MANIFESTATION OF SYMMETRY PROPERTIES OF NUCLEON STRUCTURE IN STRONG AND ELECTROMAGNETIC PROCESSES

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In this contribution we present a specific application of a result obtained by Franco Iachello (in collaboration with R. Bijker and A. Leviatan), which concerns the inelastic electromagnetic form factors on the nucleons. In particular we show examples where symmetries inherent to the structure of the nucleon resonances can manifest in complicated processes of the strong interaction.

1 Introduction

Although nucleon resonances are preferentially investigated with electromagnetic probes (due to the fact that the reaction mechanism, the one-photon exchange, is well know), there are also advantages in using hadronic probes, such as large cross sections, absence of radiative corrections, development of good polarized beams, targets, polarimeters, and, in case of α and deuterons, isoscalar selectivity.

We will show through the example of two reactions $\vec{d}+p \to d+X$ and $p+\alpha \to p+\alpha+\pi^0$, how polarization phenomena, together with adequate kinematical choices, can sort out unambiguous information on nucleon resonances.

For an incident energy of a few GeV, over the threshold for the excitation of the Roper resonance, the cross section, in these reactions, shows two structures, one related to the coherent excitation of the target, with pion production (Deck effect[1]), and a second one, of interest here, related to the N^*-excitation. These mechanisms can be described by t-channel exchange of isovector mesons, in case of Deck mechanism, and of isoscalar mesons for nucleon resonances.

The most probable mechanism to describe the N^*-excitation is, in our opinion, the ω-exchange: the $\omega NN-$ coupling is large; the exchange of spin one particles allows to obtain large polarization phenomena and an energy independent cross section. The ω-meson can be considered as as 'isoscalar photon', therefore the cross section and the polarization observables can be related through the vector dominance model (VDM) to the electromagnetic properties of the hadrons.

2 Symmetry and reaction mechanism: $\vec{d}+p \to d+X$

The inclusive production of deuterons in $\vec{d}+p \to d+X$ is dominated by one-nucleon exchange in backward scattering, and by t-exchanges at forward angles. For Roper excitation in framework of ω-exchange, the tensor analyzing power in $d+p \to d+X$,

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T_{20}, can be written in terms of the electromagnetic form factors (FFs) as[2]:

$$T_{20} = -\sqrt{2}\frac{V_1^2 + (2V_0V_2 + V_2^2)r(t)}{4V_1^2 + (3V_0^2 + V_2^2 + 2V_0V_2)r(t)}, \tag{1}$$

where $V_0(t)$, $V_1(t)$ and $V_2(t)$ are related to the standard electromagnetic deuteron FFs, G_c (electric), G_m (magnetic) and G_q (quadrupole) by:

$$V_0 = \sqrt{1+\eta}\left(G_c - \frac{2}{3}\eta G_q\right),\ V_1 = \sqrt{\eta}G_m, V_2 = \frac{\eta}{\sqrt{1+\eta}}\left[-G_c + 2\left(1 - \frac{1}{3}\eta\right)G_q\right],$$

and $\eta = -t/4M^2$. The ratio $r(t)$ characterizes the relative role of longitudinal and transversal isoscalar excitations in the transition $\omega + N \to X$. For any nucleon resonance N^* it can be written as follows:

$$r(t) = \frac{|A_S^p + A_S^n|^2}{|A_{1/2}^p + A_{1/2}^n|^2 + |A_{3/2}^p + A_{3/2}^n|^2} \equiv \sigma_L(t)/\sigma_T(t), \tag{2}$$

where $A_{1/2}$ and $A_{3/2}$ are the two possible transversal FFs, corresponding to total $\gamma^* + N$-helicity equal to 1/2 and 3/2.

