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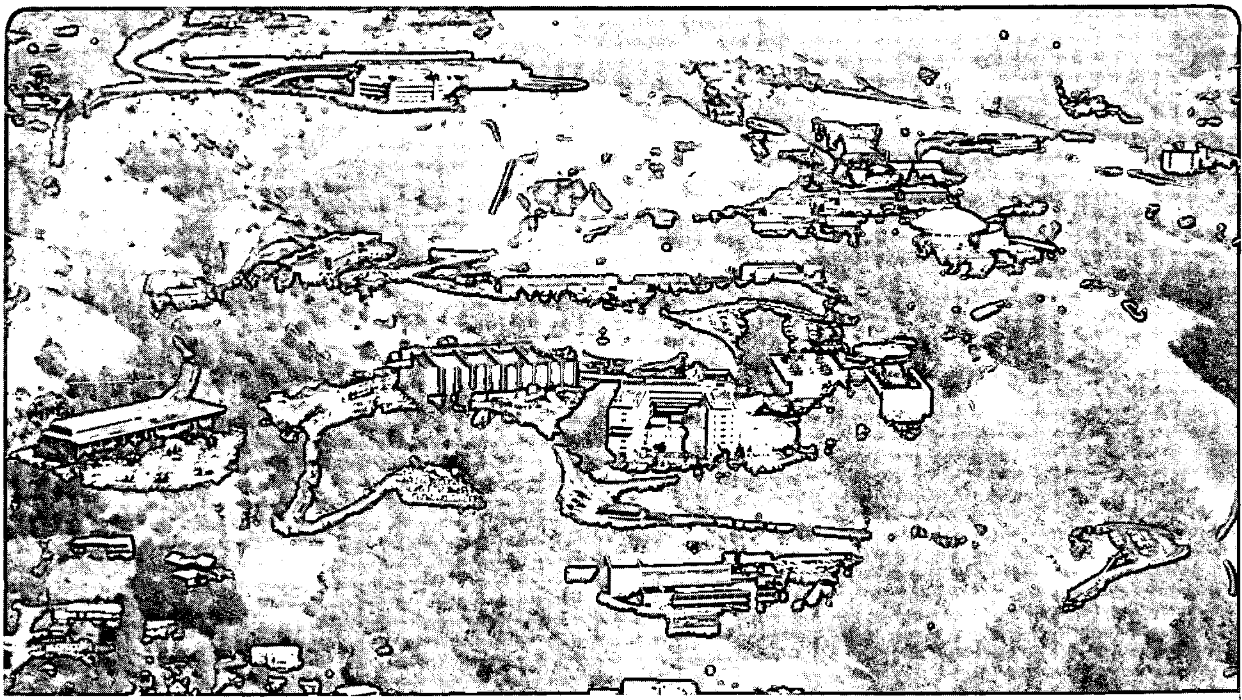

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Abstract

We describe the design of the signal processing system and considerations involved in the timing performance of the BGO scintillator Compton shield that surrounds each of the 110 large germanium detectors used in a geodesic array covering the complete sphere surrounding the target in GAMMASPHERE. It is shown that the main timing limitation results from the statistics of photoelectron emission from the photocathode of the photomultiplier tubes (PMTs) that observe the light from the scintillators and that achieving the required timing demands triggering on the first photoelectron. The circuits to do this for a single detector assembly must be able to deal with signals from 14 PMTs associated with the 7 elements of the scintillator shield surrounding each germanium detector.

1. INTRODUCTION

GAMMASPHERE is a detector system designed to study emission of multiple coincident gamma rays from highly deformed nuclei with high angular momentum(1) resulting from heavy-ion interactions in a target. The system(2) consists of a complete sphere of 110 hexagonal-shaped detector modules containing a large central coaxial germanium detector (8cm long x 7.2cm dia.) surrounded by a BGO scintillator Compton shield designed to increase the peak to total ratio for 1MeV peaks in the Ge detector's spectrum from about 25% to about 60%. The face of a Ge detector is located 25cm from the target as shown in Fig. 1. The BGO Compton shield consists of 6 wedge-shaped crystals around the periphery of the Ge detector and a cylindrical "back-plug" behind it.

