PROPERTIES OF BISMUTH GERMANATE AND ITS USE FOR ELECTROMAGNETIC CALORIMETRY*

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Summary

The calorimetric and fluorescence properties of Bismuth Germanate are discussed and compared to those of NaI(Tℓ). Results on the energy resolution of BGO are presented for energies up to 50 MeV; the energy and position resolution are studied by Montecarlos at higher energies. The performance of a 4π BGO e.m. calorimeter is compared to that of NaI and is specified for a compact fieldless calorimeter designed for the Z^0 energy region. Cost, optical uniformity and radiation sensitivity are areas needing further work before a large BGO detector can be built.

Introduction

Large solid angle, highly segmented sodium iodide detectors have emerged over the last few years as a novel and fruitful way to measure many of the parameters of the final states produced in e^+e^- annihilation. Two such detectors are at present active in e^+e^- physics: the Crystal Ball, that after more than three years of very productive existence at SPEAR is about to begin exploring b-quark physics at DORIS II, and the CUSB detector, working in the region of the Ψ's at CESR.

As plans for detectors at the next generation of e^+e^- machines are getting more detailed, considerable attention has been devoted to Bismuth Germanate (BGO) as a possible alternative to NaI(Tℓ) for large solid angle detectors that seek superior energy resolution coupled with good angular resolution.

General and calorimetric properties of BGO

Bismuth Germanate ($Bi_4Ge_3O_{12}$) is a transparent, crystalline material of high density and high atomic number with large scintillation light yield. BGO crystals are grown from a melt of a 2:3 stoichiometric mixture of Bismuth Oxide (Bi_2O_3) and Germanium Oxide (GeO_2). Crystal boules of up to 30 cm in length and ranging in diameter from 5 to 10 cm are pulled from the melt by the Czochralski method; the boules are then cut, machined and polished to the desired dimensions. Crystals are presently available from at least two manufacturers.[1] Table I lists the properties of BGO in comparison to NaI(Tℓ).

The calorimetric properties of BGO are of course the main reason for its emergence as a particle detector. The radiation length of BGO is 2.3 times shorter than that of NaI(Tℓ), and the Moliere radius (determining the scale of the lateral spread of e.m. showers) is a factor 1.75 less than NaI(Tℓ). The nuclear absorption length, Λ = 23 cm, prohibits its use as a hadron absorber, although the ratio Λ/X_0 is marginally higher than for NaI(Tℓ) and may thus improve slightly the hadron-electron separation.

The crystals are mechanically rugged, do not cleave, are reasonably hard to scratch and are impervious to most chemical solvents - water in particular. These latter properties are in marked contrast to NaI(Tℓ), that is very delicate and difficult to handle on all these counts. On the other hand, growing long (≳20 cm) crystals of uniform transparency appears to be a challenging task, requiring high-purity starting materials and carefully controlled growth conditions. The optical quality of BGO crystals is not yet on a par with that of NaI(Tℓ), although it must be pointed out that the technology for BGO is still developing.

TABLE I
BGO - NaI(Tℓ) COMPARISON

	BGO	NaI(Tℓ)
General Properties		
Specific Gravity	7.13	3.67
Hardness	~5 (soft glass)	~2 (rock salt)
Stability	rugged	cleaves, shatters easily
Chemical Stability	good	poor
Solubility (H_2O)	none	very hygroscopic
Calorimetric Properties		
Radiation Length, X_0	1.12 cm	2.59 cm
Moliere Radius	2.24 cm	4.4 cm
dE/dx (min)	~9 MeV/cm	4.8 MeV/cm
Nuclear Absorption Length Λ	~23 cm	~41 cm
Optical and Fluorescence Properties		
Refractive Index	2.13	1.85
λ_{max} Emission	480-500 nm	420 nm
Fall Time	300 ns	250 ns
Photoelectrons/MeV	300-600(tube depn'd't)	
Light Output	16	100

