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EXOTIC BARYON STATES IN TOPOLOGICAL SOLITON MODELS

H. Walliser[a*], *V. B. Kopeliovich*[b**]

[a] *Fachbereich Physik, Universität Siegen D57068, Siegen, Germany*

[b] *Institute for Nuclear Research, Russian Academy of Sciences 117312, Moscow, Russia*

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The novel observation of an exotic strangeness $S = +1$ baryon state at 1.54 GeV is to trigger an intensified search for this and other baryons with exotic quantum numbers. This state was predicted long ago in topological soliton models. We use this approach together with the new datum in order to investigate its implications for the baryon spectrum. In particular, we estimate the positions of other pentaquark and septuquark states with exotic and with nonexotic quantum numbers.

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1. INTRODUCTION

In a recent paper [1], Nakano et al. report on an exotic strangeness $S = +1$ baryon state observed as a sharp resonance at 1.54 ± 0.01 GeV in photoproduction from neutrons. The confirmation of this finding would give formidable support to topological soliton models [2, 3] for the description of baryons in the nonperturbative regime of QCD. Higher multiplets containing states carrying exotic quantum numbers arise naturally in the $SU(3)$ version of these models. These were called exotic because such states cannot be built from only three valence quarks within quark models, and additional quark–antiquark pairs must be added. The terms pentaquark and septuquark therefore characterize the quark content of these states. Strictly, there is nothing exotic about these states in soliton models, they just come as members of the next higher multiplets.

Indeed, beyond the minimal $\{8\}$ and $\{10\}$ baryons, a $\{\overline{10}\}$ baryon multiplet was also mentioned early by Chemtob [4]. Within a simple $SU(3)$ symmetric Skyrme model, Biedenharn and Dothan [5] estimated the excitation energy of the $\{\overline{10}\}$ multiplet with spin $J = 1/2$ to be only 0.60 GeV (sic!) above the nucleon. Both this multiplet and the $\{27\}$ multiplet with spin $J = 3/2$ contain low-lying $S = +1$ states, called Z and Z^* in what follows. First numbers for these exotic states with the configuration mixing caused by symmetry breaking taken into account were given in [6], although some 0.1 GeV is too high if the value found in [1] proves correct. Diakonov, Petrov, and Polyakov [7] postulated the experimental $P11(1.71)$ nucleon resonance a member of the $\{\overline{10}\}$ multiplet, and hence the Z state again with a low excitation energy (0.59 GeV). Weigel [8] showed that similar low numbers (0.63 GeV) can be obtained in an extended Skyrme model calculation that includes a scalar field.

It should be added that the excitation energies of similar exotic states have been estimated for arbitrary baryonic numbers [9]. All these states appear to be above the threshold for the decay due to strong interactions. In general, the excitation energies for the $B > 1$ systems are comparable to those for baryons, e.g., the $S = 1$ dibaryon state belonging to the $\{\overline{35}\}$ multiplet was calculated to be only 0.59 GeV above the NN threshold [10].

In this paper, we address the following questions concerning the $B = 1$ sector. Is an exotic Z state at 1.54 GeV reported in [1] compatible with soliton models and the known baryon spectrum? If Z is actually located at this position, what does it imply for the other exotic states?

*E-mail: walliser@physik.uni-siegen.de

**E-mail: kopelio@al20.inr.troitsk.ru, kopelio@cpc.inr.ac.ru

2. $SU(3)$ SOLITON MODEL

There exists a large number of different soliton models: pure pseudoscalar ones, models with scalar fields and/or vector and axial-vector mesons, and even models that include quark degrees of freedom. There is also a vast number of possible terms in the effective action for each of these models, partly with free adjustable parameters. However, the $SU(3)$-symmetric part always leads to the same collective Hamiltonian with only two model-dependent quantities determining the baryon spectrum (Sec. 2.1). The situation with the symmetry breaking part is less advantageous, unfortunately, but still there appears one dominating standard symmetry breaker, which is to be the third model-dependent quantity needed (Sec. 2.2). Thus, instead of referring to a specific model (which also involves a number of free parameters), we adjust these three quantities to the known $\{8\}$ and $\{10\}$ baryon spectra and to the recently reported Z state [1]. Using this input, we try to answer the questions posed in the Introduction. We also show that the values needed for the three quantities are not too far from what can be obtained in the standard Skyrme model.

