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HYBRID BARYONS [a]

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We review the status of hybrid baryons. The only known way to study hybrids rigorously is via excited adiabatic potentials. Hybrids can be modelled by both the bag and flux–tube models. The low–lying hybrid baryon is $N\frac{1}{2}^+$ with a mass of $1.5 - 1.8$ GeV. Hybrid baryons can be produced in the glue–rich processes of diffractive γN and πN production, Ψ decays and $p\bar{p}$ annihilation.

1 Introduction

We review the current status of research on three quarks with a gluonic excitation, called a *hybrid baryon*. The excitation is *not* an orbital or radial excitation between the quarks. Hybrid baryons have also been reviewed elsewhere. [1]

The Mercedes-Benz logo in Fig. 1 indicates two possible views of the confining interaction of three quarks, an essential issue in the study of hybrid baryons. In the logo the three points where the Y–shape meets the boundary circle should be identified with the three quarks. There are two possibilities for the interaction of the quarks: (1) a pairwise interaction of the quarks represented by the circle, or (2) a Y–shaped interaction between the quarks, represented by the Y–shape in the logo.

2 Why does one consider hybrid baryons?

(1) *You cannot avoid them.* This is because excited glue is predicted by QCD (see the lattice QCD hybrid meson excited adiabatic potentials later), so that hybrid baryon degrees of freedom should be part of baryon spectroscopy.

(2) *Gluonic excitations are qualitatively new.* While systems with more degrees of freedom than quarks are qualitatively new, the most promising place to study gluonic excitations does not appear to be hybrid baryons. Glueballs (made from gluons) and hybrid mesons (a quark and antiquark with a gluonic

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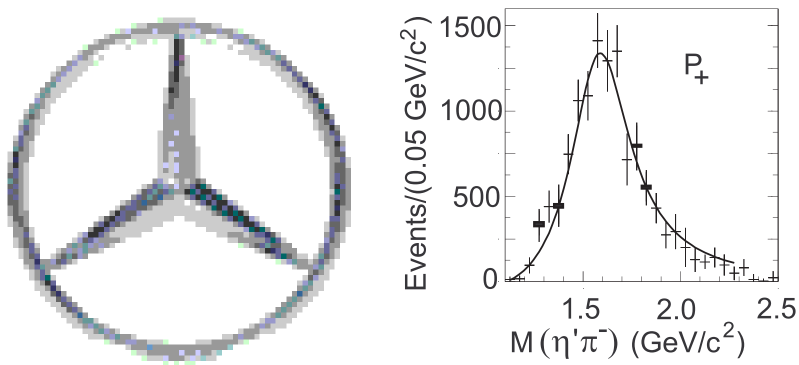

Figure 1: Mercedes-Benz logo (left) and number of events (per 50 MeV bin) as a function of $\eta'\pi^-$ invariant mass [2] (right).

excitation) are more promising since they can be J^{PC} exotic, meaning that there are no mesons in the quark model with these J^{PC}, or there are no local quark–antiquark currents with these J^{PC}. Hybrid baryons have half–integral J and no C, and there are no J^P exotics: all J^P can be constructed for baryons in the quark model. In fact, a $J^{PC} = 1^{-+}$ exotic isovector meson at 1.6 GeV has recently been reported in $\eta'\pi^-$. [2] In this analysis the exotic partial wave is in fact the dominant one. If one were shown the event shape (Fig. 1) a few decades ago when the ρ was discovered, it would be easy to conclude that a new resonance has been discovered. The exotic meson is currently thought to be a hybrid meson.

(3) *Hybrid baryons are a test of intuitive pictures of Quantum Chromodymanics (QCD).* As we will shortly detail, current lattice QCD data indicate that the interaction between three quarks is indeed a Y–shaped potential, which is expected to arise from three gluon flux–tubes meeting at a junction (see Fig. 2). Excitations of these gluon flux–tubes is expected to be very sensitive to the way that the flux–tubes connect (in this case in a Y–shape): hence the importance of hybrids for our intuitive pictures of QCD. The gluon self–interaction has no analogue in the Abrikosov–Nielsen–Olesen flux–tubes of QED.

