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Production Dependence of the $A_2(1300)$ Mass Distribution*

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We demonstrate that much of the variation in mass shape and position of the $A_2(1300)$ meson from experiment to experiment is consistent with a model of two coupled or interfering wide- and narrow-width particles which may be close to forming a double-pole system. We find that the double-pole limit of this model leads to reasonably good fits for the mass spectra of the $\pi\rho$ and $K\bar{K}$ decay channels produced in $\pi^- p$ and $\bar{p}p$ collisions. Also, the model is consistent within experimental resolution with the available $\pi\rho$-decay-channel mass spectra found in the reaction $K^- n \rightarrow A_2^- \Lambda$. Predictions for other reactions involving A_2 production are made.

IN a recent Letter[1] the prediction was made that the $\pi\rho$ mass distribution expected from decay of $A_2(1300)$ mesons produced in $K^- n \rightarrow A_2^- \Lambda$ reactions should be a relatively narrow single peak. Since a BNL experiment[2] appears to confirm this prediction except for an apparent mass shift, it would seem worthwhile to examine these data and other recently available data[3] with respect to the model used in Ref. 1. We find that these data on the A_2 mass can be explained in consistent fashion and that enough parameters (though not too precisely fixed by data) are now determined so that predictions almost can be made.

It is quite possible that the A_2 mass region has a different explanation than that of two closely mixed (coupled) or, equivalently, interfering resonances. However, this seems to be one of the simpler models one can propose if one accepts the totaled results of CERN experiments[4] as correct. These data are well fitted by either interfering Breit-Wigner resonances[4] or by a dipole formula.[4–6] Either case can be described, e.g., by Eq. (4) of Ref. 6,[7] which assumes a production amplitude G_i and a decay amplitude F_i $(i=1, 2)$ with a general 2×2 propagator matrix for the two particles connecting G to F. Interfering particles of the same J^P mixed, for example, because of some symmetry-breaking interaction or common decay modes, can be reliably treated this way. The special dipole limit[6] of this equation has the advantage of *restricting* the number of free parameters, thus allowing sooner a meaningful confrontation with experiment. At the present time, most of the existing data appear to be reasonably explained with this limited set of parameters. When the data are improved, one can relax this dipole restriction and let the data fix the preferred pole configuration.

The approach is phenomenological and relatively simple. The A_2 is assumed to consist of two coupled $J^P=2^+$ mesons with mixing strength fixed by making the poles degenerate.[6,7] The relative coupling strengths of the two mesons to $\pi\rho$, $K\bar{K}$, and $p\bar{p}$ are then determined from experiment.[8] Therefore, we write the transition amplitude as[1,6]

$$T_r{}^n \propto (F_1{}^n, F_2{}^n)\begin{pmatrix} X & \frac{1}{4}\Gamma \\ \frac{1}{4}\Gamma & X+\frac{1}{2}i\Gamma \end{pmatrix}\begin{pmatrix} G_1{}^r \\ G_2{}^r \end{pmatrix} D^{-1}, \qquad (1)$$

where $D=(X+\frac{1}{4}i\Gamma)^2$ and $X=M-M_0$, for producing the two-particle A_2 system through some initial process denoted by $\boldsymbol{r}$, and for decay of this system into some final state n. The t (momentum transfer) dependence of the production and decay form factors is neglected; this is probably safe until better data are available, since we are concerned here only with the mass shape of the A_2 meson in its rest frame. In Eq. (1), meson 1, called m_1 here, represents the particle with large width Γ in the

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[1] J. V. Beaupre, T. P. Coleman, K. E. Lassila, and P. V. Ruuskanen, Phys. Rev. Letters **21**, 1849 (1968).

[2] D. J. Crennell, U. Karshon, K. W. Lai, J. S. O'Neall, and J. M. Scarr, Phys. Rev. Letters **22**, 1327 (1969). Although the single-peak result is as predicted by the double-pole model used in Ref. 1, these authors find that $J^P=1^-$ is preferred over 2^+, but 2^+ is not conclusively ruled out. The cleanest interpretation of the CERN missing-mass and spectrometer measurements of the A_2 mass (if one does not question the addition of results from their many different experiments) requires the same spin-parity for the two peaks, in which case 2^+ appears most likely.

