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Spin asymmetry for the $^{16}O(\vec{\gamma}, \pi^- p)$ reaction in the $\Delta(1232)$ region within an effective Lagrangian approach

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A B S T R A C T

The spin asymmetry of the photon in the exclusive $A(\vec{\gamma}, \pi N)A - 1$ reaction is computed employing a recently developed fully relativistic model based on elementary pion production amplitudes that include a consistent treatment of the spin-3/2 nucleon resonances. We compare the results of this model to the only available data on Oxygen [K. Hicks, et al., Phys. Rev. C 61 (2000) 054609] and find that, contrary to other models, the predicted spin asymmetry compares well to the available experimental data in the $\Delta(1232)$ region. Our results indicate that no major medium modifications in the $\Delta(1232)$ properties are needed in order to describe the measured spin asymmetries.

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1. Introduction

The excitation of nucleon resonances embedded in nuclei has become an important research topic during last decades. Among all of them, the excitation of the $\Delta(1232)$ (Δ in what follows) is of particular relevance in nuclear reactions at intermediate energies. The possible modifications of the properties of the Δ during its propagation and decay within the surrounding medium remains an open question.

Although pion-induced reactions such as (π, π') or $(\pi, \pi'N)$ were primarily invoked to shed light on this issue [1], the cleanest way to study both the nucleon and its excitations is through electromagnetic probes, i.e., photons and electrons, whose interaction with matter is better known. Additionally, real or virtual photon-induced reactions are intrinsically much weaker than pion-induced ones, and can therefore sample the entire nuclear volume. In the last years pion photoproduction from the nucleon has focused the attention of diverse experimental [2,3] and theoretical groups [4–7] worldwide, what has allowed a good description of the Δ region.

All this research has pushed our knowledge on the low-lying resonance region to a point where a reliable extension of such studies from free to bound nucleons is feasible. The relevant observables for pion photoproduction off nuclei at the appropriate energies should, in principle, contain information on the medium modifications (if any) of the Δ. Two requirements are needed before final conclusions can be drawn: high precision data and reliable theoretical models with proper Δ-excitation content. The comparison of theory and data should provide the clue. If the reaction model reproduces the data when using the Δ properties deduced from pion production from free nucleons, then medium modifications of the Δ are either small or they have no influence on pion production observables. On the contrary, if the data cannot be explained by means of a reaction model with the same Δ parameters employed in the pion production from free nucleons, it may constitute a signature of medium modifications of the properties of the Δ. Of course, conclusions depend strongly on the reliability of the ingredients of the model, for instance the nuclear description and the elementary pion production operator.

Among the photonuclear reactions that investigate the behavior of the Δ in the nuclear medium, one of the most interesting is the exclusive $A(\gamma, \pi N)A - 1$ reaction, where only one final state is involved. During the past 20 years, this reaction has been the focus of experiments at many facilities, such as TOMSK [8], MIT-

Bates [9], MAMI [10], LEGS [11], and NIKHEF [12]. A non-sparse data set has been collected for double and triple differential cross sections, including not only $(\gamma, \pi^- p)$ but also $(\gamma, \pi^+ n)$ data, that should provide stringent constraints on theoretical models. These data have been compared to calculations ranging from factorized models—inspired in the Blomqvist and Laget pion photoproduction model off nuclei [13]—to more sophisticated distorted wave impulse approximation models [14–16]. From a careful review of the literature, one realizes that although most models succeed in reproducing partial sets of cross section data, there is no model capable of describing adequately the whole set of pion photoproduction data on nuclei. As pointed out in [15], a major concern arises when one realizes that the theoretical models [14,15] differ strongly even at the plane-wave limit. Before inferring signatures of medium modifications of the Δ from these reactions, it is mandatory to count first on reliable calculations at least at the plane wave level. There is a need to review the theoretical models for pion photoproduction off nuclei before progress in the knowledge of the in-medium Δ properties can be achieved.

