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Polarization observables in the process $d+p\rightarrow d+X$ and electromagnetic form factors of $N\rightarrow N^*$ transitions

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We analyze the properties of the inclusive $d+p$ reactions, with particular interest in the domain of nucleonic resonances excitation. The calculated cross section and polarization observables show that it is possible to disentangle the different reaction mechanisms (ω,σ,η exchange) and bring new information about the electromagnetic form factors of the deuteron as well as of the nucleonic resonances excitation. Existing data on the tensor analyzing power are in agreement with the predictions based on the ω-exchange model. [S0556-2813(96)01812-2]

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I. INTRODUCTION

The (elastic or inelastic) electromagnetic form factors of the nucleon contain important information about the microscopic structure of N and N^*. As they are the most simple dynamical characteristics of the nucleon (or N^*), they are directly related with the wave functions of N and N^*. These form factors should help to understand the nature of the transition regime from the *soft* physics of the confinement region to the *hard* physics of perturbative QCD. In general, the most suitable way to study the k^2 dependence of inelastic form factors for $\gamma^*+N\rightarrow N^*$ transitions (where γ^* is a virtual photon) is to measure the different polarization observables for meson electroproduction processes like

$$e^-+N\rightarrow e^-+B+M \tag{1}$$

with $B+M=N+\pi,\ \ N+\eta,\ \ \Delta+\pi,\ \ N+V,\ \ \Lambda+K,\ldots$ where a multipole analysis of the data is necessary in order to disentangle the contributions of different N^*. Of course similar analysis are needed in some theoretical models, but previous work on multipole analysis of pion photoproduction data has shown that, in principle, this problem can be solved [1].

Due to the isospin nonconservation in a hadron electromagnetic interaction, for the full reconstruction of the isotopic structure of the transitions $\gamma^*+N\rightarrow N^*$ ($I=1/2$) it is necessary to study reactions (1) on proton and neutron targets. This induces additional problems specific to deuteron physics: the knowledge of the spin structure of the deuteron wave function, the meson-exchange currents, nonnucleonic degrees of freedom, final-state interaction, relativistic corrections, gauge invariance, etc. So, many simplifications, which are typical for processes (1) due to their electromagnetic nature may be lost. In this respect hadron-induced reactions, in particular with isotopic spin-zero projectiles like

$$d(\alpha)+p\rightarrow d(\alpha)+X \tag{2}$$

could be an effective method for the study of nucleon structure, complementary to eN reactions. The main problem associated with these reactions is the identification of the reaction mechanism. However we will show that polarization observables in processes $d+p\rightarrow d+X(d+N+\pi)$ may bring very interesting information.

The simplest polarization observable for the processes $d+p\rightarrow d+X$, the tensor analyzing power T_{20}, has been measured at Dubna and Saclay [2]. The existing data on the differential cross section [3] for this reaction show the presence of at least two mechanisms in the intermediate-energy region ($2\leqslant E_{\rm kin}\leqslant 10$ GeV). One is the coherent excitation of d with pion production [Fig. 1(a)], which results in a Deck peak [4], in the energy spectrum of the scattered deuterons. The isotopic spin of this peak is $I=1/2$, but the spin $\mathcal{J}$ and the space parity P of the Deck peak may not have a unique value. The Deck peak has to decrease when the energy of the colliding particles increases, while the role of a second mechanism, the N^* excitation, must become more important. This results in a *t-channel* exchange by mesonic states [Fig. 1(b)], with $I=0$ and with different $\mathcal{J}^P$: $\sigma,\eta,\omega,\ldots$. The ω exchange seems to be the best mechanism to describe the N^* excitation: a spin-one exchange allows one to obtain very specific polarization phenomena and an energy-independent cross section.

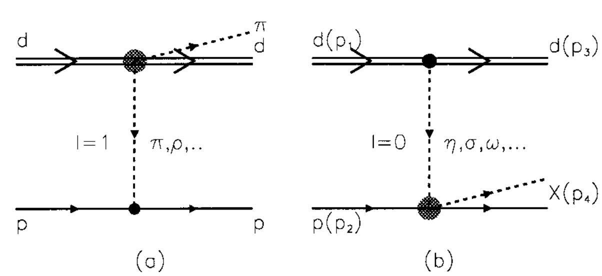

FIG. 1. Possible mechanisms for $d+p\rightarrow d+\pi+N$: (a) deuteron excitation; (b) proton excitation.

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In the framework of this mechanism, it is possible to predict all observables for the reaction $d+p\to d+X$ in terms of deuteron electromagnetic form factors and isoscalar form factors of $N\to N^*$ transitions.

Experimentally the study of the N^* structure by a hadronic probe, in comparison with the electromagnetic interaction has the following advantages: large values of cross sections; advanced technic of high-intensity $\vec{d}$, $\vec{p}$ beams, polarized targets and polarimeters; absence of a problem of radiative corrections; natural selection of isoscalar N^* excitation; different relative role of contributions of the main mechanisms (in comparison with pion electroproduction): as an example, in eN collisions the Roper resonance (RR) is hidden in the background of a strong $\Delta(1238)$ excitation and the extraction of the longitudinal form factor of the RR excitation is complicated due to the large contribution of π exchange.

In this paper we will derive the properties of the $d+p\to d+X$ reaction in the framework of ω (σ,η) exchange, with special attention to the polarization observables.

