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HODOSCOPE GAMMA SPECTROMETER GAMS-200

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ABSTRACT

A 208 channel hodoscope γ spectrometer, whose cells are made of lead-glass, is described. This detector makes it possible to measure simultaneously the coordinates (with an accuracy of 1.5 mm), and energy (to a few percent) of a large number of gammas and to reconstruct the mass and momentum of the particles decaying into gammas. The characteristics of the spectrometer have been studied in an electron beam and also under the conditions of real experiments ($\pi^0 \rightarrow 2\gamma$).

1. INTRODUCTION

Hadronic interactions at high energy generally give rise to many gammas coming mainly from the decay of π^0 mesons and other particles. Their study requires a detector able to measure the coordinates and energy of a large number of gammas simultaneously.

Scintillation hodoscope spectrometers of the sandwich type [1,2], which have been used with success these last years to study final states comprising up to four gammas [3-7], are limited in this respect. As a matter of fact, when the number of simultaneously detected gammas becomes large, shower superposition occurs in separate hodoscope planes and the accuracy of the kinematics reconstruction deteriorates rapidly.

The hodoscope spectrometer GAMS is essentially free of these limitations. GAMS is a matrix of total absorption counters made of transparent lead-glass, the lateral dimensions of the counters being comparable to the width of electromagnetic showers in this medium [8]. It measures directly the momentum of the gammas and, if its lateral dimensions are sufficient (e.g. 64×64 counters in the presently assembled GAMS-4000 at the CERN SPS), it makes it possible to detect more than ten gammas and to reconstruct the mass and momentum of the decaying particles [9]. This new apparatus has been under study at IHEP since 1973. The functioning principle of the spectrometer and its characteristics have been tested on models in a particle beam of the 70 GeV accelerator [8]. In the first experiments using this new technique, rare decays of η , ω and η' mesons [10-12] were observed and studied.

The hodoscope spectrometer GAMS-200, described below, was used during the years 1977 - 1979 to make precise measurements of the differential cross-section of the charge exchange reaction

$$n^- + p \rightarrow \pi^0 + n \quad (1)$$

at small momentum transfer [13] (Sixth CERN-IHEP Joint Experiment). Moreover, it has served the purpose of a working model in the design of the big spectrometer GAMS-4000 to be used at the CERN SPS. GAMS-type spectrometers will certainly become basic instruments at the 3 TeV UNK and other accelerators of the next generation [9,14].

2. DESCRIPTION OF THE SPECTROMETER

The spectrometer GAMS-200 comprises 208 total absorption counters (fig. 1). It has an approximately 60 cm diameter circular aperture. The radiator cells ($36 \times 36 \times 420 \text{ mm}^3$) are made of transparent lead-glass of Type F8 (analogous to F2) machined with a precision of 0.05 mm. In order to improve the light collection and to screen the radiators from each other, each cell is wrapped in aluminized mylar foil.

The basic parameter of this detector is the lateral dimension d of its cells. By reducing d , the accuracy σ_x on measured gamma or electron coordinates is improved but the number of Cerenkov light reflections on the facets of the radiator cells increases (which impairs the energy resolution) and also the number of cells in a spectrometer of fixed dimensions grows. For $d > 3 \text{ cm}$, σ_x grows exponentially with d

$$\sigma_x = \sigma_{x0} \exp(d/d_0) \quad (2)$$

while in the domain $d \lesssim 3 \text{ cm}$ (typical width of a shower in this glass) σ_x remains nearly constant [9] (fig. 2). For GAMS-200, built to measure gammas of a few ten's of GeV, d was chosen to be equal to 36 mm. This warrants an accuracy $\sigma_x < 2 \text{ mm}$ on the measured coordinates.

An important feature of this spectrometer is its capability to separate very near showers. Actually, it can discriminate between a pair of photons and a single gamma, even if the distance between the members of the pair is as small as $\sim 2.5 \text{ cm}$ [15], i.e. it can identify each individual gamma of a pair coming from the decay $\pi^0 \rightarrow 2\gamma$ even when both gammas enter the same cell of the spectrometer.

