A quark model framework for the study of nuclear medium effects

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A quark-model framework for studying nuclear medium effects on nucleon resonances is described and applied here to pion photoproduction on the deuteron, which is the simplest composite nucleon system and serves as a first test case. Pion photoproduction on nuclei is discussed within a chiral constituent quark model in which the quark degrees of freedom are explicitly introduced through an effective chiral Lagrangian for the quark-pseudoscalar-meson coupling. The advantage of this model is that a complete set of nucleon resonances can be systematically included with a limited number of parameters. Also, the systematic description of the nucleon and its resonances at quark level allows us to self-consistently relate the nuclear medium’s influence on the baryon properties to the intrinsic dynamic aspects of the baryons. As the simplest composite nucleus, the deuteron represents the first application of this effective theory for meson photoproduction on light nuclei. The influence of the medium on the transition operators for a free nucleon is investigated in the Delta resonance region. No evidence is found for a change of the Delta properties in the pion photoproduction reaction on the deuteron since the nuclear medium here involves just one other nucleon and the low binding energy implies low nuclear density. However, we show that the reaction mechanism is in principle sensitive to changes of Delta properties that would be produced by the denser nuclear medium of heavier nuclei through the modification of the quark model parameters.

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I. INTRODUCTION

The question of the influence of the nuclear medium on the properties of the nucleon and its resonances has attracted a lot of attention recently both in experiment and theory. It has also been one of the challenges to understanding strong QCD [1, 2] where the connection between the nucleon internal degrees of freedom and nuclear medium effects has been a key issue. Historically, nucleon resonances have been among the richest sources of information on low energy QCD phenomena. In particular, nucleon resonance excitations by electromagnetic probes and their decays via the strong interaction have been an ideal method for such a study. In experiment, the advent of high intensity photon beams at JLab, ESRF, ELSA, and MAMI has greatly improved the data for pion production on single nucleons at the resonance regions over the last decade. These precise measurements significantly improved our knowledge about nucleon resonances and further constrained theoretical phenomenologies [3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16]. However, our knowledge of resonance properties in nuclear reactions [20, 21, 22] is still very limited, although great strides have been made by several groups to tackle this issue with various prescriptions [23, 24, 25]. Because of the complexity of the strong interaction in nuclear reactions, many phenomena may contribute, making the theoretical analyses difficult. For instance, recent experimental work [24] on $\gamma + d \rightarrow \pi^0 + X$ and $\gamma + Ca \rightarrow \pi^0 + X$ suggested a controversial role for the $D_{13}(1520)$ by an empirical property change of the resonance [25]. It is essential for any theoretical model to introduce as few parameters as possible. This is our motivation for providing a quark-level prescription as a first step in this direction.

We propose a quark model approach for meson photoproduction on light nuclei, based on the recent success of a chiral effective theory for the pseudoscalar meson ($\pi$, $\eta$, $K$) photo- and electroproduction [17, 18, 19, 20]. Starting with an effective chiral Lagrangian for quark-pseudoscalar-meson coupling, this framework would in principle permit a self-consistent inclusion of all the $s$- and $u$-channel resonances. This is a sensible approach to the investigation of the effects of the nuclear medium on the resonances since we believe that such effects should have an overall influence on all the active baryons, i.e. both the nucleon and its resonances.

In this work, we will re-visit $\gamma d \rightarrow \pi^0d$. The deuteron, as the simplest composite nucleon system, provides the simplest example for which the effective theory can be directly applied. We will then explore the response of baryons (described by the quark model) to the nuclear medium, and establish the relation between nuclear medium effects and baryon intrinsic dynamics. Of course while we acknowledge that medium effects are hardly likely to have a significant

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effect for the case of photoproduction on the deuteron, the simplicity of the system in this preliminary work allows for a systematic study of the way such medium effects will be manifest in heavier systems, the subject of future work.

