PRODUCTION OF PSEUDOSCALAR AND VECTOR CHARMED MESONS IN COLLISIONS OF CIRCULARLY POLARIZED PHOTONS WITH POLARIZED PROTONS

Michail P. Rekalo[1] and Egle Tomasi-Gustafsson[2†]

(1) *National Science Center KFTI, 310108 Kharkov, Ukraine*
(2) *DSM/DAPNIA/SPhN, CEA/Saclay, 91191 Gif-sur-Yvette Cedex, France*
† *E-mail: etomasi@cea.fr*

Abstract

We analyze polarization effects in associative photoproduction of pseudoscalar ($\overline{D}$) and vector ($\overline{D^*}$) charmed mesons, $\gamma+p\to\Lambda_c^+ + \overline{D^0}(\overline{D^*})$. Circularly polarized photons induce nonzero polarization of the Λ_c-hyperon with x- and z-components (in the reaction plane) and non vanishing asymmetries $\mathcal{A}_x$ and $\mathcal{A}_z$ for the polarized proton target. These polarization observables can be predicted in model-independent way for exclusive $\overline{D}$-production processes in collinear kinematics. The behavior of T-even Λ_c-polarization and asymmetries for non-collinear kinematics can be calculated in framework of an effective Lagrangian approach. These polarization observables are large and show sensitivity to the magnetic moment of the Λ_c-hyperon. In case of $\overline{D^*}$-photoproduction, our predictions depend strongly on the relative value of the coupling constants of the $N\Lambda_c\overline{D}$ and $N\Lambda_c\overline{D^*}$-vertexes.

Key-words: charm, polarization, photoproduction

1 Introduction

High energy photon beams with large degree of circular polarization are actually available for physical experiments. Complementary to the linear polarized photon beams, they allow to address different interesting problems of hadron electrodynamics. Circularly polarized photon beams can be obtained in different ways, for example by backward scattering of a laser beam by high energy electron beam with longitudinal polarization. In MAMI and at JLab circularly polarized bremsstrahlung photons were generated by polarized electrons [1]. The proton polarization in the process of deuteron photodisintegration, $\vec{\gamma}+d\to\vec{p}+n$ [2] was investigated to test QCD applicability, with respect to hadron helicity conservation in high-energy photon-deuteron interactions.

The difference between linear and circular photon polarizations is due to the P-odd nature of the photon helicity ($\lambda=\pm 1$), which is the natural characteristics of circularly polarized photons. Therefore, in any binary process, $\gamma+a\to b+c$ (a, b, and c are hadrons and/or nuclei), with circularly polarized photons, the asymmetry, in case of unpolarized target, vanishes, due to the P-invariance of electromagnetic interactions of hadrons. In contrast, linearly polarized photons generally induce non-zero asymmetry, even in case of unpolarized target and unpolarized final particles. Circular polarization manifests itself only in two-spin (or more) polarization phenomena, as for example, the correlation polarization coefficient of photon beam and proton target, $\vec{\gamma}+\vec{p}\to\Lambda_c^+ + \overline{D^0}$, or the polarization of the final Λ_c-hyperon in $\vec{\gamma}+p\to\vec{\Lambda}_c^+ + \overline{D^0}$. The analysis of these processes is the object of the present paper. Note that in both cases, the components of the target polarization and the Λ_c^+ polarization lie in the reaction plane, due to the P-invariance. Note also, that all these polarization observables are T-even, i.e. they may not vanish even if the amplitudes of the considered process are real.

Another possible spin correlation with circularly polarized photons for the process $\vec{\gamma}+p \to \Lambda_c^+ + \overline{D^{*0}}$ is the vector polarization of the D^*-meson. In this connection, however, it is necessary to stress that the vector polarization of D^* can not be measured through its most probable decays: $D^* \to D+\pi$, $D^* \to D+\gamma$, $D^* \to D+e^+ + e^-$, which are induced by P-invariant strong and electromagnetic interaction. The matrix elements for these decays are characterized by a single spin structure, which is insensitive to the vector polarization.

