It follows that the one-trajectory coupling equation, which is obtained from

$$A(s,l)=\frac{\beta(s)}{l-\alpha(s)} \quad \text{as} \quad s\to 0^+, \quad \alpha(0)>-\tfrac{1}{2} \qquad \text{(A8)}$$

and (3)

$$(1/2i)=s^{1/2}A(s,\alpha^*(s))^*,$$

which leads to

$$s^{-1/2}\beta(s)=\operatorname{Im}\alpha(s), \quad s\to 0^+, \quad \alpha(0)>-\tfrac{1}{2},$$

should be replaced by

$$A(s,l)=\frac{\beta(s)}{l-\alpha(s)}+(1/2i)[e^{2\pi i(l+\frac{1}{2})}-1], \quad s\to 0 \quad \alpha(0)<-\tfrac{1}{2}. \qquad \text{(A9)}$$

This implies that, except in the neighborhood of a pole, $S(l,s)$ is given by (A7). When the unitarity condition (3) is applied to (A9) we obtain

$$s^{1/2}\beta(s)\underset{s\to 0+}{\longrightarrow}\operatorname{Im}\alpha(s)e^{2\pi i[\alpha(0)+1/2]}, \quad \alpha(0)<-\tfrac{1}{2}. \qquad \text{(A10)}$$

This is the correct residue near threshold for $\alpha(0)<-\frac{1}{2}$. The "width" of the threshold region depends on the strength of the interaction. There is therefore no obvious rule as to how and at what s one should change from (A9) to (5) in the coupling equations. If the expansions (5b) or (5c) converge in the left-hand l plane, (A10) should obtain if all the trajectories are coupled in, but as the discussion of the accumulation point indicates, it is not likely that any finite set will lead to the correct threshold behavior when $\alpha_n(0)<-\frac{1}{2}$.

PHYSICAL REVIEW VOLUME 137, NUMBER 4B 22 FEBRUARY 1965

New Resonances and the Vector-Meson System*

D. FLAMM†
The Enrico Fermi Institute for Nuclear Studies, The University of Chicago, Chicago, Illinois
(Received 24 September 1964)

Under the assumption of exact SU_3 symmetry we investigate the force between two degenerate vector-meson octets due to the exchange of a vector, pseudoscalar, and scalar octet. It is found that many of the recently discovered particles may fit into this scheme as bound states. However, the model does not reproduce the well-known pseudoscalar and vector-meson octets which are its input, but suggests a second octet of each kind at higher mass. It also gives a 0^+ and 2^+ singlet and octet as well as a 1^+ and a 2^- octet.

I. INTRODUCTION

RECENTLY, several new resonances have been reported in the $\pi\rho$ (A),[1] $\pi\omega$ (B),[2] πK^*,[3] $\bar{K}K^*$,[4] and $\eta\pi\pi$ (X^0)[5] system. This indicates that resonances may cluster to form new particles. In this paper we investigate the force between two octets of vector mesons. Under the assumption of exact SU_3 symmetry we calculate the input for an N/D calculation of the vector-meson–vector-meson scattering amplitude. From the sign and the magnitude of the Born-amplitude in the various channels, we conclude what particles may emerge from the vector-meson system and where their masses may range. We do not try, however, to determine the masses and coupling constants by solving the equations as, for instance, in the models for the π-ω resonance,[6] since it involves some parameters. A determination of these parameters by a self-consistency condition as in the bootstrap calculations[7] seems impossible in our case since the attraction in the vector-meson channel is, as we shall see, weaker than the one for other particles like 1^+ and 2^+ which have not been observed at masses below or about the vector-meson mass. Vector meson scattering as a qualitative model for SU_3 symmetry has previously been studied by Cutkosky *et al.*[8] These authors do not, however, study the dynamical details.

