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Eingang:
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Mainz Microtron MAMI

Collaboration A2: "Real Photon Experiments"
Spokesperson: R. Beck
Proposal for an Experiment
Coherent pion photoproduction from nuclei from threshold to 350 MeV

Collaborators :
CrystalBall@MAMI collaboration
Spokespersons for the Experiment : D.P. Watts - Edinburgh ; D. MacGregor - Glasgow.

Abstract of Physics :
The coherent (γ, π^0) reaction can be used to obtain information on the matter form factor of the nucleus and the real and imaginary parts of the π^0 nucleus interaction. To exploit these possibilities it is proposed to make comprehensive measurements on three spin zero nuclei with very different mass numbers and over the photon energy range from threshold to 350 MeV. The incoherent (γ, π) and the modification in the medium of the elementary $N(\gamma, \pi)$ process will also be investigated.

Abstract of Equipment :
The tagged photon spectrometer will be used with a reduced energy beam from MAMI. The Crystal Ball detector with TAPS as forward wall detector will be used to detect the photons from π^0 decays.

MAMI–Specifications :

beam energy	380 MeV
beam current	$<$ 100 nA
time structure	cw
polarization	none

Experiment–Specifications :

experimental hall/beam	A2
detector	Crystal Ball and TAPS as forward wall
target material	H_2O, ^{nat}Ca and ^{208}Pb

Beam Time Request :

set–up without beam	($\approx$ 1 week)
set–up/tests with beam	50 hours
data taking	285 hours

Title: **Coherent pion photoproduction from nuclei from threshold to 350 MeV**

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1 Abstract of Physics

The coherent (γ, π^0) reaction can be used to obtain information on the matter form factor of the nucleus and the real and imaginary parts of the π^0-nucleus interaction. To exploit these possibilities it is proposed to make comprehensive measurements on three spin zero nuclei with very different mass numbers over the photon energy range from threshold to 250 MeV. The incoherent (γ, π^0) process and the modification in the medium of the elementary $N(\gamma, \pi^0)$ process will also be investigated. The π^0 resolution will be sufficient to separate the coherent and incoherent processes in the first 100, 70 and 25 MeV above threshold for ^{16}O, ^{nat}Ca and ^{208}Pb respectively. The possibility of using the Crystal Ball to detect nuclear decay γ's following incoherent (γ, π^0) will allow this range to be extended considerably.

1.1 Scientific case.

1.1.1 Introduction

The first aim of this proposal to study coherent π^0 photoproduction from nuclei is to provide information on several points of interest.

a) The matter form factor of nuclei.

b) The π^0-nucleus interaction and the validity of its theoretical treatment by DWIA and Δ-hole model calculations in different energy regions.

Other topics which can and will be investigated using the data are the incoherent (γ, π^0) reaction and the modification in nuclei of elementary pion photoproduction amplitudes on the nucleon. These are discussed in section 1.3.

In more detail the interest in these points is:

a) In the $A_{gs}(\gamma, \pi^0)A_{gs}$ process the reaction amplitudes of all nucleons add coherently so that the cross section is essentially proportional to $A^2 F_m^2(q)$, the square of the mass number times the matter form factor. In light nuclei the extra information on the nucleon distributions, which is available in this way, is not likely to add much to what is already known from studying the charge distribution. However in a heavy nucleus like ^{208}Pb with different numbers of neutrons and protons bound in different potential wells, the comparison of an accurate matter form factor with the well-known charge form factor would provide an interesting check on the relative neutron and proton distributions. Recent calculations suggest the neutron and proton radii differ by $\sim$0.15 – 0.25 fm in ^{208}Pb[1].

b) Information on both the π^0-nucleus attraction (or repulsion) and the nuclear absorption of π^0's may be obtained from (γ, π^0) data. This will be of value since the π^0-nucleus interaction is not well established. It is also essential to understand the π^0 distortion in order to extract information on the matter distribution. The real part of the interaction produces a difference between the momentum of the π^0 inside and outside the nucleus and as a result the (γ, π^0) angular distribution suffers an angular shift. Information on the π^0 nucleus interaction from photoreactions will be especially useful since they sample the interaction through the whole nuclear volume in contrast to pion induced reactions, from which most previous information has been deduced, which take place near the nuclear surface.
Distorted wave impulse approximation (DWIA) calculations for the (γ, π^0) process have been carried out using pion optical potentials. This approach is expected to be

