A Photon Detector for COSY

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Abstract:

It is proposed to design, build and operate a compact, large solid-angle photon-detection system for use at the internal beam of COSY. While the detector will be adapted for installation at ANKE, it should also be portable to allow the use at other experimental areas as well. In addition to the general physics motivation presented at last PAC meeting, this proposal provides more detailed information about the geometry of the detector and an estimation of the required beamtime for an initial physics program. This program includes measurements of η and ω production in proton-proton and proton-neutron collisions and investigations on charge symmetry breaking in the dd $\rightarrow$ ^{4}He π^0 reaction.

Contents

1 Introduction

In the last PAC meeting in May 2000, a first proposal for a photon-detection system has been presented [1, 2]. The focus of this proposal was to show the wide range of physics reactions which can be studied at COSY using such a detector in combination with the ANKE spectrometer. The PAC welcomed the prospects for an attractive physics program and asked for a more complete proposal. In particular questions concerning the geometrical design at ANKE and the initial program including beamtime estimates should be addressed.

The actual proposal follows the advice of the PAC. The investigations concerning detector geometry, scintillator material, light readout, detector acceptance and a first physics program are presented.

2 Detector design

2.1 General remarks

The basic idea of this proposal is to build a fast, large solid-angle electromagnetic calorimeter for photon detection around the target position of the ANKE spectrometer. Due to the limited space and the magnetic environment, substantial requirements are made on such a device. Fig. 1 shows a sketch of the proposed setup in front of the magnet D2 of ANKE. The current target position at $l = 30$ cm (with respect to D2) does not allow the installation of scintillation detectors at forward angles. Therefore, starting with the use of the pellet target, a new target position at $l = 54$ cm has been chosen as a compromise between space requirements and acceptance losses in ANKE[1]. This results in a distance of the D2 bellow from the target of 31 cm and a minimum opening angle of the photon detector of $\Theta = \pm 25°$. For the final design, the goal will be to minimize this opening angle to gain in photon acceptance (see section 2.5) without losing acceptance in ANKE for coincidence measurements (e.g. for distinguishing between $pn \rightarrow dX$ and $pn \rightarrow pnX$ reactions). However, the size of the bellow can hardly be reduced without limiting the movability of ANKE relative to the COSY beam line. Therefore, simulations are currently based on the existing design.

Taking into account all boundary conditions, the total diameter of the photon detector is limited to $d \approx 75$ cm. The full setup with ANKE and the photon detector as used in the GEANT4 simulations is shown in fig. 2.

Some figures of merit of the proposed detector are given in table 1. They will be discussed in detail in the following sections.

[1] The second target, which is currently being built for ANKE, the ABS, uses an extended storage cell with a length of about 30 cm. This also requires a more upstream target position.

Main properties of the photon detector	
Solid angle	93% of 4π
Granularity	13 msr
Material	$PbWO_4$
Thickness	$13.5\ X_0$
Time resolution	$\sigma_t \approx$ 130 ps
Energy resolution	$\sigma_\gamma \approx 3\%$ @ $E_\gamma = 500$ MeV
Invariant mass resolution	FWHM $(\pi^0) \approx$ 23 MeV
	FWHM $(\eta) \approx$ 40 MeV
	FWHM $(\omega) \approx$ 50 MeV
Number of channels	900
Photosensors	fine-mesh photomultiplier

Table 1: A summary of the main properties of the proposed detector.

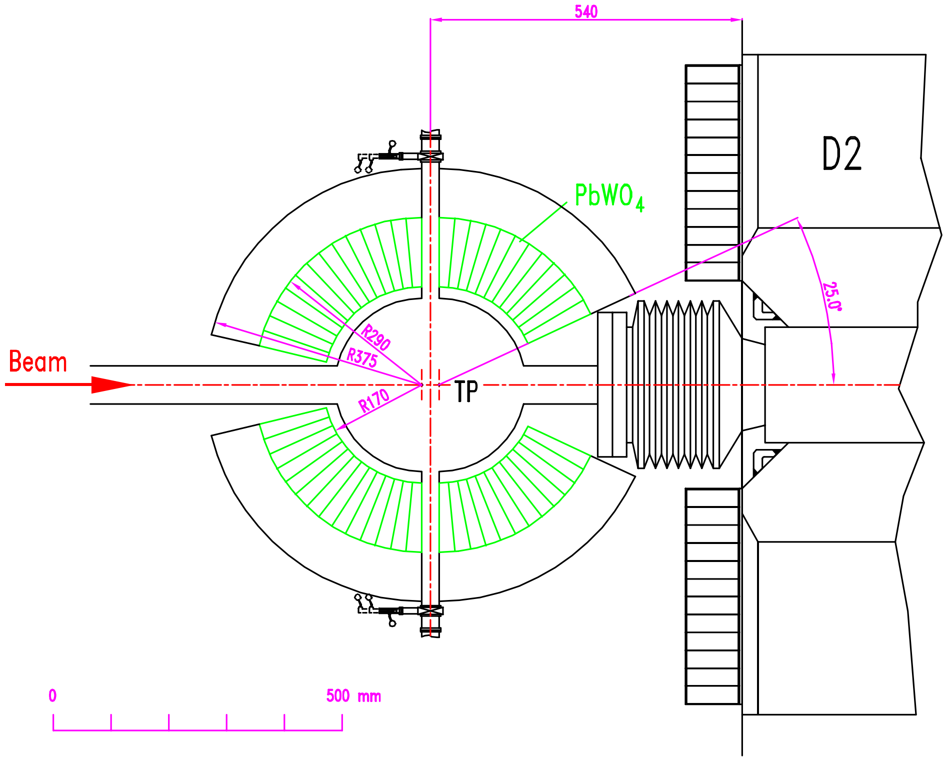

Figure 1: The target area of ANKE in front of the D2 magnet. The photon detector is positioned at a target point of $l = 54$ cm relative to the edge of D2. The minimum opening angle in forward direction is determined by the size of the bellow and is $\Theta = \pm 25°$. The resulting solid-angle is 93% of 4π. The total size of the detector is limited to a diameter of $d = 75$ cm.