* This work supported by the U. S. Atomic Energy Commission.
† Present address: Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts.
[1] G. Goldhaber, J. Brown, S. Goldhaber, J. Kadyk, B. Shen, and G. Trilling, Phys. Rev. Letters **12**, 336 (1964); S. U. Chung, O. Dahl, L. Hardy, R. Hess, G. Kalbfleish, *et al.*, *ibid.* **12**, 621 (1964); M. Aderholz *et al.*, Phys. Letters **10**, 226 (1964).
[2] M. Abolins, R. Lander, W. Melhop, N. Xuong, and P. Yeager, Phys. Rev. Letters **11**, 381 (1963); D. Duane Carmony *et al.*, *ibid.* **12**, 254 (1964).
[3] T. P. Wangler, A. R. Erwin, W. D. Walker Phys. Letters **9**, 71 (1964), R. Armenteros, D. N. Edwards, T. Jacobsen, L. Montanet, A. Shapira, *ibid.* **9**, 207 (1964).
[4] Proceedings of the 1964 Conference on High Energy at Dubna (to be published).
[5] G. R. Kalbfleisch, L. Alvarez, A. Barbaro-Galtieri, O. Dahl, P. Eberhard *et al.*, Phys. Rev. Letters **12**, 527 (1964); M. Goldberg, M. Gundzik, S. Lichtman, I. Leitner, M. Primer *et al.*, *ibid*, **12**, 546 (1964); M. Goldberg, M. Gundzik, I. Leitner, M. Primer, P. Connolly *et al.*, *ibid.* **13**, 249 (1964).
[6] R. F. Peierls, Phys. Rev. Letters **12**, 50 (1964); T. K. Kuo, *ibid.* **12**, 465 (1964); C. Goebel, Phys. Letters **9**, 67 (1964); E. Abers, Phys. Rev. Letters **12**, 55 (1964).
[7] F. Zachariasen and C. Zemach, Phys. Rev. **128**, 849 (1962); R. H. Capps, *ibid.* **134**, B460 (1964), see also references to previous papers. Chan Hong-Mo, P. C. De Celles, J. E. Paton, Nuovo Cimento **33**, 70 (1964), A. Pignotti Phys. Rev. **134**, B630 (1964), M. L. Mehta, *ibid.* **134**, B1377 (1964).
[8] R. E. Cutkosky, Phys. Rev. **131**, 1888 (1963); R. E. Cutkosky and P. Tarjanne, *ibid.* **132**, 1354 (1963).

TABLE I. Connection between the helicity states of two vector mesons and the states of definite parity.

J^P	L	Over-all factor	Coefficients of the helicity states 00	$++$	$--$	$+0$	$0+$	-0	$0-$	$+-$	$-+$
0^+	$^1S_0$	$1/\sqrt{3}$	-1	1	1						
	$^5D_0$	$1/\sqrt{6}$	2	1	1						
0^-	$^3P_0$	$-1/\sqrt{2}$			-1						
1^-	$^1P_1$	$1/\sqrt{3}$	-1	1	1						
	$^3P_1$	$-\frac{1}{2}$				1	-1	1	-1		
	$^5P_1$	$1/\sqrt{15}$	2	1	1	$\frac{3}{2}$	$\frac{3}{2}$	$\frac{3}{2}$	$\frac{3}{2}$		
	$^5F_1$	$1/\sqrt{10}$	2	1	1	-1	-1	-1	-1		
1^+	$^3S_1$	$1/\sqrt{6}$		1	-1	1	1	-1	-1		
	$^3D_1$	$-1/\sqrt{3}$		1	-1	$-\frac{1}{2}$	$-\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$		
	$^5D_1$	$\frac{1}{2}$				1	-1	-1	1		
2^+	$^5S_2$	$1/\sqrt{5}$	$2/\sqrt{6}$	$1/\sqrt{6}$	$1/\sqrt{6}$	$1/\sqrt{2}$	$1/\sqrt{2}$	$1/\sqrt{2}$	$1/\sqrt{2}$	1	1
	$^1D_2$	$1/\sqrt{3}$	-1	1	1						
	$^3D_2$	$-\frac{1}{2}$				1	-1	1	-1		
	$^5D_2$	$-1/\sqrt{7}$	$2/\sqrt{3}$	$1/\sqrt{3}$	$1/\sqrt{3}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$-\sqrt{2}$	$-\sqrt{2}$
	$^5G_2$	$1/(35)^{1/2}$	$2\sqrt{3}$	$\sqrt{3}$	$\sqrt{3}$	-2	-2	-2	-2	$1/\sqrt{2}$	$1/\sqrt{2}$
2^-	$^3P_2$	$\frac{1}{2}$				1	1	-1	-1		
	$^5P_2$	$-1/\sqrt{5}$				$\frac{1}{2}$	$-\frac{1}{2}$	$-\frac{1}{2}$	$\frac{1}{2}$	$\sqrt{2}$	$-\sqrt{2}$
	$^5F_2$	$1/\sqrt{5}$				1	-1	-1	1	$-1/\sqrt{2}$	$1/\sqrt{2}$

