

Hybrid Baryons, a brief review ¹

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Abstract:

This contribution is a brief review of the status of hybrid baryons, which are hypothetical baryons that incorporate a gluonic excitation. We first summarize the status of hybrid *mesons*, since this closely related topic has seen considerable recent activity with the identification of two exotic candidates. Next we review theoretical expectations for the masses and quantum numbers of hybrid baryons, which have come from studies of the bag model, QCD sum rules and the flux tube model. Finally hybrid baryon experiment is discussed, including suggestions for experimenters at COSY.

1 Hybrid Mesons

Hybrids are hadrons in which the dominant component of the state consists of quarks (antiquarks) and excited glue. This deliberately vague definition is necessary at present because the subject has been studied mainly through various models, and each assumes a particular description of excited glue. Fortunately the models often reach similar conclusions regarding the quantum numbers and approximate masses of these states, so from the experimental viewpoint there are relatively clear predictions regarding how one might find states with excited glue in the spectrum.

Hybrid mesons are usually modelled as $q\bar{q}$ +excited glue, and this system can have all J^{PC} quantum numbers. This implies that one can most usefully search for hybrids as mesons with the so-called “exotic quantum numbers” $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+} \dots$ because these are strictly forbidden to the nonrelativistic quark model’s $q\bar{q}$ states. Thus if one discovers a J^{PC} exotic meson, it is certain that something other than $q\bar{q}$ has been found. Whether this is a hybrid or not may be a more difficult question to answer, and depends on a comparison with theoretical predictions for the masses, quantum numbers

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and decay couplings of hybrids.

Various models and methods have been used to predict the spectrum of hybrid mesons, including the bag model, QCD sum rules, the flux tube model, and lattice gauge theory. All these approaches agree that there should be a light exotic $J^{PC} = 1^{-+}$ hybrid, with a somewhat model dependent mass from *ca.* 1.5 GeV (bag model) to 1.9 GeV (flux tube model) to 2.0 GeV (LGT). Only the flux tube model has been studied in detail for its decay mode predictions, and it leads to an *a priori* rather surprising expectation that hybrid mesons decay preferentially to meson pairs with one internal orbital excitation, the so-called “S+P” modes, for example πf_1 and πb_1 rather than the more familiar “S+S” modes such as $\pi\pi$, $\pi\eta$ and $\pi\rho$.

Experimentally we now have two candidate J^{PC} exotic mesons, with the same quantum numbers, a rather broad $I=1$ 1^{-+} $\pi_1(1400)$ seen in $\eta\pi$ [1], and a somewhat narrower $\pi_1(1600)$ seen in $\rho\pi$, $\eta\pi$ and $b_1\pi$ [2]. Although it is exciting to have *possible* confirmation of the existence of exotic hybrid mesons, it is disturbing that the masses of these states are rather lower than the *ca.* 2 GeV expected by LGT and the flux-tube model, and their observation with large partial widths in the S+S modes $\pi\eta$ and $\pi\rho$ disagrees with expectations of the flux-tube decay model. Although there have been speculations that the $\pi_1(1400)$ in particular might be a nonresonant final-state effect, there have been no model calculations that show this possibility is viable. So, we are faced with a somewhat ambiguous situation, in which hybrid mesons *may* have been discovered, but there are important disagreements with theoretical expectations for masses and important decay modes.

