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**Proposal to the PAC**

# $\eta$ PHOTOPRODUCTION MEASUREMENTS WITH BGO-OD


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**Abstract**

We propose to measure the beam asymmetry for the $\eta$ photoproduction off the proton and the neutron in the energy range from threshold up to 1.8 GeV and the differential cross section for the $\eta$ photoproduction off the neutron in an energy range around 1.1 GeV. The high neutron detection efficiency of the BGO calorimeter and its full trigger capability makes the BGO ball in combination with the TOF spectrometer particularly suited for both neutral and charged $\eta$-nucleon final states. The measurement of the $\eta$ photoproduction on the proton will represent a powerful method of offline calibration for the BGO-OD apparatus and will permit to check the procedure of extraction of the beam asymmetry at BGO-OD in the energy regions which have already been covered by other experiments.

## Equipment

For the proposed experiment the BGO-OD setup will be used. It consists of the combination of an open-dipole forward spectrometer and an electromagnetic calorimeter (BGO ball) coupled to a scintillator barrel and two cylindrical MWPC's covering the central polar angle region. In order to perform beam asymmetry measurements of the $\eta$ photoproduction, a tagged and linearly polarized photon beam, produced by means of the technique of coherent Bremsstrahlung, is requested in the energy range 0.7÷1.8 GeV.

Two different targets will be used: a liquid H2 and a liquid D2 target for the $\eta$ photoproduction off the proton and off the quasi-free proton and quasi-free neutron respectively.

## Accelerator & target specification

| | |
|---|---|
| $e^-$ beam: | 3.2 GeV $e^-$ unpolarized; |
| beam line: | BGO-OD experimental area; |
| beam intensity: | $10^7$ photons/s in the energy range 0.32 - 2.88 GeV; |
| polarization: | unpolarised and linearly polarised<br>(at 1.0, 1.2, 1.6, 1.7 and 1.8 GeV) photon beam; |
| target: | $LH_2$ and $LD_2$; |
| trigger: | Tagger and BGO coincidence<br>(a minimum deposited energy in BGO is required). |

Most of these conditions match with the requirements of other proposals, allowing a simultaneous data acquisition for different experiments (for example $\eta$, $\eta\prime$ and $\omega$ photoproduction).

## Beamtime request

| | | |
|---|---|---|
| $LH_2$target: | polarised at 1.0 GeV | **130 h** |
| $LH_2$target: | polarised at 1.2 GeV | **150 h** |
| $LH_2$target: | polarised at 1.6 GeV | **550 h** |
| $LH_2$target: | polarised at 1.7 GeV | **570 h** |
| $LH_2$target: | polarised at 1.8 GeV | **650 h** |
| $LD_2$target: | unpolarised | **1000 h** |
| $LD_2$target: | polarised at 1.0 GeV | **200 h** |
| $LD_2$target: | polarised at 1.2 GeV | **250 h** |
| $LD_2$target: | polarised at 1.6 GeV | **700 h** |
| $LD_2$target: | polarised at 1.8 GeV | **800 h** |

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# 1 Physics Motivations

Meson photoproduction on the nucleon is a powerful tool in order to extract fundamental information on baryon resonances. It is complementary to pion–induced reactions, from which in the past the bulk of known resonance properties was derived. The photoproduction of mesons other from the pion, in fact, allows to focus on those resonances which are only weakly coupled to the pion itself. In particular, the extraction of the helicity amplitudes and the measurement of polarization observables is of crucial importance for the disentanglement of specific resonant states (see [1] and [2] for a complete review on the study of baryon resonances with meson photoproduction). In the second and third resonance regions, many resonances contribute to meson photoproduction processes. Due to their short life-time (i.e. large width) they overlap in the cross-sections making difficult to separate their contribution. Despite its low cross-section, $\eta$ photoproduction exhibits several important advantages, among other channels. This reaction is an isospin filter, selecting N*(I=1/2) resonances as intermediate states, since the $\eta$ is an isoscalar meson (I=0) and the total isospin is conserved in strong decays; this considerably simplify the problem of identifying individual resonances. This is not the case for single and double pion photoproduction, for which a large number of $\Delta$ and N* resonant states can simultaneously be excited by the photon (see figure 1).