As promised, let us sketch current lattice QCD data. In Fig. 2 we define the three lengths l_1, l_2 and l_3 as the distances from the quarks (the blobs) to the equilibrium position of the junction of the Y–shaped linearly confining flux–tube system. Define $\mathrm{L_{min}} = l_1 + l_2 + l_3$. The quenched lattice potential

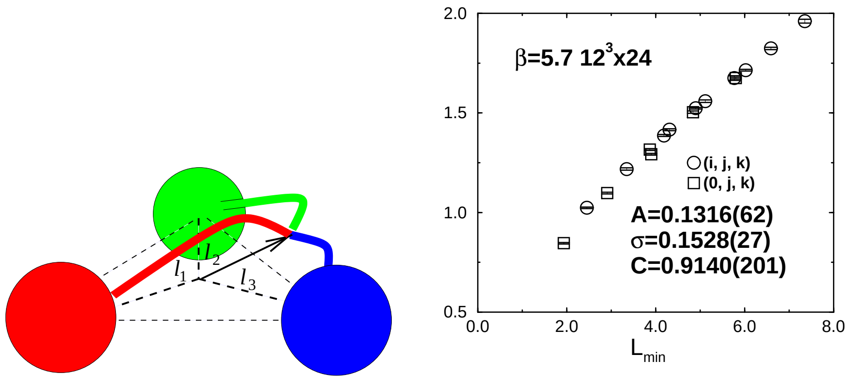

Figure 2: Definition of l_1, l_2 and l_3 (left) and lattice potential [3] (right).

for the three quarks as a function of $\mathrm{L_{min}}$ is plotted in Fig. 2. At large $\mathrm{L_{min}}$ the potential is proportional to $\mathrm{L_{min}}$. The potential was parameterized by a Coulomb and Y–shaped confining term [3]

$$V_{3Q} = -\mathrm{A} \sum_{i<j} \frac{1}{|\mathbf{r}_i - \mathbf{r}_j|} + \sigma \mathrm{L_{min}} + \mathrm{C} \tag{1}$$

and the string tension $\sigma = 0.1528(27)$ GeV^2 was found to be similar to the value measured between a quark and an antiquark, albeit somewhat smaller. A possible reason for this is a cancellation of chromo–electric fields at the junction of the Y–shaped flux–tube. [4] The value of the string tension is consistent with the value of 0.15 GeV^2 extracted from the experimental baryon spectrum by Capstick and Isgur. [5] It is found that $\chi^2/d.o.f. = 3.99$ for the Y–shaped confinement potential versus and 10.9 for pairwise confinement, so that Y–shaped confinement is clearly preferred. Another lattice work [6] concludes that pairwise confinement is preferred over Y–shaped confinement, but imposes the constraint that σ for baryons must be identical to σ for mesons, an assumption which is unjustified. [4]

3 What are hybrid baryons?

Hybrid baryons can be defined in two ways:

(1) *Three quarks and a gluon.* If states are rigorously expanded in Fock space, one can discuss hybrid (three quark – gluon) components of such an expansion, which can be accessed in large Q^2 deep inelastic scattering. [7] Historically a low–lying hybrid baryon was defined as a three quark – gluon com-

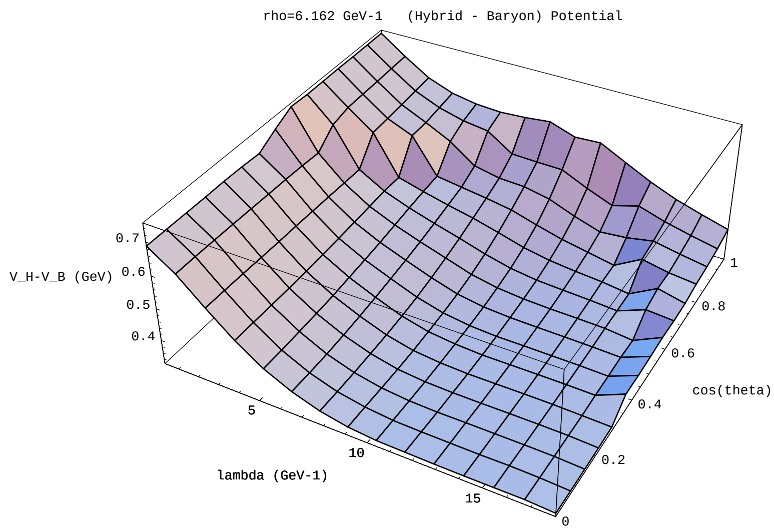

Figure 3: Difference between hybrid and conventional baryon adiabatic potentials as a function of the quark positions (parametrized in terms of the Jacobi coordinates ρ, λ and θ, with ρ fixed in this case.) [32]

posite. However, from the viewpoint of the Lagrangian of QCD this definition is non–sensical. This is because gluons are massless, and hence there is no reason not to define a hybrid baryon, for example, as a three quark – two gluon composite. Neither is one possibility distinguishable from the other, since strong interactions mix the possibilities. Moreover, sometimes the definition becomes perilous. A case in point is recent work on large N_c hybrid baryons, where their properties depend critically on the fact that the gluon is in colour octet, and hence the three quarks in colour octet, so that the entire state is colour singlet. [8] The bag model circumvents the objections raised against this definition, since gluons become massive due to their confinement inside the bag. [9,10,11,12,13]

