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A MODULAR NaI(Tl) DETECTOR FOR 20-1000 MeV PHOTONS

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ABSTRACT

A detector consisting of 54 NaI(Tl) modules is described. The detector has been optimized for the detection of 20-1000 MeV photons. An energy resolution (FWHM) of 5.5% at 130 MeV could be attained, and the stability has been better than 1% over several months.

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1. INTRODUCTION

The detection of medium-energy (20-1000 MeV) photons with good energy resolution and high efficiency presents certain problems. As a matter of fact, lead-glass detectors are not suitable for the lower part of the energy domain, and the upper part requires big volumes in order to contain the photon shower. In the past, large monocrystals of NaI(Tl) were used with some success [1]. However, their main drawback is the lack of identification of multiple hits. Also, it is difficult to achieve a good uniformity of light output for very large crystals. A good solution consists in using a modular NaI detector such as the Stanford crystal ball [2].

For the measurement of γ -ray spectra produced by the $p\bar{p}$ system at rest, we used and optimized such a modular detector [3]. In addition to good energy resolution for the whole energy domain (20-1000 MeV) and good multiple-hit rejection, the detector had to present very good-long term stability since the experiments lasted several months.

Good energy resolution was achieved in three ways: i) by having a large volume of NaI to contain the photon shower, and by the rejection of photons which did not hit the central part of the detector; ii) by very good uniformity of the light output for each module and a minimum of material between modules; iii) by very accurate energy calibration of each module (at 130 MeV) and control of its variation with time by use of a light pulser.

2. EXPERIMENTAL SET-UP

The photon spectrometer is composed of 54 modules (NaI and photomultiplier tube) assembled in a sealed housing, a light pulser for calibration and stabilization, and the associated electronics.

2.1 The NaI modules

Figure 1 shows the drawing of a typical module. Each module has the shape of a truncated triangular pyramid and is made of polycrystalline pieces of NaI(Tl)

(polyscine)^{*)}. Owing to the geometrical arrangement of the 54 modules (see next subsection) there are differences up to 12% in the dimensions and thus in the volume of the crystals. They are wrapped in white paper and then in aluminized mylar (for optical separation) covering all faces, except for a 50 mm diameter hole in the large triangular face into which is fitted the first air light-guide between the crystal and the glass window of the housing. A second air light-guide connects the window and the photomultiplier (PM) tube. A small lateral hole in this light-guide allows injection of light pulses via a light fibre (see subsection 2.3).

The PMs were semi-fast, 50 mm diameter, 10-stage tubes of the type SRC L50B01 or RTC XP2202B, shielded magnetically by 1 mm μ -metal and about 5 mm of iron.

The specifications for the energy resolution and light collection uniformity of the NaI crystals were the following: 14.5% FWHM energy resolution for 661 keV photons irradiating the small (front) end of the module, and $\pm 2.5\%$ longitudinal light collection uniformity for collimated 661 keV photons irradiating the crystal laterally for $x = 0$ to 29 cm (see fig. 1), and $\pm 1.25\%$ for $x = 0$ to 11 cm. Tests made before packing the modules in the common housing showed that they all met the energy resolution specification, and all but nine modules met the uniformity specifications. Figure 2 shows typical variations of the 661 keV photopeak position versus x . Module 44 was one of the nine modules which did not meet the uniformity specifications for $x = 0$ to 29 cm. Since they were reasonably uniform for the important first 11 cm, they were accepted but placed on the outside of the assembly (see fig. 3). As a matter of fact, for the experiments, only those photons were accepted which hit the inner 24 modules, so the outer modules (25 to 54) were used only to contain the shower, and thus their non-uniformity was much less detrimental.

*) Manufactured by Harshaw Chemical Co., Solon, Ohio, USA.

Finally, it should be noted that the light output of a module is only about 7% of that of a 2" x 2" cylindrical NaI(Tl) crystal coupled directly to the PM. This loss in light output, mostly due to the use of the two air light-guides, explains the modest energy resolution for low-energy photons but is acceptable for the energy range (20-1000 MeV) for which the detector was designed.