2 Theoretical Expectations for Hybrid Baryons

2.1 General expectations

Augmenting the quarks q and antiquarks \bar{q} by gluons g leads to additional states in the spectrum relative to the expectations of the naive $q\bar{q}$ and qqq quark model. Physically allowed (color singlet) states in the baryon spectrum may be constructed from $|qqqg\rangle$ “hybrid” basis states, in addition to the familiar $|qqq\rangle$ quark model states:

$$|qqq\rangle\Big|_{color} = \mathbf{1} \otimes \mathbf{8} \otimes \mathbf{8} \otimes \mathbf{10} ,$$

$$|qqqg\rangle\Big|_{color} = \left(\mathbf{1} \otimes \mathbf{8} \otimes \mathbf{8} \otimes \mathbf{10} \right) \otimes \mathbf{8} = \mathbf{1}^2 \otimes \mathbf{8}^5 \otimes \dots$$

The lowest hybrid baryon basis state is color octet and spatially symmetric in the qqq part of $|qqqg\rangle$, making it a **70** of SU(6). Since this qqq subsystem is combined with the angular momentum of the gluon, we find the interesting prediction that $|qqqg\rangle$ multiplets do not span the same $|\text{flavor}, J_{tot}\rangle$ states as an SU(6) $|qqq\rangle$ multiplet. Thus we should find evidence for “incomplete” or “overcomplete” SU(6) baryon multiplets due to the presence of hybrids. More detailed predictions for the multiplet content typically require the use of a specific model, although there has recently been work on the derivation of general properties of hybrid baryon states and their decays in the large quark mass and large- N_c limit [3].

2.2 Bag model

This model places relativistic quarks and gluons in a spherical cavity and allows them to interact through QCD forces such as one gluon exchange (OGE), the color Compton effect and so forth. Incorporation of these interactions to leading nontrivial order, $O(\alpha_s)$, gives predictions for the spectrum and Hilbert space decomposition of light hybrid baryons in this model.

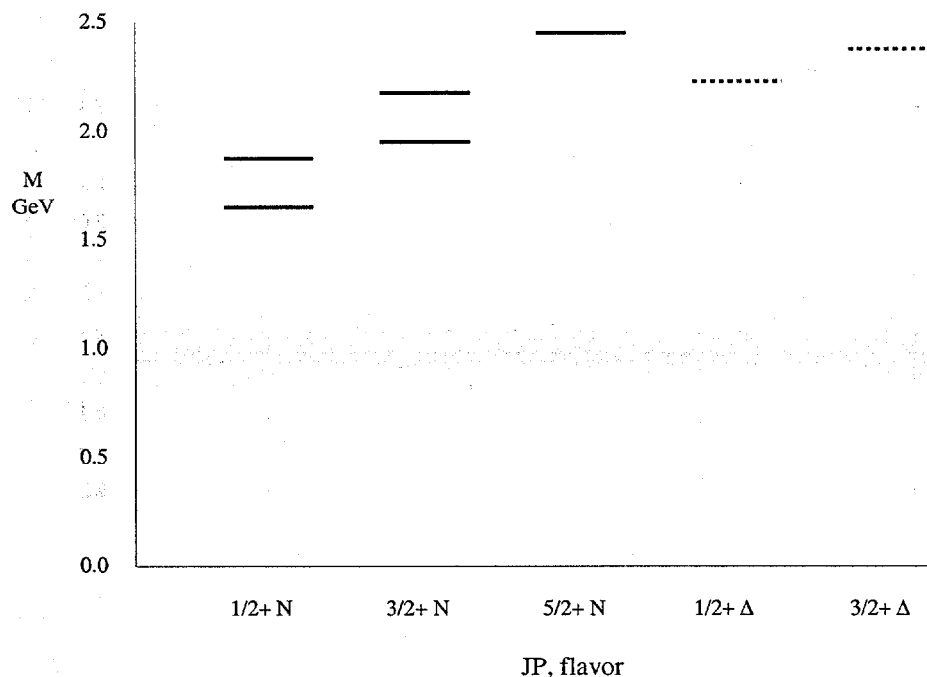


Figure 1: The spectrum of light nonstrange hybrid baryons found by Barnes and Close [4] in the bag model.