From Eq. (1) it appears that: - all information about the ωNN^*-vertex is contained in the function $r(t)$ only; - T_{20} is especially sensitive to the small value of $r(t$ in the interval $0.0 \le r(t) \le 0.5$; - a zero value of $r(t)$ results in a $t-$independent value $T_{20} = -1/2\sqrt{2}$, for any value of the deuteron electromagnetic FFs; - the position of points where $T_{20} = 0$ is determined by the model for the deuteron FF. In Fig. 1 we report the theoretical predictions, using Eq. (1), together with the existing experimental data. In such approximation T_{20} is a universal function of t only, without any dependence on the initial deuteron momentum. The experimental values of T_{20} for $p(\vec{d},d)X$ [3,4], for different momenta of the incident beam are shown as open symbols. These data show a scaling as a function of t, with a small dependence on the incident momentum, in the interval 3.7-9 GeV/c. On the same plot the data for the elastic scattering process $e^- + d \to e^- + d$ [5] are shown (filled stars). All these data show a very similar behavior: negative values, with a minimum in the region $|t| \simeq 0.35\ GeV^2$, increasing toward zero at larger $|t|$.

The full line is the result of the ω-exchange model for the $d + p \to d + X$ process, taking into account the resonances: $S_{11}(1535)$, $D_{13}(1520)$ and $S_{11}(1650)$ which overlap in this energy region. When $r \gg 0$ or if the contribution of the deuteron magnetic FF $V_1(t)$ is neglected, then T_{20} does not depend on the ratio r, and coincides with t_{20} for the elastic ed-scattering (with the same approximation).

The deuteron FFs have been taken from [6]. The values of r, are predicted by the algebraic string model of baryons [7] and give a very good description of the data, when taking into account the contribution of all considered resonances (Fig. 2).

One can see that, of the four resonances, only the Roper resonance has a nonzero isoscalar longitudinal FF. The isoscalar longitudinal amplitudes of $S_{11}(1535)$ and $D_{13}(1520)$ vanish because of spin-flavor symmetry, while both isoscalar and isovector longitudinal couplings of $S_{11}(1650), D_{15}(1675)$ and $D_{13}(1700)$ vanish identically. This behavior of the isoscalar FFs is essential for the correct description of the existing experimental data on the $t-$ dependence of T_{20} for the process $d+p \to d+X$.

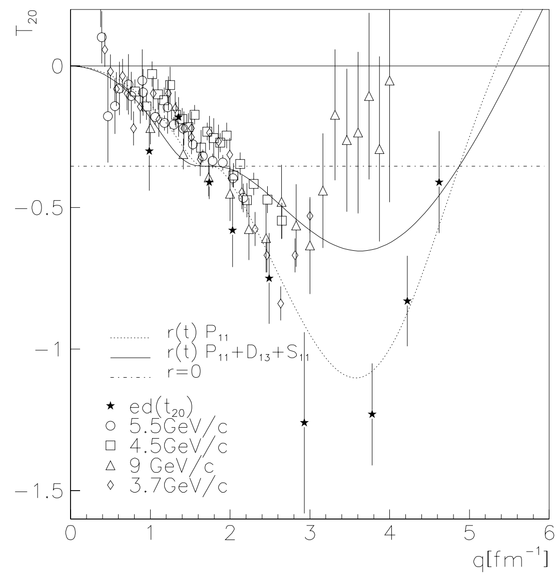

Figure 1. Experimental data on T_{20} for $d+p \to d+X$ at incident momenta of 3.75 GeV/c (open diamond) [3] 5.5 GeV/c (open circles), 4.5 GeV/c (open squares), and 9 GeV/c (open triangles) [4]. The prediction of the $\omega-$exchange model for $r=0$ is represented by the dashed-dotted line. The calculation with r from [7] is represented by the dotted line for the Roper excitation and by the solid line for the excitation of the resonances quoted in the text. The t_{20} data from ed elastic scattering (filled stars) are from [5].

From Fig. 1 it appears that the $t-$behavior of T_{20} is very sensitive to the value of r especially at relatively small r, $r \leq 0.5$. These data, in any case, exclude a very small value of r, $r \ll 0.1$ as well as very large values of r. Such sensitivity of T_{20} to the ratio of the corresponding isoscalar FFs of the N^*-excitation gives an evident indication of the excitation of the Roper resonance in this process.

This description depends on how the resonances are excited and not on their decays. An exclusive experiment, last from LNS, shows that T_{20} barely change selectioning one or two pions final state [8].

A temptative was done to select by the effective mass, the region where one of the resonances is predominantly excited [9]. T_{20} for different mass regions, for different incident beam momenta, was measured in the reaction $d+Be \to d+X$, at small forwaed angle. The results are nicely in agreement with our predictions, in the region of the Roper resonance, as well as outside, where the longitudinal FF vanishes and from Eq. (1), we find $T_{20} \simeq 0.35$.