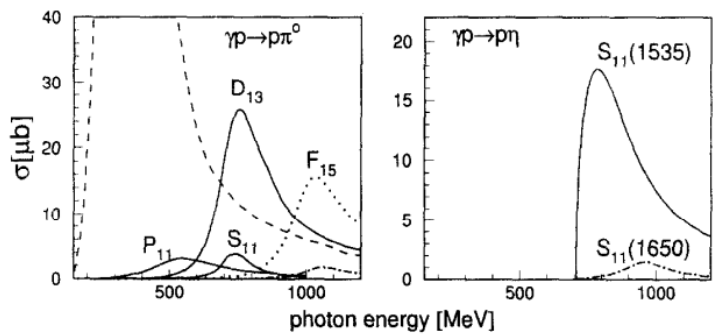


**Figure 1** Contribution of resonances in the second resonance region, for $\pi^0$ (left) and $\eta$ (right) photoproduction, respectively (from [1]).

Another important advantage of $\eta$ photoproduction is the strong dominance at threshold of a single resonance, the $S_{11}$(1535). The role of the other involved resonances (such as the $D_{13}$(1520), the $F_{15}$(1680) and others) can comfortably be investigated in polarization observables, where their contribution is amplified by the interference with the dominant $S_{11}$(1535). As an example, the simple fact that the beam asymmetry is not zero everywhere is by itself a strong indication of the contribution of other resonances to the process.

In the last 10-15 years a significant number of new measurements on $\eta$-photoproduction on the proton and the neutron has considerably enriched the world database, such as total and differential cross-sections and asymmetry values on the proton [3][4][5] and asymmetry values on quasi-free proton and neutron [6] at GRAAL in the incident photon energy range $E_\gamma$=0.7-1.5 GeV. A complete list of references can be found in the cited review on meson photoproduction[2]. Data on the proton have confirmed the strong dominance of the $S_{11}$(1535) resonance, allowing the extraction of its total width. Asymmetry data obtained at GRAAL have strongly emphasized the small contribution of the $D_{13}$(1520) and of other resonances (such as the $F_{15}$(1680)), which become more and more visible in the asymmetry angular distribution in the center of mass polar angle as soon as the incident photon energy increases (see figure 2), allowing to extract their decay B.R. into the $\eta$N channel [3]. With the BGO-OD beam and apparatus, the measurement of the beam asymmetry on the free proton will be extended up to 1.8 GeV, thus allowing to explore the third and fourth resonance regions.

The isospin represents a degree of freedom of crucial importance. On the isospin basis, cross-sections can be decomposed in terms of three independent matrix elements, $A^{IS}$, $A^{IV}$ and $A^{V3}$, among which

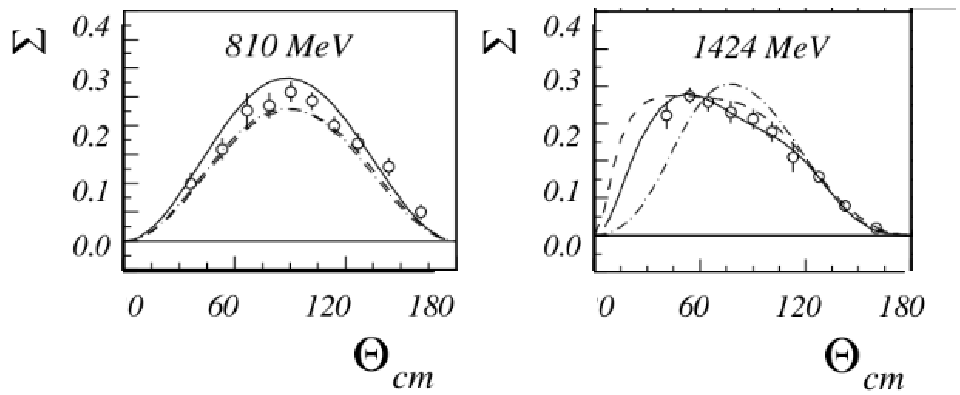


**Figure 2** Asymmetry values of $\eta$ photoproduction on the proton in two bins of fixed incident photon energy, plotted as a function of the c.m. polar angle [5].

