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$^{12}C(\vec{\gamma},pn)$ photon asymmetry for $E_\gamma = 180–340$ MeV

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Abstract

The photon asymmetry (Σ) of the $^{12}C(\vec{\gamma},pn)$ reaction has been measured using linearly polarised tagged photons at the Mainz microtron MAMI for $E_\gamma = 180–340$ MeV. The data have been analysed in separate missing energy (E_m) regions corresponding to the ejection of nucleons from $(1p)^2$ and (1p)(1s) shells. The measured Σ values for both E_m regions are smaller in magnitude than corresponding ^2H data, but the $(1p)^2$ results have a similar E_γ dependence. Calculations of direct two-nucleon emission overestimate the magnitude of Σ at all photon energies.

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Photon absorption on nucleon pairs in light nuclei [1–3] is sensitive to many parts of the nucleon-nucleon interaction including meson and isobar exchange currents (MEC) at medium range and short range correlations (SRC). Detailed measurements of (γ,NN) reactions are expected to provide insight into these nucleon-nucleon interactions by providing comparisons and constraints for theoretical models. Previous work has established that at low missing energies (γ,pn) reactions proceed by the direct knockout of interacting nucleon pairs with the residual nucleus acting as a spectator [4–6]. The emitted nucleons have a back-to-back angular correlation similar to that in the two-body photodisintegration of deuterium, but smeared by the initial Fermi motion

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of the two emitted nucleons. Further similarities with deuterium are observed in the photon energy dependence of the (γ,pn) cross section in ^{4}He, ^{6}Li and ^{12}C [7–10] and in ^{12}C(γ,pn) spectra of the average relative momenta of the ejected nucleon pair [11]. Despite these general similarities the differences between (γ,pn) reactions in light nuclei and deuterium photodisintegration are of particular interest. These reflect changes in the properties of the interacting nucleons and their interaction brought about by the nuclear environment. A recent result [12] shows that the angular distributions of the ^{12}C(γ,pn) cross section are very different from deuterium indicating significant differences in the contributing MEC. Calculations of direct two-nucleon emission incorporating one-pion-exchange (OPE) and medium-dependent Δ propagators, carried out for average kinematic conditions, reproduce the general features of the measured angular distributions [13], but do not fit the experimental data in detail.

Measurements of photon asymmetry (Σ) provide an independent test of photonuclear reaction models. Σ is given by a ratio of two structure functions $-\frac{W_{TT}}{W_T}$ [1–3] representing the response of the nucleus to transverse components of the electromagnetic interaction, whereas the (γ,2N) cross section depends only on W_T. The asymmetry is particularly sensitive to spin variables and hence to interference between different contributing terms in the nuclear current. It provides an additional observable against which models of two-nucleon photoemission can be judged and has the additional advantage of being much less sensitive to final state interactions than cross section measurements [1,2].

There have been several Σ measurements for deuterium photodisintegration in the Δ resonance region [14–19]. Of these the most extensive measurements with reasonably small statistical and systematic errors are those from the LEGS collaboration [18] and the recent DAPHNE measurements at Mainz [19]. The measurements of ($\vec{\gamma}$,pn) reactions in light nuclei are less extensive. Measurements on ^{6}Li and ^{4}He have been made using coherent bremsstrahlung in the photon energy ranges 300–900 MeV and 450–550 MeV, respectively, at Yerevan [17]. The Yerevan experiment used the angular correlation between the emitted nucleons to select two-nucleon emission events. Even so, this left significant backgrounds from multiparticle emission events which had to be subtracted. The laser backscattering technique has been used at LEGS to measure Σ for the ($\vec{\gamma}$,pn) and ($\vec{\gamma}$,pp) reactions in ^{3}He [20] and ^{16}O [21,22]. The ^{3}He data were obtained in coplanar kinematics at polar angles $\theta_p \sim 100°$ for $E_\gamma = 235$–305 MeV. The ^{16}O measurements were made in coplanar kinematics with symmetric angles of the emitted nucleons for $E_\gamma = 245$–315 MeV [21] and in quasideuteron kinematics for $E_\gamma = 210$–330 MeV [22].

