

A Plastic-BaF₂ Phoswich Telescope for Charged/Neutral Particle and Photon Detection¹

R. Novotny, W. Döring, V. Hejny, M. Kotulla, B. Krusche, V. Metag, M. Nold, H. Ströher, and M. Wolf
 II. Physics Institute, University Giessen, Germany and for the TAPS² collaboration

Abstract

BaF₂ has become a very versatile scintillator for particle and photon detection commonly applied in medium and high energy physics experiments. The intrinsic properties allow particle identification via time-of-flight, ΔE -E and pulse-shape techniques. A new NE102A-BaF₂ phoswich detector using the standard TAPS crystals has been tested at relativistic energies. The drastically improved particle identification and first results obtained with a large annular forward wall consisting of 120 phoswich modules with 15mm NE102A attached to the BaF₂-crystal will be discussed in detail.

I. INTRODUCTION

During the past years BaF₂ has become one of the most commonly used inorganic scintillators for the detection of neutral or charged particles as well as photons in medium and high energy physics experiments. The extreme fast response [1,2,3], strong luminescence and the different intrinsic sensitivity of the two major scintillation components to the nature of the impinging probe [4,5] combined with high density and short radiation length fulfill the main requirements for a versatile detector material. The production of large, homogeneous and high quality crystals has encouraged the construction of complex spectrometers such as the calorimeter TAPS [6]. The Two/Three Arm Photon Spectrometer has been designed to investigate primarily neutral mesons via an invariant mass analysis of the two high energy decay photons in relativistic and ultra-relativistic heavy ion collisions or photonuclear reactions, respectively [7,8]. The point of impact and the total energy of the electromagnetic shower contained in several calorimeter modules have to be determined precisely. In case of heavy ion reactions, the much higher multiplicity of hadronic reaction products requires the efficient discrimination against charged/neutral particles. In contrast, the exclusive study of photonuclear processes aims for the simultaneous spectroscopy of the coincident hadrons.

The short decay time and the high light output of BaF₂ allow time resolutions better than $\sigma=85$ ps even for large crystals such as the TAPS modules [9]. Therefore, particle identification and even energy determination can be performed based on the time-of-flight technique (TOF) at a typical distance of 1-2m from the vertex using a start-counter system as time reference. In particular, low and medium energy neutrons, which react via (n, γ)-processes with BaF₂ and induce

a signal-shape identical to that of photons, can only be identified via TOF.

Restricted to the typical geometrical arrangement of TAPS in blocks consisting of 64 individual modules, a plastic scintillator array of identical granularity and shape can be mounted in front. The individually read-out components (0.5cm NE102A) serve as an on-line charged particle veto-detector (CPV) and measure the specific energy loss required for particle identification by means of ΔE -E-correlations.

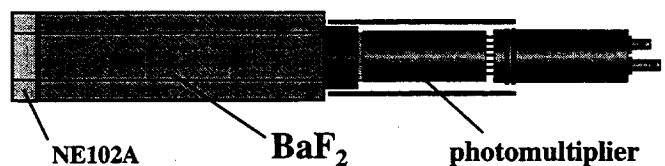


Fig. 1: Schematic view of a fully assembled TAPS plastic/BaF₂-detector. The attached plastic scintillator of the phoswich modification is indicated.

The shape of the BaF₂-signal is extremely sensitive to the nature of the penetrating probe. The contribution of the fast scintillation components (wavelength $\lambda=195,210$ nm, decay time $\tau=0.6$ ns) to the total light-output diminishes with the increase of the energy density deposited by the ionizing particle. This property has been widely exploited by TAPS and represents the most reliable technique to extract a clean photon signal in extension to the already discussed TOF and CPV information.

II. THE PULSE SHAPE OF BaF₂

A. The Detector

The geometry of an individually assembled TAPS-detector is shown in Fig. 1. The 25cm long hexagonally shaped BaF₂-crystal is optically coupled to a photomultiplier (Hamamatsu R2059-01). The processing of the BaF₂-signal foresees the determination of the time-of-impact and the integration of the total scintillation light (integration gate width $W_{int}=2\mu$ s) as well as of the fast component ($W_{int}=20$ -50ns) separately. These observables allow to extract the time-of-flight, the deposited total energy of photons or particles and a crude analysis of the individual pulse shape.