(2) *Three quarks moving is an excited adiabatic potential*. One can always evaluate the energy of a system of three fixed quarks as a function of the three quark positions, called the adiabatic potential. There is a ground–state adiabatic potential, corresponding to conventional baryons, and various excited adiabatic potentials, corresponding to hybrid baryons. The three quarks are then allowed to move in the excited adiabatic potential. This can be a perfectly sensible definition from the viewpoint of QCD. The caveat is that this definition is only exact for (1) very heavy quarks (for some potentials), or (2) for specific

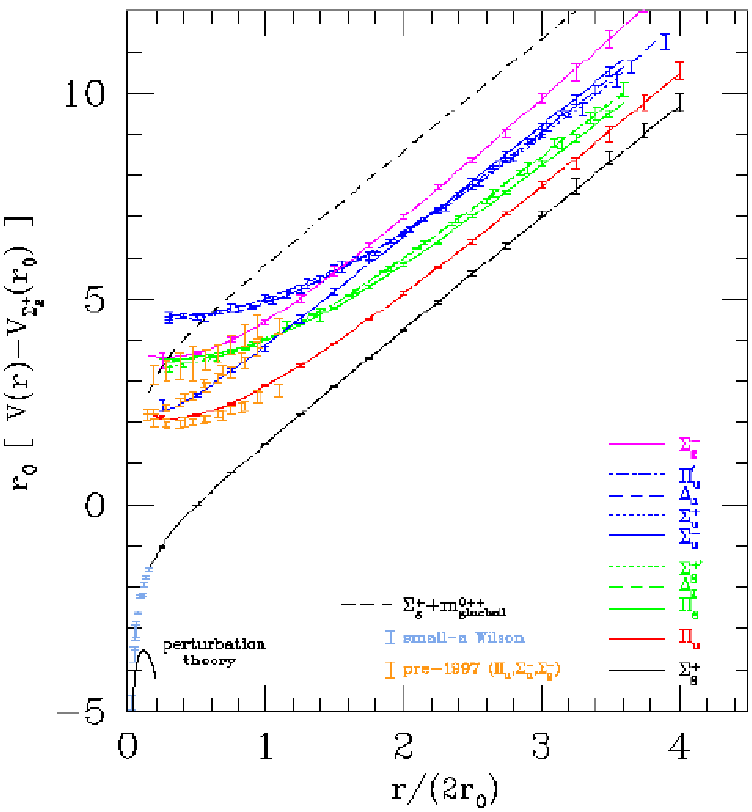

Figure 4: Adiabatic potentials as a function of $Q\bar{Q}$ separation. [33]

simplified dynamics, particularly that of three non–relativistic quarks moving in a simple harmonic oscillator potential. [14] In the latter case the definition is exact even for up and down constituent quarks if one redefines the adiabatic potential suitably. [14] For the linear potentials of the flux–tube model is was noted that "For light quarks almost all corrections may be incorporated into a redefinition of the potentials. Mixing between [new] potentials is of the order of 1%". [15] If mixing between the (redefined) adiabatic potentials is this small one can sensibly talk about hybrids even for light quarks. The redefinition depends on the quark masses, so that one would ideally start with very heavy quarks on the original adiabatic potential, and then gradually move to the quark masses of interest by redefining the adiabatic potential. An example of an adiabatic surface in the flux–tube model appears in Fig. 3. The potential peaks at small ρ and λ and the uneven rim corresponds to the transition from a Y–shaped flux–tube to a two–legged flux–tube (when the angle between two of the quarks is more than 120^o).