II. GENERAL STRUCTURE OF THE DIFFERENTIAL CROSS SECTION OF $d+p\to d+X$

The matrix element $\mathcal{M}^{(\omega)}$, corresponding to Fig. 1(b), can be written in the following form:

$$\mathcal{M}^{(\omega)}=-\frac{\mathcal{J}_\mu^{(d)}\mathcal{J}_\mu^{(s)}}{t-m_\omega^2},\quad t=(p_1-p_3)^2, \tag{3}$$

where the vector (and isoscalar) current $\mathcal{J}_\mu^{(d)}$ corresponds to the ωdd vertex and $\mathcal{J}_\mu^{(s)}$ is the isoscalar current describing the process $\omega+d\to X$. Therefore the cross section can be written as

$$d\sigma=\frac{\mathcal{W}_{\mu\nu}^{(d)}\mathcal{W}_{\mu\nu}^{(s)}}{256\pi^3 s\vec{p}^{\,2}}\frac{dt\,dw^2 d\phi}{(t-m_\omega^2)^2}, \tag{4}$$

where

$$\mathcal{W}_{\mu\nu}^{(d)}=\overline{\mathcal{J}_\mu^{(d)}\mathcal{J}_\nu^{(d)*}}$$

and

$$\mathcal{W}_{\mu\nu}^{(s)}=(2\pi)^4\sum_X\int\overline{\mathcal{J}_\mu^{(s)}\mathcal{J}_\nu^{(s)*}}\,\delta(p_1+p_2-p_3-p_4)dp_X$$

with $s=(p_1+p_2)^2$, $\vec{p}$ is the three-momentum of the initial d in the center of mass (cms), dp_X is the element of the invariant phase-space volume of the set X of the undetected particles, ϕ is the azimuthal angle of the scattered deuteron, m_ω is the ω mass, w is the invariant effective mass of X, $w^2=p_4^2$. Notation of the four-momenta of the particles are given in Fig. 1(b). The overline on $\mathcal{J}_\mu^{(d)}\mathcal{J}_\nu^{(d)*}$, in the definition of $\mathcal{W}_{\mu\nu}^{(d)}$, denotes the sum over the polarizations of the final deuteron, the overline on $\mathcal{J}_\mu^{(s)}\mathcal{J}_\nu^{(s)*}$ in the definition of $\mathcal{W}_{\mu\nu}^{(s)}$, denotes the sum over the polarizations of the X particles and the average over the polarizations of the initial proton. In the case of unpolarized particle collisions the cross section does not depend on the azimuthal angle, but in the case of the polarized beam or polarized target the effect of the polarization is contained in the ϕ dependence, Eq. (4).

For an unpolarized target the following tensor representation holds for $\mathcal{W}_{\mu\nu}^{(s)}$:

$$\mathcal{W}_{\mu\nu}^{(s)}=\left(-g_{\mu\nu}+\frac{k_\mu k_\nu}{k^2}\right)W_1^{(s)}(t,w^2)+\frac{1}{M^2}\overline{p_{2\mu}p_{2\nu}}W_2^{(s)}(t,w^2), \tag{5}$$

where M is the deuteron mass, $\overline{p_2}=p_2-kk\cdot p_2/k^2$, $k=p_1-p_3$, and $W_{1,2}^{(s)}$ are the real structure functions (SF's) for the inclusive process $\omega+N\to X$. These SF's contain the contributions of isoscalar transitions only. Information on the isotopic structure of $N\to N^*$ transitions which is contained in the SF's $W_1^{(s)}$ and $W_2^{(s)}$ is complementary to that given by $\gamma^*p\to X$ and $\gamma^*n\to X$ inclusive reactions: a photon does not have a definite value of isospin, being a superposition of states with $I=0$ (isoscalar photon) and $I=1$ (isovector photon). This mixing results in the specific isotopic structure of the SF's. In order to analyze this structure it is more convenient to consider, instead of $W_{1,2}^{(s)}$, the amplitudes of forward γ^*N scattering, $(\gamma^*+N\to\gamma^*+N)$, $F(\gamma^*N)$, which are related by $W_{1,2}^{(s)}=\mathrm{Im}\,F(\gamma^*N)$. As a result of the definite isotopic structure of the hadron electromagnetic current, one can write

$$F(\gamma^*N)=F_{ss}+F_{vv}\pm F_{sv}, \tag{6}$$

where the signs $\pm$ correspond to p and n targets and the amplitudes F_{ss}, F_{vv}, and F_{sv} describe the following transitions:

$$F_{ss}=F(\gamma_s^*N\to\gamma_s^*N),\quad F_{vv}=F(\gamma_v^*N\to\gamma_v^*N),$$

$$F_{sv}=F(\gamma_s^*N\to\gamma_v^*N).$$

One can see from Eq. (6) that it is not possible to separate the F_{ss} and F_{vv} contributions, using only data about inclusive γ^*p and γ^*n collisions, but, in the framework of the ω exchange approximation, the nucleon excitation in Eq. (2) allows one to determine the amplitude F_{ss} separately. In this respect hadronic processes may be considered as the necessary and complementary tools to study the isotopic structure of γ^*N interactions.

The situation with the tensor $\mathcal{W}_{\mu\nu}^{(d)}$ is simpler. In order to derive the spin structure of the current $\mathcal{J}_\mu^{(d)}$ it is more convenient to use the Breit system, where $k_0=0$ and the three-momenta of the initial and final deuteron are collinear: $\tilde{\vec{p}}_1=-\tilde{\vec{p}}_3=\tilde{\vec{k}}/2$, $t=k^2=-\tilde{\vec{k}}^2$. Quantities defined in this system will be noted with tildes.