Most of the applications of GAMMASPHERE require multiple coincident signals (typically five or so) in different germanium detectors in order to select interesting reactions from the general field of gamma rays produced by uninteresting reactions. To be effective in these circumstances, each Ge detector must have the maximum possible efficiency, since the overall efficiency is proportional to the individual efficiency raised to the power of the multiplicity. A small loss dE in efficiency in one detector results in a system loss of approximately M.dE (where M is the multiplicity). A consequence of this is that the BGO shield should, as far as possible, be prevented from rejecting Ge detector events except those that truly represent scattered gamma rays from the Ge into the BGO. This is the reason for the "honeycomb" Hevimet absorber designed to prevent gamma rays not related to the decay chains of interest in the target from reaching the BGO scintillator. The BGO shield and the Ge detector subtend approximately the same angle at the target, so the probability of gamma rays striking the BGO would be high in the absence of the Hevimet.

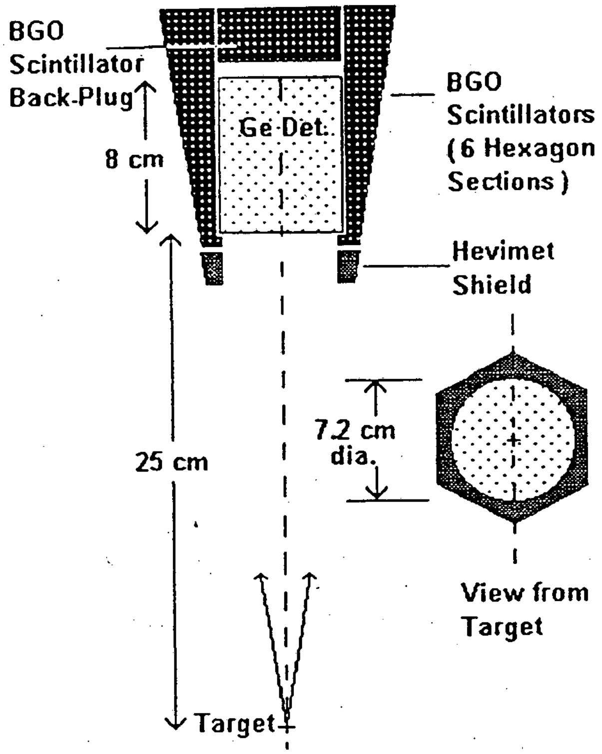

Fig. 1. Target/detector geometry for a single detector module in GAMMASPHERE. 110 modules surround the target.

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The same reactions that produce gamma rays also produce high-energy (average energy about 2 MeV) neutrons in numbers that can approach those of gamma rays. Of course, the Hevimet shield is unable to stop neutrons but the BGO is relatively efficient at absorbing them so they can produce false rejects of Ge detector signals. The intent in GAMMASPHERE is to eliminate these false rejects by flagging the time of events in both BGO and Ge detectors and using the fact that the flight time of neutrons from target to detector ranges upward from 15ns. This places stringent requirements on timing for the BGO signals - a particularly difficult problem when using large, thin slabs of scintillator and in such a complex system as GAMMASPHERE. These are the problems we address here.

Since timing is always a function of energy, we must establish immediately the energy ranges of interest. The primary range of interest for Ge signals is from 300KeV to 3MeV with some extensions to lower and higher energies. For total energy measurements with no Hevimet shield, the primary BGO energy range of interest is from 100KeV to 10MeV. Compton rejection requires detection of events in the BGO down to 15KeV. Neutrons interact in the BGO primarily with the Ge component to produce gamma rays that are absorbed in the scintillator to produce light signals. Spectra of gamma rays produced in BGO by neutrons of various energies measured at Chalk River(3) are given in Fig. 2. We see that the neutron-produced gamma rays generally have energies greater than 400KeV for neutrons typical of those produced in GAMMASPHERE experiments. Therefore, our problem is to provide BGO timing information with an accuracy of 15ns or better. The timing and energy information can be combined by software to provide neutron/gamma discrimination.

