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NEGATIVE PION PHOTOPRODUCTION OFF SPIN-1/2-NUCLEI BY LINEARLY POLARIZED PHOTONS

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1. Interest in the photoproduction by polarized photons took a new turn once the high intensity electron accelerators started to become an experimental reality. These accelerators provide high quality polarized photon beams and thus bring into focus a strong potential of polarized experiments. For example, the LEGS collaboration reported recently results of an experimental study of the neutral pion photoproduction on the proton by the linearly polarized photons [1]. The obtained very accurate data can confront different quark models in view of the evaluation of the $E2$ excitation magnitude in the presence of the dominant $M1$ one.

Up to now, there are many problems which can be resolved by means of reactions with the linearly polarized photons on nuclear targets. As well known, for the π^0 photoproduction off zero-spin nuclei the photon asymmetry $\Sigma = 1$. Thus one can measure the degree of polarization of the incident photon beam, for example, in the reaction $\gamma + ^4He \rightarrow \pi^0 + ^4He$. Another interesting branch of this topic is connected with the investigation of the non-conservation of the P-parity in $\gamma + N \rightarrow \pi + N$ processes. Such analysis can provide the very important value of the constant of the P-odd πNN-interaction.

It seems natural to extend the investigation to the spin-$\frac{1}{2}$-nuclei. First theoretical studies of the Σ, P- and T-asymmetries have already been done in Refs.[2, 3]. In this paper we present a detailed analysis of the Σ asymmetry for the π^--photoproduction off the ^{13}C and ^{15}N nuclei. The main topic of interest is the effects of the interplay of the $E0$ and $M1$ type nuclear transitions.

The standard expansion of the elementary operator reads

$$F_{\pi\gamma}^{(\lambda)} = \vec{J} \cdot \vec{\epsilon_\lambda} = iF_1(\vec{\sigma} \cdot \vec{\epsilon_\lambda}) + F_2(\vec{\sigma} \cdot \hat{\vec{q}})(\vec{\sigma}[\hat{\vec{k}} \times \vec{\epsilon_\lambda}]) + iF_3(\vec{\sigma} \cdot \hat{\vec{k}})(\hat{\vec{q}} \cdot \vec{\epsilon_\lambda}) + iF_4(\vec{\sigma} \cdot \hat{\vec{q}})(\hat{\vec{q}} \cdot \vec{\epsilon_\lambda}), \qquad (1)$$

where we introduce the unit vectors $\hat{\vec{q}} = \vec{q}/|\vec{q}|$ and $\hat{\vec{k}} = \vec{k}/|\vec{k}|$ and the photon polarization vector $\vec{\epsilon}_\lambda$ with $\lambda = \pm 1$.

The cartesian components of the current $\vec{J}$ can be found to be

$$\begin{aligned} J^{\perp} &= i(F_1 + F_4 sin^2\theta)\sigma_x + isin\theta(F_3 + F_4 cos\theta)\sigma_z, \\ J^{\|} &= -F_2 sin\theta + iF_1\sigma_y. \end{aligned} \qquad (2)$$

An examination of the above expressions shows that only the spin-flip transitions occur for the photons polarized along the x-axe ($J^{\perp}$) while for the y-polarized photons ($J^{\|}$) the non spin-flip transition contributes as well.

Following the Madison Convention [4] we directed the photon momentum $\vec{k}$ along the z axis and the vector $[\vec{k} \times \vec{q}]$ to be parallel to the y axis. The photon asymmetry is then written as

$$\Sigma(\theta) = \frac{\sigma^{\|}(\theta) - \sigma^{\perp}(\theta)}{\sigma^{\|}(\theta) + \sigma^{\perp}(\theta)}, \qquad (3)$$

where θ is the polar angle of the outgoing pion, $\sigma^{\perp}(\sigma^{\|})$ is the differential cross-section for the photon polarization along x (y).