The first published calculation of light bag model hybrids was due to Barnes and Close [4], who derived the spectrum of nonstrange $nnng$ states. This reference found the spectrum shown in Fig.1; in order of increasing mass the states are

$$(1/2^+ N)^2 ; (3/2^+ N)^2 ; (1/2^+ \Delta) ; (3/2^+ \Delta) ; (5/2^+ N) .$$

Note that the lightest hybrid baryon is predicted to be an “extra” $1/2^+ N^* P_{11}$ state (“extra” meaning an overpopulation relative to the predictions of the qqq quark model) at about 1.6 GeV, which might possibly be identified with the Roper resonance. A subsequent calculation by Golowich, Haqq and Karl [5] basically confirmed these results, but used a parameter set that gave a mass of about 1.5 GeV for this lightest hybrid, so identification with the Roper was given more support. Carlson and Hansson [6] extended these studies to strange hybrid baryons, and found that the bag model predicted two relatively light uds -flavor hybrids, with the lightest expected at $M(1/2^+) = 1.63(4)$ GeV with their parameters.

Decays are not usually considered in bag model calculations, which normally assume that the states are stable Hamiltonian eigenstates. A model of decays of bag model hybrid

baryons was developed by Duck and Umland [7], who studied the $\Delta\pi$ and $N\pi$ decay modes of the lightest N -flavor hybrid states. They concluded that the lightest hybrid has a much larger coupling to $\Delta\pi$ than $N\pi$.

2.3 QCD sum rules (and LGT)

This approach, which has been applied to hybrid baryons in several papers of the previous decade, finds the masses and other parameters of the lowest-lying states in terms of numerically known VEVs, called “condensates”. Since the sum rules relate known VEVs to a sum of resonance contributions, there are systematic uncertainties in separating the individual resonance and “continuum” parts. Identification of excited states such as hybrids is rather difficult in this approach, since higher-mass contributions to the sum rules are suppressed exponentially. This exercise can be carried out for hybrids, for example by calculating matrix elements of several operators and diagonalizing the result. In practice the calculations also use $qqqg$ operators, which one would expect to have larger hybrid couplings. To date only hybrids in the nucleon/Roper sector $1/2^+N$ have been studied using QCD sum rules.

The first published hybrid baryon QCD sum rule calculation was by Martynenko [8], who estimated the lightest $1/2^+N$ hybrid baryon mass to be near 2.1 GeV. A subsequent study by Kisslinger and Li [9] reported algebra errors in the (very intricate) matrix elements calculated in the Martynenko paper, and published a revised mass estimate of about 1.5 GeV, again very suggestive of the Roper. A more recent review by Kisslinger [10] concluded that the Roper is largely a hybrid (meaning dominantly $|qqqg\rangle$), the nucleon has little evidence for a hybrid component, and also considers how one might calculate strong couplings. Some of this program of decay calculations was carried out by Kisslinger and Li [11], who conclude that the lightest hybrid should have a rather small branching fraction ratio $N(\pi\pi)_S / N\pi$, consistent with observation for the Roper.

We note in passing that lattice gauge theory uses a very similar technique to QCD sum rules for extracting masses, and can also be used to determine hybrid baryon masses, for example as nonleading contributions to baryon operator correlation functions. Hybrids are not specifically identified as such, but will appear in any determination of excited baryon masses in LGT. In future, couplings to qqq versus $qqqg$ operators may identify states with large excited gluonic components. Preliminary results for the first $1/2^+ N^*$ resonance in LGT have been reported by Sasaki *et al.* [12], and it appears that this excited baryon may be identified through the use of a baryon operator that has little overlap with the nucleon. This approach works well for heavier quarks, but has not yet been carried out with high statistics for light quark masses.

2.4 Flux tube model

The flux tube model assumes that glue forms a dynamically excitable tube between quarks and antiquarks, and that the lightest hybrids are states in which this flux tube is spatially excited. The model is of special interest because of the reasonable agreement between its predictions for the mass of the lightest J^{PC} -exotic meson and the presumably more reliable LGT prediction (*ca.* 1.9 GeV in the flux tube model, versus *ca.* 2.0 GeV from LGT). The determination of excited states in the baryon sector ($qqq +$ spatially excited

flux tube) is a rather complicated problem which has only recently been treated. Flux tube model predictions for the lightest hybrid baryons were reported by Capstick and Page in 1999 [13]. They find that the lightest hybrid baryons in the nnn flavor sector are two each of $1/2^+N$ and $3/2^+N$, all at a mass of $1.87(10)$ GeV. Their results for the N flavor hybrids are shown in Fig.2, together with current experimental data.

