CHIRAL SYMMETRY BREAKING AND MIDDLE RANGE NUCLEAR FORCE

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It is commonly believed that the underlying theory of strong interaction is QCD. Since the non-perturbative QCD is not fully understood, the lower energy phenomenology such as the hadronization process and nuclear force of middle range cannot be derived from a fundamental principle, so far.

At very low energies, namely as two nucleons are well spatially separated, the effective pion or double-pion exchange model successfully explains data, because at so low energies, according to the long-distance QCD, hadron states are dominant. The other extreme is that when the centers of the two nucleons are so close that the overlapping region is large enough, thus quarks can interact with each other by exchanging gluons, so the perturbative QCD can result the short-distance nuclear force [1].

As to the middle range, neither the resonance scenario, nor direct exchange of gluons work. To the present understanding, the middle range nuclear force can only be induced by a residue QCD effect, in analog to the Van der Waals force in electrodynamics. The Skyrme model [2] is a plausible approach to describe such a QCD Van der Waals-type interaction. However, in the scenario of the Skyrme model, the degrees of freedom of the quarks are priori ignored and it is not a good approximation as some detailed structure are concerned. Considering that the quark effects may still be substantial, we are trying to take the quark degrees of freedom into account.

FollowingDiakonov and Petrov [3], the quark inside nucleons should be described by a modified Dirac equation

$$(i\not{\partial} - m - Me^{i\frac{1}{f_\pi}\vec{\sigma}\cdot\vec{\pi}(\vec{r})})\psi(\vec{r},t) = 0 \tag{1}$$

where m is the current quark mass and M is the constituent quark mass which occurs due to the chiral symmetry breaking and $\vec{\pi}(\vec{r})$ is the classical pion field around the quantized nucleon. In this picture, influences from other nucleons do not exist at all. Using the product ansatz borrowed from the Skyrme model, one can write a new Dirac equation where the effects from another nucleon are taken into account, so it becomes

$$(i\not{\partial} - m - Me^{\frac{1}{f_\pi}\vec{\sigma}\cdot\vec{\pi}(\vec{r})} \cdot e^{\frac{1}{f_\pi}\vec{\sigma}\cdot\vec{\pi}(\vec{r}-\vec{R})})\psi(\vec{r},t) = 0 \tag{2}$$

where $\vec{R}$ is a vector from the center of the nucleon A to that of nucleon B. Thus we have indeed considered the effect on the quark inside nucleon A from nucleon B and this interaction is mediated by the classical pion field which is the residue effect of QCD i.e. the QCD Van der Waals force. Integrating out the quark degrees of freedom in terms of the collective wavefunction of nucleon, the result becomes a function of only $|\vec{R}|$ and corresponds to the middle range nuclear force.

References

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3. D. Diakonov and V. Petrov, Nucl.Phys. 53.