We discuss properties of baryon resonances belonging to the $N$, $\Delta$, $\Sigma$, $\Lambda$, $\Xi$, and $\Omega$ families in a collective string-like model for the nucleon, in which the radial excitations are interpreted as rotations and vibrations of the string configuration. We find good overall agreement with the available data. The main discrepancies are found for low lying $S$-wave states, in particular $N(1535)$, $N(1650)$, $\Sigma(1750)$, $\Lambda^{*}(1405)$, $\Lambda(1670)$ and $\Lambda(1800)$.

1 Introduction

The development of dedicated experimental facilities to probe the structure of hadrons in the nonperturbative region of QCD with far greater precision than before has stimulated us to reexamine hadron spectroscopy in a novel approach in which both internal (spin-flavor-color) and space degrees of freedom of hadrons are treated algebraically. The new ingredient is the introduction of a space symmetry or spectrum generating algebra for the radial excitations which for baryons was taken as $U(7)^{1}$. The algebraic approach unifies the harmonic oscillator quark model with collective string-like models of baryons.

In this contribution we present an analysis of the mass spectrum and strong couplings of both nonstrange and strange baryon resonances in the framework of a collective string-like $qqq$ model in which the radial excitations are treated as rotations and vibrations of the strings. The algebraic structure of the model enables us to obtain transparent results (mass formula, selection rules and decay widths) that can be used to analyze and interpret the experimental data, and look for evidence of the existence of unconventional (i.e. non $qqq$ configurations of quarks and gluons, such as hybrid quark-gluon states $qqq$-$g$ or multiquark meson-baryon bound states $qqq$-$q\overline{q}$).

2 Mass spectrum

We consider baryons to be built of three constituent parts which are characterized by both internal and radial (or spatial) degrees of freedom. The internal degrees of freedom are described by the usual spin-flavor (sf) and color (c) algebras $SU_{sf}(6) \otimes SU_{c}(3)$. The radial degrees of freedom for the relative motion of the three constituent parts are taken as the Jacobi coordinates, which are
treated algebraically in terms of the spectrum generating algebra of $U(7)$. The full algebraic structure is obtained by combining the radial part with the internal spin-flavor-color part

$$\mathcal{G} = U(7) \otimes SU_{sf}(6) \otimes SU_c(3),$$

in such a way that the total baryon wave function is antisymmetric.

For the radial part we consider a collective (string-like) model of the nucleon in which the baryons are interpreted as rotational and vibrational excitations of an oblate symmetric top. The spectrum consists of a series of vibrational excitations labeled by $(v_1, v_2)$, and a tower of rotational excitations built on top of each vibration. The occurrence of linear Regge trajectories suggests to add, in addition to the vibrational frequencies $\kappa_1$ and $\kappa_2$, a term linear in $L$. The slope of these trajectories is given by $\alpha$. For the spin-flavor part of the mass operator we use a Gürsey-Radicati form. These considerations lead to a mass formula for nonstrange and strange baryons of the form

$$M^2 = M_0^2 + \kappa_1 v_1 + \kappa_2 v_2 + \alpha L + a \left[ \langle \hat{C}_2(SU_{sf}(6)) \rangle - 45 \right]$$

$$+ b \left[ \langle \hat{C}_2(SU(3)) \rangle - 9 \right] + c \left[ S(S+1) - \frac{3}{4} \right]$$

$$+ d \left[ Y - 1 \right] + e \left[ Y^2 - 1 \right] + f \left[ I(I+1) - \frac{3}{4} \right].$$

The coefficient $M_0^2$ is determined by the nucleon mass $M_0^2 = 0.882$ GeV$^2$. The remaining nine coefficients are obtained in a simultaneous fit to 48 three and four star resonances which have been assigned as octet and decuplet states. We find a good overall description of both positive and negative baryon resonances of the $N$, $\Delta$, $\Sigma$, $\Lambda$, $\Xi$ and $\Omega$ families with an r.m.s. deviation of $\delta = 33$ MeV to be compared with $\delta = 39$ MeV in a fit to 25 $N$ and $\Delta$ resonances. There is no need for an additional energy shift for the positive parity states and another one for the negative parity states, as in the relativized quark model.