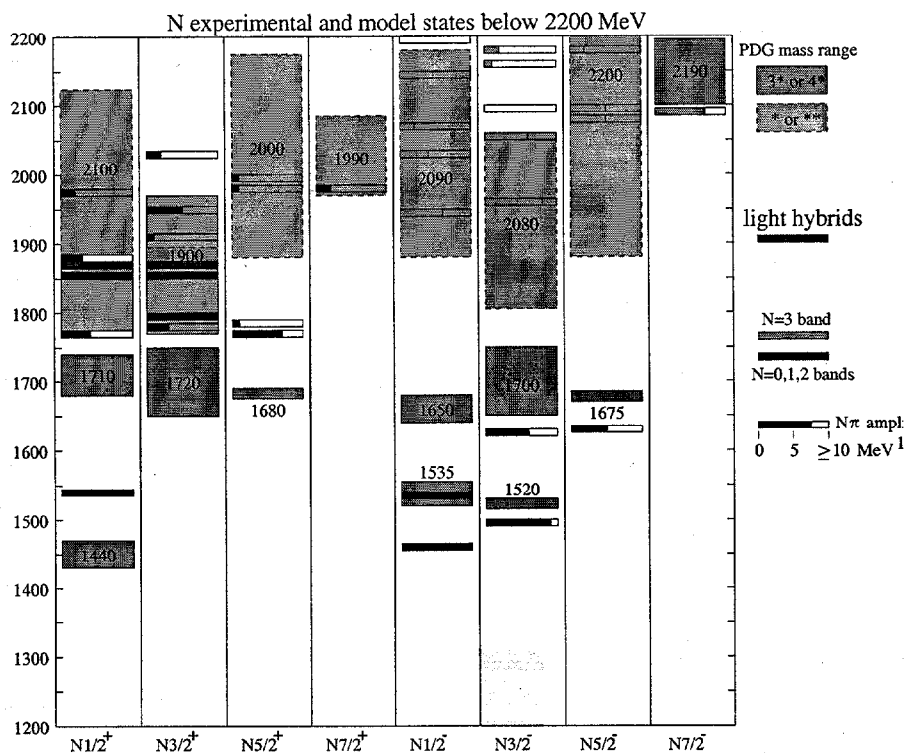


Figure 2: The four light N flavor hybrid baryons found by Capstick and Page [13] in the flux-tube model, compared to experiment. The estimated error is ± 100 MeV (light blue background).

Thus the lowest flux-tube hybrid baryon level is predicted to include Roper quantum numbers, as was found in the bag model, *albeit* twofold degenerate and at a higher mass. In addition a degenerate $3/2^+N$ pair is expected. There are other differences in the multiplet content; the flux-tube hybrid baryon multiplet contains the states

$$(1/2^+N)^2 ; (3/2^+N)^2 ; (1/2^+\Delta) ; (3/2^+\Delta) ; (5/2^+\Delta) ,$$

so the flux tube model finds a high-mass $5/2^+\Delta$; in the bag model the high-mass state was a $5/2^+N$. The flux-tube Δ hybrids are predicted to be degenerate, with a mass of $2.09(10)$ GeV.

The implications of this work for searches for hybrid baryons, including various experimental search strategies such as overpopulation, strong decays, EM couplings and production amplitudes, were recently reviewed by Page [14]. In particular Page suggests searches for hybrids in the final states $N\eta$, $N\rho$ and $N\omega$.