In Sec. II we proceed to derive the helicity amplitudes, from which we calculate the partial-wave amplitudes in Sec. III. In Sec. IV we investigate the sign and magnitude of the forces and in Sec. V we survey the resulting particles and their lightest decay products.

II. EFFECTIVE INTERACTION AND THE HELICITY AMPLITUDES

As is customary, we assume dominance of the nearest singularities and confine ourselves to the one-particle exchange graphs shown in Figs. 1 and 2. The scattered particles are members of a degenerate vector-meson octet which represents an idealization of the well known ρ, K^*, $\bar{K}^*$, and ω-φ octet. The exchanged particle is a member of the same vector-meson octet, of the well known pseudoscalar octet, or of a scalar octet which emerges from the model. The vector-meson force appears to be the strongest and most important one. From an inspection of Table I we find that there are four possibilities to couple three vector mesons. The corresponding matrix elements in momentum space are (all three particles outgoing)

$$(k_2-k_3)_\mu a_1^\mu a_2^\nu a_{3\nu}\,,\quad a_1^\nu(k_3-k_1)_\mu a_2^\mu a_{3\nu}\,,\quad a_1^\nu a_{2\nu}(k_1-k_2)_\mu a_3^\mu\,,$$

and

$$(k_2-k_3)_\lambda a_1^\lambda (k_3-k_1)_\mu a_2^\mu (k_1-k_2)_\nu a_3^\nu\,.$$

As a consequence of the symmetry between the particles in our case we remain with only two coupling constants.

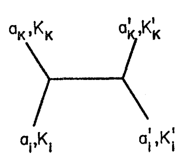

FIG. 1. One-particle exchange graph for the scattering of two vector mesons.

The effective interaction density can be written

$$\begin{aligned}\mathcal{H}=f_{ikl}\{f[(\partial_\mu A_{i\nu}-\partial_\nu A_{i\mu})A_{k\mu}A_{l\nu}\\ -A_{i\mu}(\partial_\mu A_{k\nu}-\partial_\nu A_{k\mu})A_{l\nu}\\ -A_{i\nu}A_{k\mu}(\partial_\mu A_{l\nu}-\partial_\nu A_{l\mu})]\\ +g(\partial_\lambda A_{i\nu}\overleftrightarrow{\partial}_\mu A_{k\lambda}\overleftrightarrow{\partial}_\nu A_{l\mu}-A_{i\nu}\overleftrightarrow{\partial}_\mu A_{k\lambda}\overleftrightarrow{\partial}_\nu\partial_\lambda A_{l\mu})\}\,,\end{aligned} \quad (1)$$

$$A\overleftrightarrow{\partial}_\mu B=\partial_\mu A\cdot B-A\cdot\partial_\mu B\,.$$

If A_i were instead the electromagnetic field,[9] the first term would correspond to the magnetic moment and the second and third together to the electric charge interaction. The fourth term then clearly corresponds to an electric quadrupole moment. We shall, however, neglect this last term since it gives rise to a very singular force which could lead rather to a kind of hard core than to a binding.

