Hadron Spectroscopy, Results and Ideas.

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New Results from the BnGa PWA

The BnGa partial wave analysis group has fitted a very large set of data in a coupled-channel analysis [1]. The data comprise all major reactions like $\gamma p \rightarrow p\pi^0, n\pi^+, p\eta, \Lambda K^+, \Sigma^0 K^+, \Sigma^+ K^0$, and $p\pi^0\pi^0$ and is further constrained by pion induced inelastic reactions like $\pi N \rightarrow \Lambda K, \Sigma K, N\eta, N\pi\pi$, and by the real and imaginary part of $\pi N$ scattering amplitudes, alternative from Karlsruhe-Helsinki [2] or from the GWU [3]. The analysis uses a K-matrix with up to eight constrained channels ($N\pi$, $N\eta$, $\Lambda K$, $\Sigma K$, $\Delta\pi$-low-$L$, $\Delta\pi$-high-$L$, $N(\pi\pi)_{s\text{-wave}}$) and one channel ($N\omega$) which is not constrained by data and which simulates unseen decay modes. Further decay modes like $N(1520)^{3/2-}$, $N(1535)^{1/2-}$, $N(1680)^{5/2+}$, $N(1710)^{1/2+}$, or $Nf_2(1270)$ are added in a $D$-vector formalism which does not take into account rescattering between the different channels. The background is described by reggeized $t$-channel exchange of vector mesons; for the reactions $\gamma p \rightarrow n\pi^+$ and $\gamma p \rightarrow \Sigma^0 K^+$, $\pi$ and $K$ exchanges are admitted. $N$ and $\Delta$ exchange in contribute via Born diagrams in the $s$ and the $u$-channel. In each partial wave, non-resonant transitions like $\gamma p \rightarrow p\eta$ are admitted. For most partial waves, these are constants, in the wave with $J^P = 1/2^-$, a simple function in $s$ is used. Full account of the formalism is given in [4].

The results are summarized in Table 1. A large number of parameters on baryon resonances ($N_{pp}$ in the Table) is presented in [1]. In the Review of Particle Properties [5] there are now seven new resonances. The one-star $N(1685)$ has been reported as narrow peak in analyses of $\gamma n \rightarrow n\eta$ [6]-[9]; it is proposed to belong to an antidecuplet which would require $J^P = 1/2^+$ quantum numbers. $N(2040)^{3/2-}$ - with one-star - is seen in $J/\psi \rightarrow p\bar{p}\pi$ [10]. Five resonances stem from the BnGa partial wave analysis, even though most of these resonances have been reported before but did not pass the threshold to a recognized resonance. Four of the new resonances received a two-star status. Early observations of $N(1875)^{3/2-}$, reported by Manley [11], Bell [12], Cutkosky [13], and Saxon [14] had been listed under $N(2080)$; they can now be found - jointly with the BnGa result - under a new three-star $N(1875)^{3/2-}$. $N(1900)^{3/2+}$ was upgraded from two to three stars.

In the region above 1.8 GeV, no unique solution was found by the PWA. There were distinct solutions with two or three resonances with $J^P = 3/2^+$ or one or two resonances with $J^P = 5/2^+$. Even for these “main” solutions, called BnGa2011-1 and BnGa2011-2, the resulting amplitudes depend on the inclusion or exclusion of high-mass resonances (above 2200 MeV), on the inclusion or not of additional channel couplings, also on start values. From the spread of results within a class of solutions, error bars were derived. In some cases different hypotheses lead to significantly different pole positions, and the error bars become large. In the discussion, the alternative values sometimes support different interpretations. Here we use the values which support an interpretation under discussion, either from BnGa2011-1 or from BnGa2011-2. Both are discussed in [15].
Interpretation

Baryon from quark models and the lattice: The systematics of the baryon ground states were constitutive for the development of quark models. In the harmonic oscillator (h.o.) approximation, the quark model predicts a ladder of baryon resonances with equidistant squared masses, alternating with positive and negative parity, and this pattern survives approximately in more realistic potentials (see, e.g. [16, 17]). Recent lattice gauge calculations [18] confirm these findings. However, masses of resonances with positive and negative parities are often similar, in striking disagreement with quark models and the results on the lattice. A second problem of both, lattice calculations and quark models, is the number of expected states which is considerably larger than confirmed experimentally, a fact which is known as problem of missing resonances. The number of expected states is much reduced if it is assumed that two quarks form a quasi-stable diquark [19].