Although there are no strong decay amplitude calculations reported for flux-tube hybrid baryons as yet, one can see that the qualitative arguments that are applicable to flux-tube hybrid mesons should apply here as well. Thus one would expect the flux-tube decay model to predict that the largest couplings are to hadrons with internal orbital

excitation. Phase space would clearly prefer the orbital excitation to be in the baryon, so hybrid baryons decays to $\pi S_{11}(1535)$ for example may be favored. Since the $S_{11}(1535)$ has a large and characteristic $N\eta$ branch, study of the decay chains

$$hybrid \rightarrow \pi S_{11}(1535) ; S_{11}(1535) \rightarrow N\eta \quad (1)$$

and

$$hybrid \rightarrow \eta S_{11}(1535) ; S_{11}(1535) \rightarrow N\eta \quad (2)$$

may reveal hybrids in final states in which conventional baryons have somewhat suppressed couplings. The chain $hybrid \rightarrow \eta S_{11}(1535) \rightarrow \eta\eta N$ is especially attractive for detectors with good photon detection; such a study is planned at ELSA using the Crystal Barrel detector [15].

3 Identifying Hybrid Baryons

3.1 General Strategies

Hybrid *mesons* can be studied most easily by searching for J^{PC} exotics; although we cannot be certain that a J^{PC} exotic *is* a hybrid, we can be certain that it is not a $q\bar{q}$ state. If such an exotic is found, one can then search for the exotic and non-exotic partners that would confirm the presence of a hybrid multiplet.

In baryons there are unfortunately no J^P exotics, so we must use other properties of baryons to determine whether or not they are hybrids. In this approach we classify the “background” of qqq states, learn to describe their couplings accurately, and then identify non- qqq baryons through unusual couplings or as an overpopulation of states relative to the qqq quark model predictions. One property of baryon resonances often cited as a hybrid discriminator is their EM couplings, in other words their photoproduction and electroproduction amplitudes. Other possible ways to identify hybrids are through anomalous strong decay amplitudes and production systematics in novel channels such as J/Ψ hadronic decays.

3.2 Photocouplings

Since photocouplings of baryon resonances are widely considered to be reasonably well predicted by the qqq quark model, and new experimental facilities such as Jefferson Lab will provide detailed results on baryon resonance photocouplings, the EM couplings predicted for hybrid baryons have received considerable attention.

Photocouplings of bag model hybrid baryons were derived by Barnes and Close [16]; those of the lightest “Roperlike” hybrid were of special interest due to problems with predicting the EM couplings of the Roper in the qqq quark model. Barnes and Close found a generalization of the Moorhouse selection rule [17], which in this case gave a vanishing photocoupling of the $I_z = +1/2$ hybrid state from a proton,

$$\gamma P \not\rightarrow P_g . \quad (3)$$

Experimentally this photocoupling is *not* small, which apparently invalidates the identification of the Roper with this bag model hybrid. Caution is appropriate here. First, the

photocouplings are due to the basis transitions $\gamma|qqq\rangle \rightarrow |qqq\rangle$ and $\gamma|qqqq\rangle \rightarrow |qqqq\rangle$, so $\gamma P \rightarrow P_g$ actually tests the non-valence components $|qqq\rangle$ in the hybrid and $|qqqq\rangle$ in the nucleon. These nonleading amplitudes may be strongly model dependent!

Subsequently it was noted by Li [18] that whereas Barnes and Close had assumed that the basis state $|^2S_{qqq}+^1\text{flavor}_{glue}\rangle = |^4N_g\rangle$ was the zeroth-order ‘‘Roper’’ hybrid basis state, as suggested by cavity QCD perturbation theory, one should actually use degenerate perturbation theory in this mixing problem because at zeroth order the basis states $|^2N_g\rangle$ and $|^4N_g\rangle$ are degenerate. The Moorhouse selection rule does not apply to this $|^2N_g\rangle$ component, so one might still identify the Roper with the bag model hybrid if this is indeed an important configuration.

