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SPIN OBSERVABLES AND ELECTROMAGNETIC EXCITATIONS OF NUCLEON RESONANCES

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ABSTRACT

We discuss the theoretical problems involved in relating the $\gamma N \rightarrow \pi N$ and $N(e, e' \pi)$ data to the $\gamma N \rightarrow \Delta, N^*$ transition form factors. The experimental accuracies needed to explore $\gamma N \rightarrow \Delta$ E2 and charge form factors from $p(e, e' \pi^0)$ spin observables A_{TT} and A_{TL} are presented.

In recent years QCD-inspired models have been developed to describe the structure of the nucleon (N), the Delta (Δ) and higher mass N^* resonances. An interesting way to test these models is to investigate their predictions of electromagnetic excitations of N to a Δ or N^* state. In this work we explore the extent to which this can be achieved by examining the spin observables of the $\gamma N \rightarrow \pi N$ and $N(e, e' \pi)$ reactions.

To illustrate the essential theoretical problems involved, it is sufficient to discuss the Δ excitation. Within any theoretical formulation, the unitarity condition requires that the amplitude of electromagnetic production of a pion on the nucleon has two terms

$$M_{fi} = \langle \pi N | J^\mu | N \rangle \cdot \epsilon_\mu + \langle \pi N | t_{\pi N} G_{\pi N} J^\mu | N \rangle \cdot \epsilon_\mu \quad (1)$$

where ϵ_μ is the photon polarization vector. The current operator J^μ describes how pions are electromagnetically produced from the nucleon. The second term of Eq. (1) describes the effects due to pion-nucleon final state interactions (FSI); $t_{\pi N}$ is a πN scattering operator and $G_{\pi N}$ is a πN propagator. The current matrix element can be written as

$$\langle \pi N | J^\mu | N \rangle = \langle \pi N | J_B^\mu | N \rangle + \langle \pi N | h_{\pi N \rightarrow \Delta} G_\Delta | \Delta \rangle \langle \Delta | J_\Delta^\mu | N \rangle \quad (2)$$

The first term is a nonresonant amplitude. For example, within the model of Ref. 1, it consists of nucleon-pole, nucleon-exchange, pion-exchange, ρ -exchange and ω -exchange terms. The focus of our interest is the second term of Eq. (2). It describes the $N \rightarrow \Delta$ transition; $h_{\pi N \rightarrow \Delta}$ is a $\Delta \rightarrow \pi N$ vertex and G_Δ is a Δ propagator. Lorentz invariance and gauge invariance require that

$$\langle \Delta | J_\mu | N \rangle = \bar{w}^\nu \Gamma_{\nu\mu} u$$

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with

$$\Gamma_{\nu\mu} = G_M(q^2) K_{\mu\nu}^M + G_E(q^2) K_{\mu\nu}^E + G_C(q^2) K_{\mu\nu}^C \quad (3)$$

where u and w^ν are respectively the Dirac spin-1/2 and Rarita-Schwinger spin-3/2 spinor, $K_{\mu\nu}^M$, $K_{\mu\nu}^E$, and $K_{\mu\nu}^C$ are kinematic factors given explicitly in Ref. 1. $G_M(q^2)$, $G_E(q^2)$, and $G_C(q^2)$ are respectively the magnetic M1, electric E2 and charge form factors. These three form factors contain information about the structure of N and Λ . For example, we can show that $G_E(q) = G_C(q) = 0$ and $G_M(q) \propto \exp(-\alpha q^2)$ within the s-wave nonrelativistic harmonic oscillator quark model. In a model involving coupling with a meson cloud, G_E and G_C will not be zero.

It is clear from Eqs. (1)-(2) that to determine the $N \rightarrow \Lambda$ transition form factors from the $\gamma N \rightarrow \pi N$ and $p(e, e' \pi)$ observables, we need a theory for an accurate description of both the πN scattering and the nonresonant production amplitude of $J_{\pi\pi}^H$. There is no model-independent way to extract these form factors from the data. In practice, this also means that the comparisons of the extracted form factors with the predictions of a hadron model are meaningful only within a theoretical framework in which the same hadron model can be consistently used in defining the nonresonant production amplitude and πN scattering. Within the model of Ref. 1, the extracted form factors can be interpreted properly only when we can establish the relationship between the employed phenomenological πN potential and a model which describes the structure of N and Λ as a quark-core surrounding by π , ρ and ω mesons. The progress in this direction is being made². For the present discussion, we will assume that the nonresonant term $J_{\pi\pi}^H$ of Eq. (2) and πN FSI can be described by the Hamiltonian model of Ref. 1. We focus our attention on a practical question: what are the experimental accuracies needed for determining the $N \rightarrow \Lambda$ transition form factors $G_M(q^2)$, $G_E(q^2)$ and $G_C(q^2)$ from $\gamma N \rightarrow \pi N$ and $N(e, e' \pi)$ data?