In the baryon sector, the static hedgehog soliton configuration located in the nonstrange $SU(2)$ subgroup is collectively and rigidly rotated in the $SU(3)$ space. There are other approaches like the soft rotator approach and the bound state approach, but the rigid rotator approach is probably most appropriate for $B = 1$.

2.1. $SU(3)$-symmetric part

The $SU(3)$-symmetric effective action leads to the collective Lagrangian [11]

$$L^S = -M + \frac{1}{2}\Theta_\pi \sum_{a=1}^{3}(\Omega_a^R)^2 + \frac{1}{2}\Theta_K \sum_{a=4}^{7}(\Omega_a^R)^2 - \frac{N_C B}{2\sqrt{3}}\Omega_8^R \quad (1)$$

depending on the angular velocities Ω_a^R, $a = 1, \ldots, 8$. It is generic for all effective actions whose nonanomalous part contains at most two time derivatives, the term linear in the angular velocity depends on the baryon number B and the number of colors N_C, and it appears due to the Wess–Zumino–Witten anomaly.

The soliton mass M and the pionic and kaonic moments of inertia Θ_π and Θ_K are model-dependent quantities. The latter two are relevant to the baryon spectrum. The soliton mass M, subject to large quantum corrections, enters the absolute masses only. With the right and left angular momenta

$$R_a = -\frac{\partial L^0}{\partial \Omega_a^R}, \quad L_a = \sum_{b=1}^{8} D_{ab} R_b, \quad (2)$$

which transform according to Wigner functions D_{ab} depending on the soliton orientation, the Hamiltonian obtained by the Legendre transfomation

$$H^S = M + \frac{1}{2\Theta_\pi}\mathbf{R}^2 + \frac{1}{2\Theta_K}\left(C_2(SU(3)) - \mathbf{R}^2 - \frac{N_C^2 B^2}{12}\right) \quad (3)$$

can be expressed by the second-order Casimir operators of the $SU(3)$ group and its nonstrange $SU(2)$ subgroup,

$$C_2(SU(3)) = \sum_{a=1}^{8} R_a^2, \quad \mathbf{R}^2 = \sum_{a=1}^{3} R_a^2. \quad (4)$$

For a given $SU(3)$ irrep (p, q) with the dimension

$$N = (p+1)(q+1)(p+q+2)/2$$

the eigenvalues of these operators are given by

$$\begin{aligned} &C_2(SU(3))|\{N\}(p,q),(Y_R J J_3)\rangle = \\ &= \left[\frac{p^2+q^2+pq}{3} + p + q\right]|\{N\}(p,q),(Y_R J J_3)\rangle, \\ &\mathbf{R}^2|\{N\}(p,q),(Y_R J J_3)\rangle = \\ &= J(J+1)|\{N\}(p,q),(Y_R J J_3)\rangle, \end{aligned} \quad (5)$$

where $(Y_R J J_3)$ denote the right hypercharge and the baryon spin. The latter relation is due to the hedgehog ansatz that connects the spin to the right isospin. The states are still degenerate with respect to the left (flavor) quantum numbers $(Y T T_3)$ suppressed here. The constraint

$$R_8 = N_C B / 2\sqrt{3}$$

fixes

$$Y_R = N_C B/3$$

(see [11]) and is written as the triality condition [5]

$$Y_{max} = \frac{p+2q}{3} = B + m, \quad (6)$$

with Y_{max} representing the maximal hypercharge of the (p, q) multiplet. Thus, baryons belong to irreps of $SU(3)/Z_3$. With the octet being the lowest $B = 1$ multiplet, the number of colors must be $N_C = 3$. We also obtain the spin–statistics baryon number relation

