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NOTE

A Note on Repulsive Core of Nuclear Forces from Quark-Model Point of View

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INTRODUCTION

Repulsive core of nuclear forces was introduced by Jastrow in 1949.[1] Its origin still remains an open problem in nuclear physics, although the ω-meson exchange has been often stated as contributor since Nambu's proposal in 1957.[2] Now it has become a general belief that the nucleon N is a cluster of three quarks in the color-singlet state, which are confined by the colored gluon fields. We can get rid of phenomenological stage in the problem of repulsive core by studying it from the quark-model point of view. This note presents a possible way to understand repulsive core as the orthogonality to exotic dibaryon states on the basis of the string-junction model.

At the present stage, it is suitable to divide two-nucleon relative distances r_{NN} into two regions, the outside region ($r_{NN}\gtrsim 1$ fm) where the meson-theoretical description is successful and the inside region ($r_{NN}\lesssim 1$ fm) where the quark structure of the nucleon plays a vital role. This division is also suitable from the nuclear structure viewpoint, because the NN relative wave function in the nucleus is almost uniquely determined for $r_{NN}\gtrsim 1$ fm and the success of the traditional nuclear physics is essentially independent of phenomenological versions employed in the inside, as far as they are chosen to reproduce the NN data. On the basis of such established aspects, a reasonable choice for the extension of quark structure of the nucleon is that its radius is about 0.5 fm, a half of the boundary between the inside and the outside, although the electromagnetic extension of the nucleon including meson cloud is about 0.8 fm.

CRITERIA FOR REPULSIVE CORE

In this note we presume the following criteria which repulsive core should satisfy:

1) Repulsive core is a universal nature of all the baryon-baryon (BB) interactions at small relative distances ($r_{BB}\lesssim 0.4$–0.7 fm).
2) Its repulsive nature is a manifestation of the quark confinement mechanism, which is characteristic of the BB system.
3) The aspect of originating mechanism described in the quark level (from the inside) is to be connected with the most responsible one in the outside, namely the ω-meson exchange.

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A few points on these criteria are remaked. The effects represented by repulsive core in phenomenological potential medels have been shown to exist in the NN relative S states ($^1S_0$ and $^3S_1$), indicated in the $N\Lambda$ S-states and there is no evidence against its existence in all the other two-baryon states. It seems reasonable to suppose that all the baryon-baryon (BB) pairs have repulsive core, because the confinement mechanism is inherent in the color degree of freedom and essentially independent of those of flavor and spin. It has been often stated that the neutral-vector meson (ω) exchange is responsible for repulsive core, but the strength given by the ωNN coupling constant, being consistent with the outer part of nuclear forces and other hadronic phenomena is not strong enough to explain the full aspect of repulsive core.[3)]

A typical example is shown in Fig. 1 for the $^1S_0$ NN potential: The meson-theoretical potential due to pion (π), a neutral-scalar meson (σ) as a substitute of attractive 2π exchange effect and ω is given by

$$V_{^1S_0}(r_{NN}) = -\frac{f^2}{4\pi} m_\pi Y(m_\pi r_{NN}) - \frac{g_\sigma^2}{4\pi} m_\sigma Y(m_\sigma r_{NN}) + \frac{g_\omega^2}{4\pi} m_\omega Y(m_\omega r_{NN}) \qquad (1)$$

with $m_\pi = 135$ MeV, $m_\sigma = 3.70\, m_\pi$, $m_\omega = 5.81\, m_\pi$, $f^2/4\pi = 0.08$, $g_\sigma^2/4\pi = 5$, $g_\omega^2/4\pi = 10$ and $Y(x) = e^{-x}/x$. This potential denoted by $(\pi+\sigma+\omega)_{NN}$ very close to $(\sigma+\omega)_{NN}$ for $r_{NN} \lesssim 1$ fm