We first consider the $\gamma N \rightarrow \pi N$ reaction. Here the value of $G_E(0)$ and $G_M(0)$ can be determined by fitting the multipole amplitudes. In fitting the $M1(3/2)$ and $E2(3/2)$ amplitudes we found that $G_M(0)=2.28$ and $G_E(0)=0.07$. However we found that the calculated differential cross sections and spin observables are consistent with $G_E(0) = 0 \pm 0.15$. The existing polarization data are not sufficient to pin down the value of $G_E(0)$. $G_C(0)$ does not play a role in determining the $q^2 = 0$ $\gamma N \rightarrow \pi N$ reaction.

We next explore how the $N \rightarrow \Lambda$ transition form factors are related to the observables of $p(e, e' \pi)$ electroproduction processes. We first observed that the existing unpolarized inclusive $p(e, e')$ data are fairly consistent with the following form of the form factor

$$G_M(q^2) = G_M(0) F(q^2) \quad (4)$$

with $G_M(0) = 2.8$, as determined in our $\gamma N \rightarrow \pi N$ study. The q^2 -dependence is found to be

$$F(q^2) = a + (1-a) e^{q^2/b} \quad (5)$$

where $a = 0.83$ and $b = 0.192 \text{ (GeV/c)}^2$. However the inclusive $p(e, e')$ data are not sufficient to determine G_E and G_C . Assuming $G_E(q^2) = G_E(0)F(q^2)$ and $G_C(q^2) = G_C(0)F(q^2)$, we find that the existing inclusive $p(e, e')$ data are consistent with $G_E(0) = 0 \pm 0.15$ and $G_C(0)/G_M(0) = -0.15 \pm 0.15$. To pin down their values, it is necessary to investigate the exclusive $N(e, e')\pi$ processes with either the incident electron or/and the target nucleon polarized.

The direction of the target nucleon spin is specified by an angle θ_N with respect to the photon direction, and an angle ϕ_N with respect to the (e, e') scattering plane. We have found that the value of $G_E(0)$ is sensitive to the asymmetry A_{TT} of $\vec{p}(e, e')\pi$ with the spin of the target proton polarized along the photon direction

$$A_{TT} = \frac{1}{\sqrt{1-\epsilon^2}} \left(\frac{\sigma_{h=-+1^-} \sigma_{h=-1}^-}{\sigma_{h=-+1^+} \sigma_{h=-1}^-} \right)_{\theta_N = \phi_N = 0} \quad (6)$$

where ϵ is a kinematic factor and h is the helicity of the incident electron. The value of G_C is sensitive to the asymmetry with the spin of the target proton polarized in the direction perpendicular to the photon direction and on the (e, e') scattering plane

$$A_{TL} = \frac{1}{\sqrt{1-\epsilon^2}} \left(\frac{\sigma_{h=-+1^-} \sigma_{h=+1}^+}{\sigma_{h=-+1^+} \sigma_{h=-1}^-} \right)_{\theta_N = 90^\circ, \phi_N = 0} \quad (7)$$

Our results are shown in Fig. 1. The differences between the displayed three curves characterize the typical accuracies needed in future experiments.

To investigate higher mass nucleon resonances, we need to develop a theory for describing πN scattering involving coupling with various two-pion channels. This work is in progress, following the unitary formulation pioneered by Aaron and Amado³. In addition, we need to extend the nonresonant current matrix element J_μ to include the production of $\pi\Delta$, ρN and other 2π channels. This will then allow us in the near future to extract the $N \rightarrow \Delta, N^*$ transition form factors from the experiments to be performed at CEBAF.

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Fig. 1 The dependence of the $\vec{p}(\vec{\epsilon}, e^+ \pi^0)$ polarization observables A_{TL} and A_{TT} on the $N+\Delta$ transition strength at $q^2 = -0.2 \text{ (GeV/c)}^2$. For A_{TL} , the solid, dashed and dotted curves are from setting $G_C(0)/G_M(0) = 0.15, 0, -0.15$. For A_{TT} , the dashed, solid and dotted curves are from setting $G_E(0) = 0, 0.07, 0.15$.

To end, we want to point out that the present approach is significantly different from what has been done by Stoler⁴ in determining $N+\Delta$ form factors. He assumed that the nonresonant contributions can be parameterized phenomenologically as $\sigma_b = (W-W_{th})^{1/2} \sum_{n=1}^3 C_n (W-W_{th})^n$ with $W_{th} = M_N + m_\pi$. The interference between resonant and nonresonant terms is neglected. It remains to be seen the extent to which his approach is consistent with a unitary approach to the problem, as outlined in this talk.

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