Optical and fluorescence properties

The fluorescence of BGO has been assigned to the $^3P_1 \rightarrow {}^1S_0$ transition of the Bi^{+++} ion. The large Stokes shift between the absorption spectrum[2] (peaked in the near UV) and the emission spectrum makes the material highly transparent to its own light. The index of refraction is about 2.15 over the visible range (compared to n=1.85 for NaI(Tℓ)). Such a high index makes the light transfer through photomultiplier windows (typically n=1.46) rather inefficient; graded index couplings do not help significantly. On the other hand, the high index helps in keeping most of the light into a long parallelepipedal crystal; in fact, all of the light that is within the critical angle for transmission through the interface to a PMT is totally reflected off the sides for parallelepipedal crystal geometry. This circumstance suggests that in parallelepipedal crystals light collection uniformity along a crystal could be very good. Scattering centers in crystals would worsen the uniformity of light collection; we see examples both of macroscopic scattering centers and of the expected effect in 20 cm long crystals we have under test. These issues have been investigated in detail by Montecarlo for smaller crystals in view of applications in positron emission tomography.[3]

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The emission spectrum[2,4,5] peaks at 480 to 500 nm, with a substantial tail in the green and red. It is thus not ideally matched to the response curve of bialkali photocathodes, while matching very well the response of Silicon photodiodes.

The fluorescence decay time has long been known[14] to be about 300 ns at room temperature. A recent, accurate measurement of the light pulse shape, done with the single photon method[15], confirms that the decay time is 300 nsec at room temperature but shows in addition an additional component decaying with a 60 ns time constant and accounting for ~10% of the total light. The risetime is measured in the same study to be 2.8 ns and is probably dominated by light collection time in the crystal used.

The integrated light output of BGO is often measured relative to NaI(Tℓ); it depends of course on the PMT response curve. Furthermore, it is very sensitive to crystal purity and optical quality, as well as surface treatment. Using bialkali PMT's, light yields of up to 16% of NaI(Tℓ) have been reported.[6] We have measured the photoelectron yield using an RCA 8850 Quantacon tube on a 1 inch diameter x 1 inch long, cylindrical crystal, with polished sides; we observe 192±5 photoelectrons using 0.662 photons (Cs^{137}), with a FWHM/peak resolution of 18±1%. Within the errors, the resolution is explained by photoelectron statistics. On the same crystal and similar ones, but using Hamamatsu bialkali PMT's, we get typical FWHM/peak resolution of 12.5% with Cs^{137} gamma rays. This resolution indicates a higher photoelectron yield, roughly 600 electrons/MeV.

It is known that the energy resolution of BGO scales roughly like $E^{-1/2}$ up to a few MeV.[14] The resolution falls more slowly for NaI(Tℓ) crystals; these circumstances encouraged us to investigate the resolution of BGO at higher energies.

Before closing this review of material properties, we note that both fluorescence decay time and integrated pulse height of BGO decrease rapidly with temperature. Both quantities are approximately linear vs. temperature from 10°C o 55°C, with $\Delta P/P = -1\%/°C$ at 20°C, where P is the pulse height.[7] The light output saturates at ~200°K, where it is ~5 times more than at room temperature.[2] While all this may speak for cooling BGO crystals, it also demands that any future detector be carefully temperature controlled, and that the uniformity be better than 1°C across the detector.

Energy resolution measurements for E ≤ 50 MeV

Two cylindrical crystals, 4 inches in diameter x 3 inches long, were grown for us by the Harshaw Chemical Co. The size was chosen to optimize containment of electron-induced showers up to 100 MeV using the two crystals juxtaposed. The crystals were mildly straw colored, of good transparency except for an axial region of impurities about 1.5 inch in diameter, starting from a flat face and tapering off towards the other face.

The measurements have been described in detail elsewhere[8]; only the essentials are summarized here. The results are in Fig. 1. Measurements were made at the following energies:

(a) Source region: 0.66 MeV photons from Cs^{137}; 0.51 and 1.27 MeV photons, from Na^{22}.

(b) Nuclear reaction region: Using the Crystal Ball's Van de Graaff accelerator to induce (p,γ) reactions on nuclear targets, we took data at 4.44 MeV and at 11.67 MeV ($p+B^{11} \rightarrow C^{12*} \rightarrow C^{12}+\gamma_1+\gamma_2$) and at 6.13 MeV ($p+F^{19} \rightarrow Ne^{20*} \rightarrow Ne^{20}+\gamma$).

