higher.[17]

[1]J. V. Hollweg, Phys. Rev. Lett. 32, 961 (1974).

[2]L. J. Lanzerotti, Geophys. Res. Lett. 1, 229 (1974).

[3]J. D. Scargle, Astrophys. J. 156, 401 (1969).

[4]M. A. Gintsburg, Astron. Zh. 40, 703 (1963) [Sov. Astron. AJ 7, 536 (1964)].

[5]V. L. Patel, Phys. Lett. 14, 105 (1965).

[6]A. S. Goldhaber and M. M. Nieto, Rev. Mod. Phys. 43, 277 (1971).

[7]E.g., see T. H. Stix, *The Theory of Plasma Waves* (McGraw-Hill, New York, 1962).

[8]A. Barnes and J. D. Scargle, Astrophys. J. 184, 251 (1973).

[9]A lower limit has been suggested by E. Williams and D. Park, Phys. Rev. Lett. 26, 1651 (1971), from consideration of the galactic magnetic field. However, there are a number of difficulties in their argument, and their limit cannot be considered well established (see Ref. 6).

[10]J. D. Scargle and E. A. Harlan, Astrophys. J. Lett. 159, L143 (1970); J. D. Scargle and F. Pacini, Nature (London), Phys. Sci 232, 144 (1971).

[11]G. R. Ricker, A. Scheepmaker, S. G. Ryckman, J. E. Ballantine, J. P. Doty, P. N. Downey, and W. H. G. Lewin, Astrophys. J. Lett. 197, L83 (1975).

[12]This possibility was mentioned to us by R. H. Miller (private communication).

[13]Such aliasing would not be a problem for the case of spacecraft observations, which usually are made by magnetometers designed to filter out frequencies that they cannot resolve (B. F. Smith, private communication).

[14]E.g., see A. Barnes and J. V. Hollweg, J. Geophys. Res. 79, 2302 (1974).

[15]See, e.g., N. A. Krall, in *Advances in Plasma Physics, 1*, edited by A. Simon and W. B. Thompson (Interscience, New York, 1968), pp. 153–199.

[16]A. Barnes, unpublished.

[17]After submission of this Letter we received a preprint of the paper "Limit on the Photon Mass Deduced from Pioneer 10 Observations of Jupiter's Magnetic Field" by L. Davis, Jr., A. S. Goldhaber, and M. M. Nieto. This paper contains what appears to be the best limit obtained from *in situ* observations, $\mu \lesssim 2 \times 10^{-11}$ cm^{-1}. Also, L. J. Lanzerotti recently brought some other references to our attention. One of these [J. C. Byrne and R. R. Burman, J. Phys. A: Gen. Phys. 6, L12 (1973)] gives limits comparable to the present paper. Their argument is based on estimates of the maximum current density in the interstellar medium and is very qualitative; we find this argument to be plausible but perhaps not totally convincing.

New Narrow Resonances and Separate Localization of Ordinary and Color SU(3)*

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I interpret $\psi(3095)$ and $\psi'(3684)$ as space and color excitations in a model in which a quark is a composite of a Fermi, spin-$\frac{1}{2}$, ordinary SU(3) object and a Bose, spin-0, color SU(3) object, and a meson is a four-body object. Color conservation and the absence of dipole transitions from the space mode make these two ψ's narrow for nonradiative and for radiative decays, respectively, to the usual hadrons.

Since the discovery of narrow photon- and hadron-excited resonances[1] above 3 GeV in electron-positron and hadron-hadron collisions, many attempts have been made to interpret these narrow resonances in terms of new hadronic degrees of freedom, such as charm, color, heaviness, etc.[2] These interpretations lead to the prediction of other resonances at comparable mass which have internal quantum numbers which cannot be realized in the Gell-Mann–Zweig quark model, as well as to the prediction of radiative decays to mesons. The failure, up to now, to detect such resonances, and the small observed widths for radiative decays have cast doubt on both the charm and color interpretations of the narrow resonances.

