Test of non-perturbative QCD by means of the measurement of the K-pi scattering length II

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Abstract

A basic study on the position-sensitive gamma-ray detection using YAP and LuYAP crystals has been conducted so as to develop a new technique to be used in a development of new-generation positron emission tomography (PET). Array of 16×16 YAP or 11×11 LuYAP crystals have been irradiated with gamma ray from ^{137}Cs and ^{22}Na sources, and read-out using wave-length shifter fibers and the position-sensitive photomultiplier. The amount of light as well as the timing characteristics of the detectors have been measured.

1. Introduction

1. 1 Motivation

The main objective of this study is to detect the hadronic atom in which π^- and π^+ are bound with Coulomb force ($A_{2\pi}$) and measure its lifetime. This allows to deduce the pion scattering length, which can be compared in high precision with the result of the calculation based on the chiral perturbation theory. Thus, this experiment must be useful in testing the quantum chromodynamics in the non-perturbative region.

In 1993, L. Nemenov et al. tried to measure the lifetime of the hadronic atom, but due to the experimental inadequacy, they could only see the production of 272 ± 49 atoms[1].

We had been working on a development of high-precision trigger counter both in Kyoto Sangyo University and at CERN[2]. Together with Nemenov, we proposed an experiment at CERN based on his idea of measuring the $\pi\pi$ scattering length from the $A_{2\pi}$ lifetime, and our trigger counter. The proposal was approved in 1996 as experiment PS212 (DIRAC[3]), and we started the data taking in 1999.

Since then, a good amount of data on $A_{2\pi}$ atom has been obtained[4], and now we are undertaking an experiment to measure πK atoms[5]. At the same time, the trigger detector we developed[6] was proven to be very reliable, and shows a good performance both in space and time resolution.

In the present study, we try to apply our method of detecting charged particles to the detection of other radiations. We already tried to develop a neutron counter using the same multi-channel photomultipliers, and obtained a good result. In this specific study, we concentrate our effort on the detection of 511 keV gamma-ray.

1. 2 Objective of the present study

We have started our development of the position-sensitive photomultiplier (pspm) already a long time ago. Nowadays this device is widely used in the field of nuclear physics and high energy experiment. More than ten years ago we started the R&D of the application of this fast device to the readout of scintillating fiber, and developed hodoscopes to be used to detect charged particles. This device can detect particles with efficiency of about 98% in a flux as strong as 10^7/sec. The most recent product has a spatial resolution of 63 μm (RMS)

However, this kind of "imager" is not limited to the detection of charged particles. The method can be applied to X-rays, gamma rays or neutrons. We already developed a neutron detector with a resolution of 290μm (RMS) which can be used for the study of neutron diffraction.

Among the imaging application of gamma-rays or X-rays, the application to the medical instrumentation is by far the most challenging. Especially an application to the positron-emission tomography (PET) is attractive, since the PET device based on the current technique is very expensive, and this factor, although the device is known to be useful, prohibit the device to become popular. We believe that if our method can be applied to the detection of 511 keV gamma's, PET should be produced at much lower cost.

Thus, in this report, we focus on the study carried out in FY 2003 supported by the

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The required performance to the detector used in PET is a good spatial resolution, good efficiency and high counting rate. The spatial resolution of the existing PET is a few mm. We aim at improving it to about 1 mm. In order to limit the irradiation of the "patient", a detection efficiency of nearly 100% is required. The position-sensitive photomultiplier (H6568) has a very good time response, and thus, the high counting rate would not be a big problem.

2. Experiment

2. 1 General description of the method used

Light from more than one scintillator crystals is read out with one channel of multianode photomultiplier. Scintillators are paved in a two dimensional (x, y) plane, and the light from crystals having the same x (or y) coordinate is collected with a "light guide" and lead to the single channel of the photomultiplier (PM). Thus, we need a number of PM's proportional to the square root of the total number of the crystals. This makes a contrast to the traditional method of reading each crystal with a single PM where the number of PM's needed is proportional to the number of crystals.

However, in this configuration, the "light-guide" has to deflect the light by about 90 degrees, and the loss of the light is very large. To avoid this problem, we use wavelength shifter (WLS) as the light-guide. The light produced in the crystal is transported and absorbed by the WLS, and the WLS reemits photons with longer wave length into 4π directions. A part of the light is transported to the PM by the total reflection