(c) Higher energies: We took data with the Linac of the Naval Postgraduate School at Monterey. The electron beam was run at 1 particle per pulse with energies of 30 and 50 MeV; it had an energy width of 0.4%.

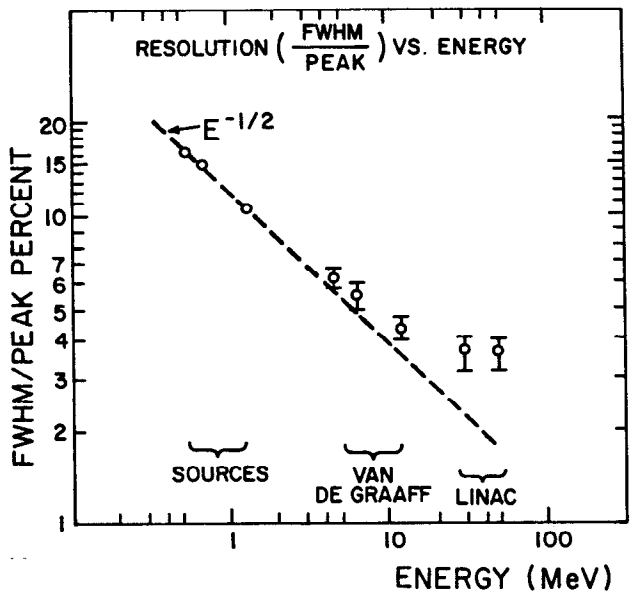

Fig. 1. Energy resolution measured with the 4 inch x 3 inch BGO crystal.

For all measurements, one of the two crystals was grease-coupled to a Hamamatsu R1069 5 inch PMT.

In the Van de Graaff data, the photons were collimated to impinge axially on an area of approximately 1 inch square, offset by 1 inch from the crystal axis. This was to assure that the scintillation light would neither be produced nor transmitted in the impurity "cloud" that faced the incoming photons. Different cloud-beam geometries gave worse resolutions than the arrangement described. At 30 and 50 MeV, the crystal was complemented with an array of 6 large NaI(Tℓ) detectors, arranged to maximize the solid angle viewed from the center of the BGO crystal. The array was used as a veto to eliminate events in which more than 0.3 MeV of the shower energy would escape the crystal and thus measure the intrinsic resolution of the crystal. We note that, at these energies, it is not possible to keep the shower or its light from the "cloud" in the crystal.

The results in Fig. 1 show a gradual departure from the $E^{-1/2}$ low-energy extrapolation; we feel this is due to the impurity "cloud" either in light generation or in light transmission, based on the tests done at Van de Graaff energies. The resolutions obtained at 30 and 50 MeV, however, compare not unfavorably with resolutions obtained with NaI(Tℓ) crystals of larger size at similar energies.[9] We conclude that BGO shows some promise as a material for electromagnetic calorimetry and discuss it further in view of large solid angle detectors for future e^+e^- experiments.

Leakage and resolution at higher energies

As the energy of the incident particle increases, total shower containment becomes impossible and the fluctuations of energy leakage dominate the resolution. Cost considerations and overall apparatus design constraints set a limit on the thickness and thus set the scale of rear shower leakage. Back scattering and leakage out of the side are a limit even for a full solid angle detector, since backscattered energy or energy deposited outside a maximum allowed volume cannot be associated to the shower they originate from if there is more than one shower in the event.

We have studied the lateral spread of showers by Monte Carlo using the EGS3 code.[10] Fig. 2 shows the fraction of the energy escaping out of a 20 R.L. thick cylinder of radius r with 100 MeV photons incident along the cylinder axis, for both BGO and NaI(Tℓ). This radial energy distribution (integrated along the axis) is to very good approximation independent of the energy and charge ($e^{\pm}$,γ) of the incident particle. Fig. 2 shows that r=7.5 cm is sufficient to contain >98% of the energy; the analogous radius for NaI(Tℓ) is about 16 cm.

