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исследований
дубна

182/84

E2-83-704

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THE POMERON COLOUR STRUCTURE AND HADRON SCATTERING ON THE SIX-QUARK DEUTERON CONFIGURATION

Submitted to "Zeitschrift für Physik C: Particles and Fields"

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1983

1. INTRODUCTION

It is obvious that deuteron cannot be treated as an n-p system if the internucleon distance is too small. If parton clouds of the nucleons overlap one another, the deuteron should be considered as a multiquark system. The confinement condition means that the six-quark deuteron wave function (WF) is not small only when all quarks are located in a volume of about 1 fm radius or if the quarks form two colourless clusters. At present the most adequate method for the investigation of a two-nucleon system at short distances is the resonating group method [1]. One can write down the WF of the two-nucleon system in the form

$$\Psi_{NN}(1,\dots,6) = \frac{1}{N_{NN}}\Big(1 - \sum_{\alpha=1}^{3}\sum_{\beta=4}^{6}\hat{P}_{\alpha\beta}\Big)\Psi_N(1,2,3)\,\Psi_N(4,5,6)\,F(R). \qquad (1)$$

Here $R = \frac{1}{3}\Big(\sum_{i=1}^{3} r_i - \sum_{j=4}^{6} r_j\Big)$; $\hat{P}_{\alpha\beta}$ is the quark permutation operator; Ψ_N is a quark WF of a nucleon; $F(R)$ describes the relative motion of nucleon clusters; N_{NN} is the normalization constant $N = \sqrt{10(1-\delta)}$, where

$$\delta = \frac{1}{9}\langle\phi_3(1,2,3)\,\phi_3(4,5,6)\,f(R)\,|\,\hat{P}_{14}\,|\,\phi_3(1,2,3)\,\phi_3(4,5,6)\,f(R)\rangle.$$

Using WF (1) one can explain qualitatively the emergence of the short distance repulsion [2-4] and $\Delta\Delta$-admixture [5,6]. Nevertheless, the high q^2 behaviour of the deuteron electromagnetic formfactor indicates existence of a six-quark component of the deuteron WF, which has a form of a bag [7-9]. Thus the deuteron WF can be written as

$$\Psi_d(1\dots6) = \alpha\Psi_{NN}(1\dots6) + \beta\Psi_{6q}(1\dots6). \qquad (2)$$

Here Ψ_{6q} is the six-quark bag WF. The analysis of the high q^2 behaviour of the electromagnetic formfactor gives the Ψ_{6q} admixture in the deuteron WF of about 2-7% [7,8]. By introducing the six-quark component one can also explain naturally the linear energy dependence in the nucleon-nucleon potential [10,11]. This approach gives the six-quark component weight of about 10% [10].

Thus, the description of the deuteron quark WF at small distances is rather of qualitative nature and one has to look for

the effects which are sensitive to the deuteron quark structure at small distances.

This paper is devoted to the correction of the Glauber approximation (GA) which emerges if one takes into account the pomeron colour structure and the deuteron quark contents. If the main contribution to hadronic inelastic cross-section results from the colour exchange, then the pomeron contribution to the elastic scattering amplitude corresponds to the double colour exchange, and each exchange can be attributed to different nucleons of a deuteron. Such a contribution contains interference of a two-nucleon deuteron WF with a state of "intrinsic colour". This interference is located at small internucleon distances and is sensitive to the quark WF details. In the GA one deals with the colourless exchanges only and considers the deuteron as a n-p system, thus, one misses the above contribution. This contribution is a correction to the main (impulse) term of the amplitude rather than to the small double scattering term and one may apriori believe it to be large. Nevertheless, the experiment does not show any considerable deviation from the GA including inelastic screening, so deuteron short distance dynamics suppresses the above corrections. The goal of this paper is to assertain the conditions of such suppression.

It will be shown below that the smallness of the correction to the GA imposes some restrictions on the WF (2). If β^2 is about a few per cent, then the condition $|\Delta\sigma| \lesssim |\sigma_{tot}^{exp} - \sigma_{tot}|$ determines with high precision the radius of the six-quark bag. It is interesting that WF (1) without six-quark bag leads to small correction $\Delta\sigma_Q$ independently of the form of the function $F(R)$.

