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Abstract

The detector system TAPS (**T**wo/Three **A**rm **P**hoton **S**pectrometer) has been designed and installed to study high energy photons as well neutral mesons produced in relativistic heavy ion reactions. The spectrometer will consist of up to 384 individual BaF_2-modules packed in arrays of 64 scintillators. Each spectrometer arm, which carries two detector blocks, can be moved around the target location independently. The design concept, the specifications of the individual scintillator and test results of sub-arrays performed with monochromatic photons and charged particles will be presented. First experiments at GANIL and SIS (GSI,Darmstadt) have been performed exploiting heavy ion beams up to a projectile energy of 1GeV/u.

1 Introduction

The photon spectrometer TAPS (Two Arm Photon Spectrometer) [1] has been designed to detect low and high energy single photons as well neutral mesons such as π^0 and η-mesons. These probes can be exploited to study reaction dynamics in relativistic heavy ion collisions (for example at the SIS/ESR facility at GSI, Darmstadt) or the excitation of sub-nucleonic degrees of freedom in photon induced reactions, using the new tagged photon facility at the electron accelerator MAMI B in Mainz.

Since neutral mesons decay predominantly into two photons (π^0: 99 %; η: 39 % of the total decay) the invariant mass reconstruction requires the coincident detection of both decay photons. The relevant momentum distributions of mesons produced in medium energy heavy ion reactions will lead to high energy decay-photons up to $E_\gamma \approx 1$ GeV emitted at relative opening angles between the photon pair of up to $\Theta_{12} \leq 180°$.

As a consequence, the TAPS-spectrometer concept comprises up to three movable towers which can be rotated around the target position independently (angular range with respect to the beam axis: $10° \leq \theta_{lab} \leq 165°$) at a variable distance to the target ranging between 0.5 m $\leq$ D $\leq$ 3.5 m, respectively. That allows to cover in several detector settings all required relative angles

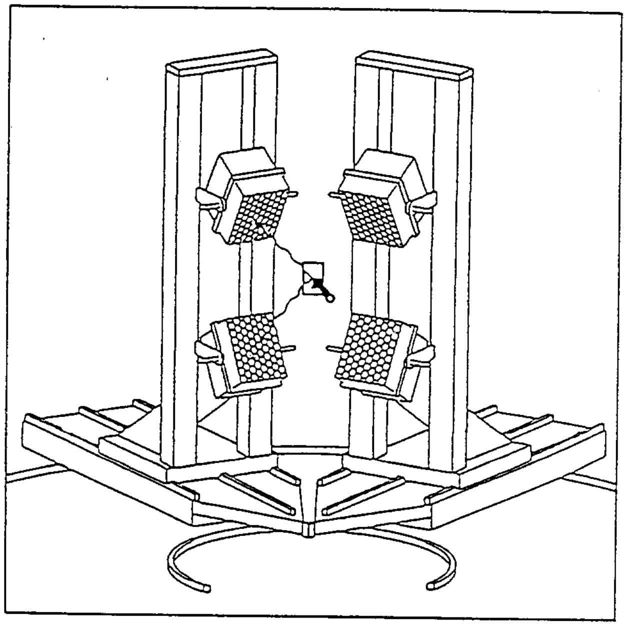

Fig. 1. Schematic view of two arms of the photon spectrometer TAPS.

between two coincident photons in order to reconstruct the full momentum distribution of the detected mesons. Each tower carries two detector arrays consisting of 64 scintillator-modules. The relative angle between these blocks and their distance to the target can be varied individually. At a distance of 1 m to the target each array (front face: x·y $\approx$ 51·42 cm^2) subtends an angle range of $\Delta\theta_x \approx 29°$, and $\Delta\theta_y \approx 24°$, respectively. The central module of each block can be positioned at relative angles between 27° and 120°. All position adjustments can be read out digitally and will be set remote controlled in a later stage. Fig.1 shows schematically the set-up of two spectrometer arms.

Clean photon identification requires an efficient discrimination against charged particles.That can be achieved via time-of-flight measurement, pulse-shape analysis of the detector response and a charged particle veto detector of the same granularity mounted in front of the BaF_2-crystals.This veto-system provides an additional on-line particle suppression.

