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GAMMASPHERE - Correction Technique for Detector Charge Trapping

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Abstract

GAMMASPHERE uses 110 very large germanium detectors. *Such detectors exhibit charge trapping effects on* energy resolution initially due to a native electron trap that is present in virtually all germanium. Furthermore, radiation damage is a serious problem in GAMMASPHERE experiments, producing hole traps that degrade resolution and eventually require annealing to restore the original performance. The technique discussed here uses the current pulse shape from a detector to develop a parameter related to the radius of the largest interaction in the "track" of a gamma ray in the detector. Since the charge trapping loss in a signal can be related to the distance carriers travel, the "radius" parameter can be used by software to apply a trap correction to the signal.

1. INTRODUCTION

The N-type coaxial germanium detectors used in GAMMASPHERE are 36mm in radius with a central core 4 mm in radius. The net donor concentration is about 6 x $10^9/cm^3$ and the bias is about 4000V. Therefore, charge carriers travel distances of up to 32mm at a velocity that approaches the saturation velocity of 10^7 cm/s and collection times ranging up to 400ns are observed. A native electron trap present in nearly all germanium manifests itself by producing significant charge loss effects in "reverse geometry" N-type detectors where electron drift toward the center in the applied field produces most of the external signal for interactions that occur in the outer regions of the volume (note that these regions constitute the bulk of the volume). The spread in charge loss, which depends on the radius of the interactions, results in degraded energy resolution and a pronounced tail on spectral peaks(1) particularly at the high gamma ray energies of major interest in GAMMASPHERE. Typical detectors of this size exhibit initial energy resolutions (FWHM) in the 2.2 to 2.4KeV range at 1MeV although these detectors would yield resolutions below 2KeV if no charge trapping were present.

The use of N-type detectors is dictated by the fact that radiation damage is a major problem in typical GAMMASPHERE experiments. Radiation damage produces hole traps and P-type detectors, whose signals are dominated by hole collection, are much more affected by radiation damage (perhaps 20 times more sensitive)(2). Even N-type detectors are eventually degraded by radiation damage in the GAMMASPHERE environment and hole trapping then becomes a serious problem requiring annealing of detectors periodically to restore their performance.

Trap correctors(3-5) were devised to add a correction signal, proportional to the expected signal loss due to trapping, to the normal signal. We must recognize that accurate trap correction of every signal is not possible because gamma ray interactions in a detector are complex, occurring in general at multiple points, with trap densities varying from point to point. Therefore, any trap corrector must be thought of as operating on a statistical basis to improve the initial energy resolution of a detector and possibly also to extend the operating life before radiation damage necessitates annealing. The specifications of detectors for GAMMASPHERE are already very tight and only very little of the native electron trap can be present, so only marginal improvements in initial performance can be expected by the use of a trap corrector except at very high energies. The possible gain in extending useful radiation life may be a more important result.

Large detectors also result in ballistic deficit effects in signals. Consequently, applying a correction to signals based on any rise-time determination can result in confusion between trapping and ballistic deficit effects. As shown in another paper presented at this meeting, we have developed a flat-topped pulse shaper for GAMMASPHERE that eliminates ballistic deficit effects. This means that a trapping correction can be applied without any concern about interactions with ballistic deficit correction. We should also note that charge trapped in a germanium detector at low temperatures (less than 100K) is not released during any practical shaping time and the loss of signal is therefore independent of the shaping time.

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2. SIGNAL PRODUCTION IN COAXIAL DETECTORS

In GAMMASPHERE, a target located 25cm away from the face of the detectors emits gamma rays that are the subject of study. The energy range of most interest is from 300KeV to 3MeV and, in this range, the interactions in a detector consist mainly of multiple Compton scatter events followed by photoelectric absorption. Each germanium detector is enclosed within a Compton shield and a Compton rejection system eliminates most of the events except those depositing their full energy in the detector. Therefore, we can focus only on full-energy events. A Monte Carlo study shows that a "streaming" effect occurs in the shower of interactions in a detector irradiated by a beam of incident gamma rays directed parallel to the detector axis. Full energy signals are generally dominated by components originating within 5mm of a constant radius - at least for the purpose of a "statistical" correction for trapping. Therefore, it is reasonable to assume that a measurement of the radius of the highest-energy interaction in a gamma ray's "track" is meaningful statistically in indicating the distance that carriers travel during charge collection for that event.

