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Even Parity Θ-Pentaquark and Stable Strange Nuclear Matter

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Abstract

The newly discovered exotic Θ baryon of mass 1540 MeV (and very small width) truly has a very low mass, if it is a pentaquark system of even parity. A schematic model in which the coherent interaction of $u\bar{s}$ and $d\bar{s}$ pairs leads to a very large residual (non-confining) attractive interaction is introduced. This collective vibrational model accounts for the mass and small decay width to the KN channel, but yields a significant coupling to the virtual K^*N channel. The schematic model predicts an attractive Θ-nucleon interaction strong enough to bind a Θ particle to a nucleus in a state that is stable against decay via strong interactions. The discovery of Θ-nuclei could be a definitive proof that the Θ parity is even.

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Stimulated by the prediction[1] of the existence of an extremely narrow positive strangeness pentaquark state Θ of mass 1.54 GeV and $J^P = 1/2^+$, a member of an antidecuplet, several experimental searches were successfully undertaken[2]-[8]. Other possible strangeness -2 partners in the Θ-antidecuplet were also detected[9].

A study of the implications of the existence of the state with the quantum numbers predicted in Ref. [1] is presented here. An even-parity, low-lying S=+1 state must have very unusual properties[10], with the most unusual being is its very low mass. Indeed, lattice calculations[11] find the expected result that the odd parity $S = +1$ state is the one of lowest energy. Furthermore, the lack of a presence in KN scattering seems to limit the width to an usual small value (perhaps on the order of an MeV)[12], but its relatively large production cross section could arise from the exchange of K^* mesons[13]. A state with such unique properties does not arise in an obvious way from previously existing quark models of baryon spectroscopy, so it would be interesting to create new models with new implications.

The unusual nature of the Θ can be seen immediately using the naive quark model. The Θ and nucleon have the same J^P, their mass difference arises from the addition of a pair of constituent quarks $d\bar{s}$ or $u\bar{s}$ (of mass 340 and 510 MeV) and one unit of orbital angular momentum to the nucleon. is present. The energy cost of the unit of angular momentum can be estimated as the mass difference between the nucleon and lowest-lying odd parity excited states, or about 600 MeV. Thus the naive quark model gives the energy of the $\Theta - N$ mass difference, $\hbar\omega_0$, as about 1.4 GeV! This truly astonishing number makes it clear that the naive quark model does not contain the interactions between quarks needed to explain low mass of the Θ. In the original work[1], the attraction was assumed to arise from the non-perturbative effects of the chiral soliton field. Such a field can only have its quark model interpretation in terms of non-confining residual interactions. Indeed the aim of understanding the Θ dynamics has attracted several proposed mechanisms, including: flavor and color hyperfine interactions (see the review in Ref. [14]), and strong quark-quark interactions leading to di-quarks[15] (perhaps caused by the influence of instantons in the vacuum[16]). We'll provide another mechanism, perhaps similar to some of the others, to obtain a wave function that differs significantly from that of the naive quark model.

Here is an outline of our logic. We'll work in the framework of the quark model, so that some gargantuan residual interaction is needed. Since no ultra-large coupling constants can be expected to arise from QCD, the extreme strength must arise from collective effects. We introduce a schematic interaction that causes the Θ to be described as a coherent set of color-singlet $d\bar{s}, u\bar{s}$ pseudoscalar excitations that move in a p-wave relative to the nucleon. This interaction between these excitations and the nucleon must be assumed to be attractive, but need not be very strong. In this case, the Θ can be regarded as a collective vibration of the nucleon. This mechanism is reminiscent of one used to describe the nuclear giant dipole resonance[17]. The model can account for the mass, width and $K*$ interactions of the Θ. But the most dramatic implication of the model is that Θ to binds to nuclei with a binding energy considerably greater than 100 MeV. This new Θ-matter would therefore be stable against decay by the strong interaction.

It is worthwhile to stress that the unusual implications we draw stem entirely from the presumed even parity of the Θ. An unambiguous experimental determination of the Θ parity would be very important, and necessary experiments are being planned[18], [19].

