A COMPACT AND FAST PHOTON DETECTOR FOR COSY*

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A compact photon detector with nearly 4π-coverage in solid angle has been proposed to be implemented into the magnetic spectrometer ANKE at COSY, Jülich. Based on the physics program and experimental constraints a first concept will be presented. As part of the R&D program, the response to monoenergetic photons between 45 and 770 MeV has been measured at the tagged photon facility at MAMI, Mainz for arrays consisting of large CeF_3 and $PbWO_4$ scintillation detectors. The applicability of a fine-mesh photomultiplier (Hamamatsu R5505) has been tested in static and variable magnetic fields.

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1. Introduction

One of the internal target facilities at the cooler synchrotron COSY at the FZ Jülich, Germany, is the magnetic spectrometer ANKE (Apparatus to study Nucleonic and Kaon Ejectiles), which consists of three C-shaped dipoles. They are designed to guide the beam to the target, serve as a spectrometer magnet and inflect the beam back to the original orbit. Equipped with a complex set of tracking chambers, Cherenkov detectors and plastic scintillators, positively and negatively charged reaction products can be

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detected and identified by momentum, energy-loss and time-of-flight techniques in the forward hemisphere within a large solid angle. The production of strangeness in elementary reactions at medium energies has been the primary physics motivation, which requires the detection of meson production in nucleon–nucleon and nucleon–nucleus collisions. Many final states are dominated by the production of neutral mesons as well. The identification or discrimination of such channels is only possible via a missing mass analysis, if the kinematical parameters are over-determined. Therefore, the direct identification of multiple neutral meson production via the direct detection of all decay photons in a nearly 4π photon detector would provide an important complement to ANKE or could be even used as a stand-alone device for neutral meson spectroscopy at COSY, Jülich. Inspired by the development and performance of high density inorganic scintillators and fast photosensors to be operated in a strong and variable magnetic strayfield, first design studies for a fast and compact photon detector have been started and proposals on the additional physics program have been evaluated. This paper presents

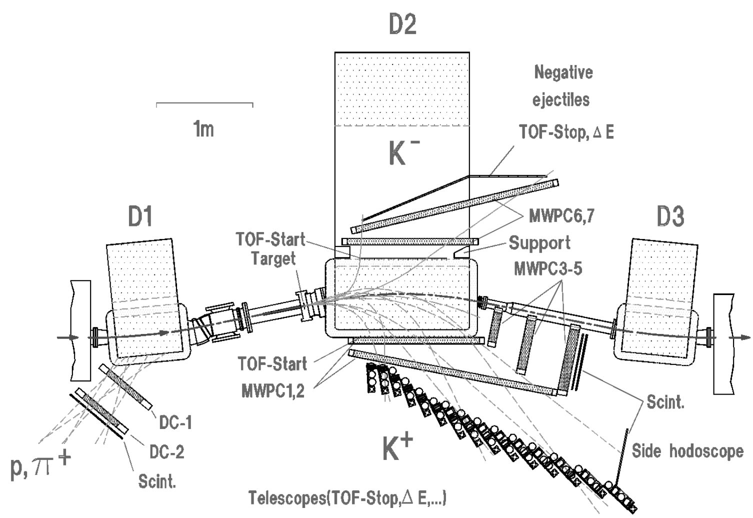

Fig. 1. The schematic lay-out of the ANKE magnetic spectrometer at COSY.

in the following the specific experimental constraints for such a dedicated detector device to be implemented into ANKE, the envisaged detector concept and reports on first performance tests of dense scintillation detectors, such as CeF_3 and $PbWO_4$, and the operation of fine-mesh photomultipliers.

2. The photon detector

2.1. Technical constraints

The detection of multiple photon events requires a nearly complete coverage of the solid angle around the target. The fixed and compact geometry of the dipole magnets, the vacuum system and the installation of various target devices limit the available space to a spherical volume of 75 cm in diameter. Therefore, a very compact design and a very dense detector material appear mandatory. The spectrometer dipoles are ramped synchronously with the COSY magnets up to a maximum magnetic field strength of 1.6 T which leads to strayfields, pointing in various directions, of up to 0.2 T in the target region.