In calculating the behavior of these detectors we will assume a pure coaxial geometry and neglect the effects of the closed end of the coaxial device because this is only a small fraction of the volume and most high energy gamma rays penetrate deep into the detector where the coaxial geometry is present. Figure 1 shows the calculated current pulse shapes for events located at different radii. We note that the peak current time is almost linearly related to the radius. This might be expected since the induced signal occurs mostly as charges move near to the central core contact and the carriers travel at a constant velocity of about 10^7cm/s at the high electric fields used in these detectors. This is similar to the signal behavior in a multi-wire proportional counter with fine central wires. Therefore, determination of the peak current time will provide a "good" radial position signal.

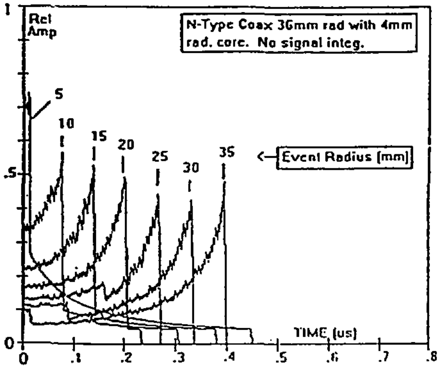

Fig. 1. Calculated current pulse shapes for the coaxial part of a GAMMASPHERE detector.

3. CIRCUIT DESIGN

Figure 2 shows the "fast-slow" transistor-reset preamplifier. It contains a charge-sensitive operational amplifier with a low-noise FET followed by a complementary cascode pair, an emitter follower and an output buffer/line driver. The feedback capacitor C_f is connected from the final slow output to the gate of the FET. Detector charge pulses deposit on the feedback capacitor producing a positive-going voltage ramp at the final slow output. When the output level exceeds a defined value (+0.5V), the reset circuitry triggers to drive current into the FET input via the reset transistor. The current is controlled to drive the output back to its low level of -2.5V. The stability of the feedback loop is ensured by rolling off the high frequency response of the loop by inserting a 22pF capacitor C_s from the high-impedance point at the cascode collector to an effective ground.

The fast output signal is derived by feeding the current in the 22pF capacitor into the virtual-ground input of a feedback amplifier. This signal is used for timing gamma ray events in the germanium detector and also provides a modified version of the current pulse from the detector. It can be shown that the current signal in the shunt capacitor Cs and, therefore the fast output signal, is the same as the detector current signal integrated by an integration time constant equal to $C_s(C_d+C_f)/C_fG_m$ where C_d is the detector plus FET input capacitance and G_m is the transconductance of the input FET. In our case, the integration time constant is 66ns. Figure 3 shows the detector current pulses of Fig. 1 processed by such an integrator and by an additional integrator of 20ns time constant that must be used in the fast channel to reduce very high frequency noise. We see that these waveshapes are an adequate representation of the detector current pulses for our purposes where about ± 5mm accuracy is required. Figure 4 shows the main features of the circuit used to determine the highest peak fast signal and also the test setup used to obtain the experimental results given later. The overall setup shown uses a routed analyzer to sort the detector energy signal in a number of groups according to the peak time derived from the peak-finder circuit. The "time-zero" signal for peak time measurements is derived from a fast discriminator. A stretcher circuit is used as the peak detector and the peak signal is used as the start signal to a time to amplitude converter (TAC) while the "time-zero" signal delayed by 400ns provides the stop signal. The stretcher circuit follows the rise of a signal, releasing on the peak and providing a tentative peak signal at that time. However, a signal may contain more than a single peak and the circuit is required to determine the time of the maximum one. Therefore, provision is made for the stretcher to follow any further rise of the input until the ultimate peak is found. The TAC is reset if a second (or further) rise is observed and restarted on the later peak.

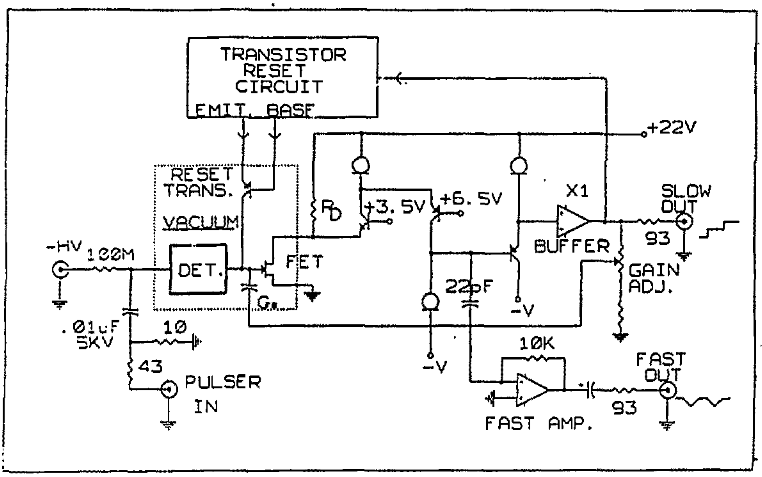

Fig. 2. Schematic of the "fast-slow" germanium detector preamplifier.