Taking into account the T and P invariances of hadron electromagnetic interactions one can derive the following expressions for the components of the deuteron electromagnetic currents:

$$\tilde{\vec{\mathcal{J}}}^{(d)}=V_1(t)\hat{\vec{k}}\times[\vec{U}\times\vec{U}_2^*],$$

$$\tilde{\mathcal{J}}_0^{(d)}=V_0(t)\vec{U}_1\cdot\vec{U}_2^*+V_2(t)\hat{\vec{k}}\cdot\vec{U}_1\hat{\vec{k}}\cdot\vec{U}_2^*, \tag{7}$$

where $V_0(t)$, $V_1(t)$, and $V_2(t)$ are the real deuteron form factors, $\hat{\vec{k}}$ is a unit vector along $\tilde{\vec{k}}$, $\vec{U}_1$ ($\vec{U}_2$) is the vector of polarization of the initial (final) deuteron. These form factors are related to the standard electromagnetic deuteron form factors, G_c (electric), G_m (magnetic), and G_q (quadrupole) by

$$V_0=\sqrt{1+\eta}\left(G_c-\frac{2}{3}\,\eta G_q\right),\quad V_1=\sqrt{\eta}G_m,$$

$$V_2=\frac{\eta}{\sqrt{1+\eta}}\left[-G_c+2\left(1-\frac{1}{3}\,\eta\right)G_q\right],\quad \eta=-\frac{t}{4M^2}.$$

The form factors G_c, G_m, and G_q determine the differential cross section of the elastic ed scattering:

$$\frac{d\sigma}{d\Omega}=\frac{\alpha^2\cos^2(\theta_e/2)}{4E_e^2\sin^2(\theta_e/2)}\frac{[A(t)+tg^2(\theta_e/2)B(t)]}{[1+2(E_e/M)\sin^2(\theta_e/2)]},$$

where θ_e is the electron scattering angle in the laboratory system, E_e is the energy of the electron beam, and $A(t)$ and $B(t)$ are the deuteron structure functions:

$$B(t)=\frac{4}{3}\,\eta(1+\eta)G_m^2(t),$$

$$A(t)=G_c^2(t)+\frac{8}{9}\,\eta^2G_q^2(t)+\frac{2}{3}\,\eta G_m^2(t).$$

It is more convenient to rewrite the tensor $\mathcal{W}_{\mu\nu}^{(d)}$ in terms of $A(t)$ and $B(t)$ which are the measured quantities:

$$\mathcal{W}_{\mu\nu}^{(d)}=\frac{1}{2}\left(-g_{\mu\nu}+\frac{k_\mu k_\nu}{k^2}\right)B(t)+\frac{1}{M^2}\left(p_{1\mu}-k_\mu\,\frac{k\cdot p_1}{k^2}\right)\times\left(p_{1\nu}-k_\nu\,\frac{k\cdot p_1}{k^2}\right)A(t). \tag{8}$$

Using Eqs. (4), (5), and (8), one can obtain the following formula for the differential cross section of $d+p\to d+X$:

$$\frac{d^2\sigma}{dtdw^2}=\frac{A(t)W_2^{(s)}(t,w^2)}{128\pi^2sp^2(t-m_\omega^2)^2}\,[y^2+\rho(t,w^2)], \tag{9}$$

where

$$y=\frac{p_1\cdot p_2-k\cdot p_2/2}{mM},$$

$$\rho(t,w^2)=\tfrac{1}{2}\,R(t)\left[-1+\frac{(w^2-m^2-t)^2}{4m^2t}\right]-(1+\eta)R^{(s)}(t,w^2)+\tfrac{3}{2}\,R(t)R^{(s)}(t,w^2),$$

$$R(t)=B(t)/A(t),\quad R^{(s)}(t,w^2)=\frac{W_1^{(s)}(t,w^2)}{W_2^{(s)}(t,w^2)}. \tag{10}$$

Here m is the proton mass. The y^2 dependence of the differential cross section is a direct consequence of the spin-one ω exchange in the t *channel*. In a general case the inclusive scattering process $p(d,d)X$ is characterized by three independent variables: t, w^2, and s. The dependence of the cross section from t and w^2 has a dynamical character and is described by the corresponding SF's for the $dd\omega$ and ωpX vertexes. But the s dependence is definite and simple:

$$\frac{d^2\sigma}{dtdw^2}=\frac{a(t,w^2)}{128\pi^2s\vec{p}^2}\,[(s-s_0)^2+4m^2M^2\rho(t,w^2)], \tag{11}$$

where

$$s_0=M^2+\frac{1}{2}\,(w^2+m^2-t),\quad a(t,w^2)=\frac{A(t)W_2^{(s)}(t,w^2)}{4m^2M^2(t-m_\omega^2)^2}. \tag{12}$$

The linearity of the dependence (9) of the double-differential cross section on y^2 can be experimentally tested by a measurement at three different energies of the initial deuteron (three different values of s), at fixed values of t and w^2. This linearity is a direct consequence of the ω-exchange mechanism, and such a measurement would be an experimental test of the validity of the ω-exchange mechanism, equivalent to the Rosenbluth fit for electron-hadron scattering. The linear $tg^2(\theta_e/2)$ dependence of the differential cross section of the $e+A\to e^-+X$ process is a result of one-photon exchange (and the P invariance of electromagnetic interaction of hadrons). Therefore, in this respect, the ω exchange for $d+p\to d+X$ and the one-photon exchange for processes $e^-+A\to e^-+X$ are equivalent. One can mention that the Rosenbluth fit also allows one to separate the contributions of longitudinal and transversal photon polarizations to the differential cross section of any process $e^-+A\to e^-+X$. Similarly, the study of the y^2 linearity of the double-differential cross section for processes $d+p\to d+X$ will allow one to separate two different combinations of SF's, $a(t,w^2)$ and $a(t,w^2)\rho(t,w^2)$. One can see that at the limit $s\gg w^2$, $|t|$, Eq. (9) becomes

$$\frac{d^2\sigma}{dtdw^2}=\frac{a(t,w^2)}{32\pi^2},\quad s\to\infty, \tag{13}$$

i.e., the differential cross section becomes s independent, as it is expected for a t-channel exchange of a spin-one meson. It is evident that in case of η or σ exchange the cross section has to decrease with s according to

$$\frac{d^2\sigma}{dtdw^2}=\frac{f(t,w^2)}{s^2}. \tag{14}$$

These different properties should help to sign experimentally the ω-exchange contribution.