Let's turn to the calculation of the Θ wave function. The goal is to model a effective interaction between the pseudoscalar excitations and the nucleon that reproduces the energy and decay properties of the Θ. Consider a color-singlet $d\bar{s}$ configuration of even parity that moves in a relative p-wave around the nucleon. The d quark can have any one of three colors, and the pair can have any of three values of L_z, so there are 9 possible states. Similarly there can be $u\bar{s}$ configurations, so there are 18 possible states. The coherence of 18 states will lead to considerable collective effects. Furthermore, we can include radial excitations. In this case, number of states will be unlimited.

We'll use a specific schematic model to see how coherent effects can cause strong attraction. Let $a_n(\mathbf{k})$ denote the operator that destroys a pseudoscalar excitation in a discrete level n, and let $b_m(\mathbf{p})$ denote the nucleon destruction operator. Our proposed wave function for the Θ state of total momentum $\mathbf{P}$ and spin m is given by

$$|\Theta(\mathbf{P},m)\rangle = \sum_n \int d^3q\; {a^\dagger}_n(\mathbf{q}) \sum_{m'} \langle m|\boldsymbol{\sigma}\cdot\mathbf{q}_r|m'\rangle {b^\dagger}_{m'}(\mathbf{P}-\mathbf{q}) c_n(\mathbf{q}_r)|0\rangle, \tag{1}$$

where $\mathbf{q}_r \equiv (M\mathbf{q} - \mu(\mathbf{P}-\mathbf{q}))/(M+\mu)$ is the relative momentum between the meson (of mass μ) and nucleon constituents of the Θ. The function c_n will be determined by solving the Schroedinger equation. The wave function of Eq. (1) is a coherent superposition of states, and this coherence will generate a huge attraction. The normalization condition is $\langle\Theta(\mathbf{P}',m')|\Theta(\mathbf{P},m)\rangle = \delta_{m,m'}\delta(\mathbf{P}-\mathbf{P}')$. We'll show below that using color-singlet pseudoscalar excitations in a p-wave relative to the nucleon substantially suppresses the decay to KN, while allowing the virtual transition to K^*N.

Now let's write the Hamiltonian. The nucleon and Θ are treated as heavy objects, and the energy carried by the the i'th excitation is denoted as ω_i, with

$$\omega_i = \mu + \Delta E_1 + \Delta E_i, \tag{2}$$

where the energy required by having a relative p-wave is ΔE_1, the energy due to a possible radial excitation is ΔE_i, and the energy required by having two extra quarks of total effect mass is μ. As noted above the naive quark model gives $\omega_0 \approx 1400$ MeV, if radial excitations are ignored. The value of μ in the naive quark model would be about 850 MeV, but this ignores the potential influence of an attractive confining and hyperfine interactions between the $\bar{s}$ and its partner. This attraction could be about 600 MeV [20] so that ω_i is at least aproximately 900 MeV, and μ is at least 250 MeV. Such energies are much larger than the expected kinetic energies of the pseudoscalar excitations and the nucleon, so the latter are neglected.

Given the above definitions and aproximations, the unperturbed Hamiltonian H_0 can be expressed as

$$H_0 = M\sum_{m_s}\int d^3p\; {b^\dagger}_{m_s}(\mathbf{p}) b_m(\mathbf{p}) + \sum_i \omega_i \int d^3k\; {a^\dagger}_i(\mathbf{k}) a_i(\mathbf{k}), \tag{3}$$

where M is the nucleon mass. The residual interaction $\widehat{V}$ is chosen as

$$\widehat{V} = -\lambda \sum_{i,j,m_s} \int d^3k d^3k' d^3p\; {a^\dagger}_i(\mathbf{k}') {b^\dagger}_{m_s}(\mathbf{p}+\mathbf{k}-\mathbf{k}') a_j(\mathbf{k}) b_{m_s}(\mathbf{p}) D_i(k_r') D_j(k_r) \mathbf{k}_r'\cdot\mathbf{k}_r, \tag{4}$$