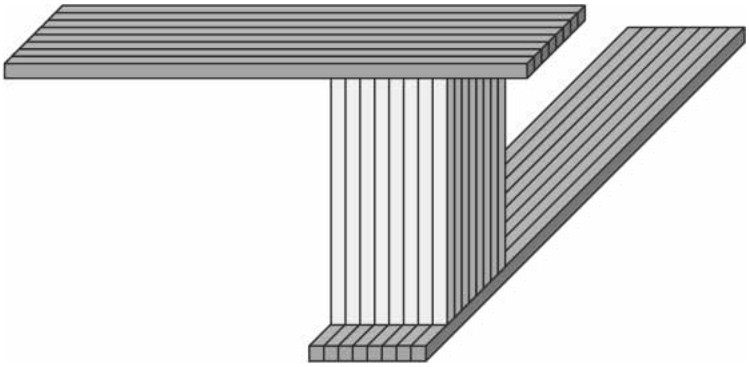

Fig. 1 Readout of scintillator crystal pad using wave-length shifter

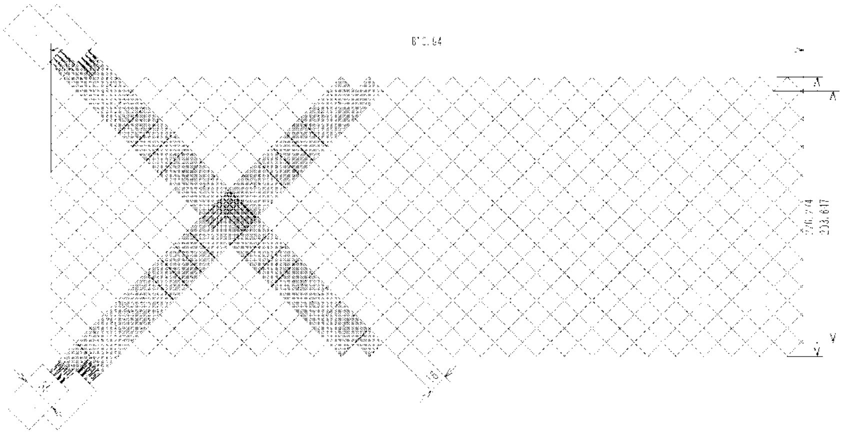

Fig. 2 Possible structure of an animal PET

mechanism within the WLS. This method is schematically shown in Fig. 1.

Fig. 2 shows the design of the "animal PET" we are now thinking about. The left edge meets the right edge and this flat plane makes a cylinder in which the gamma-emitting "animal" is inserted. 52 H6568 pspm's having 16 channels each are used to read out WLS's of one plane. Thus, about 100 pspm's are needed to make one PET. The coordinates are inclined by 45 degrees to make the reconstruction of the events easier. When two gammas are emitted in back-to-back directions, and detected at (x_1, y_1) and (x_2, y_2), one has still ambiguity of reconstruction. The signals from (x_1, y_2) and (x_2, y_1) will make the identical signal. But in this configuration, the wrong combinations correspond to two vectors whose opening angle is small, and the coincident hits are unlikely to come from these points. The draw back of this method is the smallness of the amount of photons reaching the pspm's. In the traditional method of read-out, one can discriminate gammas whose energy is smaller due to the scattering of the gamma-ray inside the body under examination. With our method, this discrimination is more difficult. Effort is needed to collect as much light as possible on one hand, and on the other hand, one has to remove the contamination of scattered gammas by using more sophisticated image processing technique.

2. 2 Experimental setup

2. 2. 1 Scintillator

In this study, we try to read out 256 scintillator crystals forming a square of 16×

16, or sometimes 121 crystals forming 11×11. The cross section of each crystal is 1 mm by 1 mm, and the length of the crystal is 20 mm.

2. 2. 2 Wave-length shifter

As the light guide, we used two times sixteen Kuraray B1(400) WLS having 1 mm ×1 mm square cross section. This absorbs light of about 350 nm, and emits photons with $\lambda=400$ nm. This WLS has a single clad construction and its refraction index is 1.49 whereas that of the core is 1.59. The length of the light guide is about 20 cm. Therefore the reemitted photons are transported to the pspm by the total reflection mechanism.

A pair of Hamamatsu H6568MOD pspm's have been used to convert the light signal to the electric signal. They have each 16 "almost" independent channels. The cross talk between channels happening mostly at the level of the photocathode is less than 1% according to our past experience.

2. 2. 3 Experimental setup

Last year, in place of 511 keV gamma source, we used ^{137}Cs source with 1 mm diameter which emits 662 keV gamma rays[7]. To measure the spatial resolution, we

