Nucleon emission with polarized and unpolarized photons:
A proposal for ALBA

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Abstract

We analyze different possibilities for nuclear physics studies offered by the proposed line of backscattered laser photons in the synchrotron ALBA, to be built in Barcelona. We propose to measure both cross sections and asymmetries for the photon-induced one- and two-nucleon emission reactions. Polarized photons with energies up to 150 MeV allow a detailed study of the effects of the meson exchange currents and of the short range correlations in medium-heavy nuclei.

1 Introduction

In the last years, nucleon emission induced by electromagnetic probes, both photons and electrons, scattered off nuclei has been used as tool to investigate different physical processes such us the effects of the short-range nucleon-nucleon correlations (SRC), those of the meson-exchange currents (MEC), the relevance of the final state interactions (FSI) between the emitted nucleons and the residual nucleus, etc. [1]. The proposal of building a line of backscattered laser photons for nuclear physics and applications in the synchrotron ALBA under construction in Barcelona, opens the possibility to perform new photon-nucleus scattering experiments.

From the experimental point of view, one of the main problems with the photon facilities is to achieve a compromise between good energy resolution, high degree of polarization and high photon flux. This difficulty has hampered the development of the experimental programs. However, laser backscattering technique allows one to gather simultaneously these three designing goals [2].

The proposed line is expected to provide photons up to 500 MeV. Up to about 150 MeV the energy selection is made by direct collimation in the backward direction. In this case a 1.5% of relative energy resolution is expected. For more energetic photons, the energy selection is done by electron tagging, and the resolution is expected to be of about 5 MeV.

An analysis of the available low energy experimental data, below the pion production threshold, shows that they are old, incomplete and not accurate enough to disentangle interesting effects predicted by the theory [3]. This indicates the need of new experiments as well as theoretical effort to implement modern realistic forces in calculations for nuclei with $A > 4$. In this report we discuss the opportunities offered by experiments with both polarized and unpolarized photons up to 150 MeV, in medium-heavy nuclei, to investigate the effects of meson-exchange currents (MEC) and short-range nucleon-nucleon correlations (SRC).

2 Experimental status

One method to produce photons for nuclear physics experiments is to use *bremsstrahlung*, at it is done at MAMI (MAinz MIcrotron) in Mainz [4]. The other adopted technique is the laser backscattering, as it has been proposed for the line at ALBA. This last technique is much more suitable for polarization measurements. In the world, there is quite a number of facilities which uses this last technique. For example, LEGS (Laser Electron Gamma-ray Source) [5], which produces photons up to 470 MeV, and HIGS (High Intensity Gamma Source) [6], with photon energies between 2 and 200 MeV. Higher energies can be achieved in Gr.A.A.L. (GRenoble Anneau Accelerateur Laser) [7], where resonances beyond the $\Delta(1232)$ region, and meson production, can be studied within the operation range between 550 and 1500 MeV. The LEPS facility (Laser Electron Photon Experiment at SPring-8) [8] has even a larger high energy limit (2400 MeV).

Almost all the experimental work relative to one-nucleon photo-emission in medium-heavy nuclei, has been done with unpolarized photons [1]. As far as we know, the $(\vec{\gamma}, p)$ reaction has been studied only by Yokokawa *et al.* in 1988 on the ^{12}C target at excitation energies between 40 and 70 MeV [10].

In recent years, two-nucleon emission has been investigated with unpolarized photons [11] by using the ^{9}Be, ^{12}C and ^{16}O nuclei as targets, and with photon energies above 100 MeV. Polarized photons, with energies ranging between 160 and 350 MeV [12] have been used to study both $(\vec{\gamma}, pp)$ and $(\vec{\gamma}, pn)$ reactions in ^{12}C and ^{16}O nuclei.

3 Proposed experiments

In this section we propose a set of experiments to be done on ^{12}C, ^{16}O and ^{40}Ca nuclei. Their doubly closed shell character requires a simpler nuclear structure description and permits a good control of the theoretical uncertainties.

Our calculations have been done in the framework of a model which permits to take into account SRC and MEC in electromagnetic processes involving nuclei with $A > 4$, in such a way that different processes, like inclusive electron scattering, one- and two-nucleon emission induced by electron scattering and, eventually, real photon scattering, can be described by using the same methodology. The idea was to have a consistent view of the different processes. The model has been applied to processes involving electron [13] and photon [14, 15] scattering.

3.1 (γ, N)

The effect of SRC and MEC in the ^{16}O(γ,p)^{15}N(g.s.) process are shown in Fig. 1 for various photon energies. The thin full lines have been calculated in the framework of the Independent Particle Model (IPM) and by using one-body (OB) currents only. The dotted lines show the results obtained by adding the SRC (see [14] for details). The inclusion of the MEC produces the dashed lines. Finally the thick full lines have been obtained by including both SRC and MEC. Our calculations overestimate the data at small emission angles. The shape of the data at high energy values is reproduced only because of the inclusion of SRC and MEC. It is evident that the MEC contributions are larger than those of the SRC.