By lengthening the spectrometer cells, the fraction ε of the energy of a shower absorbed in the radiator increases and the fluctuations on the measured energy decrease accordingly. However, radiators which are too long are useless. Beyond a certain length the gain in ε does not compensate any more for the loss of light due to multiple reflections on the facets. For $\varepsilon \simeq 1$, the accuracy of energy measurements σ_E depends only weakly on ε :

$$\sigma_E(\epsilon) = \sigma_E(\ell) [1 + 4(1 - \epsilon) + 50(1 - \epsilon)^2] \quad (3)$$

for an ideally transparent radiator [9]. For a detector made of real lead-glass with a small cell structure, $\sigma_E(\epsilon)$ differs even less from $\sigma_E(\ell)$. The length $\ell_{0.98}$ corresponding to $\epsilon = 0.98$ is a good practical limit as the resolution does not improve by making the radiator longer. In the case of F8 lead-glass

$$\ell_{0.98} \approx 29 + 4 \ln E \quad (4)$$

where ℓ is given in cm when the energy of the electrons is expressed in GeV [9] (in the case of photons, the cascade curve is shifted by ~ 1.5 cm (0.5 rad. length) relatively to electrons). This leads to an estimate for the length of GAMS-200 counters at $E \approx 20$ GeV of $41 \div 44$ cm. Actually, a counter length of 42 cm has been chosen for GAMS-200 according to the results of resolution measurements obtained with models of various lengths (each model comprising nine counters) irradiated with electrons of 5 and 25 GeV (fig. 3).

The Cerenkov radiation is detected by photomultipliers FEU-84-3, with a 24 mm diameter photocathode, one photomultiplier being glued to the end of each cell. The photomultipliers are fed through small size voltage dividers with a low current (~ 0.2 mA). The H.V. applied to each photomultiplier can be adjusted, thanks to remote controlled high precision multi-turn potentiometers. To insure a large linearity range, the last four dynodes of the photomultipliers are fed in parallel by four boosters.

The pulses from the counters are fed through 60 ns gates into 12-bit amplitude-to-digital converters and the digital information is read into an HP 2100A computer. The control of the ADC system is achieved by an electronic system previously used in the NICE experiment [2,16].

GAMS-200 is a completely autonomous detector. Its total weight is 600 kg. It has been installed on a remotely controlled stand which can be moved in the three space directions, along and across the beam, with a precision of 0.1 mm.

3. MONITORING SYSTEM

All counters of the spectrometer are monitored, at each accelerator cycle, with light pulses from a set of 12 yellow light-emitting diodes (LED) HP 4558. The light is delivered at the forward end of each radiator cell by a flexible fiberglass light guide with small light absorption (fig. 1). The LED's are powered with a generator delivering pulses of 15 V amplitude and 100 ns length. The corresponding amount of light is equivalent to the energy released in the counter by a 25 GeV electron ($\sim 20,000$ photoelectrons ejected from the photocathode of the PM) [18]. The width of the line is 2.5%.

The stability of the LED's (changes with temperature, ageing, etc.) is controlled by comparison of their light yield with that of a standard α - source (Am^{241} deposited on a plastic scintillator, $E_{\alpha} \approx 5.5$ MeV) using a separate PM. By averaging over eight pulses the width of the spectrum given by the α - source is reduced to 7%.

The drift of a single channel of the spectrometer is shown in fig. 4. It does not exceed 1% per day after a few hours of warming-up. After two weeks of continuous running, the drift of all 208 counters of the spectrometer remains within $\pm 2\%$. Reiterated calibrations of the spectrometer with electrons have shown that the described system insures efficient monitoring with an accuracy at the 1% level.