$$(-1)^{2J+B} = 1,$$

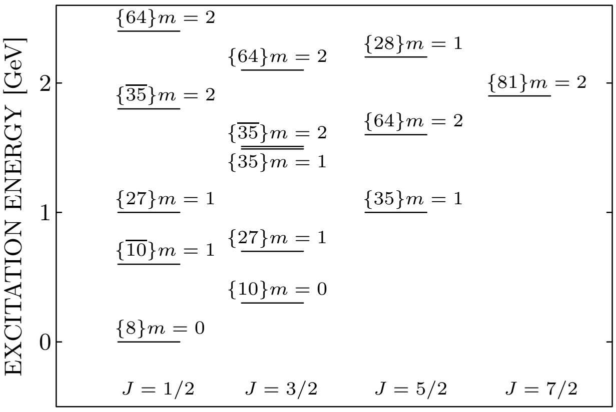

Fig. 1. $B = 1$ baryon multiplets with the excitation energy less than 2.5 GeV for $\Theta_\pi = 5$ GeV^{-1} and $\Theta_K = 2.5$ GeV^{-1}. The number m is also given

which allows only half-integer spins for $B = 1$ [5].

From the quark model standpoint, the integer m in combination with (p, q) is related to the number of additional $q\bar{q}$ pairs present in the baryon state [9]. When $B = 1$, we obtain the minimal multiplets $\{8\}$ and $\{10\}$ for $m = 0$, the family of penta- and septuquark multiplets $\{\overline{10}\}$, $\{27\}$, $\{35\}$, and $\{28\}$ for $m = 1$, and multiplets $\{\overline{35}\}$, $\{64\}$, and $\{81\}$ for $m = 2$ (Fig. 1). For the masses of the multiplets $\{8\}\,J = 1/2$, $\{10\}\,J = 3/2$, $\{\overline{10}\}\,J = 1/2$, $\{27\}\,J = 3/2$, and $\{\overline{35}\}\,J = 3/2$, simple relations

$$\begin{aligned} M_{\{10\}} - M_{\{8\}} &= 3/2\Theta_\pi, \\ M_{\{\overline{10}\}} - M_{\{8\}} &= 3/2\Theta_K, \\ M_{\{27\}} - M_{\{10\}} &= 1/\Theta_K, \\ M_{\{\overline{35}\}} - M_{\{10\}} &= 15/4\Theta_K \end{aligned} \qquad (7)$$

hold. We note that the mass difference of the minimal multiplets depends on Θ_π only[1)], whereas the mass differences between minimal and nonminimal multiplets depend on Θ_K and Θ_π. With the values $\Theta_\pi \approx 5$ GeV^{-1} and $\Theta_K \approx 2.5$ GeV^{-1} from a naive Skyrme model, the estimate $M_{\{\overline{10}\}} - M_{\{8\}} \approx 0.60$ GeV [5] was obtained in agreement with (7). The mass of $\{27\}$ then lies approximately 0.10 GeV higher. In Fig. 1, we show the spectrum of all baryon multiplets with the excitation energy up to 2.5 GeV using these moments of inertia for illustration. The sequence of the lowest baryon multiplets

$$\{8\}\,J = \frac{1}{2},\ \{10\}\,J = \frac{3}{2},\ \{\overline{10}\}\,J = \frac{1}{2}, \quad \{27\}\,J = \frac{3}{2},\ \{35\}\,J = \frac{5}{2}, \ldots \qquad (8)$$

turns out to be unique within a large range of moments of inertia $\Theta_\pi/3 < \Theta_K < \Theta_\pi/2$, covering the realistic cases. Diagrams for the lowest nonminimal baryon multiplets $\{\overline{10}\}$ and $\{27\}$ that accomodate the interesting $S = +1$ states are shown in Fig. 2.

So far, we have considered the $SU(3)$-symmetric case. To explain the splitting of baryon states within each multiplet, we must take the explicit symmetry breaking into account.

2.2. $SU(3)$ symmetry breaking

The dominant standard symmetry breaker comes from the mass and kinetic terms in the effective action that account for different meson masses and decay constants, e.g., $m_K \neq m_\pi$ and $F_K \neq F_\pi$,

$$L^{SB} = -\frac{1}{2}\Gamma(1 - D_{88}) - \Delta \sum_{a=1}^{3} D_{8a}\Omega_a^R + \ldots \qquad (9)$$

(the first term). There can be further terms of minor importance that depend on the specific effective action used. As an example, we optionally include such a term arising from $\rho - \omega$ mixing in vector meson Lagrangians (the second term). This can serve as a test for the model dependence of our results. The corresponding Hamiltonian is

$$H^{SB} = \frac{1}{2}\Gamma(1 - D_{88}) - \frac{\Delta}{\Theta_\pi} \sum_{a=1}^{3} D_{8a} R_a + \ldots \qquad (10)$$

The quantities Γ and Δ are again model-dependent quantities, they determine the strength of symmetry breaking. We first consider only the standard symmetry breaker Γ.

