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BIHEP-TH-92-25

Baryon spectrum in quark potential model*

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Key words: Baryon spectrum, Quark potential model

In the calculation of the baryonic spectrum in the quark potential model, except the conventional one-gluon-exchange term (OGE) in the quark-quark interaction, derived by Rujula, Georgi and Glashow[1] , a confinement potential should be introduced into the hamiltonian of the baryon. Although a linear type confinement potential is expected by the lattice gauge theory and string model, the exact form of this potential is still unknown. Thus, in the practical calculation, this potential should phenomenologically be introduced. In order to explain the experimental phenomenon why in the baryonic spectrum, the excited states with positive parity are very close to the states with negative parity in the baryonic spectrum, the confinement potentials in various forms are employed in the calculation. By selecting a confinement potential in the form of the combination of the linear and quadratic terms, C. S. Kalman and Tram[2] obtained a better agreement between the theoretical result and experimental data.

The adoption of the confinement potential is a phenomenological method to deal with the effect of the nonperturbative QCD. In the present stage, although it is not

*Supported by National Natural Science Foundation of China and Academia Sinica Grant No. LWTZ-1298

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possible to obtain the exact form of the confinement potential from the QCD theory, physicists have studied the nonperturbative effect by considering the contributions of fermion loop diagrams in the lattice gauge calculation or introducing the non-zero quark condensate $< 0 \mid q\bar{q} \mid 0 >$ and gluon condensate $< 0 \mid GG \mid 0 >$, so that the feature of the confinement potential can deeply be understood. Recently, we study the nonperturbative effect by modifying the gluon propagator via quark and gluon condensates[3] . In that investigation, we assumed that the main properties of the quark-quark interaction can be described by the one-gluon exchange; all loop diagram, vertex and more complicated higher order diagram corrections can be ignored and only one quark and gluon condensates are considered. In fact, under the fixed-point gauge, we calculated the correlator $< 0 \mid J^a_\mu(x) J^a_\nu(0) \mid 0 >$. By considering the diagrams in which one pair of quark-antiquark or gluons condensate into vacuum and using QCD sum rules, we obtained a full propagator of the gluon where both perturbative and nonperturbative contributions were considered to the first order. Then, we derived the Breit-Fermi type interaction in terms of this full propagator. In the M-matrix calculation, we made the non-relativistic reduction. By further performing Fourie transformation, we finally got the quark-quark interaction with the effect of the nonperturbative QCD in the coordinate space. It is noteworthy that in this potential, there exist not only the terms appeared in the commonly used OGE,but also the quark and gluon condensate induced r term, which functions like a confinement potential, and $-r^3$ term, which plays a role of deconfinement, and other terms. Our interest is the deconfinement like $-r^3$ term. It indicates that selecting the confinement potential in the form of $ar - br^3$ is under the certain basis.

Next, we choose the confinement potential between quarks in the form of $ar - br^3$ where the parameters a and b are phenomenologically determined by calculating the spectra of N and Δ. In order to compare our result with Kalman's, we compute the spectra in the same framework as Kalman's. The sole change is altering the confinement potential from $a_2 r - b_2 r^2$ to $a_1 r - b_1 r^3$. The hamiltonian of the N and Δ

system is

$$H = B_0 + \sum_i \frac{p_i^2}{2m_i} + \sum_{i>j=1} V(r_{ij}) + H_{hyp}$$

$$V(r_{ij}) = -\frac{2\alpha_s}{3r_{ij}} + V^{conf}(r_{ij})$$

$$V^{conf}(r_{ij}) = \begin{cases} a_1 r_{ij} - b_1 r_{ij}^3 & \text{ours} \\ a_2 r_{ij} - b_2 r_{ij}^2 & \text{Kalman's} \end{cases}$$

$$H_{hyp} = \sum_{i>j=1} \frac{2\alpha_s}{3m_i m_j} \left\{ \frac{8\pi}{3} \vec{S}_i \cdot \vec{S}_j \, \delta(\vec{r}_{ij}) + \frac{1}{r_{ij}^3} \left[\frac{3(\vec{S}_i \cdot \vec{r}_{ij})(\vec{S}_j \cdot \vec{r}_{ij})}{r_{ij}^2} - \vec{S}_i \cdot \vec{S}_j \right] \right\}$$