The main idea of the present article is to supplement the new internal degree of freedom, in our case color,[3] by new space or mechanical degrees of freedom in order to build a model of these resonances. I suggest that the usual SU(3) charges and the color SU(3) charges are localized in separate regions of space (for short, at different "points") so that a colored quark nonet is a two-body system[4] ($Q\overline{C}$), Q being a spin-$\frac{1}{2}$ SU(3)-triplet Fermi object carrying the usual SU(3) quantum numbers and C being a spin-0[5] SU(3)-triplet Bose object carrying the color

SU(3) quantum numbers. Then mesons are four-body ($Q\overline{C}\overline{Q}C$) systems and baryons are six-body ($Q\overline{C}Q\overline{C}Q\overline{C}$) systems.

For mesons, there are three modes of space excitation, aside from translation of the meson center of mass. Consider, as a model, the nonrelativistic harmonic-oscillator Hamiltonian

$$H=\frac{\vec{p}_1^{\,2}+\vec{p}_4^{\,2}}{2M}+\frac{\vec{p}_2^{\,2}+\vec{p}_3^{\,2}}{2N}+\tfrac{1}{2}K(\vec{x}_1-\vec{x}_4)^2+\tfrac{1}{2}L(\vec{x}_2-\vec{x}_3)^2+\tfrac{1}{2}A[(\vec{x}_1-\vec{x}_2)^2+(\vec{x}_3-\vec{x}_4)^2]+\tfrac{1}{2}B[(\vec{x}_1-\vec{x}_3)^2+(\vec{x}_2-\vec{x}_4)^2], \qquad (1)$$

where the $\vec{x}_i$ and $\vec{p}_i$ are the three-vector coordinates of Q, $\overline{C}$, C, and $\overline{Q}$, respectively, M and N are masses, and K, L, A, and B are force constants. The coordinates, momenta, and frequencies of the three normal modes can be found in a standard way. The condition for states of mesons to correspond to modes whose wave functions depend on the center-of-mass coordinates of ($Q\overline{C}$) and ($C\overline{Q}$), so that low-lying states appear to be formed from the colored quark nonet ($Q\overline{C}$) and its antiquark nonet ($C\overline{Q}$), is

$$LM-KN+B(M-N)=0\,. \qquad (2)$$

With (2), the coordinates of the three modes, which I call the r, ρ, and R modes, are

$$\vec{r}=[2(M+N)]^{-1/2}[(M\vec{x}_1+N\vec{x}_2)-(M\vec{x}_4+N\vec{x}_3)], \qquad (3)$$

$$\vec{\rho}=[MN/2(M+N)]^{1/2}(\vec{x}_1+\vec{x}_4-\vec{x}_2-\vec{x}_3), \qquad (4)$$

$$\vec{R}=[MN/2(M+N)]^{1/2}(\vec{x}_1-\vec{x}_2+\vec{x}_3-\vec{x}_4). \qquad (5)$$

The r mode, in which only the center-of-mass coordinates of ($Q\overline{C}$) and ($C\overline{Q}$) enter, corresponds to the space excitations of the usual quark model. The ρ and R modes are not present in the usual quark model; for the R mode, Q and $\overline{Q}$ and also $\overline{C}$ and C oscillate in opposite directions as in the r mode, while for the ρ mode, Q and $\overline{Q}$ and also $\overline{C}$ and C oscillate in the same direction as in the antisymmetric stretching mode of molecules.

An analogous discussion of normal modes can be given for the baryons as a ($Q\overline{C}Q\overline{C}Q\overline{C}$) system. Aside from the baryon center-of-mass motion, there are five normal modes, two of which can be chosen to depend only on the traceless coordinates of the centers of mass of the three ($Q\overline{C}$) clusters [i.e., $\vec{r}_1-\vec{r}_2$ and $\vec{r}_1+\vec{r}_2-2\vec{r}_3$, where the $\vec{r}_i$ are the centers of mass of the ($Q\overline{C}$) clusters]. Excitations of these two normal modes correspond to the usual symmetric quark model excitations. The force constants and masses can be chosen to obey inequalities which insure that the r mode for mesons and the (degenerate) $\vec{r}_1-\vec{r}_2$ and $\vec{r}_1+\vec{r}_2-2\vec{r}_3$ modes for baryons lie lowest, and that the ρ mode occurs next.