This letter reports Σ measurements for the ^{12}C($\vec{\gamma}$,pn) reaction from 180 to 340 MeV, which span the Δ resonance excitation region. Direct emission of nucleon pairs from specific shells was selected by restricting the opening angle of the two emitted nucleons and the missing energy (E_m) [5]. The measured Σ values are compared with corresponding ^{2}H data, previous ($\vec{\gamma}$,pn) data for other light nuclei, and theoretical predictions of direct two-nucleon emission.

The experiment was performed using the Glasgow tagged photon spectrometer [23] at the Mainz 855 MeV electron microtron MAMI [24]. The photon energy resolution was ~ 2 MeV. Coherent bremsstrahlung, from a thin diamond radiator mounted in a goniometer, produced linearly polarised photons [25] which were then incident on a 0.7 g/cm^2 graphite target inclined at an angle of 30°. The polarisation orientation was rotated through 90° every few minutes to minimise systematic errors. Three separate measurements with different goniometer settings were used to span the photon energy range 150–360 MeV. The photon beam was collimated to a half angle of 0.6 mrad in order to select the highest polarisation part of the bremsstrahlung angular distribution. The maximum polarisation produced was $\sim 65\%$ and data with polarisations greater than 25% were analysed. The polarisation P of the beam was modeled using a Monte Carlo code [29] incorporating both the coherent and incoherent bremsstrahlung processes. This code gave very good descriptions of the measured collimated tagged photon energy spectra for all the crystal orientations used in the experiment. A check of the photon polarisation was provided by measurements of the deuterium photodisintegration asymmetry, obtained with a perdeuterated polythene target and shown as solid squares in Fig. 1. These data are in excellent agreement with the best available deuterium measurements [18,19]. In addition, $^{12}C(\vec{\gamma},pn)$ Σ data taken in overlapping photon energy ranges, using different crystal orientations which have different associated polarisation magnitudes, are self-consistent within their statistical errors. It is estimated that the systematic uncertainty in the calculated photon polarisation, P, is less than $0.1P$ and this factor produces the largest contribution to the systematic uncertainty in the asymmetry measurements.

Protons were detected in a ~ 1sr solid angle plastic scintillator hodoscope, PiP [26], covering proton polar angles from 50° to 130° and azimuthal

