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Deuteron photodisintegration and quark models

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We have examined the behavior of the forward-to-backward ratio R of the cross section for the $^2H(\gamma,p)n$ reaction. The data show a weak dependence of R on the photon energy and group around a value of 1.5 which agrees with the prediction of a simple quark model. An energy dependence of R is predicted in the quark-gluon string model and is shown to be connected to the ratio of d/u quark distributions in the proton.

One of the central issues in nuclear physics is the question of whether the quark structure of the nucleus is detectable. Therefore, the experimental identification of quark effects in nuclei would constitute important progress toward an understanding of the nucleus in terms of nucleons and mesons and in terms of quarks to help unify the meson-nucleon theory with quantum chromodynamics.

Recently, two experiments performed at the nuclear physics injector at Stanford (NPAS) have provided results whose interpretations appear contradictory. In fact, in the first experiment,[1] designated to isolate the magnetic form factor in elastic-deuteron scattering at the highest possible momentum transfer, the diffraction minimum, observed at a momentum transfer of approximately 1.4 GeV/c, is readily explained in terms of nucleons in the deuteron, while it is not predicted by simple quark models of the deuteron.[2,3] In the second experiment[4] the differential cross section was measured for the photodisintegration of a deuteron exclusively into a proton and neutron at $\vartheta_{\text{c.m.}} \approx 90°$ for photon energies between 0.8 and 1.6 GeV. The results found disagree with existing meson-exchange calculations and suggest that, at the highest energies of the measurement, the cross section at large momentum transfer behaves according to the simple constituent-counting rule.

From the above-mentioned comments, it is clear that the study of deuteron with electromagnetic probes of high (and, maybe, intermediate) energies has very interesting features. An interesting particular case arises when, in the study of the differential cross section for the deuteron photodisintegration, protons emerging in the forward and backward directions are detected. This is because at these angles the reaction is sensitive to the spin-dependent transition operators, the deuteron D state, noncentral forces in the nucleon excited states, and possible non-nucleonic phenomena. Unfortunately, these measurements at extreme angles are difficult and, consequently, only a few data are available. Specifically, those at 0° by Hughes *et al.*[5] over the photon energy range 20–120 MeV and by Zieger *et al.*[6] at 10.74 MeV, and those at 180° by Althoff *et al.*[7] over the photon energy range 180–730 MeV. Recently, a measurement of the differential cross section has been performed of the deuteron photodisintegration between 100 and 240 MeV detecting, for the first time simultaneously, protons emitted at 0° and 180°.[8] Moreover, a simple phenomenological form has been determined which gives a reasonable fit to all existing cross-section data available in the literature. Such a fit was first obtained by Thorlacius and Fearing,[9] for photon energies between 10 and 625 MeV, and later, with a more accurate procedure, by Rossi *et al.*[10] from 20 up to 440 MeV. From the results of these works we have easily deduced the *experimental* forward-to-backward ratio of the cross section:

$$R=\frac{(d\sigma/d\Omega)_{0°}}{(d\sigma/d\Omega)_{180°}}\ , \tag{1}$$

shown in Fig. 1. Also shown in the figure are the values at low photon energies deduced by using the experimental fit of De Pascale *et al.*[11] and from the measurement of the cross section of the inverse process[12] (neutron radiative capture on proton). As seen, the ratio R has a rather weak dependence on the photon energy along the whole measured and explored energy interval.

In this Brief Report we examine this behavior and compare it to the prediction of a quark model. For the sake of simplicity, we consider the inverse reaction

$$p+n\to\gamma+{}^2\text{H}\ , \tag{2}$$

in the center-of-mass system (c.m.). Then, the case of deuteron photodisintegration with detection of protons at very forward and backward angles corresponds, in the inverse process, to the emission of photons from nucleon constituent quarks inside a small angle relative to the proton or neutron, respectively.