This paper is organized as follows. Expressions for the WF are presented in section 2. Formulae for calculation of $\Delta\sigma_Q$ are derived in section 3. Numerical results and comparison with experimental data are presented in section 4. Section 5 is devoted to discussion.

2. PARAMETRIZATION OF WF

The space part of the nucleon quark WF and WF of the six-quark component is taken here in the form of ground state of the oscillator model

$$\phi_A(r_1\dots r_A) = \frac{1}{N_A}\exp\Big[-\frac{1}{2AR_A^2}\sum_{i>j}(r_i - r_j)^2\Big], \quad N_A = (\pi R_A^2)^{3/4(A-1)}A^{3/4}, \qquad (3)$$

where A is a number of quarks. We take the nucleon radius $R_N = R_3 = 0.8$ fm. The radius R_6 of the six-quark state will be a free parameter.

The space configuration S^6 can be described by the only antisymmetrical colour spin-isospin WF of the six-quark bag with the deuteron quantum numbers /7/. It can be written as follows

$$\Psi_6^{SIC}(1,\dots,6) = \frac{1}{N_6^{SIC}}\left(1 - \sum_{\alpha=1}^{3}\sum_{\beta=4}^{6}\hat{P}_{\alpha\beta}\right)\Psi_N^{SIC}(1,2,3)\,\Psi_N^{SIC}(4,5,6)\,F_d^{SI}. \qquad N_6^{SIC} = \sqrt{80}/3. \tag{4}$$

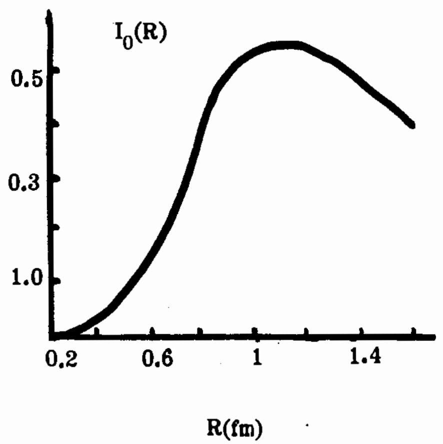
Here Ψ_N^{SIC} is a spin-isospin-colour part of the nucleon WF; F_d^{SI} is a spin-isospin part of the WF describing relative motion of three-quark clusters in a deuteron. The space part of F_d^{SI} which is denoted by $f(R)$ is parametrized in the form

$$f(R) = \frac{1}{N_f}\sum_{i=1}^{N_{max}} z_i\, e^{-R^2/a_i^2}, \quad \text{where} \tag{5}$$

$$N_f = \pi^{3/4}\left\{\sum_{i,j=1}^{N_{max}} z_i z_j\left(\frac{a_i^2 + a_j^2}{a_i^2 a_j^2}\right)^{3/2}\right\}^{1/2}.$$

The first term in (5) describes the configuration of two nucleons separated in space, $z_1 = 1$, $a_1^2 = 2R_d^2$, where $R_d = 2.55$ fm /16/. Other terms in (5) with $i>1$ are introduced to describe $f(R)$ in the region of N-N repulsive core. We shall fix further $N_{max} = 2$ and use two sets of parameters: I. $z_2 = -1$, $a_2 = 0.5$ fm, II. $z_2 = -4$, $a_2 = 0.34$ fm. In the former case the function $f_I(R)$ at $R<2$ fm is similar to the S-component of the Reid WF /17/ with soft core. The function $f_{II}(R)$ corresponds to the deuteron WF changing a sign at $R \approx 0.4$ fm, as was proposed in paper /18/. It is noteworthy that $f(R)$ behaviour at large R does not influence the result of calculations of $\Delta\sigma_Q$, which is sensitive to small R only. The normalization condition for the WF (2) has the form

$$\alpha^2 + 2\alpha\beta I_0 + \beta^2 = 1, \quad \text{where } I_0 = \langle\Psi_{6q}|\Psi_{NN}\rangle. \tag{6}$$



The relative phase of α and β is assumed to be zero to avoid additional unknown parameters. This is true if two-quark interaction Hamiltonian is real. The main part of Hamiltonian used which reproduces the confinement is real but terms with spin-orbital and tensor interaction are considered usually as small corrections.