¹ supported by BMFT, DFG and GSI

² TAPS-collaboration: Bratislava, GANIL, Giessen, GSI, KVI, Rez, Valencia

B. The Pulse-Shape Sensitivity

Fig. 2(left) illustrates schematically the typical response of BaF_2 to photons and highly ionizing particles. The pronounced prompt contribution to the signal due to the fast components ($<10\%$) as observed for detected γ -rays appears to be substantially reduced for impinging charged hadrons. However, the ratio of both contributions remains constant over the full dynamic range up to relativistic and even ultra-relativistic energies [10] for a given species of detected probes. This behavior can be related qualitatively to the difference in the luminescence mechanisms involved [11]. A quantitative theoretical understanding of the observed line shape remains still missing.

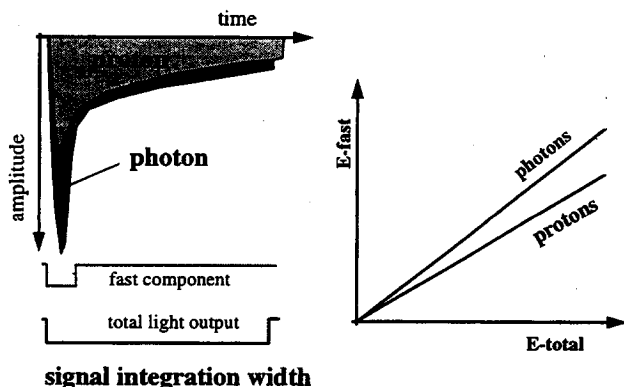


Fig. 2: Left: The typical signal shape of BaF_2 for photons and charged particles observed at the anode output of the phototube base. The integration gates for signal-processing are indicated schematically. Right: Particle identification based on the expected correlation of the measured yield of fast and total light-output.

Fig. 2(right) explains the crude pulse-shape measurement as performed in the TAPS analysis which is based on the parallel signal processing applying two different integration gates. The identification is finally deduced from the correlation of both quantities, the amount of the fast and total light-output, respectively. Fig. 3 shows as an example two scatter plots generated from data taken in photonuclear reactions. A dynamic range up to approx. 300 MeV photon equivalent energy is covered. The correlation patterns have been accumulated for neutral and charged events, respectively, separated by the information from the CPV. As marked, the distinct lines correspond to leptons, pions and protons as well as photons. The lower branch in the plot for neutral events can be addressed to secondary protons recoiled by high energy neutrons which interact in BaF_2 via (n,p) -reactions.

Therefore, the pulse-shape analysis (PSA) allows in combination with TOF and CPV an efficient spectroscopy of neutrons. Relative measurements of the response function of the TAPS detectors to neutrons up to a few GeV energy have been calibrated with a NE213 liquid scintillator. Depending on

the discriminator threshold the efficiency approaches a nearly constant value of $\epsilon=17\%$ above 750 MeV kinetic energy [12].