With the above definitions the Σ asymmetry on the free neutron can be easily evaluated in the following manner:

$$\frac{d\sigma}{d\Omega}\Sigma_n = -\frac{sin^2\theta}{2}\frac{|\vec{q}|}{|\vec{k}|}\Big(|F_3|^2 + |F_4|^2 + 2Re(F_2F_3^* + F_1F_4^* + F_3F_4^* cos\theta)\Big). \qquad (4)$$

For the pion photoproduction off a nucleus the corresponding expressions are developed in terms of the nuclear form factors:

$$M^T_{SLJ}(Q) = \langle J_fT_f|||\sum_{j=1}^{A}[\sigma_j^S \otimes Y_L]^T_J j_L(Qr_j)|||J_iT_i\rangle, \qquad (5)$$

where $\vec{Q} = \vec{k} - \vec{q}$ is the transferred momentum.

In the case of π^- photoproduction off the ^{13}C and ^{15}N nuclei two types of transitions contribute: the isovector $E0$ (with $S = 0$, $L = 0$ and $J = 0$) and the isovector $M1$ (with $S = 1$, $L = 0$ or 2 and $J = 1$). As goes from (2) the $E0$ type transition contributes only to $\sigma^{\|}$. This separation of the non spin-flip transition gives an advance for our forthcoming analysis.

2. For the qualitative understanding of the pion photoproduction off spin-$\frac{1}{2}$-nuclei we neglect for a moment the pion wave distortion effects and make following approximations. First, in the nuclear matrix elements we omit the quadrupole $L = 2$ transitions and adopt the factorization approximation [5] while averaging over the nucleon Fermi-motion. We have found the latter to be reliable for the differential cross-sections [5] and to be valid for the polarization observables as well. For further simplicity we assume that for ^{13}C the only configuration is that of a $1p_{1/2}$ neutron outside a closed ^{12}C core. After all, we are in a position to write down the Σ asymmetry in terms of the elementary amplitudes (1) as follows:

$$\frac{d\sigma}{d\Omega}\Sigma_{^{13}C} \sim -\frac{sin^2\theta}{2}\frac{|\vec{q}|}{|\vec{k}|}\Big(-8|F_2|^2 + |F_3|^2 + |F_4|^2 + 2Re(F_2F_3^* + F_1F_4^* + F_3F_4^* cos\theta)\Big). \quad (6)$$

Because of the $sin^2\theta$ dependence, it is identically zero at $\theta = 0°$ and $180°$. Besides, under the above made assumptions, Σ for p-shell nuclei contains an extra term, proportional to the non spin-flip $|F_2|^2$ amplitude. As has been shown in Ref.[3], the Σ asymmetry for the s-shell ^3He nucleus has an identical form to that for the free nucleon. The extra term in eqn.(6) reflects a change of relative weights of the spin-flip and non spin-flip transitions for the p-shell nuclei. Due to the enhancement of the non spin-flip transition's contribution in these nuclei, the photon asymmetry contains a large body of information about the isovector $E0$ form factor which is of a particular interest as it strongly depends on the Δ-isobar contribution.

We finish this section with a discussion of the pion wave distortion (or the final state interaction - FSI) effects. These effects can be treated in a quantitative way using the Distorted Wave Impulse Approximation (DWIA). The theory of the DWIA and calculations for a number of practical cases have been given in Refs. [5, 6]. Here we do not discuss the DWIA in detail.

The most important effect of the distortion is a change of the transferred momentum (Q) scale. The effective momentum of the outgoing pion being rescattered is large than the asymptotic momentum, due to the attractive nature of the πA optical potential. The increase in momentum ($\vec{q}^{\,2} \rightarrow \vec{q}^{\,2}_{eff} = \vec{q}^{\,2} - 2E_\pi\bar{U}_{\pi A}$, where the mean optical potential $\bar{U}_{\pi A} < 0$), leads to a corresponding increase in the effective momentum transfer, and to shift of diffraction minima and maxima of the nuclear form factors.