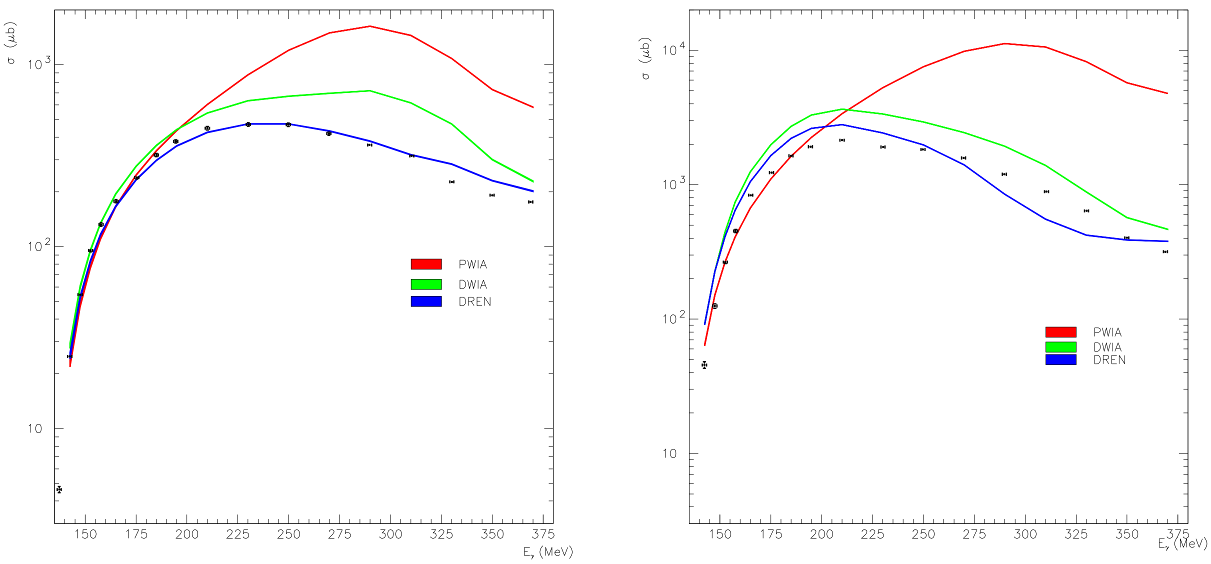

Figure 1: Left panel : Integrated cross section for ^{16}O. Black - data from [5]. Red - PWIA;Green - DWIA; blue - DREN. Right panel: Same comparison for ^{208}Pb

appropriate near threshold, where the π^0 -nucleus interaction is relatively weak. As the photon energy increases towards the Δ-resonance region the DWIA approach will fail. The π^0-nucleus interaction then becomes strong and Δ-propagation is strongly affected by the medium. In this case a Δ-hole type model is an appropriate theoretical approach and the recent results presented in the next section show it to be necessary to describe the data at higher photon energies .

To extract $F(q)$ and the parameters of the pion distortion angular distributions for photon energies from threshold to $\sim$240 MeV will be fitted simultaneously by varying parameterised $F(q)$ and distortion parameters. Since the relation between q, E_π varies with E_γ, this removes the possibility of spurious fits by varying the wrong parameter. Errors in the fitted parameters and their correlation will come out of the fits. The fit does not use $E_\gamma \geq$240 MeV since the treatment of the Δ-nucleus interaction is not so secure as diffraction at lower E_π.

1.2 Previous experiments

Early experiments in the threshold region[2] gave indications of the diffraction pattern structure in the π^0 angular distribution from medium and heavy nuclei due to the matter form factor, and reasonable nuclear size parameters were extracted from these experiments. Apart from some total cross section measurements[3] little further progress was made until the MAMI-A tagged photon beam became available.

The experiments at MAMI-A used a 176 element lead-glass Cerenkov detector to study the angular distributions from ^{12}C and ^{40}Ca [6] in the region E_γ=160-170 MeV. The basic π^0 energy resolution achieved was ~9 MeV FWHM for the T_π=25 MeV pions. This was insufficient to separate the incoherent process and its contribution to the yield was evident since it produced a reduction in the average π^0 energy compared with that expected from the coherent process alone. To suppress the incoherent contribution it was necessary to rely on the correlation between opening angle of the two detected photons and the pion energy. This results in a much reduced efficiency for

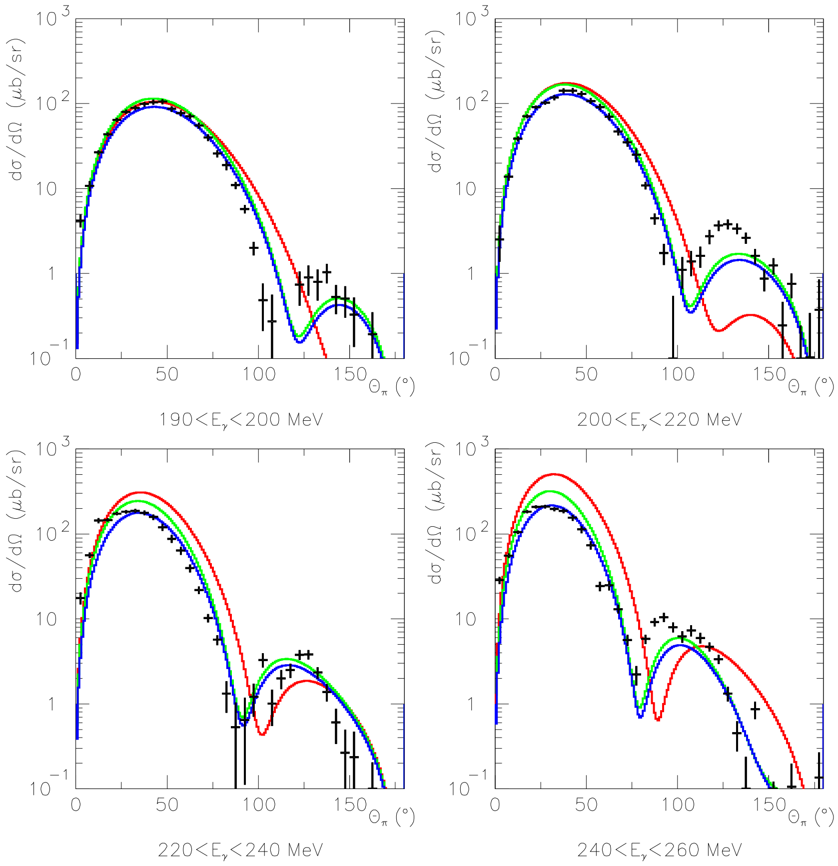

Figure 2: Differential cross sections for ^{16}O for four different E_γ regions[5] compared to theoretical calculations : Red - PWIA; Green - DWIA; blue - DREN