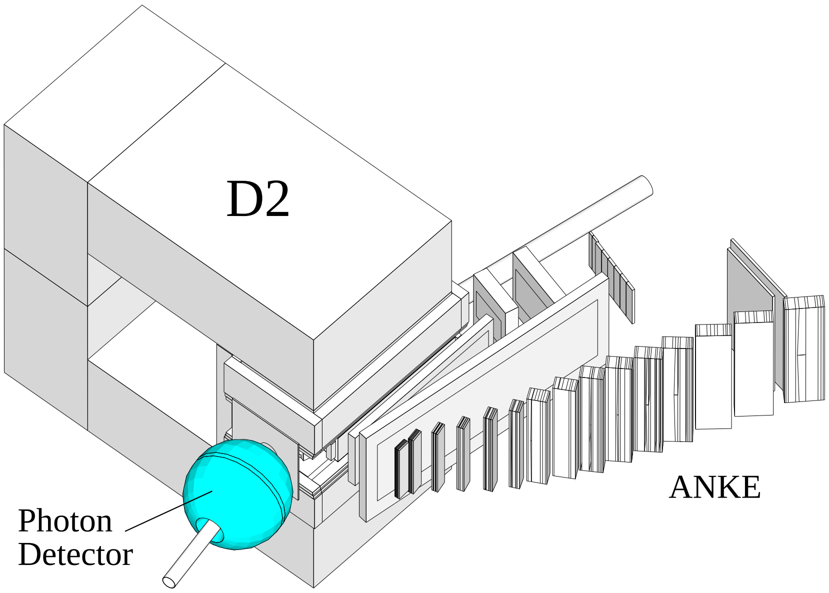

Figure 2: The combined setup of ANKE and the photon detector within GEANT4. The COSY beam enters the detection system from the lower left.

2.2 Detector material

The considerations given above imply a scintillator with a radiation length as small as possible. In recent years $PbWO_4$ has been investigated as a high density inorganic scintillator with good energy resolution for photon detection even at intermediate energies [3, 4]. For high energy physics it has been chosen by the CMS collaboration at CERN as the material for the electromagnetic calorimeter (about 80000 channels). This has the advantage that the production capabilities to produce the crystals needed will be available as long as the cross section does not exceed a size of 35x35 mm^2. So far, the production has concentrated on the barrel segments (which are smaller in diameter) of the CMS detector, but R&D for larger crystals is currently going on. It is expected to have a first test array of the demanded size available within the next months. The physical properties of $PbWO_4$ together with other possible detector materials are listed in table 2.

Recent tests at the photon beam line of the electron accelerator MAMI at the University of Mainz with $PbWO_4$ and, for the first time, CeF_3 show (fig. 3) that the resolution of $PbWO_4$ is better than CeF_3 despite of the lower light output. However, the CeF_3 crystals [2] are prototypes [5] and not yet optimized like $PbWO_4$. For $PbWO_4$ a comparison with the resolution of the existing BaF_2 modules of the TAPS spectrometer [6] is plotted. Below $E_\gamma = 300$ MeV the resolution is dominated by the low light output of the scintillator, but at higher energies the performance

[2] provided by the Crystal Clear Collaboration and ETH, Swiss Federal Institute of Technology, Zürich, Switzerland.

	$PbWO_4$	BGO	CeF_3
density ρ [g/cm^3]	8.28	7.13	6.16
index of refraction	2.16	2.20	1.68
radiation length X_0 [cm]	0.89	1.12	1.68
Molière radius R_{M} [cm]	2.2	2.4	2.6
major decay constants [ns]	< 20	300	30
peak wavelength of emission [nm]	420	480	$310 - 340$
temperature dependence of light yield [%/°C]	≈ -1.9		-

Table 2: Relevant physical properties for some scintillator materials.

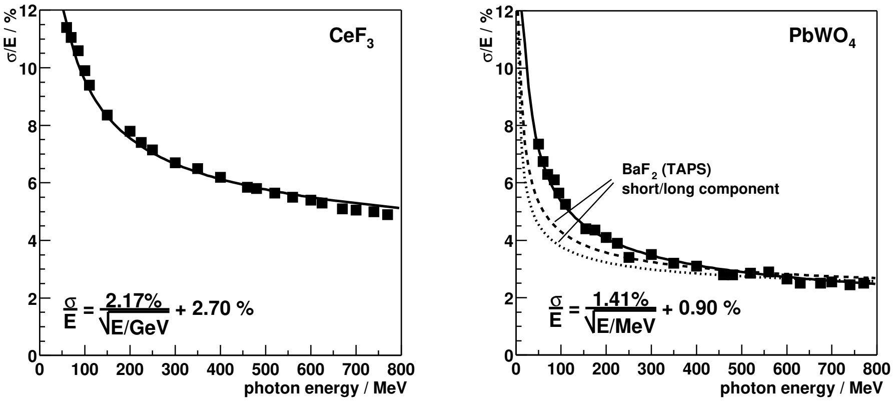

Figure 3: Test results on the resolution of $PbWO_4$ and CeF_3 obtained at the electron accelerator MAMI of the University of Mainz (August 2000 / preliminary).

gets better due to the high density and the small radiation length. The radiation resistance has been investigated by the CMS collaboration [7], where this problem is more severe than at COSY. It was found, that the loss in light output due to radiation damage saturates at about 5% at high neutron rates. Another possible candidate could be BGO, but this material is much slower in timing (which is a disadvantage when looking for photon-photon coincidences in a high count-rate environment).

Taking into account all boundary conditions, $PbWO_4$ seems to be the most appropriate detector material. Considering the energy range of the produced photons up to 2 GeV the proposed length of the crystals is 12 cm (i.e. 13.5 X_0).