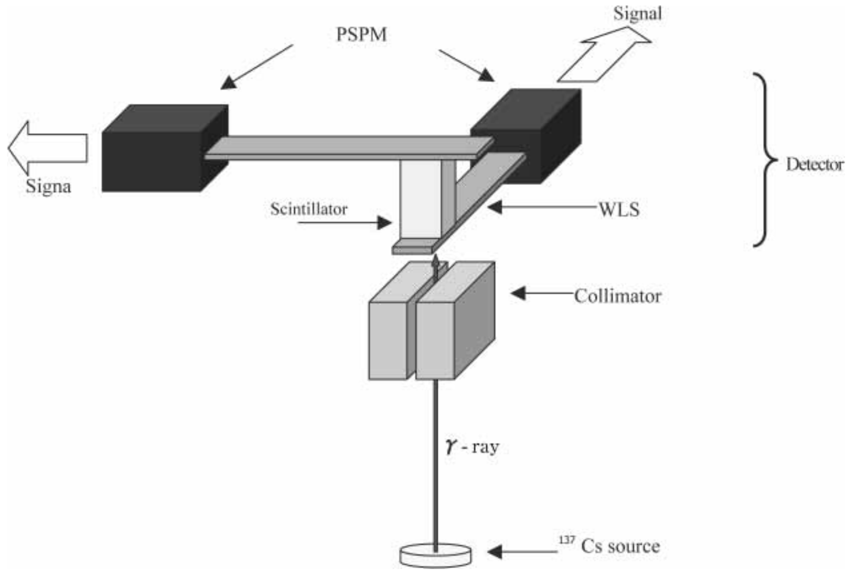

Fig. 3 Spatial resolution study using a collimator

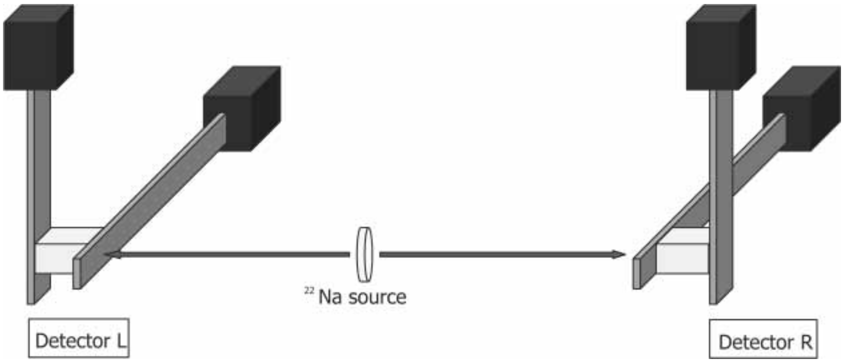

Fig. 4 Spatial resolution study using coincidence method

Table 1 Characteristics of the crystals used

Crystal	YAP(Ce)	LuYAP(Ce)
Composition	Y Al O_3	$(Lu_{0,5}$-$Y_{0.5})$ Al O_3
Index of refraction	1.94	1.95
Density	5.37 g/cm^3	8.34 g/cm^3
Effective Z	36	65
Decay time	25 ns	21 ns
Wave length	370 nm	370 nm
Dimension	1 mm×1 mm×20 mm	1 mm×1 mm×20 mm

used a collimator with a slit of 0.8 mm width formed with two blocks of lead having 40 mm thickness. This method is schematically explained in Fig. 3. Later, the collimator material was replaced by heavy alloy (mostly tungsten). The problem with this method is that not only that 40 mm of lead allows 0.74% of gamma rays to go through, but also the scattering on the inside surface of the slit is non-negligible. Nevertheless, we could obtain a spatial resolution of the detector by fitting, neglecting the flat background. We could obtain a spatial resolution of about 1.05-1.3 mm (FWHM) for YAP crystals of 1×1×6 mm[7].

To avoid this background effect, and also test the detector in a more realistic environment, this year, we tried a new setup schematically shown in Fig. 4. Here, we try to find out the spatial resolution from the spatial correlation between hit crystals in two detectors in coincidence.

In addition, we tried a new crystal, LuYAP which should show a higher detection efficiency for 511 keV gamma rays. At this stage of the study, the efficiency does not have such an importance, but the contribution of the photoelectric and the Compton effects might influence strongly the spatial resolution.

The characteristic of the LuYAP crystal we used is shown in Table 1 together with that of YAP.

2. 2. 4 Electronics and the data acquisition system

Fig. 5 shows the electronics scheme for the data acquisition. The pspm's have been modified so that all 16 (or 11, or 8) channels have a common last dynode, and from which, we can obtain an "or"ed signal of the 16 (8) channels. Each pspm is devoted to x, and y plane. Instead of taking the coincidence between the last dynode signals from the two pspm's we use a "fast clear" scheme. This is to allow measurement with scintillators having different decay times. As soon as a last dynode signal comes from one plane, the gate is open and the pulse height is recorded with CAMAC charge-sensitive ADC. When a signal from the other plane does not come within a fixed time, the recorded ADC signal is cleared. When the latter signal is existing, then the output

