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The new driving mechanism for nuclear force: lessons of the workshop[⋆]

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Abstract. Instead of the Yukawa mechanism for intermediate- and short-range interaction, some new approach based on formation of the symmetric six-quark bag in the state $|(0s)^6[6]_X, L = 0\rangle$ dressed due to strong coupling to π, σ and ρ fields are suggested. This new mechanism offers both a strong intermediate-range attraction which replaces the effective σ-exchange (or excitation of two isobars in the intermediate state) in traditional force models and also short-range repulsion. Simple illustrative model is developed which demonstrates clearly how well the suggested new mechanism can reproduce NN data. Some important lessons of the workshop discussions have been included in the talk.

It was found in recent years that the traditional models for NN forces, based on the Yukawa concept of one- or two-meson exchanges between free nucleons even at the quark level lead to numerous disagreements with newest precise experimental data for few-nucleon observables (especially for spin-polarised particles) [1–3]. There are also various inner inconsistencies and disagreements between the traditional NN force models and predictions of fundamental theories for meson-baryon interaction (e.g. for meson-nucleon cut-off factors). All these disagreements stimulate strongly new attempts to develop alternative force models based either on chiral perturbation theory or a new quark-meson models.

Our recent studies in the field [1–3] have led us to a principally new mechanism for intermediate- and short-range NN forces – the so called "dressed" bag mechanism which is able to explain the failure of the traditional Yukawa exchange models and also to solve many long-standing puzzles in the field. This mechanism has good resources in explanation of many fundamental difficulties of modern hadronic physics, e.g. the puzzles in baryon spectroscopy (e.g. normal ordering in Λ-sector and inverse ordering in nucleon sector for excited negative and positive parity states), the complicated interplay between NN short-range repulsion and intermediate range attraction, the ABC-puzzle in 2π-production in pp and pd collisions etc.

The new model is based on the important observation [4] that two possible six-quark space symmetries in even NN partial waves (for illustration we consider here the S-wave only), viz. $|s^6[6]L = 0\rangle$ and $|s^4p^2[42]L = 0\rangle$ correspond to the states of different nature. The first states have almost equal projections

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[⋆] The respective original work included in the talk was done jointly with Drs. I.T.Obukhovsky, V.N.Pomerantsev and Prof. A. Faessler

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into the NN, ΔΔ and CC channels and thus correspond to bag-like intermediate states while the states of second type are projected mainly onto NN channel and thus can be considered as clusterised NN states with *nodal* NN relative motion wavefunctions. In the present work we develop this picture much further on the quark-meson microscopic basis and derive the microscopic NN transition amplitudes through six-quark $+2\pi$ intermediate states in s-channel (see Fig. 1).

The transition is accompanied by a virtual emission and subsequent absorption of two tightly correlated pions by diquark pairs or, alternatively, by two $1p$-shell quarks when they jump from the $1p$- to the $0s$-shell orbit or vice versa. These two pions can form both the scalar σ and vector ρ mesons which surround the symmetric six-quark bag.

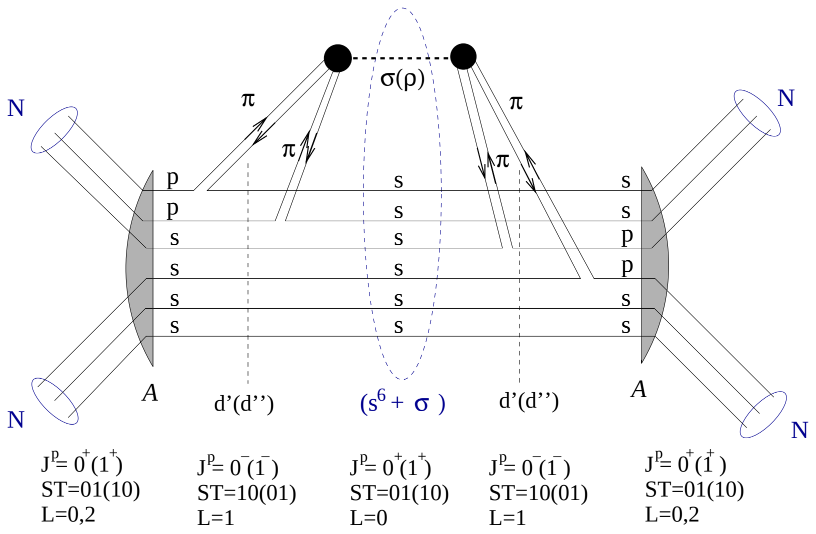

Fig. 1. The graph illustrates two sequential π-meson emissions and absorptions via an intermediate σ- (or ρ-) meson cloud and the generation of a symmetric six-quark bag.

