PHYSICAL REVIEW D VOLUME 21, NUMBER 1 1 JANUARY 1980

Standard solution to Roper-resonance puzzles

M. B. Gavela, A. Le Yaouanc, L. Oliver, O. Pène, J. C. Raynal, and S. Sood
*Laboratoire de Physique Théorique et Hautes Energies, Orsay, France**
(Received 12 April 1979)

In the frame of the quark-pair-creation model (QPCM) of strong decays, the puzzling coupling properties of the Roper resonance are shown to derive from the standard assignment as a radial excitation belonging to a 56 multiplet. The agreement is obtained through nonlocal effects specific to the QPCM.

Although usually assigned to a $(56,0^+)_2$ multiplet, the Roper resonance $P_{11}(1470)$ has always been a challenge to quark-model spectroscopists. First, there was the forward peak of the reactions $\pi p \to \pi N^*(1470)$, $pp \to pN^*(1470)$, which was found to be much steeper as well as much higher than expected.[1] A simple possible way out could be that the resonance is only a small part of the diffractive bump, the rest being ascribed to some Deck effect as in A_1 production. Stated otherwise, the identification of the true P_{11} resonance is difficult. Other cases really concern the resonant state identified in πN. The location of $P_{11}(1470)$ seems too low with respect to the other $N=2$ multiplets. Here, a simple explanation is given in Ref. 2 where they show that a spin-independent perturbation is expected to shift the $(56,0^+)_2$ much more than the other multiplets. Anyway, we do not lack explanations, since also the bag-model spin-spin force or breathing effect could explain that low location.[3,4]

Much more serious is the challenge of decay properties. The P_{11} which is essentially seen in photoproduction seems to vanish very rapidly in electroproduction.[5,6] New puzzles present themselves when one tries to understand the $P_{11}(1470)$ in the framework of the popular Feynman-Kislinger-Ravndal (FKR) model. The well-determined photodecay coupling sign comes out wrong.[7] Also, the widths $P_{11} \to N\pi$, $\Delta\pi$ come out very small, and the same for $\Delta(1690)$. Small widths for radial excitations is a general tendency of the FKR model. While the situation is unclear for mesons (see Ref. 8), it is definitely in conflict with the baryon data, as emphasized by Burkhardt and Pulido.[8]

In view of these difficulties, one might think of giving up the radial assignment of the P_{11}. For instance, one could think of a deuteron such as an exotic $\overline{10}$ π-N bound state.[9] Another way, which maintains the conventional three-quark structure is provided by the "even-wave" model of the Delhi group,[10] which amounts to a strong mixing of the two $P_{11}(940, 1470)$ states, according to $(56,0^+)_0 + (70,0^+)_0$. It is then possible to get the correct photodecay sign and the observed large widths.[11]

In this paper we want to emphasize that even the early assignment $(56,0^+)_2$ can perfectly explain most of the above puzzles if, instead of the FKR model, one uses the quark-pair-creation model completed by vector dominance for photon couplings. As this model has been discussed at length in several papers by us and other authors,[12] we simply state the basic outlines of the calculations. Any strong-decay amplitude $A \to B + C$ is described as a creation of a $q\bar{q}$ pair with the quantum numbers of the vacuum

$$M = \left\langle \psi_B \psi_C \left| \gamma \sum C_{11}(00, m\ -m)(\chi_1^m)_{ss'} Y_1^{-m}(\vec{k}_q - \vec{k}_{\bar{q}})(\Phi)_{ij} a^\dagger_{kq}(i,s) b^\dagger_{k\bar{q}}(j,s') \right| \psi_A \right\rangle, \tag{1}$$

where $a^\dagger$ ($b^\dagger$) are quark (antiquark) creation operators, χ_1 is the spin-triplet wave function, and Φ the SU(3) wave function of the pair. ψ's are the wave functions of the hadrons. For the spatial parts one may use the following simple harmonic-oscillator wave functions:

for mesons: $$\psi = N \exp(-\vec{p}_\rho^{\,2} R'^2/4)\,, \tag{2}$$

for nucleon: $$\psi = N \exp[-(\vec{p}_\rho^{\,2} + \vec{p}_\lambda^{\,2})R^2/2]\,, \tag{3}$$