4. EXPERIMENTAL RESULTS AND DISCUSSION

The following measurements were all made using a flat-topped pulse shaper in the energy-measuring channel, thereby totally eliminating any ballistic deficit effects. Two detectors have been studied. The first is a detector that has suffered no radiation damage, while the second has been used in many experiments and is severely radiation damaged.

Figure 5 shows the behavior of the undamaged detector for the full energy 1.33MeV peak of ^{60}Co. The upper curve shows a plot of the counts in the peak as a function of the time channel. The general shape seen here agrees quite well with a Monte Carlo simulation. In the middle curve, we observe a loss of charge increasing with the detector current peak time measured by our system. The total charge loss due to electron trapping amounts to 0.1% for the longest collection time. (outer region events). The bottom curve shows a slight deterioration in energy resolution for events near the outside and an even smaller one near the middle. Several mechanisms may explain this behavior, but a likely explanation is that our radial signal (time) applies only to the maximum-energy interaction point and other interactions for the same gamma ray will be scattered about this radius (probably varying about 1cm). The charge losses from the individual interactions will vary, resulting in degraded energy resolution when the average loss is large (ie near the outside for electron traps). The slight resolution degradation for events near the central core may indicate the presence of a low level of hole traps in the native material.

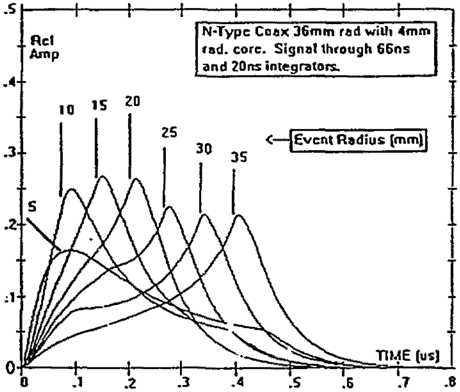

Fig. 3. The calculated detector current pulses of Fig. 2 degraded by 66ns and 20ns RC integrators in cascade.

We have demonstrated that an improvement of about 100eV (FWHM) in resolution can be achieved by shifting and adding spectra for the different time groups. This confirms our expectation that only marginal improvements can be achieved in undamaged detectors that meet the tight GAMMASPHERE specifications.

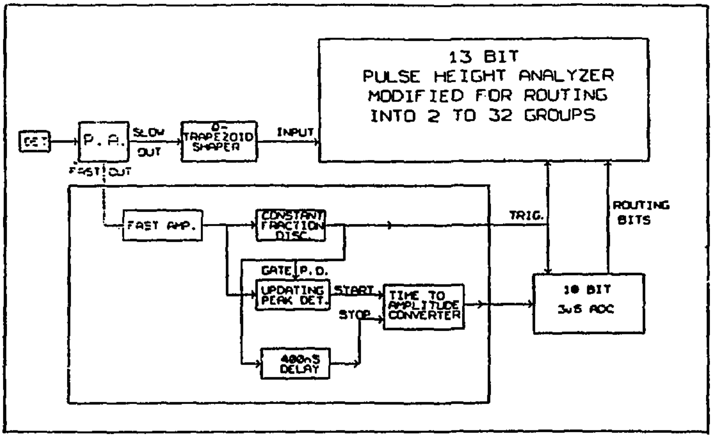

Fig. Schematic of the circuit used to pick off the time of the maximum current peak and use it to route an analyzer.

Results for the damaged detector are presented in Figs. 6 and 7. Fig. 6 shows the ^{60}Co (1.33MeV line) energy spectra obtained, in the upper half for the whole detector and, in the lower half, for counts falling within a time group corresponding to events near the core. The full spectrum shows the low-energy tail characteristic of radiation damaged detectors, while the time-gated spectrum shows a small full-energy peak and the main structure appears about 17KeV lower in energy. The full-energy peak is probably due to events in the end-cap region where charge collection is fast, while the main structure is due to events in the coaxial section where considerable hole trapping losses occur. The tail in the whole spectrum is the sum of the contributions from the time groups, mainly those corresponding to the events in the inner regions of the detector.