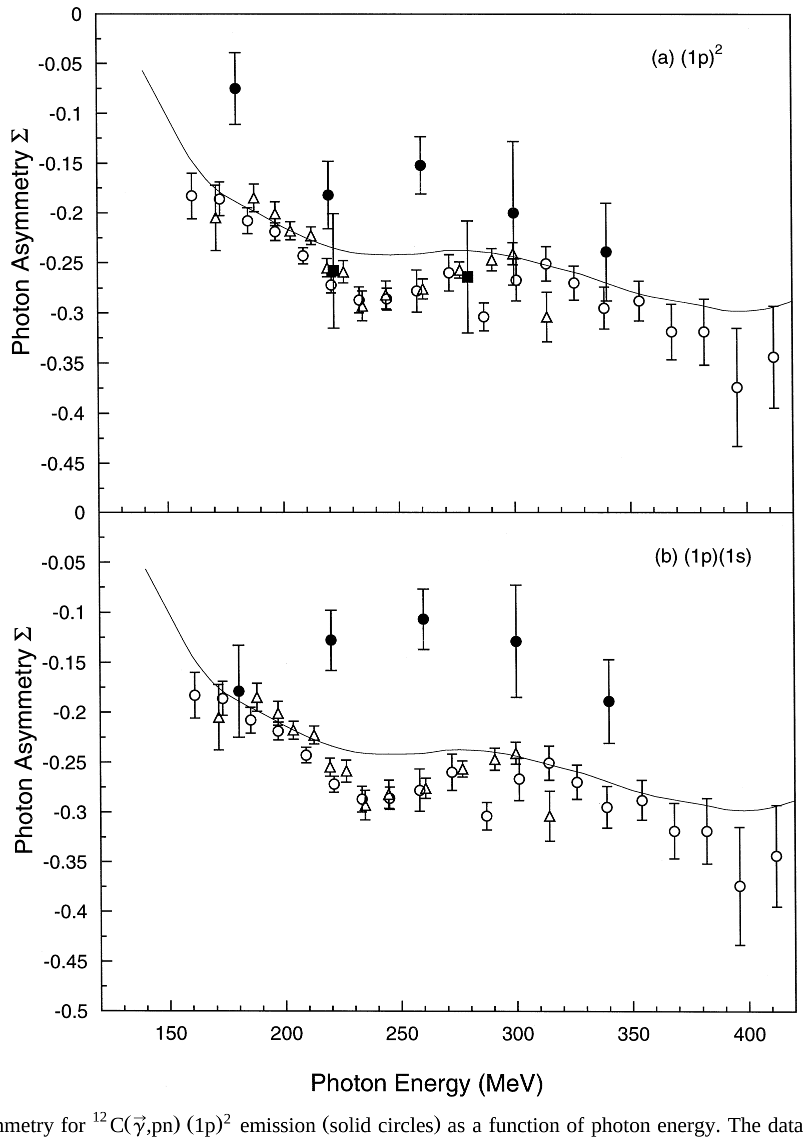

Fig. 1. (a) Photon asymmetry for $^{12}C(\vec{\gamma},pn)$ $(1p)^2$ emission (solid circles) as a function of photon energy. The data are compared to recent $^2H(\vec{\gamma},pn)$ data: the solid squares are from the present measurement, the open circles are recent Mainz measurements [19], the open triangles are from LEGS [18]. Both the Mainz and LEGS data have been averaged over the acceptance of the present experiment. The solid line is the result of a Monte Carlo ''quasi-deuteron'' simulation (see text) which takes into account the effects of initial Fermi motion. (b) As (a) for $^{12}C(\vec{\gamma},pn)$ (1p)(1s) emission.

angles of $\pm 22°$. Correlated neutrons were detected in an array of plastic scintillator time-of-flight detectors, TOF [27], deployed on the opposite side of the photon beam between polar angles of 28° and 148°. The azimuthal angular coverage of TOF varied with polar angle but was always greater than $\pm 13.5°$. The data acquisition, calibration, particle selection techniques and corrections for random and target out background were the same as in previous experiments [6,13,28].

The photon asymmetry is defined as $\Sigma = \frac{1}{P}\frac{(Y_{\parallel} - Y_{\perp})}{(Y_{\parallel} + Y_{\perp})}$, where $Y_{\parallel}(Y_{\perp})$ is the measured yield for reactions in which the reaction plane is parallel (perpendicular) to the electric vector of the polarised photons. Events with quasideuteron kinematics were selected by accepting angles $\theta_{\mathrm{diff}} < 20°$, where θ_{diff} is the difference in opening angle between the measured proton-neutron pair and the corresponding angle from $(\gamma$,2N) kinematics assuming the pair had zero initial momentum. To ensure uniformity of azimuthal acceptance with polar angle we only include events in the determination of $Y_{\parallel}(Y_{\perp})$ if the ϕ angle of the reaction plane, defined by the average azimuthal angle of the two emitted nucleons, is within $\pm 13.5°$ of 0°(90°). Accepting a range $\Delta\phi$ of azimuthal angles reduces the observed value of Σ and this is corrected by the factor $\frac{\Delta\phi}{\sin(\Delta\phi)}$, which provides a correction of 4% in the present case. The data obtained were concentrated at missing momenta P_{m} between 0 and 300 MeV$/c$ with no observable variation in Σ with P_{m} over this range. The E_{m} resolution of the experiment was ~ 8 MeV FWHM. This allowed the selection of events in two missing energy regions, $E_{\mathrm{m}} < 40$ MeV and $40 < E_{\mathrm{m}} < 70$ MeV, which are dominated, respectively, by the emission of nucleon pairs from $(1p)^2$ and (1p)(1s) orbitals. It is estimated that the small amount of mixing between these two regions due to resolution effects will give rise to systematic uncertainties in the extracted asymmetries of less than ± 0.015.