The detector should allow to measure high energy photons up to $E_\gamma =$ 2 GeV with sufficient energy and position resolution, therefore, a crystal depth of at least twelve radiation lengths X_0 and a high granularity are needed. The efficient photon detection and invariant mass resolution of multi photon events requires a large solid angle of $\geq 3\pi$. Background suppression via narrow coincidence requirements can only be achieved exploiting the fast scintillator response and consequently the read-out of the scintillation light with photomultiplier tubes. An on-line charged particle discrimination should be possible and be implemented into the trigger, to select neutral events. Finally, an upgrade to a stand alone 4π-detector has to be foreseen.

2.2. Design concept

The generally limited space as well as fixed beamline components allow the installation of a spherical detector ball of 75 cm diameter, covering an azimuthal angle range between $25^\circ \leq \Theta \leq 160^\circ$. For the segmentation, based on MC-simulations, which take into account the geometrical development of the electromagnetic showers, the expected photon and particle multiplicity and the considered single detector count-rates, two alternative concepts have been evaluated considering $PbWO_4$ as the most appropriate scintillator material due to the small values of radiation length X_0 and Molière-radius R_M, respectively (see Table I). The first concept is based on a rotational symmetric arrangement of tapered crystals with thirteen different shapes of

TABLE I

The relevant scintillator parameters of $PbWO_4$ and CeF_3.

	X_0 [cm]	R_M [cm]	τ [ns]
$PbWO_4$	0.89	2.20	< 20
CeF_3	1.68	2.63	< 30

trapezoidal cross sections. The total of 1060 modules is arranged in 20 rings and each of them covers the full polar angle at a fixed azimuthal angle. As an alternative, several polyhedral arrangements have been discussed leading in some cases to more than 1200 pentagonal and hexagonal elements with more than 50 different shapes. Based on GEANT4 simulations, photon detection with sufficient resolution up to 2 GeV energy requires at least 12 radiation lengths of detector material. CeF_3 and $PbWO_4$ have been considered as the most attractive scintillation materials (see Table I). To exploit fully the fast response of the scintillator, the read-out with photomultipliers becomes mandatory. However, due to the strong magnetic strayfield only fine-mesh photomultiplier tubes can be considered, which are commercially available only in a very limited selection of geometrical dimensions. An additional magnetic shielding with soft iron has been foreseen and will be optimized by a modification of the crystal shape. A machined cylindrical endpart of the crystal or an additional light-guide will allow that the shielding cylinder covers in addition a significant volume in front of the photocathode. Online charged particle identification will be achieved by a polyhydral array of plastic scintillators (thickness $d = 5\,\mathrm{mm}$), in a design similar to the VETO detector system of the TAPS spectrometer [4], to be mounted inside the hollow detector sphere. The processing and digitization of all detector signals as well as the generation of a first and second level trigger will be similar to the new TAPS electronics which is under development.

3. Research and development

3.1. Selection of the detector material

The proposed photon detector requires the use of a fast and dense inorganic scintillator material. In order to compare large size crystals a comparative study of two detector matrices of large $PbWO_4$ and CeF_3 crystals have been tested with monoenergetic photons between 45 and 770 MeV energy at the tagging facility of MAMI at the university of Mainz.

3.1.1. Test of a 5 × 5 matrix of $PbWO_4$

Nb/La-doped crystals of slightly tapered shape, manufactured and preselected by Bogoroditsk Techno-Chemical Plant (Russia) and RI&NC (Minsk, Belarus) have been assembled into a 5×5 matrix. The optically polished crystals of 150 mm length ($\sim$17 radiation length X_0) have a quadratic front face ($20.5 \times 20.5\,\mathrm{mm}^2$) and a tapering angle of $0.4°$. They are individually wrapped in PTFE-foil, coupled with optical grease to fast photomultiplier tubes (Hamamatsu R4125, $\varnothing = 19\,\mathrm{mm}$ — covering 35% of the crystal endface) and stacked into a light-tight box, which was temperature stabilized at $t = 6°\mathrm{C}$. The detector block can be moved by remote control to illuminate directly each crystal with the collimated photon beam ($< 6\,\mathrm{mm}$) for calibration purposes. A plastic scintillator in front of the crystal matrix serves as a charged particle veto. The detector signals are transfered via long coaxial cables ($\sim 50\,$m RG58) to the data acquisition system to deduce energy and time information by means of commercial electronics. The preliminary analysis of the energy response shows an excellent energy resolution, in particular at the lowest photon energies investigated with PWO so far. An energy resolution of $\sigma/E = 7.4\%$ can be achieved at an incident energy of $E_\gamma = 45.4\,$MeV. In addition, one has to take into consideration that the resolution is not corrected for the intrinsic beam width amounting to $\Delta E = 2.4\,$MeV, defined by the tagging coincidence, and the reduced coverage of the scintillator endface by the phototube compared to previous experiments [3]. Figure 2 illustrates the achieved lineshape. The overall