for $(56,0^+)_2$: $$\psi = N(3/R^2 - \vec{p}_\rho^{\,2} - \vec{p}_\lambda^{\,2}) \times \exp[-(\vec{p}_\rho^{\,2} + \vec{p}_\lambda^{\,2})R^2/2]\,, \tag{4}$$

for $(70,0^+)_2$: $$\psi'' = N(\vec{p}_\rho^{\,2} - \vec{p}_\lambda^{\,2}) \exp[-(\vec{p}_\rho^{\,2} + \vec{p}_\lambda^{\,2})R^2/2]\,. \tag{5}$$

The photodecay amplitude in CKO units[13] for the process $A \to B + \gamma$ is simply given by $[(2\pi)^{3/2} e/2\gamma_\rho \sim 0.95]$

$$A = (2\pi)^{3/2} e/2\gamma_\rho [\tfrac{1}{3} M(A \to B + \omega) + M(A \to B + \rho)]_{\vec{q} = \vec{k}_\gamma} \tag{6}$$

and the strong widths are

TABLE I. The FKR results are given according to Burkhardt and Pulido and to Moorhouse and Parsons. QPCM is given with the choice $\gamma=3$. Experiment is given by Burkhardt and Pulido for $P_{11}(1470)$ and $P_{33}(1690)$, and by G. Höhler *et al.*, Karlsruhe University Report No. TKP 78/11 (unpublished) for D_{13}. $P_{11}(1780)\to N\pi$ [in parentheses are the values for $P_{11}(1470)$, $P_{33}(1690)\to N\pi$]. The well known $P_{11}(1470)\to N\gamma$ is quoted from R. Crawford, Nucl. Phys. B97, 125 (1975). Widths are in MeV and $A_{1/2}$ in CKO units $\times 10^3$.

	$D_{13}\to N\pi$	$P_{11}(1470)\to N\pi$	$P_{11}(1470)\to \Delta\pi$	$P_{11}(1470)\to N\gamma$	$P_{33}(1690)\to N\pi$	$P_{33}(1690)\to \Delta\pi$	$P_{33}(1690)\to P_{11}(1470)\pi$	$P_{11}(1780)\to N\pi$	$P_{11}(1780)\to N\gamma$
FKR	105	8	0.8	$A^p_{1/2}=+27$ $A^n_{1/2}=-18$	0.4	4	7		
QPCM	50	80	13	$A^p_{1/2}=-90$ $A^n_{1/2}=+60$	33	80	6	26	$A^p_{1/2}=-40$ $A^n_{1/2}=+15$
Experiment	60	60 (70)	20	$A^p_{1/2}=-70$ $A^n_{1/2}=+44$	30 (30)	80	70	14	?

$$\Gamma=8\pi^2\frac{E_B E_C}{m_A}k\sum{}'|M|^2. \tag{7}$$

As to the estimates of the parameters a reasonable value of γ is $\gamma\sim3$, as seen from the decays of orbitally excited baryons.[14] For instance, it gives $\Gamma(D_{13}\to N\pi)\sim 50$ MeV instead of an experimental 60 MeV. R^2 and R'^2 are not really free, being determined by the Regge slopes. We take as before $R^2=6\ \text{GeV}^{-2}$, $R'^2=8\ \text{GeV}^{-2}$ corresponding to $\alpha'=1$. We give the results of the model with the assignments $P_{11}(1470)$ $(56,0^+)_2$, $P_{11}(1780)$ $(70,0^+)_2$, $P_{33}(1690)$ $(56,0^+)_2$. They are compared with the FKR results of Moorhouse and Parsons[15] and Burkhardt and Pulido[8] and with experiment (Table I).

On the whole one notices an impressive improvement *vis-à-vis* the FKR results. The widths are now reasonably large except for $P_{33}\to P_{11}\pi$. The photodecay is good in sign and magnitude for the $P_{11}(1470)$.