Particularly interesting are the spin asymmetry data obtained at LEGS for the ^{16}O$(\vec{\gamma}, \pi^- p)$ reaction. The asymmetry is free from normalization problems, is predicted to be large, and is relatively insensitive to ambiguities in the theory, such as description of non-local effects or width of the Δ resonance [14]. In addition, the spin asymmetry is almost independent of the pion and nucleon distortions [14]. Thus, this observable becomes an excellent test for the accuracy of the underlaying elementary pion photoproduction operator and provides a stringent test for theoretical models. Indeed, it was pointed out in [14] that if an experiment finds deviations of the spin asymmetry even from the simple plane-wave predictions, this could be an indication of medium modifications of the Δ propagator. The data collected at LEGS showed that the measured asymmetries were consistently below the theoretical predictions by the Li, Wright, and Bennhold's model [11, 14]. It was claimed that modifications to the properties of the Δ resonance could be necessary to achieve agreement between data and calculations [11]. However, this model used harmonic oscillator wave functions to describe the bound nucleon. Before definite conclusions are made about medium modifications of the Δ, an improvement of the model ingredients, such as the struck nucleon wave functions and Δ Lagrangian, must be done.

In this Letter we present a model for the exclusive $A(\vec{\gamma}, \pi N)A-1$ reaction, starting from the elementary process involving the photon, pion, nucleon and its resonances. We perform a non-factorized computation based on a recently developed relativistic pion photoproduction operator [5]. For free nucleons, the model developed in [5] provides a good description [7] of the latest fit to the world database of electromagnetic multipoles [3]. It is based upon an effective Lagrangian approach, fully relativistic, and it displays gauge invariance, chiral symmetry, and crossing symmetry as well as a consistent treatment of the spin-3/2 resonances which overcomes pathologies in former models [5,6,17]. The consistent treatment of the Δ should be emphasized as we intend to look for in-medium modifications of the Δ properties. In this Letter we apply the model only in the Δ region, however it can be applied in further energy regions, approximately up to 1.2 GeV of photon energy. The extension of the model to the nucleus is introduced by means of the impulse approximation (IA), as described later on. As a first approximation one can assume that the final state interactions (FSI) of the outgoing pion and nucleon with the residual nucleus can be neglected. In this case, both particles are described as plane waves, and one talks of the relativistic plane-wave impulse approximation (RPWIA) [18]. To obtain a reliable computation of the differential cross sections, the inclusion of FSI is mandatory, but as previously stated, the spin asymmetry can be reliably computed within RPWIA due to

its low dependence on distortion effects. In this Letter we focus on this last observable. We show RPWIA results in the Δ region for ^{16}O compared to experimental data from LEGS [11]. We do not consider medium modifications in the nucleon resonances and we obtain better agreement with experimental data than that the one obtained in [11] from both quantitative and qualitative points of view. These results indicate that major modifications of Δ properties in the nuclear medium are not necessary for the description of the spin asymmetry in the ^{16}O$(\vec{\gamma}, \pi^- p)$ process.

2. The model

2.1. Relativistic impulse approximation

In the exclusive $A(\vec{\gamma}, \pi N)A-1$ reaction, a photon penetrates an A-body nucleus and, as a consequence of the interaction, a nucleon and a pion are emitted and detected, leaving behind an $(A-1)$-body daughter nucleus, generally in an excited state. The process is depicted in Fig. 1, where the kinematical variables associated with the incoming photon and target, as well as those of the outgoing pion, nucleon, and residual nucleus are specified. Conservation of energy and momentum imposes that

$$E_\gamma + E_A = E_\pi + E_N + E_{A-1}, \tag{1}$$

$$\mathbf{p}_\gamma + \mathbf{p}_A = \mathbf{p}_\pi + \mathbf{p}_N + \mathbf{p}_{A-1}. \tag{2}$$

Our calculations are performed in the laboratory frame, where the target nucleus is at rest ($E_A = M_A$, $\mathbf{p}_A = 0$). The z axis is chosen along the direction of the photon beam, and the pion is ejected in the x–z plane, with azimuthal angle $\phi_\pi = 0$. Although the momenta of the ejected nucleon and residual nucleus are in general not constrained to the x–z plane, this coplanar kinematics, in which all the momenta in the final state belong to the same plane—usually known as production plane—is experimentally the most common setup and is the one we consider. As can be inferred from these equations, the recoiling nucleus allows for more flexibility in the kinematics of the reaction compared to the case of pion photoproduction from free nucleons. In fact, the three-body final state allows for the exploration of a wide range of momentum transfers to the residual nucleus.