The invariant mass of the neutral mesons is determined by

$$m_{meson}c^2 = \sqrt{2E_1E_2(1-\cos\Theta_{12})} \qquad (1)$$

E_1 and E_2 refer to the energies of the observed photon pair subtending an opening angle Θ_{12} in the Lab system. Complete conversion and reconstruction of the electromagnetic shower developed by the high energy photons determines the achievable mass resolutions.The properties of the detector material as well the shower leakage out of the detector volume limit the energy resolution. The spatial information is primarily given by the module size which has to accept high particle multiplicity in heavy ion reactions as well. The determination of the point of impact can further be improved by evaluating the center of gravity of the electromagnetic shower. Based on these requirements, BaF_2 has been chosen as the only adequate scintillator material exploiting its excellent properties which have been investigated in various applications [2,3,4] and will be documented in the test measurements described in the following.

2 The detector modules

The geometry of the BaF_2-crystal and the fully assembled individual detector, respectively, are shown in Fig.2. Each module consists of a hexagonal crystal[1]

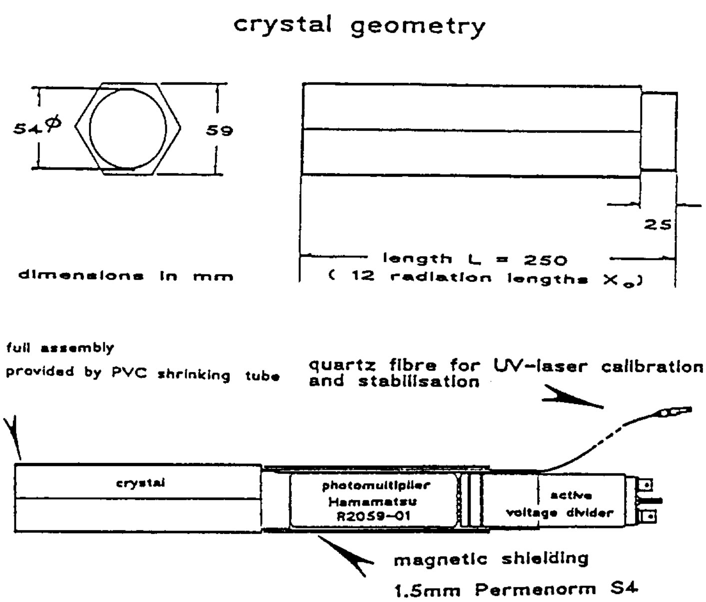

Fig 2. Geometry of a BaF_2-crystal and a fully assembled detector module.

(length = 25 cm = 12 X_0, X_0: radiation length) with a cylindrical end part (ϕ = 54 mm). All surfaces are optically polished. Eight layers of 38 μm PTFE[2] and one layer of aluminum foil (15 μm) serve as reflector. For time and energy calibration and stability control light of a N_2-laser[3] (wavelength λ = 337nm) is fed into each detector by a quartz fibre glued into a groove machined in the cylindrical end cap of the BaF_2-crystal [5].

The photomultiplier tube[4] is coupled to the crystal with silicon grease[5]. The whole assembly including the photomultiplier base housing is contained in a light-tight shrinking tube which in addition gives sufficient mechanical stability. A cylindrical magnetic shield[6] surrounds completely the tube and the cylindrical section of the crystal and provides effective magnetic shielding up to a flux of 0.02 T.