An interesting application of circularly polarized photon beams is related with the very actual question about how the proton spin is shared among its constituents. The question of how the proton spin is carried by its constituents is still very actual [3]. The determination of the gluon contribution, ΔG, to the nucleon spin is the object of different experiments with polarized beams and targets [5, 6]. In particular, the production of charmed particles in collisions of longitudinally polarized muons with polarized proton target will be investigated by the Compass collaboration [7]. In the framework of the photon-gluon fusion model [8], $\gamma^* + g \to c + \overline{c}$, ($\gamma^*$ is a virtual photon), the corresponding asymmetry (for polarized μp-collisions), is related to the polarized gluon content in the polarized protons [9]. Due to the future impact of such result, it seems necessary to understand all the other possible mechanisms which can contribute to inclusive charm photoproduction, such as $\gamma + p \to \overline{D^0} + X$, for example. One possible and *a priori* important background, which can be investigated in detail, is the process of exclusive associative charm photoproduction, with pseudoscalar and vector charmed mesons in the final state, $\gamma + p \to \mathcal{B}_c + \overline{D}(\overline{D^*})$, with $\mathcal{B}_c = \Lambda_c^+$ or Σ_c^+. The mechanism of photon-gluon fusion, which successfully describes the inclusive spectra of D and D^* mesons at high photon energies, can not be easily applied to exclusive processes, at any energy. Threshold considerations of such processes in terms of perturbative QCD have been applied to the energy dependence of the cross section of $\gamma+p \to p+J/\psi$ [10]. However, in such approach, polarization phenomena can not be calculated without additional assumptions. In this respect, the formalism of the effective Lagrangian approach (ELA) seems very convenient for the calculation of exclusive associative photoproduction of charmed particles, such as $\gamma + p \to \Lambda_c^+(\Sigma_c^+) + \overline{D^0}(\overline{D^*})$ [11, 12] at least in the near threshold region. Such approach is also widely used for the analysis of various processes involving charmed particles [13], as, for example, J/ψ-suppression in high energy heavy ion collisions, in connection with quark-gluon plasma transition [14].

Here we give the ELA predictions for the angular and energy dependences of different polarization observables, for $\overline{D}$ and $\overline{D}^*$ photoproduction in the collision of circularly polarized photons with an upolarized and a polarized proton target.

2 Polarization observables for $\overline{D}$ photoproduction

In the general case, any reaction $\vec{\gamma} + \vec{p} \to \mathcal{B}_c + \overline{D^0}(\overline{D^*})$ is described by two different asymmetries $\mathcal{A}_x$ and $\mathcal{A}_z$:

$$\frac{d\sigma}{d\Omega}(\vec{\gamma}\vec{p}) = \left(\frac{d\sigma}{d\Omega}\right)_0 (1 - \lambda T_x \mathcal{A}_x - \lambda T_z \mathcal{A}_z), \tag{1}$$

where $\lambda = \pm 1$ is the photon helicity, T_x and T_z are the possible components of the proton polarization $\vec{T}$, $\mathcal{A}_x$ and $\mathcal{A}_z$ are the two independent asymmetries. Due to the T-even nature of these asymmetries, they are non vanishing in ELA consideration, where the photoproduction amplitudes are real. We will use the standard parametrization [15] of the spin structure for the amplitude of pseudoscalar meson photoproduction on the nucleon:

$$\mathcal{M}(\gamma N \to \mathcal{B}_c \overline{D}) = \chi_2^\dagger \left[i\vec{\sigma} \cdot \vec{e} f_1 + \vec{\sigma} \cdot \hat{\vec{q}} \vec{\sigma} \cdot \hat{\vec{k}} \times \vec{e} f_2 + i\vec{e} \cdot \hat{\vec{q}} \vec{\sigma} \cdot \hat{\vec{k}} f_3 + i\vec{\sigma} \cdot \hat{\vec{q}} \vec{e} \cdot \hat{\vec{q}} f_4 \right] \chi_1,$$

where $\hat{\vec{k}}$ and $\hat{\vec{q}}$ are the unit vectors along the three-momentum of γ and $\overline{D}$; $f_i = f_i(s, \cos\theta)$, i=1-4, are the scalar amplitudes, s is the total energy and θ is the $D-$meson production angle in the reaction CMS, χ_1 and χ_2 are the two-component spinors of the initial nucleon and the produced $\mathcal{B}_c$-baryon.

