0.1$.

Identification of the $K\bar{K}$ peaks in Reactions (2a) and (2b) with the $A_2 \to K + \bar{K}$ decay has been discussed elsewhere.[12] Since the peaks correspond in position and width with those observed in Reactions (3a) and (3b), we assume that all K_1K^- events above a smooth background in the A_2^- region result from A_2^- decay; this assumption yielded the branching fraction $\Gamma(A_2^- \to K^0 + K^-)/\Gamma(A_2) = 0.055 \pm 0.015$.

$\underline{K^*(1400)}$.—The decay mode $K^*(1400) \to K + \pi$ has been observed in both Kp[13,14] and πp interactions.[15] The reactions

$$\pi^- + p \to \Lambda + K^+ + \pi^- (+\pi^0), \quad (4a)$$

$$\pi^- + p \to \Lambda + K^0 + \pi^+ + \pi^- (+\pi^0), \quad (4b)$$

were used to estimate upper limits for branching ratios of other decay modes. The three-body final states in (4a) were used to find the cross section for the sequence $\pi^- + p \to \Lambda + K^*(1400) \to \Lambda + K + \pi$. The $K\pi\pi$ mass distributions for four-body final states in (4a) and (4b) were examined separately for events with a $K\pi$ combination in the $K^*(890)$ interval or a $\pi\pi$ combination in the ρ interval. Of the five-body final states in Reaction (4b), not one was compatible with either of the decays $K^*(1400) \to K + \eta$ or $K^*(1400) \to K + \omega$. The reactions analogous to (4a) and (4b), but with a Σ^0 in place of the Λ, lead to similar but even weaker conclusions. The branching fractions given in Table II are normalized to the observed $K\pi$ mode.

We acknowledge the important contributions of our scanning and measuring group supervised by T. Bonk. The efforts of Werner Koellner were invaluable in coordinating the data-reduction operations. Dr. George R. Kalbfleisch and Dr. Gerald A. Smith participated in the early stages of the experiment.

It is a pleasure to thank Professor Luis W. Alvarez for his encouragement and support.

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*Work performed under the auspices of the U. S. Atomic Energy Commission.

†National Science Foundation Predoctoral Fellow.

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[3]The masses and widths are weighted averages of the available data. For references, see A. H. Rosenfeld, A. Barbaro-Galtieri, W. H. Barkas, P. L. Bastien, J. Kirz, and M. Roos, University of California Radiation Laboratory Report No. UCRL-8030, Pt. I, March 1965 (unpublished).

[4]Sheldon L. Glashow and Robert H. Socolow, following Letter [Phys. Rev. Letters 15, 329 (1965)].

[5]By detection efficiency we mean the fraction of a decay mode observed in the reaction under consideration. For instance, of the $f^0 \to 2\pi$ decay mode we see only $\pi^+\pi^-$ but not $\pi^0\pi^0$. With the branching ratio $\Gamma(f^0 \to \pi^0 + \pi^0)/\Gamma(f^0 \to \pi^+ + \pi^-) = \frac{1}{2}$ as appropriate for an $I = 0$ state, our detection efficiency is $\frac{2}{3}$.

[6]One-fourth of the $f^0 \to K + \bar{K}$ decays leads to K_1K_1. [M. Goldhaber, T. D. Lee, C. N. Yang, Phys. Rev. 112, 1796 (1958).] Since only about $\frac{2}{3}$ of the K_1's decay via the charged mode, we observe only about $\frac{1}{9}$ of the $K\bar{K}$ decays. Additional corrections due to finite chamber size and loss of K_1's decaying close to the production vertex are estimated to be below 10%.

[7]A similar measurement has been made by Barmin et al. in a study of $\pi^- p$ interactions at 2.8 BeV/c in a heavy-liquid bubble chamber. They observed a peak at $M(K_1K_1) = 1280$ MeV. If this peak was assigned to the f^0, they obtained the branching ratio $\Gamma(f^0 \to K_1 + K_1)/\Gamma(f^0 \to \pi^+ + \pi^-) = 0.023 \pm 0.01$. [V. V. Barmin et al., Institute of Theoretical and Experimental Physics Report No. 284, Moscow, 1964 (to be published)]. Another upper limit for the $K\bar{K}$ decay mode is quoted by Wangler, who used all events with K_1K_1n final states in a 75-MeV interval around the f^0 mass to obtain the ratio $\Gamma(f^0 \to K + \bar{K})/\Gamma(f^0 \to \pi + \pi)$ less than 0.16 ± 0.07 [Thomas Patrick Wangler, thesis, University of Wisconsin, 1964 (unpublished)].

[8]For a review of the A_2 meson, see Gerson Goldhaber, Proceedings of the Second Coral Gables Conference on Symmetry Principles at High Energies, University of Miami, January 1965, edited by B. Kursunoğlu, A. Perlmutter, and I. Sakman (W. H. Freeman & Company, San Francisco, California, 1965). A compilation of the available data on $A_2 \to \eta + \pi$ is given by J. Alitti, J. P. Baton, B. Deler, M. Neveu-Rene, J. Crussard, J. Ginestet, A. H. Tran, R. Gessarolli, and A. Romano, Phys. Letters 15, 69 (1965).

[9]Data concerning this final state will be published separately.