It will be helpful to briefly review the theoretical approaches to $\gamma d \rightarrow \pi^0 d$ available in the literature. The widely applied isobaric model has been successful in giving a reasonable description of the pion cross sections (see e.g. Ref. [28, 29]). Phenomenological methods have also been carried out based on analyses of single nucleon interactions [30, 31]. A relativistic quantum hadronic dynamical approach has also produced similar results [32]. More recently, a coupled channel approach adopting the Blomqvist-Laget operators [28] was developed [33]. In general, these approaches have reproduced the experimental data reasonably well in the Delta resonance regions due to the dominance of the Delta magnetic dipole.

A key question in nuclear reactions is the interplay of ambiguities from the reaction mechanism and short-distance components of the nuclear wavefunctions. Promisingly, for the two nucleon system, such a problem can be clarified due to the sensitivities of transition mechanisms to certain kinematics. This feature simplifies the problem and highlights the physics of interest. Here, we summarize several points which will support the simplifications, and enable us to derive novel information about the nucleon and its resonances in $\gamma d \rightarrow \pi^0 d$. Firstly, concerning the reaction mechanism, we neglect the rescattering contributions at the Delta resonance region due to the dominance of the direct scattering process above the production threshold. This is consistent with the findings of other models [29, 33]. Secondly, concerning the nuclear wavefunction, we are interested in the role played by the short-distance components and their effects on the cross section. We will show that, in the $\Delta$ resonance region, the deuteron $D$-state generally gives corrections to the backward angle cross sections, while the $S$-state dominates at forward angles. We will then investigate the impact of the nuclear medium effects on both of the kinematical regions.

II. THE MODEL FOR PION PHOTOPRODUCTION

Let us start with an effective Lagrangian for the quark-Goldstone-boson interaction [34]

$$\mathcal{L}_{\text{eff}} = \overline{\psi} [\gamma_\mu (i \partial^\mu + V^\mu + \gamma_5 A^\mu) - m] \psi + \cdots,$$

where $V^\mu$ and $A^\mu$ denote the vector and axial currents which have the following expressions:

$$V_\mu = \frac{1}{2} (\xi^\dagger \partial_\mu \xi + \xi \partial_\mu \xi^\dagger),$$
$$A_\mu = i \frac{1}{2} (\xi^\dagger \partial_\mu \xi - \xi \partial_\mu \xi^\dagger),$$

and the chiral transformation is,

$$\xi = e^{i \phi_m / f_m},$$

where $f_m$ is the decay constant of the meson $\phi_m$, which is the Goldstone boson field. In the SU(3) symmetry limit, the quark field $\psi$ is

$$\psi = \begin{pmatrix} \psi(u) \\ \psi(d) \\ \psi(s) \end{pmatrix},$$

and the meson field $\phi_m$ is a $3 \otimes 3$ matrix:

$$\phi_m = \begin{pmatrix} \frac{\sqrt{2}}{4} \pi^0 + \frac{1}{\sqrt{6}} \eta \\ \pi^- \\ -\frac{\sqrt{2}}{4} \pi^0 + \frac{1}{\sqrt{6}} \eta \\ \pi^+ \\ K^- \\ -\sqrt{2} \eta \\ K^0 \\ \eta \end{pmatrix}.$$  

Thus, the Lagrangian in Eq. (1) is invariant under the chiral transformation.

Expanding the field $\xi$ in Eq. (3) in terms of $\phi_m$, i.e. $\xi = 1 + i \phi_m / f_m + \cdots$, we obtain the standard quark-meson pseudovector coupling at tree level [15, 16]:

$$H_m = \frac{1}{f_m} \overline{\psi} \gamma_\mu \gamma_5 \partial^\mu \phi_m \psi,$$

where the Goldstone boson field $\phi_m$ is now presented by the SU(3) octet mesons ($\pi, \eta$ and $K$).
The quark-photon electromagnetic coupling is
\[ H_{em} = -e_q \bar{\psi}_u A^\mu(k, r) \psi, \]
where the photon has three momentum \( k \), and the constituent quark carries a charge \( e_q \).