It was noticed early that a perturbative treatment of this symmetry breaker leads to the splitting

$$(M_\Lambda - M_N) : (M_\Sigma - M_\Lambda) : (M_\Xi - M_\Sigma) = 2 : 2 : 1$$

for the $\{8\}$ baryons [4, 11], in variance with observation. Because symmetry breaking is strong, Eq. (10) must be diagonalized in the basis of the unperturbed eigenstates of H^S. By this procedure, the states of a certain multiplet acquire components of higher representations. We nevertheless address the mixed states as $\{8\}$ states, $\{10\}$ states, etc., according to their dominant contribution.

[1)] It was shown for arbitrary B [9] that the factor at $1/2\Theta_K$ in (3), $C_2(SU(3)) - \mathbf{R}^2 - 3B^2/4 = 3B/2$ for any minimal multiplet with $p + 2q = 3B$; $N_c = 3$.

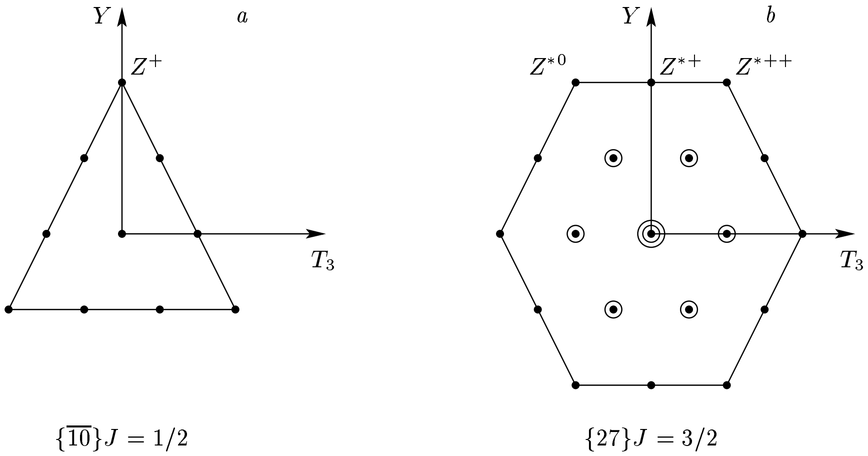

Fig. 2. The T_3–Y diagrams for the baryon multiplets $\{\overline{10}\}$ and $\{27\}$ that include the lowest $S = +1$ states

Table 1. Moments of inertia and symmetry breakers obtained from a fit to the baryon spectrum includung the novel Z datum

	Θ_π, GeV^{-1}	Θ_K, GeV^{-1}	Γ, GeV	Δ
fit A	5.61	2.84	1.45	–
fit B	5.87	2.74	1.34	0.40

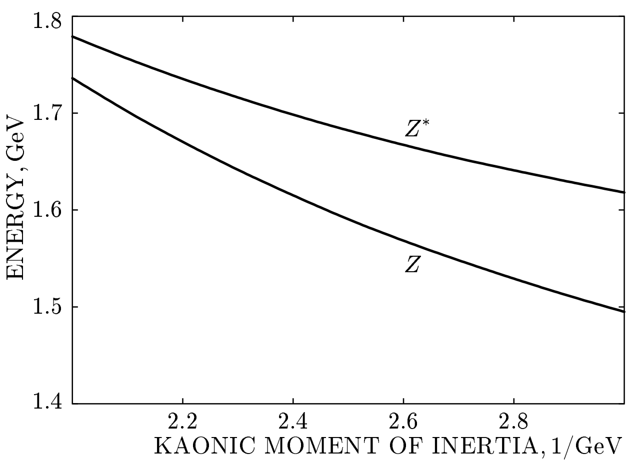

Fig. 3. The masses of the $S = 1$ baryons Z and Z^* depending on the kaonic moment of inertia. $\Theta_\pi = 5.87$ GeV^{-1} and $\Gamma = 1.34$ GeV are kept fixed

The best values for the moments of inertia Θ_π and Θ_K and the symmetry breaker Γ are listed in Table 1 (fit A). Optionally, the symmetry breaker Δ is also included (fit B). In Fig. 3, we show the dependence of the Z and Z^* energies on the kaonic moment of inertia Θ_K with the other parameters kept fixed. The sensitive dependence expected from Eq. (7) persists when symmetry breaking is included. If the experimental datum for Z proves correct, a relatively large kaonic moment of inertia (Table 1) is required.