where $\mathbf{k}_r = (M\mathbf{k} - \mu\mathbf{p})/(M+\mu), \mathbf{k}_r' = (M\mathbf{k}' - \mu(\mathbf{p}+\mathbf{k}-\mathbf{k}'))/(M+\mu)$, and $k_r =\mid \mathbf{k}_r \mid$ If the Θ is in its rest frame ($\mathbf{k}+\mathbf{p} = 0$), the relative momenta can be taken to be that of the pseudoscalar excitation (or the negative of the nucleon momentum). In this case, $\mathbf{k}_r = \mathbf{k}, \mathbf{k}_r' = \mathbf{k}'$. The real functions D_i are to be defined as part of the model, with a spatial

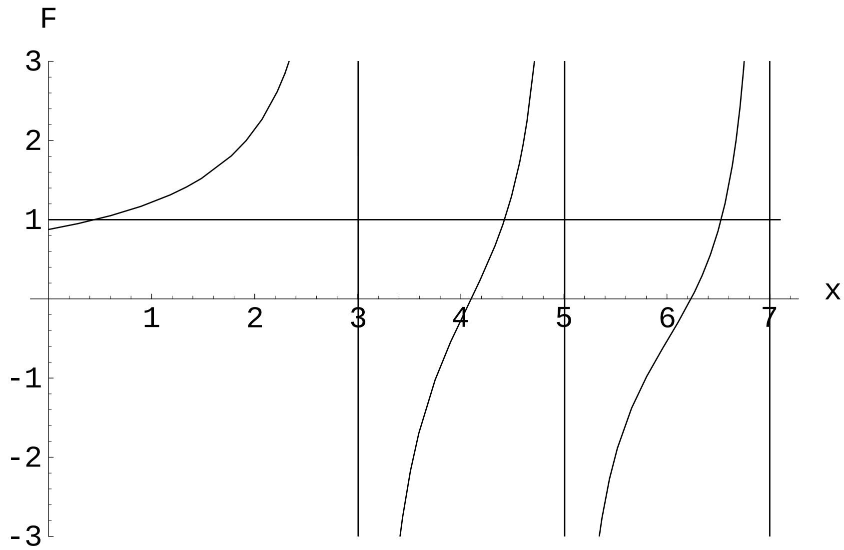

FIG. 1: Graphical solution of Eq. (6). The variable x represents the quantity $M_\Theta - M$.

extent determined by the nucleon radius, R_0. The interaction $\widehat{V}$ involves all 5 quarks, and can arise through two successive three-quark 't Hooft interactions proceeding via the instantons in the vacuum. Thus three separate flavors are required for this mechanism to occur.

Proceed by using Eq. (1) (for $\mathbf{P} = 0$) in the Schroedinger equation with the Hamiltonian $H = H_0 + \widehat{V}$, and then acting with $a_j(\mathbf{l})$, where $\mathbf{l}$ is an arbitrary momentum vector, on both sides. After some algebra, one obtains the result:

$$c_j(l) = -\frac{\lambda}{3}\frac{D_j(l)}{(M_\Theta - M - \omega_j)}\sum_n \int d^3q\; D_n(q) c_n(q) q^2. \tag{5}$$

This relation is a consistency condition between the Hamiltonian and wave function, and can be re-written as a transcendental equation for M_Θ using techniques developed long ago[17]. To see this, multiply Eq. (5) by $l^2 D_l(l)$, integrate over d^3l, sum over j and divide by a common factor to obtain:

$$1 = \frac{\lambda}{3}\sum_j \frac{\int d^3l\; l^2 D_j(l) c_j(l)}{(-M_\Theta + M + \omega_j)}. \tag{6}$$

Consider the right-hand-side to be a function of M_Θ, $F(M_\Theta)$ that has poles at $M_Z = M + \omega_i$, with $F(M_\Theta)$ small and positive at $M_\Theta = 0$, but increasing to infinity, crossing unity on its way, as M_Θ approaches $M + \omega_1$. This crossing point is the lowest value of M_Θ that solves Eq. (7). For M_Θ slightly greater than $M + \omega_1$, $F(M_\Theta)$ will rise from negative infinity and cross unity at a value between $M + \omega_1$ and $M + \omega_2$, which is a much higher value. See Fig. 1 which shows that one solution occurs at a much lower energy than all of the others; this corresponds M_Θ, with the Θ as a collective vibration.