Fig.1. The dependence of the overlap integral I_0 on the six-quark bag radius.

The dependence of overlap integral I_0 on R_6 value is shown in fig.1 for the case $f(R) = f_I(R)$. One can see that if $R_6 \gtrsim 0.5$ fm, then WF's Ψ_{NN} and Ψ_{6q} are essentially nonorthogonal.

3. CALCULATION OF $\Delta\sigma_Q$ IN THE DOUBLE GLUON MODEL OF THE POMERON

To make specific calculations we use the double gluon approximation (DGA) /12-14/ for the pomeron. This model predicts, in contrast to the additive one /15/, the dependence of hadronic total cross section both on number of quarks and on the colour distribution inside hadron. Thus for the identical particles $\sigma_{tot}^{hh} \propto \langle r_h^2\rangle$ the mean square of hadronic radius. In spite of the obvious oversimplification of the model it gives surprisingly good description of the hadronic data. The correction $\Delta\sigma_Q$ in DGA can be written as

$$\Delta\sigma_Q(hd) = \sigma_{tot}^{2g}(hd) - 2\sigma_{tot}^{2g}(hN), \tag{7}$$

where σ_{tot}^{2g} is the cross section calculated in DGA. The ordinary double scattering Glauber correction is not contained in the DGA. It is calculated correctly in GA and for this reason it is omitted in (7). It is clear that the contribution of long internucleon distances is cancelled in (7) because of small N-N overlapping.

Now, the total cross section of two systems, containing n_1 and n_2 quarks has in DGA a form

$$\sigma_{tot}^{2g}(n_1,n_2) = \frac{8\pi\alpha_s^2 n_1 n_2}{9}\int\frac{d\vec{k}^2}{(\vec{k}^2)^2}\left[1 - G_1(\vec{k}^2)\right]\left[1 - G_2(\vec{k}^2)\right], \tag{8}$$

where

$$G_j(\vec{k}^2) = \langle\Psi_j|\hat{\Lambda}_j(\vec{k})|\Psi_j\rangle, \quad \hat{\Lambda}_j(\vec{k}) = \frac{3(1-n_j)}{16}\vec{\lambda}_{(1)}\vec{\lambda}_{(2)}\, e^{i\vec{k}(\vec{r}_2-\vec{r}_2)}, \tag{9}$$

Here $\alpha_s = g^2/4\pi$, where g is the QCD coupling constant. $\lambda_{(i)}$ are the colour matrices of SU(3), which affect the quark with number i. If hadron WF's are parametrized in the Gaussian form, then one obtains for the h-N scattering

$$\sigma_{tot}^{2g}(hp) = \frac{8\pi\alpha_s^2}{9} n_h n_p J(a_h, a_p), \tag{10}$$

where $J(\alpha,\beta) = \alpha\ln\left(\frac{\alpha+\beta}{\alpha}\right) + \beta\ln\left(\frac{\alpha+\beta}{\beta}\right)$; $a_p = \langle r_p^2\rangle/2$; $a_\pi = 2\langle r_\pi^2\rangle/3$. Substituting $R_p = 0.8$ fm and $\sigma_{tot}(NN) = 3.9$ fm^2 in

(10) one can obtain $a_s^2 = 0.348$. This value will be used further.

In the case of deuteron function (9) has a form

$$G_d(\vec k^2) = a^2 G_{11}(\vec k^2) + 2a\beta G_{12}(\vec k^2) + \beta^2 G_{22}(\vec k^2), \quad \text{where} \tag{11}$$

$$G_{ij}(\vec k^2) = \langle \Psi_i | \hat\Lambda(\vec k) | \Psi_j \rangle \tag{12}$$

and abbreviation $\Psi_1 = \Psi_{NN}$, $\Psi_2 = \Psi_{6q}$ is used.