The simplest description of this process occurs when the wavelength of the photon is much smaller than the radius of the nucleon, $\lambda \ll R_N$ or $\omega R_N \gg 1$. In this case the emission of photons is expected to be incoherent, and the angular distribution of photons emitted by each constituent quark will have the form

$$\frac{\sin^2\vartheta}{\left[1-\frac{v}{c}\cos\vartheta\right]^2}\ , \tag{3}$$

where ϑ is the angle between the momenta of the photon and the quark. If the energy is high enough, $v/c\to 1$ and

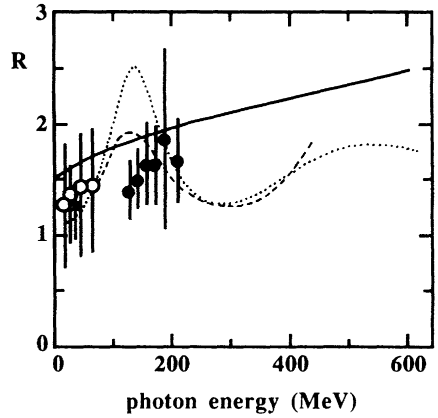

FIG. 1. Forward-to-backward ratio of the differential cross-section values for the deuteron photodisintegration process. Data points: ●, Ref. 8; ○, Ref. 11; *, Ref. 12; dotted and dashed lines are deduced from the two phenomenological fits of Refs. 9 and 10, respectively. The solid line is the prediction of the quark-gluon string model discussed in the text. (The dotted curve is too high at low energies with respect to the experimental values, because that fit was determined before the publication of the data in Ref. 9.)

the photon will be predominantly emitted under small angles. Consequently, the angular distribution should have two peaks well separated, corresponding to the emission from proton (forward peak) or neutron (backward peak), with a depletion of the differential cross section around 90°.

In the noncoherent limit one should have

$$\left[\frac{d\sigma}{d\Omega}\right]_{0°,180°}=\sum_i z_i^2 C_{0°,180°}(E)\ , \tag{4}$$

where z_i is the charge of the ith quark ($i=1$, 2, and 3) in the proton (0°) and neutron (180°), and $C_{0°,180°}(E)$ is a constant depending on energy and angle. Because $C_{0°}(E)\approx C_{180°}(E)$, the forward-to-backward ratio of the cross section will be given by the following expression, which is determined by the quark charges (the subscripts u and d represent up and down quarks):

$$R\approx\frac{2z_u^2+z_d^2}{2z_d^2+z_u^2}=\frac{9}{6}=1.5\ , \tag{5}$$

which is in pretty good agreement with the experimental determination (see Fig. 1).

As the energy decreases, the angular distribution becomes less anisotropic: when $\omega\approx\langle p_\perp\rangle$, $\langle p_\perp\rangle$ being the average transverse momentum of a quark in the nucleon, the forward and backward peaks should disappear. This is the case for the data available which correspond to $\omega\approx 1/R_N\approx 200$ MeV and do not yet show the depletion around 90°, probably because the contributions of proton and neutron emission peaks overlap.

One can push further on this exercise and try to apply similar considerations for deriving evidence for the existence of a diquark $\mathcal{D}$ admixture in the nucleon wave function, as suggested by several authors.[13–16] In this case the nucleon wave function can be represented in the form

$$|N\rangle=\sqrt{1-P_{\mathcal{D}}}\,|3q\rangle+\sqrt{P_{\mathcal{D}}}\,|\mathcal{D}+q\rangle\ , \tag{6}$$

where q, $\mathcal{D}$, and $P_{\mathcal{D}}$ are, respectively, the quark and diquark wave functions and the admixture percentage of the diquark. Therefore, in this case, considering only the ud diquark, the ratio R will have the form

$$R=\frac{(1-P_{\mathcal{D}})(2z_u^2+z_d^2)+P_{\mathcal{D}}(z_{\mathcal{D}}^2+z_u^2)}{(1-P_{\mathcal{D}})(2z_d^2+z_u^2)+P_{\mathcal{D}}(z_{\mathcal{D}}^2+z_d^2)}=\frac{9-4P_{\mathcal{D}}}{6-4P_{\mathcal{D}}}\ , \tag{7}$$

which, for $P_{\mathcal{D}}\to 1$, is equal to $R=\frac{5}{2}$. The experimental value of R shown in Fig. 1 clearly suggests a diquark percentage $P_{\mathcal{D}}\approx 0$; however, the energy range explored is too low for deriving definite conclusions.