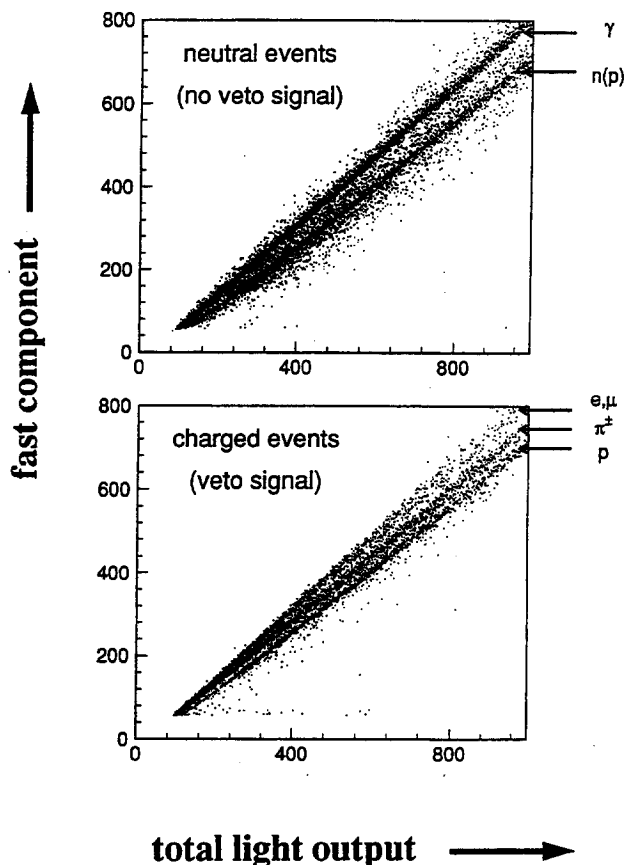


Fig. 3: Scatter plot of the fast light component versus the total light-output of a TAPS BaF_2 -detector. The correlation pattern is shown for neutral (top) and charged events (bottom) selected by the CPV system.

III. THE PLASTIC- BaF_2 PHOSWICH DETECTOR

A. The Concept

The proposed second generation of exclusive TAPS experiments, in particular, the investigation of meson-photoproduction on heavier targets requires additionally the simultaneous spectroscopy of neutrons, hydrogen- and helium-isotopes. In that particular application the kinetic energies of the light particles to be detected extend up to 200-250 MeV. The PSA allows an efficient discrimination of hadrons but the resolution is not fully sufficient for isotope identification. Initiated by similar considerations in a much lower beam energy regime [13,14,15], the applicability of a plastic- BaF_2 phoswich detector based on the existing large TAPS-crystals has been investigated. Fig. 4 illustrates schematically the changes to be expected in the integral line-shape as well as in the pulse-shape analysis. The strong light-

output proportional to the energy loss of charged particles penetrating the typically 10 mm thick layer of a fast organic scintillator (see Fig. 1) will be directly added to the fast BaF₂ scintillation component as a consequence of the phoswich technique where a common photomultiplier is used for the read-out of the scintillator sandwich.

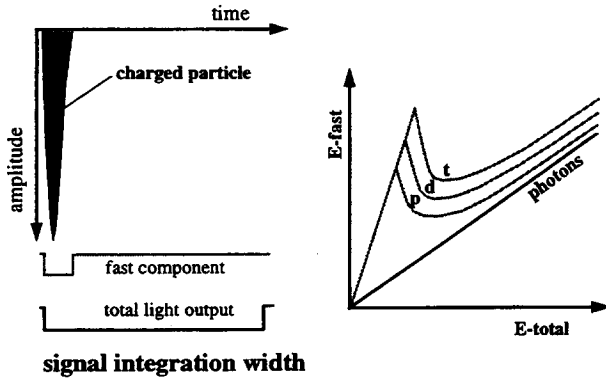


Fig. 4: Change in response shown schematically for a plastic-BaF₂ phoswich detector: Contribution of the plastic scintillator to the total light output (left) and pulse-shape response for hydrogen isotopes detected in the phoswich device (right).

Therefore, charged particles create a correlation pattern shifted well above the photon branch in the PSA spectrum. Distinguished structures appear for particles which are either stopped within the plastic section or do penetrate into the BaF₂-crystal. The sensitivity depends on the absolute energy loss of the particles, the overall kinetic energy regime in comparison to the neutral probes and the ratio of the additional light output relative to the intrinsic BaF₂-response. The latter condition will determine, if the charged particle pattern merges into the photon branch or even might cross it at the highest energies.

B. The TAPS Phoswich Detector

Hexagonally shaped plastic scintillator plates of 5 to 15mm thickness (NE102A) have been mounted in front of the standard BaF₂ crystal. UV-transparent silicon grease or a thin air gap have been used for optical coupling. All other surfaces are covered with PTFE film and an aluminum foil as reflector material. The whole phoswich detector is contained in a light-tight shrinking tube which in addition gives sufficient mechanical stability.

C. The Experimental Set-up

For the first time a test-experiment detecting neutral and charged reaction products emitted from the collision of Ca on Ca at 2GeV/u projectile energy has been performed. An array of 3 different phoswich prototypes and 1 standard TAPS-detector for comparison have been placed at an angle of 70° with respect to the beam axis located at a distance of 2m from

the target. An additional 5mm thick NE102A (size: 15x15cm²) plastic scintillator (PS) mounted in front of the whole array provided the independent charged/neutral particle selection. The time and energy response of all components have been recorded as list most data for the off-line analysis.

