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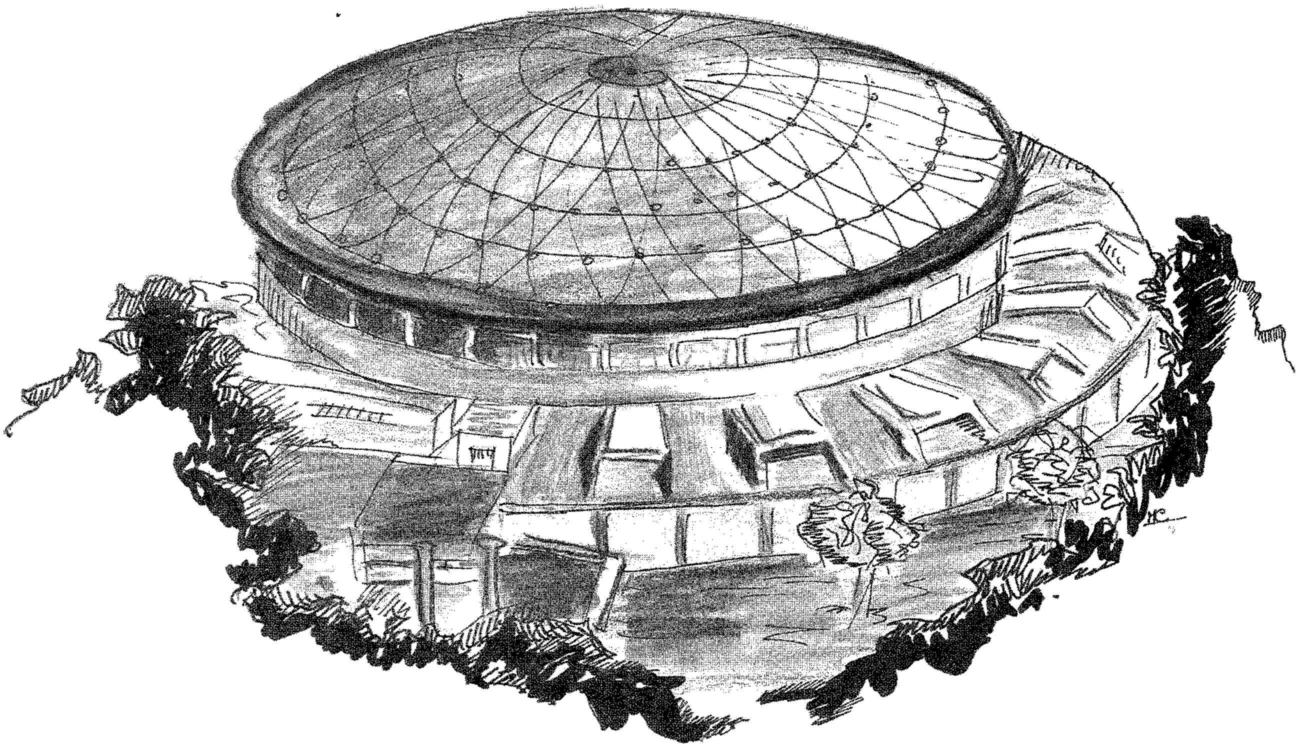

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DEUTERON PHOTODISINTEGRATION AND QUARK MODELS

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ABSTRACT

We have examined the behaviour 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 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.

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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 interpretation appear contradictory. In fact, in the first experiment,[1] designed 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

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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] it was measured the differential cross section for the photodisintegration of a deuteron exclusively into a proton and neutron at $\vartheta_{c.m.} \approx 90°$ 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 what said above, it is clear that the study of deuteron with electromagnetic probes of high (and, may be, 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 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, it has been performed a measurement of the differential cross section of the deuteron photodisintegration between 100 and 240 MeV detecting, for the first time simultaneously, protons emitted at 0° and 180°.[8] Moreover, it has been determined a simple phenomenological form which give 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 P. 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:

$$R = \frac{\left[d\sigma/d\Omega\right]_{0°}}{\left[d\sigma/d\Omega\right]_{180°}}, \qquad (1)$$

shown in Fig. 1. In the figure are also shown 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 it is 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 behaviour and compare it to the prediction of a quark model. For a sake of simplicity, we consider the inverse reaction:

$$p + n \rightarrow \gamma + {}^{2}H, \qquad (2)$$

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.