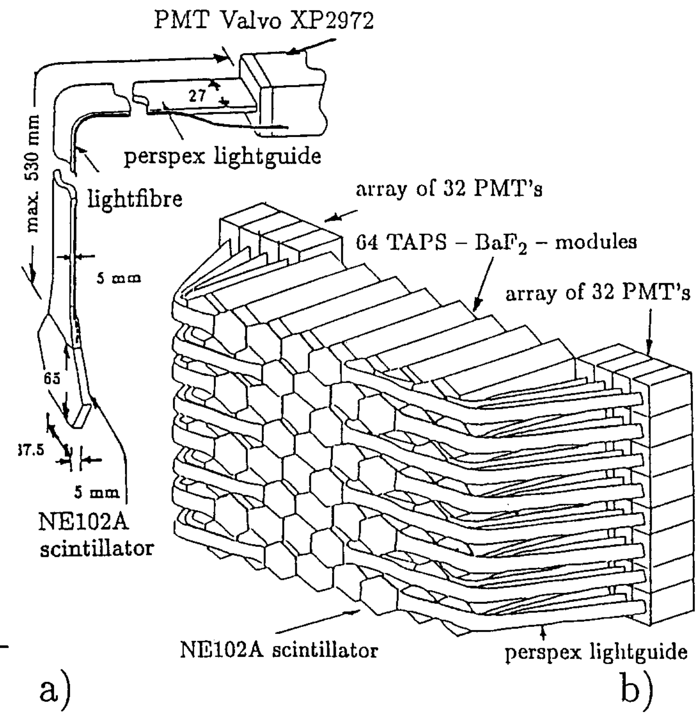

Fig. 3. Schematic viw of an individual CPV-element (a) and the full assembled array in front of a BaF_2-block.

A charged particle veto-detector (CPV) [6] of identical granularity, split into two sub-arrays of 32 individual plastic detectors, is mounted in front of each BaF_2-block.The hexagonal scintillator (NE102A, width: 65mm (diameter of inscribed circle), thickness: 5mm) is read out via perspex lightguides (length: 19-53 cm, width: 27mm) of the same thickness coupled to a photomultiplier[7].The slightly overlapping scintillator elements are arranged in three levels. The maximum plastic thickness in front of an individual BaF_2-module can add up to 24 mm (0.05 X_0) including lightguides and reflector material. Fig. 3 illustrates the assembly of an individual module and the arrangement in front of the BaF_2-array.

[1] Firma Dr. Karl Korth, Kiel, FRG
[2] Tetratec Corporation, Feasterville,PA, USA
[3] VSL-337, LSI Laser Scientific, Inc.
[4] Hamamatsu R2059-01
[5] Baysilon 300.000
[6] Permenorm 5000 S4, VAC Hanau, FRG
[7] Valvo, XP2972

3 The BaF_2-detector

The determination of energy and time response of single detector modules or sub-arrays has been performed using standard nuclear electronics. In case of time-of-flight measurements *constant fraction discriminators* and *time-to-digital-* or *time-to-amplitude-converters* have been used, depending on the required resolution. The energy information is deduced by integrating the light output of the scintillator in a *charge sensitive ADC* (integration width w =2 μs (total light output),w = 40ns (fast component)). The final TAPS electronics system uses several highly packed CAMAC modules [8] which have been developed recently within the TAPS collaboration.

3.1 The crystal specifications and acceptance tests

The performance tests [9] of each crystal involve monitoring the

- **UV-transmission** at various points perpendicular to the axis of the crystal in the wavelength range between 185 and 500 nm using a double beam UV-spectrometer[8] and the measurement of the
- **energy response** and **pulse shape** determined with low energy γ-sources.

The required *optical performance* of the crystal is specified by limits set on the transparency at the wavelengths of the major scintillation components ($\lambda \approx$ 200,220,300 nm).

performance parameter (mean value)	accepted crystals (310 samples)	specif. limits
transv. transmission	[%]	[%]
at λ=202nm	87.4	72.0
at λ=220nm	92.7	81.0
at λ=250nm	96.1	93.8
at λ=300nm	99.0	98.0
absorption length Λ	[cm]	[cm]
at λ=202nm	43.8	18.0
at λ=220nm	77.8	28.0
at λ=250nm	148.3	92.2
at λ=300nm	587.0	292.0
response to E_γ=662keV		
$\Delta E_{fast}/E$ [%]	34.6	45.0
$\Delta E/E$ [%]	11.5	12.5
fast/slow at Δt=40ns	9.5	7.0

Table 1. Obtained experimental test results of 310 accepted crystals in comparison to the required specifications

Table 1 shows the obtained transverse UV-transmission (crystal width 59mm) corrected for Fresnel reflections and the deduced attenuation length Λ ($I_{transm}=I_{inc}\ e^{-X/\Lambda}$). The results are averaged over 310 TAPS-crystals fully accepted by October 1st, 1990 [7] Those crystals, which show distinct absorption bands due to impurities (like Pb^{2+} [10]) causing a deterioration of the luminescence properties , have been rejected.

