IMPORTANT CONFIGURATIONS FOR NN PROCESSES IN A GOLDSTONE BOSON EXCHANGE MODEL

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We study the short-range nucleon-nucleon interaction in a nonrelativistic chiral constituent quark model by diagonalizing a Hamiltonian containing a linear confinement and a Goldstone boson exchange interaction between quarks. A finite six-quark basis obtained from single particle cluster model states was previously used. Here we show that the configurations which appear naturally through the use of molecular orbitals, instead of cluster model states, are much more efficient in lowering the six-quark energy.

Constituent quark models have been applied to the study of the nucleon-nucleon interaction. The Hamiltonian of such models usually contains a kinetic term, a confinement term and an effective one-gluon exchange (OGE) term. These models explain the short-range repulsion in the NN systems as due to the colour-magnetic part of the OGE interaction combined with quark interchanges between the $3q$ clusters. Nevertheless, an effective meson-exchange potential, introduced through the coupling of mesons to $3q$ cluster collectively, is required in order to reproduce the intermediate- and long-range attraction. Another category are the hybrid models. There, in addition to OGE interaction, the quarks belonging to different $3q$ clusters interact via pseudoscalar and scalar meson exchange. In these models the short-range repulsion in the NN system is still attributed to the OGE interaction between the constituent quarks. The medium- and the long-range attraction are due to meson-exchange, as expected.

In a recent exploratory work [1], by using the Born-Oppenheimer approximation, we calculated an effective NN interaction at zero separation distance, within the constituent quark model [2,3,4]. In this model the quarks interact via Goldstone boson exchange (GBE) instead of OGE of conventional models, and the hyperfine splitting in hadrons is obtained from the short-range part of the GBE interaction. An important merit of the GBE model is that it reproduces the correct order of positive and negative parity states in both nonstrange [3] and strange baryons [4]. In Ref. [1] we showed that the same short-range part of the GBE interaction, also induces a short-range repulsion in the NN system.

In Ref. [1] the height of the repulsive core was about 800 MeV for the $^3S_1$ channel and 1300 MeV for the $^1S_0$ channel. Such a result has been obtained from diagonalizing the Hamiltonian of Ref. [3] in a six-quark cluster model

basis built from harmonic oscillator states containing up to two quanta of excitation. The six-quark states have orbital symmetries $[6]_O$ and $[42]_O$, so that they contain configurations of type s^6, s^4p^2 and s^52s, with the centre of mass motion removed. In the flavour-spin space only the symmetries [33], [51] and [411] were retained. As shown in [1] they produce the most important five basis states allowed by the Pauli principle. Due to the specific flavour-spin structure of the GBE interaction, we found that the state $|s^4p^2[42]_O[51]_{FS}\rangle$ was highly dominant at zero-separation between nucleons. The symmetry structure of this state implies the existence of a node in the nucleon-nucleon S-wave relative motion wave function at short distances. This nodal structure will induce an additional effective repulsion in dynamical calculations based , for example, on the resonating group method.

A central issue of the NN problem is the construction of an adequate six-quark basis states. In principle the choice of basis is arbitrary if a sufficiently large basis is considered in the Hamiltonian diagonalization. But, as in practice one considers a finite set, its choice is very important. Ref. [5] advocated the use of molecular-type single particle orbitals instead of cluster model-type states. These orbitals have the proper axially and reflectionally symmetries and can be constructed from appropriate combinations of two-centre Gaussians. At zero-separation the six-quark states obtained from such orbitals contain certain p^ns^{6-n} components which are missing in the cluster model basis. In Ref. [6] it has been shown that for an OGE model used in the calculations of the NN potential they lead to a substantial lowering of the lowest eigenstate, used in the calculation of the NN potential. The molecular orbitals have also the advantage of forming an orthogonal and complete basis while the cluster model (two-centre) states are not orthogonal and are overcomplete.

Due to the predominance (93 %) of only one component, $|s^4p^2[42]_O[51]_{FS}\rangle$, in the ground state wave function obtained in a cluster model basis [1] the GBE model is a more chalenging case to test the efficiency of a molecular orbital basis than the OGE model, where there is some mixture of states (see e.g. [6]). Here we show that by using molecular orbitals the height of the repulsion reduces by about 22 % and 25 % in the $^3S_1$ and $^1S_0$ channels respectively.