The graphical solution shows that all but one of the eigenvalues occur between the energies of the unperturbed states. A useful simplification [17] is to let the ω_j of Eq. (6) become equal to a common value, taken as ω. Then the vertical lines of Fig. 1 coalesce and all but one the eigenvalues are equal to ω. One value is considerably lower than the others, the one of the Θ. Then

$$M_\Theta = M + \omega - \frac{\lambda}{3}\sum_j \int d^3q q^2 D_j^2(q). \tag{7}$$

Since our treatment is meant to be schematic, we take each D_i to be the same, $D_i(q) = D(q)$, and take the number of states to be $N(\geq 18)$. The essential feature here is that N is large; its exact value will not matter. Then eqn. (5) can be solved as

$$c_j(q) = \gamma D(q), \tag{8}$$

with γ determined from the normalization of the Θ as $\gamma = 1/\sqrt{N\int d^3qq^2D(q)^2}$, and Eq. (7) becomes

$$M + \omega - M_\Theta \approx \mu = \frac{\lambda}{3}N\int d^3q\, q^2 D^2(q). \tag{9}$$

The result Eq. (9) shows the power of the coherence in increasing the importance of the residual interaction by a factor of at least 18! This mechanism is an attractive version of the repulsive mechanism used to describe the nuclear giant dipole resonance[17]. The discovery of this huge collective resonance involved a puzzle. Simple shell model considerations gave the energy of the excited state as one unit of $\hbar\omega$, while the observed value is $\approx 2\hbar\omega$. The coherent effect of a repulsive particle-hole interaction was shown[17] to increase the energy of the giant dipole resonance. Here there is an attractive residual interaction between the excitations and the core nucleon. The replacement of $M + \omega - M_\Theta$ by μ involves noting that $\Delta E_1 \approx M_\Theta - M(\approx 600)$ MeV (recall Eq. (2)) and then including any effects of radial excitations in the parameter μ.

We next argue that the wave function Eq. (1) leads naturally to a very weak decay to the KN channel. What are the mechanisms for decay? One might think of gluon exchange, but the effects of one gluon exchange are eliminated by the color singlet nature of the nucleon and its excitation. One is left with multi-gluon exchanges at low energies, but these effects must be non-perturbative so it is natural to think of chiral mechanisms. Indeed, a natural model to use when considering low-energy excitations is the cloudy-bag model[21], or its relativistic form[22]. In this model, the pseudoscalar excitation interacts by exchanging a pion with the nucleon core. The pion is emitted only by the u or d quark in the pseudoscalar excitation, the interaction can be expressed as $\boldsymbol{\sigma}\cdot\mathbf{v}$ where $\mathbf{v}$ is the relative momentum between the pion and the light quark. The matrix element for the transition to a state with kaonic quantum numbers $\propto Tr\,[\sigma_2\boldsymbol{\sigma}\cdot\mathbf{v}\sigma_2] = 0$, but the one for the transition to a state with K* quantum numbers is $\propto Tr\,[\boldsymbol{\sigma}\cdot\mathbf{v}\sigma_2] \neq 0$. Thus transitions between the Θ and nucleons involving virtual K^* mesons can be strong. Indeed, the absorption of a virtual K^* by a nucleon making a Z will be strongly enhanced due to coherent collective effects.

The next step is to use the present model to estimate the Θ-nucleon interaction. We shall see that the resulting ΘN potential will be proportional to $-\mu$, and therefore very strong.