III. COLLINEAR PRODUCTION OF ROPER RESONANCE

We have derived the general structure of the inclusive process $p(d,d')X$ in the framework of the ω-exchange mechanism. The results, summarized in Eq. (9), hold for any kinematical condition, for any state X, if only ω exchange is present.

Let us now consider a particular case, when $X=N^*(1440)$, with $\mathcal{J}^P=\frac{1}{2}^+$, i.e., the Roper resonance (RR)

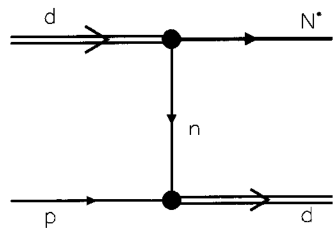

FIG. 2. One nucleon mechanism for backward deuteron scattering in the process $d+p\to d+N^*$.

excitation. This problem is very possible [5–9], as experiments are under way in SATURNE and planned in CEBAF in the future. The problem of the selection of the RR contribution will be treated separately. Here we derive a general method for the analysis of this problem, in case of collinear kinematics for the reaction $d+p\to d+N^*$, i.e., forward and backward scattering. The forward deuteron scattering is determined by small $|t|$ mechanisms (like ω exchange), and it is well adapted to the study of $p\to N^*$ excitation. On the other hand, the backward dp inelastic scattering is determined by the small values of the four-momentum transferred from the initial proton to the scattered deuteron, $u=(p_2-p_3)^2$. Another mechanism is important in these kinematical conditions, the one-nucleon exchange (Fig. 2). Like elastic backward dp scattering, this mechanism is sensitive to the NN^* component of the deuteron wave function.

Applying the conservation of the total spin *projection* for the collinear processes, five independent transitions are allowed in $d+p\to d+N^*$. The general spin structure of the collinear amplitude can be described by

$$\mathcal{M}(dp\to dN^*)=\chi_2^\dagger F \chi_1,$$

$$F=if_1\vec{U}_1\cdot\vec{U}_2^*+if_2\hat{\vec{k}}\cdot\vec{U}_1\vec{k}\cdot\vec{U}_2^*+f_3\vec{\sigma}\cdot\vec{U}_1\times\vec{U}_2^*+f_4\vec{\sigma}\cdot\hat{\vec{k}}\vec{U}_1\times\vec{U}_2^*\cdot\hat{\vec{k}}+f_5(\hat{\vec{k}}\cdot\vec{U}_1\sigma\cdot\hat{\vec{k}}\times\vec{U}_2^*+\hat{\vec{k}}\cdot\vec{U}_2^*\sigma\cdot\vec{U}_1\times\hat{\vec{k}}),\qquad(15)$$

where $\hat{\vec{k}}$ is the unit vector along the deuteron momentum, χ_1 (χ_2) is the two-component spinor of the initial proton (produced N^*) and f_i, $i=1$–5, are the scalar amplitudes, which are complex functions of t only.

For a fixed m^* (mass of N^*) the value of t is determined only by the energy of the initial-deuteron. But in a real experiment the energy spectrum of the scattered deuterons corresponds to different values of t and w^2 and for collinear kinematics there is a definite correspondence between t and $w^2=m^{*2}$ (Fig. 3).

The spin structure (15) results from P invariance for strong interactions, in collinear kinematics, where the reaction takes place in a three-momentum direction $\hat{\vec{k}}$ only. This formula has been derived using the spins and parities of d and N^*, it applies then to any mechanism of the considered process, all the information on the deuteron structure and the N^* properties being contained in the amplitudes f_i.

Let us express the polarization observables for the process $d+p\to d+N^*$, in terms of the scalar amplitudes f_i, Eq. (15).

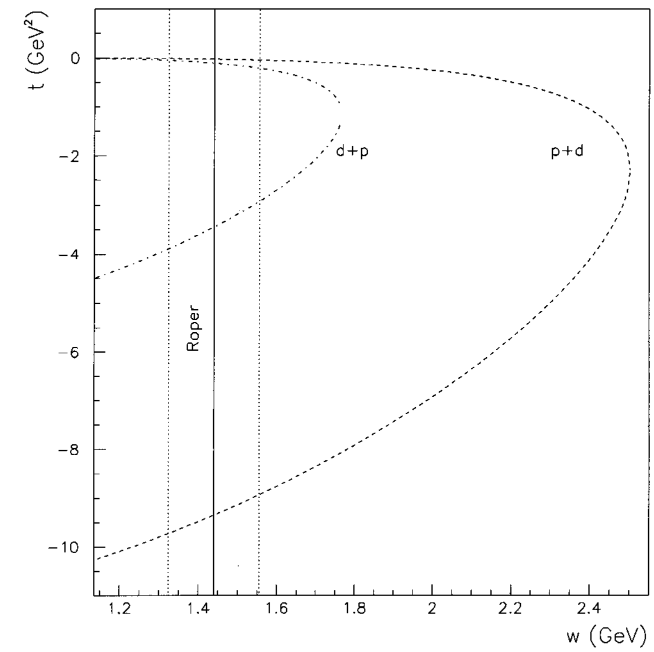

FIG. 3. Physical region for $d+p\to d+X$ at $E_{\rm kin}=2.3$ GeV and $p+d\to p+X$ at $E_{\rm kin}=3$ GeV (the maximum available Saturne energies) in the t-w plane. The region of the Roper resonance with its width is shown and it is constant in t.