4 How are hybrid baryons modelled?

To answer this question it is best to understand how hybrid mesons can be modelled. The quenched lattice QCD hybrid meson adiabatic potentials are shown in Fig. 4. (Note that at large $Q\bar{Q}$ separation, linear confinement should break down due to $q\bar{q}$ pair creation. For low–lying hybrids this effect can be incorporated as a higher order effect, i.e. as loop corrections to masses.) At small $Q\bar{Q}$ separation, the adiabatic bag model (where quarks are stationary) gives a reasonable description of the lattice data.[16] At large $Q\bar{Q}$ separations, a constituent gluon model (related to the bag model) is not applicable,[17] but a Nambu–Goto string (flux–tube) picture instead[18]. One hence needs a combined phenomenology of the "old bag" model and the flux–tube model to model hybrid mesons, and by implication hybrid baryons. This is a somewhat unhappy marriage, as the two models describe glue very differently. The exact way the glue is modelled is critical, e.g. in the flux–tube model Y–shaped confinement for low–lying hybrid baryons has been shown to be well-approximated by motion of the junction of the Y–shape.[19] The dynamics is critically dependent of what the nature of the excitation is.

We now summarize model estimates for masses of hybrid baryons. QCD sum rules estimates the low–lying $N\frac{1}{2}^+$ hybrid at $\sim$ 1.5 GeV.[20] The bag model obtains the lightest hybrid, $N\frac{1}{2}^+$, at $\sim$ 1.55 GeV,[9,10,11] between the $N(1440)$ (Roper) and $N(1710)$. Higher mass N and Δ hybrids are at $1.5-2.5$ GeV.[9,10,11] In the flux–tube model the N hybrids are at 1.87(10) GeV and the Δ hybrids at 2.08(10) GeV.[19] Hybrids with strangeness have surprisingly low mass, particularly a flavour singlet Λ at ~ 1.65 GeV in the bag model.[11,12]

What are the quantum numbers of hybrid baryons? The good quantum

Table 1: Quantum numbers in the flux–tube model.[19]

Mass	Flavour	Spin	J^P
Light	N	$\frac{1}{2}$	$\frac{1}{2}^+$, $\frac{3}{2}^+$
Light	N	$\frac{1}{2}$	$\frac{1}{2}^+$, $\frac{3}{2}^+$
Heavy	Δ	$\frac{3}{2}$	$\frac{1}{2}^+$, $\frac{3}{2}^+$, $\frac{5}{2}^+$

Table 2: Quantum numbers in the bag model.[9,10,11]

Flavour	Spin	J^P
N	$\frac{1}{2}$	$\frac{1}{2}^+$, $\frac{3}{2}^+$
N	$\frac{3}{2}$	$\frac{1}{2}^+$, $\frac{3}{2}^+$, $\frac{5}{2}^+$
Δ	$\frac{1}{2}$	$\frac{1}{2}^+$, $\frac{3}{2}^+$

numbers are flavour (to the extent that isospin is a good symmetry), J and P. The non-relativistic spin of the three quarks is also important in (non–relativistic) models, but is not a good quantum number. Table 1 lists the quantum numbers of the low–lying hybrids in the flux–tube model. The total angular momentum J is obtained by adding the spin (either $\frac{1}{2}$ or $\frac{3}{2}$) to unit orbital angular momentum L. The four N hybrids are the lightest, and the five Δ hybrids heavier, as previously remarked. Although hybrids contain the quantum numbers of the conventional N and Δ, one never obtains a full multiplet of conventional baryons like this in the quark model, even for excited conventional baryons. It is, however, possible to have $L^P = 1^+$ for conventional baryons, as is the case for hybrids. The quantum numbers of hybrids in the bag model is shown in Table 2. These differ from the flux–tube model in the last two rows: The spin $\frac{1}{2}$ and $\frac{3}{2}$ is exchanged, with corresponding changes in J. In the bag model the $N\frac{1}{2}^+$ is the lightest, then the $N\frac{1}{2}^+$, $N\frac{3}{2}^+$ and $N\frac{3}{2}^+$, then the $\Delta\frac{1}{2}^+$ and $\Delta\frac{3}{2}^+$ with $N\frac{5}{2}^+$ the heaviest. The bag model has the same number of low–lying states as in flux–tube model. When good quantum numbers are considered, the only difference is that the $J^P = \frac{5}{2}^+$ state is a Δ in the flux–tube model and a N in the bag model. In both models this is one of the highest lying states, so that the low–lying hybrids are identical. In fact, $N\frac{1}{2}^+$ is amongst the lightest hybrids in both models, and, as previously noted, is light in QCD sum rules as well. For hybrids with strangeness, the $\Lambda\frac{1}{2}^+$ and $\Lambda\frac{3}{2}^+$ were predicted in the bag model, with the $\Lambda\frac{1}{2}^+$ the lighter state.[11,12]

Recently, masses and quantum numbers of hybrid baryons have been reported in a dispersion relation technique.[21]

5 How does one find hybrid baryons?

There are currently two approaches:

- Comparison with models (which are themselves callibrated against lattice QCD *and* experiment on glueballs and hybrid mesons).

