Spin-Zero Polarimetry for Linearly Polarised Photons at MAMI

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Abstract.

Background: The tagged Coherent Bremsstrahlung technique is used to provide beams of linearly polarised photons at several of the world’s leading photonuclear facilities, including MAMI in Mainz, ELSA at Bonn, and GlueX at Jefferson Laboratory. The degree of linear polarisation in real photon experiments has direct impact on measurements of polarisation observables. Measurement of the linear polarisation is often the biggest source of systematic error in these experiments. Continuous, in-beam measurement will also allow the beam position to be adjusted to optimise the polarisation. Purpose: To determine whether it is possible to make an improved measurement of the degree of linear polarisation using a polarimeter based on a 12C target. Methods: Coherent \( \pi^0 \) meson production from a spin-zero nucleus has a photon asymmetry of 1 and hence provides a direct method of measuring the beam polarisation. Results: Current methods of measurement are being employed as a comparison. Simulated statistics of \( \pi^0 \) mesons produced off the polarimeter suggest the measurement is viable. Early results from production data support the viability of live, event-by-event measurements of the polarisation using this method. Conclusions: A spin-zero nucleus such as carbon will be developed as a polarimeter for measuring the degree of linear polarisation in hadron physics experiments with tagged photons of up to 1557 MeV.

1. Introduction
Currently, the degree to which a photon beam is linearly polarised, is measured using the energy spectrum for polarised photons, divided by that of unpolarised photons. This removes any unpolarised background, leaving the peak regions the energies of highest polarisation. These spectra have been generated by photons produced along the experimental beamline, of photon intensity plotted against energy in MeV. The systematic error on these measurements is currently accepted as 3 - 5% [1].

A new method has been proposed for improving the measurement of the degree of linear polarisation at the A2 collaboration detector hall using the Mainzer Microtron (MAMI) facility in Mainz, Germany. A 0.5mm thick disk of carbon has been positioned in the beamline of the experiment in addition to the primary target. This will enable the experiment to be continuously ran while simultaneously monitoring the degree of polarisation from the secondary target further down the beamline. Carbon is a spin zero nucleus, consequently the value of the polarisation observable \( \Sigma \), corresponding to the beam asymmetry, has a value of 1 for a uniformly polarised photon beam. In the desired coherent reaction, a photon interacts with a carbon nucleus to produce a \( \pi_0 \) meson and an unexcited carbon nucleus as in Eq. 1.
The pion carries information on the degree of linear polarisation of the photon beam. By isolating this channel and determining the amplitude of its asymmetry, given the known value of $\Sigma$, the degree of polarisation for the photon beam can be determined. Incoherent and quasi-free events are the two primary sources of background present.

$$\gamma + ^A N \rightarrow ^A N + \pi_0 \rightarrow ^A N + \gamma_1 + \gamma_2$$

The carbon polarimeter is placed downstream of the primary target, such that it may be used continuously throughout beamtimes to determine the degree of polarisation, while simultaneously collecting data for the experimental program at MAMI.

2. Degree of Linear Polarisation

To produce a linearly polarised beam of photons a crystalline radiator is oriented such that a mono-energetic electron beam is incident upon a reciprocal lattice plane, interacting with one of the reciprocal lattice vectors. Coherent bremsstrahlung photons are produced of an energy bounded by that of the electron beam with constraints placed upon the momentum transfer, as this must now coincide with a reciprocal lattice vector of the crystal. Due to the presence of additional lattice planes and phonons, this does not produce a uniformly polarised photon beam. The crystal is oriented to $\pm 45^\circ$ of the photon electric vector, $\vec{E}$. These orientations are parallel and perpendicular to the polarisation reference plane, described as 'para' and 'perp', $90^\circ$ apart.

Currently, the degree a photon beam is linearly polarised to begins with the enhancement shown by fig.1. Fitting to this spectra, the energy of the beam, number of lattice vectors in the spectrum and the geometry of the experiment, these parameters can be used to produce a function giving the peak values as a percentage of photons that are linearly polarised across the energy range [2].

![Figure 1. Diagram showing the parameters describing the fit to the enhancement spectrum. Here $\theta_r$ is the angle the photons are able to pass through to the detector at (collimation), related to I, and the smearing factors for both, $\sigma$ and $\sigma_r$, an allowed broadening to the fit to account for thermally dependent fluctuations [2].](image)

3. A2 at MAMI

The crystal ball (CB) detector is a spherical $4\pi$ detector array, when in combination with TAPS (Two Arm Photon Spectrometer). This consists of 672 optically insulated NaI crystals, read out by individual photomultipliers. Two mechanically separate hemispheres cover 94% of $4\pi$ [3].

Energies and directions of events are reconstructed through analysis of the crystal clusters. The large acceptance and high granularity are ideal for the measurement of neutral mesons, i.e. $\pi_0$.

Within the tunnel region of the ball reside two further detectors. The particle identification detector (PID), is centered on the target and cylindrical around the beam axis. The azimuthal position provided by the PID allows a signal to be matched to a subsequent cluster in the CB. Two multi wire proportional chambers (MWPC) surround the PID as shown in fig.2, providing tracking and position information for charged particles[1].