We now compare this with the implications of the standard Skyrme model [2, 3] with only one adjustable parameter $e = 4.05$. The mass and kinetic symmetry breakers are included with mesonic parameters (the only parameter of this model is $e = 4.05$). The kinetic symmetry breaker involves time derivatives that were neglected in [6] (in the adiabatic approximation), in accordance with the argument that they are suppressed by two orders in the $1/N_C$ expansion and this order must include many other symmetry breaking terms that are not taken into account either. This leads to $\Theta_\pi = 5.88$ GeV^{-1}, $\Gamma = 1.32$ GeV, and a relatively small kaonic moment of inertia $\Theta_K = 2.19$ GeV^{-1} (connected with larger Z and Z^* masses, Fig. 3). But the nonadiabatic terms in the kinetic symmetry breaker are not small actually, and give a sizeable contribution to the kaonic moment of inertia $\Theta_K = 2.80$ GeV^{-1} together with symmetry breaking terms and even terms that are nondiagonal in the angular momenta. Because the latter were never properly treated, these numbers should be compared with those in Table 1 with reservation. Nevertheless, it seems that the standard Skyrme model can potentially provide values close to fit B. Relative to fit A, the standard symmetry breaker from the Skyrme model appears too weak, indicating that an important symmetry breaking piece is missing in this model. Concluding this discussion, we emphasize that the nonadiabatic terms in the kinetic symmetry breaker are of course not the only possibility to obtain larger

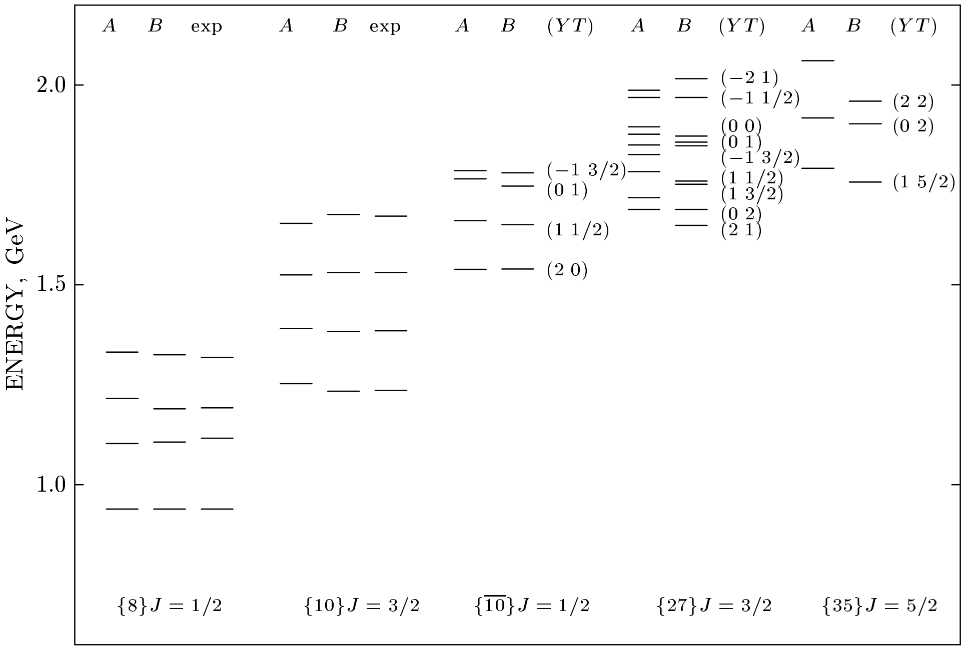

Fig. 4. The lowest rotational states in the $SU(3)$ soliton model for fits A and B. The experimental masses of the $\{8\}$ and $\{10\}$ baryons are depicted for comparison. Not all states of $\{35\}$ are shown