Let us now consider all nuclear matrix elements with the unitary BL elementary photoproduction operator [7]. Using the realistic many-body nuclear wave functions from Ref.[6], we illustrate the above arguments in Figure 1, where the results of the PWIA (dashed line) and DWIA (solid line) calculations are compared at E_γ = 170 and 300 MeV. The kinematical conditions in the first case do not provide any

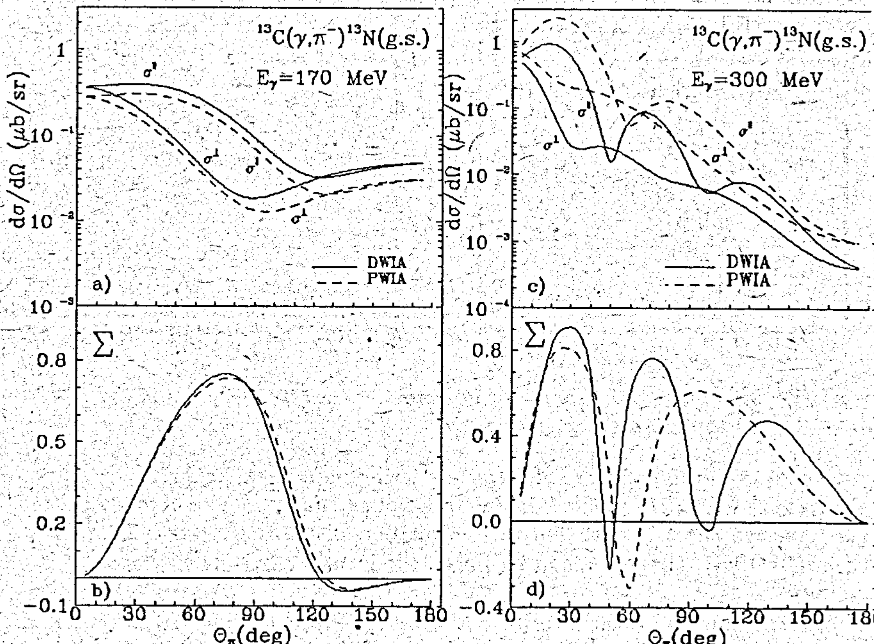

Fig. 1. The sensitivity of $\frac{d\sigma}{d\Omega}$ and Σ to the FSI at (a, b) E_γ = 170 MeV and (c, d) 300 MeV. Transition densities are from Ref.[6].

noticeable effect (see Figure 1a): the FSI simultaneously increases $\sigma^{\perp}$ and $\sigma^{\|}$ as compared with the PWIA calculations. Therefore its effect on the Σ asymmetry is slight, as can be seen in Figure 1b.

However, in the resonance region the inclusion of the FSI leads to very complicated diffractive structure of the differential cross sections in comparison with the PWIA calculations, as plotted in Figure 1c. As has already been mentioned, the FSI results mainly to the effective increase of the local pion momentum. Thus it leads to an additional minimum of $\sigma^{\parallel}$ which reflects the second minimum of the $E0$ form factor. For the PWIA calculations this minimum is out of the kinematical region. As a result we observe a significant difference of the curves obtained in terms of the PWIA and the DWIA, in particular at $\theta > 90^o$.

The curves corresponding to the photon asymmetry in the resonance region are presented in Figure 1d. We observe an additional minimum at $\theta \sim 100^o$, which is associated with the second minimum of the isovector $E0$ type transition.

3. As has already been mentioned, a central point of the present research is placed on the $E0$ and $M1$ type transitions' interplay. The first one contributes to the electromagnetic charge form factor (see Figure 2). The $M1$ type transition can

