RECENT RESULTS ON BGO CALORIMETER AND SILICON PHOTODIODES*

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Summary

We present the status of electromagnetic calorimetry using Bismuth Germanate (BGO) with silicon photodiode readout and report on recent test results in a high energy (1-10 GeV) electron/hadron beam.

A capability is emerging for high precision electromagnetic calorimetry in magnetic fields using Bismuth Germanate (BGO) or Sodium Iodide (NaI) crystals with silicon photodiode (PD) readout, thus avoiding the traditional antagonism between photomultiplier (PM) tubes and magnetic fields. We wish here to summarize the status and present some recent test results. Table 1 is a summary of properties of NaI and BGO (from ref.1). In table 2 a comparison of PM vs PD readout of BGO is given (from ref.2).

Table 1. Summary of properties.

item	NaI(Tl)	BGO	Comment
density	3.7	7.13	[g/cc]
effect.atomic#	50	74	
rad.length X_o	2.59	1.12	[cm]
hadronic absorption length λ_o	41.3	23	[cm]
λ_o/X_o	0.063	0.049	
hygroscopic	yes	no	a)
hardness	2	5	ref.7
mechanical/ thermal stability	poor	good	
flourescence signal	1	0.08	b)
emission peak	400-420	480	[nm]
emission temp gradient	-0.4	-1.0	% per ^oC at 20^oC
flourescence decay time	230	350	nsec at 20^oC
decay time temp.grad		-4.7	nsec/^oC
resolution	$\frac{2-5}{\sqrt[4]{E}}$	$\frac{0.3-1}{\sqrt[2]{E}}$	%/GeV c)
resolution ^{137}Cs	7 %	10 %	ref.8
refractive index	1.85	2.15	
radiation resistance	poor	good	ref.3
afterglow	0.5-5	.005-5	% after 3 msec , ref.8
dE/dx min	4.85	9.2	MeV/cm

a)BGO dissolves in HCl, not attacked by acetone, alhohol.
b)depends on geometry, PM coupling, sourface treatment
c)theoretical value for BGO

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Table 2. Comparison of properties of PDs vs. PMs

item	PM	PD
sensitive area	round,any diameter	any shape<3cm²
<quantum efficency>	12%	60%
int. amplification	yes	no
stabilized HT	yes	not necessary
post amplification	simple (not necessary)	high quality amplifier
noise equivalent r.m.s error	~20-50 keV	1.15 MeV for for described test, possible a)
typical dynamical range	10^4	10^8 a)
short term stability	1 (.3)% b)	<.01 %
long term stability	1 (.3)% b)	<.1 %
temperature coeff.	< .2 % /°C	<.2 % /°C
rise time	5-50 nsec	> 100 nsec (area dep.)
rate	high	low
size (height)	< 6 cm c)	< 1 cm
magn. shield	complicated, impossible for high fields	unnecessary
noise immunity	high	low
price d)	> USD 50	USD~ 10
price of amplifier	USD 5	USD 15
accidental light damage	possible	no
radiation damage	not known	
# photoelectrons for passing tracks	few tens e)	~100/micron depletion layer

a) special preamplifier required
b) for selected high stability PM's
c) Hamamatsu R 1569X
d) estimate for large quantity
e) due to Cerenkov light in glass window

BGO has many advantages for storage ring (and other) detectors:
1)It has a high density and a short radiation length, permitting compact detectors.
2)It is not hygroscopic or fragile.
3)It has very high radiation resistance. Recent measurements have shown that the scintillation efficiency reaches an equilibrium degradation of ~1% for continous running with synchrotron radiation of ~ 110R/hour, i.e. BGO has more than two orders of magnitude higher resistance against low energy γ rays than lead glass (ref.3).
4)The energy resolution is equal to or better than NaI for 'high energies' (the cross over is well below 100 MeV, although only preliminary high energy tests have been made).

Some disadvantages are:
1)The material has a high refractive index confining most of the scintillation light. The light output is about 30% that of NaI (10% for PM readout).
2)It is not yet available in large quantities at reasonable prices.

Disadvantage 1) is not relevant to high energy (HE) experiments using PM readout but is important for the practicality of PD readout. Disadvantage 2) is now under attack - alternate crystal growing methods (and suppliers) are being tested. The price of NaI for HE experiments is now about 1-2$/cc for bulk material. BGO will be fully competitive if the price can be lowered to about $5/cc because detector volume can be smaller for the shorter radiation length material. A typical small quantity price is now 12-20$/cc .

Photodiode readout has a number of advantages over PM tubes. The diodes with 'unity gain' are stable and radiation resistant devices. Maintaining stability at the 1% level is not trivial for large arrays of PM's. PD's can operate in magnetic fields above 20kG, while stray fields of a few hundred Gauss require already an elaborate shielding for PM's. The photodiodes are also extremely compact.

Photodiodes have about a factor 5 higher quantum efficiency than photomultipliers at the peak of the BGO emission spectrum but this is not enough to compensate the internal PM gain. Therefore a high quality charge sensitive amplifier has to be used. Additionally a shaping amplifier for signal filtering is required. This limits the operational frequency to <0.2 Mhz, sufficient for the presently operated or planned storage rings. The main limitation is that the photodiode capacitance, in conjunction with input noise for quality FET transistors, results in noise on the order of 1 MeV equivalent deposited energy (this is for a BGO crystal of $3x3x20\ cm^3$, viewed by 4 diodes of $1cm^2$ each (ref.2)). This is not acceptable, for example, for spectroscopy of the ~100 MeV photon lines from the ϒ state transitions in a Crystal Ball - like detector, since the signal must be summed over many crystal elements. Recent tests using BGO/PD cooled to $-30°C$ have given a noise equivalent to ~ .5MeV and another factor of 2 reduction may be obtained both from improved electronics and photodiodes with low series resistance. One advantage of resolutions of σ < 0.3 MeV is that calibration using radioactive sources (e.g. the 2.5 MeV sum line of ^{60}Co) starts to become practical.