2.3 Light readout

One advantage of $PbWO_4$ is the fast timing, which offers the possibility of efficient background suppression by selecting photon-photon coincidences. To exploit this feature it is necessary to use photomultipliers rather than slow conventional photo diodes or avalanche photo diodes (APD). Using an APD one can reach a time resolution of ≈ 1 ns, but its noise in combination with the low light output of $PbWO_4$ makes it unsuitable for this application. In addition, the sensitive area of one APD is currently limited to about 1 cm^2. While photo diodes are insensitive to the magnetic stray field of D2 ($B < 0.2$ T), only special fine-mesh photo tubes can be operated in such an environment. These tubes are insensitive to magnetic fields parallel to the multiplier axis (up to $B \leq 1$ T), but have to be shielded against the transversal component of the field. Since the photon detector is of a spherical shape close to a magnetic dipole, all directions of the magnetic field are equally important with respect to the multiplier axis.

The only available commercial model of the fine-mesh type (Hamamatsu R5505) has been tested intensively. Fig. 4 shows some test results for the unshielded tube. With the field parallel to the multiplier axis no effect on the amplification is seen, but using a perpendicular field the output already drops down at 0.02 T. In fig. 5 the latter situation is shown using a shielding tube of soft iron (wall thickness 1 mm and 2 mm): the undisturbed range increases at least up to 0.12 T. From this it is concluded that the existing stray field at ANKE can be handled with a shielding thickness of 3 mm.

All these studies have been performed in a static magnetic field. During the experiment the multipliers have to withstand the ramping between two accelerator cycles and the amplification has to recover to the same value in all data-taking cycles. This has been checked during an ANKE beamtime in September 2000. The photo tubes were equipped with a blue LED and positioned at the designated place in front of the D2 magnet. As one can see in fig. 6 the ramping (i.e. the change of the magnetic field) has some effect on the pulse height of the photomultiplier, but the output within the beam cycle (flat top) is stable and has the same value before and after each acceleration. This means that the R5505 meets the demands for the proposed photon detector at ANKE.

The R5505 has a diameter of $d = 25.6 \pm 0.7$ mm and a length of $l = 75$ mm including the multiplier base. Together with the 3 mm shielding, the total diameter is $d_{\rm tot} \approx 33$ mm. This coincides with the currently produced crystal sizes. The total length of one module is $l_{\rm tot} = 20$ cm. Therefore the inner radius of the photon detector has to be $R_i = 17$ cm.

2.4 Granularity

Considering the dimensions of the photomultiplier together with the necessary shielding the crystal size on the multiplier side will be 33 x 33 mm^2 and on the target side 19 x 19 mm^2. This corresponds to a solid angle of one module of 13 msr. The resulting granularity with respect to the Molière radius $R_{\rm M} = 2.2$ cm is reasonable (e.g., the diameter of one BaF_2 module of the existing TAPS spectrometer is 5.9 cm with $R_{\rm M} = 3.2$ cm). The total number of modules will be 700 - 900 depending on the solid angle coverage.

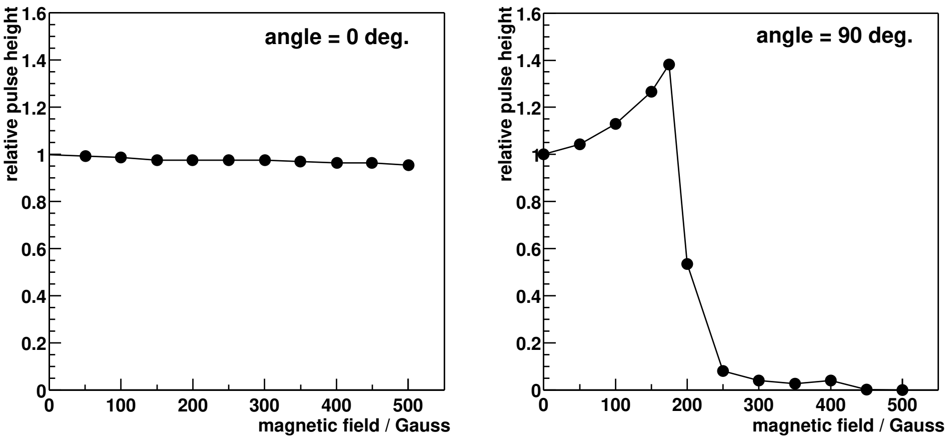

Figure 4: The behaviour of the unshielded R5505-tube within a magnetic field. The relative angles between the magnetic field and the tube axis are 0° and 90°, respectively.

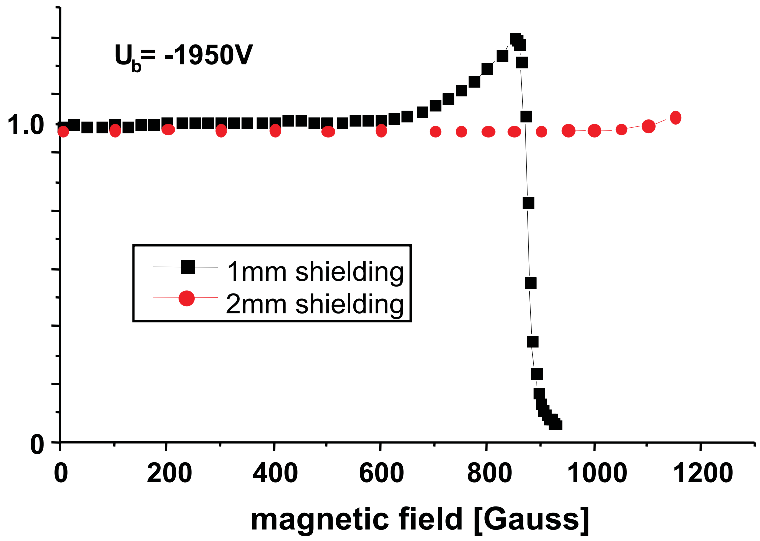

Figure 5: The shielded R5505-tube (1mm/2mm soft iron) in a magnetic field up to 0.12 T. The magnetic field is perpendicular to the multiplier axis.