Figure 7 shows the behavior of the detector as a function of time group and, therefore, event radius. The top curve shows the shift in the centroid of the peak. Note that, as events move from the outer regions toward the middle, the centroid position increases until the radius is reduced to about 1cm; after that the centroid position moves rapidly down. This behavior shows that electron trapping is still dominant in the outer regions while hole trapping becomes dominant in the middle. The explanation for this lies in the fact that the total signal is mainly produced by electron collection except for events near the core, as shown in Table 1. The lower part of Fig. 7 shows the behavior of the FWHM resolution. As with the undamaged detector, the resolution deteriorates in sympathy with trapping losses quite drastically in the central regions. The explanation given for this behavior in the case of the undamaged detector probably applies here too.

Table 1: Electron/Hole contributions to Signal

R(mm)	5	10	15	20	25	30	35
Elect %	10	42	60	73	83	92	98
Hole %	90	58	40	27	17	8	2

We do not want to speculate on the algorithms that might be used to reduce the effect of traps in experiments using GAMMASPHERE. Clearly, the availability of the radial parameter discussed here can be used in various ways. It may be used, for example, to eliminate counts occurring near to the central contact in radiation-damaged detectors and thereby to reduce the pronounced tailing observed on peaks. Alternatively, or in addition, a radius-dependent peak position correction can be applied to improve the resolution. At the very least, experience with many detectors and at different radiation damage levels will provide a generation of graduate students with an interesting exercise in trap correction algorithms!

5. ACKNOWLEDGMENTS

The GAMMASPHERE concept owes its origin to a proposal made by F. Stephens of LBL to DOE in 1986. 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.

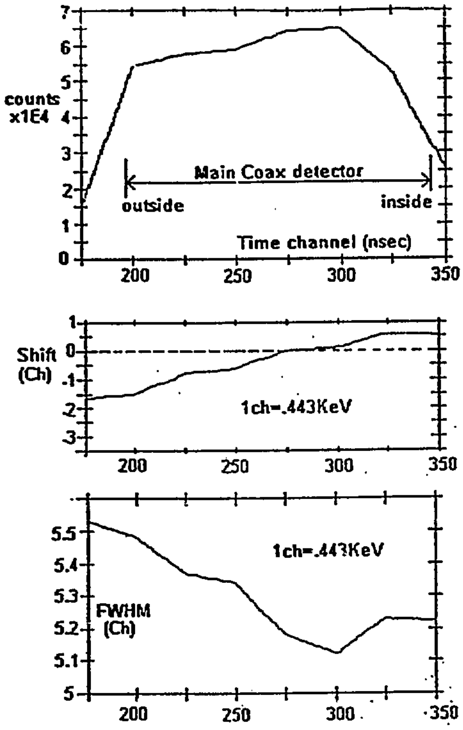

Fig. 5. Test results on the undamaged detector. See text.

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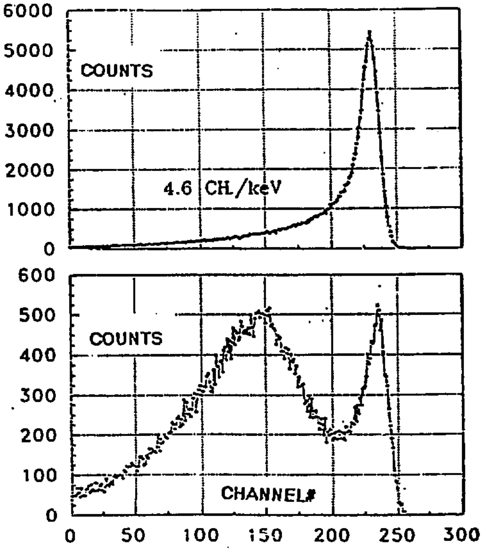

Fig. 6. Spectra from radiation damaged detector. See text.

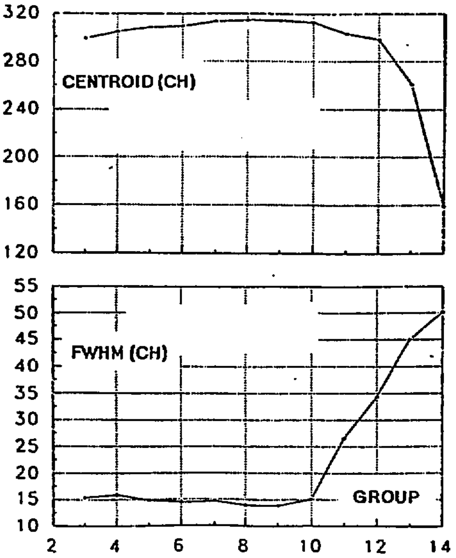

Fig. 7. Centroid shift and resolution for damaged detector. Each time group is 26ns wide. See text.