4. CALIBRATION OF THE SPECTROMETER

A preliminary adjustment of all counters is readily achieved by means of the LED's. Next, the equalization of all the channels has been done by irradiating uniformly the spectrometer in a wide muon beam [5,17]. To suppress the small background due to scattered hadrons, events where a signal appears only in a single counter have been selected for the reconstructed spectrum of the muon amplitudes A_{μ} (fig. 5). An equalization with an accuracy of a few percent is obtained.

However, a calibration with muons, though rapid and handy, has only a preliminary character due to its limited precision. As a matter of fact, the amplitude A_{μ} of the signals from muons corresponds to an energy release

in the counters of ~ 0.8 GeV only, i.e. it gives a calibration point at the very beginning of the dynamical range (fig. 6). Moreover, the Cerenkov radiation from muons and from electromagnetic showers propagates differently in the lead-glass cells and the ratio of the amplitudes of the signals from electrons and muons varies from one counter to another (in the limits $\pm 10\%$, see fig. 7), owing to differences between cells in transparency and in the quality of the polishing of the facets. This method provides a calibration with an accuracy at the 10% level.

The final calibration has been carried out with 25 GeV electrons (identified with Cerenkov counters, hadron contamination less than 1%). Two methods have been used. The first one is based on the fact that the response of a cell is maximum and constant for particles entering it in a small zone around the cell axis. This has been achieved with the help of small scintillation counters, 3×3 mm², which accept only electrons reaching the central part of each cell. In order to avoid drifts of the PM's gain [19], the beam intensity has been reduced to ~ 30 e⁻/burst ($\sim 10^4$ π^- /burst). The normalization of all counters to the maximum in the electron peak (fig. 6) immediately gives the calibration coefficients. Five hours are necessary to calibrate the spectrometer by this method.

In the second method, ~ 12 counters have been irradiated simultaneously by defocusing the beam, no special beam counters being used. The flux of electrons amounts to ~ 300 e⁻/burst. The calibration coefficients α_i are obtained after on-line minimization of the expression

$$\sum_v \left(\sum_i \alpha_i A_i^{(v)} - E \right)^2 = \min \quad (5)$$

where A_i is the amplitude of the signal in the i^{th} counter, $E = 25$ GeV is the energy of the electrons and v is a number labelling the events. As an electromagnetic shower gives a signal in a small number of cells only (~ 16), the system of linear equations leading to the minimization of (5) is easily solved (Zeidel's method). The calibration of the spectrometer by this method takes two hours.

The results obtained by the two last calibration methods differ by less than 1%.

5. ON-LINE CONTROL OF THE SPECTROMETER

After setting up and calibration, the spectrometer has been used to study reaction (1) with pions of 25 and 40 GeV/c incident momentum. Besides its intrinsic physical interest, this experiment has made it possible to test the technical solutions adopted in the design of the spectrometer and to determine its characteristics in the real conditions of a long experiment.

The proper functioning of the spectrometer is controlled on-line by a set of programs which checks the ADC pedestals, the stability of each channel in the detector and the correct behaviour of the digital part of the electronics. It also periodically controls the linearity of the channels in the detector, photomultipliers included, by a differential method.

To use this method, a supplementary LED has been added to the set of LED's of the monitoring system (see Sec. 3). If q is the signal delivered by the latter and Δq is the signal given by the additional LED with $\Delta q \ll q$, then a comparison of the signals obtained with both light sources fired simultaneously and with the principal light source only gives the characteristic derivative for each channel:

$$A_i(q + \Delta q) - A_i(q) \approx \frac{dA_i}{dq} \Delta q \quad (6)$$

Measurements have been made for several values of q and a fixed Δq . For signals A_i up to 0.3 V, dA_i/dq does not vary by more than 7%, i.e. $A_i(q)$ deviates no more than 1% from a linear dependence.