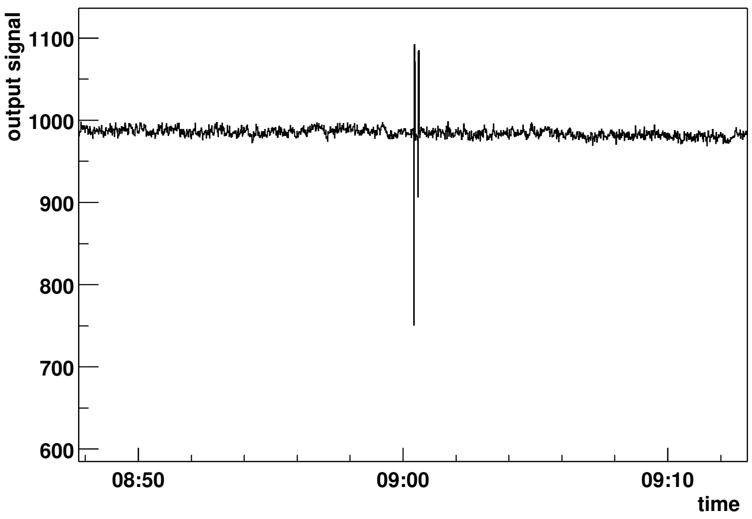

Figure 6: The behaviour of the shielded R5505-tube (3mm soft iron) at the designated position at ANKE for experimental conditions. The pulse height is plotted as a function of time. While the two peaks originate from the ramping of the magnet, the amplification before and after each ramping is the same.

2.5 Solid angle

One of the questions of the PAC in May 2000 concerns the maximum solid angle that can be reached with the photon detector. Taking into account the target position at $l = 54$ cm, a minimum opening angle in forward direction of $\Theta_{\text{min}} = 25^\circ$ (see 2.1) is found and a maximum polar angle of $\Theta_{\text{max}} = 165^\circ$ in backward direction (limited by the beam pipe): the maximum full solid angle is **93% of 4**π.

However, as shown in fig. 7 the acceptance for events with $n_\gamma < 4$ (for π^0, η, ω and η' production in pp and pd collisions) is limited by the hole in forward direction and saturates for $\Theta_{\text{end}} \approx 120^\circ$. In addition, the efficiency for $n_{\gamma,\text{det}} = 3$ from $2\pi^0$ production (i.e. one gamma is lost, the major background for ω production) does not decrease significantly when extending the photon detector to more backward angles. A hole at backward direction is useful or even necessary to install near-target detectors (spectator detector, vertex detector or an array of plastic veto counters). Nevertheless, reactions like the proposed dd $\rightarrow$ $^4\text{He}\,\pi^0$ (fig. 8, sec. 3.2) or the detection of the $\eta \rightarrow 3\pi^0$ decay need a more complete coverage of the background hemisphere. This requires at least two different setups, which have to be supported by the photon detector. Thus a flexible and modular design is necessary.

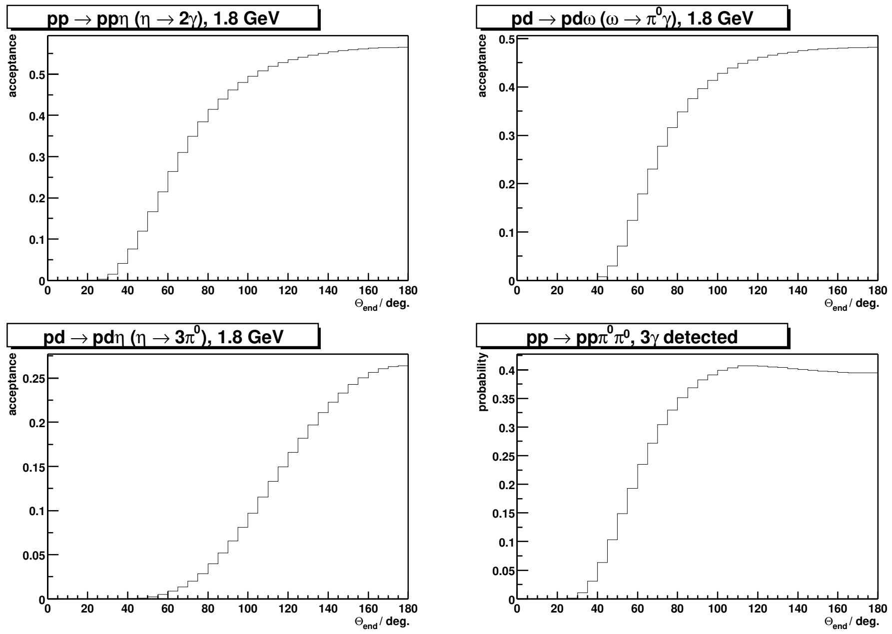

Figure 7: The typical acceptance of the photon detector for 2-, 3- and 6-γ events at a beam energy $E_{\mathrm{p}} = 1.8$ GeV versus the detector limit at backward angles (Θ_{end}). The detector starts at $\Theta_{\mathrm{min}} = 25°$. The lower right figure shows the probability to misidentify $2\pi^0 = 4\gamma$ events as 3-γ events.

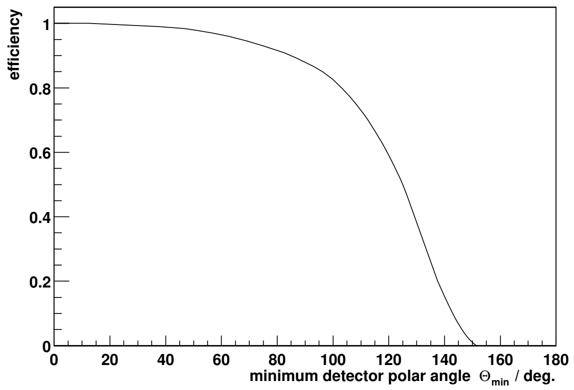

Figure 8: The acceptance of the photon detector for the π^0 in the reaction dd $\rightarrow$ $^4\mathrm{He}\,\pi^0$ versus the detector limit at forward angles (Θ_{min}), i.e. the covered solid angle starts at Θ_{min} and ends at $\Theta_{\mathrm{end}} = 180°$. Additional losses due to the beam pipe reduce the maximum efficiency to about 90 %.