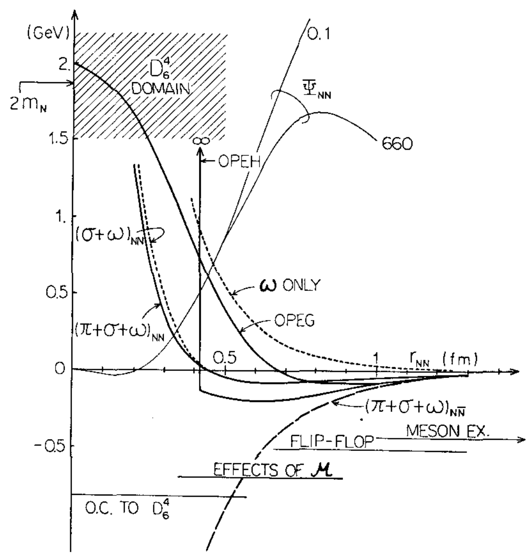

Fig. 1. Nucleon-nucleon (NN) potentials in the $^1S_0$ state and illustration of the regions where the various processes explained in the text are effective. OPEG (OPEH) is a realistic potential with the OPEP-tail and the Gaussian soft core (hard core). The solid line detoned by $(\pi+\sigma+\omega)_{NN}$ is the meson-theoretical potential given by Eq. (1) and the parts from $(\sigma+\omega)$ and ω only are shown by the dotted lines. The dashed line is the corresponding potential in the $N\bar{N}$ system. The shaded area indicates the domain of possible appearance of exotic dibaryon states D_6^4. The lines denoted by Ψ_{NN} is an example of the relative wave function with one radial node at $E_{Lab}^{NN}=0.1$ and 660 MeV (in arbitrary unit).[15b)] O. C. is the abbreviation to orthogonality condition.

shows much weaker inside repulsion, compared with the realistic potentials (OPEG and OPEH[4] for example). Therefore we regard the universal repulsion brought about by the ω-exchange as a tail part to be superposed on the originating mechanism existent in the inside region. The ω-exchang provides strong attraction in the $B\bar{B}$ system, the sign-reversed partner of the ω-exchange repulsion in the BB system because of its negative G-parity, and net BB potential (state-independent part) becomes deeply attractive, as shown by $(\sigma+\omega)_{N\bar{N}}$ in Fig. 1. Such contrast in the BB and $B\bar{B}$ systems is to be implied in the inside description.

BB INTERACTION BASED ON STRING-JUNCTION PICTURE

Here we adopt the string-junction model[5] as a realization of confinement mechanism, because the prescription given by this model is clear in discriminating exotic states from the ordinary (nonexotic) ones. The hadron structures are represented by the oriented strings with the following properties: In the ordinary mesons $M=(q\bar{q})$ a string connects q and $\bar{q}$ and in the ordinary baryons $B=(qqq)$ three strings from three q's join together at a junction J which represents pictorially the color-singlet property of B, as shown by the arrows in Fig. 2. In $\bar{B}=(\bar{q}\bar{q}\bar{q})$ three strings from three $\bar{q}$'s join together at a junction $\bar{J}$. In exotic states there appear the inter-junction strings between J and $\bar{J}$, abbreviated to IJ. Hadrons consist of three kinds of building blocks, namely, q and $\bar{q}$ with one string, J and $\bar{J}$ with three strings and IJ's. If the total numbers (associated energy) of these building blocks are denoted by N_q, N_J and N_{IJ} (m_q, m_J and v), respectively, the simplest mass formula from additivity given by Imachi and Otsuki[6] is

$$m(N_q,\ N_J,\ N_{IJ}) = m_q N_q + m_J N_J + v N_{IJ} = m_B N_J - \delta N_{IJ} \qquad (2)$$

with the baryon mass $m_B \equiv 3m_q + m_J$ and $\delta \equiv 2m_q - v$, where the relation $N_q = 3N_J - 2N_{IJ}$ (for $N_J \neq 0$) is used in the last equality. For δ (an effect exerted by the IJ string) $\ll m_B \sim 1$ GeV, m is approximately given by $m_B N_J$. The energy of a string is of the order of $m_N/3$ for u and d quarks with small masses, and its essential part is simply described by a linearly rising potential; $V(r) \sim ar$ with $a \cong 0.7$ GeV/fm at $r \sim 0.5$ fm.