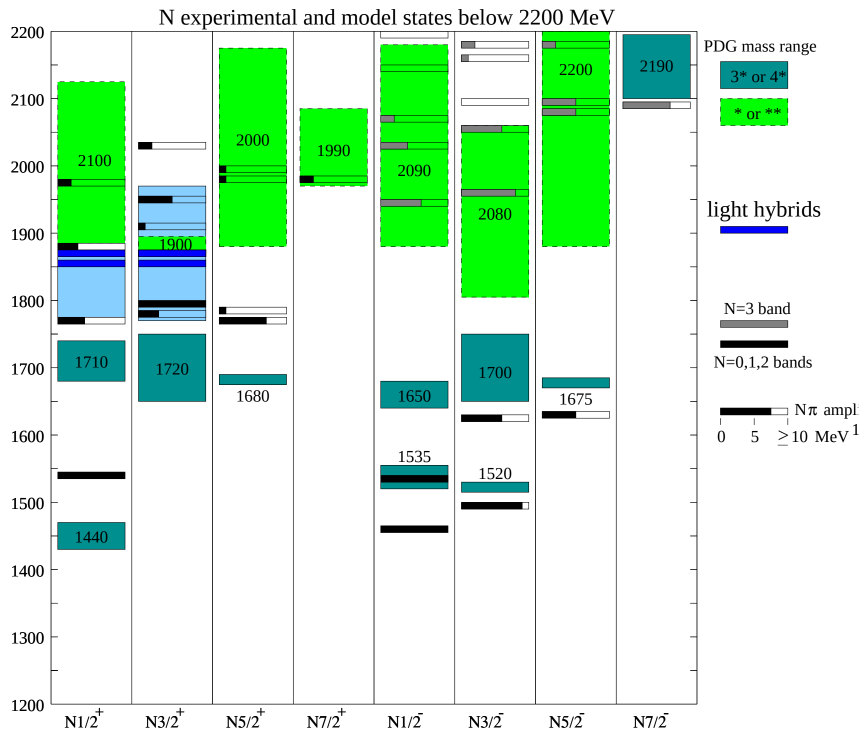

Figure 5: Model (conventional and hybrid) and experimental N baryons. For each set of quantum numbers, the mass spectrum is indicated (in MeV). The thin bars indicate quark model predictions for conventional baryon masses. [5] The four fully filled thin bars around 1870 MeV are the flux–tube model hybrids. [19] The large rectangular blocks are the mass ranges of known experimental states.

- Comparison to generic expectations for glue–rich hadrons.

Hybrid baryons can be found by

(1) *Observing more states than the conventional baryons.* This approach is very difficult in practice, and has only proved useful in the $J^{PC} = 0^{++}$ (scalar) isoscalar meson sector, which has led to the identification of a gluonic excitation: the glueball. To see how difficult this approach is for hybrid baryons, look at Fig. 5. Nowhere in the spectrum does one observe an excess of quark model (conventional) baryons above those known experimentally. There is hence no need to posit hybrids.

Another possible way to identify hybrids in the spectrum is to compare the behaviour of experimental states relative to properties conventional baryons are *known* to have. Examples of such properties is the hypothesis that the high–lying conventional baryons occupy chiral multiplets [22] or that conventional baryons follow Regge trajectories [23].

(2) Diffractive γN and πN production. The detection of the hybrid meson candidate $\pi(1800)$ in diffractive πN collisions by VES [24] may indicate that hybrid mesons are producted abundantly via meson–pomeron fusion. If this is the case, one expects significant production of hybrid baryons via baryon–pomeron fusion, i.e. production in diffractive γN and πN collisions.

(3) Production in ψ decays. Naïve expectations are that the gluon–rich environment of ψ decays should lead to dominant production of glueballs, but also signifant production of hybrid mesons and baryons. The large branching ratios [25] $Br(\psi \to p\bar{p}\omega,\ p\bar{p}\eta') \sim 10^{-3}$ may indicate hybrid baryons. Recently a $J^P = \frac{1}{2}^+$ 2σ peak at mass 1834^{+46}_{-55} MeV was seen in $\Psi \to p\bar{p}\eta$. [26]

(4) Production in $p\bar{p}$ annihilation. The fact that the scalar glueball is strongly produced in this process, although not dominantly, may make it a promising production process.

