Test of the constituent-quark hypothesis for a six-quark system

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Analysis of the correction to the Glauber expression for σ_{pd}^{tot} due to the quark structure of the deuteron leads to the conclusion that the cross section for the interaction of a proton with a quark which is part of a nucleon is equal to the cross section for the interaction of a proton with a quark which is part of a system of six interacting quarks.

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Hadrons are widely believed to be nonrelativistic nucleuslike systems of dressed valence quarks called "constituent quarks." The fact that the Levine-Frankfurt relation

$$\sigma_{NN}^{tot} = {}^3\!/_2\, \sigma_{\pi N}^{tot} \tag{1}$$

agrees with experiment implies that the role played by the sea of quark-antiquark pairs of parton and gluon quarks in the wave functions of the hadrons apparently reduces to one of forming the wave functions of the constituent quarks. A theoretical basis for the constituent-quark model might be the proof that there are two confinement radii in quantum chromodynamics, a short one, $\sim 1/m_N$, over which the wave function of a constituent quark is formed, and a long one, $\sim 1/\mu_\pi$, over which the quarks are confined.[1] Since the constituent-quark model currently has no basis in quantum chromodynamics, we would like to search for new pieces of evidence for or against this model of hadrons.

Let us examine pd scattering, using the method of multiple Glauber rescattering. Instead of treating the deuteron as a pn system, we will treat it as a bound state of six constituent quarks. The correction to the result of the ordinary Glauber approximation for σ_{pd}^{tot} can then be written

$$\Delta\sigma_{pd} = 2\int [\rho(\mathbf{r}_1,\ldots,\mathbf{r}_6) - \rho_G(\mathbf{r}_1,\ldots,\mathbf{r}_6)]\,\delta^{(3)}\Big(\tfrac{1}{6}\sum_{i=1}^{6}\mathbf{r}_i\Big) \times\Big\{1-\prod_{j=1}^{6}[1-\Gamma_{pq}(\mathbf{b}-\mathbf{r}_{j\perp})]\Big\}\, d^2\mathbf{b}\prod_{k=1}^{6} d^3\mathbf{r}_k\,. \tag{2}$$

Here $\Gamma_{pq}(\mathbf{b})$ is the profile function for pq scattering, $\rho(\mathbf{r}_1,\ldots,\mathbf{r}_6)$ is the quark distribution in the deuteron, and the function $\rho_G(\mathbf{r}_1,\ldots,\mathbf{r}_6)$ is

$$\rho_G(\mathbf{r}_1,\ldots,\mathbf{r}_6) = {}^1\!/_{10}\,\Big(1+\sum_{\alpha=1}^{3}\sum_{\beta=4}^{6}\hat{P}_{\alpha\beta}\Big)\rho_N(\mathbf{r}_1,\mathbf{r}_2,\mathbf{r}_3)\,\rho_N(\mathbf{r}_4,\mathbf{r}_5,\mathbf{r}_6)\,\rho_d(\mathbf{R}), \tag{3}$$

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where

$$\mathbf{R} = \tfrac{1}{3} (\mathbf{r}_1+\mathbf{r}_2+\mathbf{r}_3-\mathbf{r}_4-\mathbf{r}_5-\mathbf{r}_6),$$

$\hat{P}_{\alpha\beta}$ is the quark permutation operator, $\rho_N(\mathbf{r}_1, \mathbf{r}_2, \mathbf{r}_3)$ is the quark distribution in the nucleon, and $\rho_d(\mathbf{R})$ is the nucleon distribution in a deuteron treated as a *pn* system. By virtue of confinement, $\rho(\mathbf{r}_1,..., \mathbf{r}_6)$ may differ from $\rho_G(\mathbf{r}_1,..., \mathbf{r}_6)$ only for configurations in which all six of the quarks lie in a central part of the deuteron with a radius on the order of the size of the nucleon. These configurations, therefore, are the ones which are important in the integration in (2). We can quite accurately restrict (2) to the terms of second order in Γ_{pq}; then $\Delta\sigma_{pd} \approx \Delta\sigma_{pd}^{(1)} + \Delta\sigma_{pd}^{(2)}$. Under the assumption that σ_{pq}^{tot} is independent of whether the quark is in a nucleon or in the central region of a deuteron we would obviously have $\Delta\sigma_{pd}^{(1)} = 0$.