After summing over the $\mathcal{B}_c$-polarizations, one finds:

$$\mathcal{A}_x \mathcal{D} = \sin\vartheta \mathcal{R}e \left[-f_1 f_3^* + f_2 f_4^* + \cos\vartheta (-f_1 f_4^* + f_2 f_3^*) \right], \tag{2}$$

$$\mathcal{A}_z \mathcal{D} = |f_1|^2 + |f_2|^2 - 2\cos\vartheta \mathcal{R}e f_1 f_2^* + \sin^2\vartheta \mathcal{R}e \left(f_1 f_4^* + f_2 f_3^* \right), \tag{3}$$

with

$$\begin{gathered} \mathcal{D} = |f_1|^2 + |f_2|^2 - 2\cos\vartheta \mathcal{R}e f_1 f_2^* + \\ \sin^2\vartheta \left\{ \frac{1}{2} \left(|f_3|^2 + |f_4|^2 \right) + \mathcal{R}e \left[f_2 f_3^* + 2 \left(f_1 + \cos\vartheta f_3 \right) f_4^* \right] \right\}. \end{gathered} \tag{4}$$

Note that $\mathcal{A}_x$ vanishes at $\vartheta = 0^0$ and $\vartheta = \pi$. Moreover $\mathcal{A}_z = 1$, for $\vartheta = 0^0$ and $\vartheta = \pi$, for any photon energy. This is a model independent result, which follows from the conservation of helicity in collinear kinematics. It is independent from the dynamics of the process, its physical meaning is that the collision of γ and p with parallel spins can not take place for collinear regime. This result holds for any process of pseudoscalar and scalar meson photo-production on a nucleon target.

For $\vartheta \neq 0$ and $\vartheta \neq \pi$ the results for $\mathcal{A}_x$ and $\mathcal{A}_z$ are model dependent. In framework of the ELA model, the asymmetry $\mathcal{A}_z$ is large, $\mathcal{A}_z \geq 0.9$, with small sensitivity to the Λ_c^+-magnetic moment. The asymmetry $\mathcal{A}_x$ is mostly negative and smaller in absolute value. The asymmetry $\mathcal{A}_x$ is more sensitive to the Λ_c^+-magnetic moment [16].

The model of photon-gluon fusion predicts a value for the $\mathcal{A}_z$-asymmetry for the inclusive $\vec{\gamma} + \vec{p} \to \overline{D^0} + X$ process about $15 \div 30\%$, at $E_\gamma \simeq 50$ GeV, depending on the assumptions on the polarized gluon distribution, ΔG [7]. Therefore, even a 10% contribution of the exclusive process $\vec{\gamma} + \vec{p} \to \Lambda_c^+ + \overline{D^0}$ to the inclusive D-cross section can induce a 10% correction to the photon-gluon fusion asymmetry, at forward angles. It is a very large effect, which should be taken into account in the extraction of the ΔG-effect from the asymmetry in the process $\vec{\gamma} + \vec{p} \to \overline{D^0} + X$. Evidently this effect do not contribute to the D^0 production in the process $\vec{\gamma} + \vec{p} \to D^0 + X$.

The observation of the $\overline{D^0}/D^0$ or $\overline{\Lambda_c}/\Lambda_c$ asymmetry in γN-collisions will be important in order to test the validity of the photon-gluon fusion mechanism.

Note that the exclusive photoproduction of open charm will result in $\overline{D^0}/D^0$ and $\overline{\Lambda_c}/\Lambda_c$ asymmetry in γN-collisions (with unpolarized particles). Such asymmetries have been experimentally observed. For example, the FOCUS experiment found a ratio for

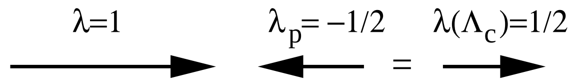

Figure 1: Conservation of helicity in $\vec{\gamma}\vec{p} \to \Lambda_c D^0$, in collinear regime

$\overline{\Lambda_c}/\Lambda_c$ production $\simeq 0.14 \pm 0.02$, demonstrating that Λ_c^+-production is more probable than $\overline{\Lambda_c}$ [17]. This is in contradiction with the model of photon-gluon fusion, which predicts symmetric $\overline{\Lambda_c} - \Lambda_c$-yields and can be considered as an indication of the presence of other mechanisms. The exclusive processes, discussed in this paper, explain naturally such asymmetry. Similar charm asymmetries have been observed also at E_γ=20 GeV, at SLAC [18]. Note also that the SELEX collaboration presented results on the Λ_c^+ over Λ_c^- asymmetries for different processes: p, π^-, $\Sigma^- + N \to \Lambda_c^\pm + X$ [19]. Similar results have been presented by the Fermilab E791 collaboration [20].

