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June 1988

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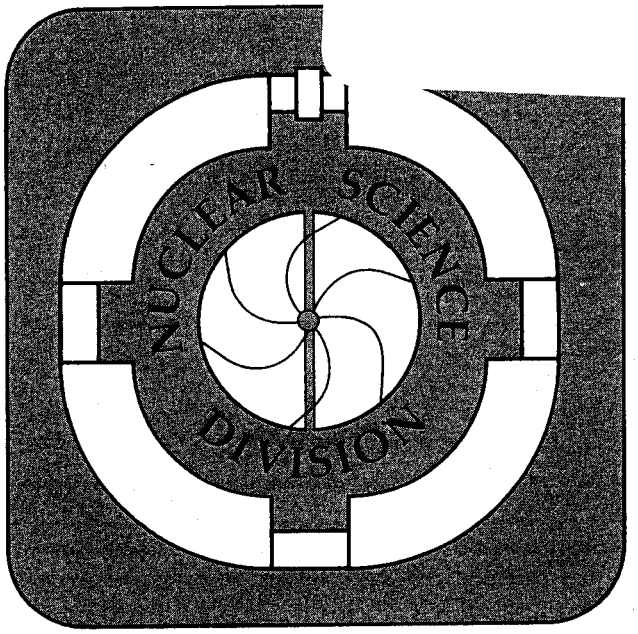

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Technical Aspects of a Germanium Calorimeter for Space-borne Gamma-ray Detection

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ABSTRACT

Our scientific objective is to search for high energy annihilation lines from dark matter candidate particles and to measure the diffuse γ–*ray* spectrum as a probe of cosmological distances and volumes. To pursue this objective we need a detector that has good energy resolution, better than 1% at 3 GeV. Such resolution is required to identify γ–*ray* lines which are separated by $\approx$ hundred MeV at energies of a few Gev and to separate these lines from the continuum background produced by high galactic latitude cosmic ray collisions. The detector must be able to locate or map sources. The directional accuracy required for pointing to the galactic center or to known pulsars is on the order of $1^0(16 mrad)$ or better. To avoid degradation of signal by the atmosphere, the detector must be flown in space. The expected signal is low, suggesting that an exposure of something like 1 m^2-yr is required to gather a statistically significant number of events. In this document we will look at alternative methods for detection of high energy γ–*ray* lines in space and argue that a fully active Ge volume is the optimum detector that can be built.

I. Introduction

We can make a detector with known technology that can measure photon energies to better that 1% at energies $E > \approx 1\text{–}10 GeV$, that can cover areas of m^2, that is compact enough and consumes low enough power to be flown aboard the space station, and that can measure photon arrival direction with an accuracy $<1^0$. This can be accomplished using Germanium (Ge) or BGO ($Bi_4Ge_3O_{12}$) calorimeters. The BGO would require an active converter, such as a layer of Ge, above the main absorber. We do not know how to make this detector with Si, since the amount of Si required exceeds the realistic limits ($\approx$5 tons) of the shuttle delivery system. Complex multi-cell systems can be calibrated to yield $dE/E < 1\%$ with these technologies, but Ge is the easiest to use for omnidirectional flux over a large range of energies. We will show that the best detector for this measurement uses multiple layers of Ge crystals since these provide the most flexibility and greatest ease of handling, calibration, and operation.

Once we have shown that Ge is the best medium for our purposes, we can contemplate some of the additional advantages of such a Ge detector. We can think of making each upper detector position sensitive in two dimensions to allow location of recoil electrons from a Compton collision. This would allow us to lower the effective minimum energy to the Compton region of a few MeV to tens of MeV. We might then be able to use such a detector to locate nuclear lines from strong astrophysical

sources.

II. Physics

There are many reasons to look at the hard component of the electromagnetic spectrum for signatures of exciting astrophysical processes. Much of the universe is transparent to hard x-rays and gamma rays. Such electromagnetic radiation can bring us information directly from throughout the universe, including from violent processes from within our galaxy or from processes occurring in or among other galaxies (1983 Ap. J. 97, 4). Figure 1 shows the limits on the distance (redshift) to which we can observe. These limits are set primarily by the electron density of the universe and the intensity of the cosmic microwave background radiation. We discuss below our two specific goals, searching for signatures of exotic dark matter candidate particles and examining the diffuse, high energy galactic gamma ray background.

II. a. *Searching for Dark Matter*

Observational evidence on formation and clustering of galaxies and on galactic rotation curves and halos indicates the presence of significant amounts of dark matter in the universe, matter seen to date only by its gravitational signature (Peebles 1987 Nature 327, 210). To account for structure within galaxies, the dark matter must be relatively cool, that is, non-relativistic at the dynamical temperature of the galaxy. This implies that the dark matter must have significant rest mass.

Big Bang cosmology provides a framework in which elementary particle theory can be used to calculate the particle nature of the universe. Observed particle abundances provide constraints on elementary particle theories in this cosmology, and these theories place constraints on the nature of exotic particle candidates that may comprise the dark matter. Among the exotic particles that have been suggested as accounting for a significant fraction of this dark matter are axions and heavy leptons, photinos, and x particles. These exotic particles may be stable or they may decay, perhaps electromagnetically. Whether stable or unstable, they should possess antiparticles and consequently undergo annihilations.

Some of these annihilation branches produce a $c\bar{c}$ or $b\bar{b}$ bound pair plus a γ (Rudaz 1986, Phys. Rev. Letters, 56, 2128 and Srednicki, Theisen and Silk 1986 PRL 56, 273). For annihilations at low velocity these should produce well defined lines. The energy separation of various lines will be set by the spacing of known quarkonium masses ($M_{q\bar{q}}$ = 3.100, 3.615, .., 9.41, 10.02, .. GeV) according to the relation $E_\gamma=(M_x - M_{q\bar{q}}^2/M_x)/2$. We may also see lower energy γs from daughters of decaying WIMF/Ps (weakly interacting massive fermion/particles), such as π^0s and η^0s, at energies of about 50 to 600 MeV.