The three resonances that were assigned as singlet states (and were not included in the fitting procedure) show a deviation of about 100 MeV or more from the data: the $\Lambda^*(1405)$, $\Lambda^*(1520)$ and $\Lambda^*(2100)$ resonances are overpredicted by 236, 121 and 97 MeV, respectively. An additional energy shift for the singlet states (without effecting the masses of the octet and decuplet states) can be obtained by adding to the mass formula of Eq. (2) a term $\Delta M^2$ that only acts on the singlet states. However, since $\Lambda^*(1405)$ and $\Lambda^*(1520)$ are spin-orbit partners, their mass splitting of 115 MeV cannot be reproduced by such a mechanism. In principle, this splitting can be obtained from a spin-orbit interaction, but the rest of the baryon spectra shows no evidence for such a
Table 1: Masses of the first three $P_{11}$ states in MeV

|        | PDG       | Zagreb    | RQM      | present   |
|--------|-----------|-----------|----------|-----------|
| $N(1440)$ | 1439 ± 19 | 1540      | 1444     |           |
| $N(1710)$ | 1729 ± 16 | 1770      | 1683     |           |
|         | 1740 ± 11 | 1880      | 1713     |           |

large spin-orbit coupling. A more likely explanation is the proximity of the $Λ^*(1405)$ resonance to the $N\bar{K}$ threshold (see next section).

A common feature to all $q^3$ quark models is the occurrence of missing resonances. In a recent three-channel analysis by the Zagreb group evidence was found for the existence of a third $P_{11}$ nucleon resonance at 1740 ± 11 MeV. The first two $P_{11}$ states at 1439 ± 19 MeV and 1729 ± 16 MeV correspond to the $N(1440)$ and $N(1710)$ resonances of the PDG. It is tempting to assign the extra resonance as one of the missing resonances. In the present calculation it is associated with the $^2S_{1/2}[20,1^+]$ configuration and appears at 1713 MeV, compared to 1880 MeV in the relativized quark model (RQM) (see Table 1).

A recent analysis of new data on kaon photoproduction has shown evidence for a $D_{13}$ resonance at 1895 MeV. In the present calculation, there are several possible assignments. The lowest state that can be assigned to this new resonance is a vibrational excitation $(v_1, v_2) = (0, 1)$ with $^2S_{3/2}[56, 1^-]$ at 1847 MeV. This state belongs to the same vibrational band as the $N(1710)$ resonance. In the relativized quark model a $D_{13}$ state has been predicted at 1960 MeV.

### 3 Strong couplings

Decay processes are far more sensitive to details in the baryon wave functions than are masses. Here we consider strong decays of baryons by the emission of a pseudoscalar meson

$$ B \to B' + M , $$

in an elementary emission model. The calculation of the strong decay widths involves a phase space factor, a spin-flavor matrix element and a spatial matrix element which is obtained in the collective model by folding with a distribution.
function over the volume of the nucleon. The calculations are carried out in
the rest frame of the decaying resonance. The transition operator that induces
the strong decay is determined in a fit to the $N\pi$ and $\Delta\pi$ channels which are
relatively well known. It is important to stress that in the present analysis
the same transition operator is used for all resonances and all decay channels.

The calculated decay widths are primarily due to spin-flavor symmetry
and phase space. $N$ and $\Delta$ resonances decay predominantly into the $\pi$ channel,
and strange resonances mainly into the $\pi$ and $K$ channel. Phase space factors
suppress the $\eta$ and $K$ decays. The use of the collective form factors introduces
a power-law dependence on the meson momentum, compared to an exponential
for harmonic oscillator form factors. In general, our results for the strong
decay widths are in fair overall agreement with the available data, which shows
that the combination of a collective string-like $qqq$ model of baryons and an
elementary emission model for the decays can account for the main features of the
data. As an example, in Table 2 we present the strong decays of three and
four star $\Delta$ resonances.

There are, however, a few exceptions which could indicate evidence for
the importance of degrees of freedom which are outside the present $qqq$ model of
baryons. The $\eta$ decays of octet baryons show an unusual behavior: the $S$-wave
states $N(1535)$, $\Sigma(1750)$ and $\Lambda(1670)$ are found experimentally to have a large
branching ratio to the $\eta$ channel with partial decay widths of $74 \pm 39$, $39 \pm 28$
and $9 \pm 5$ MeV, respectively. In our calculation these resonances are assigned
as octet partners and only differ in their flavor content. The smallness of the
calculated $\eta$ widths ($<0.5$ MeV) is mainly due to the available phase space.
The results of this analysis suggest that the observed $\eta$ widths are not due
to a conventional $qqq$ state, but may rather indicate evidence for the presence
of a state in the same mass region of a more exotic nature, such as a quasi-
molecular $S$-wave resonance $qqq$-$q\eta$ just below or above threshold, bound by
Van der Waals type forces (for example $N\eta$, $\Sigma\eta$ or $\Lambda\eta$).