IV. EXPERIMENTAL RESULTS

A. Particle Identification via PSA

Due to the relativistic energy of the Ca projectile the kinetic energies of the reaction products used for the detector test subtend the full range up to a few GeV. In particular, the charged mesons can even become minimum ionizing. The spectrum of high energy γ -rays, mostly originating from neutral meson decays, shows an exponential shape but provides sufficient statistics up to several hundreds of MeV. The full length of the BaF₂-crystals allows to stop protons completely up to an energy of approx. 380MeV. Minimum ionizing particles deposit a photon equivalent energy of 167MeV when they transverse the full length of the crystal [4]. However, at these kinetic energies secondary reactions within the crystal have to be taken into account and spoil the correlation to the incident energy.

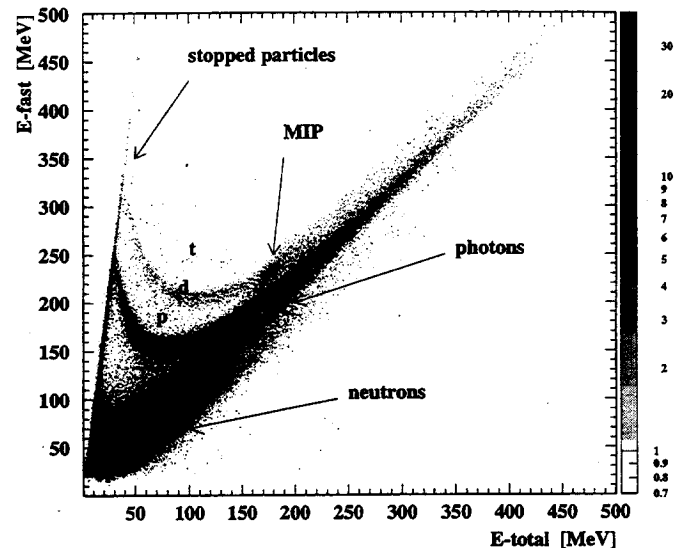


Fig. 5: Pulse shape correlation of a 15mm plastic-BaF₂ phoswich detector identifying reaction products from the collision 2GeV/u Ca+Ca.

The sensitivity of the particle identification has been studied by varying the thickness of the ΔE section of the phoswich between 5 and 15mm. The Figs. 5-7 give an impression of the achievable pulse-shape correlations which appear to be optimum with respect to selectivity for a plastic thickness of 15mm. The indicated calibration has been deduced from the known energy loss of cosmic muons and is given as photon equivalent energy. Structures in Fig. 5 above the clearly distinct branch due to photons can be related to charged particles either stopped within the ΔE -section (the fast

component E_{fast} becomes identical to the total scintillation light (E_{total}) or fully or partially stopped within the BaF_2 -crystal. Different particles and isotopes can be separated due to the mass (M) and nuclear charge (Z) dependence of the specific energy loss ($\sim M \cdot Z^2$). One can observe a clear gap between these events and the photon branch up to an energy of approx. 250 MeV. The background events in between the kinematical curves are caused due to an incomplete energy measurement due to secondary reactions. As an artifact, an enhanced area can be observed near $E_{\text{total}} \sim 170$ MeV. Minimum ionizing particles, which transverse the whole crystal, can even pass the quartz entrance window of the phototube and generate Cherenkov photons. Total reflection within the quartz plate enhances in addition the quantum efficiency for the detection of the Cherenkov light. It leads to a substantial increase (5 - 10%) of the integral fast light-output [16]. Below the photon branch neutrons identified via (n,p)-reactions can be observed.