Silk and Bloemen (1987 Ap. J. 313, L47) have estimated that "Even if a small component of the galactic spheroid consists of weakly interacting majorana fermions that are cold dark matter candidate particles for the galactic halo, there should be a substantial flux of annihilation gamma rays from a source about 1^0 in extent at the galactic center." If the dark matter is in the form of massive WIMF/Ps having $M < 30 GeV$ we can expect about 60 to 150 γs /line $-m^2-yr$ at high energies. The COS-B results put a limit of $<15\%$ on the WIMF component in the galactic spheroid model of Silk and Bloemen. With approximately 1 year of observing time with a $1m^2$ detector we can expect to discover such WIMPs or to set a limit on their concentration in the galactic spheroid and disk of $<1\%$ of the total mass.

There is no need to confine ourselves to searching the galactic center and to depending upon significant density enhancement by entrainment for evidence of exotic dark matter candidates. In fact by moving our search to the galactic halo, we can decrease the effects of the diffuse gamma ray background significantly. The flux from the diffuse background from the halo is given as (Trombka et al. 1977 Ap. J., 212, 925; Fichtel, Simpson, and Thompson 1978 Ap. J. 222, 833)

$$I_\gamma(>E) \approx 4 \cdot 10^4 (\frac{1 GeV}{E})^{1.4} \; m^{-2} \; yr^{-1} \; sr^{-1}$$

In the halo we can expect to see a flux of γ rays from annihilation of

$$I_{\gamma,h} \approx 4.5 \cdot 10^4 f_{h,x}^2 (\frac{M_x}{3 GeV})^2 (\frac{\sigma v}{10^{-26} cm^2}) \; m^{-2} \; sr^{-1} \; yr^{-1}$$

Here, $f_{h,x}$ is the fraction of the mass in the halo that is bound in x particles. Thus, if the annihilation cross section is $\sigma v \approx 10^{-26--27}$, as is expected, a search for such photon signatures using a detector of good energy resolution and a collecting power of $\geq 1 m^2-year$ will place severe constraints on the nature and distribution of dark matter in our galaxy. With a m^2-yr we can expect to see 500 to 5000 γs if $M_x = 3 GeV$ or 50 to 500 γs if $M_x = 10 GeV$. Because of the steeply falling spectrum of the diffuse γ radiation from the halo, we will have a very good signal to background ratio.

II. b. *Diffuse Background and Galactic γ-ray Astronomy*

In addition to looking for annihilation signatures from our galaxy, we can also use this technology to measure the properties of the diffuse extragalactic γ background itself, allowing us to search for annihilation and decay products from most of the observable universe. Clusters whose mass is dominated by long-lived but unstable massive x particles could be located (Dicus & Teplitz 1986 Phys. Rev. D. 34, 934). The technology we describe here leads to a detector of excellent energy resolution and pointing ability.

Such a detector would be extremely useful in gamma-ray astronomy, in investigation of the general matter distribution of the universe (Dekel & Rees 1987 Nature 326, 455), in addition to measuring the diffuse extragalactic γ background. The

significance of γ ray astrophysics lies in penetrating power of γ rays and in its ability to reveal the high energy and nuclear phenomena of the universe. Thus by being an indicator of change and evolution, γ rays provide insight into the energetic processes shaping that change. Results to date have shown the rich character of the galactic plane diffuse emission with its potential for the study of the spiral arms,the cosmic ray and matter distribution, the galactic center, molecular clouds and other features of the galaxy. We can expect this probe of galactic featurs to continue and be extended as well as the development of extragalactic studies. The large collecting area combined with good energy and time resolution is the natural next step in detector development for γ ray astronomy.

III. State of the Art

To observe hard extraterrestrial radiation it is necessary to get above the $1000 g/cm^2$ of matter that comprises our atmosphere. Astronomical gamma ray observations must be carried out in space. The successful SAS-2 and COS-B instruments and the soon to be launched Gamma Ray Observatory attest to the importance of this new branch of astrophysics to NASA and the community. The techniques we describe here could lead to an instrument with an order of magnitude increase in collecting power and an order of magnitude better energy resolution than the best instruments now being constructed for space applications in detection of γ rays.

As in any search for new particles, the detector used should have low noise, high sensitivity, and, in the face of small or unknown fluxes, have a solid angle and collecting area as large as is feasible. It should have high resolution. In addition, to search for such an electromagnetic signature from astrophysical sources, the detector must be compact enough and light enough to be placed in space, well above the interference of the atmosphere.

Given that we need to measure γ-ray energies in space to accuracies of $\leq 1\%$ at 3 GeV and to know where the γ-$rays$ came from to within 1^0, we discuss various methods that could be used. Methods based on magnetic measurements in space yield collection factors of $\approx m^2$ and efficiencies $\eta \approx 0.1$, excellent E resolution $dE/E \approx < 1\%$ at a few GeV, and, with good tracking of the $e^{+/-}$ pairs, angular resolution of 1^0 (Eichler & Adams Ap. J. 317, 551, 1987). Methods based on collection of scintillation light, such as from BGO crystals, are capable of excellent energy resolution above a few GeV ($dE \approx 0.5\%$ for $E > 4 GeV$, $dE > 1.5\%$ for $E < 1 GeV$) (NIM A, 228, 294, 1985) but are difficult to segment and require serious light collection corrections which make them difficult to construct for isotropic flux measurements. We first discuss these approaches and then go on to methods based on ionization measurement.

III. a. *Methodology*

To accurately measure a photon's energy, it is necessary to absorb it completely, converting it to charged particles whose energy can be measured. Thus to measure a $\approx GeV$ photon's energy, we must measure the energy of the electrons it

produces. We can do this with, for instance, a magnetic spectrometer or we can try to absorb the energy completely in a calorimeter.

III. a. 1. *Magnetic Spectrometers*

A large area magnetic spectrometer is an attractive idea, and we are involved with the Astromag project, an effort to build and fly a large superconducting magnetic spectrometer aboard the space station. This technique relies on measurement of charge, rigidity, and velocity to characterize the secondary electrons. However, it is difficult to get collecting areas measured in m^2 and it is difficult to achieve high efficiency without loss of energy resolution. The limits on spectrometer size are practical; installing and servicing a large magnetic field in space is difficult, especially if cryogenic liquids are involved. High detection efficiency and good energy resolution are conflicting goals. Detection efficiency requires a substantial fraction of a radiation length to convert a photon to an ionizing particle with high probability, but this means that produced electrons/positrons will have a significant probability for emitting bremsstrahlung, which would require more conversion, detection, etc.