2. BGO DETECTOR TIMING FUNDAMENTALS

The light output of BGO is small compared with inorganic scintillators such as NaI(Tl) and the decay time of the light is quite long (about 330ns)(4). These factors, together with the relatively poor light collection efficiency of the long and thin scintillator slabs used here, mean that the signal from the PMT(s) attached to the BGO crystal is best considered as due to discrete photoelectrons emitted from the photocathode with a time distribution characteristic of the BGO light decay curve. Our early work indicated the importance of maximizing the light collection and the arrangement determined to be best for these scintillators consists of attaching two 1" PMTs to the end face of the main scintillator slabs. For symmetry, we also choose to use two similar PMTs (Hammamatsu R1924) for the cylindrical back-plug. Measurements show that this arrangement yields about 1 photoelectron on the average for each 4KeV of energy absorbed in the scintillator. This means that a 400KeVgamma ray will yield about 100 photoelectrons total from the two PMT photocathodes integrated over the complete decay time of the scintillator light - an average rate of 1 every 3ns at the start of the decay. In fact, the light transmission and multiple reflections from the scintillator surface means that the initial rise (5) in the light output is limited in speed and we model this effect by assuming a 3ns RC integration in the (statistical) emission process. This simple picture illustrates that the statistical time distribution of photoelectrons will act as a major limitation in the timing capabilities for GAMMASPHERE.

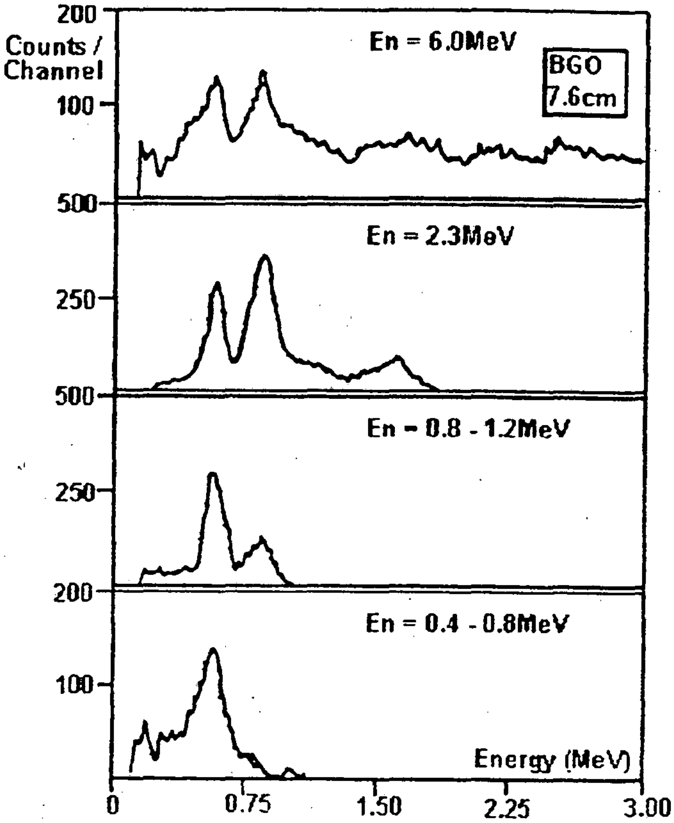

Fig. 2. Gamma ray spectra produced in BGO by high energy neutron irradition (from Ref. 3).