Above 150 MeV, the cross sections obtained in the IPM with the OB currents only have a sharp decrease for large values of the nucleon emission angle. In this region, the correlations produce cross sections which are order of magnitude larger than those obtained with the IPM. This is exactly the same, well known, behavior of the nucleon momentum distribution. However, this effect cannot be disentangled because in these cross sections the MEC play an important role, more important than that of the SRC. Therefore the effect of SRC is overwhelmed by that of the MEC.

3.2 $(\vec{\gamma}, N)$

As previously stated, one-nucleon emission experiments induced by polarized photons are scarce [10]. This situation opens interesting possibilities for the nuclear physics photon line at ALBA.

Preliminary calculations done by our group [21] show the sensitivity of the asymmetry to the MEC effects. In Fig. 2, the results obtained for the asymmetry in case of the ^{16}O($\vec{\gamma}$,p)^{15}N(g.s.) process are shown for various values of the photon energy. The OB (full lines), OB+SRC (dotted lines), OB+MEC (dashed lines) and OB+SRC+MEC (dashed-dotted lines) results are plotted. In the calculations we used two different SRC (see [21] for details).

In the figure the importance of MEC effects is evident, independently from the correlation function chosen, at angles above 90^o and the higher the photon energy is. However, the interference between the correlation function and the MEC behaves differently in both cases. It has almost no effect on the S3 correlation, while for the Gaussian one, it gives rise to an important modification of the asymmetry obtained when only MEC are taken into account. This is due to the fact that the Gaussian correlation produce a non-negligible effect at large angles and at high energies.

The dominance of the MEC effects, which appeared also in the (γ, N) process at large emission angles and for high energies, show up in the asymmetry even at rather low energies. In addition, it presents a certain sensitivity to the correlation function used.

3.3 (γ, NN)

The emission of two nucleons induced by photons offers the possibility to investigate the role of the SRC in nuclei. To this purpose, a minimization of the effects of other competing mechanisms, for example MEC, permits a clearer analysis. In the emission of two-like nucleons, two protons for example, the largest terms of MEC which are related to the exchange of charged pions, do not contribute [15]. Thus, (γ,pp) is a good choice to investigate SRC since, in this case, the only competing operators are the Δ-current terms of the MEC where a π^0 is exchanged.

Our investigation about the relative importance of the SRC and the Δ currents, has been done by using the integrated cross sections

$$S = \int \mathrm{d}\theta_1 \sin\theta_1 \frac{\mathrm{d}^5\sigma(\Omega_1, \Omega_2)}{\mathrm{d}\Omega_1 \mathrm{d}\epsilon_2 \mathrm{d}\Omega_2} \tag{1}$$

for the various final nuclear states and for various emission angles of the second proton.

In Fig. 3 we show the ratios between the S factors calculated with SRC only and those obtained by adding the Δ currents contributions. These ratios are shown as a function of the angle θ_2 of the second emitted proton. The reaction considered is ^{16}O(γ,pp), and the various panels show the results obtained for the different final states of the ^{14}C. Two different photon energies have been used.

The effects of the Δ are smaller at 100 MeV than at 215 MeV, but they show a strong dependence on the final state of the residual nucleus and on the proton emission angle. For $\omega = 100$ MeV, almost all the ratios are very close to unity, showing a small effect of the Δ currents, even in the case of the 1^+ state.

We found analogous results in other kinematics. In Fig. 4 we show the effects of the Δ-currents in the superparallel back-to-back kinematics. Again, the Δ-currents are not relevant at $\omega = 100$ MeV. Nevertheless there is noticeable effect for the 0^+_1 state at high values of the recoil momentum. However, it is possible to find kinematics where the Δ-currents are important even at 100 MeV. An example of this is given in Fig. 5 where the results obtained for the 0^+_1 state in the ^{16}O(γ,pp)^{14}C reaction in symmetric kinematics are presented.

All the results presented so far show a common feature. The largest SRC effect are produced by the same correlation: the Gaussian one. We have verified that this general trend regards the cross sections integrated on the angular distribution of one of the emitted protons, after fixing all the other kinematic variables. Also in this case, by choosing some peculiar angular distributions, it is possible to find situations where this general feature is not present. An example of this is given in Fig. 6, where the cross sections calculated for the three different correlation functions in superparallel back-to-back kinematics are shown. It is evident how the case of the 0^+_2 is out of the general trend observed for the other states.

(γ, pp) appears to be a useful tool in investigating the role of the SRC because of the possibility to strongly suppress the contribution of the Δ-current for certain kinematics mainly for photon energies around 100 MeV.