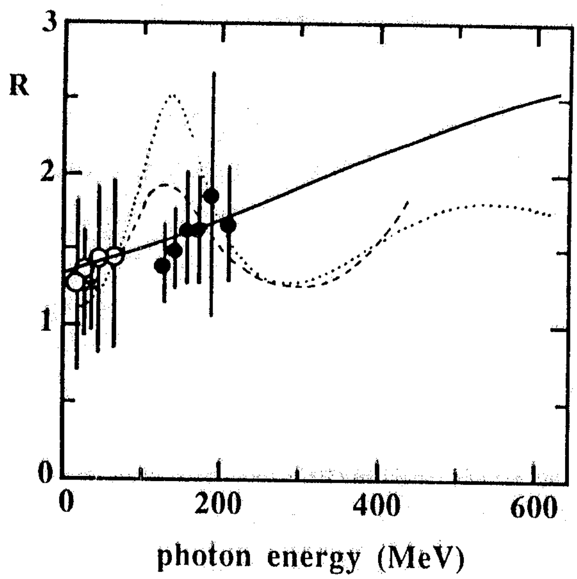

Fig. 1 Forward-to-backward ratio of the differential cross section values for the deuteron photodisintegration process. Data points: o Ref.8;o Ref 11; *, Ref. 12; dotted and dashed lines are deduced from the two phenomenological fits of Refs. 9 and 10, respectively. The solid line curve is the prediction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

The simplest description of this process occurs when the wave length 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:

$$\frac{\sin^2\vartheta}{\left(1-\frac{v}{c}\cos\vartheta\right)^2}, \qquad (3)$$

where ϑ is the angle between the momenta of the photon and the quark. If the energy is high enough, $v/c \rightarrow 1$ and the photon will be predominantly emitted under small angles. Consequently, the angular distribution should have two peaks corresponding to the emission from proton (forward peak) or neutron (backward peak). As the energy decreases, the angular distribution becomes less anisotropic: when $\omega \approx \langle p_\perp \rangle$, being $\langle p_\perp \rangle$ the average transverse momentum of quark in the nucleon, the forward and backward peaks should disappear. Then, in the non-coherent limit one should have:

$$\left(\frac{d\sigma}{d\Omega}\right)_{0°,180°} \approx \sum_i z_i^2 , \qquad (4)$$

where z_i is the charge of the i-th quark (i=1,2 and 3), respectively in the proton (0°) and neutron (180°). Therefore, the forward-to-backward ratio of the cross section would be (the subscripts u and d stay for up and down quarks):

$$R=\frac{2z_u^2+z_d^2}{2z_d^2+z_u^2}=\frac{9}{6}=1.5 , \qquad (5)$$

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

As said above, for $\lambda \ll R_N$, the peaks corresponding to the emissions of the photon by proton and neutron should be well separated in the angular distribution, and one should observe a depletion of the differential cross section at 90°. The data available correspond to $\omega \approx 1/R_N \approx 200$ MeV, and does not yet show this depletion, 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, 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:

$$|N\rangle = \sqrt{1-P_D}|3q\rangle + \sqrt{P_D}|D+q\rangle , \qquad (6)$$

where q , D and P_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:

$$R=\frac{(1-P_D)\left(2z_u^2+z_d^2\right)+P_D\left(z_D^2+z_u^2\right)}{(1-P_D)\left(2z_d^2+z_u^2\right)+P_D\left(z_D^2+z_d^2\right)}=\frac{9-4P_D}{6-4P_D} , \qquad (7)$$

which, for $P_D \rightarrow 1$, will be equal to R=5/2. Equation 7 should be valid in the region $R_D \ll \lambda \ll R_N$, where R_D is the diquark radius, while in the region $\lambda \ll R_D$ all the quarks should emit photons independently and Eq. 5 should be valid. The experimental value of R shown in Fig. 1 clearly suggests a diquark percentage $P_D \approx 0$; 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, being the reaction (2) exclusive, it is not easy to prove the incoherence condition of Eq. 4. To provide reliable arguments in favour 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 $p_{lab} >> 1 GeV/c$.