2.6 Charged particle discrimination

The high count rate environment implies the need of an online discrimination of charged particles. For this purpose a ball-shaped array of fast plastic scintillators inside the photon detector can be used. The granularity of such a device can be much smaller than the photon detector itself, i.e. a "soccer ball" made of 32 pieces will fit the requirements. The single plastic scintillators can be read out via wavelength-shifting optical fibres in combination with multi-anode photomultipliers. This method is currently used by the TAPS collaboration for its individual, hexagonal charged particle veto detectors [8]. A final decision about charged particle discrimination will be made after first photon-photon coincidence measurements at ANKE, which have to be performed with test arrays of $PbWO_4$ in the near future.

2.7 High voltage supply, readout and trigger electronics

The design of the HV supply for about 800 photomultiplier channels has not been decided yet. Due to the limited space in the target area, it is obvious, that individual HV channels cannot be installed for each PMT. Either the photo tubes have to be arranged in groups and connected to a single high voltage line or the high voltage has to be generated locally using bases with on-board miniaturized Cockroft-Walton generators. The latter devices have been developed, for example, for WA98 (CERN) [24] and the HADES time-of-flight system[3]. One advantage of such a solution is the low power consumption compared with a standard voltage divider. The power consumption observed by WA98 was less than 75 mW per channel. This is of importance, because the light output of $PbWO_4$ is strongly temperature dependent (table 2).

For the readout and trigger electronics, modern integrated concepts will be chosen. This means either a solution where several complete channels are grouped together on one board or even performing the digitization already at the photomultiplier. Electronic modules of the first type are currently developed by the TAPS collaboration. Presumably, these VME boards will have 8 complete channels including constant fraction discriminators for timing, leading edge discriminators for triggering and TDCs and QDCs. This fast and compact VME solution in combination with the specially developed Multiplicity Coincidence Units for versatile triggering seems to be well suited for application in this project.

The first level trigger of the photon detector has to be fast ($t \leq 200$ ns) in order to match the requirements of the ANKE trigger system. It has to be studied whether a multiplicity trigger (number of modules or sub-arrays above a given discriminator threshold) would be enough or if a more sophisticated system like pattern recognition is necessary.

These questions will be discussed in detail in an upcoming technical proposal.

[3] see http://hp.uif.cas.cz/hades

3 Initial program

It was shown in the last proposal [2] that the installation of a photon detector at COSY will offer the study of a wide range of interesting physical reactions with multi-photon final states. As a starting point, in this proposal an initial physics program is given, which is of great importance for understanding meson-nucleon interactions and will give new insight in the contributing reaction mechanisms. It is also an ideal tool for studying the response and the properties of the photon detector itself (one meson final states, photon multiplicity $n_\gamma = 2, 3$). This will be the basis to study more complicated reactions (like multi pion production) or rare events (like η' production) in subsequent beam times.

The expected count rates given below are based on an estimated luminosity of $10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ using the pellet target and 10^{10} particles circulating in COSY.

3.1 η and ω production in pp and pd collisions

A detailed motivation for a physics program investigating neutral meson production in proton-proton and proton-neutron collisions has already been given [2]. The major point is that for a complete understanding of η and ω production in nucleon-nucleon collisions, the whole information about all final isospin channels (pp $\rightarrow$ ppX, pd $\rightarrow$ pdX and pd $\rightarrow$ pnpX) has to be known as an input for new models and theories. In addition, it is important not only to have the total cross sections, but also to extract the differential ones. This can only be done using a direct identification of the produced meson.

Table 3 shows the acceptance of the photon detector with and without proton and deuteron detection in ANKE and the spectator detector. These numbers are the result of a GEANT4 simulation including the full ANKE setup and the photon detector.

3.1.1 pp $\rightarrow$ ppη at threshold

As a first and commissioning beamtime using the full detector setup it is proposed to investigate η production at threshold in pp collisions. The total cross section of this reaction is well known up to $Q = 120$ MeV above threshold (see [10, 11, 12, 13, 14, 15, 16, 17]). The differential cross section has been measured recently at CELSIUS at $Q = 16$ MeV and $Q = 37$ MeV [17]. Therefore, this reaction is well suited to study the properties of the photon detector and to understand and survey its acceptance.

The estimated count rates for η production in pp are given in table 4. The two different numbers are the coincidence rates with 1 proton and 2 protons in ANKE, respectively. The major background for trigger and data acquisition is neutral pion production. The given rate for a one-proton coincidence is about a factor of 4 higher than the current capability of the ANKE readout system. However, the trigger rate

reaction	beam energies / GeV						
	1.0	1.4	1.8	2.0	2.2	2.4	2.62
$pp \to pp\,\eta$							
ϵ_η	-	0.664	0.587		0.535		0.498
$\epsilon_{\eta,\mathrm{p}}$	-	0.264	0.109		0.074		0.061
$\epsilon_{\eta,\mathrm{pp}}$	-	0.034	0.005		0.0022		0.0013
$pd \to p_s d\,\eta$							
ϵ_η	0.739	0.642	0.556		0.522		0.503
$\epsilon_{\eta,\mathrm{d}}$	0.196	0.120	0.044		0.031		0.028
$\epsilon_{\eta,\mathrm{d},\mathrm{p_s}}$	$< 10^{-5}$	0.015	0.0034		0.0022		0.0023
$pd \to p_s pn\,\eta$							
ϵ_η	0.742	0.672	0.641		0.620		0.601
$\epsilon_{\eta,\mathrm{p}}$	0.123	0.039	0.028		0.024		0.021
$\epsilon_{\eta,\mathrm{p},\mathrm{p_s}}$	$< 10^{-5}$	0.00035	0.00055		0.00059		0.00061
$pp \to pp\,\omega$							
ϵ_ω	-	-	-	0.484	0.453	0.429	0.403
$\epsilon_{\omega,\mathrm{p}}$	-	-	-	0.251	0.142	0.103	0.081
$\epsilon_{\omega,\mathrm{pp}}$	-	-	-	0.049	0.013	0.006	0.0033
$pd \to p_s d\,\omega$							
ϵ_ω	-	0.618	0.520	0.480	0.445	0.415	0.393
$\epsilon_{\omega,\mathrm{d}}$	-	0.174	0.155	0.012	0.063	0.042	0.034
$\epsilon_{\omega,\mathrm{d},\mathrm{p_s}}$	-	$< 10^{-5}$	0.0061	0.014	0.0063	0.0040	0.0031
$pd \to p_s pn\,\omega$							
ϵ_ω	-	0.630	0.573	0.556	0.536	0.523	0.511
$\epsilon_{\omega,\mathrm{p}}$	-	0.200	0.046	0.035	0.030	0.026	0.023
$\epsilon_{\omega,\mathrm{p},\mathrm{p_s}}$	-	$< 10^{-5}$	$< 10^{-5}$	0.00014	0.00018	0.00016	0.00026

