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Cross section of pseudoscalar meson photoproduction within the ELA

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Abstract

We study the contributions of background and resonance terms to the total cross section of photoproduction of mesons off the free nucleon. The model we use is consistent and based on an effective Lagrangian approach (ELA) which includes nucleon Born terms, vector meson exchange terms, and nucleon resonances. The interaction Lagrangians are chiral symmetric, gauge invariant and crossing symmetric. The results we obtain are compared to available experimental data and agreement is found in the energy region from threshold up to 0.55 GeV in the case of π photoproduction. We outline the possibility to extend this calculation to the case of η meson photoproduction.

Keywords: Photoproduction, Effective Lagrangian approach, Eta meson, Pi meson

1. Introduction

The production of mesons by hadron-induced reactions has been extensively used in the study of nucleon resonances. In particular, the scattering of pions by free nucleons and nucleus has greatly contributed to the experimental data base. This type of reactions are complicated since the initial and final states are governed by the strong interaction. However, the existence of high duty-cycle electron accelerators opens the possibility for studying reactions induced by the electromagnetic interaction: photoproduction and electroproduction of mesons (π, η, etc.) off the free nucleon and off the nucleus.

Several phenomenological models have been developed for studying the properties of nucleon resonances through photoproduction of mesons: partial wave analysis, isobar analysis, effective Lagrangian approach models (ELAs), chiral effective Lagrangian models (CELs), etc.

In this paper we present a consistent formalism for the study of meson photoproduction off free nucleons. As a starting point, we show the details for the case of π-photoproduction. For the case of η-photoproduction, the situation is as follows: a bump-like structure has been experimentally observed in the $\gamma n \rightarrow \eta n$ cross section, but not in the $\gamma p \rightarrow \eta p$ one [1]. Thus, we outline here the main characteristics of the calculation for η-photoproduction and the challenge will be to extend in the near future the present formalism to explain the origin of that bump-like structure.

2. The Model

We adopt ELA because all contributions to the photoproduction reaction are derived on an equal footing from the effective Lagrangian densities corresponding to the interaction vertices. In ELAs, each particle is regarded as an effective field having mass, strong decay width, etc. In this way, the number of parameters of the model is reduced to a smaller set of coupling constants which can be taken consistently from other reactions. Our model includes different contributions: Born terms, nucleon resonances, vector-meson exchanges, etc. as described below. With respect to the meson-nucleon coupling, the frequently encountered forms of the meson-nucleon interaction in photoproduction of mesons are the pseudoscalar (PS) and pseudovector (PV) couplings.

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However, in the specific case of π-photoproduction the πNN coupling is preferred to be PV rather than PS, in accord with current algebra results and chiral symmetry [2]. On the other side, in the case of the η the Low Energy Theorems (LETs) do not apply [3, 4]. Therefore, as an example of the model we give details for the calculation of the cross section for the photoproduction of pions from free nucleons. We evaluate the contributions given by each of the diagrams shown in Fig. (1a)-(1e) to the decay amplitude.

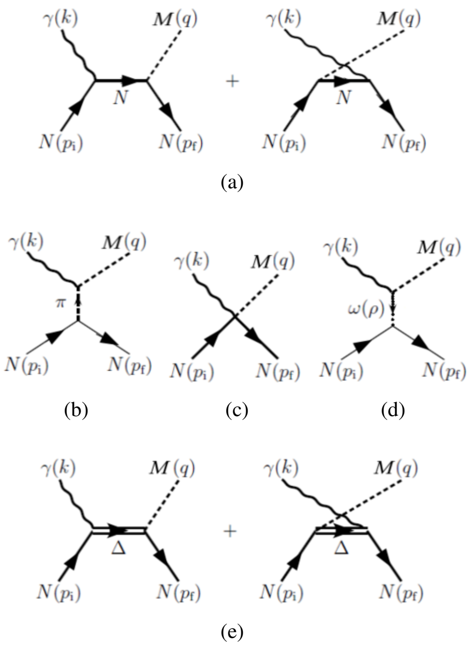

Figure 1: Born terms: (a), (b) and (c). Vector-meson exchanges: (d). Nucleon resonances: (e). $M = \pi, \eta, \cdots$ indicates the produced meson.

