Evidence for new resonances in the $\bar{K}N$ system: A prima facie case for the even-wave harmonic-oscillator model

S. G. Kamath
Department of Physics, University of Delhi, Delhi-110007, India
(Received 8 June 1977)

Arguments are presented to show that the new resonance parameters obtained by Alston-Garnjost *et al.* in a recent analysis of the $\bar{K}N$ system from 365 to 1320 MeV/c provide a prima facie case for the even-wave harmonic-oscillator theory of baryonic states in the framework of $SU(6)_W \times O(3)$. A new quantum classification of the Λ states belonging to the $(\underline{70},1^-)$ is also proposed.

The $\bar{K}N$ system has recently been studied from 365 to 1320 MeV/c using an energy-dependent partial-wave analysis by Alston-Garnjost *et al.*[1] Among the resonances reported by these authors from 1500 –1 900 MeV, two entirely new states have been observed, $S_{01}(1720)$ and $D_{23}(1700)$, whose total widths are quoted at 175 ± 40 MeV and 130 ± 40 MeV, respectively. It is also possible that the $S_{21}(1781)$ is a new resonance; more so because its total width which is quoted at 145 ± 20 MeV indicates a sizable mismatch (~60 MeV) with that[2] of the $S_{21}(1750)$.

We argue in this paper that in the usual $SU(6)_W \times O(3)$ classification of baryon resonances in constituent-quark models, the $S_{01}(1720)$, $S_{21}(1781)$, and $P_{03}(1909)$ provide a *prima facie* case for the even-wave theory of harmonic-oscillator (h.o.) forces,[3] the several advantages of which over the conventional h.o. models[4] at the level of mass spectra[3,5] and pseudoscalar partial widths[6] of baryon resonances have been reported earlier.

We shall also include in this analysis the Λ resonances $S_{01}(1760)$, $D_{03}(1520)$, and $D_{03}(1690)$, and show that together with the $S_{01}(1720)$ and the well known $S_{01}(1405)$, these states manifest a new quantum classification in the even-wave model[3] (EWM), which is in very good agreement with the experimental data on masses and partial widths, but with some reservations.

To anticipate our results in this paper, we find that the new resonances admit the following quantum classification in the EWM:

	$\underline{8}_d$	$\underline{8}_q$	$\underline{10}_d$
$(\underline{70}, 0^+)$	$P_{01}(1600)$, $P_{21}(1678)$	$\cdots$	$\cdots$
$(\underline{70}, 1^-; l)$	$S_{01}(1720)$	$S_{21}(1781)$	$D_{23}(1700)$
$(\underline{70}, 2^+; m)$	$P_{03}(1909)$	$P_{03}(1909)$	$\cdots$.

(1)

For the remaining S and D states we obtain

	$\underline{1}_d$	$\underline{8}_d$	$\underline{8}_q$
$(70, 1^-; l)$	$S_{01}(1405)$, $D_{03}(1520)$	$\cdots$	$D_{05}(1830)$
$(\underline{70}, 1^-; u)$	$S_{01}(1670)$, $D_{03}(1690)$	$D_{03}(1830)$	$D_{05}(1830)$.

(2)

In the course of this analysis we shall make a frequent comparison of our results with conventional h.o. models.[4] The calculational apparatus that we shall use is fully described in Ref. 6 and the relevant spatial overlap integrals are tabulated in Mitra and Sood.[7] Before we discuss the details let us summarize below some salient aspects of the EWM that are necessary for this paper:

(a) The most compelling feature of the model lies in its ability to produce a dual spectrum of the $\underline{70}$ states of $L^P = 1^-$, for example, without affecting the $\overline{\underline{56}}$ hadrons.

(b) A recent analysis[6] of photoproduction and hadronic decay data designed to study this "doubling" of $\underline{70}$ states gave strong indications that several resonance effects, especially those due to quartet- (q) type states, are amenable to interpretation as two or more overlapping resonances, sometimes with complementary experimental signatures. For example, we predicted two D_{05} states at 1830 MeV, of which D_{05}^u decays via $N\bar{K}$ (and not $\Sigma\pi$) and D_{05}^l decays via $\Sigma\pi$ (and not $N\bar{K}$). Similarly, there are two D_{15} states at 1670 MeV, viz. D_{15}^l and D_{15}^u which are photoproduced via $n\gamma$ and $p\gamma$, respectively, without violating the Moorhouse selection rule[8] which applies to D_{15}^l.

