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HIDDEN COLOUR AND THE ISOBAR CONTENT OF THE DEUTERON

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ABSTRACT

We show how experiments concerning the isobar content of the deuteron that apparently are contradicting each other can be reconciled by the quark model with hidden colour.

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It is now generally accepted that nucleons are colour singlets made of three coloured quarks. In principle then a system of N nucleons is a $3N$ quark system and there ought to be effects in nuclei that are difficult or impossible to explain if the existence of quarks is not taken into account.

In this letter we want to show that measurements of the Δ isobar content of the deuteron which look to be in conflict with each other can be reconciled if we regard coloured quarks as the fundamental building blocks of nuclei. We shall show that the apparent theoretical complication we obtain by introducing quarks in the deuteron is actually a great simplification when it comes to calculating properties of the deuteron at its centre.

To give a complete description of the deuteron as a six-quark system is certainly very difficult, although there are promising attempts ¹⁾ to deduce the proton-neutron potential from the fundamental quark-quark interaction.

Quarks in a single nucleon are confined to a region in space corresponding to the nucleon radius of approximately one fermi. We therefore adopt the attitude that the interaction between three-quark clusters (nucleons) can be well represented by treating the nucleons as fundamental quantities when their separation distance is greater than 1.5-2 fermi.

At small distances, however, it is certainly necessary to use the quarks as fundamental building blocks. It therefore seems natural to try a description using different fundamental fields for the central part and the not so central part of the deuteron. Such a hybrid model of the deuteron was recently proposed by Matveev and one of us ²⁾ and, independently, by Kobushkin ³⁾. At small separation, the proton and neutron would, with a 5 to 13% percent probability, make a (tunnelling) transition into the six-quark spherical s wave state. The full content of the model is then summarized by writing the deuteron state $|d\rangle$ as a sum of a two-nucleon state $|PN\rangle$ and a six quark state $|6q\rangle$

$$|d\rangle = \alpha |PN\rangle + \beta |6q\text{-bag}\rangle \quad (1)$$

$|PN\rangle$ represents here the conventional decomposition of the deuteron as a proton neutron bound state. It contains all properties of the deuteron when the inter-nucleon separation is greater than about 1.5 fermi, gives the full quadrupole moment and determines the electromagnetic form factor at low momentum transfer.

It seems a very reasonable approximation to identify the state $|6q\rangle$ with the lowest lying six quark state in a spherical (confining) cavity and use the MIT bag model ⁴⁾ to determine its properties. The six-quark bag radius which is $R \approx R_{MIT} = 1.31$ fermi therefore tells us at which distances it is necessary to use quark fields as fundamental fields. As the states

$|PN\rangle$ and $|6q \text{ bag}\rangle$ are almost orthogonal there is practically no double counting if we set $|\alpha|^2 + |\beta|^2 = 1$. The model, as expressed by Eq. (1), represents a useful approximation to the complete treatment of the six-quark deuteron system because it automatically gives simple and useful phenomenological implications.

The first one, which actually motivated the relation (1), is that it gives an explanation of the behaviour of the electromagnetic form factor $F_d(q^2)$ at large q^2 ⁵⁾. Indeed at large transferred momentum $0.8 \leq q^2 \leq 6 \text{ GeV}/c^2$ it appears that $F_d(q^2) \sim (1/q^2)^{5.0 \pm 0.5}$ in agreement with dimensional quark counting rules ⁶⁾. Extrapolation of these data near $q^2 = 0$ using the pentapole fit ⁷⁾ $F_d(q^2) = 0.07 (1 - 0.51 q^2)^{-5}$ gives $F_d(0) = 0.07$ instead of $F_d(0) = 1$, and has suggested the mixed model summarized in Eq. (1) with $\beta^2 = 0.07$.