In a similar way it is possible to consider the polarization properties of the final Λ_c^+ hyperon induced by the initial circular polarization of the photon. Again, due to the P-invariance of the electromagnetic hadron interaction, only the P_x and P_z-components do not vanish:

$$P_x D = \lambda \sin\vartheta \mathcal{R}e \left[-2f_1 f_2^* - f_1 f_3^* + \cos\vartheta \left(2|f_2|^2 + f_2 f_3^* - f_1 f_4^* \right) + (2\cos^2\vartheta - 1) f_2 f_4^* \right]$$

$$P_z D = \lambda \left[|f_1|^2 - \left(1 - 2\cos^2\vartheta\right) |f_2|^2 - 2\cos\vartheta \mathcal{R}e f_1 f_2^* + \sin^2\vartheta \mathcal{R}e \left(f_1 f_4^* - f_2 f_3^* - 2\cos\vartheta f_2 f_4^* \right) \right]. \tag{5}$$

Comparing Eqs. (2), (3) and Eq. (5) one can see that the observables A_x and A_z on one side and P_x and P_z on another side, are independent in the general case of non-collinear kinematics and contain different physical information. Note also that $P_z = 1$, in case of collinear kinematics ($\cos\vartheta = 1$), independently on the model, taken to describe the scalar amplitudes f_i. This rigorous result follows from the conservation of the total helicity in $\gamma + p \to \Lambda_c^+(\Sigma_c^+) + \overline{D^0}$, which holds in collinear kinematics. It means that collisions with parallel spins of γ and p are forbidden and only collisions with particles with antiparallel spins in the entrance channel are allowed (see Fig. 1) i.e. the final Λ_c hyperon is polarized along the direction of the spin of the initial photon. This result holds for any $\mathcal{B}_c + D$-final state independently on the P-parity of the $N\Lambda_c D$-system, which is unknown.

At $\theta = 0^0$ or $\theta = \pi$, the observable P_x vanishes. This follows from the axial symmetry of the collinear kinematics, where only one physical direction can be defined (along the z-axis). In such kinematical conditions the x- and $y-$ axis are arbitrary, therefore $P_x = \mathcal{A}_x = 0$. It is a very general result; also independent on the relative P-parity P($N\Lambda_c D$).

In non-collinear kinematics, the behavior of P_x and P_z can be predicted only in framework of a model. We again apply ELA, with real amplitudes f_i, which give a nontrivial $\cos\theta$ and E_γ dependences (see Figs. 2 and 3). One can see that P_x and P_z are large and positive in all kinematical region.

The measurement of the Λ_c^+-polarization can be done similarly to to the strange Λ_c-hyperon, because the Λ_c^+, being the lightest charm baryon, can decay only through the weak interaction. Let us mention the two particle decay $\Lambda_c^+ \to \Lambda_c + \pi^+$, which has a large decay asymmetry, $A = 0.98 \pm 0.19$, but a relatively small branching ration, $B(\Lambda\pi) =$

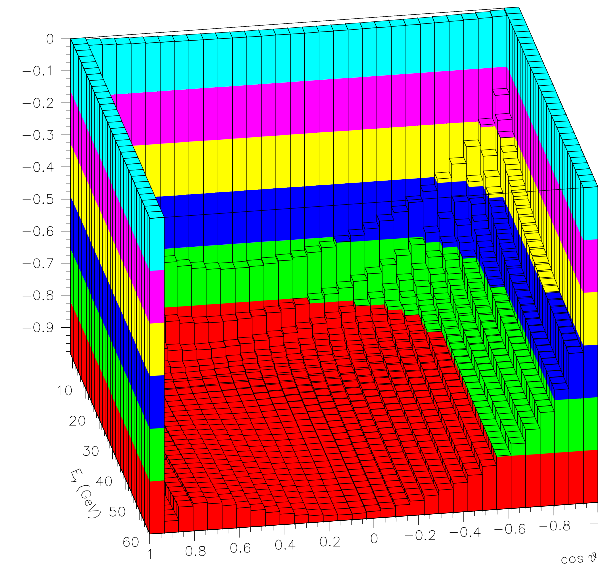

Figure 2: $\cos\vartheta$- and E_γ dependencies of the Λ_c^+ polarization P_x, for $\vec{\gamma}+p\to\vec{\Lambda}_c^+ + \overline{D^0}$, calculated for μ_{Λ_c}=0.37 μ_N [21].