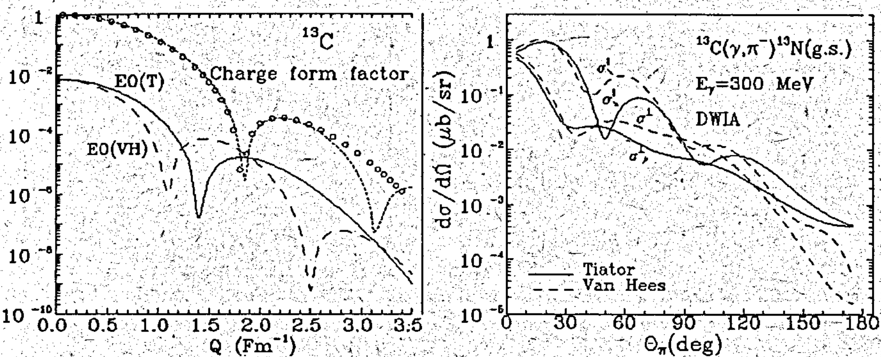

Fig. 2. The sensitivity of the charge form factors of the ^{13}C nucleus and $\frac{d\sigma}{d\Omega}(\gamma +^{13} C \rightarrow \pi^- +^{13} N)$ to different nuclear models.

be extracted from the backward electron scattering data (e.g., Ref.[8]).

At present, the ^{13}C magnetic form factor is not satisfactorily understood, despite rather intensive efforts. A shell-model calculation in the $0\hbar\omega$ space (the Cohen-Kurath model [9]) fails to explain its behaviour in particular in the region of the second maximum.

The small number of the density matrix elements in the $0\hbar\omega$ space makes a phenomenological analysis of the data possible. This way implies that the nuclear transition densities are adjusted to the electromagnetic form factors data by allowing them for a free variation with constraints that keep them close to the calculated ones. Although this procedure considerably improves the description of the magnetic form factors [6], it is not sufficient to fix the unique value of the $L = 2$ transition.

Recent analysis of the experimental data for the $^{13}C(\gamma,\pi^-)^{13}N$ reaction has shown the necessity of an essential suppression of the isovector electric transition $E0$. This goal can be achieved by adding the few-percent $2p$-shell admixtures [10, 8] within, for example, the microscopical constraints which take into account the contributions of the $2\hbar\omega$ configurations in the ground state of ^{13}C. The similar indication

has also been found for the pion photoproduction and pion scattering reactions on ^{15}N [11]. The effects of the higher configuration on the charge nuclear form factor are illustrated in Figure 2, where we compare the results of calculations done using the phenomenological TW model [6] which is restricted to the $0\hbar\omega$ configurations and the microscopic VH model [12] which covers the $(0+2)\hbar\omega$ space. Evidently, these two models provide different behavior of the isovector electric $E0$ transition. In this respect, an independent test via, for example, the photoproduction reaction is more than welcome. The sensitivity of $\sigma^{\parallel}$ to the different nuclear model input at $E_\gamma = 300$ MeV is plotted in Figure 2. Clearly, the region $40^o < \theta < 70^o$ is extremely promising in view of the direct information on the isovector $E0$ transition. Moreover, we show in Figure 2 how the different predictions for the $M1$ type transition result in the $\sigma^{\perp}$.

In Figure 3a, we summarize the results of calculation of Σ done using the TW model (solid line) and VH model (dashed line) at $E_\gamma = 170$ MeV. In the region of