The physics is controlled on-line by another set of programs which analyze events having been detected by the spectrometer (fig. 8) and give their distribution over appropriate kinematical variables. Simple algorithms (limited by the size of the computer) make it possible to determine the multiplicity m_γ of gammas in each event, to normalize the amplitudes A_i of the signals delivered by the counters with the calibration coefficients α_i and to obtain the energy of the individual gammas and the total energy

released in the spectrometer $E_{\text{tot}} = \sum_i \alpha_i A_i$ (fig. 9). The peak in fig. 9 corresponds to the binary reaction (1) while the left tail is due to inelastic events where two or more π^0 are emitted.

Further on-line kinematical analysis by the method of moments [5,6] allows a quick and precise enough determination, at least for controlling purposes, of the mass and momentum of the particles decaying into gammas (fig. 10) and of the t -dependence of the differential cross-section of reaction (1):

$$\tilde{M}^2 = \left(\frac{E_{\text{tot}}}{L} \right)^2 \left(\tilde{m}_{2x} + \tilde{m}_{2y} + g_m \right) + \tilde{t} \quad (7)$$

$$\tilde{t} = - \left(\frac{E_{\text{tot}}}{L} \right)^2 \left(\tilde{m}_{1x}^2 + \tilde{m}_{1y}^2 \right) \quad (8)$$

where g_m is a small correction (of the order $\sim b^2$, b being the width of an electromagnetic shower), L is the distance of the spectrometer from the target and $\tilde{m}_{kx}$ is the k^{th} moment of the signals A_i defined by

$$\tilde{m}_{kx} = \sum_i \alpha_i A_i x_i^k / \sum_i \alpha_i A_i \quad (9)$$

In the simple case where $m_\gamma = 2$, we can also easily determine the effective mass

$$M_{\text{eff}} = \left(E_{\gamma 1} E_{\gamma 2} \right)^{1/2} \theta_{\gamma\gamma} \quad (10)$$

where $E_{\gamma 1,2}$ are the energies and $\theta_{\gamma\gamma}$ is the opening angle of the two gammas (fig. 10).

6. CHARACTERISTICS OF GAMS-200

6.1 Energy measurements

The linearity and resolution of the energy response of the spectrometer have been studied in electron beams with energies varying from 1.8 GeV up to 40 GeV. Deviations from linearity do not exceed 1% (fig. 11) and the resolution is given by

$$\Delta E_{\text{tot}}/E_{\text{tot}} = 0.027 + 0.125/\sqrt{E} \quad (11)$$

(fig. 12) where ΔE is the width of the spectrum at half-maximum and E is measured in GeV.

Figure 13 shows the energy spectrum of γ pairs coming from the decay of π^0 mesons produced in reaction (1) at 40 GeV. The relative width of the peak is 6%, i.e. 1.4% larger than the value given by (11). This difference can be explained by the fact that the signals (noise included) of all 208 channels have been added in this measurement, while in the calibration with electrons, leading to (11), the sum of the signals has been performed locally, taking into account 25 counters only. Other factors contributing to the difference in values are the presence of absorbing matter between target and spectrometer, errors in α_i 's, etc. The energy resolution measured with $\pi^0 \rightarrow 2\gamma$ is a global characteristic of GAMS-200 as γ 's from π^0 decay irradiate the whole surface of the spectrometer.

Figure 14 shows the distribution of events in the π^0 peak as a function of $\cos \theta^* = |E_{\gamma_1} - E_{\gamma_2}| / (E_{\gamma_1} + E_{\gamma_2})$ where θ^* is the decay angle of a γ -pair in the centre-of-mass system. For π^0 mesons, as for any spin-zero particle, it is isotropic. The measured distribution is flat (the fall in the region of small angles θ^* is due to the limited acceptance of the spectrometer) which confirms the linearity of the energy response of the spectrometer for gammas.

6.2 Coordinate measurements

Several algorithms giving the coordinates of the impact point of gammas (electrons) on the spectrometer have been described previously [8]. At 25 GeV, they guarantee an accuracy $\sigma_x = 1.5 - 2$ mm. They depend on one parameter b characterizing the width of the shower in the glass.