Following the conventions in [19], the fivefold differential cross section for the $A(\gamma, \pi N)A-1$ reaction reads

$$\frac{d\sigma}{d\Omega_\pi\, d\Omega_N\, dT_N}\bigg|_{\text{lab}} = \frac{\alpha}{(2\pi)^4} \frac{E_N p_N p_\pi}{2E_\gamma} f_{\text{rec}}^{-1} \overline{|\mathcal{M}_{fi}|^2}, \tag{3}$$

where

$$f_{\text{rec}} = \left| 1 - \frac{E_\pi}{E_{A-1}} \frac{\mathbf{p}_{A-1} \cdot \mathbf{p}_\pi}{|\mathbf{p}_\pi|^2} \right|. \tag{4}$$

The nuclear transition matrix elements for the $A(\vec{\gamma}, \pi N)A-1$ reaction can be generally written as

$$\mathcal{M}_{fi} = \langle P_\pi^\mu, P_N^\mu, P_{A-1}^\mu | \hat{\mathcal{O}} | P_\gamma^\mu, P_A^\mu \rangle, \tag{5}$$

where we have represented each wave function by its corresponding four-momentum. It is clear that for the outgoing nucleon, target and residual nucleus one must know also the spin to specify the state. The operator $\hat{\mathcal{O}}$ is in general an A-body operator describing the pion photoproduction process on the nucleus.

Our model relies on the well-known IA, as usual in processes in which the kinematics favors the interaction of the probe with a single nucleonic constituent of the target. To be consistent, we restrict ourselves to the quasifree region, where the momentum transferred to the recoiling nucleus is relatively low (below 300 MeV/c). Within the IA, the general process shown in Fig. 1 is described as illustrated in Fig. 2, where the incoming photon interacts with a single bound nucleon in the nucleus. The remaining
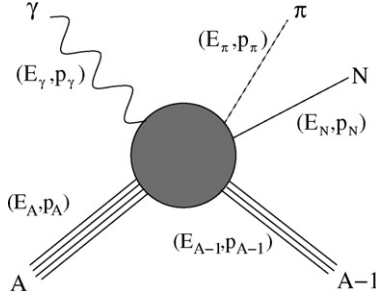
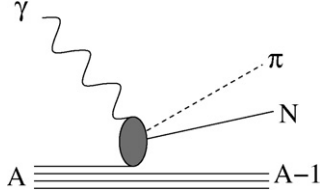**Fig. 1.** Kinematics for the pion photoproduction process from nuclei.

Fig. 2. Schematic representation of the impulse approximation for $A(\gamma, \pi N)A - 1$.

Fig. 3. Feynman diagrams for the Born terms of the pion photoproduction from the nucleon process: (a) s-channel, (b) u-channel, (c) t-channel, and (d) Kroll–Rudermann.

Fig. 4. Feynman diagrams for vector meson exchange (e) and resonance excitations: (f) s-channel and (g) u-channel of the pion photoproduction from the nucleon process.

nucleons act as mere spectators in the scattering process, except for the FSI with both the pion and the nucleon while leaving the nucleus. It can be proven that within the IA, where the nuclear operator $\hat{\mathcal{O}}$ is substituted by a sum of one-body operators, the calculation of $\mathcal{M}_{fi}$ is simplified, and the basic ingredients that enter now in the calculation are the bound nucleon wave function, the elementary pion photoproduction operator, and the outgoing pion and nucleon wave functions.

In our model, all of the ingredients are fully relativistic. For the elementary pion photoproduction operator, we use the free production operator as it is described in next section. In this work we only consider pion production from ^{16}O, where a mean field description of the nuclear states is appropriate. The bound-nucleon wave function is a solution of the Dirac equation with well-defined angular momentum obtained in the Hartree approximation to the σ–ω model including non-linear σ terms [20]. We employ the NLSH wave functions by Sharma et al. [21] which reproduce accurately binding energies, single-particle energies, and charge radius for ^{16}O. As we explained in the Introduction, we restrict ourselves to an RPWIA computation of the ^{16}O$(\vec{\gamma}, \pi^- p)$ spin asymmetry. A very common theoretical framework to pion photoproduction in the nuclear medium is the use of the factorization approximation, that can be applied either at the amplitude or cross section levels. In a factorized calculation, the matrix elements or the cross sections are separated into a part containing the elementary pion production process and a part with the typical medium mechanisms in the process under study, such as FSI. Within a fully relativistic formalism, factorization is not reached even in the RPWIA, due to the presence of negative-energy contributions in the bound-nucleon wave function [18]. Thus, our calculations are fully unfactorized even in this first stage where FSI are neglected.