Another interesting fact is that one can understand the very rapid falloff of $ep\to eP_{11}(1470)$; the q^2 dependence of $\gamma_v+N\to N^*(1470)$ is contained in the overlap of the spatial wave functions

$$J=-0.46(0.795-1.183\vec{q}^{\,2})|\vec{q}|\exp(-1.08\vec{q}^{\,2})\ \text{GeV}^{-1/2}, \tag{8}$$

where $\vec{q}^{\,2}$ is in GeV^2. It is seen that J vanishes at $\vec{q}^{\,2}=0.67\ \text{GeV}^2$ or $q^2=-0.62\ \text{GeV}^2$ and increases again beyond, giving a shape (Fig. 1) which could explain both the very steep falloff and the fact that P_{11} has been seen[6] at $q^2\simeq-1\ \text{GeV}^2$. This explanation, if confirmed, would be a new example of the important role played by the nodal structure of the excited levels and therefore of J—which has been emphasized in the context of ρ' decays[16] and ψ's Okubo-Zweig-Iizuka-rule-allowed decays.[17] In the present case, the advantage is that the nodal

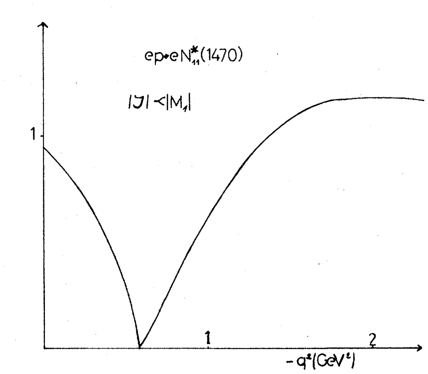

FIG. 1. The overlap of the four spatial wave functions $[P_{11}(1470), N(940), \rho$, created pair], J, as a function of $-q^2$, in conventional units (the scale is indicated by the fact that at $Q^2=0$, $A^p_{1/2}=-0.090\ \text{GeV}^{-1/2}$).

structure is directly displayed by the continuous variation of $\vec{q}^2$.

Let us now try to analyze what differentiates the QPCM model from the FKR one. There are two main differences:

(i) QPCM gives a "recoil term" not only in pion decays, but in any decay, in particular in the spin coupling of vector particles.[12] On the contrary, the FKR model for vector emission is practically identical to the CKO nonrelativistic model[13] and has no recoil in its magnetic interaction.[18] This explains the difference in photocouplings, also emphasized in a previous paper (Ref. 12, third paper) for $FP_{35} \to N\rho$. The explanation is simple in the case of P_{11} states: Photodecays and pion decays are governed by the same overlap J, so that their product is fixed by $J^2 \times \mathrm{SU}(6)$ coefficients which are of course the same for $P_{11}(940, 1470)$; therefore, there is not a change of sign between the Born term and P_{11}' [note that as $k_\gamma \sim q_\pi$, $J(k_\gamma) \sim J(q_\pi)$]. On the contrary, in the FKR model there was a change on the pion side owing to the recoil term, with no counterpart in the photocoupling. In terms of $\mathrm{SU}(6)_W$ analysis, the difference lies in the C term which is zero for FKR and not for QPCM.[19] The good effect of a pair-creation model on calculations of $P_{11}(1470) \to N\gamma$ was already noticed by Petersen in the context of l-broken SU(6) analysis ($^3P_0$ model).[20]

(ii) Still more important and more specific to QPCM is the presence of an effect due to the *nonlocal character* of the coupling, which adds to recoil-term effects. By itself, the recoil term which is included in FKR, and which has so many good effects on calculations of pion decays of orbitally excited states (as first shown by Mitra and Ross[18]), is also responsible for the excessive narrowness of radial excitations. What happens in QPCM can be seen on the analytic expression of J

$$J = C\left[\frac{R^2 + R'^2/4}{R^2 + R'^2/3}\,\frac{R'^2}{R^2} + \frac{R^2 + R'^2/2}{R^2 + R'^2/3} - \frac{1}{3}\left(\frac{R^2 + R'^2/2}{R^2 + R'^2/3}\right)^2 \vec{q}^2 (R^2 + R'^2/4)\right] \exp(-B\vec{q}^2)\,, \tag{9}$$