Many scintillator timing applications use constant-fraction discriminators. It is well known (6) that a situation like that in GAMMASPHERE is better approached by using a very low level discriminator triggering at a single photoelectron level. Since dark current in the PMT can also produce single electron signals, the elimination of counts due to this is accomplished by "validating" a real scintillation by making sure that a significant number of photoelectrons arrive in a reasonable time after the first trigger. In our case

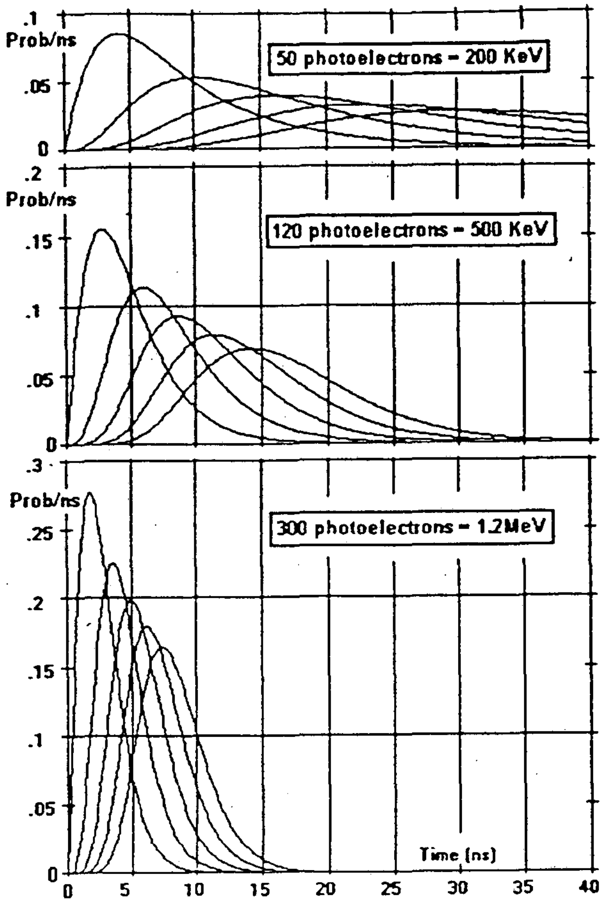

Fig. 3. Calculated timing distributions for triggering on the first 1 to 5 photoelectrons from PMTs mounted on a BGO scintillator. Results are given for total photocathode yields of 50, 120 and 300 photoelectrons.

we use the criterion that the equivalent of 4 photoelectrons must arrive within 60ns. Fig. 3 illustrates the need to trigger on a single photoelectron in order to achieve the required <10ns timing accuracy. This figure shows the calculated time distribution of photoelectrons from BGO for three signal sizes typical of GAMMASPHERE. Curves are given for triggering on 1 to 5 electrons; clearly only the single electron trigger meets the requirement that most events can be recognized in time to better than 15ns for the typical GAMMASPHERE BGO signal of 120 photoelectrons.

Beyond this fundamental limit in timing, two additional sources can contribute to the time spread. A time spread exists in the transit of electrons up the dynode structure of the PMT. For the tube we use, this amounts to about 3ns (FWHM). A further time spread is caused by electronic noise in the electronics that processes the PMT signals. We have chosen to keep the PMT voltage relatively low in order to ensure reliability and to minimize gain changes with time and radiation exposure. The limit to doing this is set by the need to make the timing contribution due to electronic noise small. We use the PMTs at 600 to 800 volts (gain of approximately $1.5\text{x}10^{5}$) and the input stages of the electronics produce noise in the range of $2\text{nV}/\sqrt{\text{Hz}}$. With the pulse shaping described in the following section, the time spread due to noise is about 3ns FWHM which only degrades the overall timing by a small amount compared with the effect of photoelectron statistics at low energies.