[8] Hitachi U3200

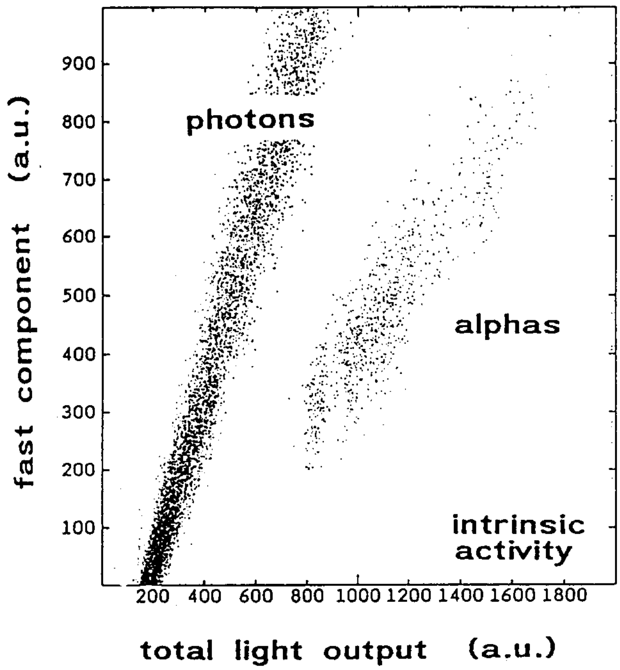

Fig. 4 Pulse shape analysis of BaF_2 signals due to intrinsic radioactivity.

The inspection of the *pulse shape* is quantified by the amplitude ratio of the fast component to the slow scintillation response measured at a delayed time (Δt=20ns, or 40ns, respectively) . A qualitative measure of the signal shape can be deduced from the sensitivity of γ/α separation (intrinsic radioactivity due to contamination [11]) based on the pulse shape analysis (see Fig. 4).The absolute amount of light output of the fast and slow component, respectively, is expressed by the obtained energy resolutions (FWHM) for low energy γ-sources. The corresponding average values are listed in Table1 in comparison to the specification limits.

3.2 Response to electrons

The response to electrons [12] in the energy range between 10 and 43.5 MeV has been investigated using the electron linear accelerator at Gießen [13]. Since electrons above the critical energy of $E_c \geq 13$ MeV in BaF_2 create electromagnetic showers the central hexagonal crystal has been surrounded by six identical detectors. An active collimator consisting of thin plastic scintillators has been used to define the point of impact and to serve as a time reference.

As a result, Fig. 5 shows the line shape of the central detector, the surrounding ring and of the entire array at

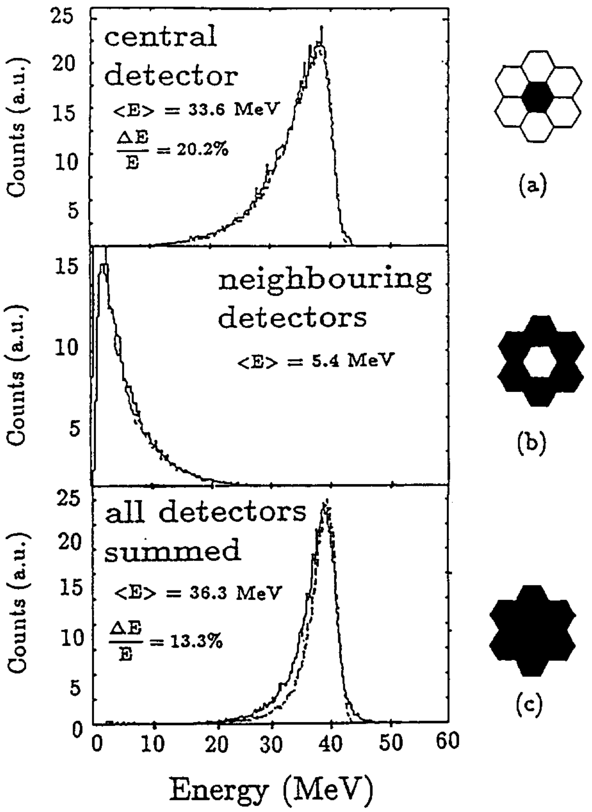

Fig. 5 Line shape of the central detector (a), the ring (b) and the entire array (c) for 43.5 MeV electrons. The dashed line represents the results of GEANT3 simulations.

43.5 MeV electron energy in comparison to GEANT3 [14] simulations. The influence on energy resolution of discriminator threshold, energy leakage and dead volume due to detector housing has been studied over the entire energy range. Table2 summarizes the deduced results in comparison to the simulations which do not fully account for energy losses due to an imperfect detector geometry.

