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NEW INTERPRETATION OF THE Q MESONS*†

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ABSTRACT

A new analysis of the SLAC 13 GeV/c data on $Kp \to K\pi\pi p$ yields a low mass Q_2 $(K^*\pi)$ state at 1.18 GeV (Γ=130 MeV), in accord with a recently proposed theoretical mechanism. Implications for A_1 production are discussed.

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Despite a long history of effort, the status of the most famous "missing" member of the anticipated axial vector nonet remains uncertain; the A_1 has been variously claimed to (a) not exist,[1] (b) have a mass of 1.2 GeV,[2] (c) exist as a very broad state near 1.5 GeV,[3] (d) have a mass of 1.1 GeV but exotic (non-Breit-Wigner) analytic structure.[4] Moreover, irregardless of whether a conventional Breit-Wigner resonance in the region 1.2-1.5 GeV is compatible with recent data on τ decay,[5] it still must be reconciled with a mass of apparently negative evidence, such as its absence in $\pi p \to A_1 \Delta$.[6] In contrast, the situation with respect to the strange (Q) members of the $C = \pm$ nonets is relatively stable; there is an apparent consensus that two Q mesons exist in the range 1.2 to 1.5 GeV. In particular, the SLAC experiment on $K^{\pm}p \to K^{\pm}\pi^{+}\pi^{-}p$ at 13 GeV/c appears to require a state $Q_1(1.30)$ coupling principally to ρK ($\Gamma_1 \simeq 200$ MeV), and a state Q_2 (1.39) decaying almost entirely to $K^{*}\pi$ ($\Gamma_2 \simeq 160$ MeV).[7] Nevertheless, in this Letter I present an alternative interpretation of the SLAC data with the following characteristics: (1) the Q_2 state appears at 1.18 GeV and permits an excellent fit to the large $J^{P}M = 1^{+}0$ ρK and $K^{*}\pi$ intensities (and the relative phase of the corresponding amplitudes), (2) the model accounts perfectly for previously unexplained features of the $1^{+}0$ data (particularly the relative phase below 1.2 GeV), (3) the model successfully predicts, without free parameters, the sharp structure below 1.2 GeV observed in the $1^{+}1$ $K^{*}\pi$ intensity (which is hard to account for in the current interpretation),[7,8] (4) the model is based on a theoretical mechanism which is specific to the 1^{+} (C = +) mesons (A_1,Q,D,E), and which generates an excellent zero-parameter prediction for their masses (if $M_{A_1} = 1.1$ GeV).[4] Implications of this interpretation for the A_1 (particularly the absence of $\pi p \to A_1 \Delta$) are discussed below.

For our purposes, the relevant experimental facts in the 1^+0 state consist of the isobar "cross sections" $d\sigma(K^*\pi)/dM_3dt$ and $d\sigma(\rho K)/dM_3dt$ (i.e., the cross sections which correspond to including only a single isobar channel in forming the total amplitude), and the relative phase $\Delta\phi = \phi(\rho K) - \phi(K^*\pi)$ between the respective isobar amplitudes. The theoretical model contains both Deck-like production terms (d_α), and a description of isobar rescattering via the multi-channel amplitude $X_{\alpha\beta}$. Schematically, the full isobar amplitude τ_α is given by

$$\tau_\alpha = d_\alpha + c_\alpha \sum_\beta X_{\alpha\beta} b_\beta, \tag{1}$$

with b_β restricted by the unitarity constraint $\mathrm{Im}(c_\beta b_\beta / d_\beta) = \mathrm{Im}\,\rho_\beta$, where ρ_β is an appropriate phase space factor. At the simplest level one might choose $c_\alpha = 1$, $b_\beta = \rho_\beta d_\beta$, and take ρ_1 and ρ_2 to be the usual unequal-mass Chew-Mandelstam functions[9] for ρK and $K^*\pi$, respectively. Correspondingly, $X_{\alpha\beta}$ is taken to be a solution of the equation

$$X_{\alpha\beta} = K_{\alpha\beta} + \sum_\gamma K_{\alpha\gamma}\, \rho_\gamma\, X_{\gamma\beta} \ , \tag{2}$$

and hence is defined in terms of the real-valued K-matrix $K_{\alpha\beta}$. In particular, if one employs the parametrization $K_{\alpha\beta} = f_\alpha f_\beta / \left(M_3^2 - s_0\right)$ and the (Deck-inspired) choice $d_\alpha = \left(M_3^2 - m_K^2\right)^{-1}$, this model is identical in all respects with that previously considered by Basdevant and Berger.[10] The unitarity constraint on b_β assumes that there is no direct resonance production (e.g., coupling of Q_1, Q_2 to the Pomeron);[11] if this is relaxed (b_β independent of d_β), the use of a two-pole K-matrix corresponds precisely to the most detailed previous analyses.[8]