The best method to reconstruct coordinates is to fit the amplitudes $A_{i,j}$ (here and below indices are ordinal numbers giving the counter position in the x and y directions) with the two-dimensional profile of the showers, as determined during calibration measurements [8]. However, this requires big computing means and it is thus of little interest for on-line work.

A simplified method has been used to measure coordinates of gammas (electrons) in real time. It takes into account the amplitude information of only four counters in the immediate vicinity of the shower axis: $A_{i,j}$, $A_{i+1,j}$, $A_{i,j+1}$ and $A_{i+1,j+1}$. First, the counter giving the largest signal is identified (fig. 8). Next, from its two horizontal adjacent neighbours the counter is chosen which delivers the biggest signal. The vertical neighbour is selected in the same way. The fourth counter is taken such as to make a square with the three preceding ones.

The x-coordinate of the shower, calculated relatively to the centre of these four counters, is then given by the polynomial expression

$$x = a_1 \xi_x + a_2 \xi_x^3 + a_3 \xi_x^5 \quad (12)$$

where $\xi_x = (A_{i+1,j+1} + A_{i+1,j} - A_{i,j+1} - A_{i,j})/A$, $A = A_{i,j} + A_{i+1,j} + A_{i,j+1} + A_{i+1,j+1}$. The y-coordinate is given by a similar expression where ξ_x is replaced by $\xi_y = (A_{i+1,j+1} - A_{i+1,j} + A_{i,j+1} - A_{i,j})/A$. The coefficients of polynomial (12) have been obtained by a least-square fit to the results of calibration measurements with 25 GeV electrons. This polynomial form of the 5th degree has been found sufficient for a determination of the coordinates with an accuracy $\sigma_x = 1.3$ mm (fig. 15). No better accuracy is obtained by using the information of more than four counters (electronic noise becomes important) and it also renders the separation of near showers more intricate.

The high accuracy achieved in coordinate reconstruction is illustrated in fig. 16, which displays the distribution of $\pi^0 \rightarrow 2\gamma$ events identified in reaction (1), versus the opening angle of the γ pairs. The steep slope of the distribution at $\theta_{\gamma\gamma} \approx \theta_{\min}$ is a clear indication of the high precision of the measured coordinates. The curve on the figure is the result of a Monte Carlo calculation taking into account the real geometry of the set-up. The accuracy of the coordinate determination, treated as a free parameter, is $\sigma_x = (1.4 \pm 0.2)$ mm, in good agreement with the results of coordinate measurements in electron beams.

Figure 17 shows the distribution of events in the π^0 peak as a function of the azimuthal decay angle in the centre-of-mass system of the γ pairs. The measured distribution is isotropic (as expected for the decay $\pi^0 \rightarrow 2\gamma$), one factor which accounts for the absence of noticeable deformation due to the finite size of the spectrometer cells.

6.3 Mass measurements

The possibilities of GAMS-200 as a mass measuring instrument are illustrated in figs 10 and 18, which show mass spectra of events with multiplicity $m_\gamma = 2$, chosen on the basis of a χ^2 analysis (one-constraint fit of reaction $\pi^- p \rightarrow M^0 n, M^0 \rightarrow 2\gamma$ at $E = 25$ GeV, $\chi^2 < 2.5$). The π^0 peak has a width of 6 MeV (FWHM) and $\sigma_M/M = 2.4\%$. The background outside the peak is very small ($< 10^{-3}$). The mass of the η meson, measured in the reaction $\pi^- p \rightarrow \eta n, \eta \rightarrow 2\gamma$ (fig. 19) is obtained with an accuracy $\sigma_M/M = 1.3\%$

7. CONCLUSION

The hodoscope gamma spectrometer described here has been used during a long period in true experimental conditions. The experience gained during this time has shown that it is a simple and reliable apparatus endowed with highly stable and interesting characteristics. It makes it possible to get a complete picture of the physical information in real time measurements.