3. PROCESSING ELECTRONICS - CIRCUIT DESIGN

Figure 4 shows the overall signal processing system. Charge signals from the two PMTs associated with each scintillator are added on a capacitor totaling 100pF (including PMT anode and the buffer input capacitances) and a parallel 51K resistor produces a signal with an RC decay time of 5us at the input to a buffer (gain = 1) stage mounted on the PMT base. The signal passes along a short cable to the detector module electronics box mounted on the dewar of the Ge detector system with which the BGO Compton shield is associated. (This box also contains the computer-controlled and regulated high voltage supplies for the PMTs and the germanium detector). Here a gain of 10 stage amplifies the signal which then travels along a 50ft. cable to the electronics house on the roof of the cave where the VXI processing electronics is housed. The entire BGO signal processing for a Compton shield (including 7 BGO channels) is implemented using surface-mount components on a daughter board that mounts on a VXI board. A photograph of this daughter board is shown in Fig. 5. It includes individual single photoelectron and 15KeV discriminators, a sum channel where the total energy signal in the whole BGO Compton shield is derived and a 100KeV discriminator on this channel. The board also includes various gates associated with the trigger system - these will not be discussed here.

The sum channel contains an operational amplifier used as a mixer with a gated wrap-around baseline restorer included to permit the system to be used at counting rates over 20 KHz. A 220ns RC integrator is also included in this stage to reduce high-frequency noise. This stage is followed by a 1us delay-line differentiator stage that includes correction for the 5us decay in the input signal to ensure that the output signal returns to the baseline accurately. The gain of the sum channel is chosen to permit linear operation up to 10 MeV. The sum channel feeds a 100KeV discriminator the output of which is used to register a BGO hit to the rest of the system.

Each individual BGO channel signal path includes a gain of 10 amplifier, a 10ns RC integrator and two 1us RC differentiators to produce the bipolar signal that feeds the single photoelectron and 15KeV discriminators. The first