For energies low enough that only the r mode is excited, the parameter $R=\sigma_T(e^+e^-\to\text{had})/\sigma_T(e^+e^-\to\mu^+\mu^-)$ will have its usual value, for example, $R=2$ below the threshold for color excitations in the Han-Nambu model which we will consider here. For energies high enough that all modes are excited, R must be calculated using the charges of the separate spin-$\frac{1}{2}$ Q and spin-0 C objects. Let the charges of the Han-Nambu nonet be realized as the sum of contributions q, $q-1$, and $q-1$ from the u, d, and s Q's and $-q$, $1-q$, $1-q$ from the $\bar{u}$, $\bar{d}$, and $\bar{s}$ $\overline{C}$'s, respectively. Then, at high energies, the contribution to R from the Q and C objects is

$$R=15q^2/4-5q+\tfrac{5}{2}\,. \qquad (6)$$

I leave the value of q unfixed for the present; note that taking the Han-Nambu nonet apart allows arbitrarily high values of R to be reached.

The present data implies that $\psi(3095)$ and $\psi'(3684)$ both have $J^{PC}=1^{--}$ and $I^G=0^-$. To discuss assignments of these and other resonances in this model, I give in Table I quantum numbers for various modes in the harmonic oscillator

TABLE I. Quantum numbers of some low-lying states. $T_{ij}(r,\rho)=r_i\rho_j-\delta_{ij}\vec{r}\cdot\vec{\rho}/3$.

Mode	L	S	J^{PC}	I^G
1	0	0	0^{-+}	0^+
1	0	1	1^{--}	0^-
r	1	0	1^{+-}	0^-
r	1	1	$(0,1,2)^{++}$	0^+
ρ	1	0	1^{++}	0^+
ρ	1	1	$(0,1,2)^{+-}$	0^-
$T_{ij}(r,r)$	2	0	2^{-+}	0^+
$T_{ij}(r,r)$	2	1	$(1,2,3)^{--}$	0^-
$r\cdot\rho$	0	0	0^{--}	0^-
$r\cdot\rho$	0	1	1^{-+}	0^+
$r\times\rho$	1	0	1^{--}	0^-
$r\times\rho$	1	1	$(0,1,2)^{-+}$	0^+
$T_{ij}(r,\rho)$	2	0	2^{--}	0^-
$T_{ij}(r,\rho)$	2	1	$(1,2,3)^{-+}$	0^+

model for states with $I=Y=0$ in ordinary SU(3). States are labeled by the polynomial coefficient of the harmonic oscillator Gaussian factor. Radial recurrences have the same quantum numbers as their parent; R excitations have the same quantum numbers as the corresponding r excitation; a state with a single ρ excitation has the same quantum numbers as the corresponding r excitation, except for opposite C and G. States occur with J^{PC} values not available in the usual quark model. The first $J^{PC}=1^{--}$ ρ excitation is the $\vec{r}\times\vec{\rho}$ $S=0$ state; I assign $\psi(3095)$ to this state and $\psi(3684)$ to its r-mode radial recurrence.

In the usual quark models, such as the charm model, radial recurrences are likely to have small photon couplings and leptonic widths if the potential has a term singular at the origin, because the required node in the radial wave function will make the wave function at the origin small. Here, the wave function evaluated at $x_1=x_4$ or at $x_2=x_3$ is relevant, and a node in r does not suppress the wave function at these points, so photon couplings and leptonic widths for r-mode radial recurrences are not suppressed.