3.4 $(\vec{\gamma}, NN)$

Two-nucleon emission induced by polarized photons is also an interesting tool to investigate SRC and MEC. In Fig. 7 we show the ^{16}O($\vec{\gamma}$,pp)^{14}C cross sections (upper panels) and asymmetries (lower panels) for 80 MeV photons. The results shown in the left panels have been obtained with the Δ-currents only, while those in the right panels consider in addition the SRC. The different curves correspond to various parameterizations of the Δ-currents operators found in literature [22]. The Gaussian correlation function have been used.

The sensitivity to the parameterization of the Δ-current operator is evident in the cross sections, especially in the results without SRC. However, the asymmetry in absence of SRC is completely unaffected by the change of such parameterizations. The situation changes when the SRC are included, they also produce a strong modification of the shape of the asymmetry.

Fig. 8 shows the ratio between the cross sections calculated with SRC and those obtained by adding the Δ-currents contribution. The results shown in the left panel correspond to the Gaussian correlation while those of the right panel give the results obtained for the S3 correlation. Two effects should be remarked. The dependence from the parameterization of the current operator and the modification of the shapes produced by the two different correlation functions.

Fig. 9 shows the asymmetries calculated for the ^{16}O($\vec{\gamma}$,pp)^{14}C reaction. The photon energy has been fixed to 100 MeV. As we can see, the effect of changing the correlation function used for SRC appears to be relevant in the case the ^{14}C nucleus is left in a 0^+ state.

Two-nucleon emission induced by polarized photons can be used to investigate the SRC role by means of the asymmetries once an adequate kinematics is selected.

4 Conclusions

Polarized and unpolarized photons with energies up to 150 MeV appear to be a useful tool to make high precision nuclear physics. By choosing the kinematics, the contributions of the different physical mechanisms can be enhanced or reduced and this permit to investigate subtle effects such as those produced by SRC and the MEC. In this respect, the proposed nuclear physics line at the ALBA synchrotron is a very interesting facility because of the estimated high energy resolution and for the possibility to obtain photons with almost 100% polarization. The wide spectrum of experimental work to be developed with this facility would cover an almost completely unexplored area since nucleon emission data obtained with polarized photons are very scarce.

Acknowledgments

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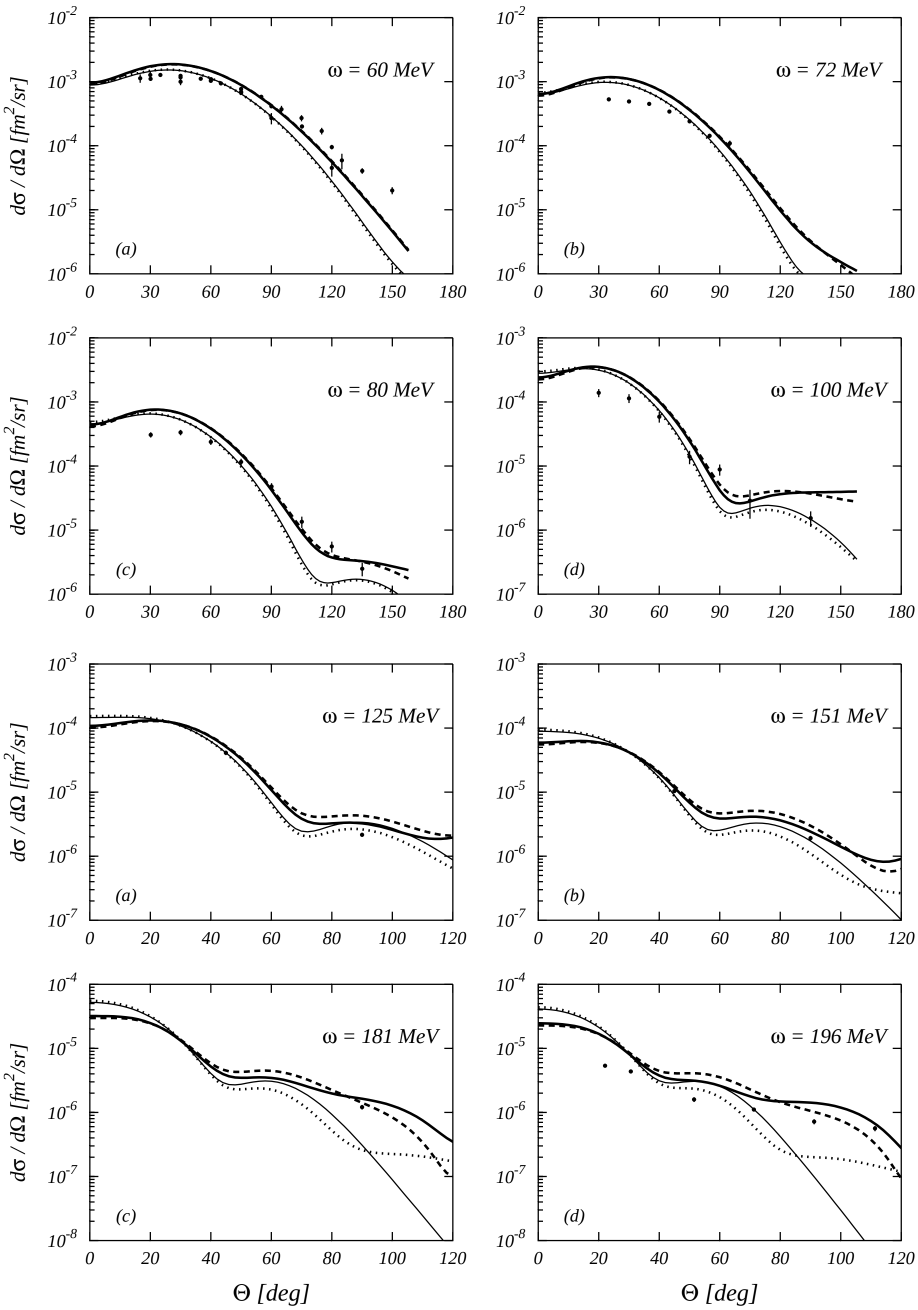