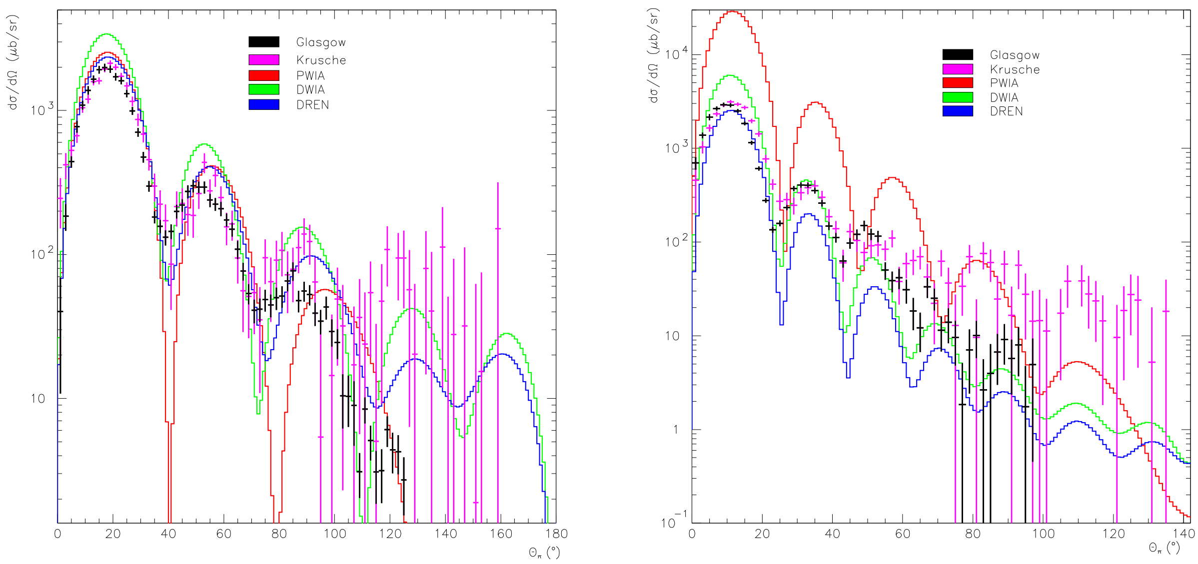

Figure 3: Comparison of the two recent TAPS measurements[5][4] for ^{208}Pb for E_γ=200 MeV (left) and E_γ=290 MeV (right)

detecting coherent events but resulted in the observation of a clear diffraction minimum for ^{40}Ca at θ_π ~105°.

Much improved data were obtained at MAMI-B using the TAPS spectrometer[4][5]. The first measurement covered photon energies from 200 to 400 MeV on ^{12}C, ^{40}Ca, ^{93}Nb and ^{208}Pb and used 5 TAPS blocks at $\pm38°, \pm88°$ and 133°. The second measurement[5] determined the cross sections with better energy resolution and a wider energy range - from threshold up to 380 MeV for ^{12}C, ^{16}O, ^{40}Ca and ^{208}Pb and used 7 TAPS blocks centred at angular regions $0°, \pm54°, \pm103°$ and 152°. These latest measurements had better separation of coherent from incoherent events, resulting in a dramatic reduction (Fig. 3) in the measured, large-angle differential cross sections for ^{208}Pb. Total cross sections from [5] for ^{16}O and ^{208}Pb are shown in Fig.1. Some of the measured differential cross sections are shown for ^{16}O[5] in Fig.2 and for ^{208}Pb[4][5] in Fig.3.

The experimental data are compared with plane wave impulse approximation (PWIA), a distorted wave impulse approximation (DWIA) and also a calculation (DREN) based on a DWIA approach but which also includes the effects of Δ excitation and propagation in nuclei via a phenomenological parameterisation of the Δ self-energy [12]. The latter approach allows description of data for pion energies above ~100 MeV where Δ excitation plays an important role in the pion FSI.

The inclusion of the Δ modification results in a good description of the total cross section for ^{16}O in the region of the Δ resonance (Fig. 1). Poorer agreement is observed for ^{208}Pb but this may be expected as the DREN model parameters are tuned for ^{4}He. At lower photon energies the DREN and DWIA predictions tend towards each other and agree with the data. The Δ contributes little to the π production process and the DREN prediction tends to follow the DWIA prediction.

Comparisons of the PWIA and DWIA models (Fig. 2,3) highlight the importance of a proper treatment of distortion of the outgoing π^0 wave since a) the angular position of the minima is shifted to smaller angle and b) the (γ, π^0) strength is modified compared to the plane wave prediction.