The interaction between the Θ and the nucleon is expressed in terms of a potential. The initial ΘN state is defined by the quantum numbers $(\mathbf{P}, m_\Theta; \mathbf{p}, m)$ and the final state is similarly $(\mathbf{P}', m_{\Theta'}; \mathbf{p}', m')$. The relevant matrix element is $\langle\Theta_{m'_\Theta}(\mathbf{P}'), N_{m'}(\mathbf{p}')|\widehat{V}|\Theta_{m_\Theta}(\mathbf{P}), N_m(\mathbf{p})\rangle_c = \delta(\mathbf{P}+\mathbf{p}-\mathbf{P}'-\mathbf{p})\langle\Theta_{m'_\Theta}(\mathbf{P}+\mathbf{p}-\mathbf{p}'), N_{m'}(\mathbf{p}')|v|\Theta_{m_\Theta}(\mathbf{P}), N_m(\mathbf{p})\rangle_c$. The subscript c indicates that the matrix element contains a reproduction of the Θ self-energy proportional to V_0 that must be subtracted. Evaluation

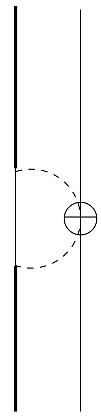

FIG. 2: ΘN interaction. The heavy lines represents the Θ and the light one the nucleon. Coherent excitations in the Θ are denoted by the dashed line $\widehat{V}$ is represented by the circle.

of the matrix element shows that only the term in which the coherent cloud of theta interacts with the nucleon survives the evaluation[23], see Fig. 2. Then one finds

$$\langle\Theta_{m'_\Theta}(\mathbf{P}+\mathbf{p}-\mathbf{p}'),N_{m'}(\mathbf{p}')|v|\Theta_{m_\Theta}(\mathbf{P}),N_m(\mathbf{p})\rangle_c =$$
$$-\mu N\delta_{m,m'}\delta_{m_\Theta,m'_\Theta}\int d^3q C(q'_r)D(k'_r)C(q_r)D(k_r)\mathbf{k}'_r\cdot\mathbf{k}_r\langle m'_\Theta|\boldsymbol{\sigma}\cdot\mathbf{q}_r\ \boldsymbol{\sigma}\cdot\mathbf{q}'_r|m_\Theta\rangle, \quad (10)$$

where $\mathbf{q}_r=(M\mathbf{q}-\mu\mathbf{P})/(M+\mu)$, $\mathbf{k}_r=(M\mathbf{q}-\mu\mathbf{p})/(M+\mu)$, $\mathbf{q}'_r=\mathbf{q}_r+\boldsymbol{\Delta}$, $\mathbf{k}'_r=\mathbf{k}_r+\boldsymbol{\Delta}$, and $\boldsymbol{\Delta}\equiv\mathbf{P}'-\mathbf{P}$. This mechanism involves the mutual polarization of two interacting composite quantum systems, and *e.g* has some features in common with the two-photon exchange interaction responsible for the Van der Waals force.

Let's see what Eq. (10) tells us about the ΘN interaction. First, simplify the integral over d^3q by changing variables: $\mathbf{q}\to\mathbf{q}+\mu/M\mathbf{P}\to(M+\mu)/M\mathbf{Q},\mathbf{Q}\to\mathbf{Q}-\boldsymbol{\Delta}/2$. This allows us to re-write Eq. (10) as

$$\langle\Theta_{m'_\Theta}(\mathbf{P}+\mathbf{p}-\mathbf{p}'),N_{m'}(\mathbf{p}')|v|\Theta_{m_\Theta}(\mathbf{P}),N_m(\mathbf{p})\rangle_c=\delta_{m',m}(-\mu N)\left(\frac{M+\mu}{M}\right)^3\gamma^2\times$$
$$\int d^3Q D(|\mathbf{Q}-\boldsymbol{\Delta}/2|)D(|\mathbf{Q}+\boldsymbol{\Delta}/2|)D(|\mathbf{Q}-\mathbf{L}-\boldsymbol{\Delta}/2|)D(|\mathbf{Q}-\mathbf{L}+\boldsymbol{\Delta}/2|)\times$$
$$\left[(\mathbf{Q}-\mathbf{L})^2-\boldsymbol{\Delta}^2/4\right]\left[\delta_{m_\Theta,m'_\Theta}\left(Q^2-\Delta^2/4\right)+2\langle m'_\Theta|i\boldsymbol{\sigma}\cdot(\mathbf{Q}\times\boldsymbol{\Delta}/2)|m'_\Theta\rangle\right], \quad (11)$$