2.2. Elementary pion photoproduction reaction

The elementary reaction model we employ is the one developed in [5,6] which has been applied successfully from threshold up to 1.2 GeV of photon energy in the laboratory reference system [7] and has been recently applied also to eta photoproduction [22]. In this section we provide a brief outlook of the model. For further details we refer the reader to Refs. [5–7].

The model is based upon an effective Lagrangian approach (ELA) which, from a theoretical point of view, is a very appealing, reliable, and formally well-established approach in the energy
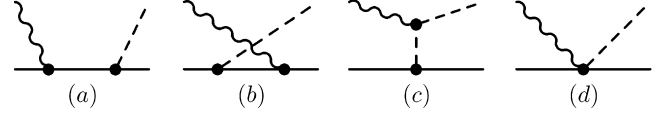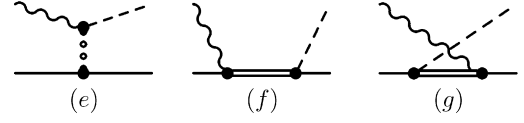
region of the mass of the nucleon. The model includes Born terms (diagrams (a)–(d) in Fig. 3), vector–meson exchanges (ρ and ω, diagram (e) in Fig. 4), and all the four star resonances in Particle Data Group (PDG) [23] up to 1.8 GeV and up to spin-3/2: Δ, $N(1440)$, $N(1520)$, $N(1535)$, $\Delta(1620)$, $N(1650)$, $\Delta(1700)$, and $N(1720)$ (diagrams (f) and (g) in Fig. 4). Born terms are calculated using the Lagrangian:

$$
\begin{aligned}
\mathcal{L}_{\text{Born}} = & -ieF_1^V \hat{A}^\alpha \epsilon_{jk3} \pi_j (\partial_\alpha \pi_k) \\
& - e\hat{A}^\alpha F_1^V \bar{N} \gamma_\alpha \frac{1}{2}\big(F_1^{S/V} + \tau_3\big)N \\
& - ieF_1^V \frac{f_{\pi N}}{m_\pi} \hat{A}^\alpha \bar{N}\gamma_\alpha \gamma_5 \frac{1}{2}[\tau_j, \tau_3]\pi_j N \\
& - \frac{ie}{4M} F_2^V \bar{N} \frac{1}{2}\big(F_2^{S/V} + \tau_3\big)\gamma_{\alpha\beta} N F^{\alpha\beta} \\
& + \frac{f_{\pi N}}{m_\pi} \bar{N}\gamma_\alpha \gamma_5 \tau_j N \big(\partial^\alpha \pi_j\big),
\end{aligned}
\tag{6}
$$

where e is the absolute value of the electron charge, m_π the mass of the pion, M the mass of the nucleon, $f_{\pi N}$ the pion–nucleon coupling constant, $F_j^V = F_j^p - F_j^n$ and $F_j^S = F_j^p + F_j^n$ are the isovector and isoscalar nucleon form factors, $F^{\mu\nu} = \partial^\mu \hat{A}^\nu - \partial^\nu \hat{A}^\mu$ is the electromagnetic field ($\hat{A}^\mu$ stands for the photon field), N the nucleon field, and π_j the pion field. The coupling to the pion has been chosen pseudovector in order to ensure the correct parity and low-energy behavior.

The main contribution of mesons to pion photoproduction is given by ρ (isospin-1 spin-1) and ω (isospin-0 spin-1) exchange. The phenomenological Lagrangians which describe vector mesons are:

$$
\begin{aligned}
\mathcal{L}_\omega = & -F_{\omega NN} \bar{N}\Big[\gamma_\alpha - i\frac{K_\omega}{2M}\gamma_{\alpha\beta}\partial^\beta\Big]\omega^\alpha N \\
& + \frac{eG_{\omega\pi\gamma}}{2m_\pi}\epsilon_{\mu\nu\alpha\beta} F^{\alpha\beta}\big(\partial^\mu \pi_j\big)\delta_{j3}\omega^\nu,
\end{aligned}
\tag{7}
$$

$$
\begin{aligned}
\mathcal{L}_\rho = & -F_{\rho NN} \bar{N}\Big[\gamma_\alpha - i\frac{K_\rho}{2M}\gamma_{\alpha\beta}\partial^\beta\Big]\tau_j \rho_j^\alpha N \\
& + \frac{eG_{\rho\pi\gamma}}{2m_\pi}\epsilon_{\mu\nu\alpha\beta} F^{\alpha\beta}\big(\partial^\mu \pi_j\big)\rho_j^\nu.
\end{aligned}
\tag{8}
$$

