Octagonal scintillator for hard X-ray polarimetory

Tatehiro Mihara, Hachitaro Miyamoto (RIKEN, Japan) mihara@crab.riken.jp

Abstract

We made an "octagonal scintillator" to study the polarization detection in the focal plane. A simple, but the most effective method to detect X-ray polarization in is to utilize the non-uniformity of the Compton scattering. It works in high energy band of 20-100keV and suitable for the hard X-ray mirror. The octagonal scintillator consists of a scatterer column made of plastic scintillator at the center, and eight surrounding NaI scintillators which detect the scattered X-ray. The count rate distribution of NaIs gives the direction and degree of polarization. It has both a high modulation factor (M-factor) of the scattering method, and a high detection efficiency (η) which is essential to detect faint X-ray from the astronomical objects. We irradiated synchrotron X-ray (30-80keV) and measured the performance. The M-factor of the octagonal scintillator was 0.41-0.57 as expected. Together with the high detection efficiency ~0.4, it gives very high M $\eta^{0.5}$ value (~0.3), which means the highest efficiency of polarization detection. Although it is a non-imaging detector, it can be improved to an imaging polarimeter by changing the plastic scatterer to multi-segment plastic scintillator.

1. Polarization detection by Compton scattering

The cross section of the Compton scattering depends on the directions of outgoing X-ray to the electric vector of incoming X-ray (Fig 1.1). Measuring the φ distribution of the scattered X-ray gives the polarization of the incoming X-ray. The φ modulation is the maximum (M=1.0) in the "equatorial" plane (θ =90°), the minimum (M=0.0) in the poles, and M=0.5 when averaged in all direction. The high modulation is the largest merit of this method.

$$\frac{d\sigma}{d\Omega} = r_0^2(1-\sin^2(\theta)\cos^2(\varphi))$$

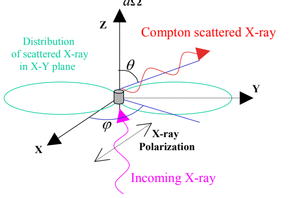

Fig 1.1. Compton scattering.

2. "Octagonal scintillator"

2.1. Scintillator

Although the polarimeter with the Compton scattering is efficient, it only works above ~20keV, since the photo-electric absorption is dominant in the low energies. The material of low atomic number is suitable for the scatterer. We chose plastic scintillator (CH_2) to detect the signal. The scatterer is surrounded by eight NaI rods, and we call it "octagonal scintillator" (Fig 2.1). The length of plastic was chosen so that it scatters a half of incident X-ray. A BaF_2 scintillator was placed at the bottom to stop the rest. It has longer decay time than NaI or plastic. All the ten scintillators are sealed up in one package.

The incident X-ray is either

1. photoelectric-absorbed by the plastic
2. scattered by the plastic and absorbed by one of the NaIs
3. scattered by the plastic and escapes out
4. penetrate plastic and absorbed by BaF_2.

	Light Yield	decay [ns]
NaI	100	230
BaF_2	16	620
Plastic BC408	29	2.1

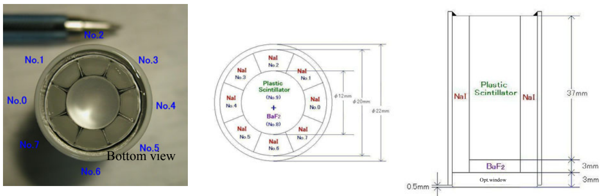

Fig 2.1. The octagonal scintillator.

2.2. Signal readouts

The scintillators are read out by a single position-sensitive photo-multiplier (Fig 2.2, 2.3). We can distinguish the events by position and rise time of the signal. The central position of scintillation light is calculated for each event and plotted in Fig 2.4. The NaIs and BaF_2/Plastic events are clearly separated by the position. Pulse heights of the slow and the fast components are plotted in Fig 2.5. The fast plastic events and the slow BaF_2 events are separated by the area. Thus we can separate signals from ten scintillators

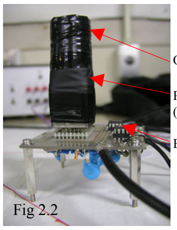

Fig 2.2

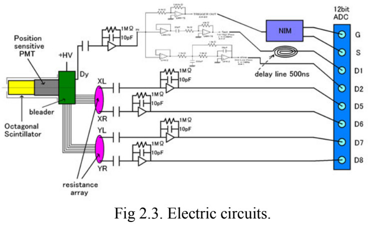

Fig 2.3. Electric circuits.

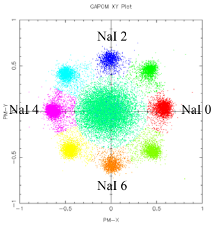

Fig 2.4. X-Y distribution.