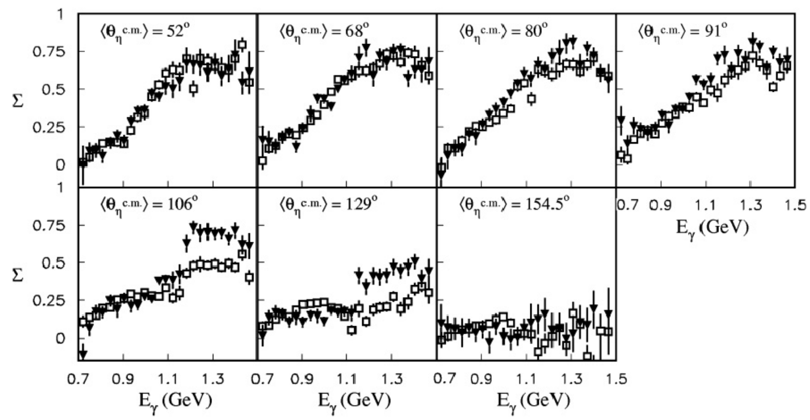


**Figure 3** Comparison between the beam asymmetry $\Sigma$ in $\eta$ photoproduction on quasi-free protons (open squares) and quasi-free neutrons (full triangles) in seven bins of fixed c.m. polar angle, plotted as a function of the incident photon energy [6].

the two former ones contribute to the photoproduction of isoscalar mesons, like $\eta$, and that can combine differently in the case of proton and neutron excitation [2]. For this reason, also data on the neutron are of fundamental importance. The status of the investigation on the neutron is still at the beginning, since a free neutron target does not exist in nature: the simplest system containing a neutron is a deuteron, whose small binding energy reasonably allows to consider the two bound nucleons as quasi-free particles, in the kinematical conditions where only one of them acts as a participant and has low Fermi-momentum. The presence of the Fermi-momentum and the final state interactions (FSI) make the extraction of the information on the pure neutron from the deuteron data dependent on the model. Asymmetry results obtained at GRAAL[6] have clearly demonstrated that nuclear effects can almost be neglected on the quasi-free proton with respect to the free one and this makes us confident that the same assumption can be done on the quasi-free neutron. The asymmetry results on the quasi-free neutron obtained at GRAAL[6] have shown a similar behaviour between the proton and the neutron for energies up to 1.1 GeV (see figure 3). For energies higher than 1.1 GeV and at backward angles in the center of mass $\eta$ polar angle, the two behaviours are substantially different, showing that the proton and neutron excitation mechanisms for the photoproduction of the $\eta$ meson are different in this energy region. These differences have been explored at GRAAL in a limited energy range (1.1-1.5 GeV), that could be considerably extended with the BGO-OD beam and experimental apparatus, where a reasonable degree of polarization (about 30-40%) can be achieved for energies up to 1.8 GeV.

As it is visible in figure 4, results on the neutron at the higher energies have excluded the large contribution of the resonance $D_{15}(1675)$ introduced in the MAID2001 model (solid line)[7] and show a better

