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SU(3) CLASSIFICATION OF BARYON RESONANCES

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SU(3) CLASSIFICATION OF BARYON RESONANCES*

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Since the discovery of SU(3) symmetry,[1,2] it has become customary at every conference to combine the new data with the old ones and check the validity of this symmetry scheme. The last complete fits of baryon resonances I know of were made in 1970: Plane et al.[3] presented their fits at the Duke Conference on Baryon Resonances, and Samios reported at the Kiev Conference the results of fits that he and his collaborators had made.[4] A more recent review, which does not include any new fits, is the one by Meshkov.[5]

In this review I will first summarize the new data presented at this Conference; then I will discuss the individual multiplets for which the amount of data available is sufficient to perform constrained fits; finally, I will mention some other possible multiplets. Large discrepancies for unbroken SU(3) fits to the couplings seem to persist in the $\frac{3}{2}^+$ decuplet and the $\frac{3}{2}^-$ octet and singlet states.

I. New and Old Data Used in the Fits

New data and analyses of data have been presented at this Conference for various resonant states. For discussion of the individual papers, I refer the reader to the reviews presented in the Baryon Resonances Parallel Session. I will report here only the data relevant to the SU(3) fits I will discuss.

The old data used in the fits are all listed in the Particle Data Group compilation,[6] unless otherwise specified.

A. New Data on S = 0 Baryons

For the elastic channel a new partial wave analysis has been presented at the Conference by the Saclay group.[7] The recently published analysis of Almehed and Lovelace[8] was already included in the PDG compilation. Table I shows the masses, widths, and elasticities of the Saclay analysis for the states used in the SU(3) fits discussed

in this paper. These values have been averaged with the values from other experiments compiled by PDG, and the mean values obtained are shown in the table. The errors are "external errors" of the individual values and were obtained as discussed at the end of this section.

For the inelastic channels, new partial wave analyses for decays into $\Delta\pi$ and ρN have been reported at this Conference. Fung et al.[9] reported results on the reaction $\pi^+ p \to \Delta^0 \pi^+$; Bunyatov et al.[10] and Herndon et al.[11] reported complete partial wave analyses of the reaction $\pi N \to \pi\pi N$. The three papers essentially agree on the general features of the partial waves; however, since Ref. 11 is more complete and covers a wider energy interval, I have used their results. The values of the amplitudes at resonance, $t = \sqrt{xx'}$, have been read from their amplitude plots; the errors have been estimated by looking at the dispersion of points in the amplitude plots. The values of $t \pm dt$ from this paper for the D13(1520), D15(1672), and F15(1687) are shown in Tables VI-VIII.

B. New Data on S = - 1 Baryons

Three new partial wave analyses have been presented at this Conference. The results relevant to the SU(3) fits discussed in this review are shown in Tables II and III. The three analyses follow.

(a) Langbein and Wagner[12] have performed an energy-independent multichannel analysis including data on $\bar{K}N$, $\Sigma\pi$, $\Lambda\pi$ channels in the 436- to 1216-MeV/c region. The solutions at different energies were linked by shortest-path technique.

(b) Lea et al.[13] have reported preliminary results on an energy-dependent multichannel analysis for $\bar{K}N$, $\Sigma\pi$, and $\Lambda\pi$ data in the 440- to 1190-MeV/c region. The energy dependence was introduced in the K-matrix elements, parametrized as a combination of resonance poles and linear background.

(c) Levi-Setti et al.[14] have reported preliminary results on an energy-dependent partial wave analysis on the individual channels $\bar{K}N$, $\Lambda\pi$, and $\Sigma\pi$. This analysis was done in the 780- to 1220-MeV/c region and included 90 000 new events from the authors' new experiment in the 860- to 1000-MeV/c region. Tables II and III include more than one line from this experiment because the individual channels occasionally yielded different M and Γ.

The results from the old partial wave analyses are listed in the PDG compilation.[6] They were individually included in obtaining the average values used in this review, but they are not individually quoted in Tables II and III for reasons of space.

The largest discrepancy among the various analyses is the elasticity of the S_{11} state $\Sigma(1760)$. Values ranging from 0.08 to 0.80 have been reported for this elasticity, too large an interval to be accepted as an uncertainty in the analysis. So for $J^P = \frac{1}{2}^-$ I did three different fits which will be discussed in Sec. III-1.

C. New Data on S = - 2 Baryon States

New experimental results on the mass and width of $\Xi(1532)$ have been reported by Baltay et al.[15] at this Conference. They are:

Baltay et al.[15]	PDG values[6]
$M(\Xi^*)^- = 1534.7 \pm 1.1$ MeV	$M = 1536.1 \pm 1.4$ MeV
$\Gamma(\Xi^*)^- = 7.8^{+3.5}_{-7.8}$ MeV	
$M(\Xi^*)^0 = 1532.0 \pm 0.4$ MeV	$M = 1531.3 \pm 0.6$ MeV
$\Gamma(\Xi^*)^0 = 9.0 \pm 0.7$ MeV	$\Gamma = 9.2 \pm 0.8$ MeV.