This method can be used to build big spectrometers, containing thousands of counters, as, e.g., GAMS-4000 (4096 cells) which is now being installed at CERN.

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FIGURE CAPTIONS

- Fig. 1 : Schematic representation of GAMS-200. 1) radiator cells made of lead-glass F8, $36 \times 36 \times 420 \text{ mm}^2$, 2) photomultipliers FEU-84-3, 3) fibre optics system for light calibration (diameter 1.3 mm), 4) aluminium plate 1 cm thick (0.1 rad. length) with holes for the fibres.
- Fig. 2 : Dependence of the accuracy on the reconstructed coordinates of electrons (γ 's) versus the width of the cell at $E = 25 \text{ GeV}$. For $d > 3 \text{ cm}$ it is well described by the exponential form (2) with parameters $\sigma_{x_0} = 0.8 \text{ mm}$, $d_0 = 65 \text{ mm}$.
- Fig. 3 : Dependence of the energy resolution (FWHM) of GAMS on the radiator length ℓ . A_1 : amplitude in the counter crossed by the electron beam, A_9 : sum of the amplitudes of nine counters (3×3), $A_8 = A_9 - A_1$, a : resolution of an ideal counter (fully transparent and with unlimited transversal dimensions) at $E = 25 \text{ GeV}$.
- Fig. 4 : a) Stability of the monitoring system after the starting-up of the spectrometer. The arrow shows the moment when the set-up was stopped for a short time;
b) The same after a few hours of warming up.
- Fig. 5 : Amplitude spectrum in a GAMS counter of 20 GeV/c muons. $A_\mu = 1$ corresponds to an energy release of $\sim 0.8 \text{ GeV}$.
- Fig. 6 : Energy release in GAMS of 25 GeV electrons (after summation of the amplitudes of nine counters, 3×3). The left peak is due to muons.
- Fig. 7 : Dispersion of the ratio of averaged amplitude signals in GAMS from electrons ($E = 40 \text{ GeV}$) and muons. The curve is a gaussian distribution with a standard error of 9%.

- Fig. 8 : Amplitudes of the signals of counters A_{ij} (vertical axis) for typical 2γ events in GAMS-200, identified as π^0 in reaction (1) at $E = 25$ GeV (photograph of display).
- Fig. 9 : Total energy release in the spectrometer for events accepted by the trigger. $E = 25$ GeV.
- Fig. 10 : Mass spectrum of events in the "elastic" peak ($E > 20$ GeV in fig. 9) obtained by the method of moments (7) - (9). Thin histogram: all events; thick histogram: $m_\gamma = 2$. The dotted line shows the effective mass spectrum (10).
- Fig. 11 : Linearity of the energy response of the spectrometer
- Fig. 12 : Energy resolution of GAMS. The straight line is given by (11).
- Fig. 13 : Energy spectrum of π^0 mesons produced in reaction (1) at $E = 40$ GeV.
- Fig. 14 : Distribution of γ pairs in the π^0 peak versus $\cos \theta^*$ in the centre-of-mass system. The curve has been calculated by the Monte Carlo method.
- Fig. 15 : Dependence of the measured coordinate of a shower (x_m) on the impact point (x_c) of the electron in a spectrometer cell. The error bars show the values of σ_x .
- Fig. 16 : Distribution of γ pairs in the π^0 peak over the opening angle $\theta_{\gamma\gamma}$. $\theta_{\min} = 2m_{\pi^0}c^2/E$. The curve has been calculated by the Monte Carlo method.
- Fig. 17 : Azimuthal distribution of γ pairs in the π^0 peak.
- Fig. 18 : Mass spectrum of γ pairs after a one-constraint fit of the reaction $\pi^- p \rightarrow M^0 n$. $E = 25$ GeV.
- Fig. 19 : The same as in fig. 18 but in the region of η meson. $E = 40$ GeV.

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