Although providing a great advance, with the diffraction pattern visible out to wider pion angles for the first time, the possibility to extract further physics from these data is severely limited.

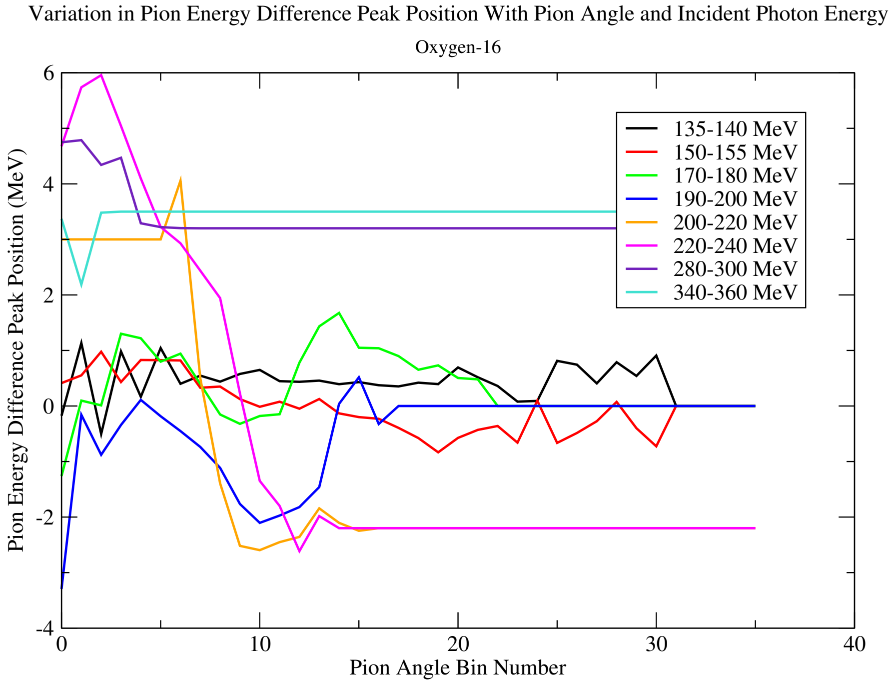

Figure 4: Position of the coherent peak in the pion energy difference spectrum as a function of pion angle.

The experiments suffered from systematic errors in the reconstructed pion momenta caused by the coarse angular block structure of the TAPS detector system. These errors are thought to arise in the reconstrucion of the angle of photons which enter TAPS blocks near their edge leading to errors in the energy and possibly angle which vary with E_π and θ_π. This is highlighted in Fig.4 where the position of the coherent peak, calculated from the incident photon and detected pion energies, is plotted as a function of pion angle. Sharp angle dependent shifts are evident in the spectra caused by the block nature of the TAPS detector system. Not only does the position of the coherent peak suffer systematic shifts but the shape of the peak when combining data in a 20 MeV E_γ bin is dependent on the position shifts which occur across the bin. When fitting the pion energy difference spectrum to obtain the coherent peak area in a situation in which the coherent and incoherent strength is not well resolved, the result of the peak shift and shape change is a large uncertainty in the coherent strength as can be appreciated from the fits shown in 5. The results of these systematic uncertainties are most clearly seen in the extracted incoherent cross sections (Fig. 6), where spurious oscillations (which can be very dramatic eg. at $\sim 50^\circ$ in the top left plot) are observed in the extracted angular distributions.

Even in the first maximum for the ^{208}Pb data (Fig.3) where the incoherent cross section is relatively small and the determination of the coherent contribution should be good there are systematic differences in the measured cross sections for the two TAPS measurements of up to 40%. The cause of this is not established although as different TAPS detector geometries were employed in the two measurements it may be due to systematic errors in the detection efficiency as a function of pion angle in both measurements.

To summarise the experimental situation, it is clear that although much progress has been made the experimental data are not yet in good enough shape to determine the coherent cross section at the few % level. In particular to attain the accuracy required to learn about matter distributions in heavier nuclei, measurements with much reduced systematic and statistical errors are necessary. The positions of the diffractive minima give a good indication of the rms size of the distribution but the relative shapes of the maxima are vital obtain more detailed information.