where $\mathbf{L}\equiv\mu/(M+\mu)(\mathbf{p}-\mathbf{P})$. The quantity $\mathbf{p}-\mathbf{P}$ is essentially the relative momentum between the Θ and the nucleon[24]. We'll apply this expression to compute the properties of the Θ in nuclear matter. In that case both $\mathbf{p}$ and $\mathbf{P}$ have small magnitudes on the order of the inverse nuclear radius. Furthermore, the symmetries of the integrand allow one to show that only terms involving powers of $\mathbf{L}\cdot\mathbf{L}\sim(\mu/(M+\mu))^2(R_0/R_A)^2$, and are neglected. Then Eq. (11) leads to an expression in which the potential is expressed as $\delta_{m_\Theta,m'_\Theta}\delta_{m',m}$ times a function of the variable Δ. Thus, the matrix element of $\widehat{V}$ is equivalent to one for a spin-independent local potential $v(r)$, where r is the distance between the nucleon and the Θ. To be specific, take

$$D(K)=e^{-\alpha K^2R_0^2}, \quad (12)$$

where $\sqrt{\alpha}R_0$ is of the order of the nucleon size ~ 1 fm. Then we obtain:

$$v(r) = -V_0 \left(1 - \frac{1}{6}\frac{r^2}{\alpha R_0^2} + \frac{r^4}{48\alpha^2 R_0^4}\right) \exp\left(\frac{-r^2}{4\alpha R_0^2}\right),\ V_0 \equiv \mu \left(\frac{M+\mu}{M}\right)^3. \tag{13}$$

The strength of $v(r)$ is constrained by the known mass of the Θ, but also depends on the paramter μ. We have argued above that possible values of μ range between 250 and 800 MeV. We use the lowest value to obtain $V_0 \approx 420$ MeV. This is amazingly strong potential persists to relatively long ranges on the order of a fm for any reasonable choice of α. Thus there will be substantial ΘN attraction, even if there is a repulsive interaction at short distances between the nucleon and the nucleon constituent of the Θ.

The result (13), with its huge attraction, is the essential finding of this paper. It arises from the assumed even parity of the Θ and the assumption that the surprisingly small mass of 1540 MeV arises from a coherent interaction.

How can the influence of such an attraction be made observable? The immediate implication is that the Θ would be bound to nuclei with a binding energy of the lowest energy state is substantially greater than the 105 MeV threshold energy. This can be seen by observing that the Θ-nucleus mean field U is the convolution of the interaction (13) with the density ρ of nucleons within the nucleus. Then, with R_Θ as the distance between the Θ and the nuclear center,

$$U(R_\Theta) = \int d^3s v(s)\rho(\mathbf{R}_\Theta + \mathbf{s}) \approx \rho(R_\Theta) \int d^3s v(s), \tag{14}$$

in which the second equation arises from taking the nuclear radius to be much, much greater than R_0. Carrying out the integral one finds

$$U(R_\Theta) \approx -V_0 \rho(R_\Theta) 10(\alpha\pi)^{3/2}. \tag{15}$$

To estimate the central maximum value take $\rho(0)$ to be the density of infinite nuclear matter, $(1/6)\mathrm{fm}^{-3}$ and $\alpha = 1/4$ so that the exponential term of the interaction $v(r)$ has a range of $R_0 = 1$ fm. This gives the central nuclear potential a value of about 490 MeV. This is a huge attractive potential. For such a deep potential, the binding energy is close to the central value of the potential. This is much larger than the 105 MeV threshold energy, so the Θ bound to the nucleus will be stable against decay by strong interaction effects. A more sophisticated calculation would include the repulsive influence of nucleon-nucleon correlations and reduce the strength of the attractive interaction. However, with the mean field calculation giving a binding energy of 490 MeV, we can be sure that a huge attraction survives. Thus we predict that a new state of nuclear matter, Θ-matter of positive strangeness and excitation energy of the order of hundreds of MeV exists.