This approach naturally places a constraint on the relative phases of those octet mesons in the SU(3) flavor symmetry limit, and relates the quark operators to the hadronic ones via explicit quark model wavefunctions for the baryons states. In this sense, the quark model transition amplitudes can be compared with hadronic ones, from which information about the baryon structure can be learned.

A systematic investigation of the four channels of pion photoproduction on a bare nucleon was carried out in [20], where it was shown that, up to 500 MeV photon energies, all the available observables could be reasonably accounted for with only one parameter for the Delta resonance coupling. Great effort was devoted in that work to restrict the number of parameters by taking advantage of the quark model symmetry in order that a complete set of resonances could be systematically taken into account. Overall quantitative agreement of the model with experimental data can be seen in [16]. In the present study, however, due to the fast fall-off of the deuteron momentum space wavefunction at large momenta and the photon energies considered \( (E_\gamma \sim 300 \text{ MeV}) \), contributions from resonances in the second resonance regions, \( (P_{11}(1440), S_{11}(1535), D_{13}(1520), S_{11}(1620), D_{33}(1700), P_{33}(1600), P_{13}(1720), F_{15}(1680) \) etc) are generally negligible. In the first resonance region, where the Delta and Born term are dominant, it is a good approximation to include only these two contributions in the direct scattering process.

III. PHOTOPRODUCTION ON THE DEUTERON

In the \( \gamma N \) c.m. system the unpolarized cross section for \( \gamma N \rightarrow \pi^0 N \) can be written as
\[ \frac{d\sigma}{dt} = \frac{1}{64\pi s} |k|^2 \sum_{m_\gamma} |\mathcal{M}_{f_1}(m_i, m_f, m_\gamma = +1)|^2, \]
where \( k \) is the photon momentum defining the \( z \)-axis, and \( s \) is the squared total c.m. energy; \( L_d = 1 \) is the deuteron total spin, while \( m_i, m_f \), and \( m_\gamma \) denote the spin projections for the initial, final state deuterons, and the incoming photon, respectively. The amplitudes with \( m_\gamma = -1 \) and \( +1 \) are not independent due to parity conservation.

The invariant amplitude \( \mathcal{M}_{f_1} \) in the direct scattering (Fig. 1) can be expressed as
\[ \mathcal{M}_{f_1} = \int d\mathbf{p}_1 \Phi_{m_f}^{d*}(\mathbf{p}_1 + \mathbf{q}/2) \langle \mathbf{p}_2, \mathbf{q} | \hat{T}_{\gamma N \rightarrow \pi^0 N} | \mathbf{p}_2, \mathbf{k} \rangle \Phi_{m_i}^d(\mathbf{p}_1 + \mathbf{k}/2), \]
where \( \Phi_{m}^{d} \) denotes the deuteron ground state wavefunction with spin projection \( m \); \( \hat{T}_{\gamma N \rightarrow \pi^0 N} \) is the transition operator for the single nucleon interaction derived within the quark model, and is the nucleon photoproduction operator averaged over the isospin wavefunction of the deuteron. The kinematical variables are defined as, \( \mathbf{p}_2 = -\mathbf{k} - \mathbf{p}_1 \), and \( \mathbf{p}_2^* = -\mathbf{q} - \mathbf{p}_1 \).

The deuteron wavefunction is defined as
\[ \Phi_{m}^{d}(\mathbf{p}) = \sum_{L=0,2; \Lambda, m_\lambda} i^L u_L(|\mathbf{p}|) Y_{\Lambda\Lambda}(\mathbf{p}) \langle L\Lambda, 1m_s | 1m \rangle \chi_{L m_\lambda}^{d}, \]
where \( L = 0 \) and 2 denote the \( S \) and \( D \)-state components and the spin wavefunction is
\[ \chi_{L m_\lambda}^{d} = \sum_{m_1, m_2} \left( \frac{1}{2} m_1, \frac{1}{2} m_2 | 1m_s \right) \chi_{m_1}^{+} \chi_{m_2}^{-}, \]
where \( \chi \) is the nucleon spin wavefunction, and \( m_1 \) and \( m_2 \) are spin projections for the spectator and active nucleon.