The total cross section can be written in the same manner

$$\sigma_{tot}^{2g}(hd) = a^2\sigma_{11} + 2a\beta\sigma_{12} + \beta^2\sigma_{22}. \tag{13}$$

The most cumbersome calculations are needed to find $G_{11}(k^2)$. Substituting WF (1) into (12) one obtains

$$G_{11}(\vec k^2) = \frac{1}{N_{NN}^2}\langle \Psi_N(1,2,3)\Psi_N(4,5,6) F(R) | \hat\Lambda_d(\vec k) - \sum_{\alpha=1}^{3}\sum_{\beta=4}^{6} [\hat\Lambda_d(\vec k)\hat P_{\alpha\beta} + \hat P_{\alpha\beta}\hat\Lambda_d(\vec k)] + \sum_{\alpha,\gamma=1}^{3}\sum_{\delta,\beta=4}^{6} \hat P_{\alpha\beta}\hat\Lambda_d(\vec k)\hat P_{\gamma\delta} | \Psi_N(1,2,3)\Psi_N(4,5,6) F(R)\rangle. \tag{14}$$

After some transformations in colour and spin-isospin parts of WF one can represent $G_{11}(\vec k^2)$ as follows

$$G_{11}(\vec k^2) = \sum_{i=1}^{9} C_i g_{11}^i(\vec k^2), \tag{15}$$

Here

$$g_{11}^i(\vec k^2) = \frac{1}{N_{NN}^2}\langle \phi_N(1,2,3)\phi_N(4,5,6) f(R) | \hat Q e^{i\vec k(\vec r_1-\vec r_2)} \hat R | \times \phi_N(1,2,3)\phi_N(4,5,6) f(R)\rangle, \tag{16}$$

where

$$\{C_i\} = \left(10, -\frac{5}{27}, -\frac{10}{27}, \frac{5}{27}, -\frac{20}{27}, \frac{5}{27}, -\frac{5}{27}, \frac{10}{27}, -\frac{10}{27}\right),$$
$$\{\hat Q_i\} = (1,1,1,\hat P_{14},\hat P_{14},\hat P_{24},\hat P_{34},\hat P_{14},\hat P_{14}), \tag{17}$$
$$\{R_i\} = (1,\hat P_{36},\hat P_{14},\hat P_{25},\hat P_{36},\hat P_{25},\hat P_{36},\hat P_{24},\hat P_{34}).$$

The Gaussian form of all WF's in (16) allows to perform explicit integration over r_3 and to get $g_{11}^i(k^2)$ in the form

$$g_{11}^i(\vec k^2) = \sum_{n,m=1}^{N_{max}} \frac{z_n z_m 216}{N_3 N_f^2 N_{NN}^2} \int \exp\{i\vec k(\vec r_1 - \vec r_2) - \sum_{\alpha,\beta=4}^{6}(\vec r_\alpha \vec r_\beta) A^i_{\alpha\beta}(n,m) - 2\sum_{\alpha=1}^{2}\sum_{\beta=4}^{6}(r_\alpha r_\beta) C^i_{\alpha\beta}(n,m) - \sum_{\alpha,\beta=1}^{2}(r_\alpha r_\beta) a^i_{\alpha\beta}(n,m)\} d^3r_1 d^3r_2 \prod_{\gamma=4}^{6} d^3 r_\gamma. \tag{18}$$

Expressions for matrices $A^i_{\alpha\beta}(n,m)$ and $C^i_{\alpha\beta}(n,m)$ are too cumbersome and can be easily found by using (17) and formulae for WF. Performing integration in (18) one obtains

$$g_{11}^i(\vec k^2) = \sum_{n,m=1}^{N_{max}} K z_n z_m \frac{\exp[-a^i(n,m)\vec k^2]}{|\hat A^i(n,m)|^{3/2}|\hat b^i(n,m)|^{3/2}}, \tag{19}$$

where

$$K = \frac{216\pi^{15/2}}{N_3^4 N_f^2 N_{NN}^2}, \quad \hat b^i_{k\ell} = a^i_{k\ell} - \sum_{\alpha,\beta=4}^{6} C^i_{k\alpha}[(\hat A^i)^{-1}]_{\alpha\beta} C^i_{\ell\beta},$$

$$a_i = (b^i_{11}+b^i_{22}+b^i_{12}+b^i_{21})/(4|\hat b^i|).$$

Finally, from expressions (15) and (19) one obtains σ_{11}

$$\sigma_{11} = \frac{8\pi a_s^2 n_h n_d}{9}\sum_{i=1}^{9}\sum_{n,m=1}^{N_{max}} \frac{K z_n z_m C_i}{|\hat A^i(n,m)|^{3/2}|\hat b^i(n,m)|^{3/2}} J[(a_h, a^i(n,m)] \tag{20}$$

The first term in the sum over i here is responsible for the most part of the hd cross section and secures the compensation of the contributions from the region of long internucleon distances in formula (7).