Summing over the polarizations of the produced particles and averaging over the polarizations of the protons, we obtain the following expression for the square of the matrix element:

$$\overline{|\mathcal{M}|^2}=X_1\vec{U}_1\cdot\vec{U}_1^*+X_2|\hat{\vec{k}}\cdot\vec{U}_1|^2,$$

$$X_1=|f_1|^2+|f_3+f_4|^2+|f_3+f_5|^2,$$

$$X_2=-|f_1|^2+|f_1+f_2|^2-|f_3+f_4|^2+|f_3+f_5|^2-8\,{\rm Re}f_3f_5^*.\qquad(16)$$

Therefore, the differential cross section and the tensor analyzing power T_{20} are

$$\frac{d\sigma}{d\Omega}\simeq 3X_1+X_2,\quad T_{20}=-\frac{\sqrt{2}X_2}{3X_1+X_2}.\qquad(17)$$

The interference of the amplitudes f_3 and f_5 results in the inequality between T_{20} and t_{20} (polarization of the final deuteron in an unpolarized collision):

$$t_{20}=-\frac{\sqrt{2}X_2'}{3X_1+X_2'},\quad X_2'=X_2+16\,{\rm Re}f_3f_5^*.\qquad(18)$$

IV. t-CHANNEL CONTRIBUTIONS TO THE AMPLITUDES OF $d+p\to d+N^*$

The general parametrization of the collinear amplitude is very convenient for the description of possible t-channel contributions and it will be applied here to the scalar σ, pseudoscalar η, and vector ω mesons. We will perform the calculations in the Breit system, where $\widetilde{k}_0=0$, so the space

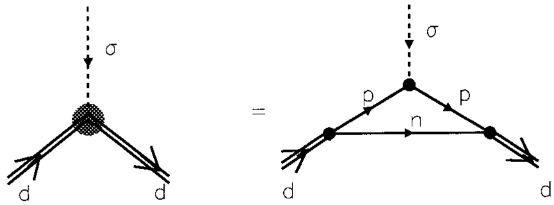

FIG. 4. Impulse approximation for the σdd vertex.

part of the conserved vector current must be transversal.

(1) σ exchange. The $dd\sigma$ vertex can be described, in the general case, in terms of two independent form factors with the following spin structures:

$$g_0(t)\vec{U}_1\cdot\vec{U}_2 \quad \text{and} \quad g_2(t)\hat{\vec{k}}\cdot\vec{U}_1\hat{\vec{k}}\cdot\vec{U}_2^*.$$

Using the evident structure of the $p+\sigma\rightarrow N^*$ vertex: $g_\sigma\chi_2^\dagger\chi_1$, where $g_\sigma(t)$ is the corresponding form factor, one can obtain

$$f_1=\frac{g_0g_\sigma}{t-m_\sigma^2},\quad f_2=\frac{g_2g_\sigma}{t-m_\sigma^2},\quad f_3=f_4=f_5=0.$$

The tensor analyzing power becomes

$$T_{20}=-\sqrt{2}g_2(t)\,\frac{2g_0(t)+g_2(t)}{3|g_0|^2+|g_2|^2+2g_0g_2}. \tag{19}$$

The surprising result contained in this formula is that it is possible to induce tensor analyzing power even in the case of σ exchange (spin-0 particle), taking into account high-order effects (interaction with derivatives).

In the framework of the impulse approximation (Fig. 4) the form factor $g_2(t)$ is proportional to the quadrupole form factor of the deuteron.

(2) η exchange. In this case the $dd\eta$ vertex is characterized by a single spin structure, $g_1(t)\hat{\vec{k}}\cdot\vec{U}_1\times\vec{U}_2^*$, and using the $NN^*\eta$ vertex in the form $\chi_2^\dagger\vec{\sigma}\cdot\hat{\vec{k}}\chi_1$, one can obtain for the collinear kinematics the following expressions for the scalar amplitudes f_i:

$$f_1=f_2=f_3=f_5=0,\quad f_4=\frac{g_1(t)g_\eta(t)}{t-m_\eta^2}.$$

This spin structure results in $T_{20}=1/\sqrt{2}$, positive and t independent. The form factor $g_1(t)$ of the $dd\eta$ vertex is proportional to the magnetic form factor of the deuteron in the impulse approximation.

(3) ω exchange. The spin structure of the vertex ωdd, Eq. (7), coincides with the corresponding structure for the $\gamma^* dd$ vertex. The vector dominance model suggests a simple relation between the form factors of the ωdd and $\gamma^* dd$ interactions (Fig. 5):

$$ef_i^{(\text{em})}(t)=\frac{e}{2\gamma_\omega}\frac{f_i^\omega(t)}{t-m_\omega^2},$$

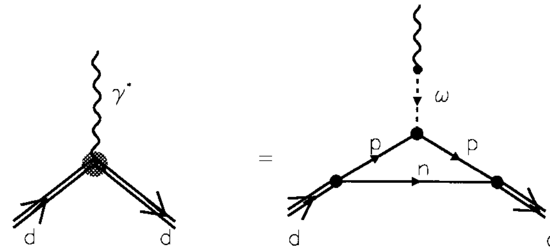

FIG. 5. Vector dominance model for the deuteron form factors.

where γ_ω is the constant of the $\gamma\omega$ transition, $f_i^{(\text{em})}(t)$ $[f_i^\omega(t)]$ is the corresponding electromagnetic (strong) form factor.

The spin structure of the other vertex, ωNN^* can be parametrized as follows:

$$\tilde{\mathcal{J}}_0=ig_e(t)\chi_2^\dagger\chi_1,$$

$$\tilde{\vec{\mathcal{J}}}=g_m(t)\chi_2^\dagger\vec{\sigma}\times\hat{\vec{k}}\chi_1, \tag{20}$$

where the electric (longitudinal), $g_e(t)$, and the magnetic (transversal), $g_m(t)$, form factors are proportional to the isoscalar form factors of the N^* electroexcitation:

$$g_{e,m}(t)=\frac{1}{2}\,[g_{e,m}^{(p)}(t)+g_{e,m}^{(n)}(t)],$$

(p) and (n) denote the proton and neutron transition form factors.