Table 3: The acceptance of photon detector in combination with ANKE for η and ω production in pp and pd collisions. For the latter a spectator detector is included. The branching ratios ($\eta \to \gamma\gamma = 0.39$ and $\omega \to \pi^0\gamma = 0.085$) are not included.

can be reduced by choosing proper discriminator thresholds depending on the polar angle of the detector module. This might result in an additional suppression factor of about 4 to 8. In any case, this beamtime has to be used to study these effects.

Within one week of beamtime it should be possible to scan 6 different energies (taken into account also the time needed for changing the beam momentum). At the lowest energy a total number of 10^5 η-mesons in coincidence with 1 proton and 12000 η-mesons in coincidence with 2 protons can be expected during 12 hours of data taking. One energy below η threshold should be used to study the background conditions. For the 5 different energies above threshold differential cross sections with high statistics will be available. One energy ($Q = 37$ MeV) is chosen such, that the resulting angular distribution can be compared with existing data.

Q value	beam energy	η cross section	count rates 1p	count rates 2p
$Q = -2$ MeV	1.24906 GeV	-	-	-
η threshold: $E_p = 1.25422$ GeV				
$Q = 2$ MeV	1.259 GeV	0.2 μb	2 s^{-1}	0.3 s^{-1}
$Q = 20$ MeV	1.306 GeV	3 μb	30 s^{-1}	4 s^{-1}
$Q = 37$ MeV	1.351 GeV	5 μb	50 s^{-1}	7 s^{-1}
$Q = 70$ MeV	1.427 GeV	20 μb	200 s^{-1}	26 s^{-1}
$Q = 100$ MeV	1.518 GeV	30 μb	300 s^{-1}	40 s^{-1}
background from π^0 production				
-	-	$\sigma_{\pi^0} \approx 4$ mb	$2 \cdot 10^4$ s^{-1}	400 s^{-1}

Table 4: Expected count rates for η production in pp $\rightarrow$ ppη. To suppress the background from π^0 production the discriminator thresholds for the multiplicity = 2 trigger has to be optimized.

Q value (η)	Q value (ω)	beam energy	$\sigma_{\eta,\mathrm{tot}}$	counts / s^{-1} 1p	counts / s^{-1} 2p	$\sigma_{\omega,\mathrm{tot}}$	counts / s^{-1} 1p	counts / s^{-1} 2p
202 MeV	-	1.8 GeV	100 μb	1000	50	-	-	-
ω threshold: $E_p = 1.890$ GeV								
273 MeV	38 MeV	2.0 GeV	100 μb	350	14	2 μb	5	1
342 MeV	107 MeV	2.2 GeV	100 μb	290	8.6	15 μb	18	1.7
409 MeV	174 MeV	2.4 GeV	100 μb	265	7	25 μb	23	1.3
481 MeV	246 MeV	2.62 GeV	100 μb	237	5.1	40 μb	28	1.1

Table 5: Expected count rates for η and ω production in pp collisions.

3.1.2 pp $\rightarrow$ ppη and pp $\rightarrow$ ppω from threshold to the maximum COSY energy

One great advantage of the photon detector is the ability to identify neutral meson via an invariant mass analysis also well above threshold. While precise data are available for η production at threshold the situation far above threshold is worse. According to data taken from [18, 19, 20] the total cross section between $E_p = 1.8$ GeV and $E_p = 2.62$ GeV is only poorly known and is about 100 μb. In case of ω production data up to $Q \approx 30$ MeV ($E_p = 1.98$ GeV) [21] and above $Q \approx 400$ MeV ($E_p = 3.1$ GeV) are available (see [22]).

Table 5 shows the expected count rates for η and ω production at beam energies of $E_p = 1.8$, 2.0, 2.2, 2.4 and 2.6 GeV. Both reactions can be studied in parallel using independent triggers (multiplicity 2 and multiplicity 3 in the photon detector in coincidence with one or two protons in ANKE). To get reasonable statistics for total and differential cross sections for the first 4 energies, a total of one week of beam time should be sufficient. As discussed in the last proposal, one open question in ω production is if there exists any resonance decaying into ωN. It has been shown

$pd \rightarrow p_{sp}dX$						
beam energy	$\sigma_{\eta,tot}$	counts / s^{-1} d	d+p_{sp}	$\sigma_{\omega,tot}$	counts / s^{-1} d	d+p_{sp}
1.0 GeV	1.4 μb	11	$< 2h^{-1}$	-	-	-
1.4 GeV	53 μb	240	30	0.2 μb	0.3	$< 2d^{-1}$
1.8 GeV	50 μb	90	7	8 μb	11	0.4
2.2 GeV	30 μb	37	2.6	32 μb	17	1.7
2.62 GeV	20 μb	22	1.8	32 μb	9	0.8