2.1 Exclusive processes: polarization phenomena in $\vec{p}+d \to \vec{p}+M^0+d,\ M^0=\sigma$ *or* π

The polarization properties of the produced protons in the processes $\vec{p}+d \to \vec{p}+M^0+d$, $M^0=\sigma$, η or π^0 depend essentially on the kind of the produced meson and on the quantum numbers ($\mathcal{J}^P$) of the nucleonic resonance in the intermediate

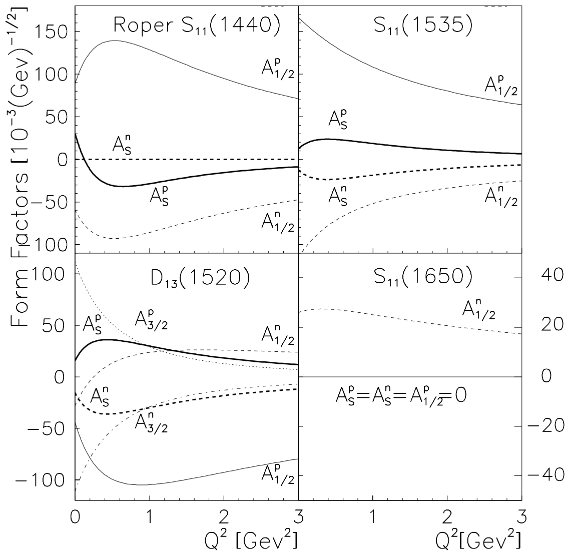

Figure 2. Longitudinal and transversal electromgnetic FFs in units $[10^{-3}\mathrm{GeV}^{-1/2}]$, as a function of Q^2 $[\mathrm{GeV}^2]$ for the four considered resonances. The thick solid (dashed) line is the longitudal FF for proton(neutron). Corresponding thin lines are the transversal FFs, for helicity 1/2. The dotted (dash-dotted) lines are transversal FF for helicity 3/2, for proton and neutron respectively.

state: $p + d \to N^*(\mathcal{J}^P) + d \to p + M^0 + d$. Let us consider the case of Roper excitation, with $\mathcal{J}^P = \frac{1}{2}^+$.

In framework of ω-exchange, the polarization transfer coefficients which do not vanish in case of σ-production: $\vec{p} + d \to \vec{p} + \sigma + d$ are :

$$K_y^{y'} = K_x^{x'} = \frac{\mathcal{R}}{4+\mathcal{R}},\ \ K_z^{z'} = -\frac{-4+\mathcal{R}}{4+\mathcal{R}},\ \ \mathcal{R}^{-1} = \frac{V_1^2}{(3V_0^2 + V_2^2 + 2V_0V_2)r(t)}, \quad (3)$$

i.e. these coefficients depend only on the momentum transfer t.

On the other hand a dependence from the M^0-production angle is contained in the decays $N^*(1/2^+) \to p + \pi^0$ (or $p + \eta$), with P-wave production of the pseudoscalar meson. In this case we all $K_a^{a'}$ coefficients allowed by the P-invariance of strong interaction are nonzero:

$$K_y^{y'} = -\frac{\mathcal{R}}{4+\mathcal{R}},\ K_x^{x'} = (1 - 2cos^2\theta_\pi)\frac{\mathcal{R}}{4+\mathcal{R}},\ K_z^{z'} = (1 - 2cos^2\theta_\pi)\frac{4-\mathcal{R}}{4+\mathcal{R}},$$

$$K_x^{z'} = (sin\ 2\theta_\pi)\frac{-4+\mathcal{R}}{4+\mathcal{R}},\ K_z^{x'} = (sin\ 2\theta_\pi)\frac{\mathcal{R}}{4+\mathcal{R}},$$

where we used a coordinate system with the $z-$axis along the momentum transfer $\vec{k}$, $y||\vec{n}$, with $\hat{\vec{n}} = \vec{k} \times \vec{q}/|\vec{k} \times \vec{q}|$, ($\vec{q}$ is the meson 3-momentum) and $x||\vec{n} \times \vec{k}$.