The following formulas hold for the scalar amplitudes in the framework of the ω exchange:

$$f_1=\frac{V_0g_e(t)}{t-m_\omega^2},\quad f_2=\frac{V_2g_e(t)}{t-m_\omega^2},$$

$$f_3=-f_4=\frac{V_1g_m(t)}{t-m_\omega^2},\quad f_5=0. \tag{21}$$

A direct consequence is that, in this particular case $T_{20}=t_{20}$. Taking into account that $f_3+f_4=0$, one obtains a simpler expression for T_{20} [in comparison with Eq. (17)]:

$$T_{20}=\sqrt{2}\left(-1+3\,\frac{|f_1|^2+|f_3|^2}{2|f_1|^2+|f_1+f_2|^2+4|f_3|^2}\right).$$

The lower limit for this observable, $T_{20}=-\sqrt{2}$, corresponds to $f_1=f_3=0$, $f_2\neq 0$, but the upper limit $T_{20}=\sqrt{2}$ is not achievable in the case of ω exchange. If $f_2=0$, then for any amplitudes f_1 and $f_3\neq 0$ this model predicts only negative values for T_{20}. It may be positive in the case of $f_3=0$, and $|f_1+f_2|^2\leqslant|f_1|^2$, and its maximum allowed value is $T_{20}=1/\sqrt{2}$ when $f_1=-f_2$ and $f_3=0$.

Using Eqs. (21) for the amplitudes f_i, T_{20} can be written in terms of the electromagnetic form factors as

$$T_{20}=-\sqrt{2}\,\frac{V_1^2+(2V_0V_2+V_2^2)r(t)}{4V_1^2+(3V_0^2+V_2^2+2V_0V_2)r(t)}, \tag{22}$$

where the ratio $r(t)=g_e^2(t)/g_m^2(t)$ characterizes the relative role of longitudinal and transversal excitation of N^*.

This formula can be easily generalized for the excitation of any nucleonic resonance N^* (in the framework of ω exchange) as follows:

$$r(t)=\frac{A_S^2(t)}{[A_{1/2}^2(t)+A_{3/2}^2(t)]}, \tag{23}$$

where $A_{1/2}$ and $A_{3/2}$ are two possible transversal form factors of the process $\gamma_S^*+N\rightarrow N^*$, γ_S^* is the isoscalar virtual photon and $A_S(t)$ is the scalar (electric longitudinal) form factor [7].

Moreover Eq. (22) is valid for any inclusive process $d+p\rightarrow d+X$, with

$$r(t)\rightarrow r(t,w^2)=\widetilde{W}_{00}^{(s)}/(\widetilde{W}_{xx}^{(s)}+\widetilde{W}_{yy}^{(s)}),$$

$$\widetilde{W}_{xx}^{(s)}=\widetilde{W}_{yy}^{(s)}=W_{1,2}^{(s)}(t,w^2),$$

$$\widetilde{W}_{00}^{(s)}=-W_1^{(s)}+\left[1-\frac{(w^2-m^2-k^2)^2}{4m^2k^2}\right]W_2^{(s)}(t,w^2).$$

In the simplest case of $X=N+\pi$, the SF's $W_{1,2}^{(s)}$ can be calculated in the framework of any model for the process $\omega+N\rightarrow N+\pi$, in the resonance energy region.

When $r(t)\gg 0$ or if the contribution of the deuteron magnetic form factor $V_1(t)$ is neglected, then T_{20} does not depend on the ratio $r(t)$, and coincides with t_{20} for the elastic ed scattering (with the same approximation). In another limiting case, $r(t)\rightarrow 0$, from Eq. (22) we have

$$T_{20}=-\frac{1}{2\sqrt{2}}\simeq -0.35,$$

i.e., T_{20} is negative and t independent. This situation applies to the RR according to some theoretical models [5,6]. All these examples show that this observable is especially sensitive to the properties of the vertex $\omega+N\rightarrow X$.

V. COMPARISON WITH EXISTING DATA

In Fig. 6 we report the theoretical predictions together with the existing experimental data. T_{20} for $p(\vec{d},d)X$ [2] for different momenta of the incident beam is shown as open symbols. These data show a scaling as a function of t, with a small dependence on the incident momentum.

On the same plot the data for the elastic scattering process $e^-+d\rightarrow e^-+d$ [10] are shown (solid stars). All these data show a very similar behavior: negative values, with a minimum in the region $|t|\simeq 0.35$ GeV^2 and they increase toward zero at larger $|t|$. The lines are the result of the ω-exchange model for the $d+p\rightarrow d+X$ process, Eq. (22), for different values of the ratio r, assumed constant.

The deuteron form factors G_c, G_q, G_m, have been taken from [11], a calculation based on relativistic impulse approximation, and they reproduce well the T_{20} data for ed elastic scattering [10].