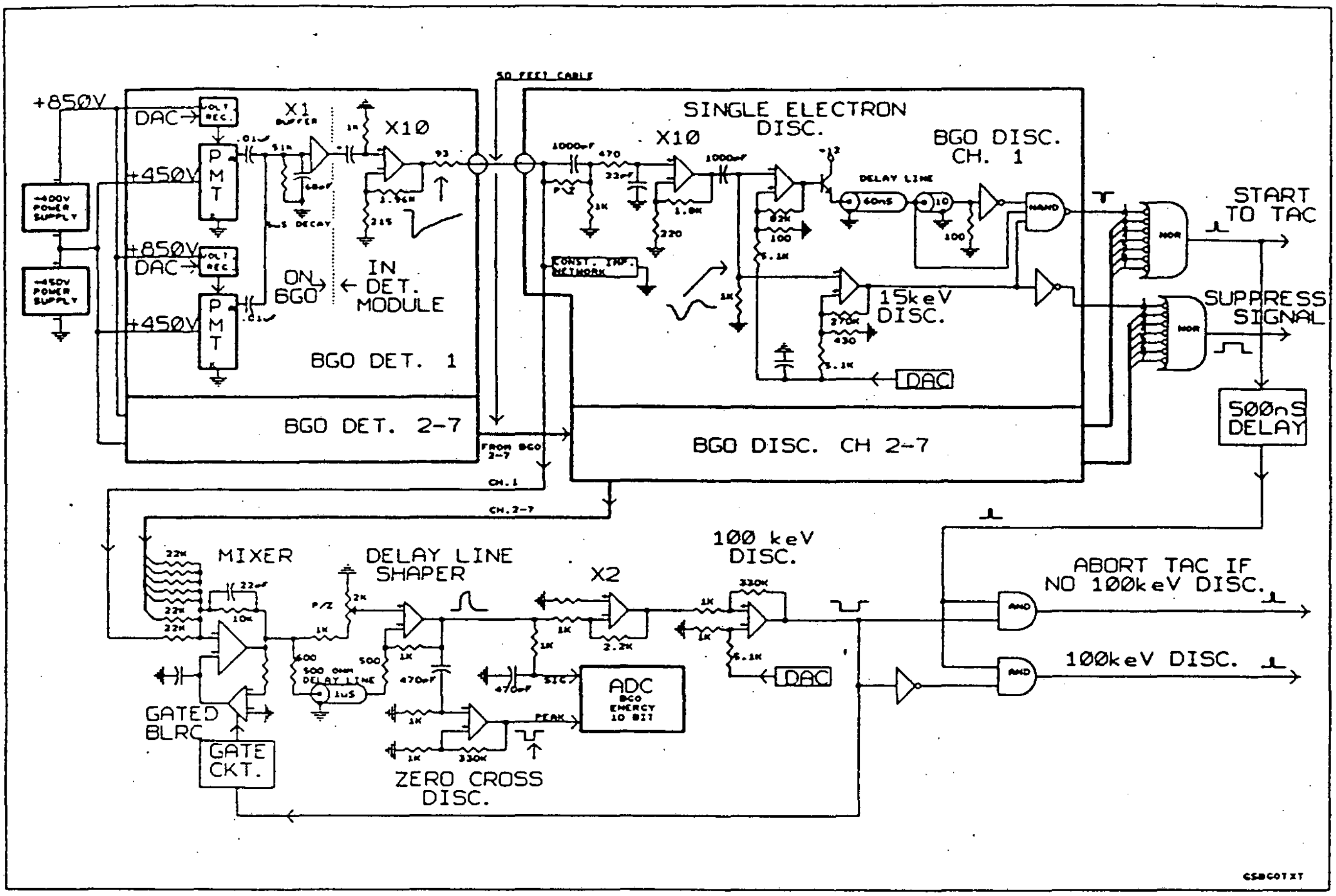

Fig. 4. A schematic of the BGO signal processing circuits.

RC differentiator has a pole-zero corrector for the 5us RC decay of the input signal. Fig. 4 also shows the important waveforms that are present at the various stages. The single photoelectron signal at the input of its discriminator is 15mV high and the discriminator is set to trigger at about 10mV, significantly above noise. The discriminator is designed to have a backlash of 6 mV to prevent noise triggering on the tail of signals. The 15KeV discriminator is set to trigger on 43mV (ie 4.3 times the single photoelectron discriminator level). The output signal from the single photoelectron discriminator is delayed by 60ns and shaped into a 10ns wide pulse. This pulse feeds an AND gate whose other input is derived from the 15KeV discriminator. Consequently, the single photoelectron signal is only "validated" if the 15KeV discriminator fires within 60ns. This "validated" single photoelectron signal is used for BGO timing measurements when the 100KeV discriminator indicates a BGO hit to the system. The 15KeV discriminator output is used to tag a possible Compton suppression signal; the actual suppression of the germanium signal is performed by software where the time information is used to prevent suppression by neutron signals in the BGO.

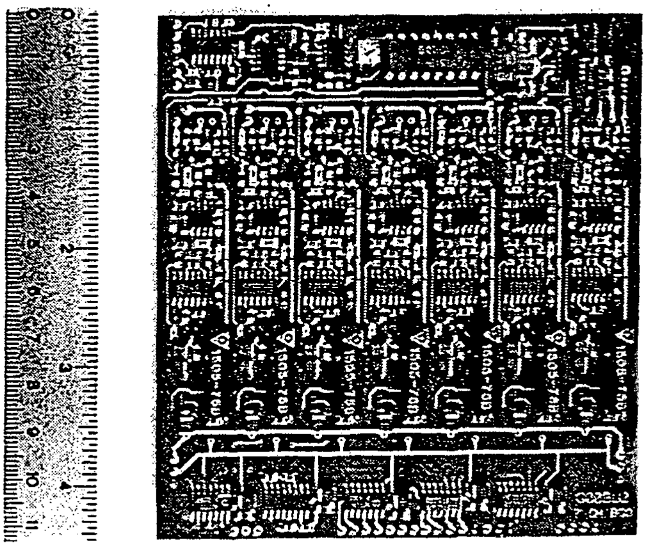

Fig. 5. Photograph of the BGO signal processor daughter board. This mounts on a VXI board in GAMMASPHERE.