The well-established Paris model [31] wavefunction for the deuteron is adopted, which means ambiguities from the nuclear wavefunctions are minimised in this examination. The Paris potential is obtained from a phenomenological momentum-dependent meson exchange model for the nucleon-nucleon \( (N-N) \) interaction with parameters chosen to fit \( n-p \) scattering data for energies from the deuteron binding energy up to several hundred MeV, thus giving a reliable description of the deuteron wavefunction down to short \( n-p \) separations.

To check the sensitivity of the reaction mechanism to the nuclear structure, we also carry out the calculation with a Hulthén wavefunction, for which the detailed description and parameters are given in Ref. [37]. This simpler wavefunction is generated by the Yamaguchi-Yamaguchi separable \( n-p \) interaction [38] which has the useful feature...
that the $S$ and $D$ components of the wavefunction have simple analytical forms in momentum space. The $n-p$ potential in this model has parameters adjusted to give the experimental deuteron binding energy, quadrupole moment, and $n-p$ triplet state effective range, and scattering length, all to high accuracy. However, it is not expected to be as accurate as the Paris wavefunction at larger momenta. Thus, since the long-distance asymptotic behavior of the deuteron wavefunction is well-known, the contrast will further pin down the nuclear structure effects arising from short-distance components. We neglect the $D$-state to $D$-state transition term in the amplitude in Eq. (4) but retain the $S$ to $D$ transition. The $D$-$D$ transition may become important at high momentum transfers and show up in the backward-angle cross sections. However, this is not the focus in this work.

Firstly, we examine the single nucleon reaction operators in $\gamma d \rightarrow \pi^0 d$ by applying the transition operators derived in the free nucleon reaction to the direct scattering process (Fig. 1). Note that the quark model parameters are determined in the free nucleon reactions while the deuteron wavefunction used is from independent studies. Our calculations are therefore parameter-free predictions of the effective theory in the quark model framework. It should also be pointed out that since the final state pions are treated as point-like particles, the size effects and possible medium effects on the mesons are absorbed into the quark model parameters. This is different from isobaric prescriptions, where the meson and baryon degrees of freedom could be influenced by the nuclear medium separately (see e.g. Refs. 24, 25, 26). In this study, we will present a new dynamic view of this phenomenon by relating the nuclear medium’s influence on the baryon properties to the intrinsic dynamic aspects of baryons via the quark model parameters. We note that similar ideas are also proposed in Ref. 39.

In Fig. 2, the results for the differential cross sections at $E_s = 300$ MeV with both wavefunctions are presented. As shown by the solid (Paris wavefunction) and dashed curve (Hulthén wavefunction) in Fig. 2, these two wavefunctions produce the same cross sections at forward angles due to the same asymptotic behavior, while discrepancies arise at large angles due to differences between these two models at short distances. Although the experimental data 40 are still sparse, the cross sections using both wavefunctions are in good agreement with the data over a wide angle region.

We also present the results without the $D$-state contributions (the dotted and dot-dashed curve stand for the $S$-state Paris and Hulthén wavefunctions, respectively), where the large-angle cross section differences highlight the $D$-state contributions.

The above result is a direct examination of the quark model treatment for the elementary process, which deserves more careful consideration. Since nucleons in the deuteron are weakly bound, one would expect a weak effect from the nuclear medium. The above result indeed suggests that the baryons behave as they do in the single nucleon reactions. Therefore, in principle no parameter change to the baryon properties is needed here. This conclusion is consistent with other previous studies 28, 29, 30, 31, 32, 33. However, where our approach has an advantage is that it also allows us to examine the impact of the nuclear medium more systematically. We consider a mechanism that changes the properties of the Delta resonance due to the change of quark model parameters, e.g. quark potential strength within the baryons.

