DECAY RATES OF $K^*(1420)$ AND THE 2^+ NONET*

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Because the most likely spin parity (J^P) values[1-4] of the $A_2(1320)$, $K^*(1420)$, $f^0(1250)$, and $f^*(1500)$ mesons are all 2^+, it is generally assumed[5,6] that they constitute an SU(3) nonet. Important additional evidence for the presumed nonet structure comes from studies of the strong decay rates of these mesons. Previous analyses,[5,7] based upon experimental information of less accuracy than that now available, indicated rough agreement with "unbroken" SU(3) predictions. The main purpose of this note is to re-examine this agreement in the light of new decay-rate information for the $K^*(1420)$, which we present in detail below, together with improved results for the $f^*(1500)$ discussed in the preceding Letter.[3]

The data relevant to the determination of various $K^*(1420)$ branching ratios come from our continuing study of K^-p interactions at 4.6 and 5.0 BeV/c, and in particular from the well-identified final states

$$\bar{K}^0\pi^+\pi^-n, \qquad (1)$$

$$\bar{K}^0\pi^-p, \qquad (2)$$

$$\bar{K}^0\pi^-\pi^0p. \qquad (3)$$

Certain general characteristics of these final states have been described elsewhere.[2,8] In particular, we have studied the mass spectra of all three- and (or) two-particle mass combinations and their momentum-transfer (Δ^2) distributions. From these we find that (1) and (2) are relatively simple and permit reliable identification of $(1420)^0$ and $(1420)^-$ events, respectively. On the other hand (3) appears to be inordinately complex, permitting only the identification of the $(1420)^-$ decaying via $K^*\pi$ modes.[9] These circumstances dictate the procedure by which (1420) branching ratios may be extracted from the data. The relative $K^*\pi/K\rho$ ratio is inferred from a study of (1). The $K\pi$ and $K^*\pi$ rates are obtained from (2) and (3), respectively. Using these, we obtain both the two-body and three-body branching ratios listed in Table I. Details concerning selection criteria considered optimum for present purposes are discussed below.

The final state (1) is dominated by $(K^*)^-$ production, with no important contribution from N^*, ρ, or Y^{0*} production. The unselected $K\pi\pi$ mass spectrum exhibits no low-mass anomalies, and a clean $(1420)^0$ peak is visible. It was shown in Ref. 2 that the (1420) events are produced by pion exchange, leading to a distribution in momentum transfer to the neutron $[\Delta^2(n)]$ which is very much peaked near zero. The

Table I. Branching ratios for various decay modes of the $K^*(1420)$ meson.

Final state	Decay mode detected	Raw No. events	Corrected totals	Derived branching ratios
(1) $\bar{K}^0\pi^+\pi^-n$	$(K^*\pi)^0$	18 ± 4	$18\times(\frac{3}{2})^2$	$\frac{K\rho}{K\pi+K\pi\pi}=0.14\pm0.10$
	$(K\rho)^0$	4 ± 4	4×3	
(2) $\bar{K}^0\pi p$	$(K\pi)^-$	39 ± 8	$39\times\frac{3}{2}$	$\frac{K\pi}{K\pi+K\pi\pi}=0.39\pm0.11$
(3) $\bar{K}^0\pi^-p\pi^0$	$(K^*\pi)^-$	32 ± 9	$32\times(\frac{3}{2})^2$	$\frac{K^*\pi}{K\pi+K\pi\pi}=0.47\pm0.10$

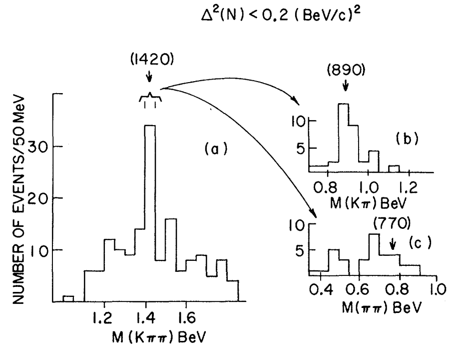

FIG. 1. (a) M $(K\pi\pi)$ distribution for a $\Delta^2(n)$ selected sample of $\bar{K}^0 n\pi^+\pi^-$ events. (b), (c) The $K\pi\pi$ and $\pi\pi$ subspectra of the 1420-MeV $K\pi\pi$ mass cut.

best $(1420)^0$ signal-to-noise ratio is obtained in a selected sample of channel (1), satisfying $\Delta^2(n) \leq 0.2$ BeV^2. The $M(K\pi\pi)$ spectrum for this subsample is shown in Fig. 1(a). The smooth background is normalized to events outside the $(1420)^0$ peak, defined for present purposes[10] in Fig. 1(a). Figures 1(b) and 1(c) show the $K\pi$ and $\pi\pi$ mass subspectra of the $(1420)^0$ peak. Since there is no significant ρ signal, we estimate the ρ contribution by subtracting the clear K^* peak from the total $(1420)^0$ signal and obtain the branching-ratio data[11] summarized in the first row of Table I.