The physical content of those analyses may be briefly summarized as follows. The peak in $d\sigma(\rho K)/dM_3dt$ as a function of M_3 ($t = t_{min}$) is attributed to (largely direct) production of a Q_1 state decaying primarily to ρK; i.e., a classical Breit-Wigner signal. In contrast, the broader enhancement in the $K^*\pi$ cross section (see Fig. 1) is interpreted in terms of a significant Deck contribution in the 1.2 GeV region; this component is suppressed above 1.4 GeV by substantial production-resonance interference. The latter effect was noted by Aitchison and Bowler,[12] and may be readily understood in terms of the simple parametrization described above. Empirically, coupling to ρK can be ignored, and one obtains

$$\tau_2 \simeq d_2\left(M_3^2 - s_0\right)/\left(M_3^2 - s_0 - f_2^2\,\rho_2\right) \quad . \tag{3}$$

The $K^*\pi$ isobar amplitude (τ_2) is thus (approximately) zero in the vicinity of the K-matrix pole; for $\sqrt{s_0} \sim 1.4$ GeV this effect satisfactorily reproduces the rapid decline of the cross section. In order to simultaneously fit the relative phase ($\Delta\phi$) it is necessary to include some direct Q_2 production as well; the conventional model thus explains the data (with some exceptions noted below) in terms of two resonances Q_1, Q_2 and substantial direct production (which is not well understood).

As shown in Ref. 11, this analysis scheme may be improved by the use of more sophisticated forms for ρ_β, d_β and b ; i.e., the threshold behavior of ρ_β can be smeared out to take into account the finite isobar widths, and both d_β, b_β may be calculated as the appropriate partial-wave projections of a generalized model of production and rescattering. In addition, the model can be extended in such a way that the quantities c_α , d_α in Eq. (1) depend on the invariant mass $M_{\beta\gamma}$ of the pair of particles (β,γ)

decaying from isobar α, as well as on M_3 ($M_{\beta\gamma}$ is often referred to as the "subenergy"). However, if one assumes that production is dominated by the simplest form of the Deck model (so that d_1 is generated by K-exchange, and d_2 by π-exchange), these technical improvements do not alter either the physical content of the model or the conclusions reached in the analysis. Thus, the fit shown as the set of dashed curves in Fig. 1 and 2 was obtained using the improved model, and is comparable in all respects with the best fits reported in Ref. 8. It is important to note that in all such fits the relative phase $\Delta\phi$ is discarded below 1.2 GeV, on the grounds that the small ρK amplitude makes its determination experimentally unreliable. This assumption is crucial, since no fit of this type can produce the requisite behavior. Nevertheless, the experimental $\Delta\phi$ behavior shown is a consistent feature of all such experiments and partial-wave analyses to date.

The alternative fit introduced here is based on two modifications of the above model. In the first instance, the Deck amplitude was generalized by incorporating structure functions at both the three-body ($K \to \rho K$ and $K \to K^*\pi$) and two-body vertices (the latter corresponding to Kp and πp elastic scattering). As shown in Ref. 11, this procedure provides a non-resonant mechanism for increasing the fall-off of $d\sigma/dM_3dt$ at large M_3. In this case, the three-body vertex was modified by the factor $\left(\bar{\varepsilon}_\alpha^{\,2} + \mu_\alpha^2\right)^{-1}$, where $\bar{\varepsilon}_\alpha$ is the energy of the bachelor particle in the isobar c.m., and μ_α is a parameter (μ_1 = .6 GeV, μ_2 = .3 GeV).[11] Similarly, a factor s_α/s'_α was employed at the 2-body vertex, where $\sqrt{s}$ is the invariant energy of the proton and the detected (outgoing) bachelor meson, and $\sqrt{s'_\alpha}$ is the corresponding quantity for the proton and the exchanged (incoming) bachelor meson (both s_α and s'_α are proportional to p_L, and hence rather large). These modifications are rather modest, and cannot be ruled out a priori.