We have calculated $\Delta\sigma_{pd}^{(2)}$, parametrizing the quark wave function of the deuteron in the form used in the resonating-group method[2]:

$$\psi(Q_1, \ldots, Q_6) = \frac{1}{A} \left(1 - \sum_{\alpha=1}^{3} \sum_{\beta=4}^{6} \hat{P}_{\alpha\beta}\right) \psi_N(Q_1, Q_2, Q_3)\psi_N(Q_4, Q_5, Q_6) F(\mathbf{R}). \quad (4)$$

Here $Q_1,..., Q_6$ are the color, spin-isospin, and spatial coordinates ot the quarks; ψ_N is the quark wave function of the nucleon; $F(\mathbf{R})$ is a function describing the relative motion of nucleon clusters; and A is a normalization factor.

It has been shown elsewhere that a wave function of the type in (4) can be used to find a reasonable description of the short-range part of *NN* potentials[3] and for the $\Delta\Delta$ component in the deuteron.[4] The nucleon wave function of the deuteron was taken in Gaussian form with the Jastrow factor $(1 - e^{-R^2/b^2})$ with $b = 0.6$ F. As the quark wave function of the nucleon we used the wave function of the oscillator model, with an *rms* nucleon radius of 0.8 F. Calculations which will be published separately yield $\Delta\sigma_{pd}^{(2)} \cong 0.06$ mb. What is important for our purposes here is the fact that the correction to σ_{pd}^{tot} due to the incorrect description of the central part of the deuteron in the ordinary Glauber approximation (in particular, with the Pauli principle ignored) turns out to be small. If, however, σ_{pd}^{tot} for a quark in the central part of the deuteron differs by an amount $\Delta\sigma_{pq}^{\text{tot}}$ from σ_{pq}^{tot} for the quark in a nucleon, we no longer have $\Delta\sigma_{pd}^{(1)} = 0$. If $\Delta\sigma_{pq}^{\text{tot}}/ \sigma_{pq}^{\text{tot}} \ll 1$, then $\Delta\sigma_{pd}^{(2)}$ changes only insignificantly. From (2) we then find the following estimate for $\Delta\sigma_{pd}^{(1)}$:

$$\Delta\sigma_{pd}^{(1)} \sim 6\, \Delta\sigma_{pq}^{tot} P_{6q}, \quad (5)$$

where P_{6q} is the probability that all the quark are in the central part of the deuteron. Experimental data on the electromagnetic form factor of the deuteron at large q^2 yield[5] $P_{6q} \sim 0.05$. A corresponding estimate of P_{6q} can be found by examining the overlap of the quark wave functions of the nucleons for a nucleon wave function with a soft-core Reid potential.[6] Since the results calculated for σ_{pd}^{tot} in the Glauber approximation with inelastic rescatterings do agree with $(\sigma_{pd}^{\text{tot}})_{\text{exp}}$ at all the energies which have been studied, within no more than ~ 0.3 mb (Ref. 7), we can use the estimate $|\Delta\sigma_{pd}^{(1)}| \lesssim 0.3$ mb (we are ignoring the small contribution of $\Delta\sigma_{pd}^{(2)}$). From (5) we then find

$$|\Delta\sigma_{pd}^{tot}| \lesssim 1 \text{ mb} \quad (6)$$

or

$$|\Delta\sigma^{tot}_{pq}|/\sigma^{tot}_{pq} \lesssim 0.08 .$$

The fact that the ratio $|\Delta\sigma^{\text{tot}}_{pq}|/ \sigma^{\text{tot}}_{pq}$ is small implies that the sea of the parton and gluon quarks is apparently concentrated in the wave functions of constituent quarks again in the case of six interacting quarks. Consequently, again in the case of multiple-quark systems the constituent quarks are apparently well-defined entities, as assumed in the constituent-quark model.

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