2.1. Born terms

Born terms are the Feynman diagrams in which only *pion*, *photon*, and *nucleon* are involved. The interacting Lagrangians involved are given by

$$\mathscr{L}_{\pi\mathrm{NN}} = -\frac{f_{\pi\mathrm{NN}}}{m_\pi}\overline{\Psi}_N\gamma_5\gamma_\mu\vec{\tau}\Psi_N\cdot\partial^\mu\vec{\Phi}_\pi, \qquad (1)$$

where $f_{\pi\mathrm{NN}}$ is the *pseudovector* coupling constant, with $f^2_{\pi\mathrm{NN}}/4\pi$ =0.0749.

$$\begin{aligned}\mathscr{L}_{\gamma\mathrm{NN}} =& -eA^\mu\overline{\Psi}_N\gamma_\mu\frac{1}{2}\left(\kappa_1^{\mathrm{s}}+\kappa_1^{\mathrm{v}}\tau_3\right)\Psi_N\\ &-\frac{e}{4M}\overline{\Psi}_N\frac{1}{2}\left(\kappa_2^{\mathrm{s}}+\kappa_2^{\mathrm{v}}\tau_3\right)\sigma_{\mu\nu}\Psi_N F^{\mu\nu}, \qquad (2)\end{aligned}$$

where $\kappa_j^{\mathrm{s}} \equiv \kappa_j^p + \kappa_j^n$ and $\kappa_j^{\mathrm{v}} \equiv \kappa_j^p - \kappa_j^n$ are the isoscalar and isovector nucleon form factors, respectively, with $\kappa_1^{\mathrm{s}}(k^2=0) = \kappa_1^{\mathrm{v}}(k^2=0) = 1$, $\kappa_2^{\mathrm{s}}(k^2=0) = \kappa^p+\kappa^n = -0.12$, and $\kappa_2^{\mathrm{v}}(k^2=0) = \kappa^p-\kappa^n$ =3.70.

$$\mathscr{L}_{\gamma\pi\pi} = e\left[\partial_\mu\vec{\Phi}_\pi\times\vec{\Phi}_\pi\right]_3 A^\mu, \qquad (3)$$

and

$$\mathscr{L}_{\gamma\pi\mathrm{NN}} = -e\frac{f_{\pi\mathrm{NN}}}{m_\pi}\overline{\Psi}_N\gamma_5\gamma_\mu\left[\vec{\tau}\times\vec{\Phi}_\pi\right]_3\Psi_N A^\mu. \qquad (4)$$

2.2. Vector-meson terms

The main contribution of *vector mesons* to π photoproduction is given by ρ and ω mesons:

$$\mathscr{L}_{\rho\mathrm{NN}} = -\frac{g_{\rho\mathrm{NN}}}{2}\overline{\Psi}_N\vec{\tau}\cdot\left[\gamma_\mu-\frac{\kappa_\rho}{2M}\sigma_{\mu\nu}\partial^\nu\right]\vec{\Phi}^\mu_\rho\Psi_N, \qquad (5)$$

$$\mathscr{L}_{\rho\pi\gamma} = e\frac{g_{\rho\pi\gamma}}{m_\pi}\tilde{F}_{\mu\nu}\partial^\mu\vec{\Phi}_\pi\cdot\vec{\Phi}^\nu_\rho, \qquad (6)$$

$$\mathscr{L}_{\omega\mathrm{NN}} = -\frac{g_{\omega\mathrm{NN}}}{2}\overline{\Psi}_N\left[\gamma_\mu-\frac{\kappa_\omega}{2M}\sigma_{\mu\nu}\partial^\nu\right]\Phi^\mu_\omega\Psi_N, \qquad (7)$$

and

$$\mathscr{L}_{\omega\pi\gamma} = e\frac{g_{\omega\pi\gamma}}{m_\pi}\tilde{F}_{\mu\nu}\partial^\mu[\vec{\Phi}_\pi]_3\Phi^\nu_\omega, \qquad (8)$$

where $\tilde{F}_{\mu\nu} \equiv \frac{1}{2}\epsilon_{\mu\nu\sigma\rho}F^{\sigma\rho}$.

2.3. Resonance terms

Resonance excitation is the dominant reaction process in photoproduction of mesons. In the *intermediate-energy* region, the $\Delta_{33}(1232)$ gives the main contributotion in photoproduction of pions:

$$\mathscr{L}_{\pi\mathrm{N}\Delta} = \frac{f_{\pi\mathrm{N}\Delta}}{m_\pi}\overline{\Psi}^\mu_\Delta\vec{T}\,\Psi_N\cdot\partial_\mu\vec{\Phi}_\pi + \mathrm{h.c.} \qquad (9)$$

$$\mathscr{L}_{\gamma\mathrm{N}\Delta} = ie\overline{\Psi}^\mu_\Delta T_3\Gamma_{\mu\nu}A^\nu\Psi_N + \mathrm{h.c.}, \qquad (10)$$

where $\vec{T}$ is the $N\to\Delta$ *isospin excitation operator* and $\Gamma_{\mu\nu} \equiv G_M(0)K^M_{\mu\nu} + G_E(0)K^E_{\mu\nu}$, with $K^M_{\mu\nu}$ and $K^E_{\mu\nu}$ as given in [5]. The Δ propagator is given in Eq.(10) from [6] and the unstable character of the Δ in the propagator is introduced through the replacement $M_\Delta \to M_\Delta - \frac{i}{2}\Gamma_\Delta$ [7] everywhere in the Δ propagator, with Γ_Δ constant.