The dashed line corresponds to $r=0$, where our model predicts a constant value of this observable in the $d+p\rightarrow d+X$, which is not consistent with the data. All theo-

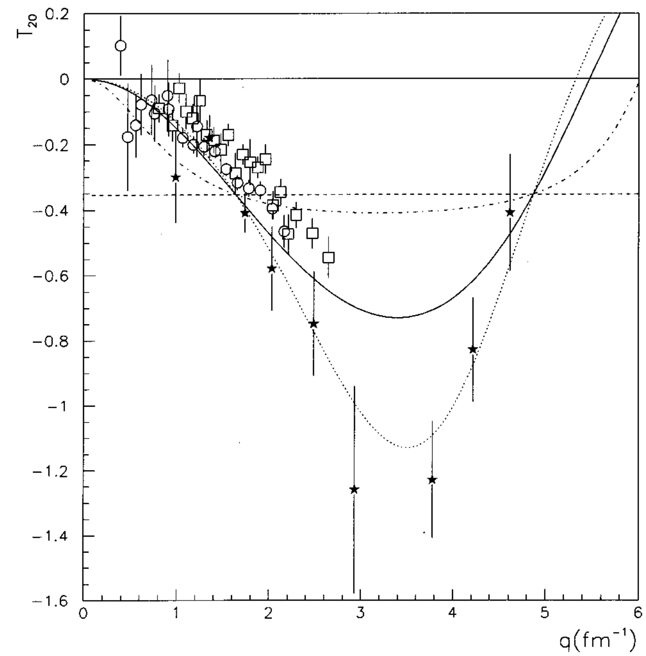

FIG. 6. Experimental data on T_{20} for $e^-+d\rightarrow e^-+d$ (solid stars), $d+p\rightarrow d+X$ at incident momenta of 5.5 GeV/c (open circles) and 4.5 GeV/c (open squares) as a function of $q=\sqrt{|t|}$. The predictions of the ω-exchange model are reported for different values of the form factors ratio r: $r=0$ (dashed line), $r=0.01$ (dash-dotted line), $r=0.1$ (solid line), $r=0.5$ (dotted line).

retical curves (corresponding to different values of r) are crossing in two points, at $q=2$ and $q=5$ fm^{-1} ($q=\sqrt{|t|}$), due to a particular cancellation between the form factors combinations: V_2 and $2V_0+V_2$, in the numerator of Eq. (22). Therefore the positions of these points are sensitive to the theoretical models used for the calculation of the deuteron electromagnetic form factors.

Our calculation shows a dependence on r, in the range 0–0.5 especially in the region of the minimum ($q\simeq 3$ fm^{-1}) and in the point where T_{20} changes sign ($q\simeq 5$ fm^{-1} for $r=0.1$–0.5 and $q\simeq 6$ fm^{-1} for $r=0.01$). The data are more consistent with the value $r=0.1$, in the simplified version of the ω-exchange model with a t-independent ratio r.

The results show clearly that this observable in the $d+p\rightarrow d+X$ reaction is mostly characteristic of the properties of the $dd\omega$ vertex, but it depends also on the properties of the ωpX vertex and can give additional important information about the electromagnetic form factors of the nucleonic resonance excitation.

VI. COEFFICIENTS OF POLARIZATION TRANSFER IN $\vec{d}+p\rightarrow\vec{d}+X$

Let us calculate the vector (tensor) transfer polarization coefficients $k_a^{a'}$ ($k_{aa}^{a'a'}$) (with $a=x,y$, or z) from initial to final deuterons, for $\vec{d}+p\rightarrow\vec{d}+X$, in the framework of σ and ω exchanges.

In the case of σ exchange these coefficients depend only from the ratio $r_g(t)=g_2(t)/g_0(t)$ of the form factors of the $dd\sigma$ vertex. For the nonzero (diagonal) coefficients the following expressions hold:

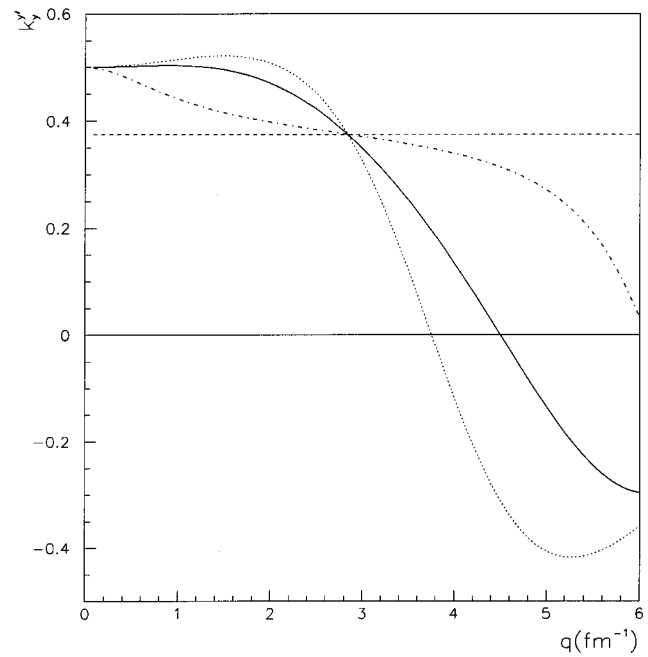

FIG. 7. Vector polarization transfer coefficient $k_y^{y'}$ as a function of $q=\sqrt{|t|}$, for $d+p\to d+X$ and different values of the form factors ratio r: $r=0$ (dashed line), $r=0.01$ (dash-dotted line), $r=0.1$ (solid line), $r=0.5$ (dotted line).

$$k_y^{y'}=k_x^{x'}=\frac{3(1+r_g)}{2(3+2r_g+r_g^2)},\quad k_z^{z'}=\frac{3}{2(3+2r_g+r_g^2)},\tag{24}$$

where the z axis is along the three-momentum transfer $\vec{k}$. In this case the observables $k_a^{a'}$ contain the same information as T_{20}, Eq. (19). Moreover these observables are connected by the following relation:

$$T_{20}-\frac{3}{\sqrt{2}}\,k_z^{z'}+\frac{9}{2\sqrt{2}}\,(k_y^{y'})=0.\tag{25}$$