Fig. 1 shows the photon energy dependence of the present $^{12}C(\vec{\gamma}$,pn) asymmetry data for emission of $(1p)^2$ and (1p)(1s) pairs. The data for both E_{m} regions have small negative asymmetries at all the measured photon energies. They are compared with the recent deuterium photodisintegration results from LEGS [18] and Mainz [19]. In order to provide a valid comparison the deuterium data have been averaged over the same proton angular acceptance as the ^{12}C data with weights proportional to the PiP solid angle at each value of θ_p. The ^{12}C $(1p)^2$ asymmetry is significantly lower in magnitude than the deuterium result for photon energies below ~ 280 MeV. Above this energy the ^{12}C and deuterium results appear to converge. Despite the relatively large statistical uncertainties the ^{12}C $(1p)^2$ data appear to have a rather similar shape to deuterium photodisintegration. For (1p)(1s) emission the magnitudes of Σ are generally lower than for $(1p)^2$ emission, except at the lowest photon energy, and there is no indication of the dip seen in the deuterium data and also indicated for $(1p)^2$ emission from ^{12}C.

In order to establish whether the observed difference in magnitude between the asymmetry for ^{12}C and deuterium could be due to the effect of initial Fermi motion in the ^{12}C case, or should be attributed to more fundamental differences in the microscopic reaction mechanisms, a series of Monte Carlo simulations, based on the spectator model of two-nucleon photoemission described by McGeorge et al. [5], were carried out. The Monte Carlo simulation was modified to include photon polarisation and used a parameterisation of the recent deuterium asymmetry data from LEGS [18] and Mainz [19], extended to lower and higher energies using the data of Gorbenko et al. [16].

The solid line in Fig. 1 shows the result of the model simulation for the detector setup of the present experiment. The Fermi motion causes a slight reduction and smoothing of Σ compared to deuterium, but the results still show a significant difference from the ^{12}C $(1p)^2$ data below ~ 280 MeV. The difference is even larger for (1p)(1s) emission.

The present ^{12}C $(1p)^2$ data are compared with the few available $(\vec{\gamma}$,pn) data on light nuclei in Fig. 2a, although these were taken under different kinematic conditions and this may well affect the asymmetry [3]. For ease of comparison an average of the LEGS [18] and Mainz [19] deuterium data point from Fig. 1 is represented here as a solid line. The LEGS $^{3}He(\vec{\gamma}$,pn)p reaction [20] data point is an average over the wide E_γ range 235 to 305 MeV at $\theta_p = 100°$ for $\theta_n = 24$–144°. It lies between the present ^{12}C $(1p)^2$ data and the deuterium data. In the figure we have shown the LEGS $^{16}O(\vec{\gamma}$,pn) data obtained