Table 2. Rotational states of nonminimal multiplets with exotic quantum numbers below 2 GeV including all members of $\{\overline{10}\}$ and $\{27\}$. The experimental Z datum enters the fits. The lowest exotic $Y = \pm 3$ baryon states are also included

		J	Y	T	Decay modes	Estimated energy, GeV	
						A	B
Z	$\{\overline{10}\}$	1/2	2	0	KN	1.54	1.54
Z^*	$\{27\}$	3/2	2	1	KN	1.69	1.65
	$\{27\}$	3/2	0	2	$\pi\Sigma$, $\pi\Sigma^*$, $\pi\pi\Lambda$	1.72	1.69
X	$\{35\}$	5/2	1	5/2	$\pi\Delta$, $\pi\pi N$	1.79	1.76
	$\{\overline{10}\}$	1/2	−1	3/2	$\pi\Xi$, $\pi\Xi^*$, $\bar{K}\Sigma$	1.79	1.78
	$\{27\}$	3/2	−1	3/2	$\pi\Xi$, $\pi\Xi^*$, $\bar{K}\Sigma$	1.85	1.85
	$\{35\}$	5/2	0	2	$\pi\Sigma$, $\pi\Sigma^*$	1.92	1.90
	$\{35\}$	5/2	2	2	$K\Delta$, $K\pi N$	2.06	1.96
	$\{27\}$	3/2	−2	1	$\pi\Omega$, $\bar{K}\Xi$, $\bar{K}\Xi^*$	1.99	2.02
	$\{35\}$	5/2	−3	1/2	$\bar{K}\Omega$, $\bar{K}\bar{K}\Xi$	2.31	2.36
Z^{**}	$\{\overline{35}\}$	3/2	3	1/2	KKN, $KK\Delta$	2.41	2.38

kaonic moments of inertia. Inclusion of other degrees of freedom or of additional terms in the effective action influences this quantity sensitively. In this respect, the position of the exotic Z baryon proves an important constraint on soliton models.

The resulting baryon spectrum is shown in Fig. 4. It can be seen that for fit A, with the standard symmetry breaker alone, the $\Sigma - \Lambda$ mass difference is too large, the splitting in the $J = 1/2$ multiplets relative to that in the $J = 3/2$ multiplets is overestimated, and the corresponding $SU(2)$ symmetry breaker can account for only half the neutron–proton split (not shown here, see, e.g., [6]). All the three deficiencies can be cured by including the second symmetry breaker, fit B. Of course, this does not mean that the additional symmetry breaker must be exacly of form (10); other operator structures are possible. As mentioned, we include fit B mainly to illustrate the model dependence of our results. It seems that the levels of the $\{\overline{10}\}$ multiplet are relatively stable in contrast to the $\{27\}$ multiplet, whose states depend sensitively on the specific form of the symmetry breakers such that even the ordering of the levels is changed.

All components of the $\{\overline{10}\}$ and $\{27\}$ multiplets are listed in Tables 2 and 3. We distinguish states with exotic quantum numbers from those with nonexotic quantum numbers $-2 \le Y \le 1$ and $T \le 1 + Y/2$. Generally, the former are «cleaner», because they cannot mix with vibrational excitations (apart from their own radial excitations). Because additional vibrations on top of these states can only enhance the energy, these turn out to be the lowest states with exotic quantum numbers starting with the $S = 1$ baryon states Z and Z^*. The latter are experimentally accessible via the reactions

$$\gamma N \to \bar{K} Z \to \bar{K} K N,$$
$$\pi N \to \bar{K} Z \to \bar{K} K N,$$
$$NN \to (\Lambda, \Sigma) Z \to (\Lambda, \Sigma) K N,$$

and in KN scattering. The novel measurement [1] was a photoproduction experiment of the first type. The $S \ne 1$ exotic states are more difficult to measure, e.g., X in Table 2 via the reactions

$$\pi N \to \pi X \to \pi\pi\Delta,$$
$$NN \to \Delta X \to \pi\Delta\Delta.$$

We also included the lowest exotic states with strangeness $S = +2$ and $S = -4$ with the main components in the respective multiplets $\{\overline{35}\}$ and $\{35\}$. The $S = +2$ state Z^{**} can still be produced in binary reactions, e.g.,

$$K^0 p \to K^- Z^{**,++},$$

but the energy of this state is already quite considerable, approximately 2.4 GeV. On the other hand, the $S = -4$ state is more difficult to produce, but detection seems to be simpler because final Ω^- and K^- are easy to see.