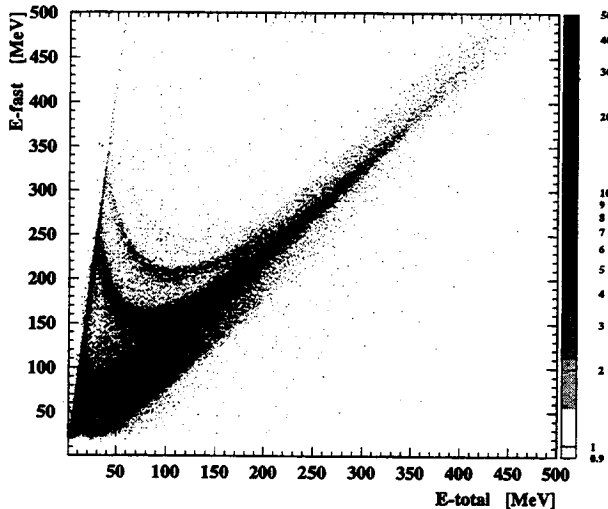


Fig. 6: Pulse-shape correlation of a 15mm plastic- BaF_2 phoswich detector identifying selected charged reaction products from the collision 2GeV/u Ca+Ca.

Fig. 6 and 7 show the same correlations individually accumulated for charged or neutral events selected by the additional PS monitor. The observed structures in Fig. 6, which show the signatures of photons and neutrons, represent pile-up events or particles entering through the side faces from one of the neighboring modules since the PS monitor has been applied to the whole array. In Fig. 7, the events triggered by high energy neutrons are well separated from the photon branch. The particle identification can be visualized more quantitatively by a cut through the two dimensional matrix along a diagonal, which encloses an angle of 64° with the horizontal axis E_{total} (see Fig. 8). Electrons, pions, hydrogen- and helium-isotopes can be well identified.

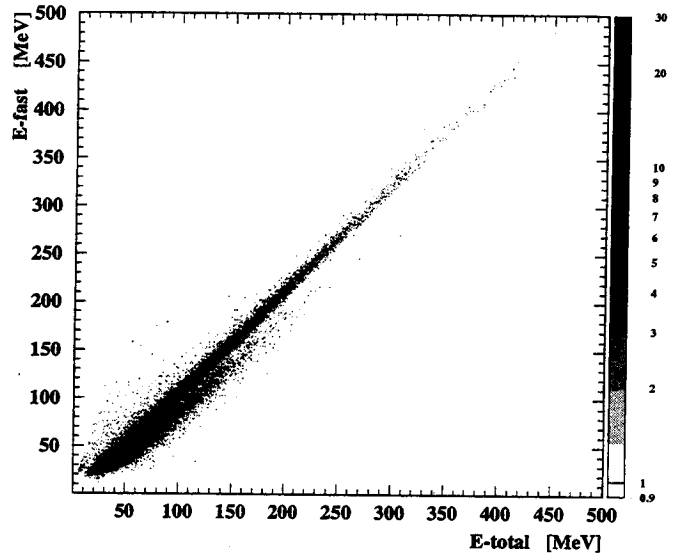


Fig. 7: Pulse shape correlation of a 15mm plastic- BaF_2 phoswich detector identifying selected neutral reaction products from the collision 2GeV/u Ca+Ca.

The discrimination of charged particles and photons exclusively via PSA is limited by the minimum energy loss and the resulting scintillation light-output of the penetrating particles which however can be optimized by the appropriate thickness of the ΔE -section. Due to the extremely wide dynamic range of the impinging probes in the performed test the chosen thickness of 15 mm of NE102A restricts already the range of applicability to energies of protons below $E_{\text{total}} < 250$ MeV. Detailed comparisons to pure BaF_2 -detectors indicate in addition a reduction of the overall pulse-shape resolution in the phoswich mode. This can be explained by absorption losses of backward scattered scintillation light because the plastic scintillator becomes opaque for the UV-light of the BaF_2 luminescence, in particular reducing the yield of the fast component. Part of the light losses can be avoided by using an air gap instead of an optimum optical coupling with silicon grease. Therefore, the shown results have been obtained with a phoswich module requiring air coupling of the scintillator sandwich.

B. Particle Identification via TOF

The fast response of both phoswich components allows to exploit time-of-flight technique in addition. This is mandatory to achieve the identification of low energy neutrons which induce due to the (n, γ)-interactions a signal shape in BaF_2 identical to that of an incident photon. The phoswich device relies on the fast response of the plastic scintillator in case of charged particles and on the pure BaF_2 for neutral probes, respectively. The Figs. 9 and 10 show typical kinematical correlations of TOF versus the total light-output E_{total} for the same subset of data as analyzed before. Fig. 10 shows selected neutral events such as photons and neutrons. Due to the

different secondary processes of neutrons in the crystal the observed energy deposition does not show a distinct correlation to the primary energy. In both spectra particles which have been completely stopped within the ΔE section have been excluded off-line. In the latter case similar correlations of TOF versus E_{fast} can be used instead.