The second interesting feature of this model is that it leads simply to the existence of $\Delta\Delta$ isobar constituents ⁸⁾ (I.C.) in the deuteron, a property of the deuteron which is well known in nuclear physics. These $\Delta\Delta$ isobars are contained in the $|6q \text{ bag}\rangle$ part of the $|d\rangle$ state. Whereas nuclear physics calculations of the $\Delta\Delta$ component are quite complicated and have rather great uncertainty, the $\Delta\Delta$ component in the mixed model is unique when the probability $|\beta|^2$ is determined. The spatial distribution of the isobars is also similar in the two approaches as will be illustrated by its Fourier transform (the distribution in momentum space).

Using Clebsch-Gordan coefficients of the group $SU(12) \supset SU(3)_{\text{colour}} \times SU(2)_{\text{spin}} \times SU(2)_{\text{isospin}}$ as well as the Pauli principle, one finds that the $|6q \text{ bag}\rangle$ can itself be decomposed into two parts :

$$|6q \text{ bag}\rangle = a |3q, C=1\rangle |3q, C=1\rangle + b |3q, C=8\rangle |3q, C=8\rangle \quad (2)$$

with amounts $a^2 = 20\%$ of doublets of colour one ($C=1$) baryon and $b^2 = 80\%$ of doublets of colour eight ($C=8$) baryons. A detailed calculation of the $|3q, C=1\rangle |3q, C=1\rangle$ or $|B^1 B^1\rangle$ part leads to the conclusion that the deuteron can be seen as constituted by about 93.8% of proton-neutron, 0.6% of $\Delta\Delta$ isobar plus 5.6% of "hidden colour" part, this last piece corresponding to the doublets of colour eight baryons $|B^8 B^8\rangle$ that form a singlet of colour. Such a "hidden colour" part cannot exist in usual $q\bar{q}$ (mesons) or qqq (baryons) states and is an important characteristic of multiquark states ⁹⁾. The amount of a 0.6% $\Delta\Delta$ component in the deuteron is consistent with theoretical nuclear physics calculations and also with experiments ⁸⁾ as long as they

measure exclusive quasi-two-body final states in deuteron break-up. In general, such experiments indicate that the $\Delta\Delta$ isobar content is in the range 0.4-0.9%. These results seem to be in contradiction with the high energy inclusive experiment ¹⁰⁾ of Benz and Söding who studied the reaction $\gamma d \rightarrow \Delta^{++}(1232) + \text{anything}$. They found that the amount of spectators like Δ 's corresponds to 3.1% of "pre-existing" isobars in the deuteron. Such a qualitative difference between different experiments can be understood in the framework of the mixed model. The explanation comes from the "hidden colour" part of the six quark bag state.

Because quarks of only two flavours are involved in the $6q$ bag state, the colour eight baryons B^8 it contained can be of three different kinds: $\Delta_{\frac{1}{2}}^8$, $N_{\frac{1}{2}}^8$ and $N_{\frac{3}{2}}^8$. We use Δ_J^8 and N_J^8 to denote the isospin $\frac{3}{2}$ and $\frac{1}{2}$ systems with spin J . Of course, these states can never be observed as free particles because they are not colour singlets. But if they are permitted to radiate off a gluon (which carries spin 1, colour 8 and isospin 0) they can, however, transform into the usual colour singlet $\Delta_{\frac{1}{2}}^1$ and $N_{\frac{1}{2}}^1$ states.

It is by a calculation of $SU(4)$ Wigner coefficients ($SU(4) \supset SU(2)_S \times SU(2)_I$) that we can determine the amount of $\Delta^8\Delta^8$ in $|B^8B^8\rangle$: the result is $(\sqrt{5}/6)^2 \simeq 14\%$, the remaining 86% being constituted by $|N_{\frac{3}{2}}^8\rangle|N_{\frac{3}{2}}^8\rangle$ and $|N_{\frac{1}{2}}^8\rangle|N_{\frac{1}{2}}^8\rangle$. With a 7% probability for the six quark bag state in the deuteron there is, as mentioned before, a 5.6% probability of hidden colour states. Of this fraction $5/36$ consist of coloured Δ^8 pairs giving a total of 0.8% of $\Delta_{\frac{1}{2}}^8\Delta_{\frac{1}{2}}^8$ pairs.