where B_0 is the zero-point energy which is determined by fitting $E_{N_{\frac{1}{2}^+}} = 939MeV, m$ denotes the quark mass, and α_s represents the quark-gluon coupling constant. Similar to Kalman's work, we take $m = 0.23GeV, \alpha_s = 1.0$, and the size parameter of the harmonic basis function b $= 0.657fm$, and consider the mixture of the basis function in the same shell. The parameters a_1 and b_1 are determined by fitting the experimental data. Then, we calculate the N and Δ spectra. In table 1, we only list the energy levels of those N and Δ states whose total angular momentum $J \leq \frac{5}{2}$ and whose experimental values are available. For convenience, we also list Kalman's result and the experimental data in the same table, and adjusts the zero-point energy B_0 so that the energies of the first $\frac{1}{2}^+$ states in both calculations to be $939MeV$.

From Table 1, one sees that both our and Kalman's results fit the experimental data very well and our calculated result is even more closer. This indicates that in order to get the agreement between the theoretical and experimental spectra, whether the confinement potential is in the $a_1 r - b_1 r^3$ or $a_2 r - b_2 r^2$ form, the coefficients of the linear and higher order terms should be in the opposite signs. As a consequence, the confinement potential shows almost linear behavior when r_{ij} is small and is no longer linearly increasing as r_{ij} goes litter bit larger. This tendency agrees with E.Laerman's finding[4] that because of the contribution of the fermion loop diagram in the lattice gauge calculation, the confinement potential is evidently lower than the linear one. This feature reflects the color screening effect devoted by the quark sea. Namely,

when the distance between quarks extends to a larger values, the interaction between the valence quark and quark sea enhances greatly. It depresses the calculated energies of the highly excited states of the baryon. However, when r_{ij} further increases, due to the existence of the $-r^3$ or $-r^2$ term, the confinement potential diminishes faster and finally turns to the negative value. Obviously, such tendency is not desirable. Since in the calculation of the baryon spectrum, the quarks which form a baryon are restricted in a rather small region, the problem is not revealed. If one keeps applying this type of potential into the calculation of the N-N interaction, the over-powerful color Van de Waals force would appear, namely, when the distance between two nucleons is in the order of kilometer, a long-range color force which is much stronger than the gravitational force would present. This would be an unexpected result. Of course, after introducing a smoothly decreased factor discussed in Ref.3, this problem can be eliminated. Anyway, we wish to have a reasonable potential between quarks,which can describe either the short- and medium-range behaviors between quarks and the reasonable physical result in the long distance region. How to improve the confinement potential will be studied in the other investigation.

Reference

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Table 1. **Spectra of N and Δ**

State	$E\,(GeV)$		
	our's $V^{conf} = a_1 r - b_1 r^3$ $a_1 = 0.342\,GeV\,fm^{-1}$ $b_1 = 0.0386\,GeV\,fm^{-3}$	Kalman's $V^{conf} = a_2 r - b_2 r^2$ $a_2 = 0.405\,GeV\,fm^{-1}$ $b_2 = 0.103\,GeV\,fm^{-2}$	exp't
$N_{\frac{1}{2}^+}$	0.939	0.939	0.939
	1.428	1.439	1.400 – 1.486
	1.775	1.786	1.680 – 1.740
$N_{\frac{3}{2}^+}$	1.754	1.761	1.690 – 1.800
$N_{\frac{5}{2}^+}$	1.749	1.762	1.670 – 1.690
	1.956	1.977	1.880 – 2.175
$N_{\frac{1}{2}^-}$	1.491	1.450	1.520 – 1.560
	1.621	1.595	1.620 – 1.680
$N_{\frac{3}{2}^-}$	1.474	1.451	1.510 – 1.530
	1.686	1.661	1.670 – 1.730
$N_{\frac{5}{2}^-}$	1.653	1.629	1.660 – 1.690
	2.109	2.086	1.900 – 2.230
$\Delta_{\frac{1}{2}^+}$	1.889	1.900	1.850 – 1.950
$\Delta_{\frac{3}{2}^+}$	1.218	1.196	1.230 – 1.240
	1.757	1.769	1.500 – 1.900
	1.919	1.931	1.860 – 2.160
$\Delta_{\frac{5}{2}^+}$	1.926	1.937	1.890 – 1.920
$\Delta_{\frac{1}{2}^-}$	1.625	1.636	1.600 – 1.650
	1.990	2.001	1.850 – 2.000
$\Delta_{\frac{3}{2}^-}$	1.623	1.634	1.630 – 1.740
$\Delta_{\frac{5}{2}^-}$	1.990	2.001	1.890 – 1.960