[3] M. Aguilar-Benitz *et al.*, Phys. Letters **29B**, 62 (1969). We use only the recent, small-bin data in this analysis.

[4] G. Chikovani *et al.*, Phys. Letters **25B**, 44 (1967); H. Benz *et al.*, *ibid.* **28B**, 233 (1968). The comment in the text refers to the total tabulation of events. Unfortunately, each individual result is not sufficiently good to back this statement solidly and independently.

[5] J. S. Bell, CERN Report No. TH.784 (unpublished).

[6] K. E. Lassila and P. V. Ruuskanen, Phys. Rev. Letters **19**, 762 (1967).

[7] Alternatively, for more detail, see P. V. Ruuskanen and K. E. Lassila, in *Proceedings of the Athens Conference on Resonant Particles, 1967* (Ohio U. P., Athens, Ohio, to be published).

[8] The $\pi\eta$ mode is not listed as the data are inadequate.

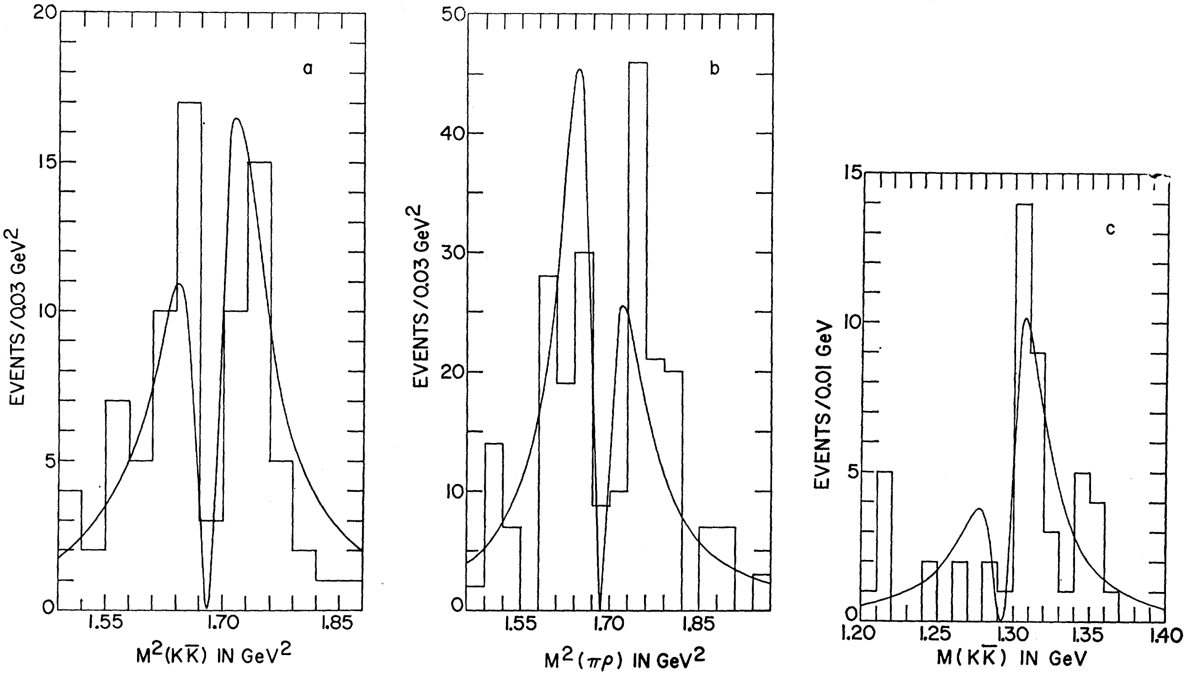

FIG. 1. Curves calculated with $\epsilon_K=0.25$ and $\epsilon_p=-0.15$ compared with A_2 mass distribution data from reactions (a) $p\bar{p}\rightarrow A_2^{\pm}\pi^{\mp}$ ($A_2\rightarrow K_1K^{\pm}$), (b) $p\bar{p}\rightarrow A_2^{\pm}\pi^{\mp}$ ($A_2\rightarrow\pi\rho$), and (c) $\pi^-p\rightarrow A_2n$ ($A_2\rightarrow K_1K_1$). The experimental resolution is not folded into the curves drawn; however, in each case it is small enough that little change results. The data shown are events above background as given in the experimental papers. Use of the total $K\bar{K}$ data[3] instead of the "cut" data[3] shown in (a) makes little difference.