Figure 1: Angular distributions of the $^{16}O(\gamma,p)^{15}N(g.s.)$ cross section. The thin full lines have been calculated in the IPM by using OB currents only. The dotted lines include the effects of the SRC correlation (see [14] for details). The dashed lines include the MEC and the thick full lines all the effects. Data up to 100 MeV are from Refs. [16, 17, 18]. Data at 126, 151 and 180 MeV are from Ref. [19] and those at 196 MeV from Ref. [20].

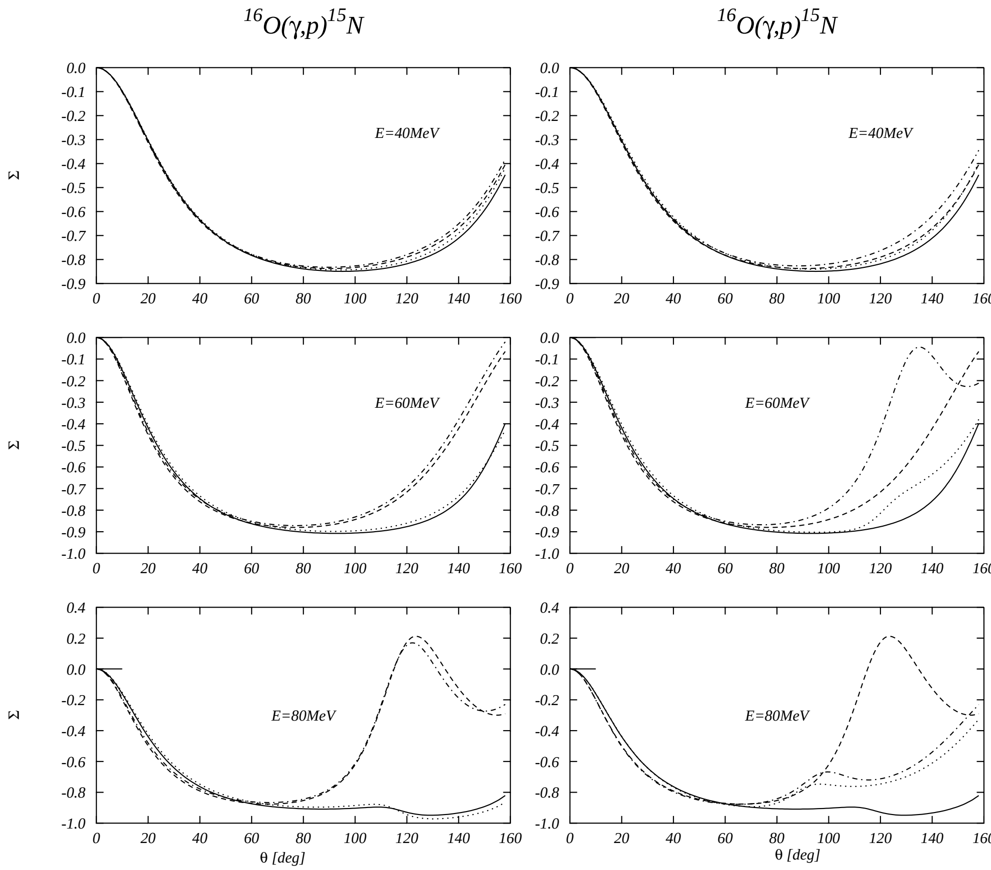

Figure 2: Angular distributions of the ^{16}O($\vec{\gamma}$,p)^{15}N(g.s.) asymmetry. The full lines have been calculated in the IPM by using OB currents only. The dotted lines include the effects of the SRC. The dashed lines the MEC and the dashes-dotted lines all the effects. In the left panels the S3 correlation is used. The Gaussian correlation has been considered in right panels (see [21] for details).