How can Θ-matter be detected? It has long been known that hypernuclei can be made in reactions in which a nucleon is replaced by a hyperon of roughly the same momentum[25]. With this in mind, it's a straightforward exercise in kinematics to see that Θ nuclei can be made using photon or kaon beams of energies from about 1 to 5 GeV or more. Denote $(A-1)_Z$ as a state of baryon number $A-1$ containing one Θ. Then reactions $\gamma + A \to \Sigma + (A-1)_\Theta, K + A \to \pi + (A-1)_\Theta$, are prime candidates for reactions that would copiously produce Θ-nuclei. This because the required transfer to the nucleus is very small. For example, for a ^{40}Ca target, Θ binding energy of 200 MeV, and a photon beam of 3 GeV, $(p_\gamma - p_\Sigma)^2 = .004\ \mathrm{GeV}^2$ for forward production. Similarly a kaon beam of 3 GeV would have $(p_K - p_\pi)^2 = .026\ \mathrm{GeV}^2$.

There are other implications of the present model. Since the low mass of the Θ is caused by a non-confining residual interaction involving a $u\bar{s}$ or $d\bar{s}$ pair, it is reasonable to expect that $u\bar{c}$, $u\bar{c}$ and $d\bar{b}$,$d\bar{c}$ will interact with nucleons in a similar manner. Thus there should be a charmed pentaquark at about 1540 MeV plus the c-s quark mass difference of about 1000 MeV. Such state would be stable against strong decay into a D meson and a nucleon. Similarly, the bottom pentaquark system would be stable against decay into a a B meson and a nucleon. Thus, in agreement with previous authors[15], we expect that the charmed and bottom versions of the pentaquark will be stable against particle decay.

The present schematic model is too naive for detailed applications to spectroscopy, which generally is a difficult subject to pursue[26]. However, discussing the energy of the doubly strange version, a possible $\Sigma(3/2)$, of the pentaquark observed in Ref. [9] is worthwhile. If the doubly strange system and the Θ really are members of the same multiplet then we may estimate $M_{\Xi(3/2)}$ as $M_{\Xi(3/2)} = M_\Theta + (M_s - m_d) + (E_{3/2} - E_{1/2})$ in which the The term in parenthesis is an estimate of the influence of the difference in angular momentum. Taking this from the mass difference between doubly strange $\Xi(1530)$ J=3/2 and $\Xi(1320)$ J=1/2 states gives $M_{\Xi(3/2)} \approx 1920$ MeV, which is in fair agreement with the experimental value of 1862 MeV.

We have presented a schematic model of quark-pair interactions with nucleons that reproduces the essential features of an even parity strange pentaquark. The attractive schematic interaction gets a huge strength from collective coherent effects and therefore reproduces the low mass (1540 MeV) small width (to the KN channel) but does not lead to a suppression of the production of a virtual kaon, K^*. In this model, the Θ can be regarded as a collective vibration of the nucleon. Determining the fundamental origin of the schematic interaction would be a task for further work.

A natural consequence of the strong attraction is that Θ nuclei, stable against strong decay, may exist. Such states can be made in photon and kaon beam experiments. Suppose the Θ has odd parity. Then one need not account for the excitation energy of 600 MeV, using an attractive residual interaction, and one would not predict that Θ-nuclear matter would be stable against decay by the strong interaction. Therefore, the discovery of such stable Θ-nuclear matter could be a definitive proof that the Θ parity is even.

Acknowledgments

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[1] D. Diakonov, V. Petrov and M. V. Polyakov, Z. Phys. A **359**, 305 (1997)
[2] T. Nakano *et al.* [LEPS Collaboration], Phys. Rev. Lett. **91**, 012002 (2003).