The model displays chiral symmetry, gauge invariance, and crossing symmetry as well as a consistent treatment of the spin-3/2 interaction which overcomes pathologies present in former analyses [17]. Under this approach for spin-3/2 interactions the (spin-3/2 resonance)–nucleon–pion and the (spin 3/2 resonance)–nucleon–photon vertices have to fulfill the condition $q_\alpha \mathcal{O}^{\alpha\cdots} = 0$ where q is the four-momentum of the spin-3/2 particle, α the vertex index which couples to the spin-3/2 field, and the dots stand

for other possible indices. In particular, for the Δ, the simplest interacting π–N–Δ Lagrangian is [17]

$$\mathcal{L}_{\pi N\Delta} = -\frac{h}{f_\pi M_\Delta}\bar{N}\epsilon_{\mu\nu\lambda\beta}\gamma^\beta\gamma^5(\partial^\mu\Delta_j^\nu)(\partial^\lambda\pi_j) + \text{H.c.}, \tag{9}$$

where H.c. stands for Hermitian conjugate, h is the strong coupling constant, $f_\pi = 92.3$ MeV is the leptonic decay constant of the pion, M_Δ the mass of the Δ, and Δ_j^ν the Δ field. The γ–N–Δ interaction can be written [24]:

$$\mathcal{L}_{\gamma N\Delta} = \frac{3e}{2MM_+}\bar{N}\left[\frac{ig_1}{2}\tilde{F}_{\mu\nu} + g_2\gamma^5 F_{\mu\nu}\right](\partial^\mu\Delta_3^\nu) + \text{H.c.}, \tag{10}$$

where g_1 and g_2 are the electromagnetic coupling constants, $M_+ = M + M_\Delta$, and $\tilde{F}_{\mu\nu} = \epsilon_{\mu\nu\alpha\beta}F^{\alpha\beta}$.

The dressing of the resonances is considered by means of a phenomenological width which contributes to both s and u channels and takes into account decays into one π, one η, and two π. The energy dependence of the width is chosen phenomenologically as

$$\Gamma(s, u) = \sum_{j=\pi,\pi\pi,\eta}\Gamma_j X_j(s, u), \tag{11}$$

where s and u are the Mandelstam variables and

$$X_j(s, u) \equiv X_j(s) + X_j(u) - X_j(s)X_j(u), \tag{12}$$

with $X_j(l)$ given by

$$X_j(l) = 2\frac{(\frac{k_j}{k_{j0}})^{2L+1}}{1 + (\frac{k_j}{k_{j0}})^{2L+3}}\Theta\left(l - (M + m_j)^2\right), \tag{13}$$

where L is the angular momentum of the resonance, Θ is the Heaviside step function, and

$$k_j = \sqrt{\left(l - M^2 - m_j^2\right)^2 - 4m_j^2 M^2}/(2\sqrt{l}), \tag{14}$$

with $m_{\pi\pi} \equiv 2m_\pi$ and $k_{j0} = k_j$ when $l = M^{*2}$ (M^* stands for the mass of the resonance).

This parameterization has been built in order to fulfill the following conditions

(i) $\Gamma = \Gamma_0$ at $\sqrt{s} = M^*$,
(ii) $\Gamma \to 0$ when $k_j \to 0$,
(iii) a correct angular momentum barrier at threshold k_j^{2L+1},
(iv) crossing symmetry.

For the resonance–pion–nucleon vertex, the form factor $\sqrt{X_\pi(s, u)}$ has to be used for consistency with the width employed.

In order to regularize the high-energy behavior of the model, a crossing symmetric and gauge invariant form factor is included for Born and vector meson exchange terms,

$$\hat{F}_B(s, u, t) = F(s) + F(u) + G(t) - F(s)F(u)$$
$$- F(s)G(t) - F(u)G(t) + F(s)F(u)G(t), \tag{15}$$

where

$$F(l) = \left[1 + \left(l - M^2\right)^2/\Lambda^4\right]^{-1}, \quad l = s, u, \tag{16}$$
$$G(t) = \left[1 + \left(t - m_\pi^2\right)^2/\Lambda^4\right]^{-1}. \tag{17}$$