It follows from previous studies (see e.g. [5]) for chiral symmetry restoration effects in multiquark systems or in high density nuclear matter that some phase transition happens when the quark density or the temperature of the system is increased, which leads to a (partial) restoration of the broken chiral symmetry. The consequence of the above restoration is a strengthening of the sigma-meson field in the NN overlap region and reduction of the constituent quark mass. This could be modeled by "dressing" of the most compact six-quark configurations $|s^6[6]_X L = 0\rangle$ and $|s^5p[51]_X L = 1\rangle$ inside the NN overlap region with an effective sigma-meson field. The resulting scalar- and vector-meson clouds will stabilize the multi-quark bag due to a (partial) chiral symmetry restoration effect in the dense multi-quark system and thus enhance all the contributions of such a type. Thus, the picture of NN interaction emerged from the model can be referred to as the $6q$ "dressed" bag (DB) model for baryon-baryon interaction [1–3].

The light "σ" or a similar "scalar-isoscalar meson" with mass $m \sim 300$ MeV is assumed to exist only in a high density environment and not in the vacuum, contrary to the π and ρ mesons. This mechanism, being combined with an additional orthogonality requirement[6], can describe both the short-range repulsion and the medium range attraction and can replace the t-channel exchange by σ- and ω-mesons in the conventional Yukawa-type picture of the NN force.

The direct calculation of the multiloop diagram on Fig. 1 [1,2] using quark pair-creation model results for S- and D-partial waves (in NN-channel) in a separable operator of form:

$$V_E^{L'L}(r', r) = \begin{pmatrix} g_0^2 G_{00}(E)|2s(r')\rangle\langle 2s(r)| & g_0 g_2 G_{02}(E)|2s(r')\rangle\langle 2d(r)| \\ g_2 g_0 G_{20}(E)|2d(r')\rangle\langle 2s(r)| & g_2^2 G_{22}(E)|2d(r')\rangle\langle 2d(r)| \end{pmatrix}, \quad (1)$$

where the generalised propagators $G_{ll'}(E)$ are related to the DB intermediate state [1,2]. The interaction given by Eq.(1) can be interpreted as an effective NN potential in our model.

In accordance with this, the contribution of mechanism displayed in the diagram in FIG. 1 to the NN interaction in the S and D partial waves can be expressed through the matrix element:

$$A^{L'L}_{NN\to d_0+\sigma\to NN} = \int d^3r' d^3r \Psi^{L'}_{NN}{}^{*}(E; \mathbf{r}') V_E^{L'L}(\mathbf{r}', \mathbf{r}) \Psi^{L}_{NN}(E; \mathbf{r}), \quad (2)$$

where Ψ^{L}_{NN} and $\Psi^{L'}_{NN}$ are the "proper" nodal NN scattering wave functions in initial and final state respectively.

The interaction operator (1) mixes S- and D-partial waves in the triplet NN channel and thus it leads to a specific tensor mixing with the range ~ 1 fm (about that of the intermediate DB state). Thus the proposed new mechanism for NN interaction induced by the intermediate dressed six-quark bag $|s^6 + 2\pi\rangle$ results in a specific matrix separable form of interaction with *nodal* (in S- in P-partial waves) form factors and a specific tensor mixing of new type [7].

An important question is arising in this development, what is an interrelation between the new above mechanism and the traditional picture of NN interaction emerged from RGM. Let us to remind that the consistent RGM description (i.e. with no σ-meson exchange between quarks), as was additionally confirmed by Fl. Stancu in this Workshop, leads to purely repulsive NN interaction. The strength of the repulsion is likely of right magnitude because it reproduces well the slope of NN S-wave phase shifts at $E > 200$ MeV. Hence the new mechanism for NN interaction considered here, which leads to a strong intermediate-range attraction, being combined to the above RGM picture, is able to provide full quark-meson microscopic framework for quantitative description of fundamental nuclear force.

Moreover, the proposed model will lead to the appearance of strong 3N and 4N forces mediated by 2π and ρ exchanges [3]. In this Workshop Prof. Moszkowski has suggested to use specific features of 3N force resulted from the new model to explain the saturation properties of nuclear matter. It should emphasized in this connection that the 3N force followed from the new model has a new feature of "substitution" when the nuclear matter density arises. In this case the enhancement of the attractive 3N force contribution should be accompanied by the respective weakening two-body attractive contributions and vice versa. So by this specific mechanism at the sufficiently high density the nuclear matter dynamics will be governed mainly by three- and four-body nuclear forces rather than two-body contributions. And this specific "substitution" mechanism leads, as is evident, to relativistic Walecka model, in contrast to conventional force models.

The new 3N force includes both central and spin-orbit components. Such a spin-orbit 3N force is extremely desirable to explain the low energy puzzle of the analyzing power A_y in N-d scattering and also the behavior of A_y in the 3N system at higher energies $E_N \simeq 250 \div 350$ MeV at backward angles. The central components of the 3N and 4N forces are expected to be strongly attractive and thus they must contribute to 3N and (may be) 4N binding energies possibly resolving hereby the very old puzzle with the binding energies of the lightest nuclei.

Future studies must show to what degree such expectations can be justified.

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