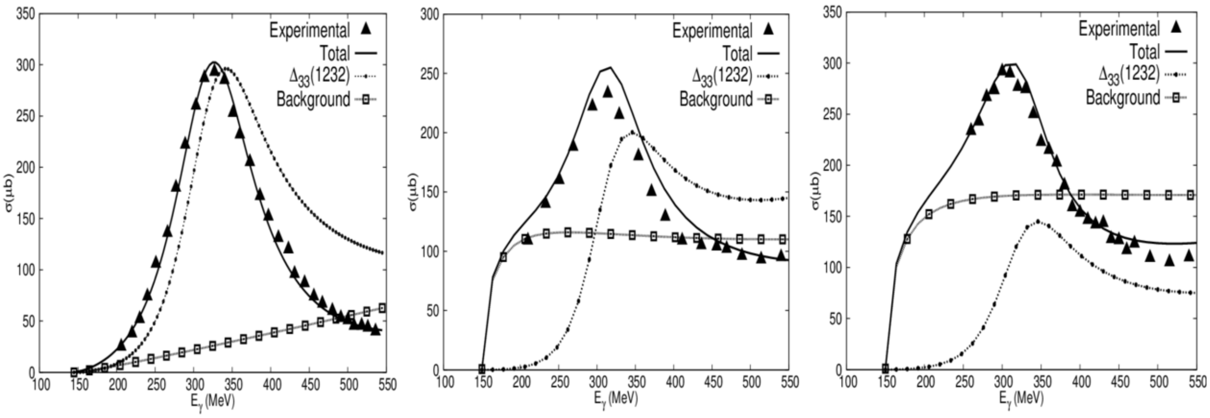

Figure 2: Calculated cross sections of $\gamma p \to \pi^0 p$ (left), $\gamma p \to \pi^+ n$ (center), and $\gamma n \to \pi^- p$ (right) reactions compared with data [8, 9].

3. Cross section

The differential cross-section for pion photoproduction will be calculated as

$$\frac{d\sigma}{d\Omega^*} = \frac{|\vec{q}|}{2|\vec{k}|} \sum_{i=1}^{4} |H_i(\theta^*)|^2, \quad (11)$$

where

$$H_1(\theta^*) = -\frac{i}{\sqrt{2}} \sin\theta^* \cos\frac{\theta^*}{2} (\mathscr{F}_3 + \mathscr{F}_4),$$
$$H_2(\theta^*) = i\sqrt{2}\cos\frac{\theta^*}{2}\left[(\mathscr{F}_2 - \mathscr{F}_1) + \sin^2\frac{\theta^*}{2}(\mathscr{F}_3 - \mathscr{F}_4)\right],$$
$$H_3(\theta^*) = \frac{i}{\sqrt{2}} \sin\theta^* \sin\frac{\theta^*}{2} (\mathscr{F}_3 - \mathscr{F}_4),$$
$$H_4(\theta^*) = i\sqrt{2}\sin\frac{\theta^*}{2}\left[(\mathscr{F}_1 + \mathscr{F}_2) + \cos^2\frac{\theta^*}{2}(\mathscr{F}_3 + \mathscr{F}_4)\right].$$

Here the $\mathscr{F}_i$'s are the so-called *CGLN-amplitudes* as functions of $\sqrt{s}$ and the c.m. angle θ^* between π and N [10]. By using the interactions given in Sec. 2, we have evaluated the contribution of each one of the Feynman diagrams shown in Fig. (1a)-(1e) to the *CGLN-amplitudes*. The total π photoproduction cross section for the reactions $\gamma p \to p\pi^0$, $\gamma p \to n\pi^+$ and $\gamma n \to p\pi^-$ are summarized in Fig. (2).

4. Conclusions

From Fig. (2) we observe that the present calculation exhibits a very good agreement with experimental data. Our results show that not only the resonance $P_{33}(1232)$ contributes significantly in the energy region considered, but also the non-resonant terms (backgroung) plays an important role. The background contributions are suppressed for the neutral channel: the contact term and the pion-pole term cannot contribute since the photon does not couple to the neutral pion, so that only nucleon Born terms mix with the resonance excitation. On the other hand, photoproduction of charged pions close to threshold is dominated by background terms, in particular the contact term. At higher incident photon energies, the contact and pion-pole terms are still important.

The good description of data within our ELA model gives confidence in the followed procedure. In the near future we will evaluate the η-photoproduction cross section. We remark the following differences with π-photoproduction: (i) for η meson we need to consider both the PS and the PV parts of the η-nucleon interaction, (ii) only spin-1/2 resonances ($S_{11}(1535)$, $S_{11}(1650)$, $P_{11}(1710)$, etc.) will contribute, and (iii) the strong ηNN and ηNR couplings and also the resonance magnetic moments are unknown parameters, and should be treated as fitting parameters.

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