The most relevant result for this review is the width for $\Xi(1532)^0$, which, averaged with the old data, gives the weighted average:

$$\Gamma = 9.1 \pm 0.5 \text{ MeV}.$$

Errors on input data. In order to perform a chi-squared fit to determine the coupling constants for each multiplet, errors should be assigned to each experimentally measured quantity. Whenever possible I have used values and errors given in the PDG compilation,[6] which are the result of the weighted average of various experiments. Often a weighted average cannot be done either because the experimenters did not quote errors or—as for amplitudes obtained in partial wave analyses—because the errors are difficult to evaluate and are often underestimated. Plane et al.[3] have arbitrarily assigned an error of 0.05 to each amplitude from partial wave analysis. However, I think that this error is sometimes too large, giving a good fit where there probably is not a good fit, and sometimes too small, therefore showing a worse situation than the data really indicate.

For both the average and errors I have adopted one of the following methods:

(a) Used weighted averages and their errors whenever possible.

(b) Evaluated the mean value of the measured quantities, $\bar{x}$, and an "independent external error" of the individual values

$$\langle \delta x_i \rangle = \sqrt{\frac{\Sigma(x_i - \bar{x})^2}{N}}$$

and then used $\bar{x}$ and $\langle \delta x_i \rangle$ as error.[6] The error on the mean is, of course, smaller by $1/\sqrt{N}$, but I used the error on the individual measurements because I feel it best represents the real situation.

(c) Estimated an error whenever either (a) or (b) above could not be used or provided an "unreasonable answer." Each entry used in the fits will be shown in a table, and for each the method used will be specified.

II. $\frac{3}{2}^+$ Decuplet

Table IV shows the data used for the SU(3) fits. The relation among Γ and the coupling constant g is

$$\Gamma = (cg)^2 B_\ell(p) \frac{M_N}{M_R} p = (cg)^2 F_b, \tag{1}$$

where c is the SU(3) coefficient from de Swart,[16] with the sign convention discussed in Ref. 6; M_N is the nucleon mass; M_R is the mass of the state for which Γ is calculated; p is the center-of-mass momentum for the channel being considered; and $B_\ell(p)$ is a barrier factor. In the past, two different forms[3,4,17] have been used for the barrier factor:

$$B_1 = \frac{(pr)^2}{1 + (pr)^2}, \qquad B_2 = p^2, \tag{2}$$

where B_1 is the form taken from Blatt-Weisskoft[18] for $\ell = 1$, and r is a radius of interaction taken to be 1 fermi. The results of the fits with these two forms of B_ℓ are shown in Table IV, in the columns g_1 and g_2. With the new precise value for the width of $\Xi(1532)$, neither of the two forms gives a good fit. Schmid[19] has suggested a new relation between Γ and g:

$$\Gamma = (cg)^2 \frac{p^3}{M_R M_D}, \tag{3}$$

where M_D is the mass of the decay baryon (N, Λ, Σ or Ξ). The results of this fit are shown in the g_3 column; the χ^2 is only 0.09 for 3 degrees of freedom. However, a derivation of this formula has not been published yet. In addition, the values of M and Γ used in these fits were derived by fitting the data with Breit-Wigner resonance forms which included barrier factors of the form B_1; therefore, it seems correct to be consistent and use the same barrier factor here too.

In view of the above considerations, fits using broken SU(3) have also been done. The relation among the individual widths derived with broken SU(3) is[20,21]

$$2(\Delta+\Xi) = 3(\Sigma^* \to \Lambda\pi) + (\Sigma^* \to \Sigma\pi). \tag{4}$$

This formula gives for the three cases:

1) $8.13 \pm 0.15 = 7.98 \pm 0.69$ $\quad \chi^2 = 0.04$,
2) $18.4 \pm 0.3 = 18.2 \pm 1.6$ $\quad \chi^2 = 0.02$,
3) $549 \pm 11 = 595 \pm 52$ $\quad \chi^2 = 0.00$,

where the χ^2 is a measure of the consistency of the equivalence. Note, however, that the goodness of fit is directly related to the fact that the best-measured quantities (Δ and Ξ) are both on the same side of the equation.

In conclusion, unbroken SU(3) gives a bad fit to the data, unless a new form for the decay rates is used; broken SU(3) seems to fit the data very well.

III. Octets and Singlets

I will discuss only the fits for multiplets with $J^P = \frac{1}{2}^-, \frac{3}{2}^-, \frac{5}{2}^-, \frac{5}{2}^+$ which have enough measured rates to make a fit worthwhile. Experimental results are available for decays into $\{8\} \times \{8\}$; that is, into a baryon member of the $J^P = \frac{1}{2}^+$ octet and a meson member of the $J^P = 0^-$ nonet. Some results have also been recently reported on $\{10\} \times \{8\}$ decays; that is, decays into baryon members of the $\frac{3}{2}^+$ decuplet and meson members of the 0^- nonet.