2.2 Arrangement of the modules

All 54 modules were tightly packed in a sealed housing as shown in fig. 3. Each crystal was individually held by screws and pressure plates acting on the large (rear) end of the crystal.

Figure 3 also shows the stacking scheme and the numbering of the modules. One can distinguish three concentric rings: modules 1 to 6, modules 7 to 24, and modules 25 to 54. Assembled in this way the detector constituted approximately 1 sr of the full sphere and was equivalent to 1/13 of the Stanford crystal ball [2]. In the following, the complete detector assembly will be called the "sector".

2.3 The light pulser

The light pulser is shown schematically in fig. 4. The light pulse was produced by a Xenon flash-tube of the type FX280^{*)}. The shape of the light pulse was tuned to be similar to that of the NaI(Tl) crystal. The intensity of the light was adjusted in a continuous manner by a diaphragm, and in steps by a set of six filters placed on a wheel. Both the diaphragm and the filter wheel could be positioned remotely.

The light then entered a white diffusion box and was distributed by 56 light guides of 1 mm diameter and 2 m length^{**) (fig. 5)}. The light pulses from 54 of these guides were injected into the air gap of the modules (fig. 1). One light-guide was mounted in a similar way on a 2" x 2" NaI(Tl) PM assembly, but the intensity

^{*)} Manufactured by EGG Electro Optics Division, Salem, Mass., USA.

^{**)} Manufactured by Fiberoptik-Heim AG, CH 8707 Uetikon am See, Zurich, Switzerland.

of the light pulse was strongly attenuated in order to be approximately the same as the light from the $2'' \times 2''$ NaI crystal irradiated by a ^{22}Na γ -source (1.28 MeV). This assembly was placed in the same thermally isolated enclosure as the sector. The comparison of the light pulse intensity with the intensity of the light produced by the 1.28 MeV photons in the $2'' \times 2''$ NaI crystal allowed a precise control of the light pulser stability, as explained later. Finally, the light of the last guide was seen directly by an RTC PM1910 photomultiplier (18 mm dia.) which produced a light-pulser trigger for the data acquisition.

The FX280 Xenon bulb was driven at a rate of five flashes per second. At this rate the decrease in light output was about 1% per week. The FWHM of the peak produced by the light pulser was 2% to 4% depending on the bulb sample. Using different filters and diaphragm settings, the whole pulse-height range corresponding to 20-1000 MeV energy deposit in the NaI crystals could be covered. The light attenuation factors of the filters were calibrated using the $2'' \times 2''$ NaI assembly, the linearity of which was checked with radioactive sources. In this way the linearity of the module PMs and the associated electronics was determined up to 1 GeV equivalent photon energy.

2.4 Electronics

Figures 6a and 6b show the two types of electronic schemes which were used:

The arrangement of fig. 6a (d.c. coupling) is well suited for high counting rates but has two drawbacks: i) the PM has to be operated with the high voltage at the photocathode, which induces irreversible gain losses (up to 5%/day) if the PM in the cathode region is not extremely well shielded electrostatically; ii) the direct coupling may introduce ground loops and, in consequence, noise which prevents the detection of low-energy (some MeV) events.

In order to avoid these two drawbacks, the arrangement of fig. 6b (photocathode at ground potential and transformer coupling) was used during a later period. However, in this case the transformer in the anode circuit caused long (many microseconds) pulse overshoots which were particularly disturbing at high counting rates.

In both configurations the trigger was produced by a constant fraction discriminator (CFD) fed by the linearly added outputs of a certain number of modules (usually modules 1-24, fig. 3). For the pulse-height measurement, each module output was split (after amplification in the case of fig. 6a) and, after attenuation in one branch, fed a separate charge-sensitive ADC in order to obtain two dynamic ranges. Usually, the low-range (LO) was chosen to cover 0-100 MeV and the high-range (HI) 0-1000 MeV.

The contents of the 108 ADCs as well as the one of the ADC belonging to the 2" x 2" NaI assembly were read out in the usual way via CAMAC and written on magnetic tape via a PDP 11-34 computer. This computer also served to perform regular on-line checks on photon and light-pulser spectra produced by the detector modules.