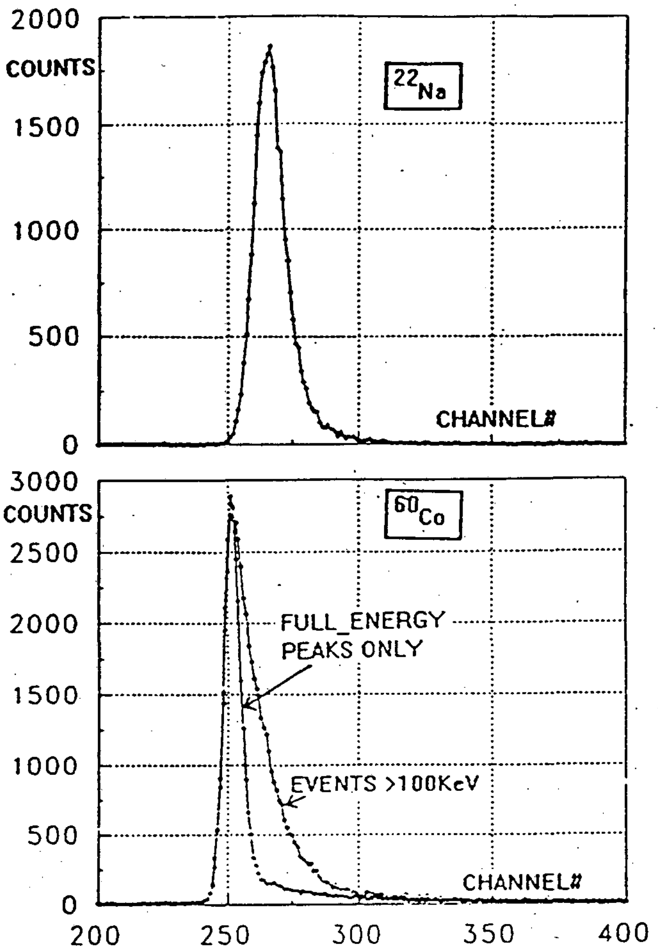

Fig. 6. Measured coincidence time distributions for the BGO assembly. See the text for details. The time calibration is 2.3 channels/ns.

4. EXPERIMENTAL RESULTS

Figure 6 shows experimental timing distributions measured on the complete BGO detector (ie. all 7 sections working together). Measurements of timing were made between a very fast barium fluoride detector and the BGO using two gamma ray sources: a) A ^{60}Co source placed in a tight geometry between the detectors to register a reasonable coincidence rate between the 1.33MeV and 1.17MeV gamma rays emitted in cascade by the source. b) A ^{22}Na source placed between the detectors to register coincidences between the two 511KeV gamma rays emitted at 180 degrees to each other by positron decay.

Two time distributions are shown for the case of ^{60}Co, first for the full energy peak and, second, for all events >100KeV. For ^{22}Na, most of the events are in the full energy peak, so only the distribution for the full energy peak is shown. In the case of ^{60}Co, where the energy spectrum contains many low-energy Compton scatter events, these result in a tail on the long time distribution. This tail reflects the behavior of Fig. 3 for low energy events while the sharp front edge is similar to Fig. 3 for high energies. Both the rise time of the front edge and the delay in the peak in Fig. 6 are longer than the calculated distributions of Fig. 3. This results from the effect of noise fluctuations and the spread in electron transit time up the PMT dynode structure.

These experimental time distributions satisfy the requirements of GAMMASPHERE. Software will be used to recognise neutrons by their signature of a BGO energy signal >300KeV and a delay >15ns from a beam pusle reference or a Ge detector event. If the BGO signal is associated with a neutron, the initial suppresion of a Ge detector event will be voided.

5. ACKNOWLEDGMENTS

The GAMMASPHERE concept owes its origin to a proposal made by F. Stephens of LBL to DOE in 1987. The general design of the detector is the result of the deliberations of a steering committee set up by DOE. Our work has benefited from discussions with several members of the committee and particularly with members of the GAMMASPHERE experimental group at LBL.

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