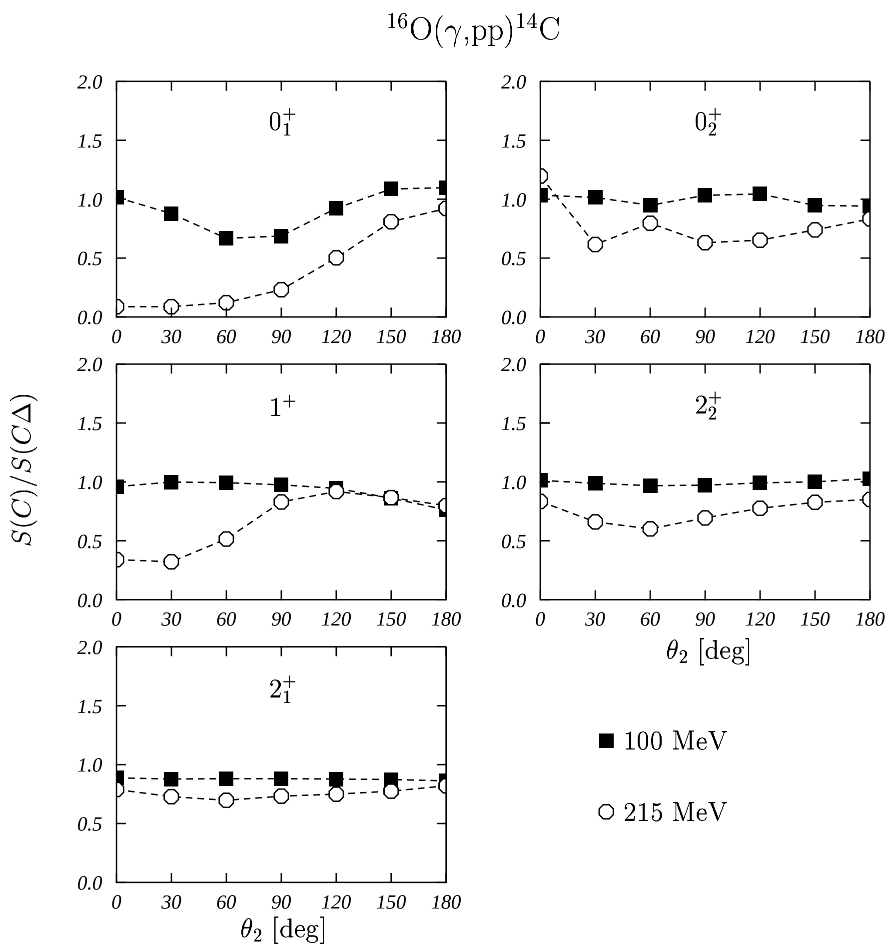

Figure 3: Ratios $S(C)/S(C\Delta)$ calculated for various values of θ_2 and for photon energies of 100 and 215 MeV. The calculations have been done with ϵ_2=40 MeV. The dashed lines have been drawn to guide the eyes.