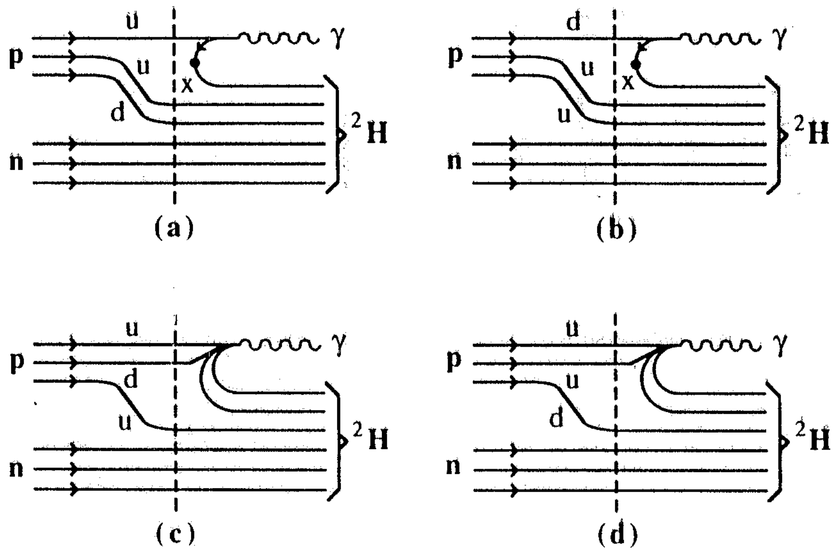

Fig. 2 The planar quark graphs which describe the reaction $p+n \to \gamma + {}^2H$ in the quark gluon model. In space time picture these graphs correspond to the creation of a string (or gluon flux tube) in the intermediate state (denoted by the vertical dashed line) with at one end a fast quark u and d for diagrams (a) and (b) and a fast diquark ud and uu for diagrams (c) and (d). At the point x these strings break up via the creation of a 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 ${}^2H$.

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 string like configuration in the intermediate state in 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:

$$R=\left[\frac{\frac{2}{3}\varphi^{p}_{ud}\varphi^{\gamma}_{u}-\frac{1}{3}\varphi^{p}_{uu}\varphi^{\gamma}_{d}+\alpha\left(\frac{1}{3}\varphi^{p}_{u}\varphi^{\gamma}_{ud}+\frac{4}{3}\varphi^{p}_{d}\varphi^{\gamma}_{uu}\right)}{\frac{2}{3}\varphi^{n}_{dd}\varphi^{\gamma}_{u}-\frac{1}{3}\varphi^{n}_{ud}\varphi^{\gamma}_{d}+\alpha\left(\frac{1}{3}\varphi^{n}_{d}\varphi^{\gamma}_{ud}-\frac{2}{3}\varphi^{n}_{u}\varphi^{\gamma}_{dd}\right)}\right]^2, \qquad (8)$$

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).The relevant normalizations of these wave functions are:

$$\int_0^1 \left|\varphi^p_{ud}\right|^2 dx = \int_0^1 \left|\varphi^n_{ud}\right|^2 dx = 2; \quad \int_0^1 \left|\varphi^p_{uu}\right|^2 dx = \int_0^1 \left|\varphi^n_{dd}\right|^2 dx = 1.$$

The functions $\varphi^N_i(x)$, $\varphi^\gamma_i(x)$, and $\varphi^\gamma_{ij}(x)$ (where the subscripts i and j stay both for u or d quarks, and the superscript N stays for p or n) have a straightforward meaning.

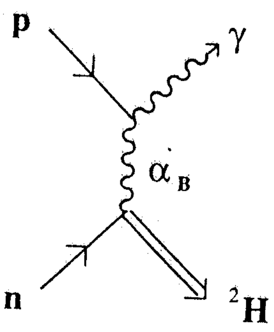

Fig. 3 Baryon Regge-pole exchange diagram for the reaction $p+n\to\gamma+{}^2H$.