III. a. 2. *Calorimetry*

A photon loses its energy by one of three processes; photoelectric absorbtion (αZ^5), Compton effect (αZ) and pair production (αZ^2). These processes produce electrons, which lose their energy through collisional and radiative processes, ie, they give up energy to other electrons or they produce more photons. Thus, to measure the incident energy it is necessary to measure something proportional to the ionization produced and it is necessary to convert photons to ionizing electrons. The use of the same material as both the converter of photons to ionizing radiation, and as the ionization medium, makes it possible to construct a completely active detector.

High energy ($E >> m_e$) electrons and photons lose their energy by creating cascades of electrons, positrons and photons. The rate at which a cascade develops and consequently the rate at which energy is absorbed is described in a medium independent fashion using the radiation length, X_0, that length of matter in which a high energy electron loses $1/e$ of its energy, on average. As the energy is converted to $e^{+/-}$ pairs and photons, it is gradually dissipated until ionization processes dominate radiative processes and the cascade ends. The point at which $(dE/dx)_{rad}/(dE/dx)_{ion} = 1$ is called the critical energy, E_c, above which pair production and bremsstrahlung production dominate. The number of $e^{+/-}$ at any point in the cascade is a function of the depth in the cascade in units of X_0 and the incident photon energy in units of the E_c. The lateral and angular spread of shower particles, electrons and photons, is known (e.g. Phys. Rev. 75, 444, 1949). Since production of these ionizing particles is a statistical process, fluctuations in their number dominate the resolution achieved by detectors that attempt to determine incident energy by sampling ionization or scintillation at various points in the cascade. The energy is ultimately dissipated as ionization $e^-/hole$ pairs, as

scintillation photons to which the medium may be transparent, and as heat.

The number of electrons in the cascade depends on the ratio of E_i / E_c . Thus, if a medium has a smaller E_c it will suffer fewer fluctuations in the number of electrons for a given E_i than a medium having a higher E_c . Lower E_c therefore means the possibility of better energy resolution at a given E_i . The critical energies and radiation lengths for selected media are shown below.

Properties					
Medium	E_c Critical Energy (MeV)	X_0 Radiation Length (g/cm^2)	Density (g/cm^3)	20 X_0 (cm)	Weight (tons)
Si	45	21.82	2.33	187.3	4.36
Ar	35	19.55	1.40	279.3	3.91
Ge	20	12.1	5.3	45.7	2.42
Xe	10	8.48	3.057	55.5	1.70
BGO	20?	7.98	7.1	22.5	1.60
NaI	?	9.49	3.67	51.7	1.90
CsI	?	9.0	4.51	40.0	1.8
BaF_2	?	9.91	4.83	41.0	2.0

If we want to stop a 1 GeV photon and contain its cascade, we need $\approx 12\ X_0$; to stop 10 GeV we need 20 X_0. However, if we want to have a detector with a large acceptance we must keep it relatively thin. For example 20 X_0 of silicon requires almost a 2 meter thickness, which restricts solid angle unless the detector is very large.

Can we regain solid angle through a decrease in detector thickness by adding a component of dense, low X_0 material? We know by the physics of e^- energy loss that we need to make a detector of some 20 X_0 thickness. Does this have to be active or can we make it passive and still get good energy resolution? An obvious method of gaining radiation lengths while keeping the detector thin is to add inert high Z material to the cascade path. The range of most of cascade electrons is on the order of X_0. If a significant fraction of the 20 radiation lengths is inert material, many of the secondary electrons will not deposit energy in the active region and will be lost to the energy measurement. The typical number of cascade particles is a few 10's at incident energies of 100 E_c and a few 100's at $E_i \approx 1000 E_c$ (from Leighton, Princ. Mod. Phys, McGraw-Hill, 1959 and Rossi and Griessen, Rev. Mod. Phys. 13, 240, 1941). The fact that the number of electrons is so small means that in the energy regime from a few to a few thousand E_c fluctuations in measured energy will be dominated by fluctuations in the point of origin of the secondary electrons and in the number that deposit energy in the active portion of the detector.

We conclude: **The only way to decrease the thickness while maintaining the energy resolution is to use a denser fully-active medium.**

We next discuss some present technologies that are used to detect high energy γ rays.

III. b. *EGRET Instrument on Gamma Ray Observatory*

The EGRET instrument consists of a stack of tracking chambers followed by large NaI crystals. EGRET has a collecting area of $\approx 2/3\ m^2$. An analysis of the efficiency, solid angle and direction of incidence indicate an effective collecting power that varies from 0.2 to 0.03 m^2 for incident angles from 0 to 35 degrees. This averages to $\approx 0.1\ m^2 sr$ for the whole detector. The energy resolution is roughly 15% (FWHM) from 100 MeV to 1 GeV and grows to about 25% at lower and higher energies with the resolution being dominated by effects of shower leakage and from losses in the tracking system. The angular resolution is fairly good depending on the energy of the incident γ ray and is roughly 5^0 at 20 MeV decreasing to 0.3^0 at 1 GeV. This is about two and a half times the limit set by pair production kinematics if the momentum of the recoil nucleus is hidden (Fichtel and Trombka 1981 Book Gamma Ray Astrophysics, NASA SP-453 pg 328). Using Ge as the active converter and tracking element would lead to an improvement in the angular resolution and energy resolution.

III. c. *Cryogenic Approaches*

An attractive device for measuring energy and direction for high energy photons is a liquid Xenon TPC. It appears to be a very good medium for detecting electromagnetic cascades: high Z, insulator, sustains electron drifts over many cm if pure. However, no one has yet used one on the ground in a real experiment. Problems that make this option less attractive include the difficulty of servicing large areas of 30 cm thick liquid Xenon in space and the fact that cascades are so short, ie, the radiation length is so short, that high position accuracy is required to use the cascade as an accurate pointer. Were such a detector readily available, however, it could be used with an active converter set above it to initiate the cascade and such a combination would provide a very interesting option. In fact, any good high resolution calorimeter following an active converter would be a good method to consider.