Let us notice that there is a weak point in the previous discussion: specifically, the reaction (2) being exclusive, it is not easy to prove the incoherence condition of Eq. (4). To provide reliable arguments in favor of it let us consider the reaction (2) at rather high energy $s\gg m^2$, where we can use the quark-gluon model developed in Refs. 17 and 18. This model merges nicely with Regge phenomenology and was successfully applied to the description of binary hadronic reactions $ab\to cd$ at $p_{\rm lab}\gg 1$ GeV/c.

In the quark-gluon model, the reaction (2) at high energies and for forward and backward kinematics is described by the diagrams of Fig. 2. The space-time picture of the process described by these diagrams corresponds to the formation of a stringlike configuration in the inter-

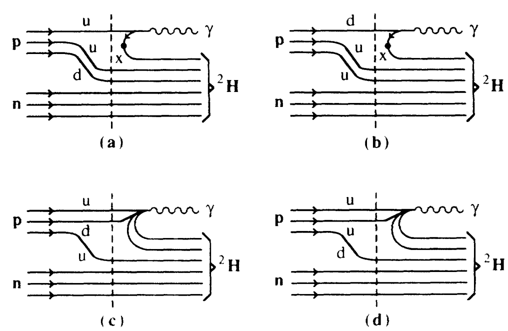

FIG. 2. The planar quark graphs which describe the reaction $p+n\to\gamma+{}^2\mathrm{H}$ in the quark gluon model. In the space-time picture these graphs correspond to the creation of a string (or gluon flux tube) in the intermediate state (denoted by the vertical dashed line) with at one end a fast quark u and d for diagrams (a) and (b) and a fast diquark ud and uu for digrams (c) and (d). At the point x these strings break up via the creation of new q-$\bar{q}$ or qq-$\bar{q}\,\bar{q}$ pairs from vacuum. Finally, the pieces of the strings lead to the production of γ and formation of deuteron ^{2}H.

mediate state in the s channel, and can be put into correspondence with baryonic Regge-exchange diagrams of the kind shown in Fig. 3. For a given exclusive channel, these diagrams add coherently. Then, postponing the discussion of their phases, the ratio R for $p\to\gamma$ ($\vartheta=0°$) and $n\to\gamma$ ($\vartheta=180°$) can be written in the form

$$R=\left|\frac{\frac{2}{3}\varphi^p_{ud}\varphi^\gamma_u-\frac{1}{3}\varphi^p_{uu}\varphi^\gamma_d+\alpha(\frac{1}{3}\varphi^p_u\varphi^\gamma_{ud}+\frac{4}{3}\varphi^p_d\varphi^\gamma_{uu})}{\frac{2}{3}\varphi^n_{dd}\varphi^\gamma_u-\frac{1}{3}\varphi^n_{ud}\varphi^\gamma_d+\alpha(\frac{1}{3}\varphi^n_d\varphi^\gamma_{ud}-\frac{2}{3}\varphi^n_u\varphi^\gamma_{dd})}\right|^2, \tag{8}$$

where $\varphi^p_{ud}(x)$ and $\varphi^p_{uu}(x)$ [$\varphi^n_{dd}(x)$ and $\varphi^n_{ud}(x)$] are the wave functions which determine the probabilities of finding a corresponding diquark in a proton [neutron] with a small ($\approx m^2/s$) fraction x of the momentum (the third quark has the fraction $1-x$ of the momentum; more details on the connection between x and the momentum in the laboratory p_{lab} will be given below). [From now on the word *diquark* will simply mean the correlated pair of quarks and not necessarily a dynamically stable object as it was assumed in Eqs. (6) and (7).] The relevant normalizations of these wave functions are

$$\int_0^1|\varphi^p_{ud}|^2dx=\int_0^1|\varphi^n_{ud}|^2dx=2\ ,$$
$$\int_0^1|\varphi^p_{uu}|^2dx=\int_0^1|\varphi^n_{dd}|^2dx=1\ .$$