Diquarks: In the fourth resonance region, at about 2 GeV, at least four positive-parity nucleon resonances were found, even though some of the solutions were ambiguous. In the most straightforward interpretation, we use solution BnGa2011-01, and assign the four states

\[ N(1875)1/2^+, \quad N(1915)3/2^+, \quad N(1860)5/2^+, \quad N(1990)7/2^+ \]

to a spin quartet of nucleon resonances [20]. This assignment excludes conventional diquark models: A S-wave diquark is symmetric with respect to the exchange of the two quarks, a third quark with even angular momentum is symmetric with respect to the diquark, but the isospin wave function of a nucleon resonance is of mixed-symmetry. Hence the overall spin-flavor-spatial wave function is of mixed symmetry. With an antisymmetric color wave function,
Table 2: Spin-parity doublets for \( J = \frac{1}{2}, \frac{3}{2}, \frac{5}{2} \) (first three boxes) and for \( J = \frac{1}{2}, \cdots, \frac{7}{2} \) (four boxes in the lower part of the table) for nucleon and \( \Delta \) resonances. Meson and baryon resonances on the leading Regge trajectory like \( \Delta(1950)\frac{7}{2}^- \) or \( a_6(2450) \) have no mass-degenerate parity partner; shown are \( \Delta(1950)\frac{7}{2}^+ \) and \( \Delta(2200)\frac{7}{2}^- \) but other parity partners not degenerate in mass exist as well.

the overall wave function has no defined exchange symmetry and the Pauli principle would be violated. With the assignment of the four resonances to a spin quartet, the diquark hypothesis - which freezes one pair of quarks into a quasi-stable S-wave flavor diquark - is ruled out as explanation of the *missing resonance problem*.

**Parity doublets:** Ground-state baryons acquire their mass due to spontaneous breaking of chiral symmetry. Thus, \( N_{1/2^-}(1535) \) is much heavier than its chiral partner, \( N_{1/2^+}(940) \). At high excitation energies, details of the chiral potential could be irrelevant, and chiral symmetry could be restored \([21]\). Then parity doublets should occur. These have been observed, indeed. Some previously known doublets are listed in Table 2. The new resonances form parity doublets as well, in particular when solution BnGa2011-02 is chosen.

**AdS/QCD:** There is, however, one caveat: both mesons and baryons on the leading Regge trajectory have no mass-degenerate parity partner. This selectivity in the formation of parity partners follows from the AdS/QCD mass formula for \( n\bar{n} \) mesons and for \( \Delta \) baryons \( M^2 = c + a(L + N) \) where \( c = 1/2 \) for mesons and 3/2 for baryons, and where \( a \) is the string constant \([22]\). For \( \Delta \) and \( N \) resonances, the formula can be extended \([23]\) to

\[
M^2 = a \cdot (L + N + 3/2) - \alpha_D
\]

which reproduces in a two-parameter fit the mass spectrum 2\times better than quark models, Skyrme models (or LQCD).

**Missing resonances:** The search for *missing resonances* has been a driving force for photoproduction experiments \([24]\). The new resonances suggest that the existing resonances fill all states expected in the ground state and the first excitation shell. In the second shell, two multiplets are completely filled, two are completely empty, in the third shell, two are full, six are empty. There seems to be a dynamical selection in the *missing resonances* which is not yet understood \([25]\). One could anticipate that the dynamical reason is due to a string-like nature of the quark-quark interaction, and that the interpretation of the mass spectrum by constituent quarks missed the increase in the mass of the string when two quarks are dynamically separated in space. The consistency between quark model and lattice predictions may teach us that quarks leading to \( m_\pi = 400 \text{ MeV} \) are still “too static”, and that considerably lower quark masses have to be reached before quantitative lattice predictions will reproduce or predict the spectrum of light-quark baryon excitations.
Do glueballs, hybrids, and multiquark states exist atop of $q\bar{q}$ and $qqq$ states? The density of nucleon excitations would increase further, and the problem of the missing resonances aggravated, if baryonic hybrids, baryons in which the gluon string is excited, would exist. This is a more general problem in hadron spectroscopy. A large variety of different species is predicted which may all be realized independently. Of course, they can mixed but the number of predicted states with the same quantum number increases when glueballs, hybrids, and multiquark states exist on their own right. A well known example are the two axial vector mesons with strangeness. According to the quark model, one meson resonance is predicted along with the $a_1(1260)$, the other one with $b_1(1230)$. They both have $J^P = 1^+$ but differ in $G$-parity. However, $G$-parity is not a good quantum number for strange mesons, the two quark model states $K^*_a$ and $K^*_b$ can therefore mix, and two resonances emerge known as $K^*_1(1280)$ and $K^*_1(1400)$.

