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Diquark Deuteron

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It is speculated that an almost stable state of hadronic and nuclear matter can be built from *diquarks*. It is suggested that this alternative form of matter has already revealed itself in existing experimental data in the form of a diquark "deuteron" with $J^P = 0^-$ and with several other anomalous properties.

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The aim of this Letter is to present evidence for the existence of a deuteronlike object consisting of *three diquarks*. Because of lack of space we will present elsewhere a much more detailed analysis of all aspects of our predictions. Here we limit ourselves to discussing some of the most important properties of such an object as well as some of the experimental support for our theoretical ideas.

In a recent experiment at the Lawrence Berkeley Laboratory indications were found[1] that nuclear matter can exist in a form with strange properties. Earlier the same effect had been observed in cosmic-ray experiments.[2] When a high-energy nucleus collides with an emulsion target, around 6% of the projectile fragments stop in the emulsion much faster than is considered normal for heavy ions. This finding suggests that those fragments contain some hitherto unexplored phase of nuclear matter ("anomalons"), with a very high reaction cross section and a long lifetime (10^{-10} to 10^{-9} s)—definitely stable against strong decays.

In order to simplify the analysis of this astonishing phenomenon we have investigated *deuteronlike* objects in search of anomalous states.

Among all possible combinations of the six quarks of a two-nucleon object we have found that a system of three diquarks has some unique properties that make it a strong candidate for a light anomalon. Preliminary speculations about this "demon deuteron" have been reported by us at two conferences.[3,4] In the following we will use the word "demon" and the symbol δ for the diquark deuteron, saving "anomalons" for the observed fragments.

It is fairly obvious that a three-cluster arrangement is needed, since any other structure gives a mass which exceeds the threshold, 2.013 GeV/c^2, for a strong decay to an $NN\pi$ system.[5,6] Our particular choice of diquark configuration, as discussed below, is guided by physical reasoning and symmetry principles.

The contribution of the color-magnetic interaction to the mass of an N-quark cluster is proportional to[7]

$$\Delta = -\tfrac{1}{3}N(6-N) + \tfrac{1}{3}\bar{J}^2 + \bar{I}^2 + \tfrac{1}{2}F^2. \qquad (1)$$

F^2 is the squared Casimir operator of $\mathrm{SU}(3)_{\text{color}}$, and J and I are the cluster total angular momentum and isospin, respectively. It is hence energetically favorable to couple the constituents of a diquark into the representations $\underline{3}^*$ of color and singlets of both spin and isospin. Each diquark therefore has $(I, S, J^P)_{\text{diquark}} = (0, 0, 0^+)$.

Having all three diquarks in S orbitals would violate the Pauli principle. We suggest that each diquark is in a P orbital. The three of them couple to a total $L=0$ state. The spatial wave function is hence *antisymmetric* (the symmetric possibility is again forbidden by the Pauli principle). The demon therefore has totally $(I, S, J^P)_{\text{demon}}=(0, 0, 0^-)$.

Such a diquark object has, to our knowledge, never been suggested in the literature. Its mass is difficult to estimate in bag models, because there is no straightforward way to handle three angular momenta. Since a diquark with the quantum numbers suggested above is effectively so light, it is in fact the P-wave composition that prevents the demon from being the absolute ground state of a two-nucleon system. Baryons with three units of orbital angular momentum seem to have masses of 1.7–2.2 GeV/c^2, the span probably caused by a constituent LS coupling. We therefore suggest that the demon, with spinless diquarks, has a mass which falls just below the pionic threshold. The assignment $J^P=0^-$ naturally also forbids any transition $\delta \rightarrow pn$.

Any attempt to estimate quantitatively the decay rates would probably be too difficult to be meaningful, since it concerns a complicated six-body arrangement decaying to a completely different state plus a number of photons. There are, however, many reasons to believe that the decay is particularly slow compared to "normal" first-order electromagnetic (e.m.) decays. The suppression mechanisms are as follows:

(i) Diquarks in P waves are presumably smaller than those appearing in quark-diquark models of the proton ground state,[8] since the relative angular momenta prevent the diquarks from disturbing each other. A smaller diquark, in turn, makes the necessary photon-quark coupling weaker.

(ii) A *first-order* electric decay, $0^- \rightarrow 1^+1^-$ for $\delta \rightarrow (np)+\gamma$, is strictly forbidden, since an extra internal photon exchange in the δ is needed to rearrange the quantum numbers. An internal soft gluon does not work because it would destroy the necessary color combinations.