[10]This value is to be compared with the following results: $\Gamma(A_2 \to \eta + \pi)/\Gamma(A_2) = 0.0 \pm 0.03$ reported by Deutschmann et al. [M. Deutschmann et al., Aachen, Berlin, CERN collaboration, Phys. Letters 12, 356 (1964)]; $\Gamma(A_2 \to \eta + \pi)/\Gamma(A_2) \approx 0.20$ found by Trilling, et al. [G. H. Trilling, J. L. Brown, G. Goldhaber, S. Goldhaber, J. A. Kadyk, and J. MacNaughton, private communication from G. H. Trilling]; and $\Gamma(A_2 \to \eta + \pi)/\Gamma(A_2 \to \rho + \pi) = 0.30 \pm 0.20$ given by Aderholtz et al. [M. Aderholz et al., Aachen, Berlin, Birmingham, Bonn, Hamburg, Imperial College–London, Munchen collaboration, "π^+p Interactions at 4 GeV/c", December 1964 (to be published)].

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the second paper is in error. The $p^-\pi^0$ decay mode was neglected, and the path length corresponding to $K\bar{K}p$ events was underestimated.

[13]N. Haque et al. (Birmingham, Glasgow, Imperial College–London, Oxford, Rutherford Laboratory collaboration), Phys. Letters 14, 338 (1965). In this experiment some indication for a $K^*(1400)\to K^*(890)+\pi$ decay mode was found. An upper limit of the order of 0.2 is given for the branching ratio into all $K\pi\pi$ final states.

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DECAY MODES OF SPIN-TWO MESONS*

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(Received 18 June 1965)

Recent evidence indicates the existence of a nonet of $J^P=2^+$ mesons. These are

$$K^*(1430):\ T=\tfrac{1}{2}, Y=\pm 1,$$
$$A_2(1320):\ T=1, Y=0,$$
$$f(1250):\ T=0, Y=0,$$
$$f'(1525):\ T=0, Y=0.$$

In this note, we compare the observed partial decay widths of these states with theoretical predictions based on SU(3). The results strongly support the assignment of these states to the reducible $1\oplus 8$ representation of SU(3) with considerable f,f' mixing. Certain remarkable regularities characterize the nonets of $J^P=1^-$ and $J^P=2^+$ mesons, and we present a theoretical framework from which these regularities may be understood.[1]

A recent determination of the partial decay widths of the A_2, $K^*(1430)$, and $f(1250)$ may be found in the preceding paper.[2] These eight $J^P=2^+$ mesons generally are not assigned to an irreducible unitary octet, since their masses do not satisfy the Gell-Mann–Okubo formula, but they are attractive candidates for a reducible nonet.[1] We speculate that the remaining $T=Y=0$ member of the nonet is the recently discovered[3] f' at 1525 MeV. The physical f and f' are thus regarded as linear combinations of the unitary singlet f_1 and the $T=Y=0$ member of the unitary octet f_8. The mixing angle θ_2 is determined[4] in terms of the observed masses under the hypothesis that mass splitting transforms like hypercharge under SU(3). We obtain[5]

$$\sin^2\theta_2=(\hat{f}'-\hat{f}_8)(\hat{f}'-\hat{f})^{-1},$$

where $\hat{f}_8=[4\hat{K}^*(1430)-\hat{A}_2]/3$ is the square of the mass of the f_8 which would satisfy the Gell-Mann–Okubo formula. This yields $\theta_2\approx 30°$, so that

$$f'\approx\tfrac{1}{2}\sqrt{3}f_8-\tfrac{1}{2}f_1,$$
$$f\approx\tfrac{1}{2}f_8+\tfrac{1}{2}\sqrt{3}f_1.$$

Consider the decays of the $J^P=2^+$ mesons into two pseudoscalar mesons. We assume that the coupling constants are given by exact SU(3), so that there are only two relevant couplings which conserve C:

$$(6)^{1/2}F\,\mathrm{Tr}(T_8\{P_8,P_8\})+Gf_1\,\mathrm{Tr}(P_8P_8),\qquad(1)$$

where P_8 is the usual traceless 3×3 matrix describing the pseudoscalar octet and T_8 is the corresponding traceless 3×3 matrix describing the $J^P=2^+$ octet. Since the amount of mixing is determined, we may express all of the coupling constants of A_2, $K^*(1430)$, and the physical f and f' to two $J^P=0^-$ mesons in terms of the two parameters F and G. Table I gives the predicted partial decay widths which result when the experimental values

$$\Gamma(f\to 2\pi)=100\text{ MeV and }\Gamma(A_2\to K+\bar{K})=6\text{ MeV}$$

are used as input. We have assumed simple p^5/M^2 phase space, as is appropriate for these $l=2$ decay modes when SU(3) is applied to their relativistic matrix elements and no structure is assumed. (M is the mass of the decaying state and p is the c.m. decay momentum.)

Some decays of the $J^P=2^+$ mesons into a vector meson and a pseudoscalar meson are kinematically allowed. There is just one SU(3)-invariant C-conserving coupling,

$$H\,\mathrm{Tr}(T_8[V_8,P_8]),$$

where V_8 is the traceless 3×3 matrix representing the vector-meson octet. The decay widths predicted in Table I are based on the input

$$\Gamma(A_2\to\rho+\pi)=70\text{ MeV}$$