Liquid argon detectors are another possible candidate. Resolutions of $2.4\%/\sqrt{(E)}$ have been achieved with fully active liquid Argon detectors for 1 GeV e^- (Doke et al NIM A, 237, 475, 1985). This resolution can be improved if both the scintillation and ionization signals are measured simultaneously (Crawford et al., NIM A 256, 47, 1987). Argon has a longer radiation length ($19 g/cm^2$); the increased cascade length would make possible more accurate pointing. However, the detector would have to be longer to contain a given energy cascade. The longer detector means the solid angle is decreased for the same surface area. To regain the solid angle, the detector could be made larger with subsequent increase in the readout channels, etc. This is an attractive possibility but it appears to be difficult at this time to build, launch, and maintain a large cryogenic detector in space.

III. d. *Scintillation Detectors*

Given the drawbacks to cryogenic liquid detectors, what are the possibilities for solid state scintillation chambers using BGO or NaI? Scintillators like BGO and NaI are obtainable as large crystals. Their use in a large system such as we need in space requires use of many photodiodes or photo-multiplier tubes, all of which need to be calibrated to better than 1% for both gain and linearity. BGO and NaI have the advantage of being compact, short X_0 materials. They have fast response times and low background. BGO can be constructed as single crystals of >20 radiation lengths and so allow reasonable segmentation in the transverse direction. However, their response is very position dependent. While they can yield excellent E resolution above a few Gev, their resolution decreases rapidly at lower energies. The survival of BGO arrays in the space environment is not well known. We could certainly make a detector for point sources that could have dE <1% for $E > 3GeV$ but it would be difficult to calibrate for off axis response. It would have limited longitudinal segmentation and may develop background problems as a result. A large array of BGO crystals read out by photodiodes would suffice for a specific search for high energy annihilation lines. However, we can do much better and extend the dynamic range in E much lower if we go to a Ge TPC type detector, as described below.

III. e. *Solid State Ionization Chambers*

Solid state ionization chambers are limited in size at present to dimensions of 12-15 cm dia. and thicknesses of < 1 cm for Si and dimensions of $\approx 5 \times 5$ cm and lengths of 5–7 cm for Ge. A stack of Si 20 X_0 deep is 200 cm thick. It is possible to construct 8 mm. thick Si detectors of 15 cm dia., so that such a stack would be 250 detectors thick [2]. Making thicker Si detectors is difficult because of problems drifting the compensating Li to greater depths. We could make the detector thinner and still completely active if we had a higher Z, denser ionization medium to use. Ge presents such a possibility.

III. e. 1. *Si ionization chambers*

The University of Tokyo group working with T. Doke have proposed to build a Si(Li) sampling ionization calorimeter having a diameter of 20 cm and a length of 57 cm (29 X_0) (30 cm gap between the converter layer and the absorber layer) to look for gamma rays from supernova 1987a. The energy and angular resolutions they quote for the GeV photon range are $17\%/\sqrt{(E)}$ (Nakamoto et al. NIM A, 238, 53, 1985) and $1.6^0/\sqrt{(E)}$ for the 50% to 75% of the cascades that can be tracked (Nakamoto et al, Proposal to view γ from SN1987a, T.Doke private communication). Their area is set by the largest diameter detector they can make, 15 cm.

[2] One of us (HC) has used similar stacks 30 detectors thick to provide isotopic identification for high energy heavy ions (Symons et al, PRL 49, 455, 1982). Calibration is straightforward.

Position sensitivity in their design is attained by placing electrode strips 5mm wide separated by 1 mm covering the surface of the converter detectors placed 30 cm above the main stack. The strips end on a resistive line whose ends are connected to pre-amplifier-shaper-ADC channels to obtain position from pulse height division or center of gravity of the cascade. The converter section consists of 2 X_0 of position sensitive detectors.

The sampling in their design is performed by 30 detectors each 2 mm thick and sandwiched between Pb plates which act as the converters and as absorbers. Without such converters, the detectors would have to be a total of 2 m thick to achieve the same number of radiation lengths. The energy resolution is sufficient for their needs since they are looking for a broad signal arising from the rotation of the remnant star. Charged particle background is vetoed by a layer of thin ($200\mu m$ thick) Si(Li) detectors arrayed over the main stack overlapped to leave no gaps. The sides and bottom are covered by anticoincidence scintillator. Accidental triggers are minimized by requiring 4-fold coincidence between detectors in successive layers. Software reconstruction of the cascade geometry reduces background still further. This is an elegant detector for space and attains excellent pointing resolution and excellent energy resolution for a sampling calorimeter.

The pointing capability of this design, which is based on location of the initial cascade particles and tracking the cascade centroid near the front of the cascade, is almost sufficient for our needs. It can be easily improved using all active volume, with each element having position sensitivity at the mm scale transverse. However, to separate the lines expected as a signal for charmonium and bottomonium decays, we need better energy resolution.

One way to get better E resolution is to build a completely active calorimeter. Instead of Pb plates as the photon converter, just add more Si. This improves both the energy resolution, and, if a high degree of segmentation is used (scale length $\approx 0.1\ X_0$), the pointing resolution. The liquid Argon calorimeter used for electron detection was a fully (95%) active volume (Doke et al NIM A 237, 475, 1985). The drawback to making a fully active Si calorimeter is in how much Si we would need to add.

III. e. 2. *Ge ionization chambers*

The technique we suggest is based on attaining a large thickness of active Ge ($20\ X_o$) by stacking thin position sensitive Ge plates. We can use present techniques to construct large area, thin Ge detectors that are position sensitive in one dimension. For $\gamma\ s$ of energy above about $50\ MeV$, segmentation in one dimension, that is, strips on only one surface of the crystal, is sufficient because produced electrons have ranges much greater than a detector thickness. Alternating x and y strip directions in successive detectors would allow accurate position and thus arrival angle determination.

There are at least two designs that have been tested for making Ge detectors position sensitive in one transverse direction. However, to use these detectors in a large array, we need to make each detector as large as possible. This means fabricating position sensitive detectors from 5 x 5 cm^2 material. The LBL semiconductor detector group (Varnell et al., IEEE Trans. Nuc. Sci., V.NS-31, 300, 1984) has fabricated and tested position sensitive Ge detectors ranging from a simple two segment wafer to a wafer covered with gold strips (IEEE Trans Nuc Sci NS-32, v2, 1204, 1985). Passivation of the Ge surface to stabilize the contact surfaces has been accomplished (IEEE NS-31, 312, 1985). Detector grade high-purity single-crystal Ge is available in 5–6 cm diameter boules and can be sliced to create detectors of length from 0.1 to 7 cm. The thickness of a planar detector is limited to a few cm by requirements on electric field uniformity. Position sensitivity in one dimension can be attained with either a pulse-height-division strip scheme or with a drift chamber scheme. Ge drift chambers have been tested to have better than $500\mu m$ position resolution with 3 cm drift lengths over surfaces of $\approx 10 cm^2$ (IEEE NS 32, 457, 1985).