Beam Energy [MeV]	Energy Resolution [%]		Time Resolution[1] [ps]
	Experiment	Simulation	
10	(15.2±1.3)	(12.8±1.5)	450±20
22	(14.1±0.7)	(12.9±0.7)	170±20
32	(12.3±0.6)	(11.7±0.7)	220±20
43.5	(12.9±0.6)	(10.7±0.6)	160±20

Table 2. Experimentally measured energy resolutions (FWHM/E) for the seven module array in comparison to GEANT3 simulations.[1] The time resolution (FWHM) contains the intrinsic resolution of the plastic start counter (Δt≈100ps).

The time resolutions (FWHM) deduced from time-of-flight measurements of the central BaF_2-detector relative to the plastic start counter are below $\Delta t \approx 200$ ps at the highest energies (see Table2). An optimum value of $\Delta t = 110$ ps has been obtained in an improved final configuration at the same electron energy.The FWHM of the neighbouring detectors increases to 800 - 1000 ps due to the low deposited energy (3 - 5 MeV) and the varying time and location of secondary shower components scattered into these modules.

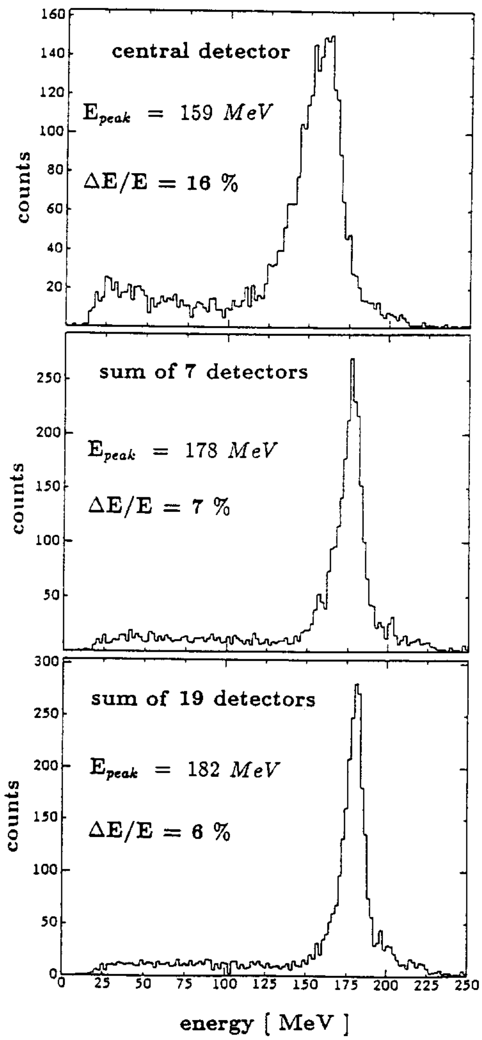

Fig. 6 Energy response to tagged photons of Eγ = 186 MeV of the central detector, 7 and 19 modules, respectively.

The beam spot of ≈ 1 cm in diameter was defined by the active collimator. The reconstruction of the impact point has been obtained from the center of gravity of the energies deposited into the individual modules by taking into account the shower geometry. The position resolution amounts typically to $\Delta x,y \approx 3$ cm (FWHM) without correcting for the beam profile.

3.3 Response to high energy photons

In a test experiment at the Mainz LINAC a collimated beam ($\phi \approx 1.2$ cm) of tagged photons of energy $E_\gamma = 186$ MeV has been used to determine the energy response of a TAPS sub-array comprising 19 BaF_2-modules [15].