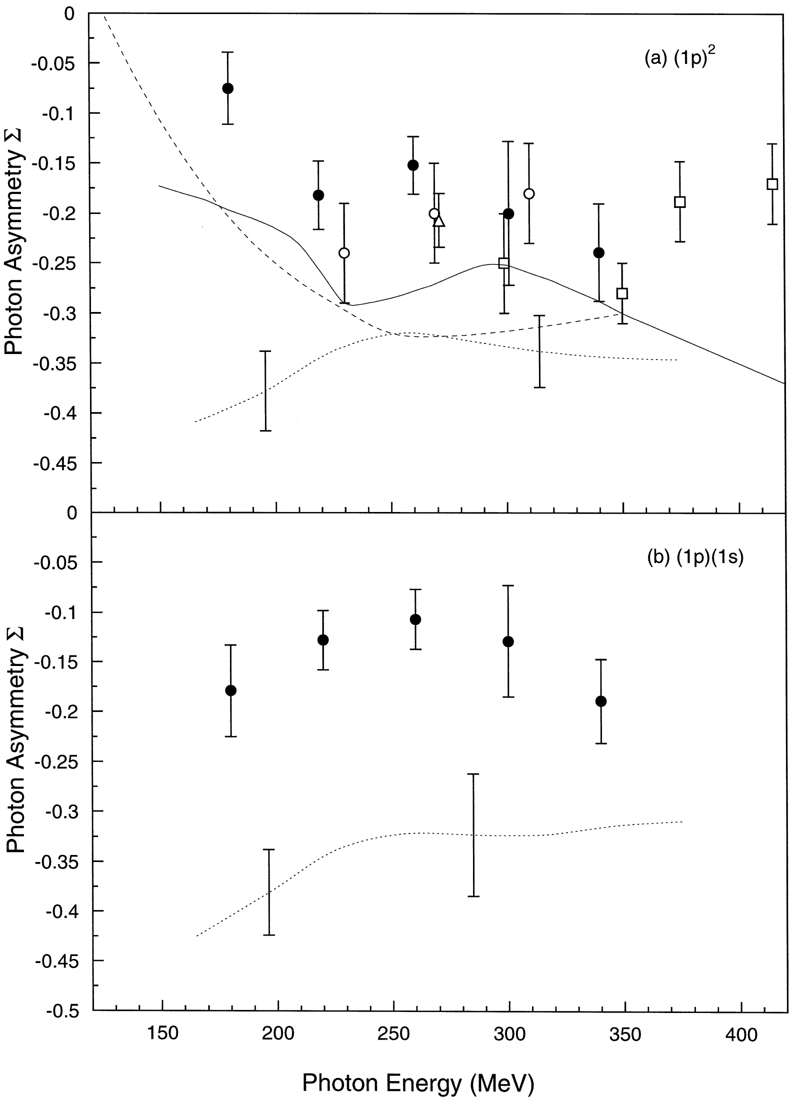

Fig. 2. (a) Comparison of $^{12}C(\vec{\gamma},pn)$ $(1p)^2$ emission Σ data (solid circles) with previous measurements in other light nuclei and with theoretical predictions. The open triangle is the ^3He datum point from LEGS [20]. The open circles are ^{16}O data from LEGS [22]. The open squares are ^6Li data from Yerevan [17]. The overlapping data points at 270 MeV and 300 MeV have been displaced laterally for the sake of clarity. The solid line is an average of the ^2H data from Mainz [19] and LEGS [18] data shown in Fig. 1. The dotted line shows the results of calculations of $^{12}C(\vec{\gamma},pn)$ $(1p)^2$ emission using the Gent model, described in the text. Sample error bars indicate the statistical error due to random sampling of the experimental kinematics. The dashed line is Σ for $^{16}O(\vec{\gamma},pn)$ calculated by Boffi et al. [2]. (b) As (a) for $^{12}C(\vec{\gamma},pn)$ (1p)(1s) emission.

in quasideuteron kinematics for E_γ from 210 to 330 MeV [22] as these give a closer comparison to the present data than the earlier data taken in symmetric coplanar kinematics [21]. The three ^{16}O data points are consistent with the present ^{12}C $(1p)^2$ data. Measurements of the $^6Li(\vec{\gamma},pn)$ reaction for $\theta_p^{cm} =$ 90° from Yerevan [17] are available for energies of 300 MeV and above. The lowest two ^6Li data points are consistent with both the present data and the deuterium data. However, as noted in Ref. [17], the data at higher photon energies, of which just two points are plotted here, exhibit a systematic reduction in magnitude compared to deuterium data. Overall it appears that the pn-emission reaction in a range of light nuclei gives Σ values which are broadly similar in magnitude to each other but which are consistently a little smaller in magnitude than the deuterium values.

The dashed line in Fig. 2a is a distorted wave calculation of $(1p)^2$ emission by Boffi et al. [2] for the $^{16}O(\vec{\gamma},pn)$ reaction in symmetric coplanar kinematics. Coplanar symmetric kinematics sample initial pair momenta $\boldsymbol{P}$ parallel to the photon direction in the laboratory and consequently Fermi motion cannot affect the azimuthal angles of the emitted nucleons. The calculated asymmetry is therefore expected to be larger in magnitude than for the less restricted kinematic region sampled in the present experiment. The calculation includes Δ isobar and π-seagull currents, but neglects π-in-flight terms. A short range correlation function based on the Reid Soft Core potential is used but found to have little effect on the calculated asymmetries. The calculations of Ref. [2] appear to give a reasonable representation of the photon energy dependence of the present data although the magnitude of the calculated asymmetry is greater than the experimental data.