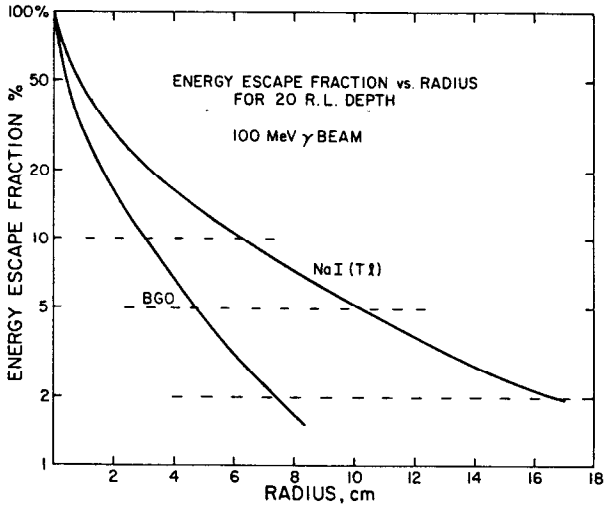

Fig. 2. Fraction of energy escaping from a BGO or NaI cylinder 20 X_0 long vs. radius of cylinder for 100 MeV photons incident on cylinder axis.

We intend to learn more about the use of BGO for future large, multisegmented calorimeters by building and instrumenting a test array of long (20 cm) parallelepipedal crystals. The results of Fig. 2 indicate that a width of 15 cm would be sufficient to contain more than 98% of the energy of the shower. We studied, again by the EGS Montecarlo, the expected energy resolution of a 15 cm x 15 cm x 20 cm BGO parallelepiped for electrons incident at the center along the major axis. The resolutions obtained for 10 MeV < E_e < 10 GeV are shown in Fig. 3; the calculation includes a photoelectron statistics term, falling like $E^{-1/2}$ and taken to give a FWHM/pulse = 16% at the Cs^{137} γ energy - a result that we get from 20 cm long crystals. It can be seen that photoelectron statistics dominates the

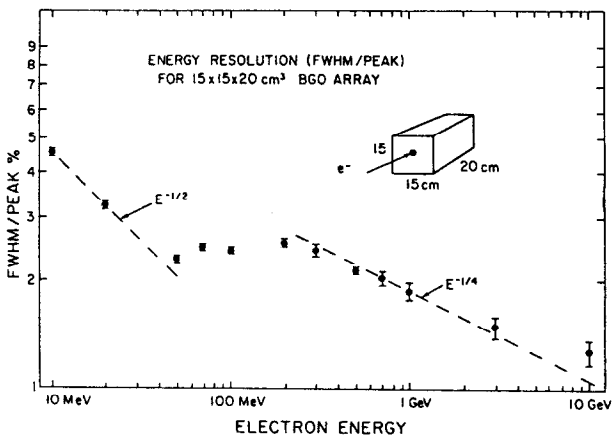

Fig. 3. Energy resolution for a 15 x 15 x 20 cm^3 BGO parallelepiped vs. incident electron energy.

calculated resolution up to about 50 MeV incident energy. Between 50 and 200 MeV the onset of significant leakage causes an increase in resolution; at higher energies, the resolution falls again, with an energy dependence close to the $E^{-1/4}$ behaviour that is often quoted for large NaI(Tℓ) detectors.

This Montecarlo does not include the effect of other inevitable contributions to the resolution that are harder to predict, such as uncertainties in the relative calibration of the readout elements, or the effect of possible nonuniformities of the material, or in light collection, etc. Such effects are almost certain to mask the curious rise of the resolution occurring above 50 MeV.

Position resolution

It is important to have a precise estimate of the resolution on the entry point of a photon in an array of crystals of given modularity in order to optimize the dimensions of modules. The quickest way to obtain an estimate of the entry point using as input the energy deposited in each module is to form the average of the modules hit weighted by their energy deposit:

$$\bar{x} = \frac{\Sigma E_i x_i}{E_i} \qquad x_i = \text{coord. of the center of each module}$$

This "center of energy" method has a bias intrinsic to the choice of the center of each module as the average for energy deposition in that module. The lateral profile of showers is sharp, as Fig. 2 shows, particularly in the central region; if the entry point is off the center of the module hit by the incident particle, the bias will not be cancelled by the energy distribution in the adjacent modules unless the granularity is very fine. To set the scale, a 1 x 1 x 22.4 cm^3 module hit along the axis will contain approximately 55% of the energy of the incident photon, for E_γ = 100 MeV.