The functions $\varphi^N_i(x)$, $\varphi^\gamma_i(x)$, and $\varphi^\gamma_{ij}(x)$ (where the subscripts i and j represent u or d quarks, and the superscript N represents p or n) have a straightforward meaning. The coefficient α is the relative weight of the diagrams (c) and (d) with respect to diagrams (a) and (b) of Fig. 2. We have included the contributions of diagrams (c) and (d), which correspond to a direct transition of a four-quark state into a photon, for the sake of generality. But it is not yet clear whether such a transition really exists: for example, this contribution is absent in the additive quark model. Then we argue that α must be $\ll 1$. In fact, in the vector dominance model a transition of a q-$\bar{q}$ pair into a photon is dominated by low-lying ρ, ω mesons, while a transition qq-$\bar{q}\,\bar{q}\to\gamma$ involves vector mesons consisting of four quarks and, therefore, having masses larger than the usual q-$\bar{q}$ vector mesons. In the theoretical models the lightest qq-$\bar{q}\,\bar{q}$ vector mesons usually have masses $\approx 1.5-2$ GeV. Thus, one can expect that at least $\alpha\sim m_\rho^2/(m_{qq\text{-}\bar{q}\bar{q}})^2\approx\frac{1}{5}$ or smaller because the γ-V transition coupling constants decrease as the mass of the vector mesons V increases. Then, in the following we will neglect the contribution of diagrams (c) and (d). At large s ($x\to 0$), $\varphi^\gamma_i(x)\approx\text{const}\times 1/\sqrt{x}$ and the value of R can be written in the form

$$R=\left|\frac{\frac{2}{3}-\frac{1}{3}\gamma(x)}{-\frac{1}{3}+\frac{2}{3}\gamma(x)}\right|^2, \tag{9}$$

where we have put $\gamma(x)=\varphi^p_{uu}(x)/\varphi^p_{ud}(x)$.

We consider now in more detail the question of the phase and x dependence of $\gamma(x)$. The phase of this function is determined by the relative phases of the diagrams (a) and (b) with ud and uu quark exchange correspondingly. The contribution of the ud diquark is connected, in Regge language, with an N_α trajectory with intercept $\alpha_N(0)\approx -0.5$, while uu at $x\to 0$ is usually connected with the Δ trajectory. It is known,[19] however, that the Δ contribution for a proton wave function at $x\approx 0$ is small (in the $p+n\to\gamma+{}^2\text{H}$ reaction the Δ exchange is forbidden by isospin conservation), and the structure function of the slow uu (fast d quark with $x\to 1$) is determined by a $\alpha_{N\pi}$ cut with $\alpha_{N\pi}=\alpha_N(0)+\alpha_\pi(0)-1\approx\alpha_N(0)-1$. This leads to a decrease of the ratio of the $f_d(x)$ to the $f_u(x)$ quark distribution functions as $x\to 1$. The phases of the diagrams (a) and (b) are determined by Regge signature factors:

$$\eta=\frac{1+\sigma\exp[-i\pi(\alpha_k-\frac{1}{2})]}{\sin\pi(\alpha_k-\frac{1}{2})}$$
$$=\exp\left[-i\frac{\pi}{2}(\alpha_k-\tfrac{1}{2})\right]\times\begin{cases}\dfrac{1}{\sin\frac{\pi}{2}(\alpha_k-\frac{1}{2})}, & \sigma=+\\[2ex] \dfrac{i}{\cos\frac{\pi}{2}(\alpha_k-\frac{1}{2})}, & \sigma=-\ .\end{cases} \tag{10}$$