(c) The location of these overlapping resonances was arrived at with the help of the decay data, which suggested that for $(\underline{70}, 1^-)$ states only there is an upward mass shift of $l(q)$ with respect to $l(d)$, so as to push the former into the mass region of a $u(q)$ state. Thus there are *two* quartets instead of *one* in a given mass region [see Eq. (3)].

(d) The resulting mass spectra in the EWM are (excluding $\underline{1}_d$)

$$\begin{array}{llll} & \underline{8}_d & \underline{8}_q & \underline{10}_d \\ (\underline{70},1^-;l) & D_{13}(1520) & D_{15}(1670) & D_{33}(1670) \\ (\underline{70},1^-;u) & D_{13}(1670) & D_{15}(1670) & D_{33}(1780), \end{array} \quad (3)$$

$$\begin{array}{lll} & \underline{8}_{d,q} & \underline{10}_d \\ (\underline{70},2^+;l) & F_{15}(1760)? & \cdots \\ (\underline{70},2^+;m) & F_{15}(1820)? & F_{35}(1890) \\ (\underline{70},2^+;u) & F_{15}(1990)? & \cdots . \end{array} \quad (4)$$

Unlike the $(\underline{70}, 1^-)$, no extra mass shift of $l(q)$ vs $l(d)$ is indicated for any other state [see Eq. (4)] including u (as well as $L \geq 2$ and radial modes), so that $l(q)$ states of $(\underline{70}, 1^-)$ should be regarded as more an exception than the rule. Let us now examine how the new resonances fit in with the above pattern separately.

$S_{21}(1781)$: Eq. (3) implies[9] that there are four S_{21} resonances in the 1750-MeV region, one each from $\underline{8}_d(u)$, $\underline{8}_q(l)$, $\underline{8}_q(u)$, and $\underline{10}_d(l)$. We now show below that these four overlapping resonances are directly responsible for the wide variation in the masses (1700–1790 MeV) and total widths (50–120 MeV) of the S_{21} referred to in the beginning of this paper. Their partial widths in MeV are (with elasticity from Ref. 1 given in parentheses)

	Expt	$\underline{8}_q(l)$	$\underline{8}_d(u)$	$\underline{8}_q(u)$	FKR $(\underline{10}_d)$
$N\bar{K}$	5–48	39	7	10	14
	(0.33 ± 0.05)	(0.29)			
$\Lambda\pi$	3–24	25	3	0	4
$\Sigma\pi$	10	15	2	11	9.

(5)

Note the following. (a) an $\underline{8}_q(l)$ assignment for $S_{21}(1781)$ matches very well with the large elasticity and large partial width quoted in Refs. 1 and 2. Apart from the $S_{21}(1781)$ the rest of the resonant structure in this region is then due to the u states which have small partial widths.

(b) In the usual h.o. model, the $S_{21}(1750)$ is taken as a $\underline{10}_d$ state, so that the $S_{21}(1781)$ can only be a $\underline{8}_q$ [since the $\underline{8}_d$ should be close to $D_{23}(1670)$]. While the latter predicts nearly the same elasticity as the $\underline{8}_q(l)$ state in Eq. (5) because l states in the EWM are the nearest equivalent[3] of the supermultiplet assignments in FKR (Ref. 4) [hence, the EWM prediction for $\underline{10}_d$ is excluded in Eq. (5)], it leaves unresolved the mass breaking between $S_{21}(1781)$ and $S_{21}(1670)$. In the EWM, however, the mass of $S_{21}(1781)$ fits in very well with that given in Eq. (5), thus supporting our conjecture on overlapping resonances in the EWM.