$(9.0\pm 2.8)10^{-3}$. The semileptonic Λ_c^+ decay: $\Lambda_c^+ \to \Lambda_c^0 + e + \nu_c$ is characterized by a larger branching ratio, $B(\Lambda e\nu) = (2.1\pm 0.6)\%$, with relatively large decay asymmetry (in absolute value): $A = -0.82^{+0.11}_{-0.007}$ [22]. Note that the possibility to measure the Λ_c^+-polarization has been experimentally confirmed in hadronic collisions. It is not the case for the Σ_c-hyperon. Its main decay, $\Sigma_c \to \Lambda_c + \pi$, is due to the strong interaction. So, whereas the Λ_c^+ is a self-analyzing particle, the Σ_c is similar, in this respect, to any baryon resonance, with strong or electromagnetic decays.

3 Photoproduction of vector mesons

The vector meson D^*-photoproduction can be considered in a similar way. As in case of photoproduction of pseudoscalar mesons, the asymmetry for polarized $\vec{\gamma}+\vec{p}$- collisions takes the largest values near threshold. Generally the processes of vector meson production on nucleons are characterized by a complicated spin structure, with twelve independent amplitudes, but the situation is essentially simplified near threshold.

Only the asymmetry $\mathcal{A}_z$ does not vanish, at the reaction threshold, and it can be written as a function of the threshold amplitudes e_1, e_3 and m_3 [11], after summing over the polarization of the final particles):

$$\mathcal{A}_z(\gamma p\to\Lambda_c^+\overline{D^*}) = \frac{3|e_1|^2 - 3|e_3|^2 + |m_3|^2 - 2\mathcal{R}e(2e_1+e_3)m_3^*}{3|e_1|^2 + 6|e_3|^2 + 2|m_3|^2}. \tag{6}$$

For pure multipole transitions, with e_1, e_3 or m_3 amplitude, we have, respectively $\mathcal{A}_z(\gamma p \to$

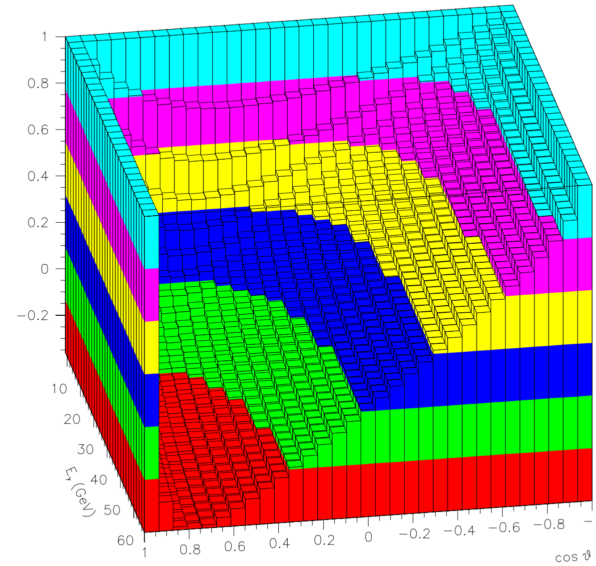

Figure 3: Same as Fig. 2, for the Λ_c^+ polarization P_z.

$\Lambda_c D^*) = 1$, -1/2 and 1/2.

A model for D^*-photoproduction [12], based on the pseudoscalar D-exchange gives $\mathcal{A}_x = 0$ and $\mathcal{A}_z$=0, for any photon energy and any production angle, because no spin correlation between the polarizations of γ and p in $\gamma p \to \Lambda_c^+ \overline{D^*}$ can be induced by the exchange of a zero spin particle. Therefore the discussed asymmetries can be considered a powerful signature of another possible exchange mechanism.

