PRAMANA — journal of physics
© Indian Academy of Sciences
Vol. 57, No. 1
July 2001
pp. 141–147

A BaF_2 crystal array for high energy γ-ray measurements

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Abstract. We shall discuss about the scientific motivation and construction of a 7×7 BaF_2 crystal array at Variable Energy Cyclotron Centre, Calcutta. This detector would be used to measure high energy γ-ray photons from GDR decay and proton–neutron bremsstrahlung reactions at the present 88$''$ cyclotron and upcoming superconducting cyclotron at VECC, Calcutta. This detector can also be used to measure photons from quark–gluon plasma at the relativistic heavy ion collider (RHIC) in USA.

Keywords. BaF_2 crystal; fast signal; slow signal.

PACS No. 29.40.Mc

1. Introduction

The measurement of high energy γ-ray photons is an important area of current research in nuclear physics. The high energy γ-rays from GDR decay gives us valuable information about the shape of nuclei and equation of state of nuclear matter.

The high energy γ-rays above GDR γ-ray energy are primarily produced due to proton–neutron bremsstrahlung as two heavy nuclei collide. The study of such γ-rays tells us about the effect of nuclear medium on proton–neutron bremsstrahlung yield.

In relativistic heavy ion collisions, one of the signatures of quark–gluon plasma should be obtained from a precision measurements of photon spectra. All these studies require a high resolution γ detector array to measure high energy γ-rays.

Earlier measurements of high energy γ-ray photons were done with NaI(Tl) crystals. At present, BaF_2 crystal array is the state of the art equipment for measuring high energy γ-ray photons. BaF_2 crystal has excellent timing property and this property is used to discriminate against neutrons which is a major source of contamination of high energy γ-ray spectrum at intermediate energies. Since the time resolution of BaF_2 crystal is much better than that of NaI(Tl) crystal, BaF_2 crystal can discriminate against neutrons using a much shorter time of flight. So BaF_2 crystal array can be placed much closer to the target, thus covering a much larger solid angle.

Many laboratories around the world have developed large BaF_2 crystal array for measuring high energy γ-ray photons. A very well-known such array is called two-arm-photon-spectrometer (TAPS) [1]. It consists of large (25 cm long) hexagonal BaF_2 crystals arranged in packs of 64 crystals. Usually people do experiments with 6 such packs (384 crystals). There are smaller arrays of 50 or less number of crystals at Oak Ridge National Laboratory, Texas A&M University and several other places.

At Variable Energy Cyclotron Centre, Calcutta, we are constructing a BaF_2 crystal array as a part of our 9th 5-year project plan. This array would be used to measure γ-ray photons from GDR decay and proton–neutron bremsstrahlung reactions at VECC using existing 88$''$ cyclotron and upcoming superconducting cyclotron. Since this detector would be modular, it can be easily taken to other laboratories also for doing experiments.

2. Principle and description of detector

A γ-ray photon can interact with matter in three possible ways: 1) photoelectric effect, 2) Compton effect and 3) pair production. A high energy γ-ray photon (above a few MeV energy) interacts with matter primarily by pair production process. So when a high energy γ-ray photon is incident on BaF_2 crystal, it produces an electron–positron pair which starts losing energy in the crystal and produces ultraviolet scintillation light. The positron eventually annihilates and produces a photon which again undergoes pair production in the crystal. Thus a shower of electron–positron pairs is produced and the electrons and positrons lose their energy in the crystal emitting scintillation light in two different ultraviolet wavelengths. The fast component has a wavelength of 220 nm with a life-time of 0.6 ns, whereas the slow component has a wavelength of 320 nm with a life-time of 620 ns. The fast ultraviolet component (220 nm) is used for the time of flight type measurement and the energy of the γ-ray photon is determined by integrating (typically using a 1–2 μs gate) over the slow component.

A BaF_2 crystal array is made by closely packing a large number of BaF_2 crystals which are read out by photomultiplier tubes. In addition to providing a large solid angle coverage, a large array is required to contain the electron–positron shower generated by a high energy photon incident on BaF_2 crystal.