$P_{03}(1909)$: Let us now consider Eq. (4). Note that the EWM predicts a $(\underline{70}, 2^+; m)$, which has no analog in the conventional h.o. model.[4] The observation of even one state belonging to this supermultiplet would then provide a *prima facie* case for the EWM, as we shall soon see. Of the resonances belonging to the $(\underline{70}, 2^+; m)$, the $F_{15}(1820)$ is the first Regge recurrence of the $N(1470)$. Its $\frac{3}{2}^+$ satellite $P_{13}(1820)$ has a Λ counterpart placed at $P_{03}(1935)$, which agrees excellently with the $P_{03}(1909)$ observed by Alston-Garnjost *et al.*,[1] and provides good proof of the viability of the EWM and its quantum classification.[10] Returning to Eq. (4), we see that the Λ states of $\underline{8}_q(m)$ and $\underline{8}_d(m)$ are both predicted to be degenerate in the EWM, so that the $P_{03}(1909)$ which we have identified with this m quantum classification above could in reality be made up of two overlapping resonances. To check that this is indeed possible, let us consider the $N\bar{K}$ and $\Sigma\pi$ widths of $P_{03}(1909)$. These work out[11] (in MeV, with elasticity given in parentheses) as

	$\underline{8}_d$	$\underline{8}_q$	PDG	Ref. 1
$N\bar{K}$	4.5	17	12–28	21–49
		(0.17)	(0.25–0.10)	(0.31 ± 0.05)
$\Sigma\pi$	13.3	0	4–8	?

(6)

Two comments are in order here:

(a) The $\underline{8}_d(m)$ and $\underline{8}_q(m)$ states are found to have complementary partial decay modes, in that the $N\bar{K}$ mode (and not the $\Sigma\pi$) is small for the former while the $\Sigma\pi$ mode (and not the $N\bar{K}$) is zero for the $\underline{8}_q(m)$ assignment. This is clearly parallel to an exactly similar situation for the $N\bar{K}$ and $\Sigma\pi$ widths of the $D^u_{05}(1830)$ and $D^l_{05}(1830)$, as well as the $n\gamma$ and $p\gamma$ photoproduction of $D^l_{15}(1670)$ and $D^u_{15}(1670)$, respectively, both of which are mentioned in the early part of this paper.

(b) The $\underline{8}_q(m)$ assignment predicts an $N\bar{K}$ width in very good agreement with the experimental data. The $\Sigma\pi$ width for $\underline{8}_d(m)$ is also in good agreement with the numbers given in the PDG tables.[2]

Λ states: The Λ states of $(\underline{70}, 1^-)$ located in the 1400–1800 MeV region have traditionally been regarded as octet-singlet mixtures[12]; the mixing angle is dependent on the barrier-penetration factor chosen. In an earlier analysis[6] of these resonances, the consequences of a purely orbital splitting mechanism as accounting for the bulk of the Λ mass spectrum [with SU(3), spin orbit, spin-spin, etc., effects ignored completely] was explored. Two possible pictures (A and B) of Λ spectroscopy, neither of which were entirely satisfactory were presented, with the Λ's grouped

as

$$\begin{aligned}
&\text{A.}\ \Lambda(1405\text{–}1520)\text{: } \underline{1}_d(l) \\
&\quad \Lambda(1660\text{–}1690)\text{: } \underline{1}_d(u), \underline{8}_d(l), \\
&\quad \Lambda(1830)\text{: } \underline{8}_d(u), \underline{8}_q(l,u)\text{:} \\
&\text{B.}\ \Lambda(1405)\text{: } \underline{1}_d(l), \\
&\quad \Lambda(1520)\text{: } \underline{1}_d(u), \underline{8}_d(l), \\
&\quad \Lambda(1660\text{–}1690)\text{: } \underline{8}_d(u), \\
&\quad \Lambda(1830)\text{: } \underline{8}_q(l,u).
\end{aligned} \tag{7}$$

The flaw in these versions lay in the following:

(a) The presence of an appreciable singlet-octet mass splitting as evident from the mass difference between $\underline{1}_d(l)$ and $\underline{8}_d(l)$ states in both A and B.