The calculation of σ_{22} is less difficult. By using the condition of colourlessness of the six-quark configuration $\langle\Psi_{6q}^{SIC}|\lambda_{(1)}\lambda_{(2)}|\Psi_{6q}^{SIC}\rangle = \frac{C}{1-n_d}$, one can show that the expression for σ_{22} is derived from expression (10) for $\sigma_{tot}^{2g}(hp)$ after replacing R_3 by R_6 and n_N by n_d. Thus if $R_6 = R_3$, the cross section of hadron scattering on the six-quark deuteron component in the configuration S^6 is doubled in comparison with the hadron-nucleon one.

The calculating procedure in the case of σ_{12} is analogous to σ_{11}. Omitting the details let us give the final result

$$\sigma_{12} = \frac{8\pi a_s^2}{9} n_h n_d \sum_{i=1}^{2}\sum_{n=1}^{N_{max}} K' z_n C'_i \frac{J[a_h, a^i(n)]}{|\hat A^i(n)|^{3/2}|\hat b^i(n)|^{3/2}}, \tag{21}$$

where

$$K' = \frac{216\pi^{15/2}}{N_6 N_6^{SIC} N_f N_{NN} N_3^2}; \quad \{C'_i\} = \left(\frac{475}{54}, \frac{5}{54}\right).$$

The matrices $A^i_{\alpha\beta}(n)$, $C^i_{\alpha\beta}(n)$, $a^i_{\alpha\beta}(n)$ can be found by calculation of the exponential factor for products of the following type $\phi_6(r_1 \dots r_6)\hat Q'_i \phi_3(r_1,r_2,r_3)\phi_3(r_4,r_5,r_6) f(R)$, where $\hat Q'_1 = 1$, $\hat Q'_2 = \hat P_{14}$.

4. NUMERICAL RESULTS

If one uses the deuteron WF (1) without the six-quark component, then for the case of pd-scattering one obtains

$$\Delta\sigma_Q\,(pd) = \begin{cases} -0.023 \text{ mb}, & f = f_I \\ -0.026 \text{ mb}, & f = f_{II}\,. \end{cases}$$

It is seen that both parametrizations lead to similar small values of $\Delta\sigma_Q$. To verify the weak sensitivity of $\Delta\sigma_Q$ to the form of $f(R)$ we have considered also the triple Gaussian parametrization of $f(R)$. $\Delta\sigma_Q$ has been calculated for $a_2 = 0.5$ fm, $a_3 = 0.25$ fm and variety of parameters z_2, z_3, restricted by $-3 < z_2, z_3 < 1$. All sets of parameters give the values of $\Delta\sigma_Q = -0.02 \div -0.027$.

It seems that regardless of the form of the radial WF $f(R)$ used the correction to the Glauber approximation turns out to be very small. It is noteworthy that separate terms in the sum over i in formula (20) are not small at all for $i > 1$, but have value of about 1 mb. The reasons for deep compensation are obscure.

Inclusion of the six-quark deuteron component changes the situation drastically. The calculation with WF (2) has been performed for the case $f(R) = f_I(R)$. The results are shown in fig.2 in the form of $\Delta\sigma_Q$(pd)-dependences upon the value of β with different values of 6q-radius R_6. It is seen that for some values of β, R_6 correction reaches significant value, exceeding even the Glauber correction. It is interesting that if $R_6 = R_N = 0.8$ fm, then the correction $\Delta\sigma_Q$ is independent of the 6q-component weight and is small: $\Delta\sigma_Q < 0.06$ mb for $|\beta|^2 \le 0.1$.