The coupling of a pseudoscalar to two vector mesons is unique

$$\mathcal{H}=f_p d_{ikl}\epsilon^{\mu\nu\rho\sigma}\partial_\mu A_{i\nu}\partial_\rho A_{k\sigma}\phi_l\,. \quad (2)$$

For scalar particles we have again two matrix elements

$$\mathcal{H}=d_{ikl}\{f_s A_{i\mu}A_{k\mu}\phi_l+g_s\partial_\mu A_{i\nu}\partial_\nu A_{k\mu}\phi_l\}\,, \quad (3a)$$

or

$$\mathcal{H}=d_{ikl}f_s'(\partial_\nu A_{i\mu}\partial_\nu A_{k\mu}-\partial_\mu A_{i\nu}\partial_\nu A_{k\mu})\phi_l \quad (3b)$$

in case the current coupled to the vector meson is conserved. With these effective interaction densities we

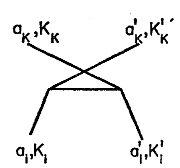

FIG. 2. Crossed graph to Fig. 1.

[9] T. D. Lee and C. N. Yang, Phys. Rev. **128**, 885 (1962).

calculate the scattering amplitude corresponding to Fig. 1.

For vector meson-exchange we get the following helicity amplitudes ($x=\cos\theta$, θ being the scattering angle in the center-of-mass system)

$$\begin{aligned}
t_{0000}&=4(1-x^2)(2R+1+x)+(R-x)^2C\,,\\
t_{++++}&=(1-x^2)(3-x)+\tfrac{1}{4}(1+x)^2C\,,\\
t_{++--}&=(1-x^2)(1-x)+\tfrac{1}{4}(1-x)^2C\,,\\
t_{++00}&=(1-x^2)(R+4+x)+(1-x)^3+\tfrac{1}{2}(1-x^2)C\,,\\
t_{+0+0}&=2(1-x^2)(1-x)-\tfrac{1}{2}(R-x)(1+x)C\,,\\
t_{+0-0}&=-2(1-x^2)(1-x)-\tfrac{1}{2}(R-x)(1-x)C\,,\\
t_{+00+}&=-(1-x^2)(R+x)-(1-x)^3-\tfrac{1}{2}(1-x^2)C\,,\\
t_{+00-}&=(1-x^2)(R+x)-(1-x)^2(1+x)+\tfrac{1}{2}(1-x^2)C\,,\\
t_{+++-}&=-(1-x^2)(1-x)+\tfrac{1}{4}(1-x^2)C\,,\\
t_{00+-}&=-(1-x^2)(R-4+x)+(1-x)^2(1+x)-\tfrac{1}{2}(1-x^2)C\,,\\
t_{+-+-}&=-(1-x^2)(1+x)+\tfrac{1}{4}(1+x)^2C\,,\\
t_{+--+}&=(1-x^2)(1-x)+\tfrac{1}{4}(1-x)^2C\,,
\end{aligned}\tag{4}$$

where $C=2/R+1+x$, $R=k^2/(k^2+m^2)$ and the complete amplitude is up to the factors of SU_3

$$T=A\cdot t\cdot D\,,\tag{5}$$

with

$$D=(x-1-m^2/2k^2)^{-1}\,,\quad A=\frac{f^2}{4\pi}\frac{1}{8\pi}k(k^2+m^2)^{-1/2}.$$

m is the mean vector-meson mass.

The contribution of the crossed graph in Fig. 2 for the amplitudes which are symmetric in the final helicities is simply obtained from (4) and (5) by the substitution $x\to -x$. For the other crossed amplitudes the relations

$$\begin{aligned}
T_{+0+0}{}^c&=T_{+00+}(-x)\,,\\
T_{+0-0}{}^c&=T_{+00-}(-x)\,,\\
T_{+00+}{}^c&=T_{+0+0}(-x)\,,\\
T_{+00-}{}^c&=T_{+0-0}(-x)\,,\\
T_{+-+-}{}^c&=T_{+--+}(-x)\,,\\
T_{+--+}{}^c&=T_{+-+-}(-x)\,,
\end{aligned}\tag{6}$$

hold.