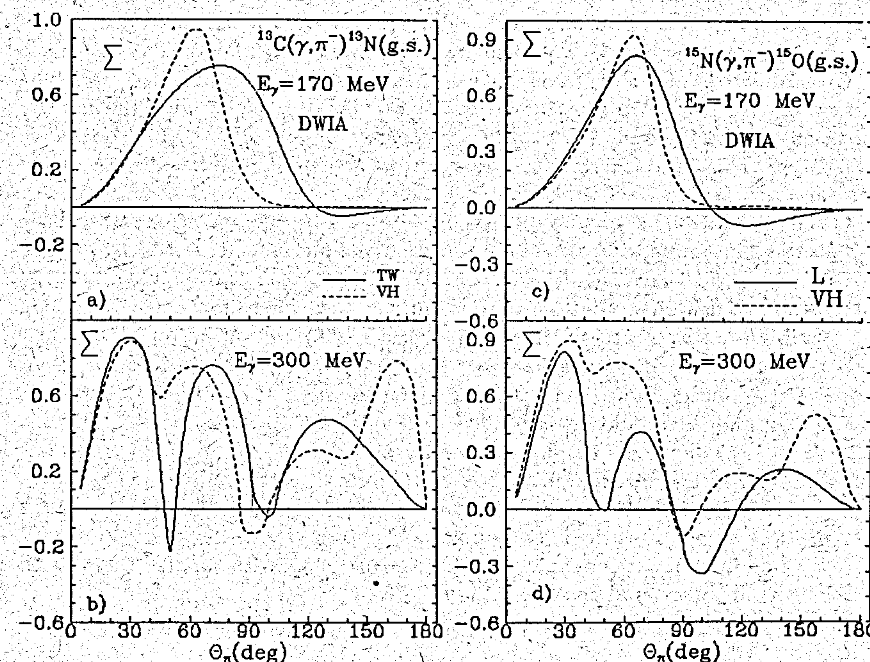

Fig. 3. The sensitivity of Σ to the nuclear model input. For the meaning of the curves see text.

small angles, the TW model predicts a large value for the $M1$ transition as compared with the VH model [8]. At the same time, the difference between the isovector $E0$ form factors, calculated within these two models in this kinematical region, is not so strong. Therefore, $\sigma^{\parallel}$ calculated within these models are close to each other, while

$\sigma^{\perp}(TW) > \sigma^{\perp}(VH)$. Consequently, according to eqn.(3), $\Sigma(TW) < \Sigma(VH)$. At large angles due to the suppression of the isovector $E0$ transition in the VH model, we find a abrupt falloff of $\Sigma(VH)$ in contrast to $\Sigma(TW)$.

The similar calculation at $E_\gamma = 300$ MeV, illustrated in Figure 3b, exhibits a pronounced diffraction feature, characterized by a number of maxima and minima of the Σ asymmetry. The most noticeable difference between two calculations occurs at $\theta \sim 40^o$, where the TW model gives a deep minimum, which reflects a significant shift of the minima of the isovector $E0$ and magnetic form factors in terms this model. It leads to the situation when the y-polarized cross-section decreases while the increase of the x-polarized one. At the same time the VH model provides a simultaneous increase of the charge and magnetic form factors and, so far, the minimum of the Σ asymmetry is not well pronounced.

The second considerable difference can be seen at large angles. The TW model gives a smooth falloff of the Σ for the pion angles from 130^o to 180^o. The VH model predicts here an additional maximum associated with the rapid decrease of the magnetic form factor and a maximum of the charge form factor.

We complete the item by mentioning that the similar results have been obtained for the ^{15}N nucleus. We illustrate them in Figures 3c and 3d with the nuclear transition densities obtained in the $0\hbar\omega$ (model L) [13] and $(0+2)\hbar\omega$ (model VH) [12] spaces. The obtained results show a strong sensitivity to the nuclear model input and to the pion wave distortion effects as well.

4. The analysis of Σ on the spin-$\frac{1}{2}$-nuclei reveals the urgent necessity to have data for the pion photoproduction with the polarized photons. These data provided with the theoretical analysis done in the present letter can throw light upon the isovector $E0$ transition strength. After solving this pure nuclear structure problem, it is possible to concentrate on the study of the Δ-isobar modification in a nuclear medium. Our preliminary analysis of the small variations of the Δ-mass, like that from Ref. [14], has shown a noticeable effect on the photon asymmetry. However, a more thorough investigation is needed to study this phenomenon, keeping the unitarity of the elementary amplitude preserved.

To our mind, the obtained results are useful for the forthcoming experiments in Mainz (MAMI), NIKHEF (Am PS), Saskatoon and MIT/Bates. In fact, the LEGS collaboration already uses the linearly polarized photon beams in experiments with ^3H. We think it to be also possible to make measurements with the ^{15}N target with final nucleus in the ground and first exited states.

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