An important property of the $\omega-$exchange model is the universal dependence of all the $K_a^{a'}$ from t, through the ratio $\mathcal{R}(t)$. An experimental check of the θ_π-

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dependence of the polarization transfer coefficient would be a signature of the validity of this model.

3 Symmetry and kinematics: the reaction $p+\alpha \rightarrow p+\alpha+\pi^0$

We give here a general formalism for the study of polarization phenomena in three body reactions and derive general properties. The application to $p+\alpha \rightarrow p+\pi^0+\alpha$ and in particular to polarization phenomena for different meson exchanges in Roper excitation will allow to conclude that out-of-plane measurements can sort out the reaction mechanism [11].

The main feature of a process with three particles in final state: $1+2 \rightarrow 3+4+5$ is the non-coplanarity of the kinematics. This can be expressed, for the case of $p+\alpha \rightarrow p+\pi^0+\alpha$, introducing the following combination of 3-momenta: $a=\dfrac{\vec{q}\cdot\vec{p}_1\times\vec{p}_2}{E_1E_2E_\pi}$, where $\vec{p}_1$ and $\vec{p}_2$ are the three momenta of the initial and final proton, $\vec{q}$ is the 3-momentum of the produced pion and E_1, E_2, E_π are the corresponding energies. This expression enters in the definition of five independent kinematical variables which are necessary for the complete description of a process $1+2 \rightarrow 3+4+5$.

The variable a is connected with the azymuthal angle ϕ, between the two reaction planes which characterize the process $p+\alpha \rightarrow p+\pi^0+\alpha$: the first is the scattering plane of the proton (i.e. the plane defined by the 3-momenta $\vec{p}_1$ and $\vec{p}_2$) and the second is the plane defined by the pion three-momentum $\vec{q}$ and the transferred momentum $\vec{p}=\vec{p}_1-\vec{p}_2$. The angle ϕ can be identified with the Treiman-Yang angle [12], which is currently used in the description of the properties of one-meson exchange in high energy collisions. This angle is also convenient for the description of the possible mechanisms for the Roper excitation, in $p+\alpha \rightarrow p+\pi^0+\alpha$. The parameter a is not only a pseudoscalar quantity, but it is a T-odd variable, as it is the product of three 3-momenta.

The non-coplanarity of the general kinematics for $1+2 \rightarrow 3+4+5$ results in specific properties of the polarization phenomena, different from the binary collisions. For example, in $p+\alpha \rightarrow p+\pi^0+\alpha$, the vector of polarization of the final proton can have, in the general case, all non-zero components, whereas, for any binary process, the proton polarization (for a P-invariant interaction) has only one non-zero component along the normal to the scattering plane, due to the presence of only one reaction plane.

The presence of the non-coplanarity ($a \neq 0$) has to be taken into account in establishing the spin structure of the matrix element for $p+\alpha \rightarrow p+\pi^0+\alpha$. If the P-invariance of the strong interaction holds, the matrix element is described by the following general parametrization (in the CMS of the considered reaction):

$$\mathcal{M}=\chi_2^\dagger\left[\vec{\sigma}\cdot\vec{m}f_1+\vec{\sigma}\cdot\vec{k}f_2+a\left(i\tilde{f}_1+\vec{\sigma}\cdot\vec{n}\tilde{f}_2\right)\right]\chi_1, \tag{4}$$

where χ_1 and χ_2 are the 2-component spinors of the protons in the initial and final states; f_1, f_2, $\tilde{f}_1$ and $\tilde{f}_2$ are the scalar independent amplitudes for $p+\alpha \rightarrow p+\pi^0+\alpha$, which are functions of the 5 kinematical variables; the unit vectors $\vec{m}$, $\vec{n}$ and $\vec{k}$ are defined as: $\vec{n}=\vec{p}_1\times\vec{p}_2/|\vec{p}_1\times\vec{p}_2|$, $\vec{k}=\vec{p}_1/|\vec{p}_1|$, $\vec{m}=\vec{n}\times\vec{k}$, The P-invariance of the strong interaction requires that all the amplitudes are even functions of the variable a.