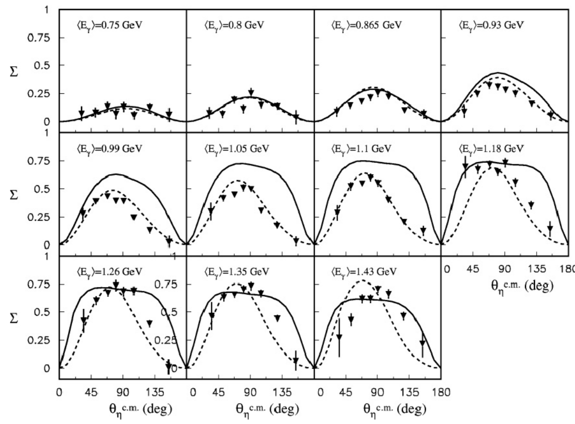


**Figure 4** Beam asymmetry $\Sigma$ in $\eta$ photoproduction on quasi-free neutrons in 11 incident photon energy bins, plotted as a function of the c.m. polar angle. Solid and dashed lines illustrate the predictions for neutrons of MAID2001[7] and of the reggeized MAID model[8] respectively.s

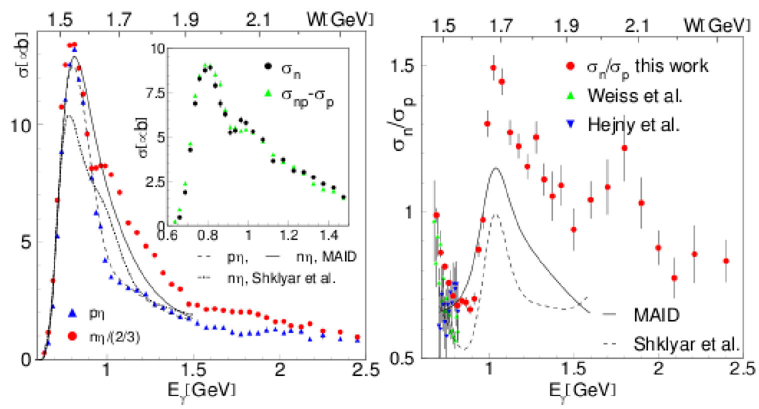


**Figure 5** Total cross-sections of $\eta$ photoproduction on proton and neutron plotted as a function of the incident photon energy (left side) and their ratio (right side)[10].

agreement with the reggeized MAID model (dashed line)[8], where the coupling of this resonance to $\eta$-N is reduced down to 1.7%. The two models, which provide a similar energy behaviour of cross-section and asymmetry for the proton, have very different predictions on the neutron. In order to fit simultaneously the cross-section and the asymmetry data, a narrow resonance $P_{11}(1670)$, member of an hypothetical penta-quark multiplet, has been added, compatibly with results obtained on the total cross-section (see after).

Results obtained and published at LEPS (SPring-8)[9], CB-ELSA[10][11] and also observed at MAMI[13] with improved statistics and at GRAAL[12], have recently opened an interesting debate about the presence of an unexpected narrow structure in the total cross-section of $\eta$ photoproduction on the neutron at a c.m. energy around 1680 MeV (see figure 5 and figure 6).

Due to the broadening caused by the Fermi motion of the neutron inside the deuteron, the structure can be explained in different ways in the frame of different models[14][15][16], in terms of a narrow $P_{11}$ state or as a conventionally broad one or even in terms of interference between partial waves. In order to improve the situation, high statistics on this channel and good energy resolution are required; in that respect more precise beam asymmetry and total cross section data, which can also be measured with the BGO-OD apparatus, could cast a new light on the identification of the contributing resonances.

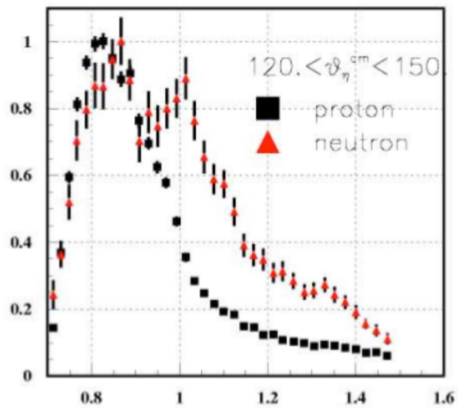


**Figure 6** Yield of $\eta$ photoproduction on the quasi-free neutron (red triangles) and on the quasi-free proton (black squares) at a specific c.m. polar angle (120°-150°), plotted as a function of the final state invariant mass W[12].