If the increment in $V(r)$ of an elongated string is large enough to exceed the self-energy of a meson, the string is separated to produce a pair of q and $\bar{q}$ as open ends

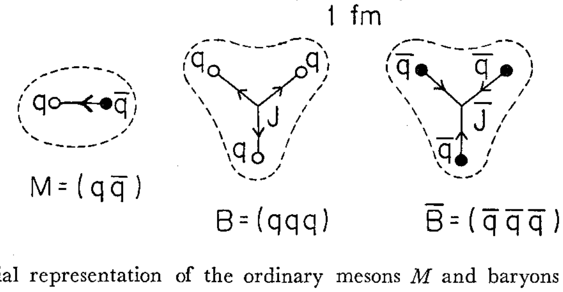

Fig. 2. Pictorial representation of the ordinary mesons M and baryons B (antibaryons $\bar{B}$) in the string-junction model. The dotted lines illustrate the bag-like extension in which quarks and gluons exist.

at the scission point. Typical mass of such radial excitation (ϵ_0) can be taken as the order of mass of the lowest vector mesons (ρ and ω); $\varepsilon_0 \sim 0.75\,\mathrm{GeV}$. In B, excitation due to hinging mode of strings possibly occures in addition to the radial excitation, as far as the Y-shape configuration is not rigid. Its excitation energy would be not so different from ε_0, because hinging motion is apt to be coupled with bending mode accompanying elongation. The string symbolically drawn by the line has its spatial extension. The $B=(qqq)$ clusters also have the bag-like space (illustrated by dotted curves in Fig. 2) in which the strings and junctions are realized, and thus predispositions of various modes of motion.

The innermost region of r_{BB} dominated by repulsive core is just the full overlap region of two $B=(qqq)$ clusters. What condition is needed for two B clusters to fuse? In a strict sense the string-junction model provides the following condition; two B clusters can fuse only when the building blocks are connected into a closed system with correct orientations. In other words, two B clusters can not fuse unless recombination of strings takes place. As a possible interaction mechanism of two $N=(qqq)$ systems without fusion, Miyazawa[7] proposed the flip-flop process of strings producing the attraction in the intermediate region ($r_{NN}=0.6\sim 1.6\,\mathrm{fm}$), which is usually described by meson exchange (2π or σ). This process is a kind of tunneling processes without change of two $N=(qqq)$ characters (Fig. 3a). At closer approach of two B clusters, more violent flip-flop processes possibly occur with string excitations of the order of two or three units in ϵ_0 (Fig. 3b). If two B clusters overlap fully (fuse into a compact system), such configuration is nothing but a kind of exotic dibaryon states. The string-junction model predicts a typical configuration of exotic dibaryon states with $N_q=6$ and $N_J=4$ at $m\sim 4m_B$, abbreviated to D_6^4 (Fig. 4a).[6] (Hadrons are denoted by $H_{N_q}^{N_J}$.) The D_6^4 states can not decay directly into BB but to $BBB\bar{B}$ through the fission of three inter-junction strings (Fig. 4 b). If we consider its inverse process, the fusion of BB can take place only through the recombination of oriented strings by virtual formation of a $B\bar{B}$ pair.

A $B\bar{B}$ pair can fuse directly into the configurations by contracting the open q and $\bar{q}$ end, as shown in Fig. 5. This aspect means strong attraction between B and $\bar{B}$ which is in sharp contrast with the BB repulsion, just like the ω-exchange effect. Such configurations form a group of boson-like states with $N_J=2$; molecular $B\bar{B}$ states, exotic mesons (M_4^2 and M_2^2) and a kind of glue-balls (S_0^2),[6] which are denoted symbolically by $\mathscr{M}$ with $m_{\mathscr{M}}\sim 2\,\mathrm{GeV}$. In order to make a connected string-junction net of D_6^4 through