$pd \rightarrow p_{sp}npX$						
beam energy	$\sigma_{\eta,tot}$	counts / s^{-1} p	p+p_{sp}	$\sigma_{\omega,tot}$	counts / s^{-1} p	p+p_{sp}
1.0 GeV	0.1 μb	0.5	$< 2d^{-1}$	-	-	-
1.4 GeV	80 μb	120	1	1 nb	$6h^{-1}$	-
1.8 GeV	300 μb	460	6	5 μb	2	$< 2h^{-1}$
2.2 GeV	400 μb	360	9	100 μb	25	0.15
2.62 GeV	500 μb	400	11	200 μb	39	0.4

Table 6: Expected count rates for η and ω production in pd collisions. The numbers may be treated as upper limits since the ROC calculations tend to overestimate the production cross sections.

that the combination of the photon detector with ANKE allows the search for such resonances exploiting the analysis of Dalitz plots. To fill such a Dalitz plot providing a total amount of 500 valid channels (see [2]) with a statistical error of 2% in each bin, the total number of detected ω mesons has to be $1.25 \cdot 10^6$. At the energy of $E_p = 2.62$ GeV (here the accessible phase space is at the maximum for COSY) requiring 2 protons in coincidence with an ω-meson 2 weeks of beam time are necessary. Therefore, the total amount of beamtime for this program is 3 weeks.

3.1.3 η and ω production on the neutron

To complete the initial experimental program on η and ω production the reaction channels involving the neutron have to be investigated. This will be done by using a deuteron target and tagging the spectator proton in a dedicated spectator detector. Such a device is currently being developed for ANKE and first experiments are under way [23] and a beam-time request will be presented at this PAC meeting to measure $pd \rightarrow p_{sp}d\,\eta$ and $pd \rightarrow p_{sp}d\,\omega$ at $E_p = 1.4$ GeV and $E_p = 2.0$ GeV, respectively. However, while the Q-dependence can be measured with a combination of ANKE and a spectator detector using a missing-mass analysis, the extraction of differential cross sections requires the identification of the meson itself.

Again, η- and ω-mesons can be measured and identified during the same beamtime. The proposed energies ($E_p = 1.0$ GeV, 1.4 GeV, 1.8 GeV, 2.2 GeV and 2.62 GeV) are chosen in a way that energies slightly below and above the free production threshold are covered. In addition, the situation at the highest possible energy will be studied.

The given count rates (table 6) are based on cross sections obtained by calculations with the Rossendorf-Collision model (ROC) [25]. The estimated angular acceptance of the spectator detector to be used is $\Theta_{\mathrm{lab}} = 90 \pm 30°$ and $\Phi_{\mathrm{lab}} = 0 \pm 30°$ in polar coordinates[4]. With this setup the combined acceptance of the complete system is not sufficient to do exclusive measurements of the break-up channel below the free production threshold. Nevertheless, at 1.0 GeV and 1.8 GeV inclusive data for $\mathrm{pd} \to \mathrm{p}\,\eta\mathrm{X}$ and $\mathrm{pd} \to \mathrm{p}\,\omega\mathrm{X}$, respectively, will be extracted. Taking into account this limitation, a total beamtime of 1 week for these energies is needed. For the highest energies (2.2 and 2.62 GeV) also the break-up channel can be studied exclusively. Due to the Fermi momenta of the nucleons at each energy a range of $\Delta Q \approx \pm 30$ MeV can be covered. Assuming 6 bins in Q and a statistical uncertainty of 3% for the differential cross sections (10 data points each) a total number of 10^5 exclusive events are needed. This means 1 week of beamtime for each energy, i.e in total 3 weeks of beamtime with the deuteron target.

3.2 Charge symmetry breaking in d + d $\to$ ^{4}He + π^0

This reaction was already presented to and accepted by the PAC as a part of proposal #59 [9]. On closer evaluation of the experiment, it was found that the original idea to use Big Karl is not feasible, because a sufficient background reduction cannot be reached. A detailed evaluation of performing this experiment with ANKE and the photon detector was given as an addendum to the last proposal.

In order to extract the $\pi^0 - \eta$ mixing angle the differential cross section for the $\mathrm{dd} \to {}^4\mathrm{He}\,\pi^0$ reaction has to be measured. According to the model prediction the maximum cross section is expected for the beam momentum of 2.336 GeV/c (this corresponds to the threshold for $\mathrm{dd} \to {}^4\mathrm{He}\,\eta$). At this beam momentum the model predicts an isotropic c.m. differential cross section of 4.4 pb/sr. The major background will be from the direct $\mathrm{dd} \to {}^4\mathrm{He}\,\gamma\gamma$ reaction. The π^0 production reaction may be distinguished from the physical background only if sufficient statistics are collected and if a very good missing mass (obtained from ^{4}He detection) resolution and invariant mass (obtained from $\gamma\gamma$ detection) resolution is reached. In order to prove the observation of $\mathrm{dd} \to {}^4\mathrm{He}\,\pi^0$ it should be also measured at somewhat higher beam momentum (about 2.35 GeV/c) where the expected cross section drops down to 1.5 pb/sr, while the physical background should be almost unchanged. The measurement at two beam momenta should be preferentially performed in a COSY supercycle.

The good missing mass and invariant mass resolution as well as a substantial background reduction may be achieved only when using the ANKE spectrometer for ^{4}He detection and the proposed photon detector for the π^0 detection. With the

[4] With the z-axis in beam direction and the y-axis pointing upwards, the spectator detector is located in the direction of the x-axis.

present ANKE setup the simulated solid angle for ^{4}He detection is about 4% of the full c.m. solid angle. For ^{4}He ejectiles emitted to the forward hemisphere with a momentum of about 2.62 GeV/c the associated π^0 is emitted to the backward hemisphere (in the laboratory frame). Therefore the photon detector covering only the backward hemisphere will be sufficient to detect the 2γ particles from the π^0 decay. Such a detector will have about 90% efficiency for the detection of π^0 mesons in the investigated reaction. An additional hole around 180° for the beam pipe reduces the acceptance to about 80%.