IV. *The Ge calorimeter*

At this point we are considering a volume of Ge consisting of a stack of 2 mm thick position sensitive detectors (<1 *mm rms*) followed by a stack of 1 cm thick position sensitive detectors, with the whole apparatus 60 cm thick. The number of detectors and consequently the number of electronics channels depends on the maximum surface area of each individual detector. Assuming today's crystal producing abilities, this means detector chips 5 *cm* x 5 *cm* in area up to 1-2 cm thick [3]. A $1m^2$ area then requires 400 such detectors. For 20 layers of 2 mm thick detector at the top, followed by 40 layers of 1 cm thick detector on the bottom, this requires 24000 detectors. Note that L3 at CERN is using 12000 BGO crystals arrayed in a geometry to point at the intersection region (NIM A 254, 535, 1987) and have calibrated a system of complexity equivalent to this to well under 1% for a point source of photons.

Our goal is to make each Ge plate position sensitive in 2 axes allowing us to determine the point of a Compton collision or the centroid of a developed shower to an accuracy of $\leq 200\mu m$ transverse and $1\text{–}2mm$ longitudinal. This improvement in position sensitive detector technology will allow us to detect γ s below the energy at which pair production dominates the energy loss process, that is, below 50 MeV. Such low energy photons lose energy by Compton processes, producing low energy electrons whose range is less than a detector thickness. Thus, each detector must

[3] We can make Ge detectors up to perhaps 3 cm in thickness. However, the voltage required to operate these detectors is given roughly as $V = 5.8 \cdot 10^{-8} t^2 \rho$ where t=thickness and ρ is the impurity concentration. We are trying to operate with relaxed constraints on the impurity level ($10^{11}/cm^3$ instead of the normal high-purity requirement of $\approx 2 \cdot 10^{10}/cm^3$) and we want to run at reasonable voltages $<2kV$. Therefore, we suggest using a detector thinner than we could make with the highest purity.

return both x and y position to allow us to use each Compton scatter in determining angle of incidence.

To make a fully active Ge volume $1m^2$ in surface area and 20 X_0 thick will require $2 \cdot 10^6$ grams of Ge (2.5 tons). Note that this is a significant weight reduction compared to 4.4 tons needed for Si. This is within the ability of the shuttle to launch and the space station to accept. We have also managed to decrease the thickness down to 50-60 cm, a factor of 4 reduction over the Si case.

IV. a. *Design*

We can construct this detector as shown in Figure 2. The top few layers should consist of detectors that can give position in at least two dimension, x and z or y and z, for instance. These should have a reasonable probability of causing a conversion for a 1 GeV photon. The pair production cross section for 1 GeV photons in Ge is 7 b/atom (J. Phys. Chem. Ref. Data, V9, no.4, 1980) implying that a detector 2 mm thick would have a 10% probability of causing a conversion. Having $\approx$20 layers of these with each layer separated by 1 cm and this whole upper converter stack separated by 10 cm from the top of a large stack of thicker position sensitive detectors would allow us to point with an accuracy much better than the 1^0 achieved in the Si-Pb calorimeter tested by Doke et al. It would also allow a very high conversion probability. Even if conversion did not occur until the last thin detector, we could still vector back to the source using the position sensitivity of the absorber stack.

It is easy to imagine trays of these detectors with the tray providing structural strength as well as signal routing. The active surface area of each tray could be better than 95%. The mass of the structural support can be made less than 1% of the total by using carbon fiber technology. Since the photon absorbtion is αZ, this means that the effective mass will be well below 0.2% as far as photon conversion losses are concerned. Each tray could act alone, having a local CPU for signal processing and control. Measuring the position in the upper converter to an accuracy of 1 mm allows pointing at the 10 mrad or 0.7^0 level. Since we are in the pair production regime, we can expect to have a continuous ionization from the produced $e^{+/-}$ through a number of detectors before a cascade develops. The Ge then acts like a normal charged particle detector, responding to the ionization trail left by the particles. A minimum ionizing particle deposits $\approx$1.3 MeV in a 2 mm Ge slice.

IV. b. *Many Detectors*

However, before concentrating on the virtues of Ge, we should discuss some of the technical difficulties associated with satisfying our other requirement, making a $1m^2$ area of solid state detector. Given available detector sizes, either Ge or Si, a single layer m^2 mosaic of such detectors would contain a few hundred detectors. To instrument a $1m^2$ x $20X_0$ volume requires $\approx$25,000 detectors. These could be held in a rigid matrix of carbon fiber with electrodes and signal routing deposited on

the surface of the matrix. Matching expansion coefficients for matrix and detector material is essential but possible. Making the whole volume position sensitive with the same method as above requires ≈75,000 channels of electronics.

IV. c. *Economics*

We must also consider the economics of such a detector. Ge is recovered as a byproduct of other mining and manufacturing operations. World production exceeded 100 tons/year during the period of peak demand. Production has varied between 30 and 80 tons/year during the 1970's (Encyc. Chem. Tech. v11, John Wiley and Sons, 3rd ed., 1980). [3] The current price for intrinsic grade polycrystaline Ge is $1 per gram. This material must then be purified (to $<\approx 10^{11}/cm^3$ impurity concentration) and grown into single crystals for detector fabrication. At this price for bulk Ge, a $10M project allows a factor of 5-7 increase in the real value of the Ge.

We recognise that only a fraction of the cost of a detector is in the raw materials. However, we imagine that a production system could be set up to fabricate large numbers of these detectors semi-automatically, allowing us to take advantage of the economy of quasi-mass production techniques. This is a crucial point that must be tested. Even though the techniques for scintillator fabrication and Ge fabrication are quite different, note that the L3 people at CERN must have faced and solved problems of similar scale in developing the 12000 BGO detectors they have fabricated.