# 2 Proposed experiments

We propose to measure the $\Sigma$ beam asymmetries for the $\eta$ photoproduction on the free proton and on the quasi-free proton and quasi free neutron with the BGO-OD setup at ELSA in the energy range from the threshold up 1.8 GeV. We also propose to measure, with the same setup, the angular distribution of the $\eta$ photoproduction on the neutron in the energy region around 1.1 GeV, in order to investigate the presence of the narrow structure in the total cross-section at c.m. energy around 1680 MeV. The proposed experiments will require the following beam/target combinations:

- $\Sigma$: LH2 and LD2 target (for the $\eta$ photoproduction on the free proton and quasi-free proton and neutron respectively) and linearly polarized photon beam with polarization maxima between 0.8 and 1.8 GeV;
- $d\sigma/d\omega$: LD2 target and unpolarized beam.

## 2.1 Setup

### *2.1.1 Photon Beam*

In order to have a high polarizaton degree of the photon beam, an electron beam energy setting of 3.2 GeV is required. We would like to cover a large energy range and to divide the beam time into six different settings (peak positions at 1. GeV, 1.2 GeV, 1.4 GeV, 1.6 GeV, 1.7 GeV, 1.8 GeV). It is important to remark that several proposals require the same experimental conditions (beam energy range and polarization, target and trigger).

### *2.1.2 Target*

The target cell is an Aluminum hollow cylinder of 4cm in diameter and 6cm length. When filled with Hydrogen, the working temperature is 18K with a density $\rho \approx 7 \cdot 10^{-2} g/cm^3$ . When filled with Deuterium the working temperature is 20K with a density of $\rho \approx 0.169 g/cm^3$.

### *2.1.3 Detector setup*

The BGO-OD detector setup is a combination of a central detector system and a forward spectrometer for charged particles, completed by a photon tagging system.