To this end we diagonalize the Hamiltonian of Ref. [3] in a six-quark basis constructed from single particle molecular-type orbitals defined as linear combinations of the same s and p states, as used in the cluster model study [1]. We calculate the NN interaction potential in the Born-Oppenheimer approximation

$$V_{NN}\left(Z\right) = \langle H\rangle_Z - \langle H\rangle_\infty \ , \tag{1}$$

where $\langle H\rangle_Z$ is the lowest expectation value obtained from the diagonalization at a given Z and $\langle H\rangle_\infty = 2m_N$ is the energy (mass) of two well separated

nucleons. Here we study the case $Z = 0$, relevant for short separation distances between the nucleons. In Tables I and II we present our results for IS = (01) and (10) respectively, obtained from the diagonalization of H. From the diagonal matrix elements H_{ii} as well as from the eigenvalues, the quantity $2m_N$ = 1939 MeV has been subtracted. Here m_N is the nucleon mass calculated also variationally, with an s^3 configuration. This value is obtained for a harmonic oscillator parameter $\beta = 0.437$ fm. For sake of comparison with Ref. [1] we take the same β for the six-quark system as well.

In both IS=(01) and (10) cases the effect of using molecular orbitals is rather remarkable in lowering the ground state energy as compared to the cluster model value [1]. Accordingly, the height of the repulsive core in the $^1S_3$ channel is reduced from 915 MeV in the cluster model basis to 718 MeV in the molecular orbital basis. In the $^1S_0$ channel the reduction is from 1453 MeV to 1083 MeV. Thus the molecular orbital basis is much better, inasmuch as the same two single particle states, s and p, are used in both bases.

Table 1: Results of the diagonalization of the Hamiltonian [3] for IS = (01). Column 1 - basis states, column 2 - diagonal matrix elements (GeV), column 3 - eigenvalues (GeV) in increasing order, column 4 - lowest state amplitudes of components given in column 1

State	H_{ii} - 2 m_N	Eigenvalues - 2 m_N	Lowest state amplitudes
$\|33[6]_O[33]_{FS}>$	2.616	0.718	-0.04571
$\|33[42]_O[33]_{FS}>$	3.778	1.667	0.02479
$\|33[42]_O[51]_{FS}>$	1.615	1.784	-0.31762
$\|33[42]_O[411]_{FS}>$	2.797	2.309	0.04274
$\|42^+[6]_O[33]_{FS}>$	3.062	2.742	-0.07988
$\|42^+[42]_O[33]_{FS}>$	2.433	2.784	0.12930
$\|42^+[42]_O[51]_{FS}>$	0.850	3.500	-0.93336
$\|42^+[42]_O[411]_{FS}>$	3.665	3.752	0.00145
$\|51^+[6]_O[33]_{FS}>$	2.910	4.470	-0.01789

The previous study [1], performed in a cluster model basis indicated that the dominant configuration is associated to the symmetry $[42]_O[51]_{FS}$. It is the case here too and one can see from Tables I and II that the diagonal matrix element H_{ii} of the state $|42^+[42]_O[51]_{FS}>$ is far the lowest one, so that this state is much more favoured than $|33[42]_O[51]_{FS}>$. Such a state represents a configuration with two quarks on the left and four on the right around the symmetry centre. At $Z \to \infty$ its energy becomes infinite and it does no more contribute to the ground state, i.e. it behaves as a hidden colour state. But at $Z = 0$ it is the dominant component of the lowest state with a probability

of 87 % for $IS = (01)$ and 93 % for $IS = (10)$. The next important state is $|33[42]_O[51]_{FS}>$ with a probability of 10 % for $IS = (01)$ and 4 % for $IS = (10)$. The presence of this state will become more and more important with increasing Z. Asymptotically this state corresponds to a cluster model state with three quarks on the left and three on the right of the symmetry centre.

Details of this study can be found in Ref. [7]. The following step will be to calculate the NN potential at $Z \neq 0$. The Yukawa potential tail, already contained in the GBE interaction [3] will bring the required long-range attraction. It would be interesting to find out the amount of middle-range attraction brought in by two correlated or uncorrelated pion exchanges.

Table 2: Same as Table I but for $IS = (10)$

State	H_{ii} - 2 m_N	Eigenvalues - 2 m_N	Lowest state amplitudes
$\|33[6]_O[33]_{FS}>$	3.300	1.083	-0.02976
$\|33[42]_O[33]_{FS}>$	4.367	2.252	0.01846
$\|33[42]_O[51]_{FS}>$	2.278	2.279	-0.20460
$\|33[42]_O[411]_{FS}>$	3.191	2.945	-0.04729
$\|42^+[6]_O[33]_{FS}>$	3.655	3.198	-0.07215
$\|42^+[42]_O[33]_{FS}>$	2.796	3.317	0.13207
$\|42^+[42]_O[51]_{FS}>$	1.167	4.058	-0.96531
$\|42^+[42]_O[411]_{FS}>$	4.405	4.459	-0.00081
$\|51^+[6]_O[33]_{FS}>$	3.501	5.070	-0.01416

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