For pseudoscalar exchange we have

$$\begin{aligned}
t_{0000}&=t_{++++}=t_{+++-}=t_{+0+0}=t_{+0-0}=0\,,\\
t_{++--}&=-t_{+--+}=(k^2+m^2)(1-x)^2\,,\\
t_{++00}&=t_{+00+}=t_{+00-}=t_{+-00}\\
&=[m^2/2(k^2+m^2)](1-x^2)\,,
\end{aligned}\tag{7}$$

where the complete amplitude is, up to SU_3 factors,

$$T=A'\cdot t\cdot D'\,,\tag{8}$$

with

$$D'=(x-1-m_P{}^2/2k^2)^{-1}\,,\quad A'=\frac{f_P{}^2}{4\pi}\frac{1}{8\pi}k(k^2+m^2)^{-1/2}.$$

m_P is the mean pseudoscalar meson mass. The contribution of the crossed graph Fig. 2 is obtained in exactly the same way as above. Similar expressions are found for exchange of a scalar meson.

III. PARTIAL WAVE AMPLITUDES

To find the partial wave amplitudes we have first to project out of (5) and (8) amplitudes with definite total angular momentum using the elements of the rotation matrix $d_{m',m}(x)$. The states of definite total angular momentum and parity P are linear combinations of the helicity states[10]

$$\langle JM;LS|=\left(\frac{2L+1}{2J+1}\right)^{1/2}\sum_{\lambda_1,\lambda_2}C(LSJ;0,\lambda)\times C(S_1S_2S;\lambda_1,-\lambda_2)\langle JM;\lambda_1\lambda_2|\,,$$

where λ_1, λ_2 are the helicities of the two particles and $\lambda=\lambda_1-\lambda_2$. The relation between the two kinds of states up to $J=2$ is given in Table I. Using Table I we establish the relation between the partial wave amplitudes and the amplitudes with definite J and initial and final helicities. The partial wave amplitudes thus obtained provide the input for an N/D calculation. Such a calculation would actually involve a multichannel problem since we see from Table I that there are in general several realizations for each particular J^P assignment. We shall not, however, solve the equations since their solution involves a number of parameters, but rather content ourselves with drawing conclusions from a listing of the input amplitudes. The result of the numerical calculation of these amplitudes, which has been performed on the IBM computer 7094 of The University of Chicago, is exhibited in Figs. 3, 4, and 5.

These figures do not yet include the numerical factors due to the crossing matrix. Figs. 3(a) and (b) show the largest partial-wave amplitudes for vector-meson exchange versus the center-of-mass momentum k in units of the vector-meson mass. The plotted amplitude includes a damping factor $10/(k^2+10)$ corresponding to a subtraction. Analogously, Figs. 4 and 5 show the largest partial wave amplitudes for pseudoscalar and scalar-exchange, the first one including a damping factor $100/(k^2+10)^2$ to make it decrease for large k.

IV. SIGN AND MAGNITUDE OF THE FORCE

To find in which channels the force is attractive and what its magnitude is, we have to combine Figs. 3–5 with the crossing matrix. The crossing matrix for octet-octet scattering has been evaluated by various authors.[11] For the exchange of an octet with antisymmetric coupling 8_A its elements are 1, $\frac{1}{2}$, $\frac{1}{2}$, 0, 0, $-\frac{1}{3}$ for the 1,

[10] M. Jacob and G. C. Wick; Ann. Phys. **7**, 404 (1959).

[11] J. J. de Swart, Nuovo Cimento **31**, 420 (1964); R. E. Cutkosky, Ann. Phys. (N. Y.) **23**, 415 (1963), D. E. Neville, Phys. Rev. **132**, 844 (1963).