For vector mesons $\hat{F}_V(t) = G(t)$ is adopted with the change $m_\pi \to m_V$. In the pion photoproduction model from free nucleons [5,6] it was assumed that FSI factorize and can be included through the distortion of the πN final state wave function (pion–nucleon rescattering). πN–FSI was included by adding a phase δ_{FSI}

to the electromagnetic multipoles. This phase is set so that the total phase of the multipole matches the total phase of the energy dependent solution of SAID [3]. In this way it was possible to isolate the contribution of the bare diagrams to the physical observables. The parameters of the resonances were extracted from data fitting the electromagnetic multipoles from the energy independent solution of SAID [3] applying a modern optimization technique based upon genetic algorithms combined with gradient based routines [6,25] which provides reliable values for the parameters of the nucleon resonances. Once the bare properties of the nucleon resonances have been extracted from data, their contribution to more complex problems, such as pion photoproduction from nuclei, can be calculated.

3. Results

In this section we compare the predictions of our model to the available spin asymmetry data. This asymmetry, here noted as Σ, is given by:

$$\Sigma = \frac{\sigma(\theta_\pi, \theta_p)_\perp - \sigma(\theta_\pi, \theta_p)_\parallel}{\sigma(\theta_\pi, \theta_p)_\perp + \sigma(\theta_\pi, \theta_p)_\parallel}, \tag{18}$$

where the subindices $\perp$ and $\parallel$ stand for the perpendicular and parallel photon polarizations respectively and $\sigma(\theta_\pi, \theta_p)_{\perp,\parallel}$ is obtained by integrating over the nucleon kinetic energy:

$$\sigma(\theta_\pi, \theta_p)_{\perp,\parallel} \equiv \frac{d\sigma_{\perp,\parallel}}{d\Omega_\pi\, d\Omega_p} = \int\frac{d\sigma_{\perp,\parallel}}{d\Omega_\pi\, d\Omega_N\, dT_N}dT_N. \tag{19}$$

Precise measurements of Σ for the $^{16}\text{O}(\vec{\gamma}, \pi^- p)$ reaction at incident photon energies between 290 and 325 MeV were carried out at LEGS and reported in Ref. [11]. Data were provided at proton angles of 55° and 75° and pion angles from 36° to 140° in 8° steps for the sake of facilitating the comparison with theoretical calculations by preventing the need of kinematical averagings. In this work, we compare our theoretical predictions to those data. Our calculations include contributions from both $s_{1/2}$, $p_{1/2}$, and $p_{3/2}$ shells in Oxygen, consistently with the experimental setup. The integration over the nucleon kinetic energy in Eq. (19) is done numerically within the same range as for the above mentioned Σ data, i.e., $T_N \in [50, 100]$ MeV. Our results for different pion angles θ_π as a function of the proton angle θ_p are shown in Fig. 5, where also the data have been plotted. The presentation of this figure follows the one in Ref. [11], thus a straightforward comparison with what is shown in that work can be made.

As can be seen in Fig. 5, our theoretical predictions provide in general a rather good description of the data both from the qualitative and quantitative points of view, although the comparison worsens slightly with increasing pion and nucleon angles. The agreement between theory and experiment is a clear improvement with respect to what was observed in Ref. [11], where it was found that the theoretical calculations based on the model in [14] lied systematically above the measured spin asymmetries (mainly for $\theta_p > 60°$). The agreement of our calculations with data is presumably attributed to a better description of the underlaying photon–nucleus interaction, including the elementary pion photoproduction operator and struck nucleon wave functions. We thus find no indication of Δ medium modifications in the spin asymmetry as was suggested in Ref. [11]. Of course the absence of in-medium effects in Σ cannot be claimed as an absence of in-medium effects in the Δ. One has to be cautious and has to notice that what can be claimed is that the spin asymmetry does not seem to be sensitive to these effects, if any.