The decay of $^4S[70, L^P] \Lambda$ states into the $N\bar{K}$ channel is forbidden by a
spin-flavor selection rule which is similar to the Moorhouse selection rule in
electromagnetic couplings. Therefore, the calculated $N\bar{K}$ widths of $\Lambda(1800)$,
$\Lambda(1830)$ and $\Lambda(2110)$ vanish, whereas all of them have been observed exper-
imentally. The $\Lambda(1800)S_{01}$ state has large decay width into $N\bar{K}^*(892)$.
Since the mass of the resonance is just around the threshold of this channel,
this could indicate a coupling with a quasi-molecular $S$ wave. The $N\bar{K}$ width
of $\Lambda(1830)$ is relatively small ($6 \pm 3$ MeV), and hence in qualitative agreement
with the selection rule. The situation for the $\Lambda(2110)$ resonance is unclear.

The $\Lambda^*(1405)$ resonance has an anomalously large decay width ($50 \pm 2$ MeV)
into $\Sigma\pi$. This feature emphasizes its quasi-molecular nature due to the prox-
Table 2: Strong decay widths of three and four star delta resonances in MeV. For the $\eta$ mesons we introduce a mixing angle $\beta_P = -23^\circ$ between the octet and singlet mesons. The experimental values are taken from \textsuperscript{6}. Decay channels labeled by $-$ are below threshold.

| Baryon          | $N\pi$ | $\Sigma K$ | $\Delta \pi$ | $\Delta \eta$ | $\Sigma^*(1385)K$ |
|-----------------|--------|------------|--------------|---------------|------------------|
| $\Delta(1232)P_{33}$ | 116    | $-$        | $-$          | $-$           | $-$              |
|                 | $119 \pm 5$ |           |              |               |                  |
| $\Delta(1600)P_{33}$ | 108    | $-$        | 25           | $-$           | $-$              |
|                 | $61 \pm 32$ |           |              | $193 \pm 76$ |                  |
| $\Delta(1620)S_{31}$ | 16     | $-$        | 89           | $-$           | $-$              |
|                 | $38 \pm 11$ |           |              | $68 \pm 26$  |                  |
| $\Delta(1700)D_{33}$ | 27     | 0          | 144          | $-$           | $-$              |
|                 | $45 \pm 21$ |           |              | $135 \pm 64$ |                  |
| $\Delta(1905)F_{35}$ | 9      | 1          | 45           | 1             | 0                |
|                 | $36 \pm 20$ |           |              | $< 45 \pm 45$ |                  |
| $\Delta(1910)P_{31}$ | 42     | 2          | 4            | 0             | 0                |
|                 | $52 \pm 19$ |           |              |               |                  |
| $\Delta(1920)P_{33}$ | 22     | 1          | 29           | 1             | 0                |
|                 | $28 \pm 19$ |           |              |               |                  |
| $\Delta(1930)D_{35}$ | 0      | 0          | 0            | 0             | 0                |
|                 | $53 \pm 23$ |           |              |               |                  |
| $\Delta(1950)F_{37}$ | 45     | 6          | 36           | 2             | 0                |
|                 | $120 \pm 14$ |           |              | $80 \pm 18$  |                  |
| $\Delta(2420)H_{3,11}$ | 12     | 4          | 11           | 2             | 1                |
|                 | $40 \pm 22$ |           |              |               |                  |

Summary and conclusions

In this contribution we have analyzed the mass spectrum and the strong couplings of both strange and nonstrange baryons. The combination of a collective
string-like $qqq$ model of baryons in which the orbitally excited baryons are interpreted as collective rotations and vibrations of the strings, and a simple elementary emission model for the strong decays can account for the main features of the data.

The main discrepancies are found for the low-lying $S$-wave states, specifically $N(1535)$, $N(1650)$, $\Sigma(1750)$, $\Lambda^*(1405)$, $\Lambda(1670)$ and $\Lambda(1800)$. All of these resonances have masses which are close to the threshold of a meson-baryon decay channel, and hence they could mix with a quasi-molecular $S$ wave resonance of the form $qqq - q\bar{q}$. In contrary, decuplet baryons have no low-lying $S$ states with masses close to the threshold of a particular decay channel, and their spectroscopy is described very well.

The results of our analysis suggest that in future experiments particular attention be paid to the resonances mentioned above in order to elucidate their structure, and to look for evidence of the existence of exotic (non $qqq$) configurations of quarks and gluons.

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