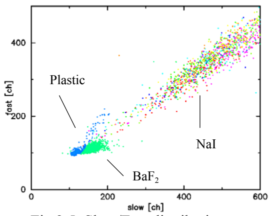

Fig 2.5. Slow/Fast distribution.

3. Experiment

We irradiated polarized synchrotron X-ray at KEK Photon Factory BL14A on 2003. 2.9-11 as Fig 3.1. The energies were 30, 40, 60, 80 keV. The 60 keV case was plotted in Fig 2.4 and 2.5. The spectra of ten scintillators are shown in Fig 3.2. The obtained efficiency of each scintillator is shown in Fig 3.3. The curves can roughly explain the data. The counts of eight NaIs showed a double-peak modulation as Fig 3.4. The observed modulation and obtained M-factor of the octagonal scintillator are listed in Table 3.1. The lower M-factors in 40 and 60 keV are due to smearing effect by I K escape of NaI. We rotated the octagonal scintillator by 45 degrees to make sure that the modulation is not systematic in Fig 3.5.

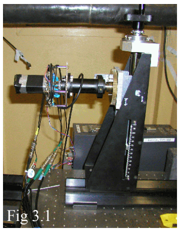

Fig 3.1

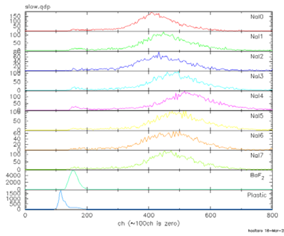

Fig 3.2. Scintillators' spectra of slow signals for 60 keV. The eight NaIs have similar pulse heights. They correspond to about 54 keV, since an 60 keV X-ray looses 6 keV by the 90-degrees Compton scattering. The BaF_2 peak is for 60 keV. The plastic shows a 60keV photoelectric peak like a tail, and a low energy peak of a back-scattered X-ray out of the octagonal scintillator. The Compton loss of back-scattered event is 12 keV at maximum.

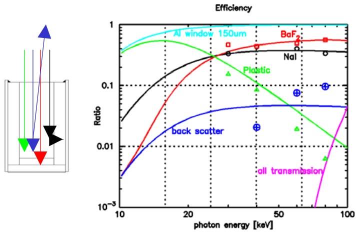

Fig 3.3. Efficiency of scintillators. The curves are based on cross sections without enough accuracy, and cannot fit the data perfectly. The 40 keV point of back scatter is low, because some of the events are below the discrimination.

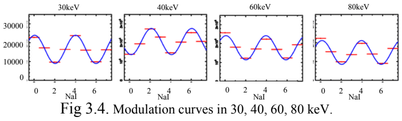

Fig 3.4. Modulation curves in 30, 40, 60, 80 keV.

Energy [keV]	Modul. (obs.)	Pol.of Beam	M-factor of oct.sci.
30	0.47	0.82	0.57
40	0.33	0.80	0.41
60	0.37	0.78	0.48
80	0.41	0.75	0.54

Table 3.1. Modulation values.

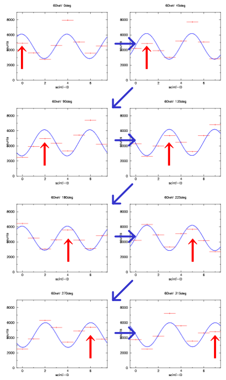

Fig 3.5 Counts modulation of NaI peaks at 60 keV. The maximum point, indicated by red arrow, shifts with rotation.

4. Sensitivity calculation

Since we confirmed the M-factor, detection efficiency, background rate of the octagonal scintillator, we can calculate the performance of the polarimeter when it is placed in the focal plane of a hard X-ray mirror. We assumed one multi-layer mirror designed for the NeXT mission. The calculation result is shown in Fig 4.1 by solid lines for 1ks ~ 1Ms exposures. The dashed line is the cases without background which obeys $F^{-0.5}$. The turn over in left is due to the background, where it has F^{-1} dependence.

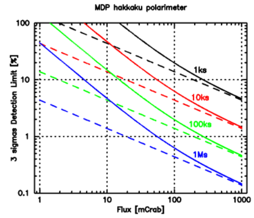

Fig 4.1. Calculated Minimum Degree of Polarization of the octagonal scintillator.

5. Summary

We made the "octagonal scintillator" and measured the performance in the synchrotron facility.

Eight NaIs, BaF_2, and Plastic events were clearly separated. Their pulse heights and ratios were almost as expected.

We succeeded to detect X-ray polarization. The M-factor was 0.41-0.57 in 30-80 keV as designed.

Together with a hard X-ray mirror, the 3 σ detection limit of polarization will be 2% for a 100mCrab source with 100ks exposure.