Using a very large number of detectors has some distinct advantages that offset to some extent the apparent disadvantages. A serious problem with calorimetry involves calibration of the individual cell response. In our scheme, a cell is a single detector. As such, it is easy to calibrate using minimum ionizing particles or a simple source. We imagine stacking the detectors in such a way that calibrations could be performed in situ periodically to account for gain drifts over the course of a year in space. Another advantage of large numbers derives from the fact that no individual detector is essential to make a measurement. The cascade develops over many detectors and deposits energy in perhaps 50-100 separate cells. From our positional sensitivity, we could easily correct for detectors that are missing in an event. Using on board intelligence, we can imagine having a small CPU dedicated to every 25-100 detectors, controlling ADC operations and routing signals to different channels when one electronics chain goes bad. These are new approaches made possible by the availability of cheap CPUs and are now being tried at CERN and could well work into the plans of the VLSI group here at LBL.

Present Ge detectors are constructed of high purity, single crystal Ge. These are limited by current growth techniques to diameters of about 6 or 7 cm. and

[3] Newly developing markets that are expected to increase demand, and hence production with subsequent lowering of price, are in the fields of ir optics and fiber optics.

lengths of 7 cm. or more. Such detectors provide excellent resolution and are the tools of choice for all high resolution γ-*ray* spectroscopy. Although segmentation methods and drift techniques can provide some position information from such detectors, the granularity of the information is far from adequate for our purpose. Consequently, the proposed detector will be made from multiple plates of germanium. The purity of the germanium required can be 10 times worse than that employed in large high-purity germanium detectors ($10^{11}/cm^3$ *versus* $10^{10}/cm^3$) making it possible to use relatively inexpensive reject material from the manufacture of high purity germanium.

IV. d. *Cooling*

To attain sufficiently low leakage currents, it is necessary to cool the Ge detectors. In the lab, this is typically done using LN, transmitting the heat from the detector to the LN via some conducting material such as an Al rod. In space, the temperature of the detector environment can be made 140 K or even lower by passive heat radiation into space. We believe that this is a low enough temperature to operate the Ge devices we are considering. We are investigating this point and considering the use of solid state refrigeration techniques to lower the temperature of the stack if necessary.

IV. e. *Power in Space*

In addition to weight, operation in the space environment requires attention to overall power requirements. A 5 *in.dia.* x 3 *mm* thick Si detector connected to a JFET input pre-amp has a capacitance of $C = \epsilon A / s = 4500pF$ and noise of 40 keV rms. There are presently available pre-amplifier - shaper amplifier systems capable of 10–20 keV rms electron equivalent noise for $5000pF$ input capacitance using multiple JFET inputs. Individual detectors in the mosaic would have smaller capacitance, typically 3000 pF or less, and smaller noise. Improvements in such preamps to make the noise even smaller would be a project that could fit in the scheme of the VLSI operations at LBL. It is possible to construct pre-amp - shaper - ADC chains having 10^3–10^4 dynamic range that draw less than 25 mW per chain [5]. Using the same position sensitivity scheme as above requires three such chains per detector. Consequently, a single layer of 100 such detectors would consume $\approx 7.5\,W$. The electronics could all be placed at the edge of the detector volume to minimize heat transfer to the detector stack itself.

[5] In our ISEE-C satellite we had a stack of 10 Si(Li) detectors each 5 mm thick using a 10^4:1 dynamic range ADC system that required less than 200 mW total power per channel. This was launched in 1978.

IV. f. *Data Rate*

Assuming that each detector is made position sensitive in one direction, this requires 72000 channels of ADC having a dynamic range of 10^3. A typical 1 GeV cascade will leave signals in the top 12 X_0 of detectors. Assuming the first 2 X_0 consists of 20 2 *mm* detectors, and the remaining 10 X_0 are accounted for by 20 1 *cm* thick detectors, and that each detector is typically 5 cm on a side, >80% of a shower could be contained within a single tower of 40 Ge detectors. The event would then consist of 120 ADC values. More likely, it would cross a tower boundary and include a number of neighbor detectors, leading to an event containing perhaps 80-100 detectors. Signal validity (hit patterns and cascade profile) would be checked with a local CPU to verify that these were created by electromagnetic showers rather than by high energy charged particles. The whole event would then be formatted and sent to telemetry.

Our overall data rate will be determined by the trigger conditions we select. If we trigger only on high energy γ–*rays* with $E > 1 GeV$ our rate will be very low, a few an hour. We can select a trigger scheme that optimizes our data rate by selecting trigger conditions with a control CPU. The logic conditions can easily be altered from ground command to allow for various different types of searches.

We may be able to make each detector effectively larger by bridging from one detector to its neighbor by connecting the stripped surface of one detector to another. This technique may allow us to join, for instance, four 5 x 5 cm^2 detectors to form one 10 x 10 cm^2 in area, effectively reducing the number of detectors, and electronics channels, by 4. This would not decrease our position sensitivity significantly. This is not an outrageously large number of detectors, nor is it out of the question electronically, even if all are position sensitive requiring 3 channels of electronics each. At a power consumption of 7.5 W per 100 detectors, this amounts to less than 2 kW of power, well within the 5-10 kW allocated for large space station projects. Note that a tiny fraction of this power is actually dissipated within the detectors.

We note that the requirement for a large number of channels is set by the position sensitivity of each detector. This is necessary for both pointing capability and for background rejection. The degree to which position capability is required in each detector is a matter to be investigated. Deep in the stack a real cascade reaches lateral extent that is a significant fraction of X_0 at the shower maximum. Clearly we do not need the same position accuracy in determining cascade centroids that we need for locating the origin of the original pair and position on the surface of the absorber stack from which the incident angle is derived. The accuracy required near the top of the detector is set by the pointing capabilities required while the position sensitivity required in the bulk of the active volume is set by background rejection considerations.