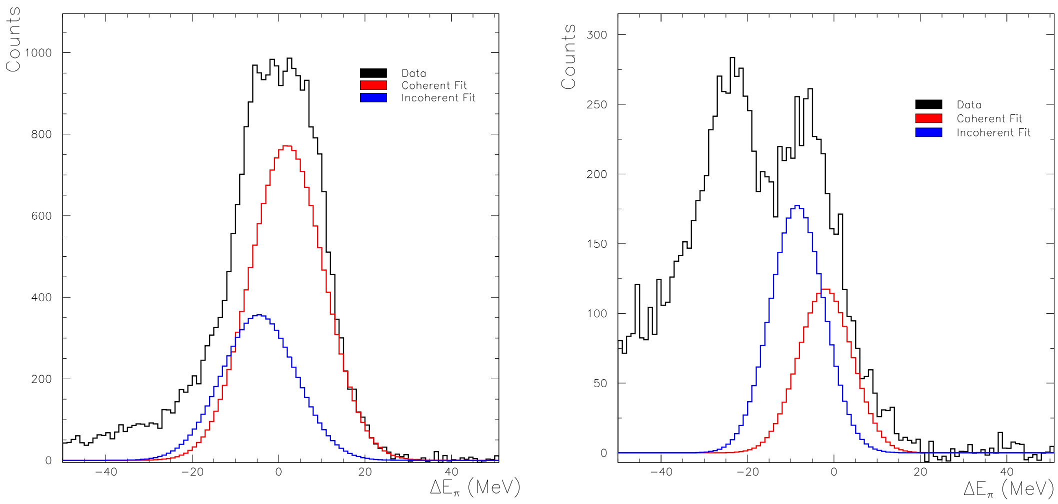

Figure 5: Pion energy difference spectrum for ^{16}O obtained near the first diffraction maximum for θ_π=40-45 ° (left) and near the first diffraction minimum θ_π=65-70 ° (right) for E_γ=220-240 MeV. The red and blue lines show gaussian fits to the coherent and incoherent processes respectively

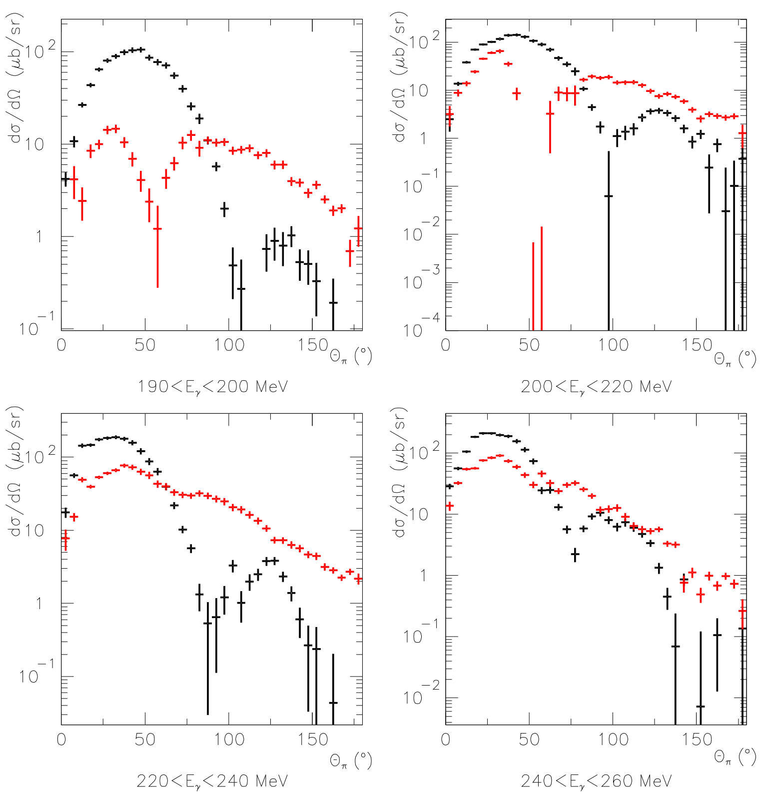

Figure 6: Differential cross section for ^{16}O for four photon energy regions from 190 to 260 MeV: Coherent and incoherent cross sections are shown by the black and red points respectively.

1.3 Other measurements

In measuring the coherent cross sections data relevant to two further physics aspects will automatically be collected and will be analysed.

1.3.1 Incoherent (γ, π^0)

There are virtually no measurements of incoherent (γ, π^0) . It would be interesting to measure the incoherent $\frac{d\sigma}{d\Omega}$ - to see which states are strongly excited and study behaviour of transition form factors. It is not likely that incoherent (γ, π^0) will become a standard technique for examining nuclear excited states (like electron scattering) but the process may have something to contribute for certain classes of states.

1.3.2 Photoproduction amplitudes

Analysis of nucleon (γ, π) data has established the elementary amplitudes with reasonable accuracy, although significant disagreements remain even for some of the more important multipoles. If other factors are under control, information on these amplitudes may also be accessible through the angular distribution and energy variation of the nuclear (γ, π^0) cross section. For a self-conjugate spin zero nucleus for example only the combination $\mathrm{P}_3 = \mathrm{M}_{1+} + \mathrm{M}_{1-}$ contributes to the coherent (γ, π^0) cross section, which in the plane wave approximation can be written

$$\frac{d\sigma}{d\Omega} = A^2 \frac{q}{k_\gamma} P_3^2 |F_m(q)|^2 sin^2(\theta_\pi)$$

It may however be found that the effective (γ, π^0) amplitudes are modified in the nuclear medium. Since the dominant M_1^+ amplitude comes from Δ excitation even near threshold, and the complex nature of the Δ-nucleus interaction is known to modify the free popagation of the Δ in the nuclear environment, a change in the amplitudes may be expected in nuclei. An analysis of this type has been attempted by Bergstrom[14] for ^{12}C in the energy range from threshold to 160 MeV and he finds no evidence of modification of the elementary amplitudes. However in the measurement it was not possible to separate coherent and incoherent processes experimentally. The analysis relied on a calculation of the incoherent strength to make a subtraction which ranged up to ~15%. It would therefore be valuable to use coherent data alone from this measurement to make further tests.

2 Experimental aspects

The measurement will use the Crystal Ball and TAPS detector system (CBTAPS) with the Glasgow tagged photon specrometer at MAMI.