same octet as the f^0, f^*, and $K^*(1420)$, which is strongly coupled to $\pi\rho$. For production from pion-nucleon initial states at high energy, because of dominance of the high-lying (compared with η) ρ trajectory, we approximate $G^{\pi p}$ as proportional to

$$\begin{pmatrix}1\\0\end{pmatrix}$$

and for study of the mode $n=\pi\rho$, $F^{\pi\rho}\propto(1,0)$. This is how the dipole form was obtained from Eq. (1) in Ref. 6. The zero element in each vector is allowed some variation ($\lesssim 0.06$) by the data of Ref. 4.

In Ref. 6 a simple model was proposed in which meson 2 (m_2) is exotic, coupling to m_1 via the (symmetry-breaking) mixing term in the mass matrix, and is also responsible for a large part of the $K\bar{K}$ decay from the A_2 region so that $F^{K\bar{K}}\approx(0,1)$. With this for $F^{K\bar{K}}$ in Eq. (1), the mass distribution $|T_{\pi N}{}^{(K\bar{K})}|^2$ of the $K\bar{K}$ mode in $\pi N\rightarrow A_2N$ was expected[6] to be a single narrow peak given by a Breit-Wigner squared mass distribution. The 1968 BNL results[9] indeed showed such a single peak, but shifted in mass; this shift could be explained[1] as a result of both m_1 and m_2 coupling to $K\bar{K}$, with $F^{K\bar{K}}\propto(1,\epsilon_K)$. The data[9] fit yielded 0.20 $(0.08)\leq\epsilon_K\leq 1.25$ at the 40% (10%) confidence level (CL).

With the ratios of couplings of the two-meson system to $K\bar{K}$ thus limited, one may ask whether the $p\bar{p}\rightarrow A_2\pi\rightarrow K\bar{K}\pi$ data[3] at 0.7 GeV/c which show two-peak structure are consistent with these limits on ϵ_K. Thus, these data can be used to determine $\epsilon_p=G_2{}^{p\bar{p}}/G_1{}^{p\bar{p}}$, which, in the simplest mechanism of nucleon exchange for $p\bar{p}\rightarrow A_2\pi$, could be interpreted as the ratio of the couplings of m_2 and m_1 to $p\bar{p}$. Therefore, $T_{p\bar{p}}{}^{K\bar{K}}$ will be given by Eq. (1) with $F^{K\bar{K}}\propto(1,\epsilon_K)$,

$$G^{p\bar{p}}\propto\begin{pmatrix}1\\ \epsilon_p\end{pmatrix},$$

and the $K\bar{K}$ mass distribution by $|T_{p\bar{p}}{}^{K\bar{K}}|^2$. Good fits are found for $\epsilon_K<0.5$ (consistent with the smaller ϵ_K values found earlier[1]), and with $-0.5<\epsilon_p<0.2$. Two peaks in the $K\bar{K}$ mass distribution thus are not inconsistent with one peak in the earlier experiment since the production dependence gives a satisfactory explanation.

We next ask whether these limits on ϵ_p allow a description of the recent $\bar{p}p\rightarrow A_2\pi\rightarrow(\pi\rho)\pi$ data[10] at 1.2 GeV/c. The mass distribution for this process is determined (within the rather wide limits on ϵ_p) by the $p\bar{p}\rightarrow(K\bar{K})\pi$ experiment and by $F^{\pi\rho}\propto(1,0)$. Fairly

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[9] D. J. Crennell *et al.*, Phys. Rev. Letters **20**, 1318 (1968). Compilations of $K\bar{K}$ data tend to support the narrow single peak found by these authors: K. W. Lai, New York Meeting of the American Physical Society, 1969 (unpublished); and, also, B. French, in *Proceedings of the Fourteenth International Conference on High-Energy Physics, Vienna, 1968* (CERN, Geneva, 1968), p. 104.