(5) Studying hybrid baryon decays. Except for a QCD sum rule motivated suggestion that the $N\frac{1}{2}^+$ hybrid baryon has appreciable[b] decay to $N\sigma$, [27] and a bag model calculation which predicts a $N\frac{3}{2}^+$ with large $\pi\Delta$ decay and minute πN decay, [13] no decay calculations have been performed. However, decay of hybrid baryons to $N\rho$ and $N\omega$ is *a priori* interesting since it isolates states in the correct mass region, without contamination from lower–lying conventional baryons.

(6) Electroproduction. In the flux–tube model, which is an adiabatic picture of a hybrid baryon, there is the qualitative conclusion that "$ep \to eX$ should produce ordinary N^*'s and hybrid baryons with comparable cross–sections". [28] However, the conclusions obtained from the three quark – gluon picture of a hybrid baryon is different. For large Q^2 electroproduction, the Q^2 dependence of the amplitudes is summarized in Table 3. Since the photon has both a transverse and longitudinal component, the amplitude for a conventional baryon is expected to dominate that of the hybrid baryon as Q^2 becomes large. [7] For small Q^2 the conclusion agrees with the large Q^2 result for transverse photons, but is more dramatic for longitudinal photons: the amplitude vanishes. [29,30] It has accordingly been concluded that the (radially excited) conventional baryon is dominantly electroproduced (depending on the

[b] They find that $\Gamma_\sigma/\Gamma_{tot}$ = only 10% (modulo phase space), consistent with the Roper, although Γ_σ is still much larger than for other resonances.

Table 3: Q^2 dependence of amplitudes for the electroproduction of conventional or hybrid baryons with transverse or longitudinal photons, valid at large Q^2. [7]

	Conventional	Hybrid
Transverse	$1/Q^3$	$1/Q^5$
Longitudinal	$1/Q^4$	$1/Q^4$

details of the calculation), with the hybrid baryon subdominant relative to the resonances $S_{11}(1535), D_{13}(1520)$ and Δ as Q^2 increases. [29] The Q^2 dependence of the electroproduction of a resonance can be measured at Jefferson Lab Halls B and C and an energy upgraded Jefferson Lab. A hybrid baryon is expected to behave different from nearby conventional baryons as a function of Q^2. One needs to perform partial wave analysis at different Q^2. For large Q^2 cross–sections are small, which would make this way of distinguishing conventional from hybrid baryons challenging.

Various characteristics of the $N(1440)$ (Roper) have been argued to be consistent with its being dominantly a hybrid baryon: Its mass is consistent with bag model [10] and QCD sum rule [20] estimates, it is suppressed in large Q^2 electroproduction [29] and the width ratio $\Gamma_\sigma/\Gamma_{tot}$ is consistent with QCD sum rule decay calculations [27].

The $\Lambda(1405)$ ($J=\frac{1}{2}$) and $\Lambda(1520)$ ($J=\frac{3}{2}$) have recently been proposed to be hybrid baryons based on the idea that this hypothesis solves a J ordering problem in this system: for hybrid baryons the ordering in a constituent gluon model is as observed, while it is opposite in (most) quark models. [31]

We highlight current experimental searches for hybrid baryons. Photo– and electroproduction efforts at Halls B and C at Jefferson Lab (Newport News) can isolate hybrid baryons in $\gamma N \to$ hybrid $\to (\rho,\omega,\eta)N$ at masses less than 2.2 GeV. As previously remarked, the higher mass decay channels are of most interest. Similar searches at the Crystal Barrel and SAPHIR detectors at ELSA (Bonn) is under way. Particularly, at Crystal Barrel hybrid baryons is planned to be isolated in $\gamma N \to$ hybrid $\to (\eta,\pi^0)\ S_{11}(1535) \to (\eta,\pi^0)\ \eta N$. Hybrid mesons in flux–tube model decay strongly to $P+S$–wave mesons and not to $S+S$–wave mesons. If this is also true for hybrid baryons, decay to a P–wave baryon ($S_{11}(1535)$) and an S–wave meson (η or π^0) should be prominent. In Ψ production hybrid baryons are searched for at BES at BEPC. Searches for hybrid baryons in $\Psi \to$ hybrid $\bar{p} \to p\bar{p}\ (\eta,\pi^0)$ have been undertaken. [26]

Acknowledgments

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