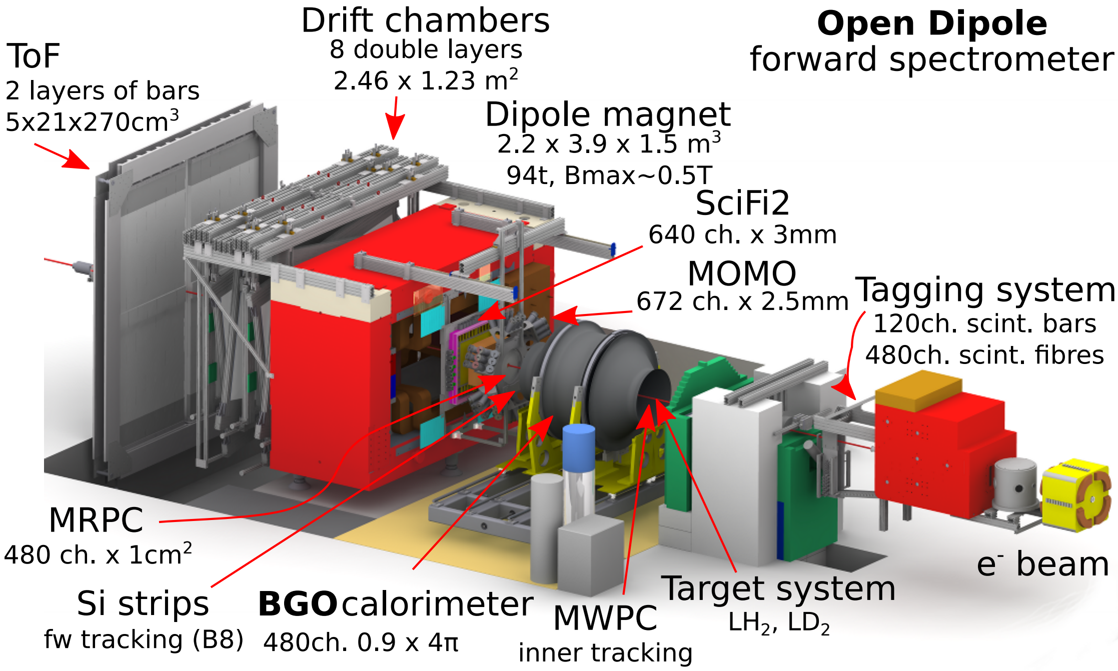


**Figure 7** The BGO-OD experimental setup

The central detector of the experimental setup is the high resolution and large solid angle $(0.9 \cdot 4\pi)$ BGO[a] electromagnetic calorimeter of the former GRAAL experiment [17, 18, 19, 20]. The calorimeter is combined with two multi-wire proportional chambers (MWPC) for inner tracking and a plastic scintillator barrel for particle identification through the measurement of dE/dx. The calorimeter consists of 480 BGO crystals with a length of 24cm ($>$ 21 radiation lengths).

The region between the acceptance of the central detector and the forward spectrometer will be covered by an azimuthally symmetric Multi-gap Resistive Plate Chamber (MRPC).

The MRPC will be located between the BGO calorimeter and the MOMO detector. It consists of two stacks, which are divided into 16 independent azimuthal sectors with a total of 480 channels.

The forward spectrometer is based on a large open dipole magnet, a permanent loan by DESY. Tracks are reconstructed in front of the magnet by two fiber hodoscopes, MOMO and SciFi2.

Behind the magnet, tracking is done using a set of 8 double layer drift chambers in four different orientations, vertical wires to measure the $x$-coordinate, horizontal for the $y$-coordinate, and tilted by $\pm 9^\circ$ from vertical, for a $u$- and $v$-coordinate.

The forward spectrometer is completed by a set of time-of-flight walls that are used to discriminate the various particles.

The photon tagging system uses a series of 120 adjacent, partially overlapping plastic scintillators with fast photomultiplier readout. It is designed to cover an electron energy range between 10% and 90% of the ELSA energy.

In 2013 an additional scintillating fiber hodoscope will be added to perform precise determination of the degree of polarisation for linearly polarized photons, by measuring the shape of the coherent edge. It will also allow to improve the energy resolution for low photon energies.

[a] $Bi_4Ge_3O_{12}$

| Part | Acceptance | angular resolution | time resolution | $p/E$ resolution |
|---|---|---|---|---|
| BGO Ball | $25^\circ < \Theta < 155^\circ$ | $\Delta\Theta < 6^\circ$,$\Delta\Phi < 7^\circ$ | $< 3\,\mathrm{ns}$ | $\approx 3\,\%$ for 1 GeV photons |
| MWPC | $18^\circ < \Theta < 163^\circ$ | $\Delta\Theta \approx 1^\circ$,$\Delta\Phi = 2^\circ$ | n.a. | n.a. |
| MRPC | $8^\circ < \Theta < 25^\circ$ | $< 1^\circ$ | 50 ps | n.a. |
| forward spec. | $\Theta_{vert} < 8^\circ$ | $\Delta\Theta_{\Theta<4^\circ} < 0.2^\circ$ | n.a. | $< 3\,\%$ for $p < 1.5\,\mathrm{GeV}$ |
| | $\Theta_{hor} < 12^\circ$ | $\Delta\Theta_{\Theta<10^\circ} < 0.3^\circ$ | n.a. | $< 6\,\%$ for $p < 3\,\mathrm{GeV}$ |
| ToF | $\Theta_{vert} < 8^\circ$,$\Theta_{hor} < 12^\circ$ | | 500 ps | n.a. |
| Tagger | n.a. | n.a. | 275 ps | 10 MeV to 40 MeV |

**Table 1** Parameters of the BGO-OD setup

#### *2.1.4 Considerations*

The $\eta$ meson will be identified by its neutral and charged decay products:

- $\eta \to 2\gamma$
- $\eta \to \pi^0\pi^0\pi^0$
- $\eta \to \pi^+\pi^-\pi^0$

The signal coming from the sum of the BGO crystals can be used for trigger purposes and this will allow to detect events when the $\eta$ decays in both neutral channels. The combination of the BGO calorimeter with the forward spectrometer, the MRPC detector and the cylindrical MWPC will also allow to fully detect the final products of the charged decay channel. This fact makes the BGO-OD particularly suitable for this kind of experiment, especially in the energy region above 1.6 GeV which is not covered by the Mainz facility. On the other side, in the energy regions which have already been covered by other experiments, the measurement of the eta photoproduction on the proton will provide a powerful check of the offline calibration procedure for the BGO-OD apparatus and the beam polarization.