3. ENERGY CALIBRATION

The modular structure of the system was conceived in such a way that a high-energy γ shower extends over several modules. Proper reconstruction of the event thus required a precise intercalibration of the modules and then an absolute calibration. The usual standards for calibrating γ spectrometers, such as γ radiation from radioactive sources or nuclear reactions, are not higher than 25 MeV and hence not relevant for the energy range up to 1000 MeV. Therefore a special method was developed in order to intercalibrate the different modules and to obtain an absolute energy calibration.

3.1 Intercalibration of the modules

3.1.1 Rough intercalibration

A rough calibration of the modules relative to each other was obtained by irradiating the spectrometer with the 660 keV γ -rays from a ^{137}Cs source and the 2.6 MeV γ -radiation from a Th source. The signals had to be additionally amplified in order to obtain pulse heights falling into the dynamic range of 10-1000 MeV. The signals were multiplexed to an amplifier, and the high voltage for the PMs of each module was adjusted so as to give the same outputs for all.

Owing to the limited resolution at these energies ($\Delta E/E \approx 15\%$ FWHM) the precision of this type of intercalibration was not better than 5%, and the resolution finally obtained at 130 MeV when using the event reconstruction described later was $\sim 12\%$ FWHM. This is demonstrated in fig. 7a.

3.1.2 Intercalibration at higher energies

The final intercalibration was obtained from γ -radiation of ≈ 130 MeV. The low-energy secondary beam k_{23} of the CERN Proton Synchrotron (PS) was tuned to slow π^- (200 MeV/c) which were then stopped in a liquid-hydrogen target. The π^- then underwent the reaction

$$\pi^- p \rightarrow n + \gamma \quad (E_\gamma = 129.4 \text{ MeV}) , \quad (1)$$

$$\pi^- p \rightarrow n + \pi^0 \quad (55 \leq E_\gamma \leq 83 \text{ MeV}) . \quad (2)$$

Since the initial state is a pionic atom at rest, the final-state energies were extremely well determined. Reaction (1) resulted in a monoenergetic peak, reaction (2) in a uniform distribution.

The procedure of finding the calibration factors for the single modules was the following. The 129.4 MeV peak of reaction (1) was assigned to the module v if at least 60% of the energy was deposited in that module (central module of the shower). The remaining 40% or less of the total energy being spread over the twelve neighbouring modules was added to the energy in the central module in order to obtain the full energy of 129.4 MeV. This procedure of γ reconstruction needs, of course, the rough intercalibration described above. It worked well for the 24 inner modules. Reconstruction of the energy for the 30 outer modules suffered somewhat from uncontrolled energy escapes. This was estimated by Monte Carlo simulations of the showers using EGS [4], and then corrected accordingly.

In a first step of several iterations, the peak positions c_v for each module were obtained with the intercalibration from the source calibration, i.e. with intercalibration factors $a_v^{(1)} = 1$. The deviation of these peak positions from the average peak position $\langle c \rangle$ determines the correction for the a_v 's. The new intercalibration factors are thus

$$a_v^{(2)} = 1 + \left[\frac{\langle c \rangle - c_v}{c_v} \right] .$$

In the second iteration the new intercalibration ($a_{\gamma}^{(2)}$'s) was taken to obtain more accurate factors $a_{\gamma}^{(3)}$. Not more than three iterations were necessary until stability was reached. The accuracy obtained for each a_{γ} was limited by statistics but was always better than 5%. The improvement in total energy resolution after the first step of iterations was approximately 50%. The final energy resolution was 5.5% FWHM at 130 MeV, if only the inner 24 modules were used as trigger modules. Figure 7a shows the improved γ spectrum after this intercalibration procedure .

It should be noticed that the calibration factors determined in such a way were applied only in the off-line analysis.