The tagging facility at MAMI B ($E_0 \leq 855$ MeV) can tag bremsstrahlung photons in the energy range $40 - 800$ MeV with a resolution of ~ 2 MeV at rates up to 10^8 s^{-1}. For this experiment the system will use a lower electron beam energy of 380 MeV to improve the resolution to ~ 1 MeV. The system consists of a momentum-dispersing electron spectrometer, with an intrinsic energy resolution of 120 KeV [7]. This spectrometer focuses the post-bremsstrahlung electrons onto the focal plane where the position and time of arrival are established. The focal plane detector [8] consists of 353 half overlapping plastic scintillators. The overlap region between two detectors defines the energy resolution of the tagged photon beam. The maximum tagged photon flux is $\sim 10^6 s^{-1}$ per single focal plane detector.

The CB is constructed of 672 optically isolated NaI(Tl) crystals, 15.7 radiation lengths thick. The counters are arranged in a spherical shell with an inner radius of 25.3 cm and an outer radius of 66.0

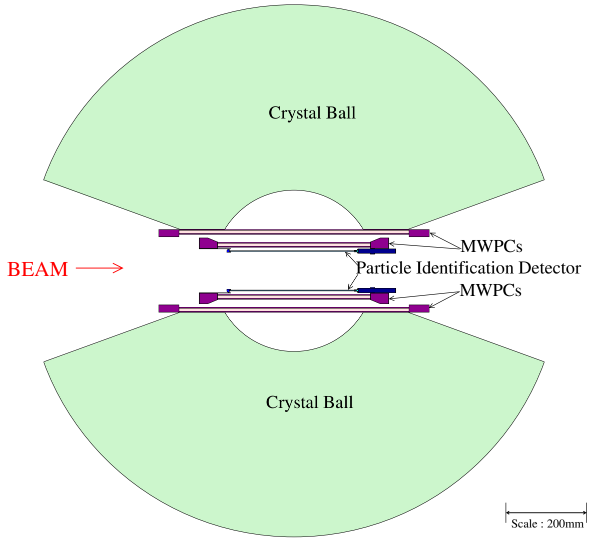

Figure 7: Left panel: The Crystal Ball with TAPS as forward wall. Right panel: A section through the Crystal Ball showing the positioning of the wire chamber and particle-ID detector.

cm. Each crystal is shaped like a truncated triangular pyramid, 40.6 cm high, pointing towards the center of the Ball. The sides on the inner end are 5.1 cm long and 12.7 cm on the far end. The Ball has an entrance and exit opening for the beam which results in a loss of 4.4% of acceptance. A charged particle tracker, comprised of two coaxial cylindrical multiware proportional chambers (MWPC) developed for the DAPHNE large-acceptance tracking detector [9] will be used with the Crystal Ball. A plastic scintillator particle-identification detector (PID)[10] will be placed between the wire chamber and the target to separate different charged particle species.

The TAPS detector system will cover the exit (downstream) opening of the Crystal Ball. TAPS[11] is comprised of 540 individual barium fluoride (BaF_2) crystals. The crystals are hexagonally shaped with an inscribed diameter of 59 mm and a length of 250 mm (12 radiation lengths). BaF_2 has three scintillation components in the UV region, two fast ones and a slow one. The relative light yield depends on the ionization density and, therefore, allows particles discrimination by pulse-shape analysis. The fast component provides excellent timing characteristics. In front of each tile a hexagonal plastic scintillator (NE102A) slice is mounted and read by a separate photomultiplier. This tile acts as the "VETO" for charged events.

Measurement of coherent pion photoproduction with the Crystal Ball and TAPS detector system (CBTAPS) (Fig.7) will greatly improve the detection efficiency and largely eliminate the systematic effects which have limited the impact of previous measurements. The suitability of the detector systems to the proposed measurement has been explored using GEANT3 detector simulations, the results of which are presented in the following sections.

2.1 Pion detection efficiency

One of the most obvious advantages of CBTAPS over previous spectrometers for measuring neutral photopion production is the greatly improved efficiency for detecting neutral pions. The magnitude is greatly increased and the variation with pion energy and angle is reduced. The predicted efficiency of the detector setup is shown as a function of pion angle in the left panel of Fig 8. The efficiency is uniform for pion angles up to $\sim 100°$ and then falls off at larger angles due to a gap in the coverage in the entrance tunnel region in the Crystal Ball. The detection efficiency obtained in the most recent TAPS measurement is shown in the right panel. The new CBTAPS detector setup has a π^0detection efficiency $\sim$40 times larger than in the previous TAPS measurements and the