Immediately after the CB is a 24 panel plastic scintillator detector, Pizza. This is a charged particle detector, working similarly to the PID barrel. The carbon polarimeter is housed in
the centre. For a target in the CB, forward angles of $4^\circ<\theta<20^\circ$ are covered by the two arm photon spectrometer (TAPS). This is comprised of 366 BaF2 and 72 PbWO4 crystals in a wall arrangement [3] as shown in fig.2. In front of this is a layer of 384 5mm thick veto plastic scintillators [4].

4. Spin-Zero Nuclei as Polarimeters

The known value of the beam asymmetry, $\Sigma$, for coherent $\pi^0$ photoproduction enables the use of spin zero nuclei as a polarimeter. The $\pi^0$ is a spin-zero pseudoscalar which when the polarisation vector of an incoming photon is parallel to the reaction plane of the photon and pion, the differential cross-section reduces to zero [5]. Where, the cross section and degree of linear polarisation measurements are uniform despite the polarisation of light, $\Sigma$ reduces to -1. This is the case for spin zero nuclei.

We define the flux in each polarised plane from the $\phi$ distribution as in 2, where $N(\phi)$ is the distribution produced with a $\cos(2\phi)$ shape, for the two crystal settings 'para' and 'perp' and $N$ is the total flux. These are values extracted from the experimental distributions directly. In using a spin zero nucleus, $\Sigma$ has a known value. We are thus left with two unknowns, $a$, the detector acceptance and $p_\perp$ and $p_\parallel$, the linear polarisation. To remove the additional unknown, we make the asymmetry measurement of the pion. This is measured as in Eq. 3 where $a(\phi)$ is removed as a common term, reducing the number of unknowns to the degree of linear polarisation itself. If $P = P_\perp = P_\parallel$ and the histograms are scaled to make the integral of $N_\parallel$ and $N_\perp$ equal then:

$$N_{\parallel/\perp}(\phi) = a(\phi) N_{\parallel/\perp} \left( 1 \pm P_{\parallel/\perp} (\Sigma \cos (2\phi + \phi_0)) \right)$$

Therefore $P \Sigma$ can be extracted from a fit of the form $A + B \cos(2\phi + C)$.

Consequently the required measurement is of the coherently produced pions by the carbon polarimeter only. This is a multiplicity 2(M2) analysis, with two final state particles, the two decay photons from the $\pi^0$ meson. The vertex is placed in the carbon polarimeter in the pizza detector rather than the primary CB target. The $\pi^0$ signal is reconstructed and with cuts placed on the $\pi^0$ invariant mass and timing peak, is used for the pion missing energy, $\Delta E_\pi$, analysis.

For a carbon polarimeter the coherent and incoherent (excited state) channels are strongly overlapping. The first excited state of carbon is 4.44MeV, with the second excited state decaying heavily through the first. This cannot be directly resolved with the detector setup at A2, however the regions where the coherent channel dominate can be identified and consequently separated.
5. Pion Missing Energy and sPlots

To differentiate the background processes from the signal, the pion missing energy $\Delta E_\pi$ is used as the differentiable variable, defined as:

$$\Delta E_\pi = E_{cm}^{\pi} (E_\gamma) - E_{cm}^{\pi} (\gamma_1 \gamma_2)$$  \hspace{1cm} (4)

where $E_{cm}^{\pi} (E_\gamma)$ is the energy of the $\pi^0$ in the pion-nucleus centre-of-mass frame and $E_{cm}^{\pi} (\gamma_1 \gamma_2)$ is the detected $\pi^0$ energy, Lorentz transformed into the pion-nucleus centre-of-mass frame. The calculation for the $E_{cm}^{\pi} (\gamma_1 \gamma_2)$ is dependent on the pion energy and $\phi$ angle, which will vary by number of daughter particles from the reaction. For coherent $\pi^0$ photoproduction, the detected pion energy, $E_{cm}^{\pi} (\gamma_1 \gamma_2)$ equals $E_{cm}^{\pi} (E_\gamma)$, the calculated energy. Therefore the missing pion energy, $\Delta E_\pi = 0$MeV. For the incoherent and quasi-free contributions, additional energy either to eject a nucleon from the nucleus or to leave the recoiling nucleus in a discrete excited state is required. Consequently, less energy is available to the $\pi^0$ hence $\Delta E_\pi$ shifts towards larger missing energies for non-coherent background processes.

The M2 analysis provides a noticeably narrow $\Delta E_\pi$ peak at zero. This is due to previous $\Delta E_\pi$ measurements covering both the forward angles where coherent and incoherent results dominate [6] and larger angles, introducing a greater quasi-free signal. The tail tends towards higher pion missing energies with the energy difference in the peak and tail suggesting this is primarily quasi-free events. This will extend under the peak as at this theta range, predominantly higher energy pions will be present. Consequently, the shape of the background cannot be determined to be removed by using the M2 analysis.