[3] V. V. Barmin *et al.* [DIANA Collaboration], Phys. Atom. Nucl. **66**, 1715 (2003) [Yad. Fiz. **66**, 1763 (2003)].
[4] S. Stepanyan *et al.* [CLAS Collaboration], Phys. Rev. Lett. **91**, 252001 (2003).
[5] J. Barth *et al.* [SAPHIR Collaboration], Phys. Lett. B **572**, 127 (2003).
[6] V. Kubarovsky *et al.* [CLAS Collaboration], arXiv:hep-ex/0311046.
[7] A. Airapetian *et al.* [HERMES Collaboration], arXiv:hep-ex/0312044.
[8] A. Aleev *et al.* [SVD Collaboration], arXiv:hep-ex/0401024.
[9] C. Alt *et al.* [NA49 Collaboration], arXiv:hep-ex/0310014.
[10] S. L. Zhu, Phys. Rev. Lett. **91**, 232002 (2003); J. Sugiyama, T. Doi and M. Oka, Phys. Lett. B **581**, 167 (2004); see also R. D. Matheus, *et al.*Phys. Lett. B **578**, 323 (2004).
[11] F. Csikor, Z. Fodor, S. D. Katz and T. G. Kovacs, JHEP **0311**, 070 (2003); S. Sasaki, arXiv:hep-lat/0310014.
[12] R. N. Cahn and G. H. Trilling, Phys. Rev. D **69**, 011501 (2004); R. A. Arndt, I. I. Strakovsky and R. L. Workman, Phys. Rev. C **68**, 042201 (2003) [Erratum-ibid. C **69**, 019901 (2004)]; J. Haidenbauer and G. Krein, Phys. Rev. C **68**, 052201 (2003); S. Nussinov, arXiv:hep-ph/0307357.
[13] M. Karliner and H. J. Lipkin, arXiv:hep-ph/0401072. see also N. Auerbach and V. Zelevinsky, arXiv:nucl-th/0310029.
[14] B. K. Jennings and K. Maltman, arXiv:hep-ph/0308286.
[15] R. L. Jaffe and F. Wilczek, Phys. Rev. Lett. **91**, 232003 (2003).
[16] E. Shuryak and I. Zahed, arXiv:hep-ph/0310270.
[17] G. E. Brown, in "Unified Models of Nuclear Structure", North Holland (Amsterdam) 1964; G. E. Brown and M. Bolsterli Phys. Rev. Lett. **3**, 472 (1959).
[18] A. W. Thomas, K. Hicks and A. Hosaka, arXiv:hep-ph/0312083.
[19] C. Hanhart *et al.*, arXiv:hep-ph/0312236.
[20] N. Isgur and G. Karl, Phys. Rev. D **18**, 4187 (1978).
[21] S. Théberge, A. W. Thomas and G. A. Miller, Phys. Rev. **D22** (1980) 2838; (1981) 2106; A. W. Thomas, S. Théberge, and G. A. Miller, Phys. Rev. **D24** (1981) 216; S. Théberge, G. A. Miller and A. W. Thomas, Can. J. Phys. **60**, 59 (1982). G. A. Miller, A. W. Thomas and S. Théberge, Phys. Lett. B **91**, 192 (1980).
[22] G. A. Miller, Phys. Rev. C **66**, 032201 (2002).
[23] There are exchange terms which occur if $\mathbf{P} = \mathbf{P}'$, but this corresponds to a set of zero measure and does not contribute to scattering.
[24] The expression for the interaction matrix element Eq. (11) is invariant under the transformation $\mathbf{q} \to \mathbf{q} + \mu\mathbf{v},\ \mathbf{p} \to \mathbf{p} + M\mathbf{v},\ \mathbf{P} \to \mathbf{P} + M\mathbf{v}$. For a weakly bound system the difference between the mass of the nucleon consituent and M_Θ would be small, so that $\mathbf{p} - \mathbf{P}$ would be the correct relative momentum. Here we have strong binding caused by the effects of the residual interaction. Keeping such effects in the transformation between frames is a relativistic effect and is ignored here.
[25] W. Bruckner *et al.*, Phys. Lett. B **55**, 107 (1975).
[26] Difficulties in computing the spectrum abound in many models. See *e.g.* T. D. Cohen, arXiv:hep-ph/0402056; T. D. Cohen, arXiv:hep-ph/0312191. See also Ref. [14].