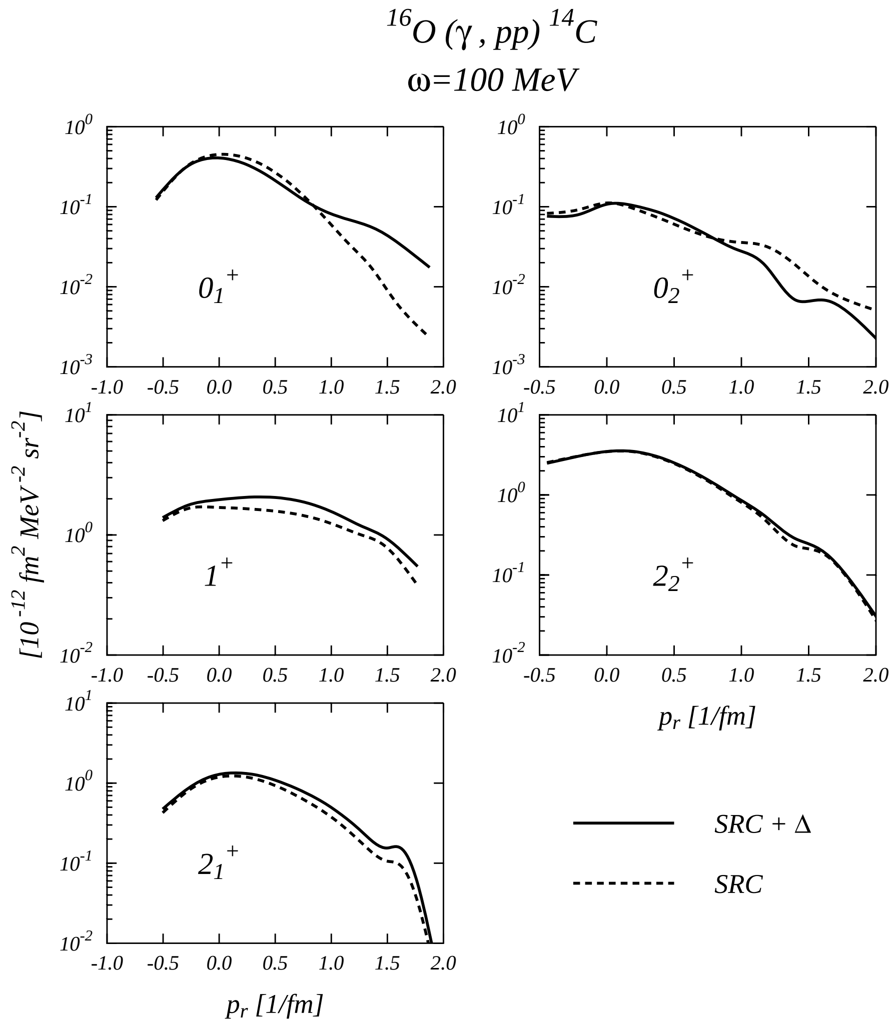

Figure 4: ^{16}O (γ,pp) ^{14}C cross sections in superparallel back to back kinematics ($\theta_1 = 0^o$,$\theta_2 = 180^o$) for various states of the ^{14}C. The full lines have been obtained by considering both SRC and Δ current terms, while the dashed lines show the results obtained without the Δ currents.

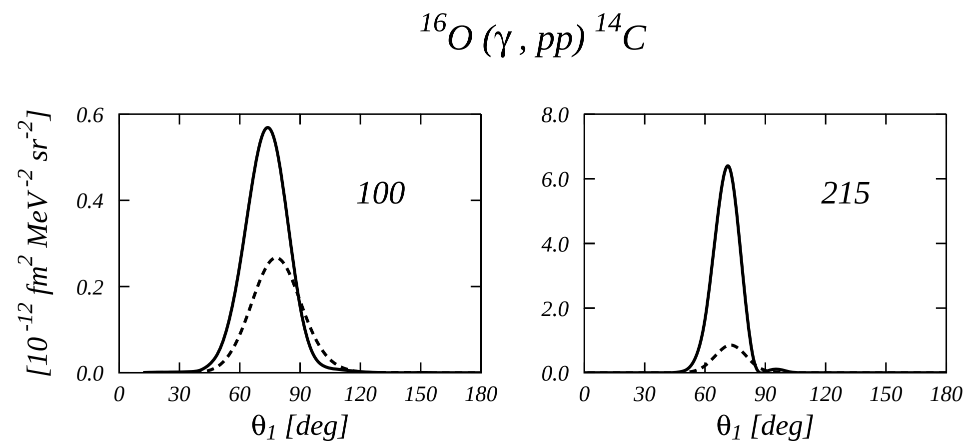

Figure 5: ^{16}O (γ,pp) ^{14}C cross section angular distributions for the 0_1^+ final state in ^{14}C in symmetric kinematics. The full lines show the results obtained by considering both SRC and Δ-currents. The results shown by the dashed lines have been obtained with SRC only. The numbers characterizing the two panels indicate, in MeV, the photon energy.