Carlson and Mukhopadhyay [19] noted that electroproduction amplitudes of baryon resonances with dominant hybrid components might be very characteristic. They concluded that the transverse-photon $qqqq$ electroproduction form factor should fall faster than the corresponding qqq form by an additional factor of $1/Q^2$. Thus a rapid fall of electroproduction amplitudes with increasing Q^2 is a possible hybrid signature.

This suggestion was considered by Li, Burkert and Li [20], who compared theoretical models for the Q^2 dependence of electroproduction amplitudes of radial- qqq and hybrid states with experiment. In their study the theoretical radial- qqq electroproduction amplitude was quite large, and unlike the hybrid electroproduction amplitude did not fall rapidly with Q^2 . They concluded that the rapid fall of the experimental Roper electroproduction amplitude with increasing Q^2 favored the identification of the Roper with a hybrid (see Fig.3).

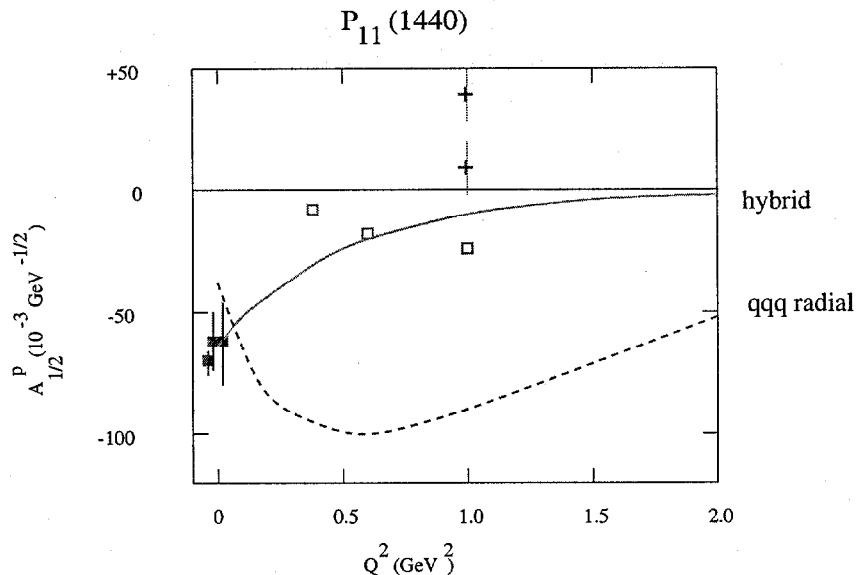


Figure 3: An early comparison of hybrid and radial- qqq electroproduction amplitudes with experimental Roper results (from [20]).

Unfortunately for this simple picture, subsequent calculations have shown that the amplitude $\gamma(qqq)_{1S} \rightarrow (qqq)_{2S}$ is sensitive to the details of the calculation, and small radial- qqq electroproduction amplitudes can also be accommodated. Although electroproduction shows great promise as a way to identify anomalous baryon resonances, until such time as electroproduction calculations are shown to be reliable for a wide range of

qqq states, including radial excitations, the classification of resonances through their EM couplings will be problematic.

3.3 J/Ψ hadronic decays.

Rather surprisingly, BES at BEPC is being used to study N^* spectroscopy using J/Ψ hadronic decays. Zou *et al.* [21] note that one might expect hybrid baryons to have larger production amplitudes from J/Ψ than conventional qqq baryons, because a ggg state produced in J/Ψ annihilation should have a larger overlap with a final hybrid baryon (see Fig.4). It is certainly interesting to establish which baryons are produced with large amplitudes in J/Ψ annihilation, as any unusual states thus produced are possible hybrid baryon candidates.