In baryon spectroscopy, five-quark $qqqq\bar{q}$ resonances could exist in addition to the conventional three-quark states \[26\]. Resonances generated dynamically by channel-channel effects might lead to additional resonances. Here, the question arises: is $N(1535)1/2^-$ a $qq$ quark model state, does its strong $\Lambda K$ coupling indicate a $qqqq\bar{q}$ resonance, or is it a $N\eta - \Lambda K$ coupled channel resonance of dynamical origin? Likely, it is all of it, and the wave function contains all components. But then, are there orthogonal states in the spectrum?

Scalar mesons with different hadronic content are all predicted in the 1 - 2 GeV mass range. Do they mix and can they be observed experimentally as five different states?

| $q\bar{q}$ mesons | $qqqq\bar{q}$ tetraquarks | $qqq$ hybrids | $qq$ glueballs | $m_1m_2$ molecules |
|-------------------|---------------------------|--------------|--------------|-----------------|
| $qqq$ baryons      | $qqqq\bar{q}$ pentaquarks | $qqq$ hybrids | $b_1m_2$ molecules |

This question can best be answered in a discussion of low-lying scalar nonets. Jaffe suggested that the lightest scalar mesons can be interpreted as four-quark states with a pair of quarks in color $\bar{3}$ and a pair of antiquarks in color $3$. In SU(3) this condition can be fulfilled by nine quarks, and this is just the number of light $q\bar{q}$ mesons in the scalar nonet. In SU(4), adding charm, this pattern is different \[27\]. Restricting us to scalar mesons with open charm, there are now 10 configurations with a pair of quarks in color $\bar{3}$ and a pair of antiquarks in color $3$. Six of them can couple to $c\bar{n}$ or $n\bar{c}$, four of them are flavor exotic. The latter configurations have never been observed. We conjecture that the bindings forces between quark and antiquark are essential to form mesons, that all mesons must have a $q\bar{q}$ component. This conjecture may exclude the existence of spin-parity exotics as well and likely also the existence of glueballs as additional states. The conjecture does not exclude that a scalar state has a sizable glueball fraction, but supernumerosity is not expected.

For baryons, we then expect no additional states; some baryon resonances are generated dynamically, but they need a $qqq$ seed to exist. Flavor exotics are not expected.

**Outlook**

Large data sets on photoproduction off protons and off neutrons have been taken at Bonn, Jlab, and Mainz with longitudinally and linearly polarized photons and with longitudinal and transverse target polarizations. The aim is to gather a complete data base which will define unambiguously the nucleon excitation spectrum. The impact of double polarization data on...
Figure 1: The polarization observable $G$ as a function of $\cos \theta_\pi$ from $E_\gamma = 800$ MeV up to $E_\gamma = 1100$ MeV. Systematic errors are shown in gray bars. The curves represent predictions from different partial wave analyses. Solid (black) curve: BnGa; dashed (red): SAID; long-dashed (black): BnGa with $E_0^+$ and $E_2^-$ amplitudes from SAID; dotted (blue): MAID; dashed-dotted (black): BnGa with $E_0^+$ and $E_2^-$ amplitudes from MAID. Gray area shows the systematic error due to interactions on nuclei and uncertainty in the photon polarization.

The spectrum can be seen from first data on the double polarization variable $G$. The data on $G$ are shown in Figure 1 and compared to the predictions from the SAID (SN11), MAID, and BnGa partial wave analyses. The results are surprising. The predictions of the three PWA differ considerably even in the region of the first negative-parity resonances. The data follow the prediction from BnGa rather well while MAID and SAID are disfavored. The reason for the discrepancies can be assigned to the different photo-couplings of $N(1535)1/2^-$ and $N(1520)3/2^-$.

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