IV. g. *Background*

Major sources of background arise from cosmic ray particles, atmospheric gamma rays, neutrons, and internal activation. Assuming a typical orbit (28.5^0, 556 km) we can expect to acquire good data for 20-22 hours per day, neglecting data taken during passes near the south Atlantic anomaly. The expected charged particle flux in space, assuming a cutoff rigidity near 5 GV, is approximately $0.01/cm^2$/sec (Stassinopoulos and Barth, GSFC report X601-82-9, 1982). These charged particles can be vetoed by surrounding the sides and bottom of the detector stack with a fast plastic scintillator. Assuming it has an area of $5m^2$ it should count at a rate of $\approx$1 kHz. With a response time of 10 $ns/particle$ it will cause a dead time of $\approx 10^{-6}$. This will veto electrons as well as protons. With good light collection, we can expect this to have an inefficiency of $<10^{-6}$. The top surface could be covered in the same fashion used by the Tokyo group, an overlapping mosaic of very thin Si(Li) detectors, which have the property that they can easily detect minimum ionizing particles without introducing a significant fraction of a radiation length above our primary converter layer. The fact that our stack is completely active gives excellent rejection for charged particles that make it through the top anti-coincidence layer, since they would, on average, appear as single minimum ionizing track for the first 5-10 layers. Note that the background in space is much lower than the background at balloon altitudes because there is no atmosphere to generate large n and γ backgrounds.

Requirements on segmentation deeper in the stack are dictated by background considerations. Varnell et al(IEEE Trans. Nuc. Sci. NS-31, 300, 1984) have measured the "internal" background at a $5g/cm^2$ altitude at Palestine, Texas ($R_{\min} \approx 5GV$) as $3 \cdot 10^{-2}/cm^2$sec–MeV above 0.1 MeV. The signal from this background is from "slow" electrons having a range less than a few mm in Ge and will thus be local to a single detector, even if it is thin. Our volume of Ge, $5 \cdot 10^5 cm^3$ implies a singles counting rate of 15 kHz for a threshold at 100 keV. For our trigger detectors we may want lower thresholds but there will be a smaller volume for them and consequently a lower rate. Requiring signals from at least two upper and two lower detectors, and perhaps from some deeper detectors as well reduced this background trigger rate essentially to zero. Gehrels et al. suggested the technique of detector segmentation to eliminate the background based on its local nature.

IV. h. *Radiation Dose Damage*

The radiation dose, even including passage through the South Atlantic anomaly, is expected to be $<10^6 particles\ cm^{-2} yr^{-1}$. We don't expect this dose to degrade detector performance.

IV. j. *EngineeringParameters*

We show below a table summarizing the basic engineering data for the detector discussed above.

Engineering parameters	
item	number
event rate	1000/sec
channels	75,000
signal min.	100,000 e-
noise	<20,000 e-
dynamic range	1000:1
power	< 2kW total
weight	< 4 tons

V. Conclusions

We have looked at a variety of methods that can be used in a search for high energy γ rays of extraterrestrial origin. We have seen that cryogenic detectors are difficult to use and maintain in space. Scintillation chambers such as BGO or NaI are relatively easy to construct and maintain but they do not offer high resolution over a large enough dynamic range in energy. Si technology is available today, and is fairly inexpensive, but it is not within the ability of the shuttle program to orbit a sufficiently large Si array to accomplish our goals. We are left with Ge as the ideal detector for studying γ rays in space and have shown that such a detector can be constructed with very little technological development.