At VECC, we are building a square faced array (7×7) of BaF_2 crystals. The dimensions of each crystal are 3.5 cm $\times$ 3.5 cm$\times$ 35 cm. Each crystal would be read out by a photomultiplier tube which is sensitive to ultraviolet light. The photomultiplier tube should have a fast rise time and the transit time spread should be small. Then it would be possible to obtain good timing using the fast ultraviolet component of BaF_2 crystal. One can get very good time of flight (FWHM = 300–400 ps) using such an array and so it is possible to distinguish incident photons from fast neutrons which usually contaminate photon spectra produced in intermediate energy nuclear reactions. Since we are doing a close pack of the crystals, so the diameter of the photomultiplier tube has to be less than 35 mm which is the dimension of a face of the crystal. We are using Philips XP 2978 photomultiplier tube having a rise time of 1.9 ns and transit time spread = 0.25 ns. The diameter of the photomultiplier tube is 29 mm. Each crystal was at first wrapped with 5 layers of teflon wrapping (each layer 38 micron thick). Then one layer of aluminum foil (thickness = 130 micron) was wrapped on each crystal. The purpose of these wrappings is to reflect back ultraviolet light so that the light propogates along the length of the crystal through total internal reflection. There should be no wrapping at one end where the photomultiplier tube is attached. The photomultiplier tube is attached using a small amount of ultraviolet transmitting grease. A square shaped teflon reflector (35 mm $\times$ 35 mm) with a 30 mm hole at the centre is placed at the photomultiplier end of the crystal to reflect back the ultraviolet

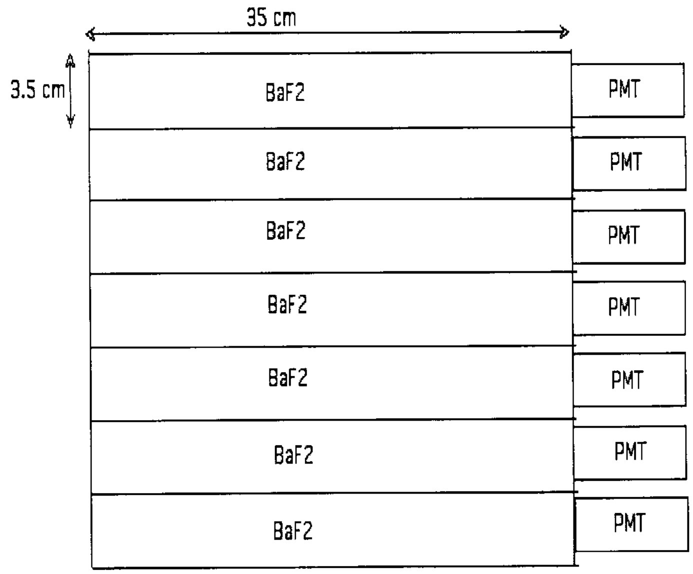

Figure 1. Sketch of BaF_2 crystal array.

light which may not reach the photomultiplier tube. A sketch of the detector is shown in figure 1.

The energy resolution of individual crystal is between 13%–14% at 680 keV. The uniformity of response of each crystal is measured by moving a Cs-133 source along the length of the crystal and the corresponding peak position is monitored. The results of our measurement are shown in figure 2. Along X-axis, the distance (X) of Cs-133 source from the one end of the crystal (which is opposite to the end where photomultiplier tube is attached) is plotted. The peak position (channel number) is plotted along Y-axis.

It is found that if uniform wrapping is used throughout the length of the crystal, then there is rather large nonuniformity. The photomultiplier tube sees more light (30% more) when the source is placed near the photomultiplier tube. We found that if teflon wrapping was removed from 5 cm region near photomultiplier end of the crystal, then there is good uniformity (within 5%) of response throughout the length of the crystal. So all the crystals would be prepared in this way and then a photomultiplier tube would be attached at the appropriate end of each crystal. Finally the whole array would be placed in an aluminum box that would be on a stand with a wheel arrangement. There would be an arrangement to flow dry nitrogen gas inside the box.

We have also simulated the response of this (7$\times$7) array of detectors for various γ-ray energies using GEANT code. In this simulation, the detector array is placed normally at a distance of 50 cm from the target position from where the γ-rays are incident isotropically on the front face of the detector. A total of 100,000 events were processed for each energy. Since some of the electron–positron pairs produced as a result of the interaction of γ-ray photon with BaF_2 crystals would escape from the crystal array without depositing their