Since the expected cross section is rather small, the measurements should be performed with maximum available luminosity. With the pellet target, which is currently under construction, a target density of about 10^{16}atoms/cm^2 may be expected. With 10^{10} deuterons stored in COSY a luminosity of at least 10^{32}cm^{-2}s^{-1} may be used. While a polarized measurement would be of great interest, the required high luminosity can currently not be reached using a polarized beam and/or target: the upcoming ABS storage-cell target will provide a target thickness approximately up to 10^{14}atoms/cm^2 and a high-intensity polarized beam relies on the installation of a new injector for COSY.

Before proceeding to the final experiment some test measurements will be necessary in order to understand the response of the photon detector and the acceptance of the whole detection system. The most suitable reaction for such a test measurement will be pd $\to$ ^{3}He π^0. At a beam momentum of 1.492 GeV/c the π^0 momentum distribution in the backward hemisphere will be very similar to the designated reaction. The simulated solid angle for ^{3}He detection is about 2% of the full c.m. solid angle and the photon detector acceptance is 78%. The cross section for pd $\to$ ^{3}He π^0 is known and is equal to 30 nb/sr in the c.m. system for the ^{3}He emitted parallely to the incident proton.

To perform the proposed experiment the following experimental equipment is necessary:

1. A deuteron beam with a momentum of about 2.35 GeV/c and 10^{10} deuterons stored in COSY
2. The ANKE spectrometer with the forward detection system
3. The pellet deuteron target with a density of 10^{16}atoms/cm^2
4. The proposed photon detector covering the backward hemisphere

With the luminosity of 10^{32}cm^{-2}s^{-1} the following count rates are expected:

reaction	beam momentum	$\frac{d\sigma}{d\Omega_{c.m.}}$	$d\Omega_{c.m.}$	count rate / day^{-1}
dd $\to$ ^{4}He π^0	2.336 GeV/c	4.4 pb/sr	0.5 sr	15
dd $\to$ ^{4}He π^0	2.350 GeV/c	1.5 pb/sr	0.5 sr	5
pd $\to$ ^{3}He π^0	1.492 GeV/c	30 nb/sr	0.25 sr	52000

Beam-time estimates:
For the test measurement using pd $\rightarrow$ ^{3}He π^0 1 week of beam time is necessary. Each run for the goal reactions would need 4 weeks of beam time. This would enable to collect 420 events for 2.336 GeV/c beam momentum and 140 events for 2.350 GeV/c beam momentum. In total the requested beam time will be 9 weeks.

3.3 Beam-time summary

The estimated beam time is summarized in the following table:

experiment	total beam time
pp $\rightarrow$ pp η at threshold (commissioning)	1 week
pp $\rightarrow$ pp(η, ω) from threshold to 2.62 GeV	3 weeks
pd $\rightarrow$ pd(η, ω) and pd $\rightarrow$ pnp(η, ω)	3 weeks
charge symmetry breaking	9 weeks

4 Future experiments

The program given above is only the start of a series of experiments which can be done with the proposed detector. In addition to the attractive physics it will be used to study the whole detection system and understand the detector response and acceptance. This is important to investigate more complex and rare reaction channels subsequently. Some of these experiments have been discussed already in the previous version of our proposal [2].

- The next step in single meson production will be the measurement of NN $\rightarrow$ NN η'. This meson has three major decay branches in multi-photon final states: $\pi^0\pi^0\eta$ (21%), $\omega\gamma$ (3%) and $\gamma\gamma$ (2.1%).
  The total cross section has been measured up to Q= 24 MeV through the missing mass method and its energy variation is dominated by phase space folded with s-wave pp-FSI, though with a strength which is more than an order of magnitude larger than for the η [26, 27]. The prediction of the η'/η ratio from pion exchange is wrong by a factor of two.
  Data on the γp $\rightarrow$ η' p photoproduction suggest that p-waves enter far more quickly than for the η and, if vector meson exchange dominates in the pp-reaction, this is likely to be of significance there.

- The ω-production in pA-collisions can be considered as a natural way [28, 29] to study the ω-properties at normal nuclear density under rather well controlled conditions. The in-medium ω- spectral function can be measured directly by the decay into dileptons or $\omega\gamma$. The advantage of the latter mode is due to the isolation of the ω-signal, while the dileptonic mode always has to fight with background from ρ^0 decays.

- $2\pi^0$ production will already be present as background in many of the single-meson production experiments. While a first analysis will be made from these data, based on the results, it has to be considered performing a dedicated experiment for multi-π^0 production. One will get information about baryon resonances and/or reaction dynamics such as the excitation of the ABC effect. For example, the $N^*(1440)$, the Roper resonance, may decay via pion emission to the $\Delta(1232)$, which emits one more pion when dropping down to the nucleon ground state. Even cleaner, but rarer, signatures of such cascade decays will come when one or both of these pions is replaced by a photon. Thus it will be important to analyze the $\pi^0\pi^0$ and $\pi^0\gamma$ final states.

Obviously, a complete list of future experiments with the photon detector cannot be given at this place. It is only an outlook, what physics can be studied subsequently to the proposed initial experimental program.

5 Time schedule

If this proposal is accepted by the PAC, the next activities will be according to the following rough time schedule.

December 2000	Start preparation of tests with two subarrays of $PbWO_4$. 2x16 crystals and 2x16 R5505 will be ordered (delivery time $\approx$ 3-4 months). Development work for support and electronics starts.
April 2001	Setup of test arrays.
Summer 2001	Parasitic tests at a few angles during ANKE beam times. The new target chamber, which will be installed in summer 2001 will help by moving the target point 5 cm further upstream.
November/ December 2001	Final decision is made about detector design (support, photosensors, high voltage, electronics, integration in ANKE). Presentation of a technical proposal. Total number of crystals and photo tubes will be ordered (delivery time for photo tubes $\approx$ 18 months).
2002 / 1. half 2003	Construction of support structures, electronics, etc. Test and setup of delivered modules.
end of 2003/ begin of 2004	Setup of the detector outside of ANKE.
Summer 2004	Installation at ANKE (including implementation of readout and trigger in ANKE DAQ, tests).
End of 2004	First beam time.

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