Secondly, the analytic structure of the isobar scattering amplitude ($X_{\alpha\beta}$) was altered via a different choice of $K_{\alpha\beta}$, and by incorporating a singularity suggested by some recent theoretical work.[4] Thus, in preliminary work on the $K\pi\pi$ system using a similarly generalized production model, it was found that the parametrization

$$K_{\alpha\beta} = f_\alpha f_\beta/(M_3^2 - s_1) - \delta_{\alpha 2}\delta_{\beta 2}\, g_o\, (M_3^2 - s_o) \tag{4}$$

resulted in a fit qualitatively similar to the solid curves of Figs. 1, 2a.[11] The fit differed, however, in that it missed the rapid variation in $\Delta\phi$ near 1.15 GeV (it essentially interpolated between the solid curve values at 1.10 and 1.17) and the corresponding low mass peak in $\sigma(\rho K)$. An examination of the resulting ($X_{\alpha\beta}$) amplitude revealed a Q_2 pole on the proper sheet ($M_3 = 1.15 - i\,0.12$), but its behavior on the real axis was not of the familiar Breit-Wigner type. In particular, X_{22} (the elastic $K^*\pi$ amplitude) did not peak near 1.15 due to a nearby zero in the numerator function (near $\sqrt{s_o} \simeq 1.20$).

This unusual result is very suggestive in view of Ref. 4, in which it was proposed that a singularity in the pion-exchange diagram for $K^*\pi \to \varepsilon K$ could give rise to a non-Breit-Wigner Q_2 state near 1.18 GeV. Thus, letting channel #3 correspond to εK, I had noted that a sharp peak occurs in the effective phase space factor ρ_3 at that energy, and that this in turn could generate an associated resonance nearby. With this in mind, the $K\pi\pi$ analysis was repeated as an explicit 3-channel problem. In so doing, the $K_{\alpha\beta}$ form of Eq. (4) was replaced by $K_{\alpha\beta} \to K_{\alpha\beta} - g_\alpha g_\beta$, and the theoretically deduced (singular) form for ρ_3 was employed in Eq. (2). Specifically, ρ_3 was calculated via a dispensive integral ($m_t \leq M_3 < \infty$), with $\mathrm{Im}\rho_3 = (\mathrm{const}) \times \left[(M_3 - M_s)^2 + \mu_s^2 \right]^{-1/2}$. This form arises when the logarithmic singularity discussed in Ref. 4 is (numerically) averaged over the ϵK phase space. Here M_s, μ_s are not free parameters, but are determined to be $M_s = 1.18$ GeV, $\mu_s \simeq 2$ MeV via this argument. In particular, M_s is the unique three-body mass such that the pion-exchange diagram for $K^* \to K(\pi\pi)$ can occur as an <u>on-shell</u> process with the final dipion pair (relatively) at rest,[14] and μ_s is determined empirically by a fit to the results of the numerical average. In addition to the normalization parameters N_1, N_2 multiplying the production terms d_1, d_2 ($d_3 \simeq 0$), the resulting model is then defined by the parameters $s_0, s_1, g_0 f_\alpha, g_\alpha$. In practice, the new terms constitute a perturbation, except in the energy range 1.10 to 1.20 GeV. As a result, it proved adequate to take g_2 and g_3 as constants, but g_1 was represented as $g_1 = g_4/(M_3^2 - s_2)$. In all, this yields the twelve free parameters whose values are summarized in Table I (for comparison, the "orthodox" fit required fifteen parameters).