[10] R. A. Donald *et al.*, Nucl. Phys. **B12**, 325 (1969). The authors would like to acknowledge a useful conversation with Professor Foster.

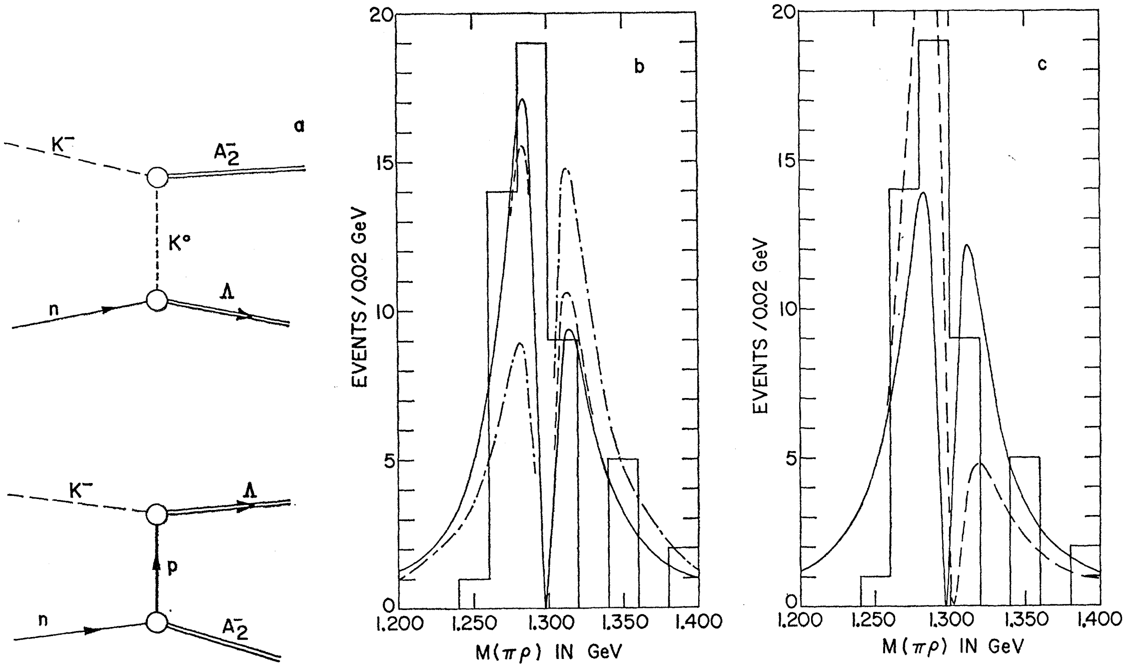

FIG. 2. Graphs related to the analysis of the A_2 mass distribution in $K^-n \to A_2^-\Lambda$ ($A_2 \to \pi\rho$). (a) The K-exchange graph contributes to A_2's going forward and the proton-exchange diagram to A_2's going backward with respect to the incident K direction. (b) Fits with incoherent mixtures ($\cos\varphi = 0$) of the two amplitudes in Fig. 2(a). The ratios (β) of the K-exchange and p-exchange amplitudes are $\beta = 0$ (solid line), $\beta = 0.4$ (dashed line), and $\beta = 1.0$ (dot-dash line). (c) Examples of fits with a coherent sum of the diagrams in Fig. 2(a) for $\beta = 0.4$ and $\cos\varphi = +1$ (solid line) and $\cos\varphi = -1$ (dashed line). The dashed line reaches a peak value of 24 events. A resolution function ($\Delta M = \pm 15$ MeV) is not folded in so that the structure will be visible.

satisfactory fits to $p\bar{p} \to (\pi\rho)\pi$ are found with ϵ_p in the range $-0.2 < \epsilon_p < 0.1$, which is in the allowed range found above.