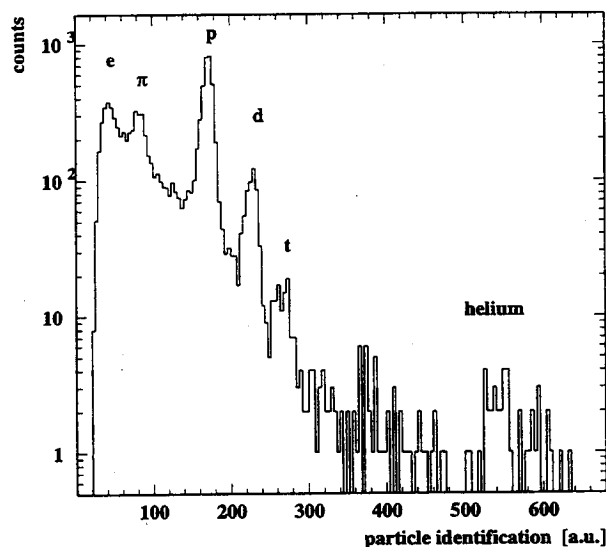


Fig. 8: Particle identification exploiting PSA: cut through the 2-dimensional correlation matrix along a diagonal in Fig. 5 as explained in the text. The identified charged particles are marked in the spectrum.

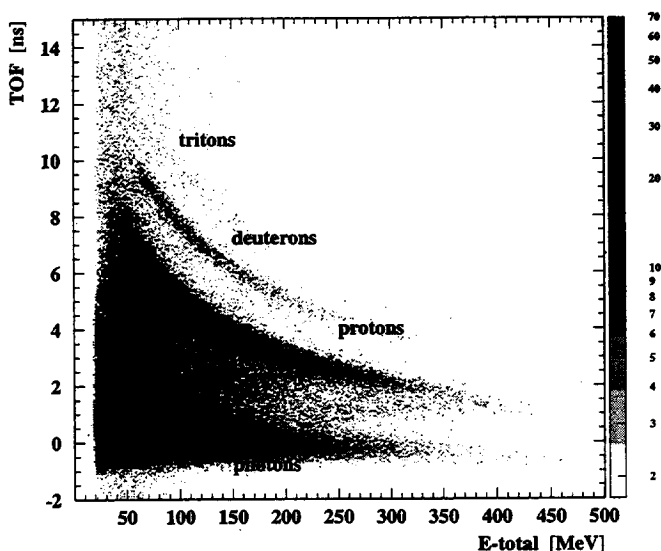


Fig. 9: Correlation of TOF versus the total light-output E_{total} measured with the phoswich detector identifying reaction products from the collision 2GeV/u Ca+Ca.

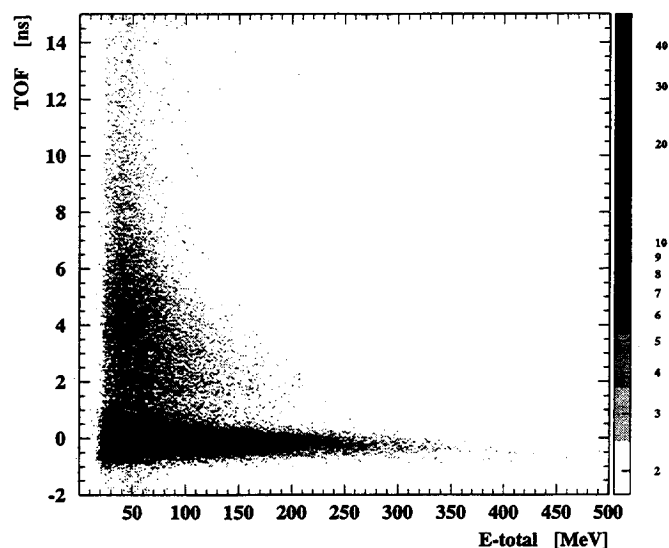


Fig. 10: Correlation of TOF versus the total light-output E_{total} measured with the phoswich detector selected for neutral reaction products from the collision 2GeV/u Ca+Ca.