where C and B are well defined constants, unimportant for this discussion. If we take the "elementary emission" limit as in Ref. 12 (first paper), i.e., $R'^2 \to 0$ with R^2 fixed, only the last two terms survive: The last term inside the bracket corresponds to the old $\vec{\sigma} \cdot \vec{k}_\pi$ model, while the second term represents a recoil effect such as suggested by Mitra and Ross. These two terms almost cancel, yielding a very small Γ. However, $R'^2 \sim R^2$ and then the first term is of the same order as the other two, and leads to reasonable widths. This first term comes from the nonlocality of the interaction. It corresponds to the overlap of the *three* spatial wave functions $\psi_{A,B,C}$ at $\vec{q} = 0$. If $R'^2 = 0$, it is simply the scalar product $(\psi_B, \psi_A) = 0$. It is not present in orbital-excitation decays because the orthogonality of spherical harmonics is operating even if $R'^2 \neq 0$. Of course the magnitude of the term depends crucially on R'^2/R^2. The values obtained from the Regge slope $\alpha' = 1$ are not necessarily those which give the best fit in every particular quark-model calculation. But we prefer to stick to them and try to explain eventual discrepancies by specific corrections to the naive model.[21]

Let us finally comment on the accuracy of the predictions and their agreement with experiment. On the theoretical side, admitting the quoted values of R^2, R'^2, there remain a lot of uncertainties: The true potential could be nonharmonic (e.g., linear); we do not know the effect of mass differences so that the mass dependence of Γ is not very typical; the model is nonrelativistic. We could then expect 50% errors or more in some critical cases [we must also consider the possibility of mixing between SU(6) states]. What is typical is the trend of having rather large widths with respect to FKR and the sign change in $P_{11} \to N\gamma$. The photoproduction data for $P_{33}(1690)$ and $P_{11}(1710)$ being rather uncertain, the main disagreement concerns the $P_{33} \to P_{11}(1470)\pi$ which is $\frac{1}{10}$ of the empirical value. We do not know the experimental uncertainty. But we must stress that the narrowness is not due to a specific cancellation, as was the case of most widths in the FKR model; it comes from the smallness of k_π and from normalization factors. However, finite-width effects could be very important here.

In conclusion, the large widths of $N\pi$ and $\Delta\pi$ decays of the P_{11}' and P_{33}' can be explained with the usual harmonic-oscillator assignments. We are led to take with caution the widespread statements of "symmetric quark-model predictions" since QPCM can induce very different patterns of decay with respect to previous decay models. We must certainly make a revision of a number of spectroscopic conclusions taken from those older decay models. The recourse to exotics is no longer necessary. Our proposal of assigning the $P_{11}(1470)$ to a $(70, 0^+)_2$ (Ref. 11) is not favored since the $(70, 0^+)_2$ assignment of $P_{11}(1780)$ explains the observed narrow width better than a $(56, 0^+)_2$ and since photoproduction is now not a problem for $P_{11}(1470)$.[22] Finally, let us emphasize that in addition to the general prediction of decay signs opposite to those predicted by $SU(6)_W$,[12] QPCM is now shown to exhibit very interesting features coming from the *nonlocality* of the emission process.

---

*Laboratoire associé au Centre National de la Recherche Scientifique. Postal address: Bât. 211, Université de Paris-Sud, 91405 Orsay, France.

[1]A. Le Yaouanc, L. Oliver, O. Pène, and J. C. Raynal, Nucl. Phys. B29, 204 (1971).

[2]D. Gromes and I. Stamatescu, Nucl. Phys. B112, 213; (1976), found that effect for the linear potential. A general demonstration is given by N. Isgur and G. Karl, Phys. Rev. D 19, 2653 (1979).

[3]K. C. Bowler and P. J. Walters, Phys. Rev. D 19, 3330 (1979), correcting previous estimates of K. C. Bowler and A. J. G. Hey, Phys. Lett. B69, 469 (1977).