In contrast, the states with nonexotic quantum numbers in Table 3 mix strongly with vibrational excitations of the $\{8\}$ and $\{10\}$ baryons. For example, the N^* rotational state, identified with the nucleon resonance $P11(1.71)$ in [7], mixes strongly with a $2\hbar\omega$ radial excitation, which can even lead to a doubling of states found in [8]. This situation renders an easy interpretation difficult. Probably the cleanest of these states with nonexotic quantum numbers is the one called Λ^*, which predominantly couples to the nonresonant magnetic dipole mode. But even here, it is not excluded that the good agreement with the position of the experimental Λ resonance $P03(1.89)$ is accidential. Also, there is not even a candidate for the rotational state called Δ^* listed by the PDG in the required energy region with the empirical Δ resonance $P33(1.92)$ lying approximately 0.1 GeV too high. On the other hand, we do have candidates close to the estimated energies in five cases. There is certainly some evidence that the numbers presented are not unreasonable.

It should be added that the energies for the $\{\overline{10}\}$ baryons presented here differ substantially from those obtained in Ref. [7] using simple perturbation theory. Their $\{\overline{10}\}$ total splitting is overestimated by a factor greater than 2.

3. THE $S = 1$ BARYON SPECTRUM

So far, we have considered only the rotational states. The real situation is complicated because there is an entire tower of vibrational excitations connected with each of these rotational states. We briefly address this issue on a quite qualitative level, particularly for the $S = 1$ sector. This may possibly be of help for experimentalists in search for further exotic baryons.

The lowest states in the $S = 1$ sector are the rotational states Z and Z^* discussed in the previous section. As mentioned, we believe that the energies of these two states must be close to each other and the energy of Z^* somewhat larger (about 0.10–0.15 GeV). Such rotational states appear as sharp resonances with small widths relative to the broader vibrational states. The width of Z was given in [1] to be smaller than 25 MeV, and that of Z^* must be somewhat larger due to phase space arguments. The Z^* state will probably be the next exotic state detected.

Table 3. Rotational states of higher multiplets with nonexotic quantum numbers below 2 GeV including all members of the $\{\overline{10}\}$ and $\{27\}$ multiplets

	J	Y	T	Candidate	Estimated energy, GeV	
					A	B
N^* $\{\overline{10}\}$	1/2	1	1/2	$N\,P11(1.71)***$	1.66	1.65
Σ^* $\{\overline{10}\}$	1/2	0	1	$\Sigma\,P11(1.77)*$	1.77	1.75
Δ^* $\{27\}$	3/2	1	3/2		1.83	1.75
$\{27\}$	3/2	1	1/2	$N\,P13(1.72)****$	1.78	1.76
$\{27\}$	3/2	0	1	$\Sigma\,P13(1.84)*$	1.90	1.86
Λ^* $\{27\}$	3/2	0	0	$\Lambda\,P03(1.89)****$	1.88	1.87
$\{27\}$	3/2	-1	1/2	Ξ ?? (1.95) $***$	1.97	1.97