(b) The mass difference between $D_{03}(1520)$ vs $S_{01}(1405)$ in A was not explained. Again, we did not offer any reason why the $\underline{8}_d(l)$ resonances at 1660–1690 MeV in A should have such large $N\overline{K}$ widths (as in the FKR model), and yet go unreported in the PDG tables.[2]

(c) The choice of $D_{03}(1520)$ as an $\underline{8}_d(l)$ in B is clearly inconsistent with the mass position of $D_{13}(1520)$ in the same octet, more so when the general pattern for all baryon states shows that $S \neq 0$ states are situated at a higher-mass level relative to $S = 0$ states.

Before we take up the case of the $S_{01}(1720)$ in the EWM, let us first make it clear that the usual h.o. model[4] cannot accomodate the $S_{01}(1720)$ because of the following:

(a) As an $\underline{8}_d$ state the $S_{01}(1720) \to N\overline{K}$ width quoted in Ref. 1 is smaller by about two orders of magnitude compared to the usual h.o. prediction, which is of the order of 400 MeV (see FKR). Besides, the $S_{01}(1670)$ is already assigned to this octet in company with $S_{11}(1535)$.

(b) As an $\underline{8}_q$ state the same width is predicted to be zero because of a vanishing SU(6) coefficient as in the case of $D_{05}(1830) \to N\overline{K}$.

(c) The $\underline{1}_d$ assignment is already well accounted for by the $S_{01}(1405)$.

In the EWM on the other hand, the following Λ classification is found to produce an excellent fit to the mass and partial widths (see Table I):

$$\begin{aligned}
&\Lambda(1405\text{–}1520)\text{: } \underline{1}_d(l), \\
&\Lambda(1660\text{–}1690)\text{: } \underline{1}_d(u), \\
&\Lambda(1720)\text{: } \underline{8}_d(l), \\
&\Lambda(1830)\text{: } \underline{8}_d(u),\ \underline{8}_q(l,u).
\end{aligned} \tag{8}$$

Let us discuss Eq. (8) now (see Table I for results).

(a) The mass of $S_{01}(1720)$ fits in very well as a member of the $\underline{8}_d(l)$ consisting of $S_{11}(1535)$ and $S_{21}(1680)$?. Its $N\overline{K}$ width also compares quite well as an order-of-magnitude level with the experimental value. With $S_{01}(1670)$ instead as the $\underline{8}_d(l)$ state neither of these fits are possible in either the EWM or FKR calculations.

TABLE I. Partial decay widths in MeV for the $(\underline{70}, 1^-)$ Λ resonances with quantum classifications given in Eq. (8) and Eq. (7)—the latter for comparison. The elasticities given in Ref. 1 are enclosed in parentheses under Expt., with the appropriate EWM predictions in other columns.

Decay	Expt.	Widths obtained for assignments as $\underline{1}_d(l)$	$\underline{1}_d(u)$	$\underline{8}_d(l)$	FKR
$S_{01}(1405) \to \Sigma\pi$	40	20	⋯	⋯	56
$D_{03}(1520) \to NK$	7 (0.45±0.04)	5 (0.33)	0.5	5	7
$D_{03}(1520) \to \Sigma\pi$	6.3	11	1.5	1.2	12
$S_{01}(1670) \to N\overline{K}$	6–14 (0.16±0.03)	⋯	5 (0.15)	163	415
$S_{01}(1670) \to \Sigma\pi$	8–24	⋯	2	10	22
$S_{01}(1720) \to N\overline{K}$	(0.31±0.05)	⋯	⋯	169 (0.79)	⋯
$S_{01}(1720) \to \Sigma\pi$	?			11	
$D_{03}(1690) \to N\overline{K}$	12–18 (0.21±0.03)	⋯	6 (0.14)	63	102
$D_{03}(1690) \to \Sigma\pi$	9–24	⋯	7	24	11

(b) The pattern of uniformly low widths for the $S_{01}(1670)$ and $D_{03}(1690)$ is now excellently reproduced with the $\underline{1}_d(u)$ assignments to these states [cf. A and B versions in Eq. (7)]. In particular, the respective elasticities of these states agree very well with the numbers quoted in Ref. 1. Note that the squared mass difference between $\Lambda(1660)$ and $\Lambda(1520)$ is nearly the same as that between u and l states (0.45 GeV^2 vs 0.37 GeV^2).