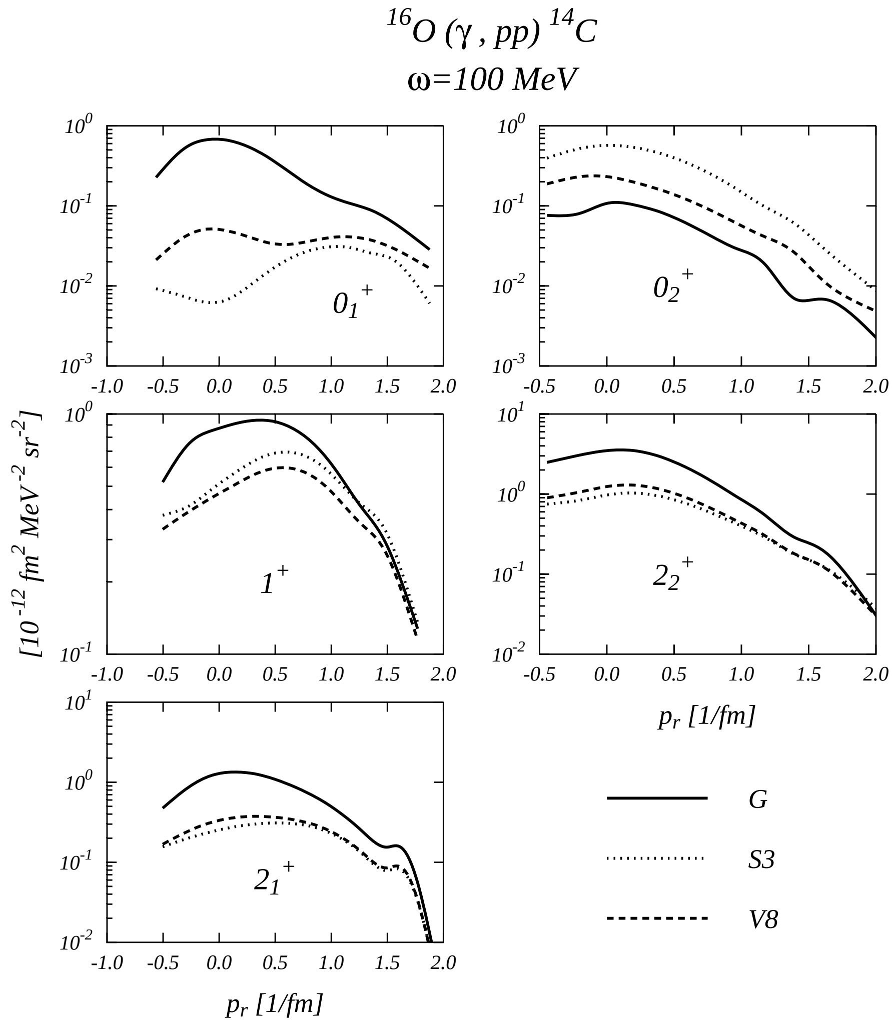

Figure 6: ^{16}O (γ,pp) ^{14}C cross sections calculated for various final states in superparallel back to back kinematics ($\theta_1 = 0^o$,$\theta_2 = 180^o$).

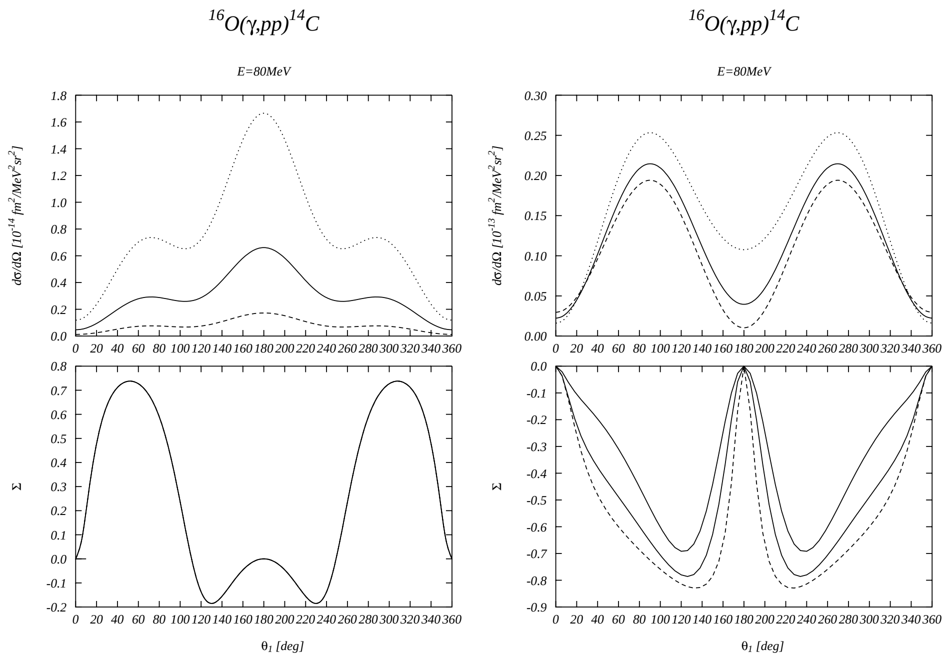

Figure 7: Cross section and asymmetry of $^{16}O(\vec{\gamma},pp)^{14}C$ process for 80 MeV photons. The results shown in the left panels have been obtained by considering the Δ-currents effects only. Those shown in the right panels include also the SRC calculated with the Gaussian correlation function. The three lines correspond to three different parameterizations of the Δ-currents operators (see [21] for details).