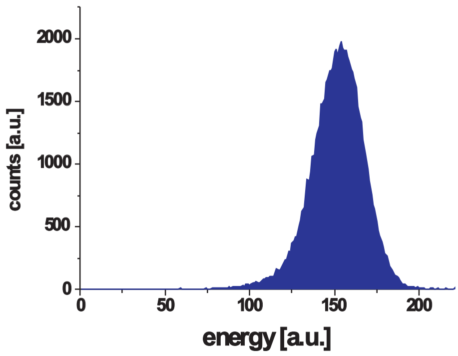

Fig. 2. The energy response of a 5×5 matrix of PWO crystals measured for photons of 45.4 MeV energy.

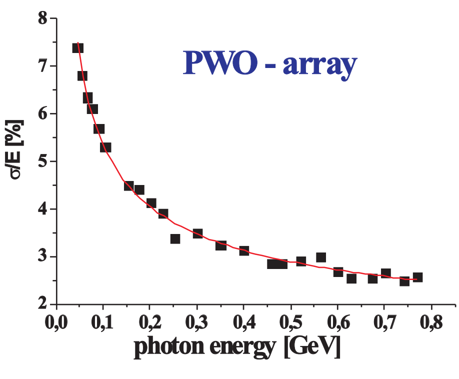

Fig. 3. The energy response of a 5×5 matrix of PWO crystals as a function of the incident photon energy.

energy dependence of the resolution can be parametrized by

$$\frac{\sigma}{E} = \frac{1.41\%}{\sqrt{E\,[\mathrm{GeV}]}} + 0.90\%$$

and is shown in Fig. 3.

3.1.2. Test of a 3×3 matrix of CeF_3

A cerium fluoride matrix composed of nine longitudinally segmented towers (up to 4 individual elements), approximately $25\,X_0$ long, has been provided by the Crystal Clear Collaboration and ETH, Swiss Federal Institute of Technology, Zürich, Switzerland [5]. The towers were $3 \times 3\,\mathrm{cm}^2$ in cross section, except for the 4 corners being $2 \times 2\,\mathrm{cm}^2$. The crystals, individually wrapped in PTFE- and aluminum-foil, were read-out with photomultiplier tubes (Hamamatsu R4125 (19 mm ∅), R1668 (28 mm ∅)) and mechanically stabilized by thin PVC shrinking tubes. The uniformity of the light collection was optimized by stripes of black paper. The photon response has been tested at the tagged photon facility at MAMI in a similar way as described above for the PWO-matrix. The analysis of the energy response deliver a good energy resolution, which can be represented by

$$\frac{\sigma}{E} = \frac{2.17\%}{\sqrt{E\,[\mathrm{GeV}]}} + 2.70\%$$

over the investigated energy range up to 770 MeV. The lineshapes at four selected energies are presented in Fig. 4 for illustration. Fig. 5 shows the energy dependence of the deduced resolution values. The high energy tails, in particular at the higher photon energies, which become visible in Fig. 4 can

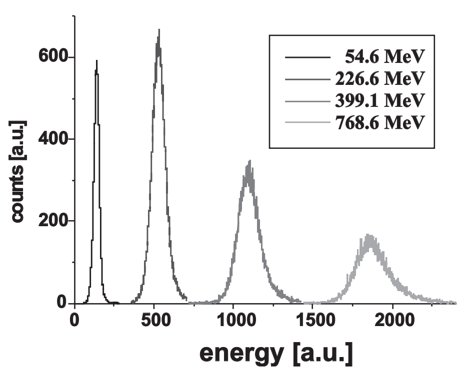

Fig. 4. The energy response of a 3×3 matrix of CeF_3 crystals to four different incident photon energies.