With the exception of the two highest mass points in the $K^*\pi$ intensity, it is clear that the resulting fit (solid curves) is superior to the conventional one (dashed curves) in virtually all respects. For example, eliminating those two points and the $\Delta\phi$ data below 1.2 GeV, the new fit has $\chi^2/NDF = 1.7$, vs. 2.6 for the old one. In addition, the new fit accounts perfectly for the low mass ($M_3<1.2$) behavior of $\Delta\phi$, and generates a corresponding bump in the ρK intensity (the data appear to support this effect, but the statistical significance is rather low). On the other hand, the high mass $K^*\pi$ intensity is quoted with very small errors, and so dominates the χ^2 as to eliminate the proposed alternative. There are, however, several counter-arguments one may make in response to this objection. Thus, accepting the data, a realistically rapid decline in $\sigma(K^*\pi)$ could be accomplished by suitably adjusting the vertex corrections. For example, in Ref.11 it was shown that the discrepancy can be reduced by more than one-half by using a Gaussian factor $\exp(-\bar{\varepsilon}_\alpha^2/\mu_\alpha^2)$. Alternatively, it is possible that the partial-wave analysis (PWA) is misplacing the content of the various isobar channels in that region. Here one observes that the (large M_3) solid curve in Fig. 1a looks very much like the total 1^+0 cross section. In the PWA this total is almost entirely $K^*\pi$ and εK, with the two amplitudes roughly 90° out of phase. Hence, if the εK events were attributed instead to $K^*\pi$, the same $\sigma(1^+0)$ would result. As noted in Ref.11, such a misidentification could occur as a consequence of the neglect of subenergy dependence in the PWA, coupled with the very broad character of the "ε". In fact, such effects have been demonstrated in the application of PWA codes to Monte Carlo calculations of theoretical (Deck) amplitudes.[13] Also, the corresponding curve for the (diffractively produced) A_1 system exhibits precisely such a break in slope at the high mass end; Basdevant and Berger require a significant coupling to the (inelastic) $K^*\bar{K}$ channel in order to explain this.[2]

As an illustration, additional "data points" in Fig. 1a (open circles) show the effect of redesignating 3/4 of the ϵK intensity as $K^{*}\pi$.

However, the most striking piece of evidence in support of the proposed interpretation arises in the M=1 magnetic substate, in which the PWA demands a sharp peak at approximately 1.18 GeV. The failure of the conventional fit to reproduce this is illustrated by the dashed curve in Fig. 2b, which was calculated by adjusting only the production amplitudes (the $X_{\alpha\beta}$ remain fixed). In contrast, the solid curve clearly exhibits the right character, with the peak arising as a direct consequence of the low mass state and the associated singularity. While this is obviously qualitative and not a fit, it is also clear that the $1^{+}1$ $K^{*}\pi$ intensity is much more sensitive to the precise details of the $X_{\alpha\beta}$ amplitudes below 1.2 GeV than the $1^{+}0$ data. For example, by modifying the fit to produce the alternative $\Delta\phi$ shown as the dashed-dot curve in Fig. 2a (i.e., by suitably adjusting the $\Delta\phi$ "data" at 1.14 and 1.17 GeV), one generates the alternate $K^{*}\pi$ intensity shown in Fib. 2b (same notation); the latter provides a fairly good description of the data. In order to improve this it is likely that an explicit three-body $(K\pi\pi)$ treatment will be required; i.e., not only is the "ϵ" very broad, but the singularity argument of Ref. 4 implies important subenergy effects.

On this basis I find M_{Q_1}=1.30, Γ_{Q_1}=0.16 and M_{Q_2}=1.18, Γ_{Q_2}=0.13 GeV in a model which replaces large direct production and a high-mass Q_2 state by a low-mass Q_2 and plausible structure in kaon dissociation. This result clearly supports the previously proposed mechanism as the source of both the 1^{+} (and certain other) mesons, and of the perplexing difficulties encountered in their analysis.[4] In addition, the nature of the fit obtained has some interesting implications with respect to the A_1 controversy. Thus, one would expect by analogy that $M_{A_1} \simeq 1.1$ GeV, and that <u>the A_1 would not appear as a peak in $\rho\pi$ scattering</u>! The latter follows as a consequence of the specific structure of K_{22} (see discussion following Eq. (4)). Experimentally, one would not see A_1 production via ρ-exchange (e.g., in $\pi p \to A_1 \Delta$), but would see the reaction $X \to A_1 \to \pi\rho$, where X is some inelastic channel (e.g., in τ decay).