(iii) A first-order magnetic decay, $0^- \rightarrow 1^-1^-$, is possible. It is, however, suppressed, and perhaps even prohibited, because np must be in a P state, which takes more energy. On the diquark level the transition starts with a spin flip of one of the quarks, which takes the diquark to a $(ud)_{I=S=1}$ state with higher mass before decay. Such a "tunneling" through a virtual high-lying level suppresses the decay further.

(iv) A transition from a three-diquark to a two-nucleon state with widely different quantum numbers must also be suppressed by a small overlap integral between the spatial wave functions.

All these effects work together, making it probable that the demon decay is several orders of magnitude slower then a normal first-order e.m. decay between two single-particle levels with the same energy split.

Could this object have a total cross section several times that of the deuteron? Since a diquark is $\underline{3}^*$ in color the whole system resembles an antinucleon in composition. The crucial difference is, however, that the δ has an antisymmetric spatial wave function, while baryons are symmetric in space. Hence the colors of the constituents do not cancel each other as easily in a δ as in a baryon, and the color fluctuations on the "surface" become much more violent in the demon case. It is generally believed that strong interaction between hadrons is nothing but a weak leakage of the strong color forces inside hadrons, reminiscent of van der Waals forces between atoms. Such forces are very sensitive to surface charge (color) fluctuations. Compare the importance of the outermost electron shell for chemical reactions. We therefore believe that a demon and a baryon might have drastically different effective sizes as a result of different "tails" of color van der Waals forces, although they have the same net color as well as almost the same purely geometric size.

It remains to relate the demon to the anomalons with nucleon number $A>2$. If a δ is present inside a nuclear fragment, we believe that each diquark will try to compensate its anticolor with a quark from a nearby nucleon, thereby polarizing the surrounding nuclear matter. A particularly stable configuration should be a three-center system of a δ and three polarized nucleons, because it is very similar to the original demon. The net color of each center is still uncompensated and a two-quark cluster in a $\underline{3}^*$ color representation is still carried close to the surface of the fragment, explaining its high cross section, and maintaining the potential for polarizing even more nucleons.

A momentum transfer of a few hundred megaelectronvolts is needed to force two nucleons together in a six-quark state,[9,10] which decays either to a two-nucleon system or to the metastable demon. The δ is therefore created in the collision and is not present in normal nuclear matter. Considering estimates[10] of the probability to find the deuteron in a six-quark state, we think a demon production rate on the percent level is realistic whenever the momentum transfer is high enough.

There are three ways, different in principle, to observe the demon in experiments, namely through its high cross section, through its mass, or through its decay.

As a complement to the original "anomalon" experiments it is of utmost importance to measure the cross sections of produced deuteronlike objects in any kind of strong reaction where the momentum transfer is sufficiently high, for instance by following their tracks on bubble-chamber pictures.

The obvious method for a mass determination is a time-of-flight measurement with fragments from high-energy nuclear collisions. We have not been able to find any experiment with the right combination of good mass resolution and a time of flight less than 10^{-9} s. It might be advantageous to look for anomalous nuclear states with $A=5$, because the normal ^{5}He and ^{5}Li have lifetimes shorter than 10^{-20} s and hence will not leave competitive signals. A few unexplained objects with masses around 4.3 GeV/c^2 have in fact been observed.[11]

The δ mass must also reveal itself in the kinematics of reactions like $NN \rightarrow d+$anything. There is in fact a wealth of data from this kind of process, showing many interesting and hitherto unexplained structures in the "anything" system. However, most of these data (see Barry[12] for a review) are missing-mass spectra from measurements of the outgoing nuclear momentum, which means that we cannot analyze the situation properly as long as we do not know if a demon lives long enough to reach the detector. Data from direct measurements on the "anything" system are much more scarce. In a recent experiment[13] with the reaction $np \rightarrow d+(\pi^+\pi^-)$ at $\sqrt{s}=2.3$ GeV a sharp peak was found in the two-pion effective mass at $M_{\pi\pi} \simeq 300$ MeV/c^2. No peak is seen at higher $\sqrt{s}$ values. We interpret this structure as evidence for the reaction $np \rightarrow \delta+(\pi^+\pi^-)$. The peak in $M_{\pi\pi}$ is caused by the reduction in phase space due to the high demon mass.

Considering demon decay, it should be fully possible to see the conversion of outgoing photons in bubble-chamber pictures, and perhaps even to relate them to a weak recoil in the dueteronlike track. To increase statistics one should use a propane- or neon-filled bubble chamber and concentrate on deuterons with a high momentum transfer.

We are at present performing a tedious search for further signatures of demons in the existing experimental literature. Three experimental investigations are at present in the planning stage at the Lawrence Berkeley Laboratory[14,15] and at the Joint Institute for Nuclear Research, Dubna.[16]

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