The final state (2) is dominated by $(K^*)^-$ production. The N^* contribution can be readily identified and removed.[12] The $M(K\pi)$ spectrum of the remaining sample exhibits a clear $(1420)^-$ signal which, in principle, is sufficient to obtain the $K\pi$ decay rate. However, for purposes of comparison with the $(K\pi\pi)^-$ spectrum from (3), it is profitable to deal with a subsample selected on the basis of criteria involving momentum transfer to the proton, $\Delta^2(p)$. The effect on the $(1420)^-$ signal in final state (2) which occurs as the result of varying a lower $\Delta^2(p)$ cutoff $\Delta_L^{\ 2}$ for a fixed upper cutoff equal to 2.0 BeV^2 is shown in Figs. 2(a)-2(d). Although the signal shape and size are not very sensitive to the choice of Δ_L, it is clear that a value of $\Delta_L^{\ 2} \approx 0.2$ BeV^2 yields the best signal-to-noise ratio. With this choice one also finds that the background is very well accounted for by a Δ^2-truncated phase-space shape [solid curve of Fig. 2(c)]. Using a "1420" mass cut of $1380 \leq M(K\pi) \leq 1460$ MeV, one obtains the branching-ratio data given in the second row of Table I.

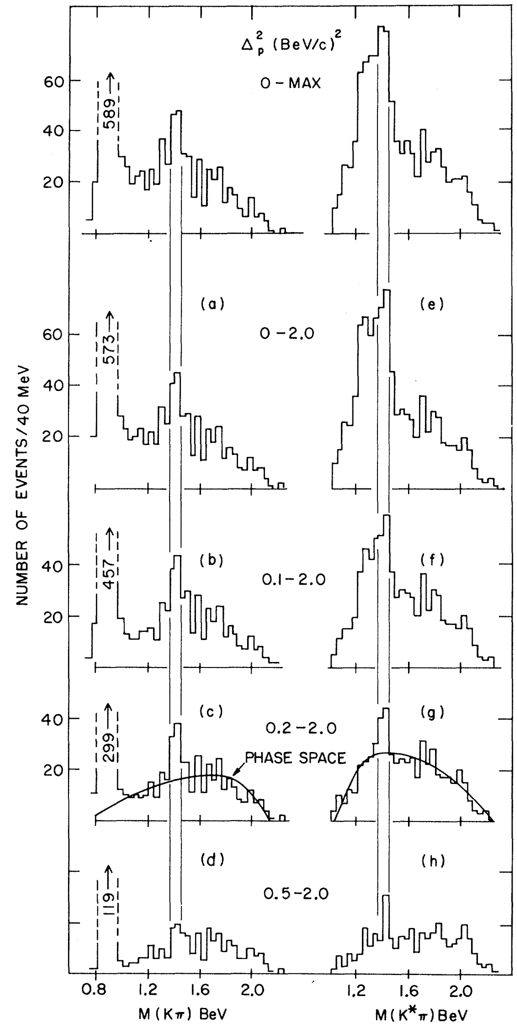

FIG. 2. Variation of $K\pi$ and $K^*\pi$ mass spectra (from $\bar{K}^0\pi^-p$ and $\bar{K}^0\pi^-p\pi^0$ final states, respectively), for a fixed upper cutoff and a variable lower cutoff in $\Delta^2(p)$.

The final state (3) is made up of many reaction channels: N^*K^*, $N^*K\pi$, $(K^*)^0\pi^-p$, $(K^*)^-\pi^0p$, $Kp\pi\pi$, $(1420)^-p$, and (probably) $(1790)^-p$. The complexity of this channel is discussed in detail in Dornan et al.[8] After removing N^*'s, and selecting both K^*'s and ρ's, the $M(K\pi\pi)$ spectrum exhibits the well-known broad enhancement between 1200 and 1500 MeV. This enhancement contains hundreds of events and engulfs the $(1420)^-$ signal which contains only about 40 events. In order to detect such a small signal within such a large background, one must make use of further selection criteria. These criteria are based on the properties of the (1420) observed in channels (1) and (2), as well as on the known[8] properties of the background in channel (3).