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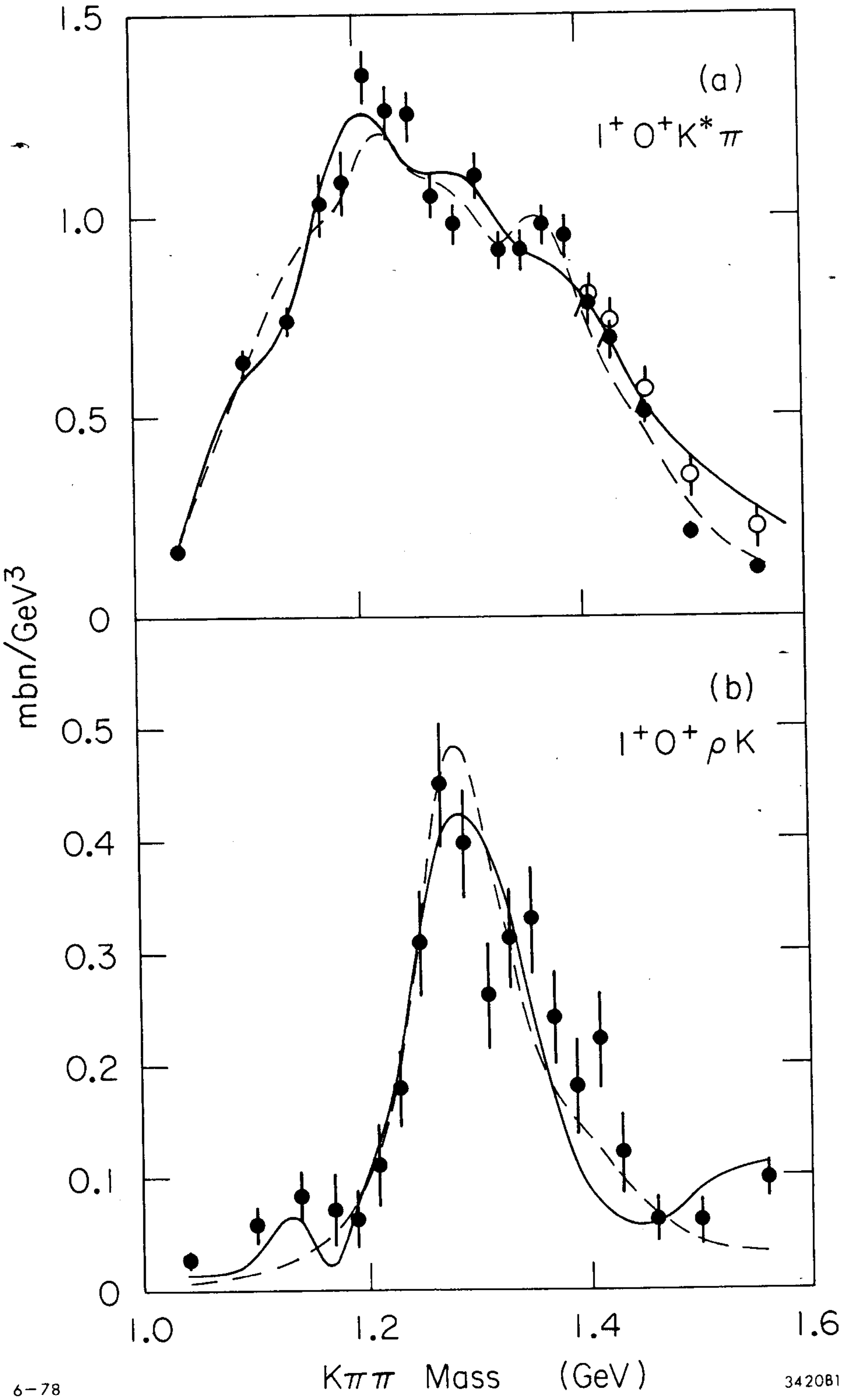
14. This condition is similar to the well known Peierls singularity [R. F. Peierls, Phys. Rev. Lett. 6, 641 (1961)], but leads to a different sheet structure.

TABLE I: Fit Parameters (GeV/c Units)			
N_1	4.770	f_1	-2.735
N_2	4.730	f_2	0.274
s_0	1.532	f_3	1.514
s_1	1.885	g_2	-1.128
s_2	1.304	g_3	1.685
g_0	8.048	g_4	-0.063

Figure Captions

1. Fits to the 1^+0 state of $K^+\pi^+\pi^-$ (data points from Ref. 7). The solid curves correspond to the new model discussed in the text, and the dashed to a conventional two-pole K-matrix. Results are shown for (a) the $K^*\pi$ intensity and (b) the ρK intensity.

2. (a) Relative phase for the fits shown in Fig. 1 (same notation). The dashed-dot curve results from artificially modifying $\Delta\phi$ "data" near 1.15 GeV and has slightly larger χ^2. (b) the 1^+1 $K^*\pi$ intensity predicted on the basis of the 1^+0 fits (same notation).