$\{8\} \times \{8\}$ decays. There are two couplings for members of an octet, g_D and g_F. However, since there can be mixing between the isospin-zero member of the octet and the singlet, we have to include the singlet coupling in the fits. We have

$$\text{Singlet} \quad \Gamma = (c_1 g_1)^2 \, B_\ell(p) \, \frac{M_N}{M_R} \, p, \tag{5}$$

$$\text{Octet} \quad \Gamma = (c_D g_D + c_F g_F)^2 \, B_\ell(p) \, \frac{M_N}{M_R} \, p, \tag{6}$$

where c_i are the SU(3) coefficients[6,16] and the other symbols are the same as for Eq. (1). If we define

$$G_1 = c_1 g_1, \tag{8a}$$

$$G_8 = c_F g_F + c_D g_D, \tag{8b}$$

the mixing between the two physical states Λ, mostly octet, and Λ', mostly singlet, in terms of a mixing angle θ is

$$\begin{aligned} \Lambda &= G_8 \cos\theta + G_1 \sin\theta, \\ \Lambda' &= -G_8 \sin\theta + G_1 \cos\theta. \end{aligned} \tag{9}$$

Since the experimentally measured quantities are not Γ, but $t = \sqrt{xx'}$ (see Tables II and III), I will follow the suggestion of Plane et al.[3] and use as input data t_i instead of Γ_i. In this case we have

$$t = \sqrt{xx'} = \frac{GG'}{\Gamma_T} \sqrt{B_\ell B_\ell \, pp'} \, \frac{M_N}{M_R} = \frac{GG'}{\Gamma_T} F_b, \tag{10}$$

where x is the incoming channel (always the elastic channel); x' is the outgoing channel, either elastic or inelastic; Γ_T is the total width of the resonant state; G and G' are (8a) or (8b) depending upon whether we are considering a singlet or an octet state; F_b is a kinematical factor defined in (10); and the other symbols are the same as in Eq. (1). Since only products of couplings are measured, as seen in Eq. (10), there are sign ambiguities inherent to the above definitions, so I assume, by convention, that g_1 and g_F are always positive. The sign convention for $t = \sqrt{xx'}$ adopted here (Tables II and III) is the one advocated by Levi-Setti[22] and discussed in Ref. 6. The relations among g_D, g_F and F/D and α are as follows:

$$\frac{F}{D} = \frac{\sqrt{5}}{3} \frac{g_F}{g_D}, \tag{11}$$

$$\alpha = \left[1 + \frac{\sqrt{5} g_F}{3 g_D}\right]^{-1}. \tag{12}$$

The expected values of α from the quark model, taken from Meshkov,[5] are shown on the tables reporting all the relevant data for each multiplet.

$\{10\}\times\{8\}$ decays. For these decays there is only one coupling constant. The experimentally measured quantities are $t = \sqrt{xx'}$, where x is the elasticity related to couplings in the $\{8\}\times\{8\}$ configuration. With some algebra from Eq. (1), we get

$$g = \frac{\sqrt{xx'}}{c}\sqrt{\frac{\Gamma}{xF_b}}, \tag{13}$$

where $F_b = B_\ell \frac{M_N}{M_R} p$ is the usual kinematical factor and c is the usual SU(3) coefficient.[6,16] Not many results are available for these types of decay; the $N \to \Delta(1233)\pi$ decays are from Herndon et al.,[11] the $Y^* \to \Sigma(1385)\pi$ decays are from Prevost et al.[23]

1. $J^P = \frac{1}{2}^-$ States

For these states, Eqs. (5) and (6) have to be multiplied by the extra factor

$$\left[\frac{M_R - M_D}{\overline{M}_R - \overline{M}_D}\right]^2,$$

where M_D is the decay baryon, and $\overline{M}_R - \overline{M}_D = 564$ MeV is the difference of the mean $\frac{1}{2}^-$ and $\frac{1}{2}^+$ baryon octet masses. This kinematic factor comes from PCAC arguments, and it was advocated by Graham et al.[24] For the $\frac{1}{2}^-$ states it has been used in this form first by Gell-Mann et al.[25]

The new data for $J^P = \frac{1}{2}^-$ states are shown on Tables I-III; all the data used in the SU(3) fits are shown on Table V and require some comments:

a. For the $\Lambda(1405)$ all the previous fits have used only the $\Sigma\pi$ decay mode (assumed to be the only channel), because it is the only decay detectable in production experiments. However, by doing the appropriate analysis of low-energy $\overline{K}N$ data, one finds that the coupling to the $\overline{K}N$ channel is very large. The value used here is from the analyses of Kim[26] and Galtieri.[27]

b. For the decays $\Lambda(1673) \to \Lambda\eta$ and $N(1530) \to N\eta$, the signs of $\sqrt{xx'}$ are not known. If fact, whenever a partial wave analysis is performed there is an overall sign ambiguity; therefore, only relative

signs can be measured. For the decays of Σ and Λ states into $\Sigma\pi$ and $\Lambda\pi$, as mentioned in Sec. III, the convention adopted is the one chosen by Levi-Setti[22] and discussed in Ref. 6. For decays into $\Lambda\eta$ and $N\eta$ this convention has to be picked up from SU(3). Three fits were made with the different sign combinations for these two decays, and the minus-minus combination for fit 1 in Table V was found to give $\chi^2 = 15$ compared with $\chi^2 = 27$ and $\chi^2 = 31$ for the other two combinations. Therefore this combination was also used for fits 2 and 3.

c. The elasticity of $\Sigma(1760)$ has been found to be 0.08 in one experiment, 0.45 in another, and 0.8 in others (see Table III); therefore, three fits have been done, as shown in Table V, using two possible values for x or no value at all. The value of $x = 0.6\pm0.1$ gives a better fit than the other value.