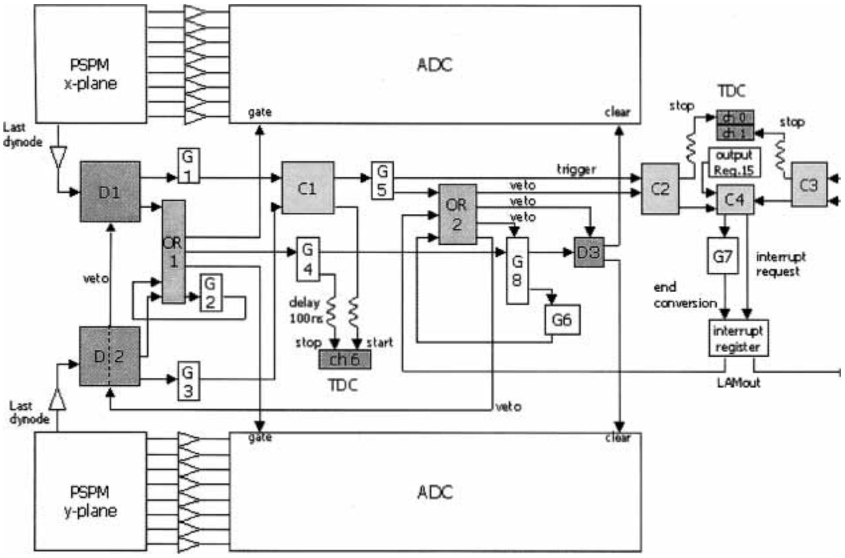

Fig. 5 Electronic scheme

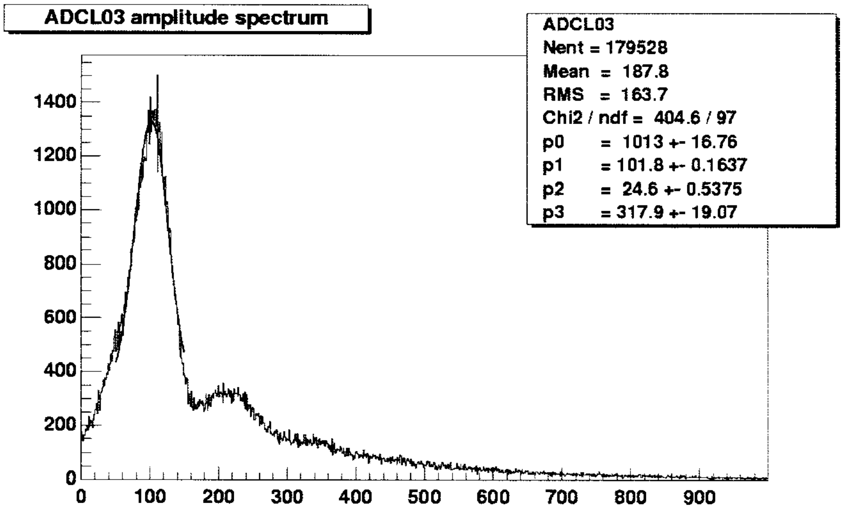

Fig. 6 Typical ADC spectrum (YAP)

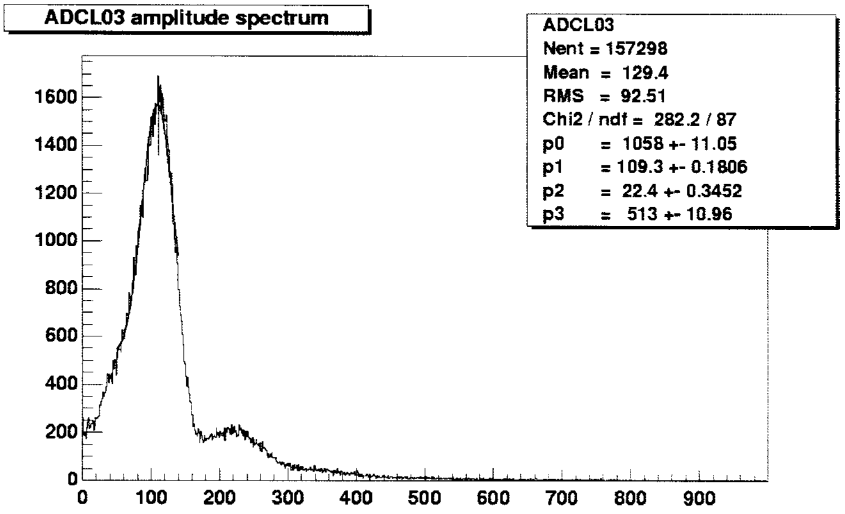

Fig. 7 Typical ADC spectrum (LuYAP)

from this plane is also recorded, and an interrupt signal to the data acquisition system is formed. Then all the information is transported to the computer through a KineticSystems parallel bus CAMAC crate controller Model 3922. By using a TDC, we recorded the time difference between the two last dynode signals of the recorded events.

To make the coincidence measurement, we duplicated the scheme for the second detector. In addition we added the part to make the coincidence between the two