To separate the signal and background channels the sPlot technique is applied. The sPlot technique is developed in the context of a maximum likelihood method making use of the discriminating variables. Events are assumed to be characterised by a set of variables which can be split into two components [7]. The first is a set of variables for which the distributions of all the sources of events are known - the discriminating variable (in this analysis, simulations). The second component is a set of variables for which the distributions of some sources of events are either truly unknown or considered as such, the control variables (data). The distributions for the control variable are reconstructed independently for each of the various sources of events, without making use of any a priori knowledge on this variable.

Using the knowledge available for the discriminating variables, the behavior of the individual sources of events with respect to the control variable can be determined. An essential assumption here is that the control variable is uncorrelated with the discriminating variables.

The application of sPlots is shown in fig. 3, where the pion missing energy distribution is used as the discriminating variable. The black markers and red solid line are the data points and the total fit to data respectively. The coherent channel has been simulated using a monte-carlo, shown by the black broken line. The quasi-free background shape determined from the M3 analysis of the quasi-free channel, containing three particles in the final state, is the red broken line, a Landau distribution. The signal and background are separated through the application of weights to the data on an event-by-event basis, determined by the fit.

**Figure 3.** Plot of the pion missing energy distribution. The control variables/data are the black markers. The discriminating variable/simulations are the black broken line for the simulated coherent channel. The red broken line is the M3 quasi-free events.
The impact of sPlots on the data when separating the signal and background channels is demonstrated by a plot of $\Delta E_\pi$ against $\theta_\pi$. For the forward biased coherent channel this is smaller than for incoherent and quasi-free events. For a given photon energy, the nuclear momentum transfer increases with $\theta_\pi$. There is often a region at low $\theta_\pi$ where the coherent cross section is much larger than the incoherent cross section, which varies slower with pion emission angle[8]. This produces a preferential region for coherent events, known as the coherent maxima. This is the region shown in fig.4 and fig.5 focussed around $\Delta E_\pi = 0\text{MeV}$ and $0.2 < \cos\theta < 1$. Comparing fig.4 and fig.5 the background subtraction nearly exclusively removes events outside the region identified as the coherent maxima.

Figure 4. $\Delta E_\pi$ is plotted against $\theta_\pi$ for data from the M2 $\Delta E_\pi$ distribution. The sPlots technique has not yet been applied. The region bounded by $\theta_\pi > 0.2$ and $\Delta E_\pi < 0.1$ is the coherent maxima.

Figure 5. The sPlots technique has been applied to data from the M2 $\Delta E_\pi$ distribution, plotted $\Delta E_\pi$ against $\theta_\pi$. The region identified in fig.5 as the coherent maxima is largely what remains.

To further separate signal and background channels, a cut on all remaining values with a $\Delta E_\pi < 0.1$. It would not be expected that coherent events would be found with greater values than this (section 5).

6. Asymmetries and Degree of Polarisation
The $\cos(2\phi)$ dependence of the polarised cross section can be exploited to extract the degree of polarisation, assuming the beam asymmetry is well determined, as demonstrated in section 4. Forming an asymmetry using Eq.3, fig.6 is formed and fitted with a $\cos(2\phi)$ distribution. This is rebinned in $\cos\theta$ and the amplitude of each fit determined. Due to the analysis using a secondary target, the statistics are limited. For a data set where the position of the crystalline radiator has been well studied it can be assumed $P_\parallel$ and $P_\perp$ are equivalent. This is of particular use when maximising statistics to illustrate a method, as shown in fig 6.

Figure 6. The asymmetry for the remaining coherent $\pi^0$ signal after sPlots. This is across all values of $\cos\theta$. To measure the degree of linear polarisation, an asymmetry is usually formed with $P_\parallel$ and $P_\perp$ data and amorphous data rather than using Eq. 3, which presumes the degree of polarisation is consistent for both settings.
Fig. 7 plots the variation of $P\Sigma$ with $\theta_\pi$. The degree of polarisation remains at its highest and most stable across $0.5 < \cos \theta < 0.9$ at around 60%, dropping rapidly at $\cos \theta < 0.5$. This is in reasonable agreement with previous attempts to measure the degree of linear polarisation using the crystal ball alone for a given lattice plane [9]. It is encouraging that, as a result of the new techniques discussed here, this stability extends to a higher angular region than previously shown, where the background channels were found to dilute this measurement.

7. Conclusions

The determination of the degree of polarisation is a significant source of error for linearly polarised photon experiments performed. An alternative method of calculating the degree of linear polarisation of the beam with a secondary target has been successful. The coherent region for the secondary target has been found for $270 < E_\gamma < 370$ MeV, after using $s$Plots, between $0.5 < \cos \theta < 0.9$, $\Delta E_\pi < 0.1$ MeV. An investigation of alternative spin-zero targets for use with this method, and the modelling of the dilution from background processes is ongoing. A detailed analysis of the systematic errors alongside the minimum amount of data required to produce reliable measurements during production running is necessary for any polarisation observable measurements to be obtained.

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