Table V shows that none of the three fits is very good. The major contribution to $\chi^2 = 15$ comes from $N(1530) \to N\eta$, which gives a contribution of $\chi^2 = 5$, the measured value being too large. The value of $\alpha = 1.2$ is somewhat lower than the quark-model prediction of $\alpha = 1.5$; on the other hand, $\alpha = 1.2$ is too large to interpret this octet as the $8^{3/2}$ member of the $70(L = 1^-)$ quark-model configuration.

2. $J^P = \frac{3}{2}^-$ States

Table VI shows all the relevant input data, taken from Tables I-III and from Refs. 11 and 23.

The $\{8\}\times\{8\}$ decays give an acceptable overall fit ($\chi^2 = 9.1$ for 4 degrees of freedom). The $\Lambda(1518)$ and $\Lambda(1688)$ mix, the latter being the mostly octet member. The mixing angle $\theta = (-23\pm4)°$ is consistent with the value obtained from the mass formula using $M(\Xi^*) = 1830$ MeV. The value of α is very close to the value expected for the $8^{1/2}$ octet in the $70(L = 1^-)$ configuration (for $8^{3/2}$, $\alpha = 1.5$ is expected).

For the $\{10\}\times\{8\}$ decays the results are not very consistent: g_Δ is considerably larger than g_Σ and $(g_\Lambda)_8$; the χ^2 is very bad ($\chi^2 = 16/2DF$). A pure singlet state is not allowed to decay into $\{10\}\times\{8\}$, and this fact allows calculation of the mixing angle through the relation

$$tg^2\theta = \frac{\Gamma(1518)}{\Gamma(1688)} \times \frac{F_b(1688)}{F_b(1518)} = 9.52 \times \frac{\Gamma(1518)}{\Gamma(1688)} .$$

The value $\theta = \left(75^{+5}_{-10}\right)^\circ$ obtained is in large disagreement with the one obtained above, as pointed out by Mast et al.[28] However, since all the g's for $Y^* \to \Sigma(1385)\pi$ seem to be too small and the analysis of Prevost et al.[23] is preliminary, we should probably await more partial wave analysis results before drawing any conclusion of SU(3) violation. If the analysis of Prevost et al.[23] is confirmed, a plausible explanation of this discrepancy is that mixing occurs among two $J^P = \frac{3}{2}^-$ octets and a $J^P = \frac{3}{2}^-$ singlet and not between one octet and a singlet. The quark model, in fact, predicts two octets and a singlet to all be part of the $70(L = 1^-)$ configuration. Faiman and Plane[29] have recently written a paper on this subject. However, as noted earlier, α for the $\{8\}\times\{8\}$ decays is close to the $8^{1/2}$ prediction, which would indicate no mixing between 8-1/2 and $8^{3/2}$.

3. $J^P = \frac{5}{2}^-$ States

Table VII shows all the relevant input data taken from Tables I-III and from Refs. 11 and 23. The fitted values of g_D and g_F as well as the value of α are given in the table. The fits look very good, although for $\{10\}\times\{8\}$ g_Λ and g_Σ are, again, on the low side, or g_Δ is somewhat large. Notice that α is very close to the value expected by the quark model, which expects only one $J^P = \frac{5}{2}^-$ octet and no singlets in the $70(L = 1^-)$ configuration.

4. $J^P = \frac{5}{2}^+$ States

Data and results of the fit are shown on Table VIII. The fit is good for $\{8\}\times\{8\}$ decays; the value of α is very close to the expected one if this octet is part of the $56(L = 2)$ configuration of the quark model. For $\{10\}\times\{8\}$ decays we notice the usual effect: the coupling for $N \to \Delta\pi$ decay, g_Δ, is larger than the one for $\Lambda \to \Sigma(1385)\pi$ decay.

5. Conclusions on Octet and Singlet States

$\{8\}\times\{8\}$ decays. The $J^P = \frac{5}{2}^+$ and $\frac{5}{2}^-$ octets fit SU(3) very well. The $J^P = \frac{1}{2}^-$ states do not fit very well, the chi- squared being 15 (for 6 degrees of freedom), and an octet-singlet mixing angle $\theta_1 = (8.3\pm4.3)^\circ$ is required. The $J^P = \frac{3}{2}^-$ states fit reasonably well ($\chi^2 = 9/4DF$) and require a mixing angle $\theta_3 = (-23\pm4)^0$.

$\{10\}\times\{8\}$ decays. These rates do not fit SU(3) very well where data are available. In particular, the mixing angle θ_3 calculated from these decays is $\theta_3 = (75\pm^{5}_{10})^0$, in bad disagreement with $(-23\pm4)^0$. However, the partial wave analysis for $Y^* \to \Sigma(1385)\pi$ used in these fits[23] is preliminary, and new results should be obtained before a violation of unbroken SU(3) is claimed, or a three-way mixing of two octets and a singlet is advocated.[29]

IV. Candidates for Other $J^P = \frac{1}{2}^-$ and $\frac{3}{2}^-$ Multiplets

The $70(L = 1^-)$ configuration of the quark model[30] predicts: two $J^P = \frac{1}{2}^-$ octets (one discussed in Sec. III), two $J^P = \frac{3}{2}^-$ octets (of which one is discussed in Sec. II), two singlets (also in Sec. II), a $J^P = \frac{5}{2}^-$ octet (Sec. II), and two decuplets, with $J^P = \frac{1}{2}^-, \frac{3}{2}^-$. So there are four multiplets to be completed before we have all the states for this configuration.