On the basis of our previous consideration [12] of possible baryon exchange contribution to the threshold multipole amplitudes e_1, e_3 or m_3, one can derive the following formula for the asymmetry $\mathcal{A}_z(\gamma p \to \Lambda_c^+ \overline{D^*})$:

$$N\mathcal{A}_z(\gamma p \to \Lambda_c^+ \overline{D^*}) = \frac{r}{M}\left\{-2(W-m) + \frac{r}{M}\left[(M+m)^2 - 2m_{D^*}(W+M)\right]\right\}, \qquad (7)$$

with

$$N = \left(\frac{W-m}{m_{D^*}}\right)^2 + 2r\frac{(W-m)(W+M)}{m_{D^*}M} + \left(\frac{r}{M}\right)^2\left(m^2 + 2W^2 + 2mW + 3M^2\right),$$

where $W = M + m_{D^*}$ and m, M, m_{D^*} are the masses of nucleon, Λ_c-hyperon and D^*-meson, respectively. The real parameter r characterizes the relative role of D-exchange mechanism and baryon exchange mechanisms for $\gamma + p \to \Lambda_c^+ + \overline{D^{*0}}$ [12].:

$$r = 2\frac{g_v}{g_{D^{*0}D^0\gamma}\, g_{p\Lambda_c D}}.$$

where g_v is the vector coupling constant for the vertex $p \to \Lambda_c^+ + \overline{D^{*0}}$ and $g_{D^{*0}D^0\gamma}$ is the magnetic moment for the $D^{*0} \to D^0$ transition. This moment determines the width of the radiative decay $D^{*0} \to D^0 + \gamma$, with experimental branching ratio $\simeq 40\%$. Only the upper limit is experimentally known for the total width of the neutral D^{*0}: $\Gamma(D^{*0}) \leq 2.1$ MeV [22]. The total width of the charged D^{*+}-meson is determined from the recent measurements of the CLEO collaboration [23]: $\Gamma(D^{*+}) = (96 \pm 4 \pm 22)$ keV. Using the known value for the branching ratio of the radiative decay $\Gamma(D^{*+}) \to D^{+} + \gamma$ [24]: $BR =$ $(16.8 \pm 0.42 \pm 0.49 \pm 0.03)\%$, one can find a value of the magnetic moment for the transition $D^{*+} \to D^{+} + \gamma$, which agrees with different theoretical predictions. Therefore it seems reasonable to use these models for the calculation of the coupling constant $g_{D^{*0}D^{0}\gamma}$. But the main problem, in our case, is how to determine the coupling constants for the vertexes $N\Lambda_c D$ and $N\Lambda_c D^*$. The $SU(4)$-symmetry, which connects these coupling constants with the corresponding coupling constants for the vertexes $N\Lambda K$ and $N\Lambda K^*$ is essentially violated. We showed earlier [12], that the parameter r can be determined, in principle, in the reaction $\gamma + p \to \overline{D^{*0}} + \Lambda_c^+$ through the angular dependence of the pseudoscalar D-meson produced in the subsequent decay $D^{*0} \to D + \pi$. Only for $r \simeq -1$ the asymmetry $\mathcal{A}_z(\vec{\gamma}\vec{p} \to \Lambda_c^+ \overline{D^*})$ is positive, being negative, $\mathcal{A}_z \simeq -0.25$, in the overall range.

From this brief discussion it appears that the prediction of the asymmetry $\mathcal{A}_z$ for vector meson photoproduction is more model dependent in comparison with $\overline{D}$-photoproduction, as this asymmetry depends on the value of r. We can suggest the study of the asymmetry in $\vec{\gamma} + \vec{p} \to \Lambda_c^+ + \overline{D^*}$ as a possible way to determine the fundamental coupling constants for the vertexes involving charmed particles.

The polarization properties of the produced $\overline{D^*}$ are induced by the circular polarization of the photon. The $\overline{D^*}$- density matrix $\rho_{ab}(\lambda)$, in the near threshold region, can be parametrized as: $\rho_{ab}(\lambda) = i\rho\lambda\epsilon_{abc}k_c$, where ρ is a real coefficient, dependent on the three multipole amplitudes e_1 and e_3 and m_3. Being a T-even polarization observable, $\rho \neq 0$ in the ELA model. However this parameter describes the vector polarization of the $\overline{D^*}$, therefore it is not easily accessible from an experimental point of view.

4 Conclusions

We calculated the T- and P-even asymmetries for the process $\vec{\gamma} + \vec{p} \to \Lambda_c^+ + \overline{D^0}(\overline{D^*})$, induced by circularly polarized photons on a polarized proton target and the polarization of the Λ_c- hyperon in $\vec{\gamma} + p \to \vec{\Lambda}_c^+ + \overline{D^0}$. Using an effective Lagrangian approach, we found that these polarization observables are large in absolute value for all considered photon energies. It is important that for pseudoscalar meson production the $\mathcal{A}_z$ asymmetry is essentially positive, large in magnitude and of the same sign of the predictions based on the photon-gluon fusion mechanism. This means that exclusive processes of associative charmed particle photoproduction have to be viewed as a non negligeable contribution to charm photoproduction at high energies.