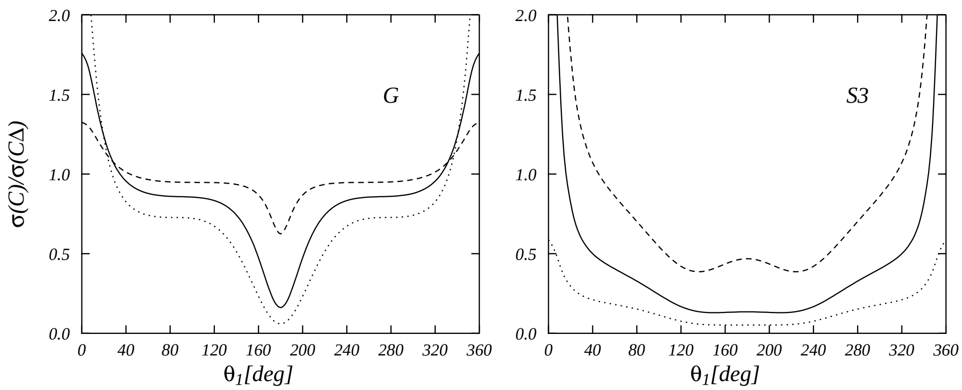

Figure 8: Ratio between the $^{16}O(\vec{\gamma},pp)^{14}C$ cross sections for 80 MeV photons calculated with the SRC only and those calculated including also the MEC contribution. The results shown in the left panel have been obtained with the Gaussian correlation, while those of the right panel correspond to the S3 correlation. The three lines have been obtained by using three different parameterizations of the Δ currents operators (see [21] for details).

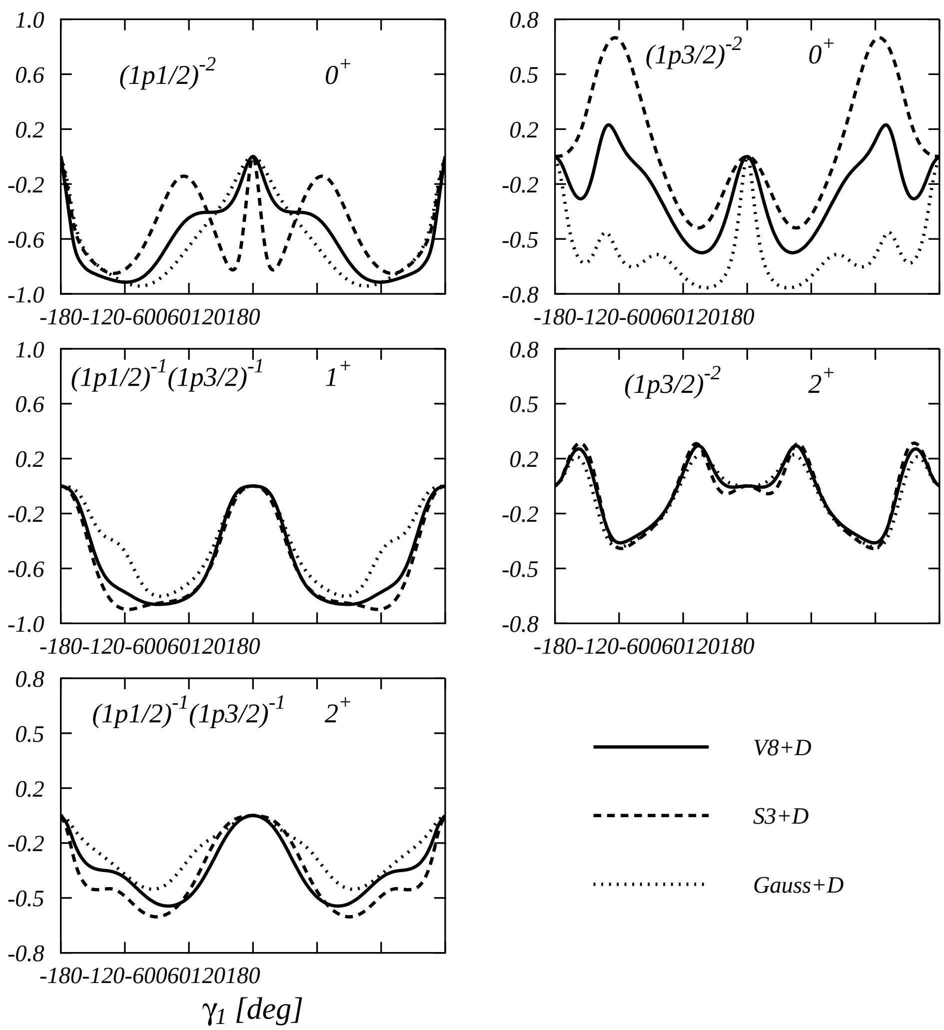

Figure 9: Asymmetries for the ^{16}O($\vec{\gamma}$,pp)^{14}C process, for different final states and for 100 MeV photons, calculated with three different correlation functions. The Δ contribution is fixed to one of the parameterizations previously discussed.