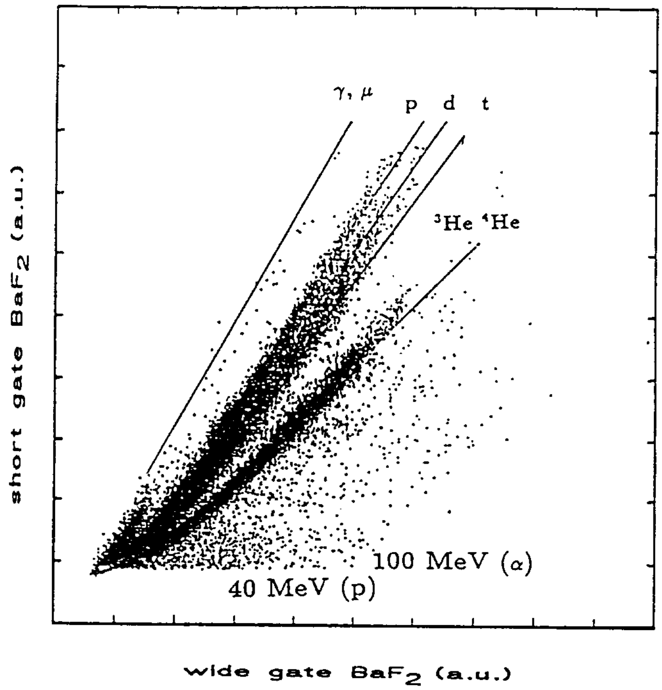

Fig. 7 Scatter plot of the fast scintillation component versus the total light output. Photons and charged particles are separated by pulse shape analysis.

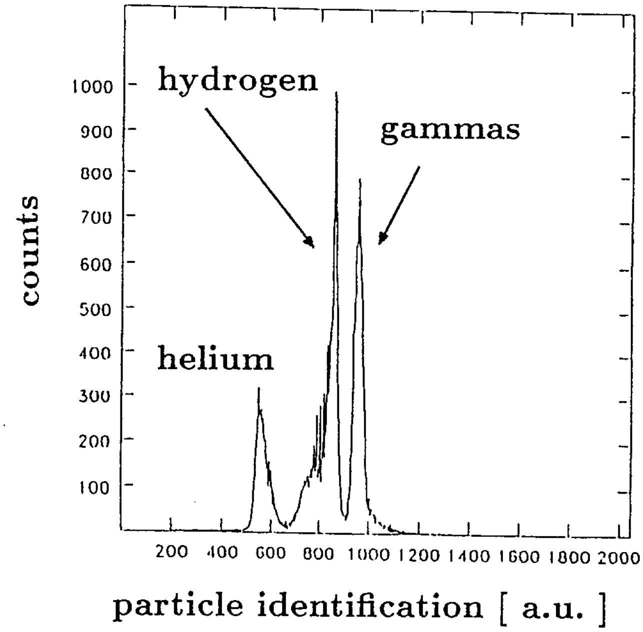

Fig. 8 Projection of the particle separation via pulse shape analysis as given in Fig. 7.

Fig. 6 shows the line shape of monoenergetic photons (E_γ = 186 MeV) impinging on the central detector module. The achieved energy resolution of $\Delta E/E = 16\%$ (FWHM) can be drastically improved by adding in the shower leakage deposited into the first (6 modules) and second (12 modules) surrounding rings of BaF_2-detectors, respectively.The resulting energy resolution of the array reaches $\Delta E/E = 6\%$ (FWHM) which is in agreement with expectations based on GEANT3 simulations. Contributions to the spectrum due to pile-up and electrons from conversion in the Pb-collimator have not been fully rejected. The mean energies deposited into the first and second ring of surrounding detectors amount to E_{mean} = 19.0 MeV and 5.6 MeV, respectively. Similar to the results with monoenergetic electrons spatial resolutions of Δx,y $\approx$ 2.5 cm have been obtained as preliminary results. The size of the beam spot has not been unfolded. However, in order to reproduce the absolute point of impact a more refined procedure has to be developed to take the hexagonal crystal shape and the electromagnetic shower profile fully into account.

3.4 Response to charged particles and neutrons

TAPS-detectors have been exposed to light charged particles produced in p- and α-induced reactions at the KVI cyclotron in Groningen [16].Targets of C,ZnS and Pb have been bombarded by 55 MeV protons and 100 MeV α-particles. The BaF_2-detector was mounted at a scattering angle $\Theta_{lab} \approx 45°$ outside the scattering chamber to detect light reaction products passing a 25μm Kapton foil.

The scatter plot in Fig. 7 illustrates the photon and charged particle identification exploiting pulse shape analysis.The fast component and the total light output of the BaF_2-signal have been integrated separately in charge sensitive ADC's. Well separated bands can be observed and identified as photons, Hydrogen and Helium isotopes, respectively. Fig. 8 shows the photon/particle separation after a projection along the bands marked in the previous scatter plot.