The narrowness of ψ and ψ' for hadronic decays is due to conservation of color SU(3) quantum numbers, as in most color models of the ψ's.[6] For the present, I do not choose specific color SU(3) assignments. The narrowness of ψ and ψ' for radiative decays to hadrons is a problem for most color models; in particular $M1$ radiative decays to pseudoscalar mesons such as η or η' with monoenergetic photons are likely, in most color models, to have widths much larger than observed experimentally. In my model $E1$ and $M1$ radiative decays to single hadrons are forbidden: The $E1$ decays lead to $J^{PC}=(0,1,2)^{++}$ states with $S=0$ and the $M1$ decays to $J^{PC}=(0,1,2)^{-+}$ states with $S=1$, neither of which exists among the meson states in the usual quark model. More generally, because the dipole moment of the ρ mode vanishes, the ρ mode is not radiated away in dipole transitions, so the ρ-mode excitations do not make radiative decays to ordinary hadrons; however, the ρ mode can make dipole transitions to other ρ modes. There is an analog of this situation in molecular vibrational spectra: Modes which are infrared active do not make Raman transitions, and vice versa. I have guessed the spectrum of states, see Table II, with one quantum of ρ excitation and various numbers of r-excitation quanta by assuming equal spacing in mass squared for the r-excitation states, and assuming that $\psi'(3684)$ is an r-mode recurrence of $\psi(3095)$.[7] The most striking prediction is that there will be a set of narrow neutral states with $J^{PC}=1^{++}$, $I^G=0^+$, and $J^{PC}=(0,1,2)^{+-}$, $I^G=0^-$ at about 2750 MeV. Such states are not present in other models. Many ρ-mode states lie below $\psi'(3684)$; allowed radiative decays to these states can account for its missing decay modes, adding up to an unaccounted-for partial width of about 65 keV,[2] without having a partial width greater than 10 keV to any one state.

The growth of R above ~3.5 GeV in e^+e^- annihilation is due to single production of ρ-mode states listed in Table II together with ordinary mesons. In hadronic collisions ψ's and their partners cannot be produced singly, because of conservation of color quantum numbers. The observation that ψ's are photoproduced with a smaller b parameter (in $d\sigma/dt=A\exp bt$) than other vector mesons implies that excitation of the ρ mode takes place within a smaller radius than that of

TABLE II. Quantum numbers and rough masses of ρ-mode excitations. The J^{PC} are listed together with the multiplicity in parentheses for an $I=Y=0$ state. A broken-SU(3) nonet of such states should occur.

No. of r quanta	No. of ρ quanta	Approximate mass (MeV)	$I^G=0^+$ states	$I^G=0^-$ states
3	1	3684	0^{-+}, (4)1^{-+}, (4)2^{-+}, (4)3^{-+}, (2)4^{-+}, 5^{-+}	0^{--}, 1^{--}, (2)2^{--} 3^{--}, 4^{--}
2	1	3402	(2)1^{++}, 2^{++}, 3^{++}	(2)0^{+-}, (3)1^{+-}, (4)2^{+-}, (2)3^{+-}, 4^{+-}
1	1	3095	0^{-+}, (3)1^{-+}, (2)2^{-+}, 3^{-+}	0^{--}, 1^{--}, 2^{--}
0	1	2754	1^{++}	0^{+-}, 1^{+-}, 2^{+-}

the r mode, which is consistent with the present model, as is the smaller total cross section for ψN scattering than for other vector-meson–nucleon scattering. Scaling in $s\,d\sigma/dx$ holds when only a fixed set of space modes are excited, but is violated when a new space mode enters. The failure of scaling below 4.8 GeV is due to excitation of the ρ (and, perhaps, R) mode. The R modes can also be excited; possibly the broad resonance or resonances at 4150 MeV are R-mode excitations. The mass spectra for the r, ρ, and R modes can be different. Pending discovery of new resonances with $I \neq 0$, we cannot discuss the ordinary SU(3) and color SU(3) splittings of the ρ and R modes, nor do we understand why color SU(3) and ρ-mode excitation occur together in $\psi(3095)$ and $\psi'(3684)$. As in other color models, I predict doubly charged and other exotic mesons, but not necessarily at comparable masses.