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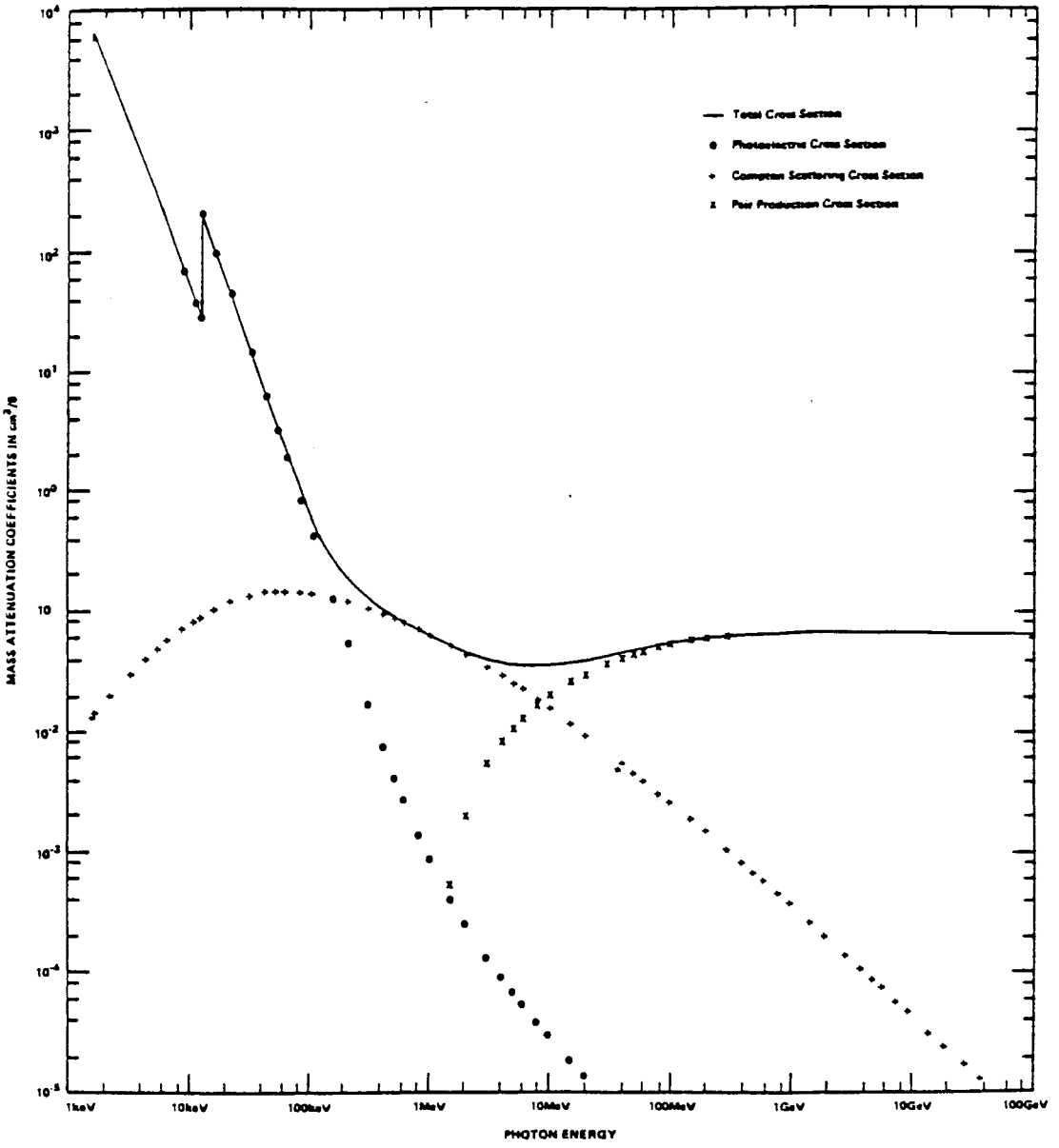
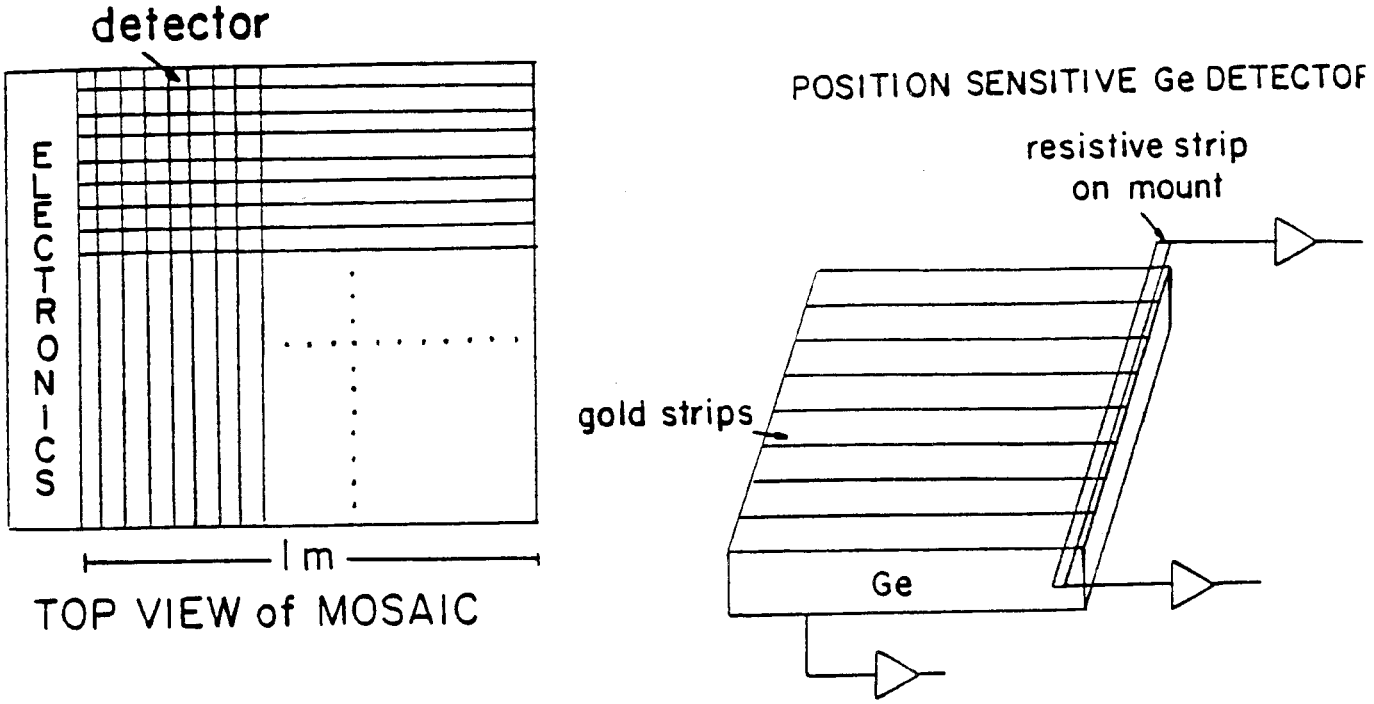


Figure 10-4. The photoelectric, Compton scattering, pair production, and total mass absorption coefficient for Ge (from Hubbell, 1969, 1977, and Hubbell et al., 1979).

GAMMA RAY INTERACTION PROCESS 237

Figure 1


detector
ELECTRONICS
1 m
TOP VIEW of MOSAIC
POSITION SENSITIVE Ge DETECTOR
resistive strip
on mount
gold strips
Ge

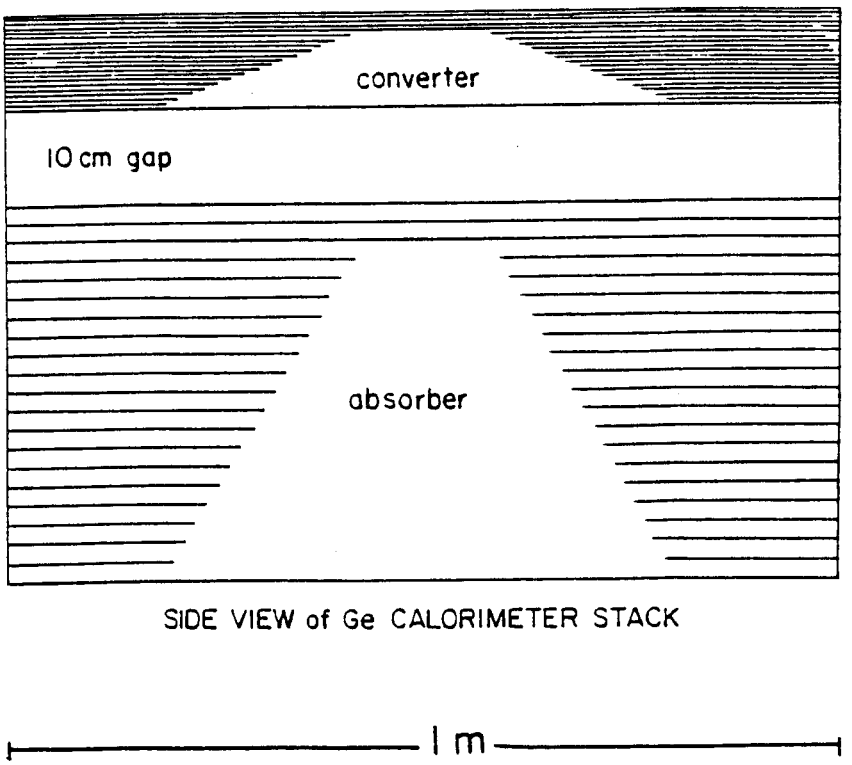

converter
10 cm gap
absorber
SIDE VIEW of Ge CALORIMETER STACK
1 m

Figure 2