However, it is now recognised [1,3] that interference between π-seagull and π-in-flight terms, omitted in Ref. [2], have a large effect on Σ. We have therefore carried out detailed calculations of Σ for $^{12}C(\vec{\gamma},pn)$ using a microscopic model for direct two-nucleon emission developed by the Gent theory group [1]. This model is a distorted wave treatment which includes the π-seagull, π-in-flight and Δ excitation mechanisms and also incorporates short range correlations. A Monte Carlo sampling technique [30] was used to average the calculated parallel and perpendicular cross sections over the kinematic region determined by the detector acceptances, taking into account the additional constraints applied in the data analysis. Separate calculations were made for each combination of nucleon subshells ($1p_{3/2}$, $1p_{1/2}$ and $1s_{1/2}$) and the results were averaged using relative spectroscopic factors obtained from an analysis of $^{12}C(e,e'p)$ data [31]. The asymmetry was then obtained from the calculated average parallel and perpendicular differential cross sections. As in the case of the experimental data a correction $\frac{\Delta\phi}{\sin(\Delta\phi)}$ was applied to account for the azimuthal acceptance.

Trial calculations which excluded the π-in-flight term showed a similar photon energy dependence to the calculations of Ref. [2]. The apparently reasonable representation of the present data at low photon energies by the previous calculation [2] is therefore seen to be fortuitous, due largely to the neglect of the important π-in-flight term.

The full calculations for $(1p)^2$ and (1p)(1s) emission, including the π-in-flight term, are shown by the dotted lines in Fig. 2. Sample error bars indicate the statistical uncertainty in the calculations due to the random sampling of the experimental phase space. The calculated $(1p)^2$ asymmetry has a significantly larger magnitude than the ^{12}C data at all photon energies. The largest difference is seen below ~ 230 MeV where the data and the calculations diverge. It is interesting to note that above 250 MeV, where the Δ term is dominant, the asymmetry predicted by Boffi et al. is practically the same as that from the Gent model. The calculations for (1p)(1s) pairs are shown in Fig. 2b. These generally overestimate the magnitude of Σ by a factor of ~ 2.

This work has shown that the photon asymmetry Σ in the $^{12}C(\vec{\gamma},pn)$ reaction for $E_\gamma = 180$–340 MeV is small and negative for missing energy regions corresponding to $(1p)^2$ and (1p)(1s) knockout. The (1p)(1s) data are slightly lower in magnitude and the photon energy dependence in the two regions appears to be different. The Δ resonance, which was clearly observed in $^{12}C(\gamma,pn)$ cross section measurements for both missing energy regions [13], is not clearly visible in the asymmetry data. This may be interpreted as an indication of the importance of interference effects between the contributing nuclear currents, particularly below the Δ resonance. The $(1p)^2$ results for ^{12}C are broadly similar in magnitude to the few available measurements for other light nuclei. The Σ values are consistently lower in magnitude than those from deuterium, even after the effects of Fermi smearing are taken into consideration. This provides new evidence that direct two-nucleon emission is more complex than a simple scaling of deuterium photodisintegration. The Gent model provides the most detailed calculations available of direct two nucleon emission and have been averaged over the acceptance of the present detectors. However these calculations fail to account for the measured $^{12}C(\vec{\gamma},pn)$ asymmetry for either $(1p)^2$

or (1p)(1s) knockout. The discrepancies are largest at photon energies below the Δ resonance region where the asymmetry is known to be sensitive to strong interference effects.

Although the present $^{12}C(\vec{\gamma},pn)$ asymmetry data is the best available for nuclei heavier than deuterium there is a clear need to extend the range and quality of the measurements. Data with better statistical accuracy are needed to expose differences between light nuclei, which may depend on nuclear density and shell structure. This will also allow a better determination of the differences in magnitude and shape between two-nucleon knockout in light nuclei and in deuterium. Recent calculations [1,3] suggest that Σ may depend strongly on the J^{π} states of the residual nucleus. To investigate this will require data with improved missing energy resolution. Further data are needed at lower and higher E_{γ} to provide tests of models in regions away from the Δ resonance. The present results average a rather wide kinematic range and hence more detailed investigations will be required in order to study Σ in specific kinematic regimes.

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