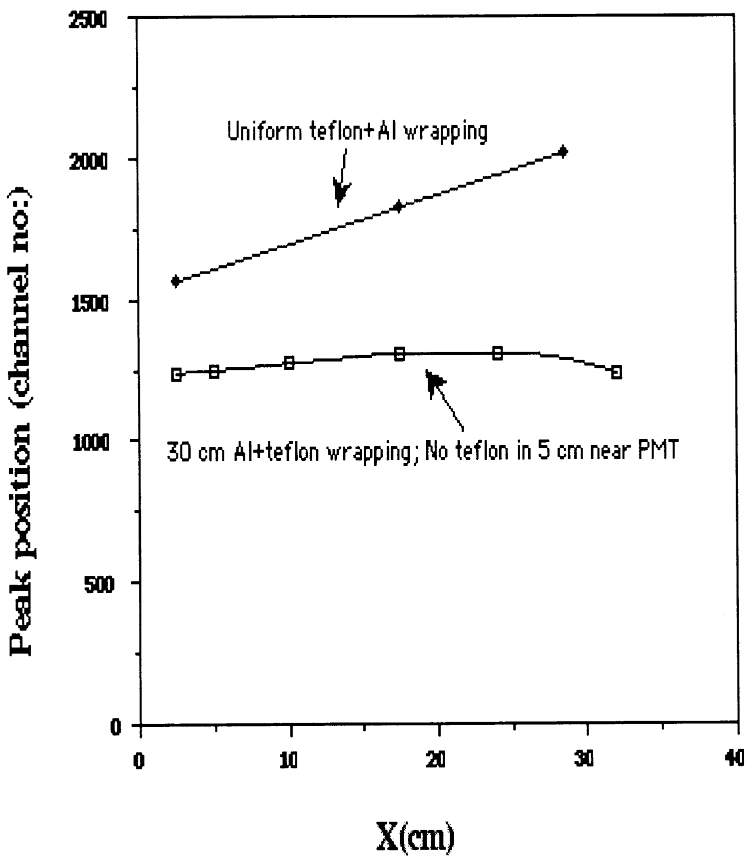

Figure 2. Uniformity of response along the length of crystal.

energies, the total energy deposited in the array would always be less than the incident energy of the photon. According to our GEANT simulation results, if 100 MeV γ-ray photons are incident normally at the centre of our array, the average energy deposition would be 86.7 MeV and FWHM of the peak = 34 MeV. If 1000 MeV γ-ray photons are incident normally at the centre of our array, then the average energy deposition would be 955 MeV with FWHM = 123 MeV. Hence there would be leakage of energy from the back and side of the array and this energy leakage would increase as the incident energy increases. In figures 3 and 4, we show the results of our GEANT simulation for 200 MeV and 50 MeV γ-rays incident isotropically on the face of the detector array. In each case, the total energy deposited, side leakage, back leakage, number of crystals hit per event, hit pattern and energy deposit pattern are shown.

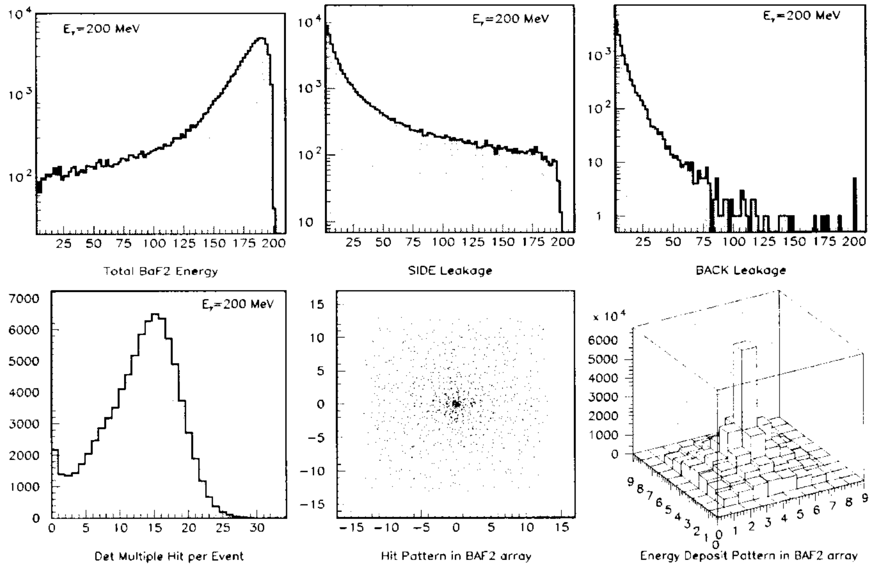

Figure 3. GEANT simulation of 200 MeV γ-rays.

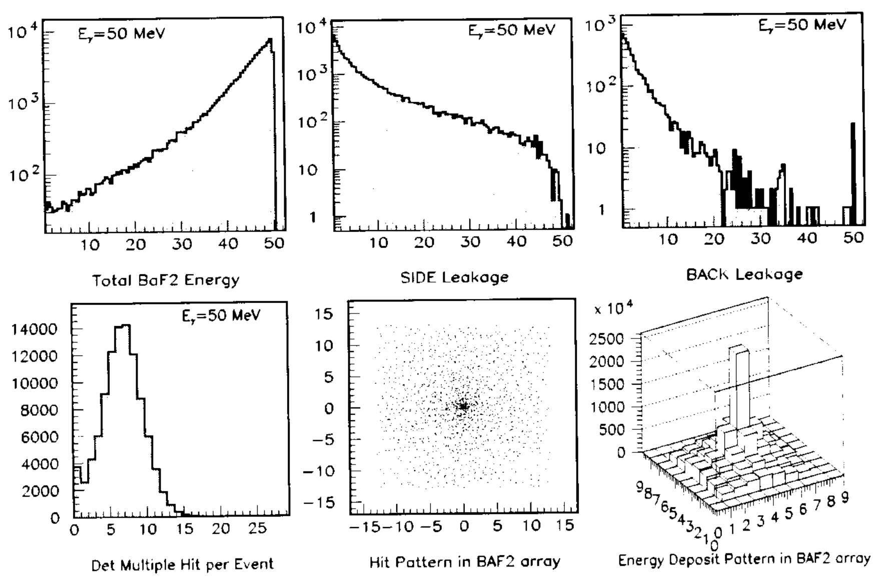

Figure 4. GEANT simulation of 50 MeV γ-rays.