Fig. 9 demonstrates the excellent energy resolution achieved for protons inelastically scattered on ^{12}C measured at a projectile energy of E_p = 55 MeV. The deduced energy resolutions (FWHM) amount to $\Delta E/E \approx 2.4$ % for 40 to 55 MeV protons, respectively. A comparable result of $\Delta E/E \approx 3.5$ % has been determined in case of 82 MeV α-particles.

The identification and discrimination of high energy neutrons is based on the complete information provided by time-of-flight, response of the veto-detector and pulse shape analysis of the BaF_2-signal. Low energy neutrons (far below 100 MeV) interact within the detector material predominantly via (n,γ)-reactions [17] and can be discriminated only by a time-of-flight measurement. Using the secondary neutron beam at the SATURNE facility at Saclay the response of $BaF_2$to neutrons in the energy range between 200 MeV and 850 MeV has been investigated using a sub-array consisting of seven 20 cm long prototype BaF_2-detectors [18].

The pulse shape analysis confirmes that (n,p) reactions play the dominant role in the studied energy region. There-

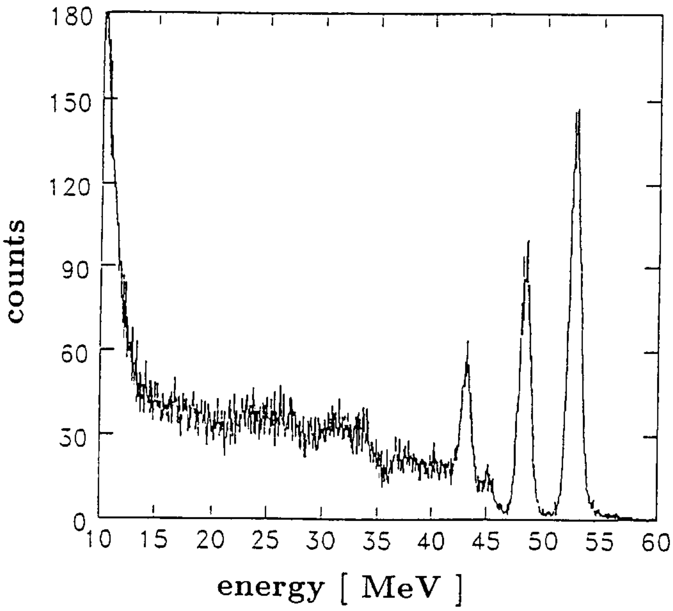

Fig. 9 Energy response of a TAPS-detector to protons from the reaction $^{12}C(p,p')^{12}C$ at a 55 MeV bombarding energy.

fore, neutrons which do not trigger the CPV-system will be identified as protons applying pulse shape analysis. The kinetic energy can be deduced from the measured time-of-flight. In addition, the deposited energy (photon-equivalent) decreases from $\approx$ 40 % at E_n = 200 MeV down to $\approx$ 24 % at E_n = 850 MeV mostly due to energy leakage. An overall detection efficiency for neutrons (for an energy threshold of 5 MeV) of $\epsilon = 17\pm3$ % can be deduced and stays nearly constant over the studied energy range.

4 First Experiments

The TAPS photon spectrometer has come into operation beginning 1990. After first experiments at GANIL, which have been performed in a spherical arrangement of 19-module detector blocks, two completely installed spectrometer arms have been used to take first data at the new SIS-facility. Fig. 10 shows the experimental invariant mass spectrum obtained in a first experiment at GSI to investigate the π^0 production probability in the system ^{20}Ne + ^{27}Al at 350 MeV/u [19]. Fig. 11 documents the quality of photon/particle discrimination via pulse shape technique. in an on-line spectrum of the reaction of 1GeV/u ^{40}Ar + ^{nat}Ca. The separation appears to be efficient up to the highest energies covering the range of the total light output up to $\approx$ 400 MeV of photon-equivalent energy. The calibration is based on cosmic radiation passing the crystals in transverse or longitudinal direction, respectively.