In Fig. 6 we display the spin asymmetry computed with different contributions from the elementary photoproduction model. The dashed curve provides the result just accounting for Born
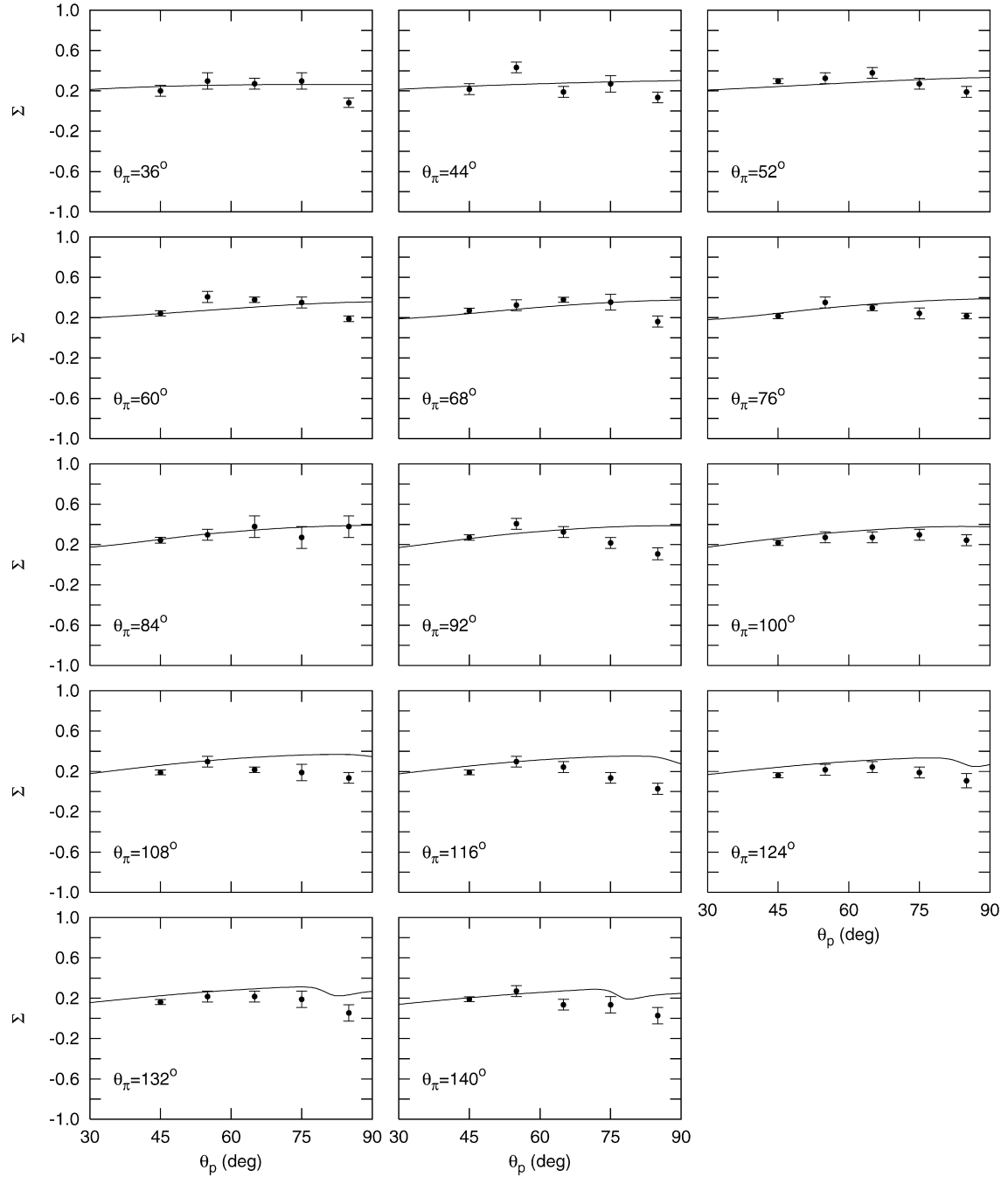
Fig. 5. Spin asymmetry integrated over the range $T_N = 50$–100 MeV. Experimental data from [11] compared to the theoretical prediction. Combined results for the $s_{1/2}$, $p_{1/2}$, and $p_{3/2}$ shells.

terms and vector mesons. The short-dashed curve provides the calculations with Born terms, vector mesons, and Δ. The dotted curve accounts for Born terms, vector mesons, Δ, and $N(1440)$ (Roper) contributions and the solid for the full computation including all the resonances. These two last results practically overlap, what means that the contribution of higher resonances is negligible for the studied observables, as expected. In the right panel it is found that Born terms and vector mesons by themselves provide an excellent agreement with the experimental data, agreement that is spoiled after including the Δ. However, in the left panel we see that the Δ improves agreement for larger pion angles. The Roper resonance shows its influence in the process although we are in the Δ energy region. This is small but not negligible. It is important to notice the effect in the threshold energy for the produc-

tion of the resonances due to the fact that the knocked nucleon is bound inside the nucleus. Indeed, when we study pion photoproduction from the nuclei, the threshold energy to produce a certain resonance is lowered compared to its threshold value on free nucleons. This is due to the fact that the whole residual system participates in the recoil so that less energy is transferred to the heavier system and, thus, more is available to produce the resonance (see Fig. 7). This means that it is likely that a resonance may affect observables for lower energies than in the free case.