1.5
1.0
0.5
0
(a)
1⁺0⁺K*π
mbn/GeV3
(b)
1⁺0⁺ρK
0.5
0.4
0.3
0.2
0.1
0
1.0
1.2
1.4
1.6
Kππ Mass (GeV)
6-78
342081

Fig. 1

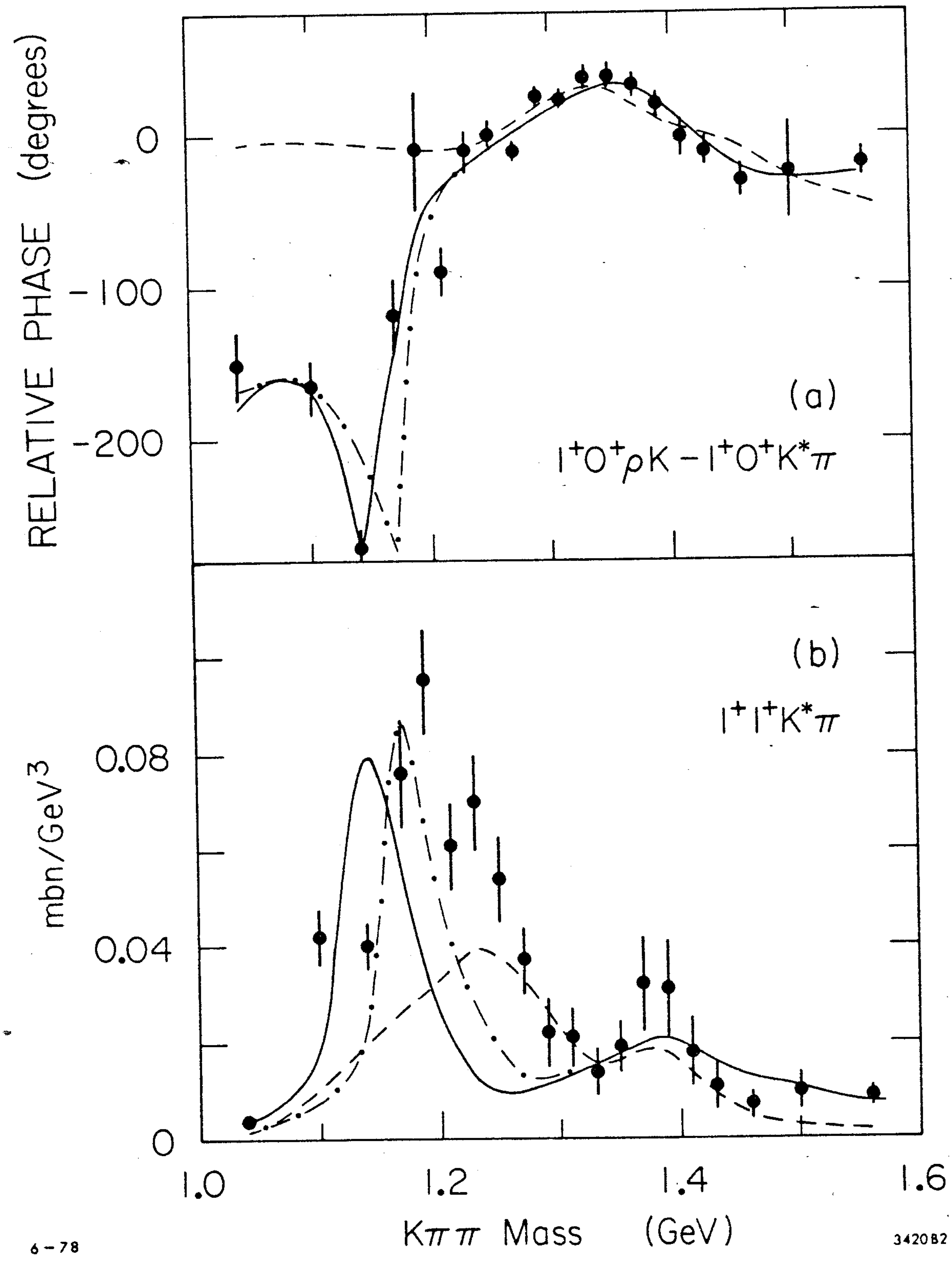

RELATIVE PHASE (degrees)
0
-100
-200
(a)
1⁺0⁺ρK − 1⁺0⁺K*π
mbn/GeV³
0.08
0.04
0
(b)
1⁺1⁺K*π
1.0
1.2
1.4
1.6
Kππ Mass (GeV)
6-78
3420B2

Fig. 2