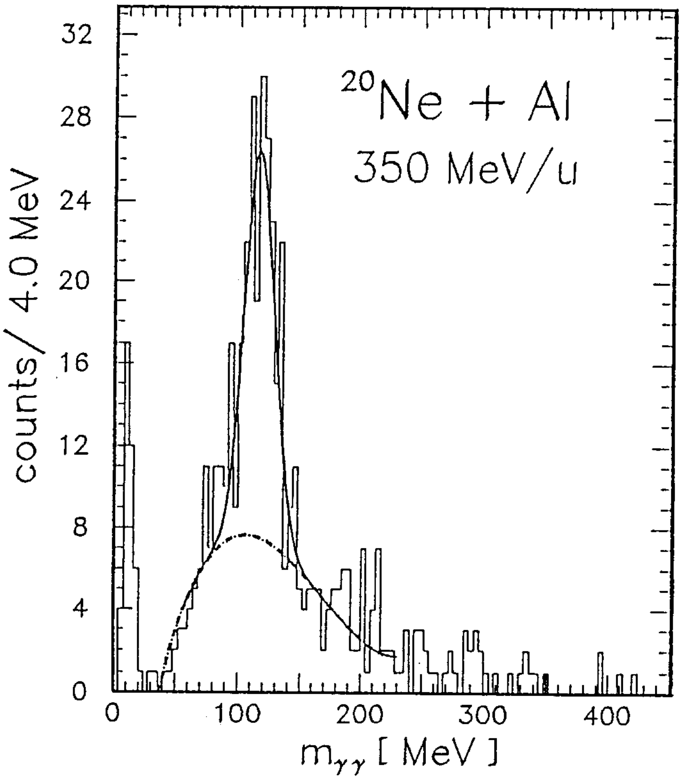

Fig 10 Invariant mass spectrum for pairs of prompt neutral hits in two coincident detector blocks. The dashed curve is a spline fit to the background.

5 Summary

The comissioning of the apparatus and the first performed experiments have shown that the envisaged performance has been fully achieved. The strict specifications, the detailed performance tests, the careful assembly of the individual modules and the development of several instrumental components optimized to the needs of the TAPS-applications make it possible to install and operate such a highly segmented detector system at several medium energy facilities. The detector performance based on the test measurements performed with prototypes makes it obvious that the application of the spectrometer is not restricted to a pure photon detection. The excellent response of BaF_2 to charged particles (expressed by energy resolution as well as particle identification due to pulse shape analysis) provides in combination with the CPV-system the basis for a high resolution ΔE-E detector system with the capability to detect neutrons with high efficiency in the same device.

6 Acknowledgements

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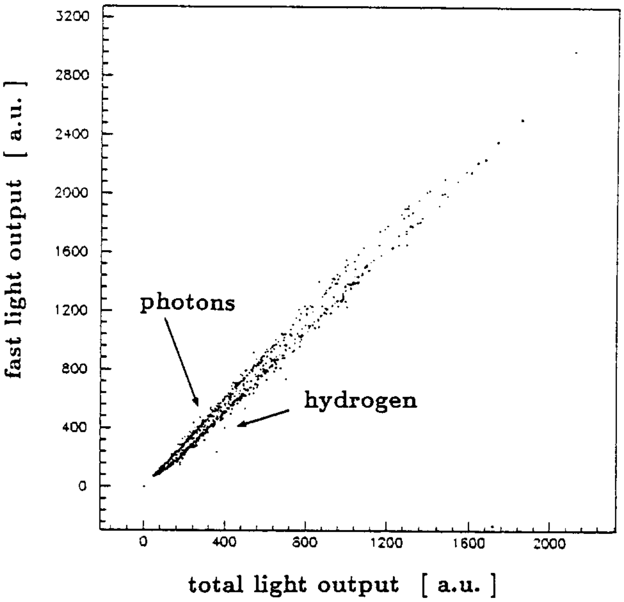

Fig. 11 Pulse shape analysis performed in the reaction 1 GeV/u ^{40}Ar + ^{nat}Ca.

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[8] 8-fold CAMAC-controlled modules: FFC8[1] (Constant Fraction Discriminator) - RDV[1] (multiple gate generator, provides two independent gate outputs per input which are necessary for pulse shape analysis (short and wide integration gate)) - QDC[1] (high resolution charge sensitive analog-to-digital-converter, optimized for pulse shape analysis by allowing two individual gates per analog input channel) - TDC[1] (high resolution time-to-digital converter)

16-fold NIM module: Active analog fan-out (4 outputs of equal amplitude per analog input) [[1]available from GANELEC]

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