This bias can be all but eliminated by using a different procedure that has been used extensively in the Crystal Ball software.[11] The entry point is varied until the best fit is found between a Montecarlo-calculated average shower profile (which is a function of the entry-point coordinate) and the observed shower profile. The fundamental limit is set by the lateral fluctuations of the shower energy distributions that have a scale of 10 to 30 MeV.

Fig. 4 and 5 show the resolutions we obtain on the entry point of photons of three energies for three module sizes, using the center of energy method and the shower profile method respectively to determine the shower entry point. The latter algorithm is obviously superior, in particular at high energy. The results of the shower profile method show - as expected - that one does not gain resolution in direct proportion to the number of segments, due to the shower fluctuations. At the higher energies, of course, the latter are less important and the resolution gets to be 10% or less of the module size.

Comparing BGO and NaI(Te) for a 4π electromagnetic calorimeter

On the basis of our experimental results on BGO, the Montecarlo studies and the experience of some of us with the Crystal Ball at SPEAR, we can now attempt a more general comparison between the performance of two hypothetical large calorimeters, one built with BGO and the other with NaI(Tℓ).

First we can ask which one will have the best energy resolution. This is a natural question to ask even if energy resolution will not be the most important parameter for the physics aims of such detectors,

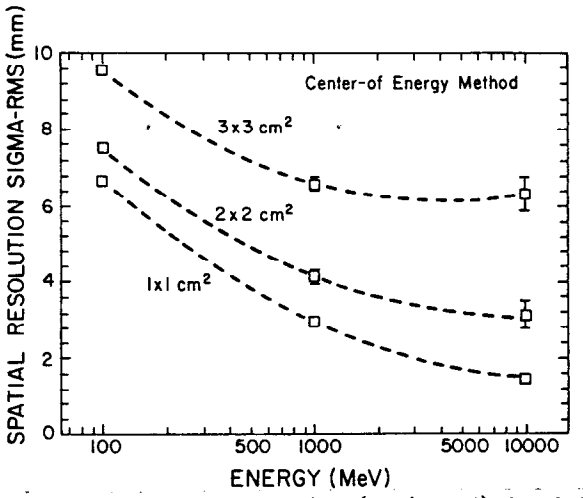

Fig. 4. Rms position resolution (projected) for 1x1 cm^2, 2x2 cm^2 and 3x3 cm^2 segmentation vs. incident photon energy. The entry point is calculated with the center of energy method.

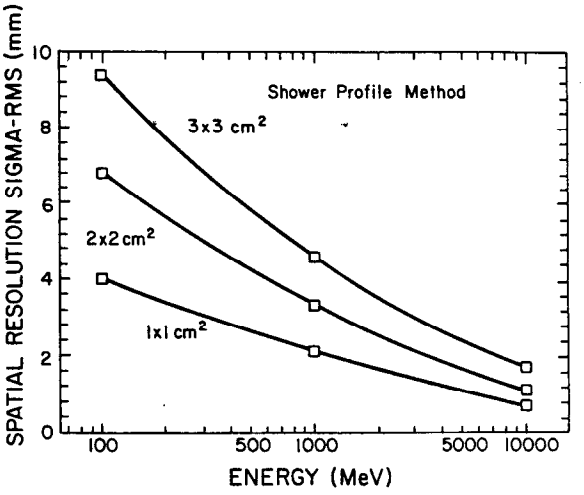

Fig. 5. Like Fig. 4 but with the entry point calculated using the shower profile method.