For $\overline{D^*}$-photoproduction the predictions for the discussed asymmetries are more model dependent. Vanishing for $D-$ exchange, the threshold asymmetry $\mathcal{A}_z$ shows large sensitivity to the ratio of the coupling constants for the different vertices with charmed particles.

References

[1] K. Aulenbacher *et al.*, Nucl. Instrum. Meth. A **391**, 498 (1997).

[2] K. Wijesooriya *et al.* [Jefferson Lab Hall A Collaboration], Phys. Rev. Lett. **86** (2001) 2975.

[3] D. Adams *et al.* [Spin Muon Collaboration (SMC)], Phys. Lett. B **329**, 399 (1994); (E) Phys. Lett. B **339**, 332 (1994);

D. Adams *et al.* [Spin Muon Collaboration], Phys. Lett. B **357**, 248 (1995);

K. Abe *et al.* [E143 Collaboration], Phys. Rev. Lett. **74**, 346 (1995).

[4] K. Abe *et al.* [SLD Collaboration], Phys. Rev. Lett. **73**, 25 (1994).

[5] D. L. Adams *et al.* [FNAL E581/704 Collaboration], Phys. Lett. B **336**, 269 (1994).

[6] G. Bunce *et al.*, Part. World **3**, 1 (1992).

[7] G. Baum *et al.* [COMPASS Collaboration], CERN-SPSLC-96-14.

[8] F. Halzen and D. M. Scott, Phys. Lett. B **72**, 404 (1978);
H. Fritzsch and K. H. Streng, Phys. Lett. B **72**, 385 (1978);
V. A. Novikov, M. A. Shifman, A. I. Vainshtein and V. I. Zakharov, Nucl. Phys. B **136**, 125 (1978) [Yad. Fiz. **27**, 771 (1978)];
J. Babcock, D. W. Sivers and S. Wolfram, Phys. Rev. D **18**, 162 (1978).

[9] M. Gluck and E. Reya, Z. Phys. C **39**, 569 (1988);
M. Gluck, E. Reya and W. Vogelsang, Nucl. Phys. B **351**, 579 (1991).

[10] S. J. Brodsky, E. Chudakov, P. Hoyer and J. M. Laget, Phys. Lett. B **498**, 23 (2001).

[11] M. P. Rekalo, Ukr. Fiz. Journ. 22 (1977) 1602. M. P. Rekalo and E. Tomasi-Gustafsson, Phys. Lett. B **500**, 53 (2001); M. P. Rekalo and E. Tomasi-Gustafsson, Phys. Rev. D **65**, 014010 (2002);

[12] M. P. Rekalo and E. Tomasi-Gustafsson, Phys. Rev. D **65**, 074023 (2002).

[13] Z. W. Lin and C. M. Ko, Phys. Rev. C **62**, 034903 (2000) and refs herein.

[14] T. Matsui and H. Satz, Phys. Lett. B **178**, 416 (1986).

[15] G. F. Chew, M. L. Goldberger, F. E. Low and Y. Nambu, Phys. Rev. **106**, 1345 (1957).

[16] M. P. Rekalo and E. Tomasi-Gustafsson, Phys. Lett. B **541**, 101 (2002).

[17] S. Bianco, arXiv:hep-ex/9911034.

[18] K. Abe *et al.* [SLAC Hybrid Facility Photon Collaboration], Phys. Rev. D **30**, 1 (1984).

[19] F. G. Garcia *et al.* [SELEX Collaboration], Phys. Lett. B **528**, 49 (2002).

[20] E. M. Aitala *et al.* [E791 Collaboration], Phys. Lett. B **495**, 42 (2000).

[21] M. J. Savage, Phys. Lett. B 326, 303 (1994).

[22] D. E. Groom *et al.*, Eur. Phys. J. **C 15**, 1 (2000).

[23] A. Anastassov *et al.* [CLEO Collaboration], hep-ex/0108043.

[24] J. Bartelt *et al.* [CLEO Collaboration], Phys. Rev. Lett. **80**, 3919 (1998).