In our case $\sigma=+$ for both the α_N exchange and the $\alpha_{N\pi}$-cut exchange diagrams [diagrams (a) and (b), respectively], but the values of α_k differ by 1. Therefore, these diagrams have a phase difference equal to $e^{-i\pi/2}$ and $\gamma(x)$ is purely imaginary. Thus the diagrams (a) and (b) do not interfere and the function $R(s)$ can be written as follows:

$$R(s)\approx\frac{4+\gamma^2(x)}{1+4\gamma^2(x)}\ , \tag{11}$$

and $\gamma^2(x)=f_d(1-x)/f_u(1-x)$, where f_d and f_u are the d and u quark distribution functions in the proton. Equation (11) is a generalization of Eq. (5) for the realistic case of the ratio f_d/f_u depending on x; therefore it is equal to Eq. (5) for $f_d/f_u=\frac{1}{2}$. This ratio can be taken from deep-inelastic scattering experiments. Let us notice that while both the functions f_d and f_u depend on the squared momentum transfer q^2, their ratio is practically q^2 independent. The connection between x in Eq. (11) and s can be established as follows. At large energies one

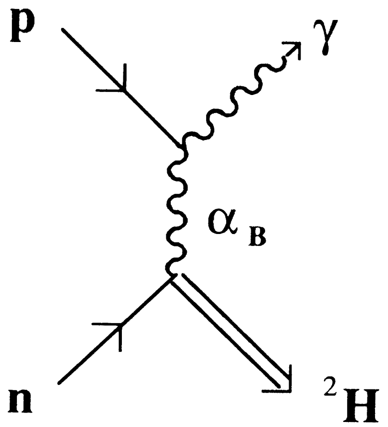

FIG. 3. Baryon Regge-pole exchange diagram for the reaction $p+n\to\gamma+{}^2\text{H}$.

can write a rapidity difference between the diquark, which enters into ^{2}H (slow in the laboratory frame of the reaction $\gamma + {}^2\text{H} \to p + n$) and its mean value in the fast moving initial proton:

$$\Delta y = \ln \frac{(E^L + p_{\parallel}^L)_{qq}}{m_{qq}} \approx \ln \frac{(E^L + p_{\parallel}^L)_p}{m_p} ,$$

where L represents the laboratory system. On the other hand, $\Delta y \approx \ln(\bar{x}_{qq}/x_{qq})$, with $\bar{x}_{qq} \approx \frac{2}{3}$. Thus, the value of x can be determined from the relation $\bar{x}_{qq}/x = (E^L + p_{\parallel}^L)/m_p$, which satisfies a low-energy condition: for $p_{\parallel}^L \to 0$, $x \to x_{qq}$.

The prediction of the quark-gluon string model for the energy dependence of the ratio R is shown in Fig. 1 as a solid line: for small $p_{\parallel}^L$, $x \approx 0.85$ and $\gamma^2 \approx 0.5$, and therefore $R \approx 1.5$, a value in close agreement with experimental data. As energy increases and γ^2 decreases, R tends to 4. We used the parametrization of structure functions f_d and f_u proposed in Ref. 20, which gives $\gamma^2(x) = 0.6x$. The coefficient 0.6 is fixed by the normalization conditions (9) for quark distributions and their functional forms, which are in agreement with the data on deep-inelastic processes.

In conclusion, we have examined the behavior of the forward-to-backward ratio R of the differential cross section for the $^2\text{H}(\gamma,p)n$ reaction. The data, available only at low energies, show a weak dependence of R on the photon energy and are close to the value 1.5 which is easily predicted by a simple quark model. The quark-gluon string model also agrees with the data and predicts an increase of R with energy. In order to check the theoretical predictions it is, therefore, necessary to extend to higher energies the measurements of the differential cross section at extreme angles.

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