[4]T. De Grand and C. Rebbi, Phys. Rev. D 17, 2358 (1978).

[5]R. C. E. Devenish and D. H. Lyth, Nucl. Phys. B93, 109 (1975).

[6]J. Gayler in *Proceedings of the Topical Conference on Baryon Resonances Oxford, 1976,* edited by R. T. Ross and D. H. Saxon (Rutherford Laboratory, Chilton, Didcot, England, 1977).

[7]R. G. Moorhouse and N. Parsons, Nucl. Phys. B62, 109 (1973), an error concerning the $(70,0^+)_2$ and which is noticed there has however been repeated through a number of tables.

[8]H. Burkhardt and A. J. G. Hey, Nucl. Phys. B108, 514 (1976); H. Burkhardt and J. Pulido, Phys. Rev. D (to be published).

[9]J. W. Alcock, W. N. Cottingham, and A. C. Davis, Nucl. Phys. B11, 233 (1976).

[10]A. N. Mitra, Phys. Lett. 51B, 149 (1974). For more recent references on the work of the Delhi group see S. Kamath, Phys. Rev. D 18, 1731 (1978). In this scheme the $(70,0^+)$ is a ground state.

[11]The effects of our mixing $(56,0^+)_0+(70,0^+)_2$ proposed in Phys. Rev. D 12, 2137 (1975), would be, on the contrary, negligible in view of the discrepancies observed here.

[12]A. Le Yaouanc, L. Oliver, O. Pène, and J. C. Raynal, Phys. Rev. D 8, 2223 (1973); 9, 1415 (1974); 11, 1272 (1975). In this model all the calculations are conventionally done in the rest frame of the resonance.

[13]L. A. Copley, G. Karl, and E. Obryk, Nucl. Phys. B13, 303 (1969).

[14]See Ref. 12, third paper, and O. Pène, Orsay thesis, 1974 (unpublished).

[15]We have not quoted the results for $(70,0^+)_2$. See Ref. 7.

[16]W. B. Kaufmann and R. J. Jacob, Phys. Rev. D 10, 1051 (1974), in the context of QPCM; M. Böhm, H. Joos, and M. Krammer, Nucl. Phys. B69, 349 (1974), in the context of the Bethe-Salpeter approach.

[17]A. Le Yaouanc, L. Oliver, O. Pène, and J. C. Raynal, Phys. Lett. 71B, 397 (1977); 72B, 57 (1977); J. D. Jackson, in *Weak Interactions at High Energy and the Production of New Particles*, Proceedings of SLAC Summer Institute on Particle Physics, 1976, edited by M. Zipf (SLAC, Stanford, 1976); M. Chaichian and R. Kogerler, University of Helsinki Report No. HU TFT 78/10 (unpublished).

[18]A. Mitra and M. Ross, Phys. Rev. 158, 1630 (1967); see also the review of A. N. Mitra and S. Sood, Fortshcr. Phys. 25, 649 (1977). This feature of the magnetic interaction term seems to be shared by all models using the bare quark electromagnetic coupling. Our model of radiative coupling, on the contrary, corresponds, via the vector-dominance model (VDM), to a strong-interaction structure at the photon-quark vertex.

[19]Note that in contrast the S_{11} is getting worse (much too small; the condition $C=A$ is probably too strong.

[20]W. Petersen, Phys. Rev. D 12, 2700 (1975). According to a nonpublished calculation, in our model the photocouplings of the $(70,1^-)$ and $(56,2^+)$ multiplets are not so different from the CKO calculation, especially for large amplitudes. The ratio $A^p(D_{13})/A(D_{13})\,\lambda=\frac{3}{2}$ is known even to be improved. The remaining problem is S_{11}, see Ref. 19.

[21]For instance, R^2 is obviously much smaller than the nucleon radius. But we explain the nucleon radius by a combination of the wave-function radius and a VDM contribution. See, for instance, our paper Nucl. Phys. B37, 552 (1972).

[22]This does not weaken at all the relevance of our $(56,0^+)_{0\mp}+(70,0^+)_2$ mixing; nucleon mixing need not occur only with nearby states.