since this parameter is one of the attractive characteristics of both materials. We have seen that for BGO energy leakage dominates photoelectron statistics as the main cause of resolution above ~100 MeV incident energy. We note in this context that the resolution of the Crystal Ball's prototype[12] (a cluster of 56 crystals) above 1 GeV is only marginally better than what we obtain from our Montecarlo: at 1 GeV, we calculate FWHM/peak = 1.9± 0.1% and the cluster-of-54 prototype measured 3.0±0.2%. It is easy to explain the difference with any of a number of instrumental effects. The first conclusion is that there seems to be no intrinsic difference between the ultimate resolution of the two kinds of detectors in the leakage-dominated region. At lower energies we should compare our results with the 4 inch BGO crystal to results obtained with large NaI(Tℓ) crystals; here, BGO performs marginally below NaI(Tℓ), largely due to problems of crystal purity on which progress has recently occurred (see below). The tentative conclusion at the present time is that we do not expect a significant improvement in energy resolution over NaI(Tℓ) from a BGO detector; improvement over the Crystal Ball's performance, if achieved in the future, will rather depend on better intercalibration of the readout elements or other material-independent instrumental matters.

The more important advantage of BGO is the fact that the radial energy spread is a factor of two less than for NaI(Tℓ), as can be checked using Fig. 2. We only need to specify the inner radius of the e.m. calorimeter to compare the performance of the alternative approaches; we assume that this choice would not be determined by cost considerations only, but would have the most crucial inputs from the design aims of the whole detector. It is easy then to list the advantages that a BGO calorimeter would have over an NaI(Tℓ) calorimeter of the same inner radius.

(a) The solid angle "lit up" by e.m. showers or nuclear interactions in BGO would be 4 times less than for NaI(Tℓ), leading to a large reduction in overlaps of particles. The precise numbers are of course model-dependent.

(b) The angular resolution for photons would be x2 better for BGO.

(c) Overlap of photons from symmetric π^0 decays would occur above a π^0 momentum value 2x higher for BGO than the corresponding momentum for NaI(Tℓ).

(d) π^0 mass resolution would improve (due to (b)) and the combinatorial background would correspondingly be reduced.

(e) Improved π^0 reconstruction efficiency would dramatically reduce the background in inclusive photon spectra.

Last, if the e.m. calorimeter is followed by a hadron calorimeter, the latter would be more compact if the e.m. part consists of BGO. Whether this would result or not in an overall cost saving depends on the large quantity cost of BGO (see below).

A design exercise for a compact calorimeter for E_{CMS} = 100 GeV

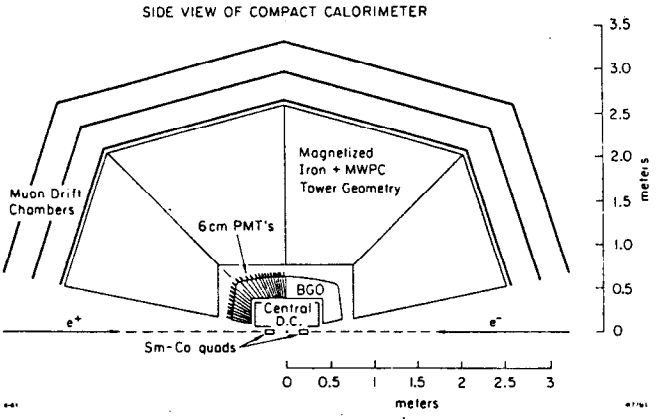

Fig. 6. Schematic diagram of the compact calorimeter (SLC note #34) discussed in text.

Some of the above considerations can be made more precise by referring to the design of a full detector. Fig. 6 schematically represents a compact detector system for physics in the region of the Z^0 at the Stanford Linear Collider.[13] The design and performance parameters are described more in detail in the reference. The detector is based on a fieldless electromagnetic calorimeter using BGO, followed by a magnetized iron hadron calorimeter and by drift chambers for muon momentum measurements. We quote here some of the characteristics of the electromagnetic calorimeter. The inner radius was chosen to be 40 cm, due primarily to cost; it is not clear, though, that there is much to be gained from a larger inner radius in the absence of magnetic field and for any reasonable (not too high) calorimeter segmentation. The inner cavity was chosen

to be cylindrical, rather than spherical like the Crystal Ball, to use optimally the limited internal volume available. The BGO shell is 20 X_0 thick, and is segmented in ~10^4 modules. Projective tower geometry was chosen to optimize solid angle segmentation in view of the very high multiplicities expected. Each module would have an inner side of 1.4 x 1.4 cm^2 and an outer side of 2.4 x 2.4 cm^2, and would be viewed axially by a PMT in this design.