The difference $|\sigma_{tot}^{exp} - \sigma_{tot}^{Gl}|$ for pd-scattering is less than 0.3-0.5 mb in the whole measured energy interval [19]. If one imposes such a restriction on $\Delta\sigma_Q$ one can get some bounds for values of parameters β and R_6. The shaded region in fig.3 shows the permitted sets of β and R_6, for which $\Delta\sigma_Q < 0.4$ mb. It is seen that for $\beta^2 \gtrsim 0.04$ one can predict the R_6 value quite precisely $R_6 \approx 0.76 \div 0.84$ for positive β and $R_6 \approx 0.66 \div 0.85$ for negative

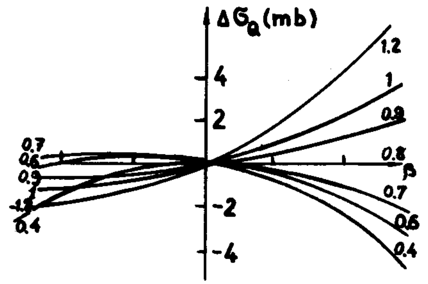


Fig.2. The correction $\Delta\sigma_Q$(pd) depending on the R_6- radius of the six-quark bag and its amplitude β in the deuteron WF.

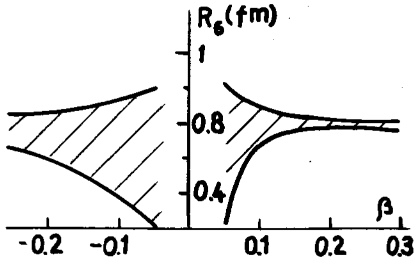


Fig.3. The shaded area shows the collection of the values of the parameters R_6 and β, which are consistent with the experimental data on σ_{tot} (pd).

5. CONCLUSION

Due to pomeron colour structure and nucleon overlapping in deuteron one can believe that the Glauber approximation, which does not take into account all these effects should have some corrections. The calculations performed here in the DGA have given the following results:

i) two clusters WF (1), antisymmetrized over quarks, provide a small correction $\Delta\sigma_Q$, regardless of the form of function $f(R)$, describing the relative motion of clusters.

ii) if one adds the six-quark bag to the deuteron WF one can obtain considerable correction $\Delta\sigma_Q$ much larger than the difference $(\sigma_{tot}^{exp} - \sigma_{tot}^{Gl})$, for some values of the radius R_6 and weight β^2. If β^2 is not too small $(\beta^2 \gtrsim 0.01)$ then experimental restriction on the value of $\Delta\sigma_Q$ allows to determine with high precision the value of the radius R_6.

These two results seem to be in contradiction. Indeed, WF (1) in the region of NN repulsive core can be approximated by the sum over eigenfunctions of the six-quark bag. Nevertheless, this sum is organized in such a way that though each term is large the sum becomes small after considerable compensation, regardless of the form of the radial WF $f(R)$.

One can compare the above radius R_6 with the value $R_6 = 0.9$ fm claimed in [20]. The method used there, however, demands exact knowledge of the two-nucleon WF of deuteron $f(R)$ and some model of deuteron stripping on nuclei.

The authors are indebted to F.Niedermayer who has read the manuscript and made some valuable comments.

After completing the work the authors were informed that the analogous results were obtained by N.N.Nikolaev.

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Received by Publishing Department
on October 12,1983.

Копелиович Б.З., Захаров Б.Г. E2-83-704
Цветовая структура померона и рассеяние адронов на шестикварковой компоненте дейтрона

Цветовая структура померона приводит к определенному вкладу в амплитуду упругого адрон-дейтронного рассеяния, который не учитывается в подходе Глаубера, включающем неупругое экранирование. Рассмотренный вклад чувствителен к волновой функции дейтрона на малых расстояниях и дает возможность определить с большой точностью размер шестикваркового мешка в дейтроне.

Работа выполнена в Лаборатории ядерных проблем ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна 1983

Kopeliovich B.Z., Zakharov B.G. E2-83-704
The Pomeron Colour Structure and Hadron Scattering on the Six-Quark Deuteron Configuration

The pomeron colour structure provides some contribution to the elastic hadron-deuteron amplitude which is not contained in the Glauber like approach. This contribution is very sensitive to the deuteron wave function at short distances and poses one to fix with a high precision a size of the six-quark bag in the deuteron.

The investigation has been performed at the Laboratory of Nuclear Problems, JINR.

Preprint of the Joint Institute for Nuclear Research. Dubna 1983