IV. MECHANISM FOR MEDIUM MODIFICATION

The quark model potential strength $\alpha_h$ and constituent quark mass $m_q$ are explicitly related to the mass of the baryons in the nonrelativistic constituent quark model (NRCQM), where the nucleon and Delta resonance belong to the same representation 41. A simple mass relation from the quark hyperfine interaction will allow us to make an empirical connection:

$$M_N(\alpha_h, m_q) = M_0(\alpha_h, m_q) - \frac{1}{2} \delta_q(\alpha_h, m_q),$$

$$M_\Delta(\alpha_h, m_q) = M_0(\alpha_h, m_q) + \frac{1}{2} \delta_q(\alpha_h, m_q),$$

(12)

where $M_0$ is the degenerate mass between the nucleon and Delta before the hyperfine splitting, and $M_N$ and $M_\Delta$ are the physical masses of the nucleon and Delta. The quantity $\delta_q$ is determined by the contact coupling:

$$\delta_q = \frac{4\alpha_s \alpha_h^2}{3\sqrt{2}\pi m_q^2},$$

(13)

where $\alpha_s$ is the electromagnetic coupling. It is reasonable to assume, for the case of the deuteron, that the nucleon mass $M_N$ is fixed for any set of parameters. We can then express the mass formula as:

$$\tilde{M}_\Delta(\tilde{\alpha}_h, m_q) = \left( \frac{\delta_q}{\delta_q^*} \right) [M_\Delta(\alpha_h, m_q) - M_N] + M_N,$$

(14)
where the “barred” quantities refer to the values given by the medium-modified parameters.

The Delta’s strong decay width for $\Delta \to \pi^0 N$ can be also related to the quark model parameters:

$$\Gamma_\Delta = \left( \frac{g_{N\Delta}^2}{4\pi} \right) \frac{|q|^3 (E_f + M_N)}{8M_\Delta M_N^2} \left( \frac{\omega_m}{E_f + M_N} + 1 \right)^2 e^{-q^2/3\alpha^2},$$

where $E_f = (M_N^2 + |q|^2)^{1/2}$ and $\omega_m = (m_q^2 + |q|^2)^{1/2}$ are the nucleon and pion energies in the Delta c.m. system. These variables are determined by the Delta mass, which hence are related to Eq. (14). Also, the change of the potential strength will influence the form factors for baryons, i.e. both nucleon and Delta. Therefore, even though we fix the mass of the nucleon, its size may change due to the change of quark potential strength in the nuclear medium. For the Delta, we can simply express $\Gamma_\Delta = \Gamma_\Delta(\alpha_h, m_q)$. The $\pi N \Delta$ coupling $g_{\pi N \Delta} = g_{\pi NN} C_{\pi N \Delta}$ is determined in the single free nucleon reaction [16], where $C_{\pi N \Delta}$ is the strength given by the experimental data.

The simple relations from the static properties of baryons introduces new aspects in the reaction mechanism. If the medium influence leads to a significant change to $\alpha_h$ and $m_q$, from Eq. (14) and (15), the mass shift and the width change of the Delta will be correlated. As a sensitivity test, we assume the quark mass is fixed, and find that a change of the quark potential strength from $\alpha_h = 330.31$ MeV (determined in the free nucleon reaction [16]) to $\alpha_h = 342$ MeV results in a mass increase of about 36 MeV as suggested by other calculations and total width change from $\Gamma_\Delta = 120$ MeV to $\Gamma_\Delta = 156.7$ MeV.

In Fig. 3 we present the calculated results (dashed curve) for the differential cross sections with such a property change to the baryons. By comparison with the unchanged-parameter calculation (solid curve), we see that the cross section is very sensitive to the quark model parameters at forward angles. This can be understood as follows. The overall shape of the cross section is governed by the behaviour of the deuteron wavefunctions, which ensure that the integrand in Eq. (9) is only non-negligible when the arguments of both wavefunctions are small. This is when $p_1$ is of the same order as both $k/2$ and $q/2$, and when $k$ and $q$ are parallel (forward scattering). In the c.m. frame we also have $p_1 + p_2 = -k$ and hence at forward angles where $p_1$ is large, $p_2$, the momentum of the active nucleon, is at its smallest; at larger scattering angles it carries away more momentum from its interaction with the photon. Since the photon energy is chosen to be close to the Delta threshold in the photon-active nucleon lab system, the forward angles correspond to the kinematics where the Delta will contribute significantly to the cross section, and medium effects on the Delta will also show up most here. At backward angles, most of the momenta carried by the deuteron will be on the active nucleon, resulting in a shift of the photon-active-nucleon c.m. energy far away from the Delta mass position leading to the small effects from the parameter change.