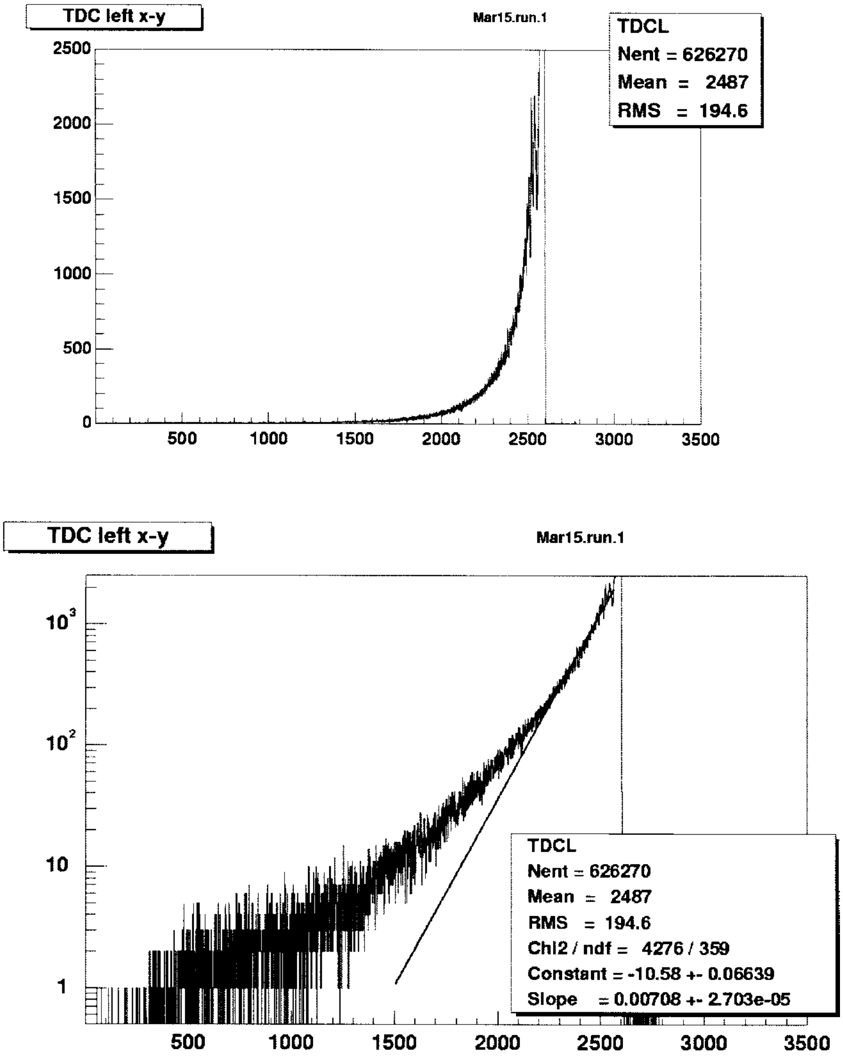

Fig. 8 Timing correlation between last dynode-signals (YAP)
Top : linear scale, Bottom : logarithmic scale with a fit

detectors, and record the timing correlation between the two.

The data acquisition has been performed using an IBM IntelliStation with Pentium 3 running under TurboLinux 6.0. We used the daq software together with a monitoring program "omon" developed by Igor Manuilov of IHEP based on ROOT program developed at CERN. The code is written in C++, and one can easily modify it by adding modules also written in C++ to the data acquisition system.

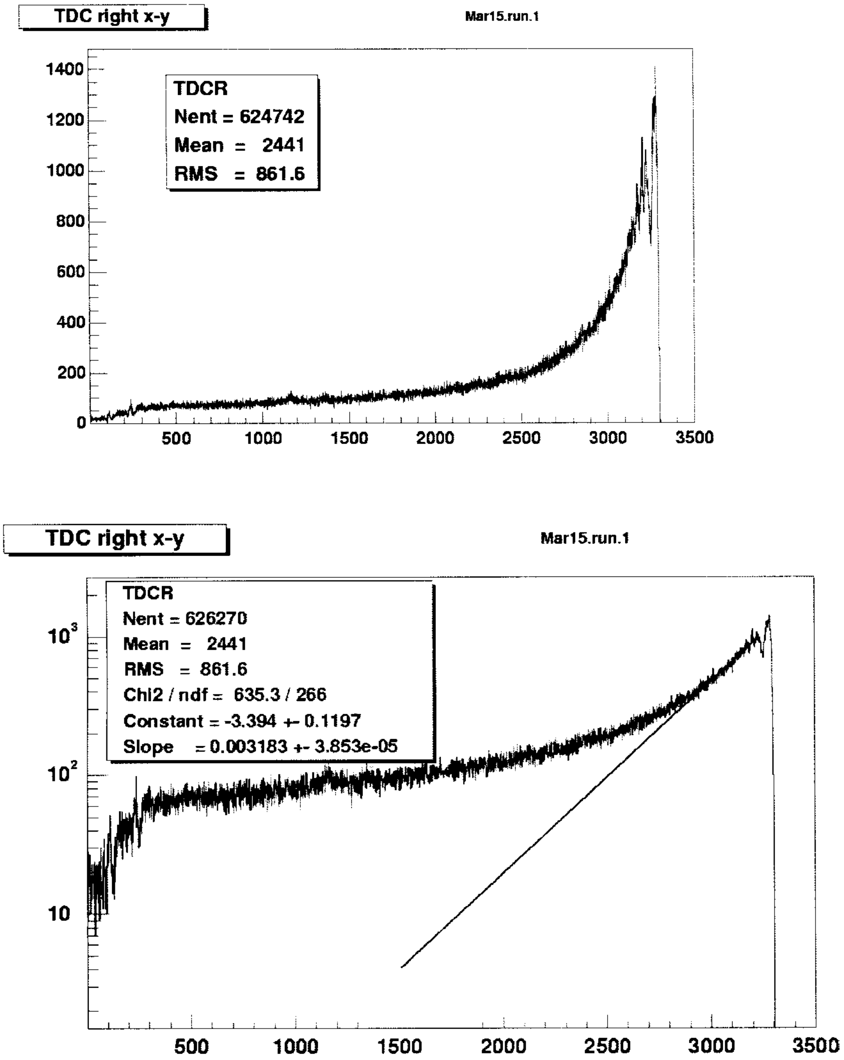

Fig. 9 Timing correlation between last dynode-signals (LuYAP)
Top : linear scale, Bottom : logarithmic scale with a fit

3. Results

3. 1 Pulse height

Signals from each anode are amplified by a factor 5 using a fast amplifier before being sent to the ADC. The following figures (Fig. 6 and 7) show typical ADC spectra of the pulse height for YAP and LuYAP crystals. The advantage of this pspm is that one can very clearly see the single photoelectron peak.