Since the three experiments discussed above seem compatible when treated separately in this overlapping resonance model, all three [$p\bar{p} \to (K\bar{K})\pi$, $p\bar{p} \to (\pi\rho)\pi$, $\pi p \to (K\bar{K})p$] were taken simultaneously and the best over-all values of ϵ_p and ϵ_K determined. Within 40% CL's, ϵ_K and ϵ_p are restricted to $0.14 < \epsilon_K < 0.40$ and $-0.23 < \epsilon_p < -0.07$. The best χ^2 value (55% probability) occurs near $\epsilon_K = 0.25$ and $\epsilon_p = -0.15$ for which data comparisons are given in Figs. 1(a)–1(c); the values of M_0 and Γ are fixed from the CERN dipole fit[4] to their data. Better fits to the data of Fig. 1(b) than that shown do exist within the allowed parameter range; however, the curves are at the over-all minimum χ^2 value.

An important check on the above analysis could be provided by the $K^-n \to A_2^-\Lambda \to (\pi\rho)\Lambda$ of Ref. 2 if statistical accuracy were improved. The existing angular distribution [Fig. 3(j) of Ref. 2] is *not*, in our opinion, inconsistent with forward and backward A_2 production as expected from K^0-meson and proton exchange [depicted in Fig. 2(a)], respectively. In such a particle-exchange picture, according to the model developed above, the mass distribution in the forward peak is determined by our restrictions on ϵ_K and should show a dominant peak and a smaller secondary one. The backward peak might well have a mass distribution like that of Fig. 1(b) if this and the annihilation proceed through similar mechanisms, e.g., baryon exchange. The t distribution for the A_2 mesons produced in the annihilation reactions would thus be of considerable interest as ϵ_p would give the ratio of the $m_1N\bar{N}$ and $m_2N\bar{N}$ coupling constants.

The forward and backward mass distribution for $K^-n \to A_2\Lambda$ from Ref. 2 are separately not statistically good enough for such a cross check on our analysis. Therefore, we have compared the available data[2] with the absolute value squared of the incoherent and coherent sums of the amplitudes for the exchange processes of Fig. 2(a). For the latter case, since we are interested in the A_2 mass only, we write

$$|T_{K^-n}{}^{\pi\rho}|^2 \propto \left|\beta(1,0)\mathbf{N}\begin{pmatrix}1\\ \epsilon_K\end{pmatrix}D^{-1} + e^{i\varphi}(1,0)\mathbf{N}\begin{pmatrix}1\\ \epsilon_p\end{pmatrix}D^{-1}\right|^2, \qquad (2)$$

where $\mathbf{N}$ is the 2×2 matrix appearing in Eq. (1), φ is a possible allowed relative phase, and β the relative magnitude of the two contributions determined by the ratio of the $m_1K\bar{K}$ and $m_1p\bar{p}$ couplings.[11] The comparison of the incoherent sum ($\cos\varphi=0$) with data is shown in Fig. 2(b) for various values of β ranging from zero to 1. The resolution is not folded into the curves shown so that the "theoretical" structure is visible. When smeared out with *any* resolution function characterized by $\Delta M=\pm15$ MeV, the structure disappears. For the values of β used in Fig. 2(b), the χ^2 probability is greater than 40%, and, within a 10% limit, $\beta<1.7$. To illustrate that φ also has a wide range of variation, representative fits with $\cos\varphi\neq0$ are given in Fig. 2(c) ($\beta=0.4$, $\cos\varphi=\pm1$). Both are statistically very good, with the indicated structure washing out in averaging over the large bin size and in including resolution. Better resolution data on this reaction would thus be quite useful.

Therefore, we feel it is likely that the experimental results on the A_2, which appear contradictory on the surface, have a relatively simple interpretation in terms of two mixed mesons. This means that normal variation of single-particle production and decay amplitudes from reaction to reaction has a dramatic effect on the mass distribution. The double-pole condition is not essential to this effect; however, this restriction considerably reduces the number of parameters and the existing data[12] are consistent with it. Furthermore, the fact that the same ϵ_K and ϵ_p values could be used for different experiments with different charge states of the particle-antiparticle coupled to the A_2 system suggests that the two mesons m_1 and m_2 could have the *same* isospin. With unequal isospin (V breaks isospin symmetry[6]), an unknown Clebsch-Gordan coefficient makes correlation of differently charged decays difficult.