A restriction to K^* events only is suggested by two factors. Firstly, as we have seen from channel (1), the $K\pi\pi$ decay is predominantly due to $K^*\pi$, not $K\rho$. Secondly, because there are many more K^* events than ρ events, and because there is a tendency for an event with a "ρ mass" to satisfy also the K^* mass criterion, the identification of ρ events is not so reliable. The use of a $\Delta^2(p)$ acceptance region is suggested by the fact that the $(1420)^-$ events have a very different $\Delta^2(p)$ distribution from the background events. The variation in the $K^*\pi$ spectrum with choice of $\Delta_L{}^2$ is shown in Figs. 2(e)-2(h). Owing to the sharp $\Delta^2(p)$ variation of the background and its dominant size, both the signal-to-noise ratio and the apparent shape of the $(1420)^-$ peak vary considerably with the choice of $\Delta_L{}^2$. It is for $\Delta_L{}^2 \approx 0.2$ BeV^2 only that the shape of the $(1420)^-$ peak is consistent with that observed in channel (2). With this choice, the selection criteria for channel (3) are identical to those for channel (2). The appropriate selected data, shown in Fig. 2(g), exhibit a background shape which cannot be fitted by a simple "2 out of 3" phase space because the background is due to either other resonances [i.e., $K^*(1320)$ etc.] or Deck-effect mechanisms.[8] Thus we estimate the background level by drawing a smooth curve under the (1420) [and possibly (1790)] peaks. Using the same "(1420)" mass cut as in channel (2), we obtain the "$K^*\pi$" data given in the third row of Table I.

After appropriate Clebsch-Gordan coefficient corrections one finds the (1420) branching ratios listed in Table I. The quoted errors include estimates of the systematic uncertainties associated with the $\Delta^2(p)$ criteria imposed on this data. The results are in reasonable agreement with preliminary results from this investigation and early estimates from two other experiments.[13]

From the combined data of Figs. 2(c) and 2(g), we obtain mass and width values[14] of $M = 1423 \pm 7$ MeV, $\Gamma = 65 \pm 20$ MeV.

A compilation of new decay-rate information for all 2^+ mesons is given in Table II. Generally speaking the new rates are definite improvements over earlier ones resulting either from increased statistical accuracy or from a better understanding of the nature of the background.

To compare the observed two-body decay rates (Γ) with the predictions of "unbroken" SU(3), we assume the usual phenomenlogical relation[15]

$$\Gamma = |M|^2 C^2 \left(\frac{p}{m^2}\right)\left(\frac{p^2X^2}{p^2+X^2}\right)^2, \tag{4}$$

where M is the effective decay matrix element (our coupling constant), C is an appropriate SU(3) Clebsch-Gordan coefficient, X is the inverse interaction radius, and p/m^2 is the phase-space factor. In addition we assume particle mixing for all meson nonets. The magnitudes of the mixing angles θ_J ($J = 0, 1, 2$) are obtained from the requirement that the squared masses of the mesons obey the usual mass formula.[16] With these assumptions, the five decays of the type $2^+ \to 1^- + 0^-$ (listed in Table II as "Type A") are described by only two independent parameters, $|M_A|$ and X_A, while the ten decays of the type $2^+ \to 0^- + 0^-$ (called "Type B"), are described by three additional parameters, $|M_B|$, X_B, and a quantity α which is proportional to the ratio of singlet to octet decay amplitudes.[7] Thus we may attempt to fit type-A decays with three constraints and type-B decays with seven constraints. The fit is carried out by minimizing[17] the quantity

$$\sum_{\text{all decays}} \frac{(\Gamma_{\mathrm{SU(3)}} - \Gamma_{\mathrm{exp}})^2}{(\Delta\Gamma_{\mathrm{exp}})^2} \tag{5}$$

for type-A and -B decays separately.

The results are displayed in Table II, where we compare the observed rates with those predicted on the basis of the best-fit parameters. The agreement is quite good (the overall χ^2 probability being ~20 %); so the new data are still consistent with the 2^+-nonet hypothesis. The agreement indicates that the SU(3) coefficients and (especially) the particle-mixing parameters play a significant role in accounting for the 2^+ decay-rate data at the present time.