After fitting the single photoelectron peak, one can calculate the average amount of

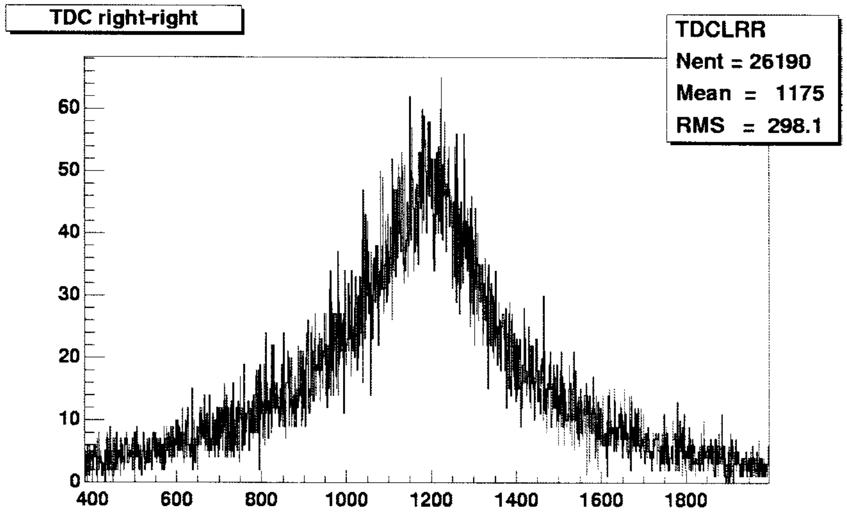

Fig. 10 Timing correlation between the two detectors in coincidence

photoelectrons. According to the measurement, the average amount of photoelectrons is about 1.84 for YAP, and 1.18 for LuYAP. All the channels of two planes show about the same result. After taking into account the case where no photoelectrons are produced, one can deduce the average number of photoelectrons to be 1.375 for YAP and 0.34 for LuYAP.

3. 2 Timing

The following figures (Figs. 8 and 9) show the timing correlation between the last dynode signals of the two PSPM for YAP, and the same for LuYAP detectors.

The gain of the TDC is 0.122 ns/chan. The obtained histogram has been fitted to find out the "decay time of the curve" of the YAP crystal which was found to be 17.2 ns, and 38.3 ns for LuYAP crystal. Note that this decay time is determined both by the light emission decay time of the crystals and the amount of photoelectrons. Even if the emission decay time is long, if the number of photoelectrons is large, the average time interval between the two last dynode signals becomes short. As shown in Table 1, the emission decay time for LuYAP is similar to, or even shorter than that for YAP. However, in this measurement, the "decay time" for LuYAP is longer. This reflects the fact that the amount of the light emitted from LuYAP crystal is smaller.

Fig. 10 shows the timing correlation between the two detectors. The gain of the

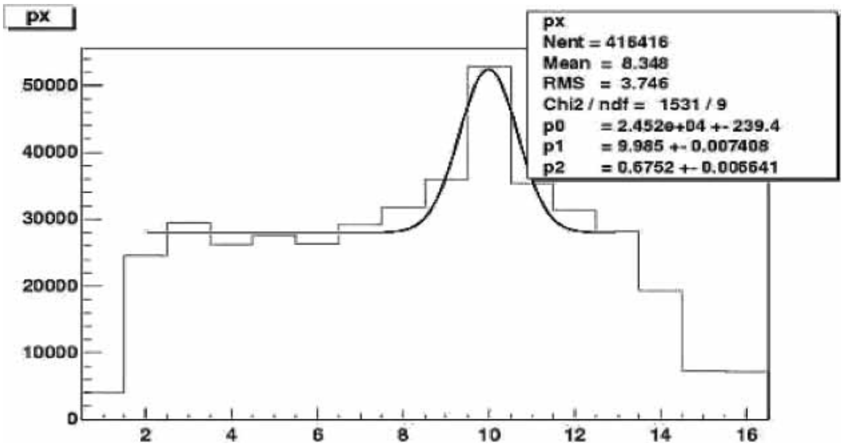

Fig. 11 Slit image projected to X-plane (YAP 1×1×20 mm)

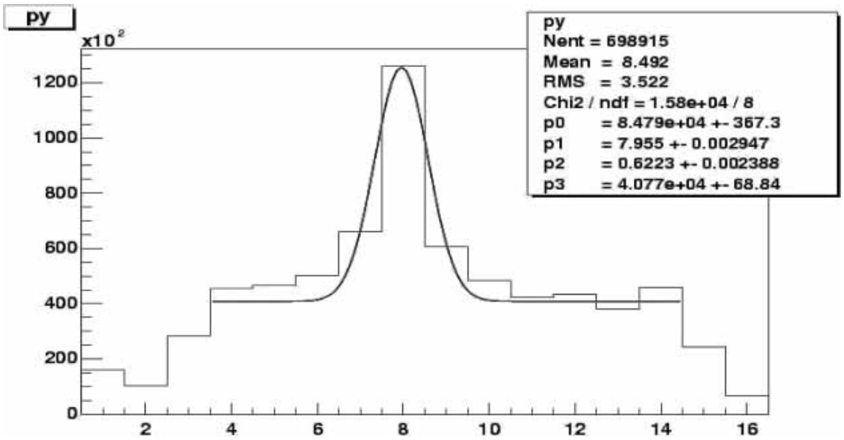

Fig. 12 Slit image projected to Y-plane (YAP 1×1×20 mm)

TDC is the same as before (0.122 ns/chan). Although this is preliminary, we anticipate that by tuning the system more carefully, it will be conceivable to design a PET with a counting rate of 10^7/sec.