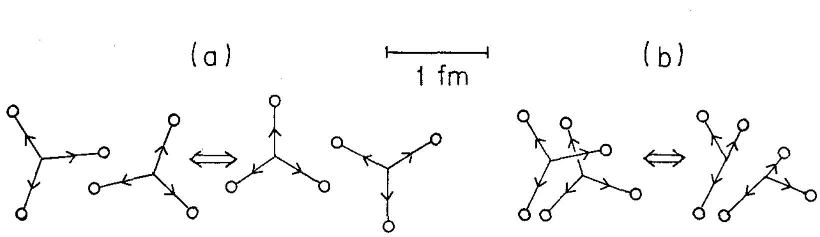

Fig. 3. Flip-flop processes at close approach of two $B=(qqq)$ clusters without change of the $B=(qqq)$ structure; (a) the Y-shape structure of strings is also kept and (b) the hinging and shrinkage (deformation of the Y shape) take place. If we write the dotted lines as in Fig. 2, the domains of the dotted lines do not overlap.

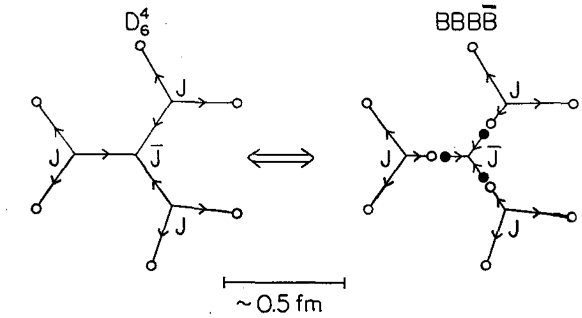

Fig. 4. Exotic dibaryon states D_6^4 and the $BBB\bar{B}$ system appearing through fission of three inter-junction strings.

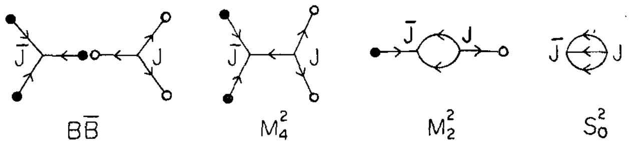

Fig. 5. A series of boson-like states, $\mathscr{M}$: M_4^2, M_2^2 and S_0^2 are exotic baryonium states produced by connecting q and $\bar{q}$ ends successively in $B\bar{B}$.[6)]

virtual creation of $\mathscr{M}$, the energy of about $2m_B \sim 2$ GeV is required. This is just of the same order of repulsive core height when the Gaussian type of soft core is adopted,[4)] as shown by OPEG in Fig. 1.

REPULSIVE CORE IMPLYING THE ORTHOGONALITY TO EXOTIC DIBARYON STATES

If such exotic D_6^4 states exist with compact size at about 2 GeV excitation as shown in Fig. 1, the wave function of the ordinary BB channel (Ψ_{BB}) should be almost orthogonal to $\Psi(D_6^4)$:

$$\langle \Psi(D_6^4) | \Psi_{BB} \rangle \cong 0. \qquad (3)$$

Since this aspect comes from the color degree of freedom, it is universal for all the BB states, even though the D_6^4 states split somewhat by symmetry breaking effects dependent on the spin and flavor quantum numbers. The almost energy-independent radial node resulting trom the orthogonality plays a role equivalent to repulsive core in the BB channel, the lowest configuration of the $6q$ system. The only difference from the di-nucleus case is that here the D_6^4 states are actual states, while the orthogonality condition is taken with respect to the Pauli forbidden states in nuclear cluster theory.[8)]