If, by the impact of a projectile, the two Δ^8 isobars are forced to separate in space, the colour electric energy between them will be so big that pions are created. In quasi-two-body final states there will be no spectator-like isobars originating from the coloured baryons. Strong final state interactions will destroy the conditions for any impulse approximation. In situations leading to some multiparticle final states, however, there is the possibility that a Δ^8 isobar emits a soft gluon that hadronizes with the rest of the primary reaction products. This can then cause a transition of Δ^8 to Δ^1 where the momentum of Δ^1 is very close to the momentum that Δ^8 had in the deuteron. If we treat this gluon emission as if a soft gluon was simply radiated off, we even know its energy. The colour magnetic energy ¹¹⁾ of $\Delta_{\frac{1}{2}}^8$ is $10\bar{c}$, that of $\Delta_{\frac{3}{2}}^1$ is $8\bar{c}$, so the energy of the radiated gluon is $2\bar{c} \approx 40$ MeV. In an inclusive experiment such states are contributing to the production of isobars and one could estimate that the amount of "spectator" isobars is the sum of the $\Delta^1\Delta^1$ and $\Delta^8\Delta^8$ components of the deuteron. We therefore arrive at an expected value of 1.4% of the spectator-like isobars in inclusive high energy break-up reactions, more than twice the

expected amount in quasi-two-particle break-up. This is not quite enough to explain the amount of 3.1% found by Benz and Söding but the qualitative effect might be understood.

To compare the observed momentum distribution in the Benz and Söding experiment ¹⁰⁾ on $\gamma d \rightarrow \Delta\Delta^{++}(1232) + \text{anything}$ we use $\Delta\Delta$ and $\Delta^8\Delta^8$ wave functions for particles enclosed in a spherical box (bag) of radius R . The Fourier transform of this wave function gives us then the expected spectator momentum distribution in the laboratory. Results are shown in the figure for $R = R_{MIT} = 1.31$ fermi and for a radius 25% bigger than R_{MIT} . We have calculated the deformation of this distribution by the emission of a 40 MeV gluon and verified that it is of no importance.

Thus, for the momentum distribution, there is no disagreement between theory and experiment. We have shown that a mixed model of the deuteron, where the notion of fundamental fields are chosen differently for different spatial separations between constituents, gives results that agree well with data. Let us note that nuclear physics calculations give mostly $\Delta\Delta$ in d waves, whereas the mixed model puts all isobars in s waves. At the moment, there is no experiment that can distinguish between these two alternatives.

One can ask the question : what will be the proportions of $|9q \text{ bag}\rangle$ in ${}^3\text{He}$ and ${}^3\text{H}$ or $|12q \text{ bag}\rangle$ in ${}^4\text{He}$. We believe this amount to be small. Indeed, the colour magnetic interaction makes the mass difference between the $3N$ quark bag and the N nucleon states bigger and bigger as N increases ²⁾. This increase in mass of the $|3Nq\rangle$ quark bag together with the small probability for N nucleons to be simultaneously in a region with the volume of a typical bag state, will greatly depress virtual formations of $|3Nq\rangle$ bag states. The $|6q\rangle$ bag states will therefore be the most important sources of isobars also for heavier nuclei.

If future experiments confirm that the percentage of spectator-like Δ 's is greater in inclusive break-up reactions than in two-body break-up reactions, this would be a signature for the existence of colour non-singlet $|3q\rangle$ systems in the deuteron.

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FIGURE CAPTION

Expected and measured ¹⁰⁾ laboratory momentum distributions
for the backward product Δ .
Solid line : nuclear physics calculation, Ref. 12);
Dash-dotted line : from bag with radius 1.31 fermi;
Dotted line : the same with 25% increase by bag radius.