3. 3 Spatial resolution

Last year, we made a measurement of the spatial resolution using the collimator method with 1×1×6 mm YAP crystals. We repeated the same measurement with a new YAP crystals newly obtained of 1×1×20 mm. The result is shown in Figs. 11 and 12.

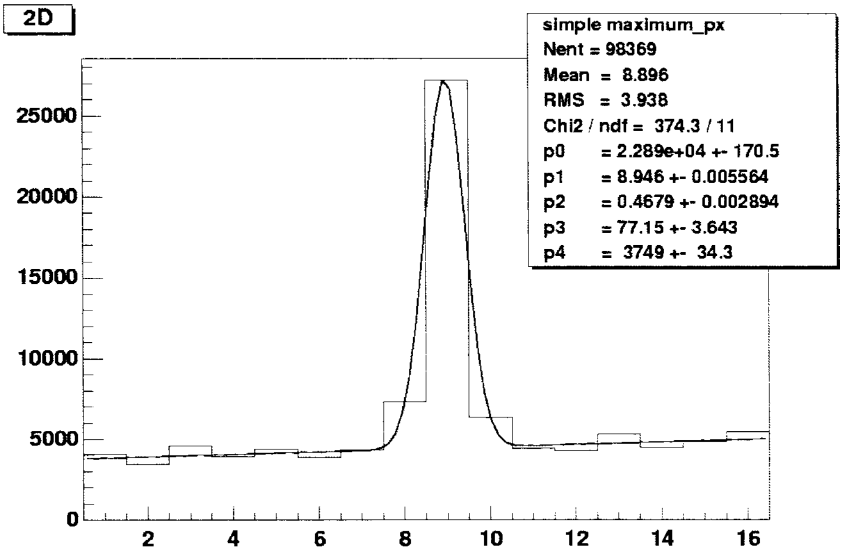

Fig. 13 Slit image projected to X-plane (YAP 1×1×6 mm)

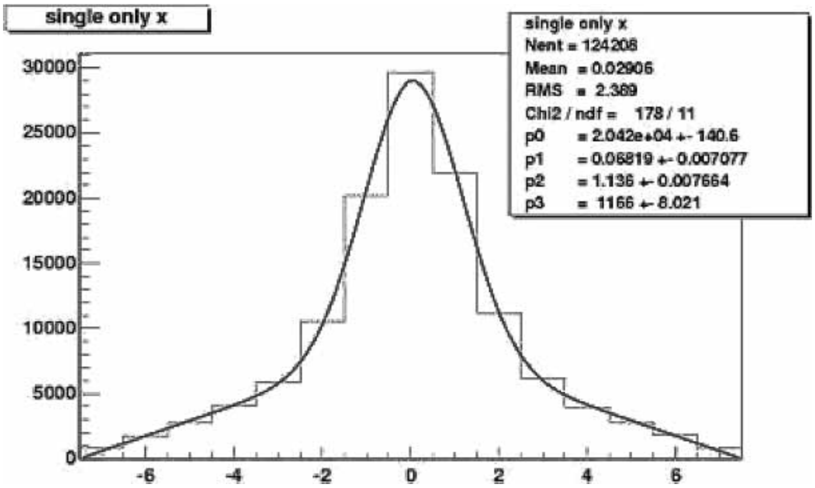

Fig. 14 Spatial correlation between two detectors and fit (X-plane)
Detectors placed at 50 cm from the source

One can notice that the central peak is sitting on a flat background in both planes. But the amount of the background is much larger than with the YAP crystal of 6 mm length obtained last year (reproduced in Fig. 13)

Very recently, we have started the measurement of the spatial resolution with the

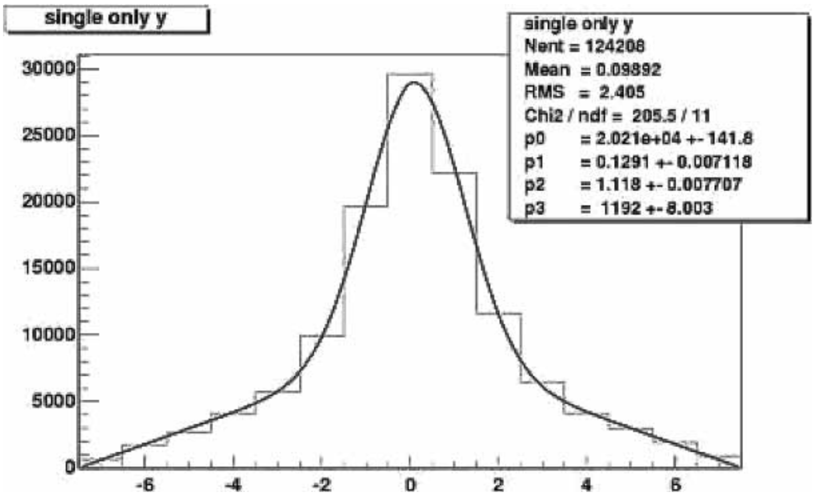

Fig. 15 Spatial correlation between two detectors and fit (Y-plane)
Detectors placed at 50 cm from the source