The fact that the overall shape of the cross section is governed by the behaviour of the deuteron wavefunctions, also accounts for the negligible effects from the energy conservation breaking at the initial photon-nucleon and final meson-nucleon interaction vertices in this reaction. For denser nuclear medium, such effects may become important due to larger contributions from short-range components of nuclear wavefunctions. This could be a possible mechanism by which the nuclear medium can change the quark model parameters.

In Fig. 4 the medium influence on the Delta magnetic dipole is compared with the free nucleon case in the photon-nucleon c.m. frame. The largest effects are from the region where the Delta is excited close to its mass shell. As discussed above, for a photon energy $E_\gamma = 300$ MeV, the close-to-threshold region corresponds to the forward scatterings, with the off-shell region to the backward angles. When the Delta goes far off-shell, the parameter change effects become negligible. Thus, one would expect that the forward angle scattering is the ideal place for the investigation of the Delta property changes due to the medium.

It is noted that the major contributions to the small angle cross section come from deuteron configurations in which the neutron-proton ($n-p$) separation is larger than the range of strong interactions. For these configurations any medium modifications to $\alpha_h$ will be negligible. Figure 4 should therefore only be used as an indication of the relative sensitivity of the pion production process at different momentum transfers to a ‘fixed’ density-independent change to $\alpha_h$. Any density dependent mechanism which produced a change at small $n-p$ separations (and large momentum transfer) of the magnitude used in our sensitivity test would be expected to be associated with much smaller changes at large $n-p$ separations and small momentum transfers.

V. SUMMARY

We have studied the photoproduction of $\pi^0$ on the deuteron at the energy of the Delta excitation in a quark model framework with an effective chiral Lagrangian. The advantage of this approach has been that the nucleon and its resonances were introduced into the nuclear reaction with only a limited number of parameters [16]. In this approach we propose that the nuclear medium effects on the baryon properties can be recognized through the change of quark
model parameters for baryons. In particular, the nuclear medium may influence the quark potential strengths of a baryon state, and further lead to changes to its mass and width. It thus naturally relates the resonance property changes to their intrinsic dynamical aspects. Mechanisms by which the nuclear medium changes the quark model parameters need to be addressed by investigating reactions on heavier and denser nuclei.

We expect that a systematic investigation of reactions on heavier nuclei will establish the medium-density-dependence of the quark model parameters. It is also important to extend this approach to the second resonance region, where higher resonances such as $P_{11}(1440)$, $D_{13}(1520)$, $S_{11}(1535)$, etc., can be investigated. Consequent work will be reported elsewhere.

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FIG. 1: Schematic diagrams for: (a) the direct scattering process in $\gamma d \to \pi^0 d$; (b) the $s$-channel process for the pion production; and (c) the $u$-channel process for the pion production. In (b) and (c), the photon and pion will couple to the constituent quarks of the baryons as illustrated in Ref. [16].

FIG. 2: Angular distributions for $\gamma d \to \pi^0 d$ at $E_\gamma = 300$ MeV. The solid and dashed curve denotes the calculations adopting the Paris and Hulthén wavefunctions with both $S$ and $D$ states, while the dotted and dot-dashed curves denote those with only the $S$ state components, respectively. Data are from Ref. [40].
FIG. 3: Estimation of effects from the Delta property change. The solid curve is the result of the unchanged-parameter calculation (the same as the solid one in Fig. 2). The dashed curve denotes the results for a changed Delta with a flattened width and larger mass. Data are the same as in Fig. 2.

FIG. 4: The Delta magnetic dipole plotted in term of the photon energy in the γN lab system. Data are from SAID analyses [42].