We list rough estimates of some performance parameters referred to in the previous section:

(a) The angular resolution for photons, based on Fig. 5, depends on energy and lies in the range of 15 to 3 mr for 100 MeV < Eγ < 10 GeV.

(b) The angular resolution for noninteracting hadrons is ~10 mr.

(c) Scaling with radiation length from the Crystal Ball experience, we estimate that we can separate overlapping photons from π^0 decays for opening angles >17 mr, corresponding to $p(\pi^0) < 8$ GeV/c.

(d) The rms resolution on π^0 mass is 6%, for $p(\pi^0) = 1$ GeV/c; it deteriorates rapidly with momentum.

(e) Separate energy measurements for each e.m. particle in a jet will not be possible due to overlaps; the situation will be helped somewhat if, as QCD Montecarlos indicate, ~1/3 of all particle lie in a ±200 mr core. Outside this core, most of the showers should be separable. Within the jet core e.m. energy flow measurements can be done.

Are we ready to build a 4π BGO detector?

We conclude that BGO is not only an attractive material for electromagnetic calorimetry, but that a BGO calorimeter would be a very useful component in a 4π non magnetic calorimeter. The promising first results on photodiode readout of BGO (presented in the next talk) make the magnetic calorimeter option possible and very appealing. Therefore we should ask whether we can design and construct a large BGO calorimeter at the present time. We feel that three problems need more work.

(a) Cost. The current cost of BGO is about 14\$/cm^3 in quantities of a few liters. This translates to 10.5×10^6\$ for the crystals only in the design exercise we described - and would certainly rule out more ambitious designs. We have investigated in some detail both the material and growing costs of the crystals, and feel that the quoted cost would be largely unjustified for amounts of a few tons. We estimate that a reasonable cost on this scale should not exceed 5\$/cm^3. One uncertainty in the projected cost is due to the relative scarcity of Germanium and the demand for it on the world market. GeO_2 dominates the price of materials in BGO production; the current cost is 600\$/kg in the required purity and represent 21% of the projected cost of finished crystals assuming that none of the purchased GeO_2 is wasted in the production process.

(b) Optical uniformity of crystals. All designs for future detectors are based on crystals at least 20 cm long. Obtaining such crystals with good transparency throughout has proved to be a challenge. There has been progress in the last few months at Harshaw in this regard, and we received in the last few weeks crystals of much improved quality. Thin transversal bands of scattering centers are still visible, though, irregularly distributed along the main axis of crystals. We do not know yet whether these bands produce a significant deterioration of the uniformity of the crystal response along its axis. We feel, though that given the recent trend the prognosis in this respect is good.

(c) Radiation hardness. The radiation background at some of the future e^+e^- colliding facilities is expected to be very large, and to put heavy constraints on any future detector. A paper contributed to this conference by M. Kobayashi et al working at KEK on BGO contains encouraging results; BGO is shown to be more resistant to radiation damage from low-energy photons and high energy hadrons than NaI(Tℓ) and Cerenkov or scintillating glasses. The damage is seen as a loss of light transmission through 1 cm of BGO, and, for e.m. radiation in particular, disappears in a few weeks. The typical exposure to see an effect several hours after irradiation is 10^5R for e.m. radiation and 10^4R for hadrons.

We have observed a loss of tranmittance in 20 cm long crystals irradiated with UV. The effect totally disappears in about 2 weeks and may be the same as that observed by the KEK group; however, most of the transmittance loss we observe decays in a few minutes, and we also observe a component that decays in a few hours. These effects would not have been seen in the KEK experiments, while our experiments would not have seen damages that disappear in a few seconds or less. Our UV exposures correspond to particle fluxes much larger than what can be realistically expected.

We feel that more work is needed on at least the following points: (1) a 1% loss of transmittance/cm is intolerable over a 20 cm long crystal. Either very precise tests on short crystals or tests on long crystals are necessary. (2) It must be checked whether the optically impure parts of the presently available crystals are more or less sensitive to radiation damage. (3) The possibility of very short-duration radiation effects must be investigated, probably down to the 1 ms time scale.

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