V. THE TAPS PHOSWICH FORWARD WALL

The investigations of the phoswich performance has been initiated by the need for a simultaneous measurement of light particles in photonuclear meson production. In order to discriminate coherent and incoherent processes on heavier targets like deuteron or helium all final reaction products beside the mesons have to be detected in coincidence preferentially at forward angles. The experimental program with tagged photons up to 800MeV incident energy limits the kinetic energies of the hadrons below 300MeV. Therefore, the already presented phoswich geometry meets ideally the experimental needs as shown in the previous chapter.

In total, 120 TAPS BaF_2 -detectors have been equipped with an additional plate of 15mm NE102A coupled via an air gap ($<0.1\text{mm}$) to the BaF_2 -crystal. All detectors have been arranged in a large annular hexagonal cluster symmetric around the beam axis at forward angles. The positions of the inner 7 detectors have been left open to provide room for the vacuum beam pipe. Fig. 11 shows schematically the full TAPS set-up operating at the tagging facility of MAMI at Mainz (Germany). Included are the 6 TAPS blocks mounted closely in a horizontal plane around the target.

The first experiments have been performed already. Fig. 12 shows as a result the achieved clean separation between neutrons, photons, electrons and protons, respectively. The upward shift of charged particle events, in particular in case of electrons, above the photon branch is clearly visible. It corresponds at least to the amount the light-output corresponding to a minimum ionizing particle. The data has been taken for the reaction $p(\gamma, X)N$ [with $X=\pi^0, \pi^+, \eta, \dots$ and $N=p, n, \dots$] in the photon-beam energy range between 300 and

800MeV. The selected detector was positioned at a distance of 1m from the target at an angle of 19.8° with respect to the beam axis.

The energy calibration of the BaF₂ detector is obtained from the known energy loss of cosmic muons. The calibration as well as the estimation of the detection efficiency of the identified protons, for example, can be directly reconstructed from kinematically fully determined events such as from the reaction $p(\gamma, \pi^0)p$ when the two decay photons of the meson have been observed in the TAPS blocks. The maximum energy of a proton which is completely stopped within the plastic section can be directly read-out from the pulse-shape correlation (see Fig. 12) as an additional reference point. The energy of identified neutrons has to be deduced from the simultaneous TOF measurement. The detection efficiency will be deduced in particular by analyzing distinct reaction channels such as $p(\gamma, \pi^0 \pi^+)n$ or $p(\gamma, \pi^+)n$, respectively.

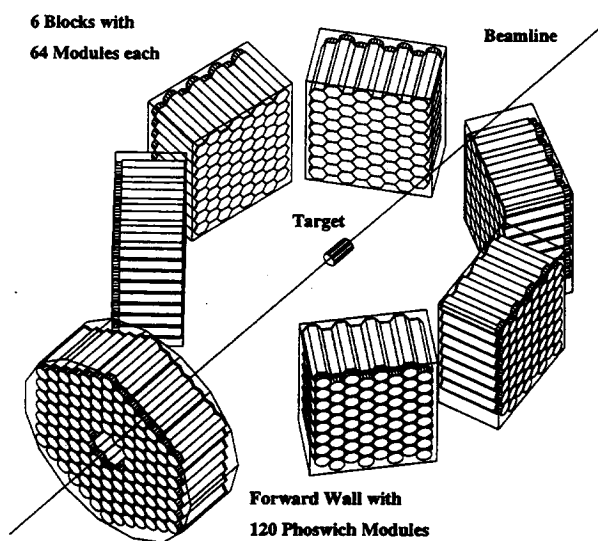


Fig. 11: The TAPS set-up at the tagged photon facility of MAMI. Beside the 6 TAPS blocks the new forward wall composed of 120 phoswich detectors is shown schematically in the arrangement around the target.