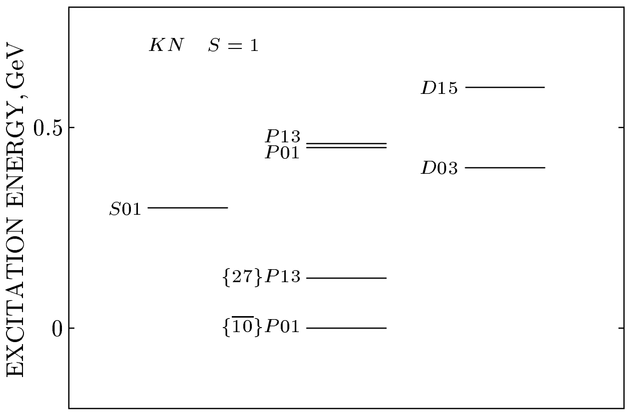

Fig. 5. Tentative baryon spectrum for the $S = 1$ sector

In soliton models, there certainly exist radial excitations (breathing modes) for each rotational state. For most of the $\{8\}$ and $\{10\}$ baryons, such excitations correspond to the well-known resonances, e.g., the Roper resonance for the nucleon. The breathing mode excitation energy of Z calculated in [8] is approximately 0.45 GeV, and that of Z^* should be considerably smaller because the latter object is more extended due to centrifugal forces related to a larger spin (similarly to the Roper and the Δ resonance $P33(1.60)$). We can therefore expect the excited $P01$ and $P13$ states to occur close to each other, as indicated in Fig. 5 (the order may be reversed!).

In addition, there must be strong quadrupole excitations, as those obtained in soliton models [12] and seen empirically in the well-studied $S = 0$ and $S = -1$ sectors (with roughly 0.4 and 0.6 GeV excitation energy). In these sectors, there also appear a number of S-wave resonances through $\bar{K}N$, $K\Lambda$, $K\Sigma$, and $K\Xi$ bound states just below the corresponding thresholds [12]. Although such an interpretation seems less clear in the $S = 1$ sector, a low-lying $S01$ resonance is nevertheless expected, just by inspection of the other sectors.

Tentatively, this leads to an $S = +1$ baryon spectrum depicted in Fig. 5. The T-matrix poles $P01(1.83)$, $P13(1.81)$, $D03(1.79)$, and $D15(2.07)$ extracted from early KN scattering experiments [13] qualitatively fit such a scheme, but the spacings are considerably smaller than in Fig. 5. Therefore, if these T-matrix poles prove correct, a strong quenching of the spectrum shown in Fig. 5 has to be understood. The existence of such poles, particularly in the D-waves, would likewise favor the location of Z considerably below these resonances, compatible with the datum 1.54 GeV.

4. CONCLUSIONS

We have shown that a low position of the exotic $S = +1$ baryon Z with quantum numbers $J = 1/2$ and $T = 0$ at the reported energy 1.54 GeV is compatible with soliton models and the known baryon spectrum. For all members of the $\{\overline{10}\}$ and $\{27\}$ multiplets with nonexotic quantum numbers, we find candidates close to the estimated energies, with one exception: the empirical Δ resonance $P33(1.92)$ lies approximately

0.1 GeV too high. A strong mixing of these states with vibrational modes of the {8} and {10} baryons may lead to considerable energy shifts and even to a doubling of states. Also the T-matrix poles of early KN scattering experiments favor a low Z baryon sufficiently below these resonances, with the caveat that when these poles are correct, a strong quenching of the $S = 1$ baryon spectrum compared to other sectors has to be explained.

However, the soliton model by itself does not exclude a Z baryon at higher energies. Confirmation of this datum, which proves a stringent constraint on these models, is therefore most important.

Under the assumption that the exotic Z baryon is actually located at the reported position, we have estimated the energies of other exotic baryons. First of all, there is a further $S = +1$ baryon Z^* with quantum numbers $J = 3/2$ and $T = 1$, some $0.10 - 0.15$ GeV above Z. This will probably be the next state to be discovered in similar experiments also as a sharp resonance with a somewhat larger width. Moreover, there will be a tower of vibrational excitations built on these two exotic states, which should appear as broader resonances several 0.1 GeV above these energies.

There are also several low-lying $S \neq 1$ baryons with exotic isospin, starting with a $J = 1/2$ state with quantum numbers $S = 0$ and $T = 2$ at approximately 1.7 GeV. These states are more difficult to access experimentally. The lowest $S = +2$ and $S = -4$ baryon states may also be of some interest, although they are already expected at high energies about 2.3–2.4 GeV.

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Note added in proof (1 July 2003). In a recent paper by V. V. Barmin et al. (hep-ex/0304040), the Z^+ hyperon is observed in K^+ collisions with Xe nuclei. The spectrum of the K^0p effective mass shows an enhancement at $M = 1539 \pm 2$ MeV with the width $\Gamma \leq 9$ MeV, in agreement with the result by T. Nakano et al. [1].