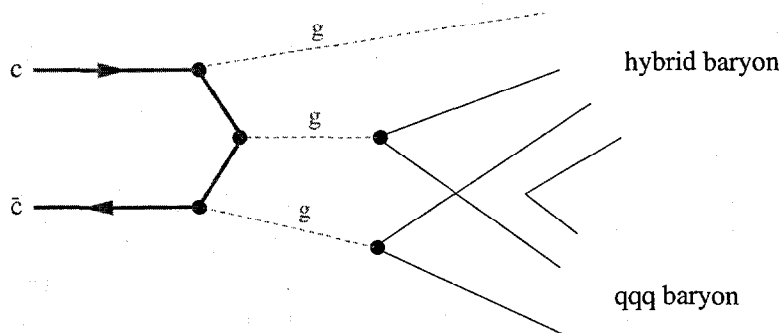


Figure 4: Production of $qqqg$ states from J/Ψ radiative decays occurs at $O(\alpha_s^5)$ (followed by nonperturbative pair production), which leads $J/\Psi \rightarrow ggg \rightarrow (qqq) + (\bar{q}q\bar{q})$ by one power of α_s .

To date BES has 7.8M J/Ψ events, from which they select $p\bar{p}\pi^0$ and $p\bar{p}\eta$. This approach has the additional advantage that it is an $I=1/2$ filter, so the many Δ (and hybrid Δ) states will not be present to complicate the analysis. The only clear peak in the present data is the $S_{11}(1535)$, in the $p\bar{p}\pi^0$ channel (see Fig.5). Since *ca.* 50M J/Ψ events are expected in the near future, hybrid baryon candidates may yet be identified in this process.

Another interesting possibility, which may be undertaken at COSY, is the selection of isospin states through the choice of unusual beams. This might be possible for example using an α beam, as discussed at this meeting by Morsch and collaborators [22]. This technique has previously been shown to be effective in enhancing the Roper signal, and could be useful in a search for the light N-flavor hybrids because the production of Δ states may be much weaker than in the more familiar πN and γN reactions.

3.4 Overpopulation of the spectrum; strong decays

Since there are no J^P exotic baryons, searches for baryon hybrids are in effect searches for evidence of *overpopulation*, in which one attempts to establish whether there is clear experimental evidence for more states in the spectrum than predicted by the qqq quark model alone.

This suggests that establishing the conventional qqq baryon spectrum and studying the properties of these "ordinary hadrons" is a very important part of the search for exotica; what is unusual may only be evident once the background of conventional states is