By way of predictions, we would expect the $\pi\rho$ and missing-mass spectrum of the A_2 produced through ρ exchange in pion-nucleon (π-N) collisions, e.g., $\pi N\rightarrow A_2\Delta$ or $\pi N\rightarrow A_2N$, to show two peaks and the corresponding $K\bar{K}$ decay to be mainly single peaked. However, the curve in Fig. 1(c) becomes markedly double peaked as ϵ_K gets smaller without very seriously affecting the fits in Figs. 1(a) and 1(b). As noted earlier, at the 10% CL the data in Fig. 1(c) fix the lower limit of ϵ_K as 0.08. Thus, even though these data [Fig. 1(c)] indicate statistically a single peak, they actually do not rule out a twin-peak structure for the $K\bar{K}$ decay mode of A_2's produced in pion-nucleon collisions.

Furthermore, ascribing the annihilation processes[3,10] to baryon exchange, we expect that the curve or data in Fig. 1(b) could be a fairly characteristic result of "A_2" baryon-antibaryon coupling. Thus, reactions like backward A_2 production[13] in $p+d\rightarrow A_2+\mathrm{He}^3$, $p+d\rightarrow A_2+\mathrm{H}^3$, $K^-n\rightarrow A_2\Lambda$, etc., should have two-peak structure, or, if resolution is poor, show a relatively broad $\gtrsim$60-MeV-wide bump for both $\pi\rho$ and $K\bar{K}$ modes.

In closing, we note that there have been other recent attempts to interpret the "A_2" meson data with *two*- (or less) pole models. However, few of these papers include any specific data analyses and none studies the A_2 decay modes seen in proton-antiproton annihilations. Coulter and Shaw[14] argue that structure in an inelastic resonance can result from the inelasticity factor deviating from Breit-Wigner form. Fujii and Kato[15] demonstrate that such structure in the inelasticity (η) can exist in a two-pole model for $\pi\rho\rightarrow\pi\rho$ which is consistent with the CERN missing-mass data. The decay of the A_2 into $K\bar{K}$ and $\pi\eta$ determines (η) by taking flux away from the $\pi\rho$ scattering process. Also, Rosdolsky[16] shows that in processes involving several scattering channels, proper choice of eigenphase shifts can lead to differences in the cross sections in the different possible reactions (among different A_2 decay products). The problems associated with unitarity, which we have not treated exactly in the present work, are studied in detail by Rebbi and Slansky.[17]

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[11] One might expect that the incoherent sum would be the logical way to fit a backward and forward peak since the form of Eq. (2) implies an angle integration has been done. However, the interference indicated in Eq. (2) could be important since the angle integrals of $(u-\mu_n{}^2)^{-2}$ and of $(u-\mu_n{}^2)^{-1}(t-\mu_k{}^2)^{-1}$ are essentially equal. As this angle integration is assumed done, $\cos\varphi$ which occurs in the absolute value squared of Eq. (2) is not precisely related to the relative phase. But, as seen from the fits of Fig. 2, the data place no real restriction on β and φ, and the particular form used in Eq. (2) may be taken for convenience.

[12] Photoproduction of the A_2 system is not included here. The results of J. Ballam *et al.*, Phys. Letters **30B**, 421 (1969), indicate that the $\gamma\pi$ coupling to the two-meson system might be similar to that for $K\bar{K}$. However, a DESY photoproduction experiment which could provide a check finds no obvious A_2 signal. J. Erbe *et al.*, Phys. Letters **27B**, 54 (1968).

[13] Recently, R. C. Arnold and J. L. Uretsky, Phys. Rev. Letters **23**, 444 (1969), predicted that $pd\rightarrow A_2\mathrm{He}^3$ would show single-peaked A_2's. Preliminary results from a missing-mass experiment at the Penn-Princeton Accelerator on $pd\rightarrow A_2\mathrm{He}^3$ presented in a seminar by B. Maglić at BNL indicate that A_2 structure probably exists.

[14] P. W. Coulter and G. L. Shaw, Phys. Rev. Letters **21**, 634 (1968).

[15] Y. Fujii and M. Kato, Phys. Rev. **188**, 2319 (1969).

[16] H. Rosdolsky, Phys. Rev. **180**, 1403 (1969); see also T. J. Gajdicar and J. W. Moffat, *ibid.* **181**, 1875 (1969).

[17] C. Rebbi and R. Slansky, Phys. Rev. **185**, 1838 (1969).