Tables IX and X show all the candidates for these states. Two Δ and one N state are confirmed by many different analyses. The N(1730), $J^P = \frac{3}{2}^-$, is not seen by all the analyses of the elastic channel, but the $\Delta\pi$ channel has a reasonable signal, therefore is very likely to be "good." As for the Λ and Σ states, the situation is very confusing; there is little agreement among the various analyses--however, the new data of Levi-Setti et al.[14] will certainly help to clarify the situation.

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Footnote and References

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Table I. New parameters of Ayed et al.[7] for the non-strange baryon states used in SU(3) fits. The last three columns show the mean values and "External Errors," discussed in the text, obtained from the new as well as old results.[6]

State	M (MeV)	Γ (MeV)	x	$\bar{M}$ (MeV)	$\bar{\Gamma}$ (MeV)	$\bar{x}$
S11	1523	78	0.33	1530 ± 27	104 ± 38	0.32 ± 0.05[a]
D13	1528	119	0.57	1520 ± 9	121 ± 12	0.54 ± 0.04
D15	1655	141	0.40	1672 ± 9	143 ± 26	0.42 ± 0.04
F15	1679	133	0.60	1687 ± 5	128 ± 22	0.62 ± 0.05

[a]Error increased from 0.04.

Table II. Old and new parameters for isospin zero, S = 1 baryon states included in the SU(3) fits. Values in square brackets [ ] have been kept constant in the fits. Values in parentheses ( ) have been constrained to be near the PDG values.

	M (MeV)	Γ (MeV)	$\bar{K}N$ x	$\Sigma\pi$ $\sqrt{xx'}$	$\Lambda\eta$ $\sqrt{xx'}$	Authors	Ref.
S01	1640 ± 40	45 ± 20	0.35 ± 0.05	?		Langbein +	12
	(1668)	(29)	(0.16)	(-0.27)		Lea +	13
	[1676]	[26]	0.38 ± 0.05	[-0.30]		Levi-Setti +	14
	1670	15 to 38	0.20	-0.30	0.26	PDG	6
	1673 ± 7[a]	30 ± 10[a]	0.25 ± 0.08[a]	-0.30 ± 0.04[a]	0.25 ± 0.04[b]	This review	
D03	1680 ± 20	40 ± 10	0.15 ± 0.05	-0.26 ± 0.07		Langbein +	12
	(1689)	(54)	(0.24)	(-0.32)		Lea +	13
	[1690]	63 ± 5	0.35 ± 0.05			Levi-Setti +	14
	[1690]	90 ± 10		-0.42 ± 0.05		Levi-Setti +	14
	1690	31 - 85	0.20	-0.35		PDG	6
	1688 ± 5[a]	53 ± 17[a]	0.28 ± 0.05[c]	-0.35 ± 0.05[c]		This review	
D05	1810 ± 10	60 ± 20	0.10 ± 0.03	-0.27 ± 0.07		Langbein +	12
	(1830)	(80)	(0.08)	(-0.16)		Lea +	13
	[1831]	128 ± 20	0.07 ± 0.02			Levi-Setti +	14
	1831 ± 10	113 ± 10		-0.12 ± 0.02		Levi-Setti +	14
	1835	74 - 150	0.07	-0.16		PDG	6
	1827 ± 11[a]	89 ± 32[a]	0.07 ± 0.03[a]	-0.16 ± 0.04[a]		This review	
F05	1818 ± 3	70 ± 5	0.47 ± 0.02	-0.25 ± 0.03		Langbein +	12
	(1817)	(79)	(0.61)	(-0.26)		Lea +	13
	[1818]	86 ± 5	0.65 ± 0.02			Levi-Setti +	14
	[1818]	95 ± 10		-0.29 ± 0.03		Levi-Setti +	14
	1820 ± 5	64 - 104	0.62	-0.26		PDG	6
	1819 ± 6[c]	80 ± 15[c]	0.58 ± 0.08[c]	-0.26 ± 0.03[c]		This review	

[a]Mean values and "External Errors" (see text).

[b]Error increased.

[c]Average and errors estimated from the dispersion of reported values.

Table III. Old and new parameters for isospin-1, S = -1 baryon states included in the SU(3) fits. Values in square brackets [ ] have been kept constant in the partial wave analysis fit. Values in parentheses ( ) have been constrained to be near the PDG values.