We wish to emphasize that most of the SU(3) predictions of Table II should remain stable against reasonable changes in most of the basic input rates. This is so because the basis parameters $|M_A|$, $|M_B|$, and α are already quite well determined by the experimental rates for $A_2 \to \rho\pi$, $f^0 \to \pi\pi$, and the limit for $f^* \to 2\pi$, respectively. On the other hand, changes in the experimental values of particular decay rates could dramatically alter the current acceptable status of the fit. For example, the fit predicts that $\Gamma(f^* \to K\bar{K})$ be 33 MeV. At pres-

Table II. Experimental and SU(3) predicted partial widths for different decay modes of members of the $J^P = 2^+$ nonet.

Decay Mode	Γ_{expt} (MeV)	SU(3) Coefficients	SU(3) Rates Γ (MeV)
		Type A Decays $2^+ \to 1^- + 0$	
$A_2(1320) \to \rho\pi$	56 ± 19	4	67
$K^*(1420) \to K^*\pi$	34 ± 12	3/2	22
$K^*(1420) \to \rho K$	10 ± 9	3/2	6
$K^*(1420) \to \omega^0 K$	4 ± 3[a]	$3/2 \sin^2\theta_1$	2
$f^*(1500) \to K^*K$	9 ± 9[a]	$6 \cos^2\theta_2$	10
		Type B Decays $2^+ \to 0^- + 0^-$	
$A_2 \to K\bar{K}$	2.5 ± 2	12	4
$A_2 \to \eta^0\pi$	6.5 ± 6	8	7
$K^*(1420) \to K\pi$	29 ± 13	18	29
$K^*(1420) \to K\eta^0$	3 ± 3[a]	2	1
$f^0 \to \pi\pi$	117 ± 21	$3(2\sin\theta_2 + \alpha\cos\theta_2)^2$	121
$f^0 \to K\bar{K}$	0 ± 12	$4(\sin\theta_2 - \alpha\cos\theta_2)^2$	7
$f^0 \to \eta^0\eta^0$	0 ± 12[a]	$(2\sin\theta_2 - \alpha\cos\theta_2)^2$	1
$f^* \to \pi\pi$	0 ± 6[a]	$3(2\cos\theta_2 - \alpha\sin\theta_2)^2$	1
$f^* \to K\bar{K}$	62 ± 15	$4(\cos\theta_2 + \alpha\sin\theta_2)^2$	33
$f^* \to \eta^0\eta^0$	0 ± 16[a]	$(2\cos\theta_2 + \alpha\sin\theta_2)^2$	8

[a]Only two standard deviation upper limits appear to be significant for these rates. For the purpose of fitting, such upper limits are recorded as [zero ± one standard deviation].

ent, the errors on the experimental value of $\Gamma(f^* \to K\bar{K})$ are large enough to accommodate this predicted value. However, if further work should significantly reduce the upper limits on the small f^* decay rates, the inferred experimental value of $\Gamma(f^* \to K\bar{K})$ would approach the total width of ~85 MeV, and this would badly violate the SU(3) predictions. We conclude that more precise measurements of the minor decay modes of the f^* are needed before a truly sensitive test can be achieved.

Finally, note must be taken of the possible effects of a splitting of the A_2 mass peak, as recently reported by Chicovani et al.[18] If either of the two alternative interpretations of the A_2 peak, i.e., two separate ~20-MeV wide resonances,[19] or a single ~25-MeV wide dipole resonance, should be borne out by further investigation, the basic input partial rate Γ("$A_2 \to \rho\pi$") would be reduced by a factor of about 3 from the present value. This, in turn, would predict a smaller $1420 \to K^*\pi$ rate, and make it difficult to maintain agreement between SU(3) predictions and current experimental values for 1420 decay.

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[1]For the A_2, see S. U. Chung et al., Phys. Rev. Letters 18, 100 (1967); G. E. Chikovani et al., Phys. Letters 25B, 44 (1967).

[2]For the $K^*(1420)$, see M. Goldberg et al., Phys. Rev. Letters 18, 688 (1967).

[3]For the $f^*(1500)$, see V. E. Barnes et al., preceding Letter [Phys. Rev. Letters 19, 964 (1967)].

[4]For the $f^0(1250)$, see K. Lai et al., private communication, based on 6-BeV/c π^-p studies.

[5]S. Glashow and R. H. Socolow, Phys. Rev. Letters 15, 329 (1965). Additional references are given in this paper.

[6]V. E. Barnes et al., Phys. Rev. Letters 15, 322 (1965).