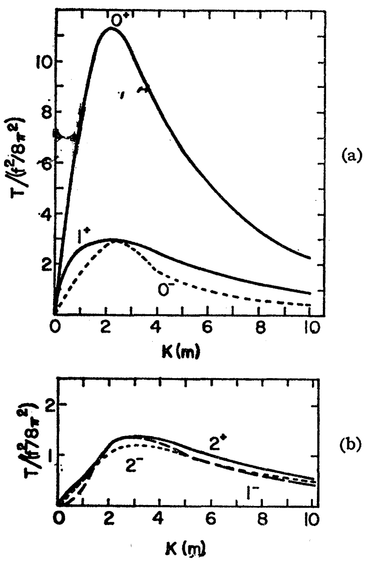

FIG. 3. (a) and (b) show the largest partial wave amplitudes for vector-meson exchange versus the center-of-mass momentum in units of the vector-meson mass m.

8_A, 8_S, 10, $\overline{10}$, and 27 channel, respectively. For the contribution of Fig. 2 everything remains unchanged except that the element in the 8_A channel changes sign. Similarly the crossing matrix elements for exchange of the symmetric octet 8_S are 1, $\frac{1}{2}$, $-\frac{3}{10}$, $-\frac{2}{5}$, $-\frac{2}{5}$ and $\frac{1}{5}$, respectively. Again the sign changes in the 8_A as well as 10 and $\overline{10}$ channels for the contribution of Fig. 2.

Putting together the numerical factors from the crossing matrix with the plots of the partial wave amplitudes we see that the strongest force by far appears for the scalar singlet $1(0^+)$.[12] Since the positive sign means attraction there may well be a $1(0^+)$ bound state of the two vector-meson octets. Next follow with decreasing binding strength $8_S(0^+)$, $1(0^-)$, $8_A(1^+)$, $8_S(0^-)$, $1(2^+)$, $8_A(1^-)$, $8_S(2^+)$, and $8_A(2^-)$. While the spacing up to $8_A(1^+)$ involves approximately a factor 2 in each step, $8_A(1^+)$, $8_S(0^-)$, and $1(2^+)$ lie close together. Then follows another step by a factor 2 to where $8_A(1^-)$, $8_S(2^-)$ lie together. For 1^-, 1^+ and 2^- there is no singlet. For the 10 and $\overline{10}$ representation the crossing matrix vanishes and for the 27-plet the forces are repulsive.

The pseudoscalar exchange gives attraction for $1(0^+)$ and $8_S(0^+)$, repulsion for $8_S(0^-)$ and small attraction for $8_A(2^-)$. The force from scalar exchange is numerically much smaller. Its largest terms give attraction for

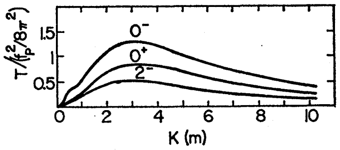

FIG. 4. Largest partial wave amplitudes for pseudoscalar exchange versus c.m. momentum. The amplitudes which we have omitted are much smaller.

[12] We shall denote the states by writing first the representation in SU_3 and then in brackets the spin-parity assignment (J^P).

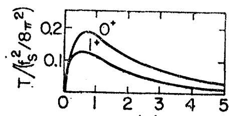

FIG. 5. Largest partial wave amplitudes for scalar meson exchange versus c.m. momentum. The above curve accounts only for the first term in 3(a). A strongly momentum-dependent form factor as in 3(b) might enhance the amplitude.

$1(0^+)$ and $8_A(1^-)$ repulsion for $8_S(0^+)$. The force due to singlet-exchange (forbidden in the vector case) is depressed by the small value $\frac{1}{8}$ of the crossing matrix.

V. THE PARTICLES AND THEIR LIGHTEST DECAY PRODUCTS

How the individual members $\psi_R(Y,I)$ of the vector-meson–vector-meson system are built from the two octets is found from the isoscalar factors of SU_3.[13] One finds for the singlet

$$\psi_1(0,0)=\tfrac{1}{2}[(K^*\bar{K}^*)_0-(\bar{K}^*K^*)_0]+\frac{\sqrt{6}}{4}(\rho\rho)_0-\frac{1}{2\sqrt{2}}(\varphi\varphi);$$

for the symmetric octet

$$\psi_{8S}(0,0)=\frac{1}{\sqrt{10}}[(K^*\bar{K}^*)_0-(\bar{K}^*K^*)_0]-(\tfrac{3}{5})^{1/2}(\rho\rho)_0-\frac{1}{\sqrt{5}}(\varphi\varphi),$$