Tests of this model are (1) resonances with J^{PC} values not present in the usual quark model, (2) a band of narrow resonances with quantum numbers given in Table II near 2700 MeV, (3) similar bands near 3095, 3402, and 3684 MeV, and (4) radiative transitions to states in the bands just mentioned constituting the missing modes of $\psi'(3684)$ decay.

The main idea of this model is that the ψ resonances are excitation of both color SU(3) and a new mechanical or space mode. Conservation of color SU(3) makes the ψ's narrow for hadronic decay as in most other color models. The vanishing dipole moment of the ρ mode makes the ψ's narrow for radiative decays to the usual hadrons.

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Notes added.—After this article was submitted, groups working at DESY[8] and Stanford Linear Accelerator Center[9] reported evidence for four states χ which occur as radiative decay products of $\psi(3095)$ and $\psi'(3684)$. Assuming radiative decays to be $E1$ or $M1$, and, tentatively, that all four states have $I^G = 0^+$, the J^{PC} assignments $\chi(2800)$, $(0 \text{ or } 2)^{-+}$; $\chi(3410)$, 2^{++}; $\chi(3500)$, 1^{++}; $\chi(3530)$, $(0, 1, \text{ or } 2)^{-+}$ which occur in Table II are consistent with present data on the χ decay modes. The present data imply that our lowest C-even state 1^{++} must lie below 2800 MeV. Also note that our lowest-mass $I^G = 0^-$ and 1^+ states have $J^{PC} = 1^{++}$ and $(0, 1, 2)^{+-}$, respectively. I thank G. Feldman, G. Goldhaber, and J. C. Pati for stimulating discussions.

It is premature to compare (6) with the value of R between 5 and 7 GeV, because the R mode is not fully excited in that range, and because heavy leptons may contribute.

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[1]J. J. Aubert *et al.*, Phys. Rev. Lett. 33, 1404 (1974); J.-E. Augustin *et al.*, Phys. Rev. Lett. 33, 1406 (1974); G. S. Abrams *et al.*, Phys. Rev. Lett. 33, 1453 (1974).

[2]The literature can be traced from references in F. J. Gilman, SLAC Report No. SLAC-PUB-1600, 1975 (unpublished), and in *Theories and Experiments in High-Energy Physics,* edited by A. Perlmutter and S. M. Widmayer (Plenum, New York, 1975), p. 29; O. W. Greenberg, *ibid.*, p. 71.

[3]Our main idea of the new space excitation can also be implemented, with changes in details, using charm, various types of color, etc.

[4]Several authors have speculated that the usual quark nonet might be a two-body system: C. K. Chang, Phys. Rev. D 5, 950 (1972); J. Bartelski and W. Krolikowski, to be published, and earlier references cited there; K. Matumoto, Prog. Theor. Phys. 52, 1973 (1974); J. C. Pati and A. Salam, Phys. Rev. D 10, 275 (1974), footnote 7; H. J. Lipkin, in Proceedings of the International Conference on High Energy Physics, Palermo, Italy, June 1975 (unpublished); J. C. Pati, *ibid.*; J. D. Bjorken, unpublished; C. A. Nelson, unpublished; C. H. Woo, unpublished; O. W. Greenberg, unpublished.

[5]Other integral spin values are possible.

[6]Color models of the ψ's are reviewed in Greenberg, Ref. 2.

[7]We choose $\psi(3095)$ and $\psi'(3684)$ both to be in that $I = 0$ state which leads to a small K/π ratio in decays, in order to agree with SPEAR data. C. C. Morehouse, invited talk at meeting of The American Physical Society, Washington, D. C., 28 April–1 May 1975.

[8]W. Braunschweig *et al.*, Phys. Lett. B57, 407 (1975), and in Proceedings of the Conference on Lepton and Photon Interactions at High Energies, Stanford Linear Accelerator Center, Stanford, California, 21–27 August 1975 (to be published).

[9]G. J. Feldman *et al.*, SLAC Report No. SLAC-PUB-1621 (unpublished), and in Proceedings of the Conference on Lepton and Photon Interactions at High Energies, Stanford Linear Accelerator Center, Stanford, California, 21–27 August 1975 (to be published).