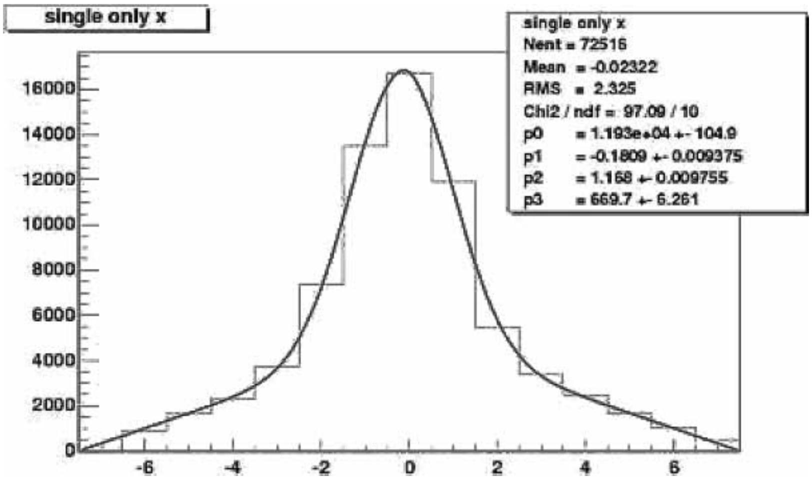

Fig. 16 Spatial correlation between two detectors and fit (X-plane)
Detectors placed at 30.5 cm from the source

coincidence method. The result shown here of the coincidence measurement is very preliminary. We need a much more careful tuning of the system to find out the spatial resolution.

When a coincidence hit was found, we extended the straight line connecting the hit scintillator piece in one detector and the center of the source to the other detector. We

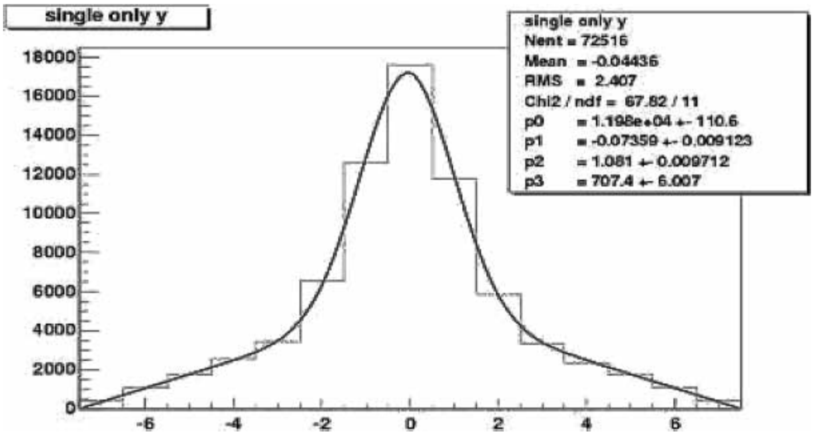

Fig. 17 Spatial correlation between two detectors and fit (Y-plane)
Detectors placed at 30.5 cm from the source

measured the distance between this projected position and the position of the hit crystal in the second detector, and plotted this distance in the following figures. We made this procedure in two planes independently.

We made this coincidence measurement with the distances between the source and one detector of 50 cm and 30.5 cm. The results were very similar.

We found that the distribution seems to consist of two components, the central peak and a symmetric base. The flat background we observed in the measurement with a collimator disappeared, but the "base" seems to constitute another background. We are now making effort to understand this shape.

The fit result of the central peak shows RMS "spatial resolution" of about 1.1 to 1.2 mm in two planes and in two measurements. This number, if taken as a spatial resolution of the detector, is much larger than the result obtained with the collimator method.

One of the main problems in this measurement is, although we tried to obtain a ^{22}Na point source, it could not be smaller than 1 mm in diameter. As the coincidence measurement system is now working, it might be interesting to use a smaller source, although its intensity is lower. We are now trying to "subtract" the effect of the size of the source.

As this measurement has just started, we have to spend much more effort to find out the real spatial resolution from the result.

4. Conclusion

We made fundamental tests using 256 YAP crystals, 121 LuYAP crystals of the size 1 mm×1 mm×20 mm, and ^{137}Cs, ^{22}Na sources. In the measurement with a collimator, we find that the spatial resolution of the detector is about 1.2 mm (FWHM). However, in this measurement, we see a fairly large background. We also proceeded a measurement using a coincidence method. The width of the found central peak is about 1.1-1.2 mm (RMS). It seems, however, that the size effect of the source is too large. But the result is still very preliminary, and there is a lot of space to improve the result. All the measurements were done with WLS of a section 1 mm×1 mm and H6568 pspm.

The light collection is the fundamental problem in this light-collection method. We need to study more carefully the configuration including the connection between crystal-WLS-pspm.

5. Future plan

We plan to improve the method of coincidence measurement. If the large size of the source is the problem, we plan to use a smaller one, although the intensity might be small.

We also plan to make a more detailed comparison between YAP and LuYAP crystals. The difference in the mechanism of the gamma absorption will give us hints so as to improve again the spatial resolution, and the light collection.

We also plan to make further study on the image processing. We plan to make tests using realistic images. At the same time, it is necessary to improve our computing resources.

6. Funding

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About Russian collaborators

Since long time, we are collaborating with the Russian group including K. Kuroda, A. Gorin, I. Manuilov and A. Riazanthev. Although the tests are done independently, we are in close contact in exchange information and materials