$$\psi_{8S}(1,\tfrac{1}{2})=3(\tfrac{2}{5})^{1/2}[(K^*\rho)_{1/2}-(\rho K^*)_{1/2}]-\frac{1}{2\sqrt{5}}[(K^*\varphi)+(\varphi K^*)],$$

$$\psi_{8S}(-1,\tfrac{1}{2})=-3(\tfrac{2}{5})^{1/2}[(\bar{K}^*\rho)_{1/2}-(\rho\bar{K}^*)_{1/2}]-\frac{1}{2\sqrt{5}}[(\bar{K}^*\varphi)+(\varphi\bar{K}^*)],$$

$$\psi_{8S}(0,1)=-(\tfrac{3}{10})^{1/2}[(K^*\bar{K}^*)_1+(\bar{K}^*K^*)_1]+\frac{1}{\sqrt{5}}[(\rho\varphi)+(\varphi\rho)];$$

and for the antisymmetric octet

$$\psi_{8A}(0,0)=\frac{1}{\sqrt{2}}[(K^*\bar{K}^*)_0+(\bar{K}^*K^*)_0],$$

$$\psi_{8A}(1,\tfrac{1}{2})=\tfrac{1}{2}[(K^*\rho)_{1/2}+(\rho K^*)_{1/2}+(K^*\varphi)-(\varphi K^*)],$$

$$\psi_{8A}(-1,\tfrac{1}{2})=\tfrac{1}{2}[(\bar{K}^*\rho)_{1/2}+(\rho\bar{K}^*)_{1/2}-(\bar{K}^*\varphi)+(\varphi\bar{K}^*)],$$

$$\psi_{8A}(0,0)=\frac{1}{\sqrt{6}}[(K^*\bar{K}^*)_1-(\bar{K}^*K^*)_1]+(\tfrac{2}{3})^{1/2}(\rho\rho)_1.$$

[13] J. J. de Swart, Rev. Mod. Phys. **35**, 916 (1963); S. J. P. McNamee and F. Chilton, Rev. Mod. Phys. **36**, 1005 (1964).

TABLE II. Possible bound states of two vector mesons. Column 7 shows the maximum of the partial wave amplitude as calculated from the graphs in Fig. 1 and 2 with exchange of a vector-meson octet. Decay modes allowed by G parity but forbidden by A parity are in brackets.

Rep. of SU^3	J^P	Y	I	G	Amplitude maximum	Lightest decay products	Possible candidate (Ref. 17)
1	0^+	0	0	+	11.32	2π	$\sigma(400)$ (Ref. 14)
8_S	0^+	0	0	+	5.66	2π, 4π, $K\bar{K}$	
		1	$\frac{1}{2}$		5.66	$K\pi$	$\kappa(725)$ (Ref. 17)
		0	1	−	5.66	(3π), $K\bar{K}$	
1	0^-	0	0	+	2.78	4π, $(K\pi\bar{K})$	$X^0(959)$ (Ref. 5)
8_A	1^+	0	C	−	1.45	(3π), $(K\pi\bar{K})$	$H(975)$ (Ref. 18)
		1	$\frac{1}{2}$		1.45	$(K\pi\pi)$, $K3\pi$	
		0	1	+	1.45	4π, $(K\pi\bar{K})$	$B(1220)$ (Ref. 2)
8_S	0^-	0	0	+	1.39	4π, $(K\pi\bar{K})$	
		1	$\frac{1}{2}$		1.39	$(K\pi\pi)$, $K3\pi$	$K\pi^*$(1175 or 1230) (Ref. 3)
		0	1	−	1.39	(3π), (5π), $(K\pi\bar{K})$	
1	2^+	0	0	+	1.39	2π, 4π, $K\bar{K}$	$f^0(1250)$ (Ref. 19)
8_A	1^-	0	0	−	0.71	(3π), $K\bar{K}$	$E(1415)$ (Ref. 4)
		1	$\frac{1}{2}$		0.71	$K\pi$	
		0	1	+	0.71	2π, 4π, $K\bar{K}$	
8_S	2^+	0	0	+	0.70	2π, 4π, $K\bar{K}$	
		1	$\frac{1}{2}$		0.70	$K\pi$	
		0	1	−	0.70	(3π), (5π), $K\bar{K}$	$A_2(1310)$ (Refs. 1 and 4)
8_A	2^-	0	0	−	0.60	(3π), $(K\pi\bar{K})$, $K\pi\pi\bar{K}$	
		1	$\frac{1}{2}$		0.60	$(K\pi\pi)$, $K3\pi$	
		0	1	+	0.60	4π, $(K\pi\bar{K})$, $K\pi\pi\bar{K}$	