The coefficient α is the relative weight of the diagrams (c) and (d) with respect to diagrams (a) and (b) of Fig. 2. At large s ($x\to 0$), $\varphi^N_j(x)\sim\varphi^\gamma_j(x)\sim 1/\sqrt{x}$ and $\varphi^N_{ij}(x)\sim\varphi^\gamma_{ij}(x)$, so that Eq. (8) can be written:

$$R=\left[\frac{\frac{2}{3}-\frac{1}{3}\frac{\varphi^p_{uu}}{\varphi^p_{ud}}+\alpha_1\left(\frac{2}{3}+\frac{4}{3}\frac{\varphi^p_{uu}}{\varphi^p_{ud}}\right)}{-\frac{1}{3}+\frac{2}{3}\frac{\varphi^p_{uu}}{\varphi^p_{ud}}+\alpha_1\left(\frac{2}{3}-\frac{2}{3}\frac{\varphi^p_{uu}}{\varphi^p_{ud}}\right)}\right]^2, \qquad (9)$$

where $\alpha_1=(\alpha\varphi^p_u\varphi^\gamma_{ud})/(2\varphi^p_{ud}\varphi^\gamma_u)$. The value of α_1 should be small, because the diagrams (a) and (b) correspond to the transition of a q-$\bar{q}$ pair (ρ,ω mesons in the vector dominance model) into a photon, while the diagrams (c) and (d) include a transition qq-$\bar{q}\bar{q}\to\gamma$ which involve vector mesons consisting of four quarks and, therefore, having masses larger than the usual q-$\bar{q}$ vector

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* From now on the world *diquark* will simply mean the correlated pair of quarks and not necessary a dynamically stable object as it was assumed in Eqs. (6) and (7))

mesons. In the theoretical models the lightest $qq\text{-}\bar{q}\bar{q}$ vector mesons usually have masses $\approx$1.5-2 GeV. Thus, one can expect that $\alpha_1 \approx m^2_p/(m_{qq\text{-}\bar{q}\bar{q}})^2 \approx 1/5$, and consequently the corresponding terms in Eq. (9) can be neglected, obtaining:

$$R = \left[\frac{\frac{2}{3} - \frac{1}{3}\gamma(x)}{-\frac{1}{3} + \frac{2}{3}\gamma(x)} \right]^2 , \tag{10}$$

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

We consider now in more details 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 ud-diquark is connected, in Regge language, with N_α-trajectory with intercept $\alpha_N(0) \approx -0.5$, while uu at $x \to 0$ is usually connected with Δ-trajectory. It is known,[19] however, that the Δ-contribution for a proton wave-function at $x \approx 0$ is small (in the $p+n \to \gamma + {}^2H$ 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:

$$?\eta = \frac{1 + \sigma\, exp\left[-i\pi\left(\alpha_k - \frac{1}{2}\right)\right]}{\sin \pi\left(\alpha_k - \frac{1}{2}\right)} = exp\left[-i\frac{\pi}{2}\left(\alpha_k - \frac{1}{2}\right)\right] \begin{cases} \dfrac{1}{\sin \frac{\pi}{2}\left(\alpha_k - \frac{1}{2}\right)} & \sigma = + \\[2ex] \dfrac{i}{\cos \frac{\pi}{2}\left(\alpha_k - \frac{1}{2}\right)} & \sigma = - \end{cases} \tag{11}$$

In our case σ=+ 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 the 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:

$$R(s) \approx \frac{\frac{4}{9} + \frac{1}{9}\gamma^2(x)}{\frac{1}{9} + \frac{4}{9}\gamma^2(x)} , \tag{12}$$

and $\gamma^2(x) = f_d(1\text{-}x)/f_u(1\text{-}x)$, where f_d and f_u are the d and u quark distribution functions in the proton. 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 the Eq. (12) and s can be established as follows. At large energies one can write a rapidity difference between the diquark, which enters into ^{2}H (slow in the laboratory frame) and its mean value in the fast moving initial proton:

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

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

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 $p^L_{||}$, $x \approx 0.6\text{-}0.7$ and $\gamma^2 \approx 0.5$, and therefore the ratio $R \approx 1.5$, that is a value in close agreement with experimental data. As energy increases and γ^2 decreases, R tends to 4 (for numerical calculations we used the parametrization $\gamma^2(x)=0.6x$, as proposed in Ref.20).

In conclusion we have examined the behaviour of the forward-to-backward ratio, R, of the differential cross section for the ^{2}H(γ,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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