For the reaction on the proton all three decay channels will be analysed, while for the neutron only the decay channel $\eta \to 2\gamma$ will be analyzed, not excluding the possibility to analyze in the future also the charged decay channel, when a full understanding of the capabilities of the detector will be achieved.

The final products will be detected in the following way:

- $\gamma$: all photons will be detected in the BGO (the detection of all final photons is required) providing angular and energy information;
- charged pions: will be detected in the BGO combined with scintillator barrel and MWPC (dE/dx vs. E particle discrimination, tracking, angular information), in the forward spectrometer (track and momentum/energy information) and in the MRPC (angular information);
- protons: will be detected in the BGO combined with the scintillator barrel and MWPC (dE/dx vs. E particle discrimination, track and energy information), in the forward spectrometer (track and momentum/energy information) and in the MRPC (angular and energy information by means of TOF measurements);
- neutron: will be detected in the BGO (angular information) and in the forward TOF detector (angular and energy information by means of TOF measurements).

## 2.2 Beam time estimates

Starting from kinematical studies and simulation we have estimated the angular acceptance and reconstruction efficiency for all $\eta$ decay final states. For the proton, an efficiency reconstruction of about 70% has been estimated all over the apparatus (central and forward regions); for the neutron an efficiency reconstruction of 40% and 15% has been estimated in the central region (BGO calorimeter) and in the forward spectrometer respectively. These efficiencies weighted by the geometrical acceptance (estimated from the simulation) of the two regions provide an overall reconstruction efficiency for the neutron of about 35%. For the photons the efficiency reconstruction has been extracted taking into account the probability of overlapping of two photons in the same bgo crystal. Results are summarized in table 2.

| Target | $\eta$ channel decay | $\epsilon_{geom}$ | $\epsilon_{rec}$ | $\epsilon_{eff} = \epsilon_{rec} \cdot \epsilon_{geom}$ |
|---|---|---|---|---|
| Proton | $\gamma p \to p\eta \to p\gamma\gamma$ | $\sim 0.7$ | $\sim 0.7$ | $\sim 0.5$ |
| Proton | $\gamma p \to p\eta \to p\pi^0\pi^0\pi^0 \to p\,6\gamma$ | $\sim 0.3$ | $\sim 0.5$ | $\sim 0.15$ |
| Proton | $\gamma p \to p\eta \to p\pi^+\pi^-\pi^0 \to p\pi^+\pi^- 2\gamma$ | $\sim 0.5$ | $\sim 0.35$ | $\sim$0.2 |
| Neutron | $\gamma n \to n\eta \to n\gamma\gamma$ | $\sim 0.3$ | $\sim 0.35$ | $\sim 0.1$ |

**Table 2** Geometrical ($\epsilon_{geom}$), reconstruction ($\epsilon_{rec}$) and effective ($\epsilon_{eff}$) efficiencies for the $\eta$ photoproduction measurements proposed.

The necessary time for the measurements can be calculated from the following formula:

$$T_{tot} = \frac{N(\theta) \cdot N(E)}{(\Delta\Sigma)^2} \cdot \frac{1}{\dot{N}_\eta} \tag{1}$$

where:

- $\dot{N}_\eta$: number of $\eta$ mesons detected in one hour;
- $\Delta\Sigma$: statistical uncertainty (we will require $\Delta\Sigma \simeq 0.05$);
- $N(\theta)$: number of bins in the c.m. polar angle;
- $N(E)$: number of $\gamma$ energy bins used to divide the energy range under study.