The threshold for vector-meson scattering is $2m$, which lies in the range 1500 to 1800 MeV. The $1(0^+)$, $8_S(0^+)$, $1(0^-)$, and $8_A(1^+)$ with strong binding force might, however, lie much lower. The $1(0^+)$ might, for instance, coincide with the σ meson,[14] the $K\pi(725)(\kappa)$ might be a member of the $8_S(0^+)$, and $X^0(959)$[5] might be the $1(0^-)$. $8_A(1^+)$, $8_S(0^-)$, and $1(2^+)$ might all lie around 1200 MeV, $B(1220)$[2] being a member of $8_A(1^+)$, πK^*(1175 or 1230)[3] a member of $8_S(0^-)$, and $f^0(1250)$ the $1(2^+)$. $8_A(1^-)$, $8_S(2^+)$, and $8_A(2^-)$ have larger masses and may possibly coincide with resonances between 1400 and 1600 MeV.

The decay of 0^-, 1^+, 2^-, etc. into two pseudoscalar mesons is forbidden by spin-parity. 3π decay for the singlets as well as for $\psi_{8S}(0,0)$ is forbidden by G parity.[15] Selection rules can also be derived from A parity,[16] which is especially useful for decays with photons. The A parity of all our bound states is even.

Owing to these selection rules the lightest decay product for many of the above particles, especially for 0^-, 1^+, and 2^- are 4π or more, $K\pi\pi$, $K\pi\bar{K}$, and so on, which may explain why many of these particles have not been discovered earlier. A survey of the lightest decay products and the quantum numbers of the particles which emerge from our model is given in Table II.[17–19] Concluding we want to remark that an explanation of the original vector and pseudoscalar octet which served as input lies beyond the scope of this model. Apart from this many of the recently discovered particles may be fitted into it.

ACKNOWLEDGMENTS

The author is indebted to Dr. P. G. O. Freund for discussions out of which this work arose. Further he wants to thank Professor Y. Nambu and Dr. C. Schumacher for many stimulating discussions.

[14] L. M. Brown and P. Singer, Phys. Rev. **133**, B812 (1964).

[15] T. D. Lee and C. N. Yang, Nuovo Cimento **3**, 749 (1956); M. Goldhaber, T. Lee, and C. Yang, Phys. Rev. **112**, 1796 (1958).

[16] J. B. Bronzan and F. E. Low, Phys. Rev. Letters **12**, 522 (1964).

[17] For references, see also M. Roos, Nucl. Phys. **52**, 1 (1964).

[18] J. Bartsch, L. Bondar, W. Brauneck, M. Deutschmann, K. Eickel *et al.*, Phys. Letters **11**, 167 (1964).

[19] W. Selove, V. Hagopian, H. Brody, A. Baker, and E. Leboy, Phys. Rev. Letters **9**, 272 (1962); Y. Y. Lee, B. Roe, D. Sinclair, and J. Vander Veede, *ibid.* **12**, 342 (1964); N. Gelfand, G. Lütjens, M. Nussbaum, J. Steinberger, H. Cohn, W. Bugg, and G. Condo, *ibid.* **12**, 567 (1964); G. Benson, L. Lovell, E. Marquit, B. Roe, D. Sinclair, J. Vander Velde, and K. Weaver, *ibid.* **12**, 600 (1964).