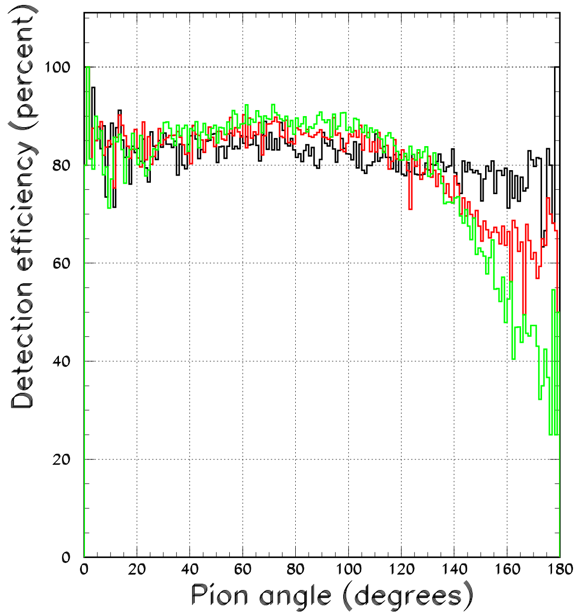

Figure 8: Pion detection efficiency as a function of pion angle for the CBTAPS detector system (left) and from the recent TAPS measurement [5] (right). Left plot: Pion kinetic energies of 10, 50 and 100 MeV are shown by the black, red and green lines respectively. Right plot: results for different pion energies as indicated on the plot

possibility of systematic error in the simulation, from which the efficiency is deduced, is evidently less when its magnitude is high and it has no strong angular variations.

2.2 Pion energy determination

As already discussed the reconstruction of the pion energy is crucial to get a reliable separation of the coherent and incoherent cross sections. The strong pion angle and energy dependent shifts (Fig.4) in the reconstructed pion energy seriously limited the impact of our previous measurements with TAPS. The symmetric and more complete angular coverage of the CBTAPS detector system is expected largely to eliminate these effects which were attributed to shower loss when photons are incident near to the edges of the TAPS blocks. A GEANT3 based Monte Carlo simulation of the CBTAPS detector system has been carried out. In these simulations the predicted energy deposits in the crystals from π^0 events are smeared in accord with the measured experimental energy resolution. The event-by-event output of the simulation is analysed according to the standard cluster finding algorithms established for the Crystal Ball. The results (Fig.9) show the mean reconstructed pion energies for incident energies of 10, 50 and 100 MeV. Apart from the extreme pion angles the mean reconstructed energy is within 1 MeV of the incident pion energy, confirming the much smaller role for shower loss effects. The situation is a great improvement on that observed in the previous TAPS measurements (Fig.4). At extreme angles the reconstructed energy is low is due to events where one or both of the photons from the pion decay enter the Crystal Ball near to its' edge. The effect is due to shower loss from such events and it will be simple to just remove the events from the analysis with only small reduction in the overall efficiency. In fact further analysis of the GEANT simulations (not presented) indicates that it may be possible to avoid most of the shower loss in forward-angle events when the TAPS detectors are included in the cluster reconstruction.

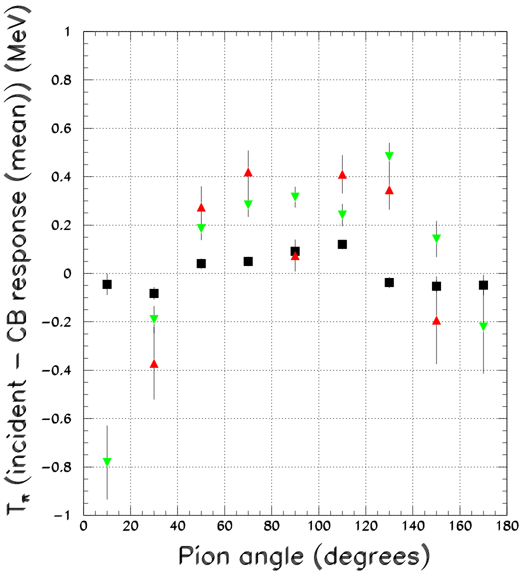

Figure 9: GEANT3 simulation of the response of the Crystal Ball. The difference between the reconstructed and incident pion kinetic energy is plotted as a function of pion angle. Results for pion kinetic energies of 10, 50 and 100 MeV are shown by the black squares, red triangles and green triangles respectively.

Figure 10: Energy resolution of Crystal Ball as a function of photon energy

The pion energy resolution obtained with the CBTAPS system is similar to that of the previous TAPS measurements as the intrinsic angular resolutions for photon detection are similar (∼2-3°). There is a good chance we can improve the resolution by replacing the present reconstruction algorithm (which uses only the ratio of the two photon energies) with a kinematic fit and we will investigate this.

2.3 Decay photon detection

Previous measurements of pion photoproduction from nuclei have been limited by the π^0resolution and the required separation of the coherent and incoherent processes has only been possible in limited photon energy and pion angle ranges. The proposed measurement will explore the capability of the Crystal Ball to detect and identify nuclear decay photons in coincidence with the high energy products of photonuclear reactions. This technique would greatly aid the separation of coherent and incoherent cross sections and more generally would open up new opportunities for other photonuclear measurement using the Crystal Ball. For example, coherent η production from nuclei may be possible despite the poorer η energy resolution.