3.2 The absolute energy calibration

The energy scale for the modular γ spectrometer was defined by the peak position of the 129.4 MeV line, the two edges of the γ distribution of reaction (2), and the source peak positions. This still required an extrapolation when measuring energies higher than 130 MeV. Two more calibration points (774 MeV and 938 MeV) were available in the final experiment [5]. The linearity could be influenced by energy dependent shower escapes through the rear face of the detector. EGS-calculations show, however, that such non-linearities amount to 0.5% at most in the energy range from 100 MeV to 1 GeV.

3.3 Stabilization

As the calibration, once established, had to be maintained over periods of several months, a light-pulser system was developed as described above. The light-pulser information (i.e. the PM signals from the 54 modules measured by the same ADCs as those used for the actual data, and the signals from the reference module) was stored on magnetic tape and evaluated off-line. The stabilization, hence, was done only off-line.

In order to stabilize the light-pulser bulb, it first had to be ensured that the reference module PM and its electronics were stable. This was done by adjusting the amplification of the reference module off-line by a time-dependent correction

factor A_{ref} so that the ^{22}Na peak (P_{source}) stayed at its defined ($t = 0$) position:

$$A_{\text{ref}} = \frac{P_{\text{source}}(0)}{P_{\text{source}}(t)} .$$

The stability of the light-pulser bulb was then obtained by maintaining (correction factor A_{lp}) its peak position in the stabilized reference module ($p_{\text{lp}}^{\text{ref}}$) at the position it had at $t = 0$ with respect to the ^{22}Na peak:

$$A_{\text{lp}} = \frac{p_{\text{lp}}^{\text{ref}}(0)}{A_{\text{ref}} \cdot p_{\text{lp}}^{\text{ref}}(t)} .$$

Once the light pulser was stabilized, it could be used for correcting the instabilities of the single modules of the system. The calibration factors a_v were corrected off-line so as to maintain the light-pulser peaks (P_{lp}^v) at the positions defined at $t = 0$:

$$a_v(t) = \frac{P_{\text{lp}}^v(0)}{A_{\text{lp}} \cdot P_{\text{lp}}^v(t)} .$$

The light pulser was measured in the experiment every four hours. In between the four-hourly measurements, the $a_v(t)$'s were interpolated. This was possible because the real time was recorded for each individual event during the experiment.

This stabilization controlled only the PMs and the subsequent electronics, but did not control stability of the light output of the NaI module directly. Thus temperature shifts could still take place. However, by housing the reference module and the system of 54 modules in the same heat isolated cabinet, the temperature shifts were minimized.

The quality of the stabilization is demonstrated in fig. 7b: using unstabilized calibration factors [$a_v(0)$], the instabilities of the system led to a resolution of 11% after a period of 2 months. The absolute energy calibration also changed by $\sim 2\%$. Switching on the stabilization resulted in a resolution of 7%, as compared to the initial 5.5%. The absolute calibration did not shift by more than 1%.

4. RESPONSE TO PIONS AND ELECTRONS

The system's response to pions and electrons of well-defined momenta was investigated separately. The detector was placed in the beam in such a way that its virtual centre was in the focus of the beam. A specially designed support allowed the system to be positioned so that particles could be shot into single modules along their axes. A small plastic scintillator served as the trigger for impinging particles.

Pions (and muons) are expected to lose their energy by ionization only. If their energy is low enough for them to be stopped in the module, part of their rest mass is seen in the detector through their decay or reaction products.

Positive and negative pions are expected to react differently if they stop in the detector. A stopped π^+ can only decay, thus releasing a slow muon (5 MeV), which will stop again but whose decay positron will not be recognized by the system because of the long times involved. A π^- , on the other hand, when stopped will be totally absorbed by nuclear reactions whose decay products will partly be seen by the detector.

In consequence, fast through going pions release energy mostly in the module into which they are shot. Slow stopping pions release all of their kinetic energy in the trigger module. For stopping π^- 's, in addition, some of their rest mass energy is also seen by neighbouring modules. This is demonstrated in fig. 8, where the ratio of the energy deposited in the trigger module to the totally observed energy is displayed for different incident energies.