We also point out the qualitative behavior of the model for high angles of both ejected pion and nucleon. In Fig. 6, the asymmetry decreases slightly with increasing proton angle. The results of [11] besides overestimating the asymmetry data, did not follow
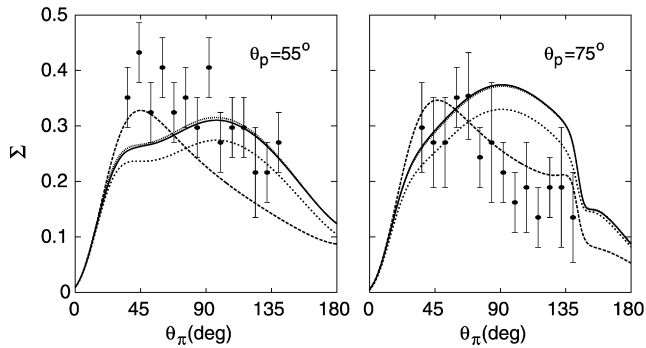
Fig. 6. Spin asymmetry integrated over the range $T_N = 50$–100 MeV. Combined results for the $s_{1/2}$, $p_{1/2}$, and $p_{3/2}$ shells. Curve conventions: Solid: Full computation; Dashed: Born terms and vector mesons contributions; Short dashed: Born terms, vector mesons, and Δ contributions; Dotted: Born terms, vector mesons, Δ, and $N(1440)$ contributions. Experimental data have been taken from [11]. Dotted and solid lines almost completely overlap.
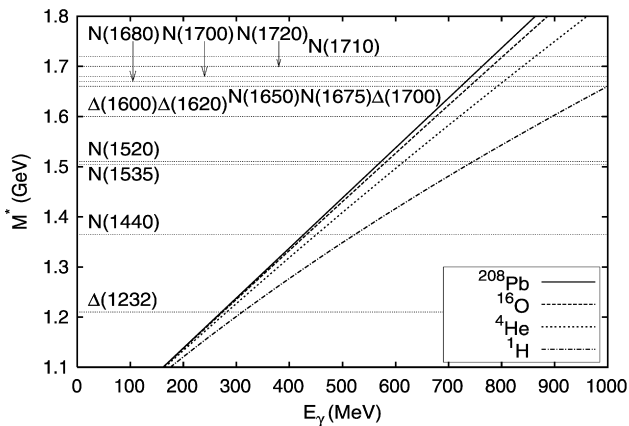

Fig. 7. Available energy for resonance excitations with different targets depending on the incident photon energy in the laboratory frame. Pole masses of the nucleon resonances are marked in the figure as horizontal lines.

this trend of the data. Our model reproduces this trend of the data, at least qualitatively. This behavior of the asymmetry is found even for Born terms (see Fig. 6) and it is a kinematical effect. When the asymmetry is compared to the mean value of the kinetic energy of the outgoing nucleon $\langle T_N \rangle$, it can be seen that it is the variation of $\langle T_N \rangle$ what is seen in this behavior of the asymmetry.

4. Summary and final remarks

It has been suggested that the spin asymmetry in $A(\vec{\gamma}, \pi N)A - 1$ reaction may serve to signal in-medium Δ modifications. In this Letter we have presented results of a new model for pion photoproduction on nuclei to the description of this observable in the $^{16}O(\vec{\gamma}, \pi^- p)$ reaction measured at LEGS [11]. The model is an extension to nuclei of the model of [5–7] for free nucleons. A salient feature of the model is the improved treatment of the spin-3/2 resonances. One must keep in mind that a consistent description of the Δ-resonance is compulsory previous to any comparison with data. Our results within the plane-wave limit are in fair agreement with the experimental data on the spin asymmetry. This indicates that FSI are not significant in the description of this asymmetry, in agreement with the findings in [14]. Within our model, the description of the spin asymmetry is obtained with the same Δ parameters used to describe pion photoproduction data on free nucleons. This result indicates that major in-medium Δ effects are not needed to reproduce asymmetry data.

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