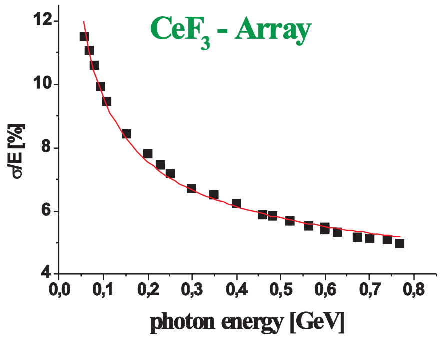

Fig. 5. The energy response of a 3×3 matrix of CeF_3 crystals as a function of the incident photon energy.

be addressed to a not fully uniform light collection. The achieved resolution in the investigated energy regime was influenced by the not hermetic coverage of the electromagnetic shower due to the not perfect crystal geometry, the mechanical arrangement and the inhomogeneity of the crystal samples. However, the obtained results deliver for the first time an extension of the measured energy response for electromagnetic probes from the multi GeV range [5] down to a few MeV photon energy. By directing the collimated photon in between two matrix elements, the intrinsic time resolution can be deduced from the measurement of the relative time difference. Assuming identical response an individual time resolution of $\sigma = 170$ ps can be deduced.

3.2. Test of a fine-mesh photomultiplier

The applicability of a fine-mesh photomultiplier tube R5505 (Hamamatsu, 25 mm ∅, 15 stages, gain $= 5 \times 10^5$ at 0 Tesla) has been investigated. The gain stability of the fine-mesh photomultiplier R5505 has been tested in static and ramped magnetic fields up to 0.15 T. The photomultiplier, mounted in a light tight aluminum housing, was illuminated by a fast blue emitting LED pulser of constant amplitude and count rate ($\sim$ few kHz) and the amplitude of the anode signal was recorded. The photomultiplier was placed into the gap of a C-shaped magnet. The mechanical set-up allowed to change the orientation of the tube with respect to the direction of the magnetic field lines and to rotate the photomultiplier along its symmetry axis. The unshielded tube in a static magnetic field up to 0.11 T shows now reduction of the gain for an orientation parallel to the field lines. In the case of a perpendicular external field, the anode signal remains unaffected only up to a field strength of $\sim$150 Gauss. An additional variation of up to 20%

is superposed by rotating the tube along its symmetry axis. Independent on the field orientation, the sensitivity to a magnetic field up to 0.11 T can be avoided by an external shielding cylinder of soft iron of at least 2 mm wall thickness as illustrated in Fig. 6. A similar set-up equipped with a soft iron cylinder of 3 mm thickness, which completely covered the phototube including the voltage divider and reached beyond the photocathode by 15 mm, was operated in a beam test in the ANKE environment at COSY. Except during the short periods of the ramping of the magnets up to 1.6 T, the anode amplitude remained fully constant during the operation lasting several hours.

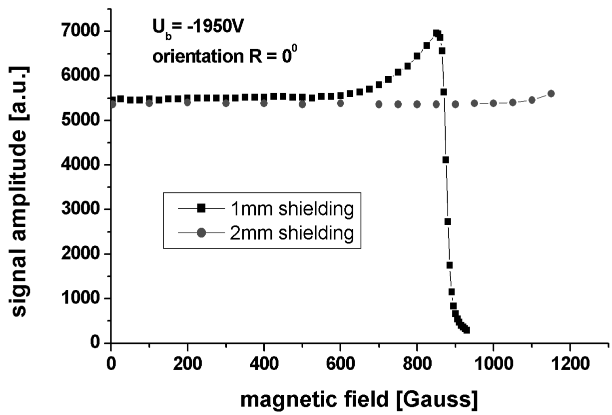

Fig. 6. Signal amplitude of the fine-mesh photomultiplier R5505 as a function of the field strength of a perpendicular external magnetic field. The tube is shielded by a soft iron cylinder of 1 mm, respectively, 2 mm wall thickness.

4. Conclusions and outlook

The proposed spherical photon detector to be implemented into the magnetic spectrometer ANKE at COSY can become the first PWO application in medium energy physics. Based on the previous experiences and the test results presented in this paper $PbWO_4$ appears to be the ideal detector material due to its compactness and fast response accompanied by sufficient resolutions in energy and time. The applicability of fine-mesh phototubes as photosensors has been proven. Tests at COSY with large diameter crystals ($32 \times 32\,\mathrm{mm}^2$ cross section) read out with R5505 photomultipliers are in preparation.

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