[7]M. Goldberg et al., Nuovo Cimento 45A, 169 (1966).

[8]P. Dornan et al., Phys. Rev. Letters 19, 271 (1967). References to other studies of $Kn\pi\pi$ final states are given here.

[9]The symbol "K^*" when used without a mass subscript denotes the established resonance at 890 MeV.

[10]The $(1420)^0$ peak appears to be narrower than the $(1420)^-$ peak discussed later, but statistics are too small to consider the difference significant. In any event, since we do not "mix" neutral- and charged-(1420) branching-ratio information, different mass criteria for the peaks are irrelevant.

[11]The background shape in Fig. 1(b) was determined by studying the behavior of mass cuts adjacent to the (1420) peak of Fig. 1(a).

[12]After subtraction of the huge K^* peak, the resultant $M(p\pi)$ spectrum shows a clear N^* peak. The "N^* criteria" are $M(p\pi) = 1235 \pm 75$ MeV and cos($p\pi$ production angle) ≥ 0.9.

[13]J. Badier et al., Phys. Letters 19, 612 (1965); J. Bishop et al., Phys. Rev. Letters 16, 1069 (1966); B. Shen et al., Phys. Rev. Letters 17, 726 (1966).

[14]This value is obtained either from channel (2) alone by fitting with a Breit-Wigner plus phase-space shape, or from a combined plot in which the background is estimated by a smooth curve.

[15]A critique of the limitations inherent in any analysis which makes use of this formula is given in Ref. 7.

[16]See M. Gell-Mann, California Institute of Technology Pasadena Synchrotron Laboratory Report No. CTSL-20 (6) (unpublished); S. Okubo, Progr. Theoret. Phys. (Kyoto) 27, 949 (1962). This yields $|\theta_0| \approx 10°$, $|\theta_1| \approx 30°$. Owing to the small size of the 0^- mixing angle, the effect of mixing between the 0^- decay products of 2^+ mesons is negligible and is thus ignored. See A. MacFarlane and R. H. Socolow, Syracuse University Report No. NYO 3399-4.4, 1965 (unpublished). As is customary, the signs of θ_J are chosen in order to achieve the desired supression of certain decay rates.

[17]Here we make use of the University of California Radiation Laboratory "Minifun" program as revised by M. Sakitt of Brookhaven National Laboratory. We include in $\Delta\Gamma$ the experimental error, all uncertainties, including for example the error in mixing angles, etc. The dependence of the "best fit" solution on X_A, X_B is trivial as long as $X_i \geq 200$ MeV. See Ref. 7.

[18]Chikovani et al., Ref. 1.

[19]The possibility of two separate resonances in the A_2 region has also been discussed by D. R. O. Morrison [Phys. Letters 25B, 238 (1967)] on the basis of excitation function evidence.

EVIDENCE FOR $K^*(1250)$ RESONANCE PRODUCTION IN K^+p INTERACTIONS AT 9 BeV/c †

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We present evidence for $K^*(1250)$ resonance production in K^+p interactions at 9 BeV/c. We observe that the large $K\pi\pi$ mass enhancement in the region 1.1 to 1.5 BeV probably consists of three resonances at the observed masses 1.25, 1.36, and 1.42 BeV above a broad background due primarily to diffraction dissociation.

The $K\pi\pi$ mass enhancement in the region 1.1 to 1.5 BeV has been a phenomenon of great interest and much investigation.[1-7] It has been suggested in an earlier communication that the complex structure in this enhancement observed in K^+p interactions at 4.6 BeV/c consists of at least two resonances, $K^*(1320)$ and $K^*(1420)$, on top of a broad kinematical background produced via the Deck mechanism.[8] In this Letter we wish to present, as preliminary results of a study of K^+p interactions at 9 BeV/c, evidence for the existence of a resonance at 1250 MeV in addition to $K^*(1320)$ and $K^*(1420)$. This resonance may be the same effect as the C meson observed in $\bar{p}p$ annihilations at rest.[9,10] The production rates of these resonances depend sensitively on the momentum transfer to the recoil proton in such a way that the resonance effects are partially separated from the background events and partly from each other for different regions of momentum transfer. In our data the observed masses of the three resonances are 1250, 1360, and 1420 MeV, and full widths at half-maximum are 50, 80, and 80 MeV, respectively. We also speculate that the apparent masses and widths of the peaks depend on the interference effects between resonances of the same spin and parity and possibly with coherent background. Details of an investigation into such effects are described