VI. SUMMARY

The presented plastic-BaF₂ phoswich detector, which has been successfully tested and applied over a very wide dynamic range in energies and particle species has proven to be an ideal particle telescope applicable for many complex experiments in medium and even high energy physics. The phoswich combination can be even adapted to the extreme regime of relativistic heavy ion collisions when many particles already become minimum ionizing. The first large scale application as an annular forward wall shows that the sensitivity of a pure BaF₂-crystal can be substantially extended. In comparison to commonly used phoswich detectors composed of two organic plastic materials of different decay times [17], the use of BaF₂

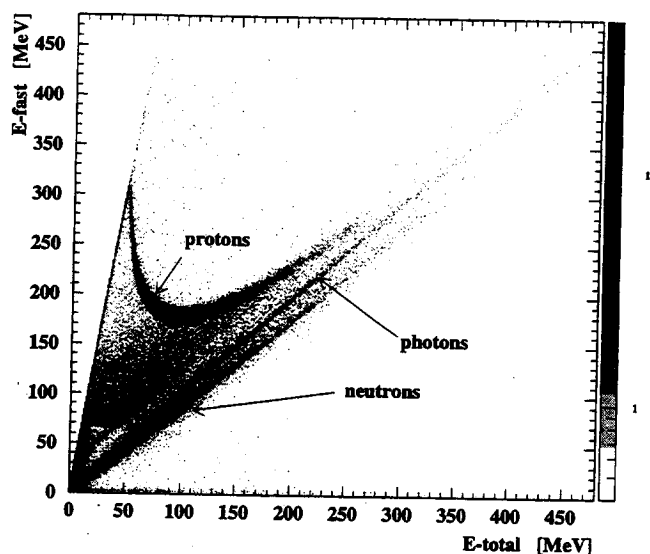


Fig. 12: Pulse-shape correlation of a TAPS forward wall phoswich module. The identified particles are produced in the reaction of 300-800MeV photons on a hydrogen target

provides in addition the full operation as a fast electromagnetic calorimeter and a highly efficient device for neutron detection.

As common for all phoswich concepts, such a device can be built very compact and the modularity avoids most of the restrictions in the geometrical arrangement. In particular for TAPS applications, the phoswich design can optionally replace the CPV-systems, which is geometrically fixed to the rectangular block arrangement of 64 modules each. The read-out of both phoswich components with the common phototube reduces the number of detector channels as well as avoids additional absorber material in front as needed for the individual perspex light guides. In general, the detection threshold of the phoswich version is nearly negligible. Due to the fast response time-of-flight technique still provides a sufficient particle identification for probes stopped within the ΔE -section.

VII. REFERENCES

- [1] N.N.Ershov et al., Opt.Spectroscop. USSR 53 (1982) 51
- [2] M.Laval et al., Nucl. Instr. and Meth. 206 (1983) 169
- [3] G.Gratta et al., Ann. Rev. Nucl. Part. Sci. 44 (1994) 453
- [4] R.Novotny et al., Nucl. Instr. and Meth. in Phys. Res. A262 (1987) 340
- [5] G.Lanzano et al., Nucl. Instr. and Meth. in Phys. Res. A312 (1992) 515
- [6] R.Novotny, IEEE Trans. Nucl. Sci. 38 (1991) 379
- [7] F.D.Berg et al., Z.Phys. A337 (1990) 351 and A340 (1991) 297
- [8] B.Krusche et al., Z.Phys. A351 (1995) 237
- [9] O.Schwalb et al., Nucl. Instr. and Meth. in Phys. Res. A295 (1990) 191
- [10] The ratio of the fast to total light output determined for ultra-relativistic charged particles from the reaction 450GeV/c p+Be,Au is significantly reduced compared to the pulse-shape initiated by electromagnetic probes.

- [11] P.Rodny, Mat.Res.Soc.Symp.Proc. 1994, Vol. 348, p.77
- [12] V.Wagner et al., GSI Scientific Report 1992, GSI 93-1, p.357
- [13] S.Kubota et al., Nucl. Instr. and Meth. In Phys. Res. A270 (1988) 598
- [14] G.Lanzano et al., Nucl. Instr. and Meth. in Phys. Res. A323 (1992) 694
- [15] Y.Futami et al., Nucl. Instr. and Meth. in Phys. Res.A326 (1993) 513
- [16] E.Kistenev et al., BNL, Upton NY, internal report, unpublished
- [17] D.Shapira et al., Nucl. Instr. and Meth. in Phys. Res. A301 (1991) 76