	M (MeV)	Γ (MeV)	$\bar{K}N$ x	$\Sigma\pi$ $\sqrt{xx'}$	$\Lambda\pi$ $\sqrt{xx'}$	Authors	Ref.
S11	1790 ± 15	100 ± 20	0.45 ± 0.05	0.13 ± 0.02	-0.30 ± 0.05	Langbein +	12
	(1750)	(60)	(0.79)	(0.15)	~0	Lea +	13
	1730 ± 10	50 ± 20	0.08 ± 0.03			Levi-Setti +[a]	14
	1719 ± 10	90 ± 20		0.11 ± 0.02		Levi-Setti +	14
	1727 ± 10	65 ± 10			-0.12 ± 0.03	Levi-Setti +	14
	1750	50 - 80	0.1 - 0.8	0.16[b]	-0.25 to -0.10	PDG	6
	1756 ± 24[c]	65 ± 20[c]	0.08 or 0.6[d]	0.14 ± 0.04[e]	-0.18 ± 0.08[e]	This review	
D13	1675 ± 15	65 ± 20	0.10 ± 0.03	0.23 ± 0.05	0.13 ± 0.03	Langbein +	12
	(1670)	(51)	(0.08)	(0.19)	(0.09)	Lea +	13
	1670	50	0.08	~0.18	0.08 to 0.16	PDG	6
	1669 ± 8[c]	50 ± 9[c]	0.08 ± 0.03[c]	0.19 ± 0.04[c]	0.11 ± 0.03[c]	This review	
D15	1770 ± 5	123 ± 10	0.39 ± 0.01	≤0.09	-0.15 ± 0.04	Langbein +	12
	(1766)	(105)	(0.38)	(0.06)	(-0.25)	Lea +	13
	[1765]	[110]	0.35 ± 0.03	0.09 ± 0.02		Levi-Setti	14
	1768 ± 5	119 ± 10			-0.28 ± 0.03	Levi-Setti	14
	1765 ± 5	60 to 146	0.42	0.07	-0.25	PDG	6
	1765 ± 8[e]	108 ± 28	0.40 ± 0.05[e]	0.07 ± 0.03[e]	-0.22 ± 0.04[e]	This review	
F15	(1915)	(80)	(0.15)	(-0.10)	(-0.10)	Lea +	13
	[1915]	[65]			-0.05	Levi-Setti +	14
	1910	70	0.11 to 0.18	-0.06 to -0.14	-0.07 to -0.11	PDG	6
	1910 ± 10[e]	70 ± 20[e]	0.15 ± 0.05[e]	-0.10 ± 0.04[e]	-0.09 ± 0.03[e]	This review	

[a] For another very close state see Table IX.

[b] Value from J.K. KIM, Ref. 31.

[c] Mean values and "External Errors" (see text).

[d] Three fits were performed (see Table V): one with x = 0.08 ± 0.06, another with x = 0.6 ± 0.1, and one without this information at all.

[e] Average and errors estimated from the dispersion of reported values.

Table IV. Unbroken SU(3) fits to the $3/2^+$ decuplet. The data used are listed in the PDG compilation;[6] new data are discussed in Sec. I. The three values of g correspond to different forms for the kinematical factor, as discussed in the text.

Decay	Γ (MeV)	Partial mode (%)	g_1	g_2	g_3
$\Delta(1233) \to N\pi$	115 ± 5	99.4 ± 0.6	2.29 ± 0.05	5.02 ± 0.11	149 ± 3
$\Xi(1532) \to \Xi\pi$	9.1 ± 0.5	100	1.78 ± 0.05	4.21 ± 0.12	148 ± 4
$\Sigma(1385) \to \Lambda\pi$	36 ± 6	88 ± 5	2.02 ± 0.18	4.53 ± 0.40	147 ± 13
$\Sigma(1385) \to \Sigma\pi$	36 ± 6	12 ± 5	1.91 ± 0.43	4.6 ± 1.0	155 ± 35
$\langle g \rangle$			2.04 ± 0.04	4.65 ± 0.08	149 ± 3
χ^2			50.0/3DF	24.0/3DF	0.09/3DF

Table V. Mass and width are listed for each state, as well as the values of the amplitude, $\sqrt{xx'}$, at the resonance mass for each decay mode. For a discussion of how average values were obtained, see Sec. I. F_b are kinematical factors, $F_b = B_\ell(p)\frac{M_N}{M_R}p$, where B_ℓ is the Blatt-Weisskopf barrier factor.[18] The g_i, α, and θ are defined in the text.

State	M (MeV)	Γ (MeV)	Mode	$\sqrt{xx'}$	F_b (MeV/c)
Λ(1405)	1402 ± 4	38 ± 8	$N\bar{K}$	0.80 ± 0.06[a]	65
			Σπ	0.20 ± 0.06[a]	29
N(1530)	1530 ± 27	104 ± 38	Nπ	0.32 ± 0.05	312
			Nη	[b](-)0.42 ± 0.05	191
Λ(1670)	1673 ± 7	30 ± 10	$N\bar{K}$	0.25 ± 0.08	394
			Σπ	-0.30 ± 0.04	249
			Λη	[b](-)0.25 ± 0.04	131
Σ(1760)	1756 ± 24	65 ± 20	$N\bar{K}$	0.08 or 0.6[c]	550
			Σπ	0.14 ± 0.04	364
			Λπ	-0.18 ± 0.08	440

Fits	g_F	g_D	g_1	α	θ (deg)	χ^2
1. No $\bar{K}N$ for Σ(1760)	0.41 ± 0.05	-0.08 ± 0.04	1.1 ± 0.1	1.2 ± 0.1	8 ± 4	15
2. x[Σ(1760)] = 0.08 ± 0.05	0.28 ± 0.04	0.05 ± 0.06	1.1 ± 0.1	0.88 ± 0.04	-3 ± 6	26
3. x[Σ(1760)] = 0.6 ± 0.1	0.41 ± 0.04	-0.09 ± 0.04	1.1 ± 0.1	1.2 ± 0.1	8 ± 3	15

[a] Values obtained in low-energy $\bar{K}N$ partial wave analyses (Refs. 26 and 27).