In the case of an ω-exchange approximation, using the corresponding parametrization of the ωdd vertex, one can find the following formulas for the nonzero vector polarization transfer coefficients:

$$k_y^{y'}=k_x^{x'}=\frac{3}{2}\,\frac{V_1^2+(V_0V_2+V_0^2)r(t)}{4V_1^2+(3V_0^2+V_2^2+2V_0V_2)r(t)},\tag{26}$$

$$k_z^{z'}=\frac{3}{2}\,\frac{V_1^2+V_0^2r(t)}{4V_1^2+(3V_0^2+V_2^2+2V_0V_2)r(t)}.\tag{27}$$

For $r=0$ we obtain simply $k_x^{x'}=k_y^{y'}=k_z^{z'}=\frac{3}{8}=0.375$: all coefficients are positive and t independent. As in the case of T_{20} the ratio $r(t)$ contains all the information about the properties of $\omega p\to X$ vertexes. From Fig. 7, one can see that $k_y^{y'}$ has a strong q and r dependence. The point where all lines for different r are crossing is due (as for T_{20}) to a special combination of V_0 and V_2 [see the numerator of Eq. (26)]. At $q=0$, $k_y^{y'}=1/2$, for any value of r, as $V_1=V_2=0$. The largest sensitivity to r is in the region $q\geqslant 3$ fm^{-1} and the position of zero crossing is strongly r dependent.

A tensor polarized deuteron beam can produce only tensor polarization of the scattered deuteron:

$$k_{xx}^{x'x'}=k_{yy}^{y'y'}=k_{xy}^{x'y'}=k_{yx}^{y'x'}=\frac{V_0^2r(t)}{4V_1^2+(3V_0^2+V_2^2+2V_0V_2)r(t)},\tag{28}$$

$$k_{zz}^{z'z'}=\frac{-2V_1^2+(V_0+V_2)^2r(t)}{4V_1^2+(3V_0^2+V_2^2+2V_0V_2)r(t)},\tag{29}$$

$$k_{xz}^{x'z'}=k_{yz}^{y'z'}=\frac{-2V_1^2+(V_0^2+2V_0V_2)r(t)}{4V_1^2+(3V_0^2+V_2^2+2V_0V_2)r(t)}.\tag{30}$$

The vector to tensor (and tensor to vector) polarization transfer coefficients are zero, in the considered approximation.

VII. CONCLUSIONS

We have shown that the ω-exchange mechanism in exclusive and inclusive dp interactions, $d+p\to d+N+\pi$, $d+p\to d+X$ allows one to extract interesting information about the properties of isoscalar nucleon excitation. This constitutes essential and complementary information to the results which can be obtained from ep and en interactions in the region of the excitation of nucleon resonances.

The main problem in the hadron-induced reaction is the understanding of the reaction mechanism. We suggest here a model-independent way to test experimentally the validity of the ω-exchange mechanism: the linearity of the double-differential inclusive cross section in the variable y^2, for the process $d+p\to d+X$. The azimuthal asymmetry in exclusive processes like $d+p\to d+N+\pi$ and in particular the polarization observables should also help in identifying the ω-exchange mechanism.

The reaction mechanism which corresponds to ω exchange is especially important to determine the isoscalar structure of N^* excitation. The electroproduction experiments on neutron and proton targets will not allow to determine completely the isotopic structure of the γN interaction, as the isoscalar information is missing. Moreover the use of a deuteron target implies the knowledge of specific properties of the deuteron. In this respect the electromagnetic interaction does not look preferable compared to hadron probes.

Of course, a realistic model to describe processes $d+p\to d+X$ has to include, in addition to ω exchange, the contribution of η and σ exchanges; the excitation of all resonances (with mutual interference), which can contribute in the mass region of interest; contribution of nonresonant background; effects of a strong interaction in the initial and final states; contribution of deuteron excitation (Deck mechanism). All these contributions have a complicated spin structure, producing strong interference effects with large polarization phenomena.

The best way to study the N^* structure with hadronic probes seems to be the diffractive excitation of proton in high-energy pp collisions. A small t-diffractive production. $p+p\to X+p$ (Fig. 8) can be described in terms of Pomeron exchange, with a large cross section, nondecreasing with energy: the contribution of the diffractive dissociation is about

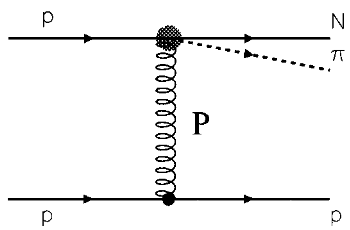

FIG. 8. Pomeron exchange for the diffractive dissociation of the proton in the process $p+p\to p+\pi+N$.

20% of the total cross section for the pp interaction. The phenomenological photon-Pomeron analogy has described successfully many properties of high-energy hadronic interactions: elastic processes and diffractive inelastic processes [12,13]. Therefore the subprocess $\mathcal{P}+p\to N+\pi$ has to be similar to the process $\gamma^*+N\to N+\pi$ and even simpler as the isotopic spin of $\mathcal{P}$ is equal to zero. So the Pomeron exchange behaves as an isotopic spin separator to sign the isoscalar contributions. Moreover at large values of s and small values of t the Pomeron exchange mechanism is free from any large background similar to the Deck mechanism which is the main background for $d+p\to d+X$ at intermediate energies.

One can mention that the process of diffractive excitation (or diffractive dissociation) unifies the high-energy physics of the specific t-channel exchange (i.e., Pomeron exchange) with the low energies, i.e., the resonance physics of the processes $\mathcal{P}+p\to N+\pi$. The properties of this subprocess can be calculated with good accuracy in the framework of the models which are currently used for the pion electroproduction. Their main ingredients are the contributions of different N^* excitations in the s channel and some background. The presence of the isoscalar part of the corresponding $N\to N^*$ form factors makes the diffractive dissociation of proton a very sensitive tool for the test of different models of N^* structure and of the mechanisms of its electroexcitation.

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