The energy resolution of the Crystal Ball for low energy photons has been established (Fig. 10) and is expected to be ∼12% (FWHM) for 2 MeV photons. We have also carried out GEANT3 simulations of the reponse of the Crystal Ball to low energy photons. These assumed a 1.0 MeV energy threshold for signals in the crystals. The energy deposits in the crystals were smeared to match the measured resolution of the crystals for photons in this low energy region. The standard cluster finding algorithms used in the Crystal Ball analysis software were employed to analyse

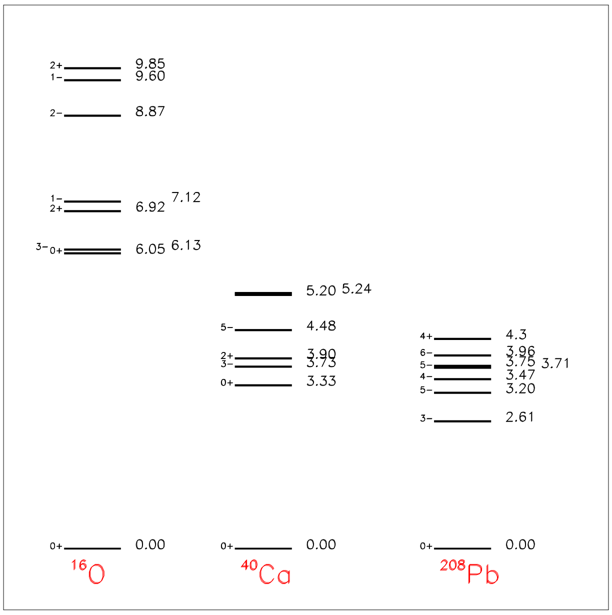

Figure 11: Nuclear level schemes for ^{16}O, ^{40}Ca and ^{208}Pb targets. The energy of the level in MeV is shown on the right. Spin and parity assignments are shown on the left. The eight lowest lying states are shown.

the energy deposits predicted by the GEANT software. The photopeak efficiency for energies of photons above 2 MeV is ∼90% and the overall efficiency (including the solid angle) is ∼80%.

The nuclear level schemes for the targets are shown in Fig 11. Without going into detailed discussion of the decay schemes the general conclusion is that we would expect to be able to detect one or more of the photons in decay cascade for almost all particle stable states of Oxygen, Calcium and Lead. The only obvious exceptions are 0^+ states in ^{16}O and ^{40}Ca which decay by e^+e^- pair emission, and for the 6.05 MeV state in ^{16}O we at least should detect these in the wire chamber and particle-ID detector. Nuclear decay photon data will be easiest to analyse for lighter nuclei because the average photon energies are higher. This is where the technique will be most important because the incoherent cross section is expected to be larger compared to coherent in the first maximum of the angular distribution.

Based on the anticipated performance of the Crystal Ball we can be optimistic about the possibilities for decay photon detection.

2.3.1 Background rates

Some understanding of the low energy background rates expected in the ball are important to assess the feasibility of the decay gamma technique. These rates can be estimated from previous TAPS measurements at Mainz, although the difference in scintillator material may affect the final accuracy of the estimate (eg. for NaI neutron capture by I isotopes could be important). From TAPS measurements in 1999 the maximum rate per CB detector with full beam intensity is expected to be below 1 kHz for detector angles backward of 30 degrees and a 2 MeV discriminator threshold. The energy spectrum has been measured[13] for a large single NaI detector and from this we can expect the rate to approximately double to 2 kHz with a lower threshold of 1.0 MeV. An independent estimate can be obtained by scaling the count rate obtained from this NaI test detector used in [13] according to the relative surface areas of the test detector and the CrystalBall. This gives a similar result to that obtained above. These estimates also agree with a very recent test measurement at Mainz in which the count rates produced in the Crystal Ball with a lead target were obtained.

Assuming a 10ns coincidence timing resolution with the photons detected from the decay of the π^0 and a rate of 2 kHz per crystal then a total random coincidence rate of 1.3% is expected in the ball. If it is assumed 50% of the cross section for pion production leads to an excited state in the residual nucleus, which decay by gamma emission, the approximate prompt to background ratio is expected to be ~38:1

3 Beam time request

We estimate the beam time required to obtain adequate statistics in the pion angular distributions of three nuclei. The estimate was made using the following input

- **Tagged photon flux:** Tagger channels corresponding to $E_\gamma \leq$120 MeV will be turned off and the lowest channel in use will be run at the maximum permissible rate. With a tagging efficiency of 0.4 this will produce a tagged photon rate of 2.10^6 per 5 MeV bin at E_γ=140 MeV, falling to 10^6 per bin at 280 MeV. It is assumed that the data can be corrected for the change in angular distribution across each 5 MeV bin so that adding in 5 MeV bins will not smear out the structure of the form factor.
- **Targets:** These are chosen to have a thickness equal to 2cm or 0.1 radiation lengths (whichever is smaller), so that neither the angular resolution of CBTAPS nor the quality of the tagged beam is significantly degraded. The corresponding target thicknesses in nuclei/cm^2 are:
  H_2O : 6.6×10^{22}
  Ca : 3.0×10^{22}
  Pb : 0.22×10^{22}
- (γ, π^0) **cross section:** The minimum cross section to be measured is taken to be 0.2μb/sr for O and Ca and 1.0 μb/sr for Pb. The statistical accuracy required for these cross sections is $\leq$10%.
- π^0**detection efficiency:** A value of 50% was taken as an estimate of the efficiency expected at backward pion angles.
- **Data acquisition system live time:** ϵ_{DA} **~70%**
- **Count rate:** From the above one estimates a beam time of 142 hours for Pb, 37 hours for O, 81 hours for Ca. If 10% of time is taken for backgound runs the total beam required is:

Beam time - 285 hrs

References

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