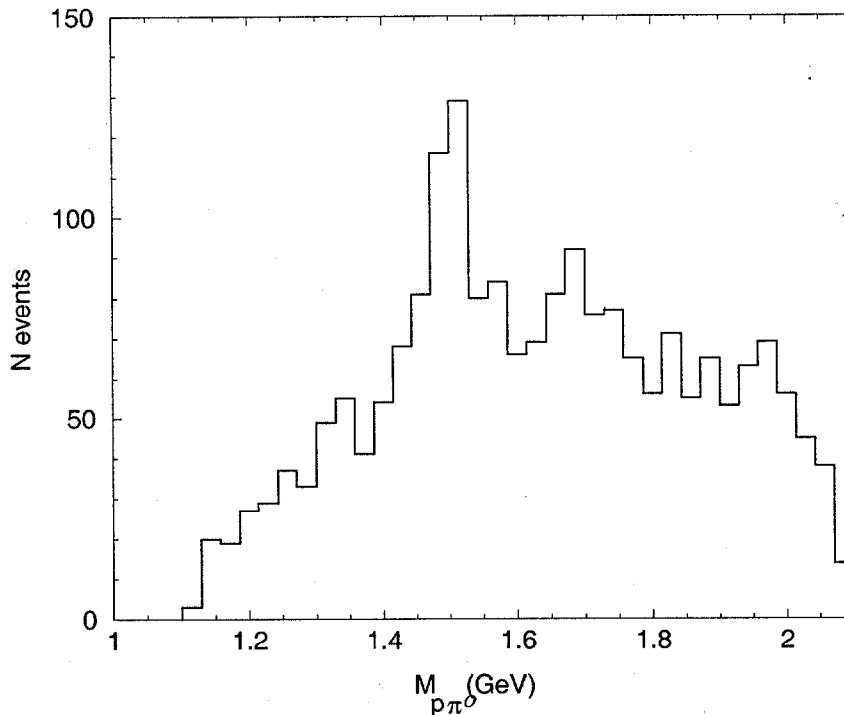


Figure 5: BES data for the $p\pi^0$ invariant mass distribution in $J/\Psi \rightarrow pp\pi^0$ [21], showing evidence for the $1/2^- N_{11}(1535)$.

very well understood. This includes not only the quantum numbers, masses and widths of the baryons, but also their EM couplings and strong decay amplitudes, since these may be useful as probes of the internal structure of unusual resonances. This program of establishing *all* nonstrange baryon resonances should be pursued at least to *ca.* 2.2 GeV, since this is somewhat above the highest mass estimate for the lightest nonstrange hybrid baryon. This conservative strategy of identifying all states is especially appropriate because we have little evidence regarding which model of hybrids is most accurate, and this must be decided by comparing with a reasonably complete experimental spectrum. In the worst case there could be large mixing angles between conventional and hybrid baryons, so that the distinction between these states is rather artificial; simple state counting is then the most direct approach for establishing the presence of additional degrees of freedom. Another complication is that there are probably additional types of baryons, such as $(qqq)(q\bar{q})$ “molecular” states, which would presumably also be found in a detailed experimental study of the baryon spectrum.

Strong decay amplitudes may also prove useful in identifying hybrid baryons, so the careful determination of strong branching fractions and decay amplitudes of experimental baryon resonances is especially important. In the meson case there are striking predictions that hybrids should decay preferentially to states with internal orbital excitation, and if this rule is confirmed we have a very useful signature that may also be applicable to hybrid baryons. (This is being investigated by Black and Page [23].) One should note however that the strong decays of conventional qqq baryons may not be well understood; the usual models simply assume $q\bar{q}$ pair production with 0^{++} quantum numbers, which appears to work well in certain test cases but has not been compared to high-statistics

experimental resonance data for a wide range of states, simply because such data has not been available. Since very detailed predictions for baryon resonance decay amplitudes have now been published by Capstick and Roberts in this model [24] and data from CEBAF is becoming available, we should soon be able to establish whether we can predict conventional qqq baryon strong decays accurately. If so, hybrid baryons and other exotica might be identifiable through their anomalous strong decays.

4 Summary and Conclusions

An *overpopulation* of baryon resonances is expected relative to the predictions of the qqq quark model, due to excitation of the glue degree of freedom. Excited glue will lead to novel baryon resonances, which are known as “hybrid baryons”. Analogous J^{PC} exotic meson hybrids may already have been identified (the $\pi_1(1400)$ and $\pi_1(1600)$). Theorists have derived the spectrum of light hybrid baryons and some of their properties using various models, and expect that the lightest hybrid will have $1/2^+N$ “Roper” quantum numbers and a (rather model dependent) mass of *ca.* 1.5-1.9 GeV. (It is amusing that this range of masses is also predicted for the lightest exotic hybrid meson.) Strange baryon hybrids are also anticipated, and a relatively light $1/2^+\Lambda$ hybrid is predicted. Hybrids may be identifiable through distinctive decay modes such as $\pi + P$ -wave baryon (similar to the $S+P$ modes of meson hybrids) and unusual photo- and electroproduction amplitudes.

A systematic search for these light hybrids can be carried out by completing the study of N^* spectroscopy to *ca.* 2.2 GeV, and by accurately determining the decay amplitudes and flavor partners of all observed states. COSY can contribute to the search for hybrids by helping to establish the baryon resonance spectrum and strong decay amplitudes up to this mass scale, ideally in both nonstrange and strange sectors.

5 Acknowledgements

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