From Eq. 4 we can calculate any polarization observable in terms of the scalar amplitudes and of the parameter a, analyzing powers, polarization transfer etc.. For example, the dependence of the differential cross section on the polarization $\vec{P}$ of the proton beam, in the general case of non-coplanar kinematics, is characterized by three independent analyzing powers, i.e.:

$$\frac{d\sigma}{d\omega}(\vec{p}\alpha \to p\pi^0\alpha) = \left(\frac{d\sigma}{d\omega}\right)_0 \left[1 + P_n A_n + a(P_m A_m + P_k A_k)\right], \tag{5}$$

where $\left(\frac{d\sigma}{d\omega}\right)_0$ is the differential cross section (with unpolarized proton beam), $d\omega$ is the element of the phase space for the 3-particle final state and P_n, P_m and P_k (A_n, A_m and A_k) are the three independent and non-zero components of the initial proton polarization vector (analyzing powers). The components P_m and P_k appear multiplied by the parameter a, therefore non contributing in the case of coplanar kinematics.

The dependence of the components of the final proton polarization $\vec{P}_f$ on the initial polarization $\vec{P}$ can be parametrized in the following way:

$$\begin{aligned} \vec{m}\cdot\vec{P}_f &= aD_{mm}\vec{m}\cdot\vec{P} + D_{mk}\vec{k}\cdot\vec{P} + D_{mn}\vec{n}\cdot\vec{P}, \\ \vec{n}\cdot\vec{P}_f &= aD_{nm}\vec{m}\cdot\vec{P} + aD_{nk}\vec{k}\cdot\vec{P} + D_{nn}\vec{n}\cdot\vec{P}, \\ \vec{k}\cdot\vec{P}_f &= D_{km}\vec{m}\cdot\vec{P} + D_{kk}\vec{k}\cdot\vec{P} + aD_{kn}\vec{n}\cdot\vec{P}, \end{aligned} \tag{6}$$

where D_{ij}, $i,j = m,n,k$, are the coefficients of polarization transfer from the initial to the final proton.

Let us give here only the expressions for the coefficient D_{nn}, in terms of the scalar amplitudes f_i, $\tilde{f}_i$ and the parameter a:

$$D_{nn}\left(\frac{d\sigma}{d\omega}\right)_0 = -|f_1|^2 - |f_2|^2 + a^2\left(|\tilde{f}_1|^2 + |\tilde{f}_2|^2\right),$$

One can see that $D_{nn} = -1$, for coplanar kinematics ($a = 0$). This is a known result, which follows from the P-invariance of strong interaction and this result is valid for any amplitudes f_1 and f_2 and for any model of the considered process and for any kinematical conditions, provided $a = 0$. In non-coplanar kinematics, in general, the presence of non-coplanar amplitudes gives $D_{nn} \geq -1$, therefore the quantity $1 + D_{nn}$ characterizes the relative role of non-coplanar amplitudes $\tilde{f}_1$ and $\tilde{f}_2$.

From the general properties of $\pi\alpha$-scattering (for the Deck mechanism) and of the process $\sigma + N \to N + \pi$ (for the Roper excitation), one can show that the non-coplanar amplitudes $\tilde{f}_1$ and $\tilde{f}_2$ are zero for both mechanisms, independently on their parametrizations. The numerical values of the amplitudes f_1 and f_2, and their dependence on the kinematical variables are different for σ and π-exchanges, but for any amplitudes f_1 and f_2 the polarization phenomena have some general properties: - $D_{nn} = 1$, in the whole region of kinematical variables (for coplanar and non-coplanar kinematics); - the polarization of the final proton has only one non-zero component, in the $\vec{n}$-direction, i.e. along the normal to the proton scattering plane; - the sign and absolute value of this component depend on the relative role of the considered mechanisms, and this dependence is very sensitive to the details of the corresponding amplitudes.

This 'coplanar-like' behavior of σ -and π- exchanges in $p+\alpha \to p+\pi^0+\alpha$ is related to the fact that these mediators are spinless particles. Such mechanisms can not connect different reaction planes. This conclusion does not depend on details, approximations, values of the constants or shape of FFs which are typically taken in the numerical applications, because it is based only on the value of the spin of the exchanged particles.

The most important difference of ω-exchange with respect to σ-exchange for the Roper excitation is due to the spin and has evident implications for the polarization phenomena: a vector particle exchange induces all four amplitudes different from zero, in the general case.