The $\eta$ rate $\dot{N}_\eta$ can be calculated from the following expression:

$$\dot{N}_\eta = \dot{N}_\gamma \cdot P_\gamma \cdot \delta_{target} \cdot \Delta\sigma \cdot \epsilon_{eff} \cdot \epsilon_{acq} \tag{2}$$

where:

- $\dot{N}_\gamma$: Flux of photons in the energy range (under the polarization peak) where the polarization degree is larger than 30%;
- $P_\gamma$: minimum beam polarization degree that we assume being of about 30% for all energy bins;
- $\delta_{target}$ : number of scattering centers/cm$^2$ ($\delta_H = 0.252 \cdot 10^{-24} cm^{-2}$, $\delta_N = 0.305 \cdot 10^{-24} cm^{-2}$);
- $\Delta\sigma$: Minimum Cross section value in the bin energy under study;
- $\epsilon_{eff}$: detection and reconstruction efficiency;
- $\epsilon_{acq}$=0.5: running efficiency (including macroscopic duty cycle of the accelerator, expected life time of the DAQ and safety margin for problems).

For the measurement of the $\Sigma$ beam asymmetry for the $\eta$ photoproduction on the free proton we will use an energy binning width between 40 MeV and 50 MeV, depending on the energy range covered by the bin and we will require a statistical uncertainty $\Delta\Sigma \simeq 0.05$ (for a cross section of $\Delta\sigma$ varying from 1.5 to $3\mu b$). For the measurement of the $\Sigma$ beam asymmetry for the $\eta$ photoproduction on the quasi-free neutron (and on the quasi free proton), we will use a binning width of about 50 MeV and we will require a statistical uncertainty $\Delta\Sigma \simeq 0.1$.

The time request for linearly polarized beam and LH2 target (free proton) is summarized in Table 3.

| $E_\gamma$ at polarization peak(GeV) | $\dot{N}_\gamma(10^6\gamma/s)$ | $\dot{N}_\eta(\eta/h)$ | $N(E)$ | $N(\theta)$ | Time Request (h) |
|---|---|---|---|---|---|
| 1. | 1.59 | 180 | 10 | 6 | ∼130 |
| 1.2 | 1.16 | 140 | 9 | 6 | ∼150 |
| 1.6 | 0.52 | 30 | 7 | 6 | ∼550 |
| 1.7 | 0.38 | 25 | 6 | 6 | ∼570 |
| 1.8 | 0.25 | 15 | 4 | 6 | ∼650 |
| | | | | | TOT∼2050 |

**Table 3** Time needed for the measurement of the beam asymmetry in the $\vec{\gamma}p \to \eta p$ reaction.

The time request for linearly polarized beam and LD2 target (quasi-free neutron and quasi-free proton) is summarized in Table 4.

| $E_\gamma$ at polarization peak(GeV) | $\dot{N}_\gamma(10^6\gamma/s)$ | $\dot{N}_\eta(\eta/h)$ | $N(E)$ | $N(\theta)$ | Time Request (h) |
|---|---|---|---|---|---|
| 1. | 1.59 | 29 | 10 | 6 | ∼200 |
| 1.2 | 1.16 | 21 | 9 | 6 | ∼250 |
| 1.6 | 0.52 | 5 | 6 | 6 | ∼700 |
| 1.8 | 0.25 | 2.5 | 4 | 5 | ∼800 |
| | | | | | TOT∼1950 |

**Table 4** Time needed for the measurement of the beam asymmetry in the $\eta$ photoproduction on quasi-free neutron (together with quasi-free proton) reaction.

For the data with unpolarized beam and LD2 target, for which a high energy resolution is required in the extraction of the total cross-section on the neutron and the proton in the energy region around 1.06 GeV, we have estimated that about 1000 h are needed in order to divide the energy range into a larger number of energy and theta bins.

# 3 Conclusions

The time request to perform our experiments are:

- 2050 hours of linearly polarized beam and LH2 target
- 1950 hours of linearly polarized beam and LD2 target
- 1000 hours of unpolarized beam and LD2 target

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