POSSIBLE EXPERIMENTS TO FIND OUT D_6^4

For the explanation for origin of repulsive core mentioned above, it is crucial whether the exotic D_6^4 states with small size are realized or not. When they are once formed, they turn into something like little bag states[9] (substatially exotic for $N_q>3$) due to the asymptotic free nature. Because of their high excitation energies, they can not be identified to the dibaryon resonances[10] with large widths recently found at much lower energies. If these D_6^4 states be lower than the threshold of $NNN\bar{N}$, experimental test is to search narrow peaks of nucleon yields corresponding to the two-body reaction;

$$\bar{p}+{}^4\mathrm{He}\to N+D_6^4$$

appearing over the background of many-pion emission processes. Widths of these states depend on the strength of their coupling to the BB channel, and are expected to be small because D_6^4 can not decay directly to BB through fission of strings. If the D_6^4 be realized at higher energy than the threshold of $NNN\bar{N}$, they may be found as resonances in $\bar{p}+{}^3\mathrm{He}$ scattering. The problem of D_6^4 is related to that of exotic baryonium states whose existence is still open. From the string-junction model point of view, three problems-repulsive core, exotic dibaryons and exotic baryoniums-are linked.

Due to the coupling between Ψ_{BB} and $\Psi(D_6^4)$, although it is weak, the exotic and compact components are mixed into the ordinary (nonexotic) two $B=(qqq)$ cluster states. Studies of the charge form factors of d, ^{3}He and ^{4}He from the quark-model viewpoint suggest compact multi-quark components through high momentum transfer region.[11,12] Also cumulative processes studied in hadron reactions on nucleus targets for high momentum transfer are related to this problem.[12]

COMMENTS ON OTHER APPROACHES

Finally comments to other approaches of the repulsive core problem from the quark-model viewpoint are given. In the cluster-model approach, the confinement condition is taken into account by the color-singlet property of 6q system, and the NN short-range repulsion is attributed to the color magnetic interaction.[13] The resulting effect is dependent on the spin and flavor quantum numbers (a kind of symmetry-breaking effects), and not universal for all the BB states, as pointed out by Jaffe.[14] The original idea from the cluster viewpoint was proposed at the "pre-color stage" by taking analogy to the α-α effective repulsive core originating from the Pauli principle.[15] In the nucleus-nucleus interaction such exchange repulsion is independent of details of models and interactions, because the orthogonality to the Pauli forbidden states plays a vital role. Validity of direct analogy to the nucleus-nucleus interaction was lost when the color degree of freedom was introduced. Then, in the "post-color stage," the problem has been inevitablly correlated with details of $N=(qqq)$ structure and of q-q interaction.[16] In the bag-model approach, the confinement is assured by the boundary condition at the bag surface. In an approach to BB systems, where six quarks are confined in a single bag, it is not clear whether the calculated energies are those of exotic $6q$ states or of the ordinary states.[17] Comparison of the energies of $6q$ system with those of two B system may be useful, when the stability problem of bag states in the presense of surrounding meson clouds will be solved.[18] In the context of the present note, it is important to make clear whether multi-quark ($6q$, $9q$, $12q$, ……) states have metastable configurations with much smaller extension than 1 fm or not. Evidently multi-quark states with large size seriously disturb the nuclear structure already verified.

SUMMARY

The situation considered in the present note is illustrated in Fig. 1. (We regard r_{NN} as r_{BB}). In the outer region ($r_{BB} \gtrsim 1$ fm), the ω-meson exchange repulsion exists with various effects from other mesons. In the innermost region ($r_{BB} \lesssim 0.6$ fm) the large energy expense is necessary for two baryon to fuse through formation of exotic baryonium states $\mathcal{M}$. In the boundary ($r_{BB} \cong 0.6 \sim 1$ fm), there appear various modes of string excitations shown in Fig. 3 and effects of $\mathcal{M}$ formation in the pre-fusion stage. In order to avoid such large exitation, two baryons keep their positions to be apart, and this aspect correspond to repulsive core in potential description to suppress the BB relative wave functions at small distances. Although the argument given in this note is of speclatuive nature, the originating mechanism of repulsive core is accordance with the criteria 1)$\sim$ 3), and independent of details of $B=(qqq)$ structures and of q-q interactions. It may be said as a reflection of the exotic dibaryon states with compact size. Conversely repulsive core of nuclear forces links to possible existence of such exotic states and of their small mixing in the nucleus.

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