Let us consider the spin structure of $\omega-$exchange, taking into account, for simplicity, in the ωNN^*-vertex only the transverse, i.e. M1 form factor. In this case the matrix element for $p+\alpha \to p+\pi^0+\alpha$ can be written in the following form:

$$\mathcal{M}_\omega = \chi_2^\dagger \vec{\sigma}\cdot\vec{q}\vec{\sigma}\cdot\vec{k}_1 \times \vec{k}_2 \chi_1 F_\alpha(t) F_{NN^*}(t) \frac{1}{t-m_\omega^2} \frac{f_{N^*}}{w_1 - m^* + i\dfrac{\Gamma}{2}}, \qquad (7)$$

where $\vec{k}_1$ and $\vec{k}_2$ are the 3-momenta of the initial and final α-particles in CMS of the considered reaction, $F_\alpha(t)$ and $F_{NN^*}(t)$ are the FFs of the $\omega\alpha\alpha$ and ωNN^*-vertexes, f_{N^*} is the constant for the decay $N^* \to N+\pi$, m^* and Γ are the mass and the width of the Roper resonance N^*. For ω-exchange all four scalar amplitudes, coplanar and non-coplanar, are present. This is due to the exchange by vector particles, which connects strongly the different planes of the considered reaction and it depends only on the spin 1 nature of the exchanged particles. In general, ω-exchange, induces acoplanarity and, therefore, deviations from the relation $D_{nn}+1=0$.

4 Conclusions

High energy $d+p \to d+X$-reactions, which are driven by the strong interaction and electromagnetic processes as elastic $e+d$ scattering and electroexcitation of nucleonic resonances, $e+N \to e+N^*$, can be treated in a unified dynamical description. We show that the inelastic electromagnetic FFs of protons and neutrons, calculated in the algebraic model, can be successfully applied to the field of the hadronic interaction for quantitative predictions of different polarization observables. As an example we predict polarization phenomena for forward deuteron emission, in the GeV range, in $d+p \to d+X$, where X contains the possible nucleonic resonances, starting from the Roper (the Δ-resonance being forbidden by the conservation of the isotopic spin). We showed that the tensor analyzing power in this process, is especially sensitive to the Roper resonance excitation. This is due to the fact that among the resonances which can be excited in this kinematical region, only the Roper resonance has a non zero longitudinal isoscalar FF, due to the symmetry properties of the quark structure of these resonances, which are implicitely contained in the algebraic model. We generalized this model for exclusive channels as $d+p \to p+\pi+d$, $d+p \to p+\sigma+d$ and $\alpha+p \to \alpha+p+\pi^0$. We can consider the existing data about T_{20} not only as an evidence for the Roper resonance excitation, but also a specific indication of the properties of the isoscalar form factors for the excitation of N^* resonances, complementary to the inelastic electron-nucleon scattering, $e^- + N \to e^- + N^*$.

The possibility to unify in a common picture such different processes, as $e^-+d \to e^-+d$ and $e^-+N \to e^-+N^*$, from one side, and a hadronic process as $d+p \to d+X$, from another side, suggests a new perspective to study nucleon structure through electromagnetic and hadron excitation of nucleonic resonances.

In the process $p + \alpha \to p + \pi^0 + \alpha$, we showed that the matrix element for $\sigma-$exchange, often advocated to describe the Roper excitation and for the π-exchange (Deck-mechanism), has an evident 'coplanar-like' form, with vanishing non-coplanar amplitudes $\tilde{f}_1$ and $\tilde{f}_2$. But the ω-exchange (which seems the most probable physical candidate for the Roper excitation) induces a very rich spin structure of the corresponding contribution to the matrix element (with all four non-zero amplitudes), and specific polarization phenomena, which differ essentially from the case of $\sigma-$exchange. Only ω-exchange can induce non-coplanar polarization phenomena.

Future experimental data on polarization observables for $p + \alpha \to p + \pi^0 + \alpha$, which require a detection system in non-coplanar kinematics, will constitute a crucial test in order to disentangle the mechanisms involved.

Experiments, which confirm these predictions, were done in Saturne and Dubna. Further measurements are planned at COSY.

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