In the same figure this ratio is displayed also for electrons. The electron being almost massless, it releases its energy like a γ -ray through an electromagnetic shower. Consequently a much larger fraction of its energy is deposited in modules adjacent to the trigger module. The "error bars" in fig. 8 indicate the width of the distribution at half maximum.

The energy dependence of the energy resolution of the detector was measured with electrons in the energy range from 150 MeV to 800 MeV. The nominal momentum

resolution of the beam being $\Delta p/p = \pm 2\%$, the resolution showed a weak energy dependence, which can be described by

$$\frac{\Delta E}{E}(\text{FWHM}) = \frac{3.3\%}{\sqrt[4]{E(\text{GeV})}}.$$

5. SHOWER IDENTIFICATION FOR γ -RAYS

The conditions leading to an acceptable γ -event have been defined in such a way as not to introduce any energy dependence of the efficiency nor to reject too many events:

- One of the 24 inner modules was required to contain at least 40% of the totally registered energy.
- The trigger module together with its 12 direct neighbours was required to contain more than $90 \times [1 - e^{-E(\text{MeV})/58}]\%$ of the total energy. This condition was imposed in order to reject double events, but was empirically weakened at lower energies in order to maintain a constant cut-efficiency.
- The γ -to-pion selection as discussed above was finally not applied, as the efficiency losses would have been severe. Instead, a large plastic scintillator in front of the detector was used to reject charged particles.

6. CONCLUSIONS

A 54-module NaI(Tl) detector of spherical geometry (1/13th of the full sphere) was optimized to detect γ -rays from 20 MeV to 1000 MeV. A resolution of $3.3\%/\sqrt[4]{E(\text{GeV})}$ FWHM was obtained. A gain stability of $\pm 0.5\%$ could be maintained over periods of several weeks. The reconstruction efficiency for γ 's was energy independent for energies higher than 70 MeV. The response to charged pions and electrons was measured.

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Figure captions

- Fig. 1 : Cross-section of a detector module.
- Fig. 2 : Variation of the photopeak-height produced by a collimated ^{137}Cs source (661 keV) placed at a distance x from the front end of the NaI crystal. Results for three module samples are shown. About two thirds of the modules had longitudinal uniformities similar to the one of module 6.
- Fig. 3 : The detector assembly: at right -- stacking and numbering of the 54 modules; at left -- cross-section A-A. For details of the coupling between the NaI and the PM, see fig. 1.
- Fig. 4 : The light pulser (schematic). Not shown are the motor and encoder for the diaphragm, and an additional retractable filter between the diaphragm and the filter wheel.
- Fig. 5 : Distribution of the light pulses to the different PMs.
- Fig. 6 : The two electronic schemes used for the NaI-detector pulse processing.
- Fig. 7 : The spectra from the reaction $\pi^- p \rightarrow n\pi^0$ and $\pi^- p \rightarrow n\gamma$ [(a) as obtained from the calibration run, (b) 2 months later]. Open dots (O) in (a) show the 129.4 MeV peak as obtained from the source calibration alone. Open dots (O) in (b) show the 129.4 MeV peak as obtained without light-pulser correction.
- Fig. 8 : Response of the detector to π^+ , π^- and $e^\pm$. The fraction of energy released in the trigger module ($E_{\text{central}}/E_{\text{total}}$) is plotted as function of particle energy. The error bars indicate the width at half maximum.

- 1 AIR LIGHT GUIDE
- 2 SEALED GLASS WINDOW
- 3 REAR PLATE (AL)
- 4 AIR LIGHT GUIDE
- 5 MUMETAL SHIELD
- 6 IRON SHIELD
- 7 PM BASE
- 8 FRONT PLATE (STAINL. STEEL)
- 9 NaI CROSS SECTION AT $X = 0\text{cm}$
- 10 NaI CROSS SECTION AT $X = 39\text{cm}$
- 11 LIGHT GUIDE (FROM LIGHT PULSER)

Fig. 1

Fig. 2

CUT A-A

Fig. 3

Fig. 4

Fig. 5

a

b

Fig. 6

Fig. 7

Fig. 8