3. Experiments using BaF_2 array

The BaF_2 crystal array would be used to measure high energy γ-ray photons produced in nuclear reactions at 88″ cyclotron and upcoming superconducting cyclotron at VECC. One can study γ-rays from giant resonances and also higher energy γ-rays from proton–neutron bremsstrahlung.

The study of giant resonances from highly excited states of nuclei formed by energetic collisions of two heavy ions is still an exciting field of research [2]. It is still not clearly understood to what extent the temperature or angular momentum affect giant resonance characteristics. The primary mode of decay from such resonances is by γ-ray emissions. The study of these γ-rays ($E_\gamma > 10$ MeV) enables us to probe into some very exciting and still unresolved nuclear phenomena. For example, the study of the giant resonance width with the increase in temperature of the decaying system enables us to probe into the damping mechanism in the vibrating nucleus. The evolution of the line shape of the resonance gives the surface properties of the nucleus. The γ-ray emission from the decay of giant dipole resonance is a very sensitive tool in studying fission fragment dynamics thereby probing into the viscosity effects and its temperature dependence through fission hindrance.

It is also not yet understood how and when the collectivity in a nucleus gets completely washed off as we go on increasing the temperature of the nucleus. Our BaF_2 crystal array is an ideal detector for studying such phenomena at Variable Energy Cyclotron Centre. We can also study higher energy ($E_\gamma > 30$ MeV) γ-ray emission in heavy ion reactions using our BaF_2 array and learn about the collision dynamics.

High energy photon emission is one of the cleanest probes of intermediate-energy nucleus–nucleus collisions. High energy photons are produced directly in the interaction zone and leave it virtually interaction free. So one can get an untainted view of the collision dynamics from the study of high energy photons produced in nuclear reactions. A large amount of mostly inclusive data on high energy photon production already exists [3–5]. One finds that above 30 MeV, the hard photon spectrum has an exponential shape, with an inverse slope parameter increasing with bombarding energy. The angular distribution of high energy γ-rays is strongly forward peaked in the laboratory frame, but transformed into the nucleon–nucleon centre of mass frame, it is nearly isotropic with a small dipole component. The intensity of high energy γ-rays increases with the number of individual leading proton–neutron collisions.

The body of experimental evidence has led to the conclusion that the high energy γ-ray photons produced in intermediate energy heavy ion collisions come primarily from first chance incoherent proton–neutron bremsstrahlung yield [6]. However the proton–neutron bremsstrahlung yield inside the nuclear medium is different from that in free space. The nuclear medium modifies the proton–neutron bremsstrahlung yield. One can learn about the effect of nuclear medium on proton–neutron bremsstrahlung yield from the study of high energy γ-rays produced in intermediate energy heavy ion collisions. We can undertake such studies at Variable Energy Cyclotron Centre using our BaF_2 crystal array.

Recently hard photon production in ^{36}Ar + ^{197}Au and ^{36}Ar + ^{12}C reactions at 95 MeV/nucleon was studied [7] at GANIL using a large BaF_2 array known as TAPS. This work clearly showed that at this energy for central ^{36}Ar + ^{197}Au collisions, the high energy photon emission is not solely dominated by first-chance proton–neutron collisions, but also carries information on the stopping phase of the reaction. So high energy photons not only probe the very first phase of a heavy ion reaction, but also carry information on the later, stopping stage of the collision. We plan to undertake such studies at VECC using the BaF_2 crystal array.

The study of photon spectrum at relativistic heavy ion collider (RHIC) should tell us about the formation of quark–gluon plasma. Since the photons can escape the interaction region with a low probability of secondary interaction, they can provide valuable information about the formation of quark–gluon plasma in such reactions. Unfortunately most of the photons are produced due to the hadronic decay such as the decay of π^0 meson. Moreover the photon background in a high energy experiment is usually very large. All these things complicate the interpretation of data. However precision measurements of photon spectra at different rapidities are certainly required to understand the formation of quark–gluon plasma produced in relativistic heavy ion collisions. Such studies can also be done using our BaF_2 crystal array in collaboration with broad range hadron magnetic spectrometer (BRAHMS) group at the Relativistic Heavy Ion Collider in USA.

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