[b] The signs of these two amplitudes were not measured, they both have been chosen — because this choice gave better fits.

[c] Different partial wave analyses give different results; see Table III and Sec. I.

Table VI. $J^P = 3/2^-$ states. The mass (in parentheses with the symbol) and total width are listed for each state, as well as the values of the amplitude $\sqrt{xx'}$ at the resonance mass for each decay mode. For a discussion of how each value has been obtained, see Tables I-III and Sec. I. F_b are kinematical factors, $F_b = B_\ell(p) \frac{M_N}{M_R} p$, where for B_ℓ the Blatt-Weisskopf form was used.[18] The results of the fits are shown in the lower part of the table (for both $\{8\}\times\{8\}$ and $\{10\}\times\{8\}$ decays).

State	Γ (MeV)	$\{8\}\times\{8\}$ Mode	$\sqrt{xx'}$	F_b (MeV/c)	$\{10\}\times\{8\}$ Mode	$\sqrt{xx'}$	F_b (MeV/c)
Λ(1518)	16 ± 2	$\bar{K}N$	0.45 ± 0.03	19.8	Σ(1385)π	0.20 ± 0.02[a]	14.2
		Σπ	0.43 ± 0.03	23.7			
N(1520)	121 ± 12	Nπ	0.54 ± 0.04	150	Δ(1233)π	0.32 ± 0.05[b]	135
Λ(1688)	53 ± 17	$\bar{K}N$	0.28 ± 0.05	117	Σ(1385)π	-0.06 ± 0.03[a]	135
		Σπ	-0.35 ± 0.05	109			
Σ(1669)	50 ± 9	$\bar{K}N$	0.08 ± 0.03	106	Σ(1385)π	-0.01 ± 0.03[a]	125
		Σπ	0.19 ± 0.04	99			
		Λπ	0.11 ± 0.03	118			

$\{8\}\times\{8\}$	$\chi^2 = 9.1/4DF$	$g_F = 0.30 \pm 0.04$	$g_\Delta = 0.47 \pm 0.08$
		$g_D = 0.80 \pm 0.04$	$g_\Sigma = 0.06 \pm 0.18$
$\{10\}\times\{8\}$	$\chi^2 = 16/2DF$	$g_1 = 0.87 \pm 0.07$	$(g_\Lambda)_8 = 0.12 \pm 0.04$
For 70, $8^{1/2}$		$\alpha = 0.34 \pm 0.09$	$g_{av} = 0.19 \pm 0.04$
$\alpha_{exp} = 0.375$		$\theta = -(23 \pm 4)^\circ$	$\theta = (75^{+5}_{-10})^\circ$

[a] Prevost et al.[23]
[b] Herndon et al.,[11] see Sec. I.

Table VII. $J^P = 5/2^-$ states. The mass (in parentheses with the symbol) and total width are listed for each state, as well as the values of the amplitude $\sqrt{xx'}$ at the resonance mass for each decay mode. For a discussion of how each value has been obtained, see Sec. I. F_b are kinematical factors, $F_b = B_\ell(p) \frac{M_N}{M_R} p$, where for B_ℓ the Blatt-Weisskopf form was used.[18] The results of the fits are shown in the lower part of the table (for the two types of decays $\{8\}\times\{8\}$ and $\{10\}\times\{8\}$).

State	Γ (MeV)	Mode	$\{8\}\times\{8\}$ $\sqrt{xx'}$	F_b (MeV/c)	Mode	$\{10\}\times\{8\}$ $\sqrt{xx'}$	F_b (MeV/c)
N(1672)	143 ± 26	$N\pi$	0.42 ± 0.04	209	$\Delta(1233)\pi$	0.50 ± 0.15[a]	74
Λ(1827)	89 ± 32	$\bar{K}N$	0.07 ± 0.03	183	$\Sigma(1385)\pi$	0.11 ± 0.03[b]	76
		$\Sigma\pi$	-0.16 ± 0.04	170			
Σ(1765)	108 ± 28	$\bar{K}N$	0.40 ± 0.05	156	$\Sigma(1385)\pi$	-0.12 ± 0.03[b]	47
		$\Sigma\pi$	0.07 ± 0.03	146			
		$\Lambda\pi$	-0.22 ± 0.04	162			

$\{8\}\times\{8\}$	$\chi^2 = 1.9/4DF$	$g_F = 0.82 \pm 0.05$	$g_\Delta = 1.2 \pm 0.4$
$\{10\}\times\{8\}$	$\chi^2 = 2.0/2DF$	$g_D = -0.12 \pm 0.04$	$g_\Lambda = 0.6 \pm 0.2$
For 70, $8^{3/2}$		$F/D = -0.11 \pm 0.04$	$g_\Sigma = 0.8 \pm 0.2$
$\alpha_{exp} = 1.5$		$\alpha = 1.13 \pm 0.05$	$g_{av} = 0.76 \pm 0.13$

[a] Herndon et al.,[11] see Sec. I.