(c) There are, however, two problems with Eq. (8), both of which are present in Eq. (7). First, there is an appreciable spin-orbit effect between $D_{03}(1520)$ and $S_{01}(1405)$, and, second, there is also an SU(3) singlet-vs-octet mass splitting between the $\underline{1}_d(l)$ and $\underline{8}_d(l)$ states. But for Eq. (8), it is clear however that neither of the two versions of Λ spectroscopy in Eq. (7) can easily accomodate the $S_{01}(1720)$.

In concluding this paper, let us now finally consider the remaining resonances, namely, $P_{01}(1600)$, $P_{21}(1678)$, and $D_{23}(1700)$ reported in Ref. 1. The P-wave states fit in very well as $(\underline{70}, 0^+)$ states[3] in the EWM as $\underline{8}_d$ partners of the $N(1470)$; their mass positions are placed at $P_{01}(1616)$ and $P_{21}(1650)$, respectively.

However, while the $P_{01} \to N\bar{K}$ width (~80 MeV) compares somewhat favorably with the EWM prediction (~212 MeV), the $P_{21} \to N\bar{K}$ mode as reported in Ref. 1 is surprisingly small (~4 MeV). For the record, the latter is calculated to be 70 MeV in the EWM. The $D_{23}(1700)$ can only be an l state by virtue of its mass position. However, its SU(3) assignment as a $\underline{10}_d(l)$ state [the $D_{23}(1670)$ fits in very well[4,6] as an $\underline{8}_d(l)$ state] does not measure up (~3 MeV) to the observed $N\bar{K}$ width (17 MeV). The $\Sigma\pi$ mode offers an easy way to distinguish between the $\underline{8}_d(l)$ and $\underline{10}_d(l)$ assignments inasmuch as the respective widths are related in the ratio of nearly 20 : 1. We would therefore urge an estimation of the $D_{23}(1700) \to \Sigma\pi$ partial width so as to settle this question.

It is a pleasure to thank Professor A. N. Mitra for his encouragement and kind interest in this investigation.

---

[1]M. Alston-Garnjost *et al.*, Phys. Rev. Lett. 38, 1007 (1977).
[2]Particle Data Group, Rev. Mod. Phys. 48, S1 (1976), referred to as PDG.
[3]A. N. Mitra, Phys. Rev. D 11, 3270 (1975); Phys. Lett. 51B, 149 (1974).
[4]D. Faiman and A. W. Hendry, Phys. Rev. 173, 1720 (1968); R. P. Feynman, M. Kislinger, and F. Ravndal, Phys. Rev. D 3, 2706 (1971), referred to as FKR; Y. S. Kim and M. E. Noz, Phys. Rev. D 8, 3521 (1973).
[5]A. N. Mitra and S. Sen, Lett. Nuovo Cimento 10, 16 (1974).
[6]S. G. Kamath and A. N. Mitra, Phys. Rev. D 17, 340 (1978).
[7]A. N. Mitra and S. Sood, Phys. Rev. D 15, 1991 (1977).
[8]R. G. Moorhouse, Phys. Rev. Lett. 16, 771 (1966).
[9]The $\Delta^2 - N^2$ and $\Sigma^2 - \Lambda^2$ spacing is taken from FKR and is equal to 0.45 GeV^2 and 0.16 GeV$^2 \times$ parity of the supermultiplet, respectively.
[10]The $P_{03}(1909)$ is too high in mass to be a $(\underline{56}, 2^+)$ partner of the $F_{05}(1815)$, but it could well be an $\underline{8}_q(l)$ state in the EWM belonging to the radial $(\underline{70}, 0^+)_2$, since $P_{11}{}^2(1780) + 0.45\ \text{GeV}^2 = P_{03}{}^2(1910)$. However, with the radial assignment, the $N\bar{K}$ width is predicted to be zero by virtue of SU(6).
[11]We believe that the $P_{03}(1909)$ and the $P_{03}(1860)$ of the PDG tables are the same inasmuch as their respective total widths and masses are nearly the same.
[12]See, e.g., D. Faiman and D. E. Plane, Nucl. Phys. B50, 379 (1972); also W. Petersen and J. L. Rosner, Phys. Rev. D 6, 820 (1972).