[b] Prevost et al.[23]

Table VIII. $J^P = 5/2^+$ states. The mass (in parentheses with the symbol) and total width are listed for each decay mode. For a discussion of how each value has been obtained, see Tables I - III and Sec. I. F_b are kinematical factors, $F_b = B_\ell(p) \frac{M_N}{M_R} p$, where for B_ℓ the Blatt-Weisskopf form was used.[18] The results of the fits are shown in the lower part of the table (for both $\{8\}\times\{8\}$ and $\{10\}\times\{8\}$ decays).

State	Γ (MeV)	Mode	$\{8\}\times\{8\}$ $\sqrt{xx'}$	F_b (MeV/c)	Mode	$\{10\}\times\{8\}$ $\sqrt{xx'}$	F_b (MeV/c)
N(1687)	128 ± 22	$N\pi$	0.62 ± 0.05	116	$\Delta(1236)\pi$	0.25 ± 0.05[a]	160
$\Lambda(1819)$	80 ± 15	$\bar{K}N$	0.58 ± 0.05	90	$\Sigma(1385)\pi$	0.11 ± 0.03[b]	142
		$\Sigma\pi$	-0.26 ± 0.03	78			
$\Sigma(1910)$	70 ± 20	$\bar{K}N$	0.15 ± 0.05	128			
		$\Sigma\pi$	-0.10 ± 0.04	114			
		$\Lambda\pi$	-0.09 ± 0.03	130			

$\{8\}\times\{8\}$ $\chi^2 = 6.5/4DF$	$g_F = 0.71 \pm 0.05$	$g_\Delta = 0.32 \pm 0.07$
$\{10\}\times\{8\}$ $\chi^2 = 5.0/1DF$	$g_D = 0.58 \pm 0.08$	$g_\Lambda = 0.14 \pm 0.04$
For 56, $8^{1/2}$	$F/D = 0.61 \pm 0.09$	$g_{av} = 0.19 \pm 0.04$
$\alpha_{exp} = 0.6$	$\alpha = 0.62 \pm 0.04$	

[a] Herndon et al.,[11] see Sec. I.

[b] Prevost et al.[23]

Table IX. Candidates for other $J^P = 1/2^-$ multiplets. Old results are listed in the PDG compilation.[6] States listed with a status of "good" are established; the ones listed as "possible" are still in doubt, essentially because the different partial wave analyses do not agree.

State	M (MeV)	Γ (MeV)	Mode	$\sqrt{xx'}$	Reference	Status	Multiplet
Δ(1650)	1615 - 1695	130 - 200	Nπ	0.28	PDG[6]	Good	{10}
N(1700)	1665 - 1765	100 - 400	Nπ	0.60	PDG[6]	Good	{8}
Λ(1800)	1780 - 1872	40 - 100	$N\bar{K}$	0.18 - 0.80	PDG[6]	Possible	{8}
	1830 ± 20	70 ± 15	$N\bar{K}$	0.35 ± 0.15	Langbein[12]	Possible	
			Σπ	0.24	Kim[31]	Possible	
Σ(1620)	1620	40	$N\bar{K}$	0.05	Kim[31]	Possible	{8}, {10}
			Σπ	0.08	Kim[31]	Possible	
			Λπ	0.15	Kim[31]	Possible	
	1620	65 ± 20	$N\bar{K}$	0.22 ± 0.02	Langbein[12]	Possible	
			Σπ	0.40 ± 0.06	Langbein[12]	Possible	
Σ(1725)	1730 ± 10	50 ± 20	$N\bar{K}$	0.08 ± 0.03	Levi-Setti[14]	Possible	{8}, {10}
	1719 ± 10	90 ± 20	Σπ	0.11 ± 0.02	Levi-Setti[14]	Possible	
	1727 ± 10	65 ± 10	Λπ	-0.12 ± 0.03	Levi-Setti[14]	Possible	

Table X. Candidates for other $J^P = 3/2^-$ multiplets. Older results are listed in the PDG[6] compilation. States listed with a status of "good" are established; the others are still in doubt.

State	M (MeV)	Γ (MeV)	Mode	$\sqrt{xx'}$	Reference	Status	Multiplet
Δ(1670)	1650 - 1720	175 - 300	Nπ	0.15	PDG[6]	Good	{10}
N(1730)	1730	130	Nπ	0.10	Ayed[7]	Likely	{8}
			Δπ	?	Herndon[11]		
Λ(2010)	2010	130	Σπ	-0.20	Galtieri[32]	Possible	{8}
Σ(1710)	1719 ± 10	50 ± 10	Σπ	-0.06 ± 0.03	Levi-Setti[14]	Possible	{8}, {10}
	1700 ± 20	48 ± 10	Λπ	-0.04 ± 0.02	Levi-Setti[14]	Possible	
Σ(1740)	1731 ± 10	56 ± 10	Σπ	0.05 ± 0.03	Levi-Setti[14]	Possible	{8}, {10}
	1752 ± 20	80 ± 30	Λπ	0.06 ± 0.02	Levi-Setti[14]		
Σ(1860)	1863	95	$N\bar{K}$	0.22	Lea[13]	Possible	{8}, {10}
			Λπ	-0.12	Lea[13]		
Σ(1940)	1940	220	Σπ	-0.13	PDG[6]	Possible	{8}, {10}
			Λπ	-0.09			

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