Recently a segment of a BGO calorimeter (9 elements of $3x3x20cm^3$ arranged in a cluster of 8x8 r.l. cross section and 18 r.l. deep) has been tested in the T6 beam at CERN (ref.4). The crystals were viewed by 1,2 or 3 PD's of $1cm^2$ area each. The integrated noise was 13 MeV, and ranged between 2 to 5.5 MeV for individual slabs (besides the small number of PD's, the test arrangement required long connection cables and a short shaping time constant of 2 μsec, also the RF shielding was imperfect). The crystals were calibrated with minimum ionizing particles which deposit about 190 MeV. A small scintillation counter in front of the central slab defined the incident beam to $1x1cm^2$ area. The calorimeter was surrounded by lead-scintillator sandwich counters (15 layers of 1mm lead, 16 layers of 3 mm scintillator). The information from the counters was used for later off line analysis. Fig.1 shows the results of a linearity test with electrons up to 10 GeV. A difference of $2.5\pm0.5\%$ between the measured point at 10 GeV and the one extrapolated from 1 GeV is expected due to the increase of rear and side shower leakage with increasing energy. Table 3 lists the resolution at 1, 4 and 10 GeV. The distributions are asymmetric, therefore also the rms error of the higher side is given. The resolution can be broken up into contributions coming from the intrinsic BGO resolution, the shower leakage fluctuations σ_{sl}, the beam momentum spread σ_{pb}, the photodiode noise σ_n and fluctuations σ_{ep}* of the number of shower electrons passing through the depletion layer of the photodiodes.
Thus we are lead to the following equation for the resolution

$$\sigma/E = \sqrt{(0.5\%/\sqrt{E} + 0.3\%)^2 + \sigma_{sl}^2 + \sigma_{pb}^2 + \sigma_n^2 + \sigma_{ep}^2}$$

*the passage of electrons will shift the spectrum by incremental steps of 15-20 MeV.

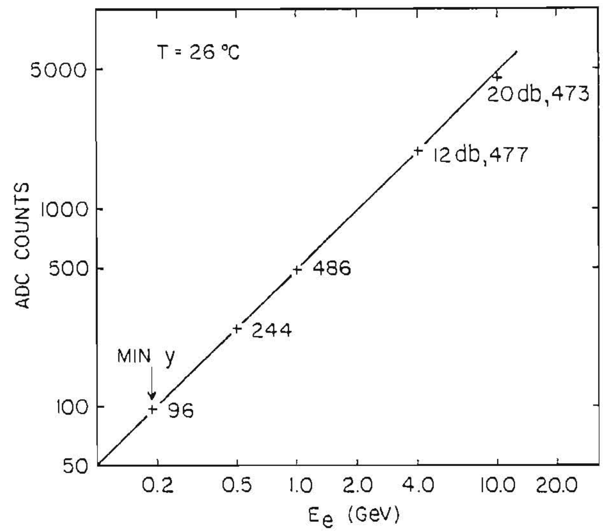

Fig.1 Linearity test with electrons up to 10 GeV. The numbers indicate the channel number after attenuation (attenuator error ±1%).

Table 3. Measured energy resolution of BGO test calorimeter

#	P_{inc} [GeV]	σ_{obs} [%]	σ^+_{obs} [%]	σ^+_{sl} * [%]	σ_n [%]	σ^+_{BGO} ** [%]	COMMENTS
1	1	2.35	2.2	1.4	1.4	<1.0	
2a	4	1.75	1.3	0.8	0.4	<0.9	substantial material in front
2b	4	0.94	.95	-	0.4	<0.9	substantial material in front, and lead scint. counters in veto
3	4	1.25	.90	0.7	0.4	<.4	better PD,3 cm more BGO
4	10	1.1	.90	0.8	0.2	<.4	better PD,3 cm more BGO

* Predicted from Monte Carlo calculations using the EGS code[6].
** Both the unknown contribution from the beam momentum spread, σ_{pb}, and the fluctuations from electrons passing the photodiode depletion layer, σ_{ep}, are neglected.

Also quoted is the resolution for a subsample of data at 4 GeV with the lead-scintillator sandwich counters in anticoincidence (#2b in table 3), thus suppressing substantially the shower leakage. Figs.2a,2b show pulse height spectra for the measurements 2a and 2b of table 3. In summary, this preliminary test demonstrates both the feasibility of PD readout and the good energy resolution of BGO (for the evaluation of the limit of the resolution a beam spectrometer is needed). In addition to the resolution, the e/hadron rejection has been measured. In order to do this, the electrons were removed by allowing the hadron beam to pass through 5 cm of lead. The electron/hadron rejection ratio was calculated from the number of events depositing energy within a $\pm2\sigma$ region for electrons of the same momentum. This could be further improved by applying the same method to the central slab alone. Table 4 gives some preliminary numbers.

The results show that the transverse segmentation is a very powerful method with which to separate electrons from hadrons, if the initial momentum is known. It should be noted that the rejection is high even at low momenta where charge exchange is significant. Low momentum π^0's have such a big opening angle between the 2 γ's that they deposit only a fraction of their energy in the 'hit' slab. One can expect to achieve substantially better rejection ratios if the γ calorimeter is backed up by a hadron calorimeter and/or a shower shape analysis is used.

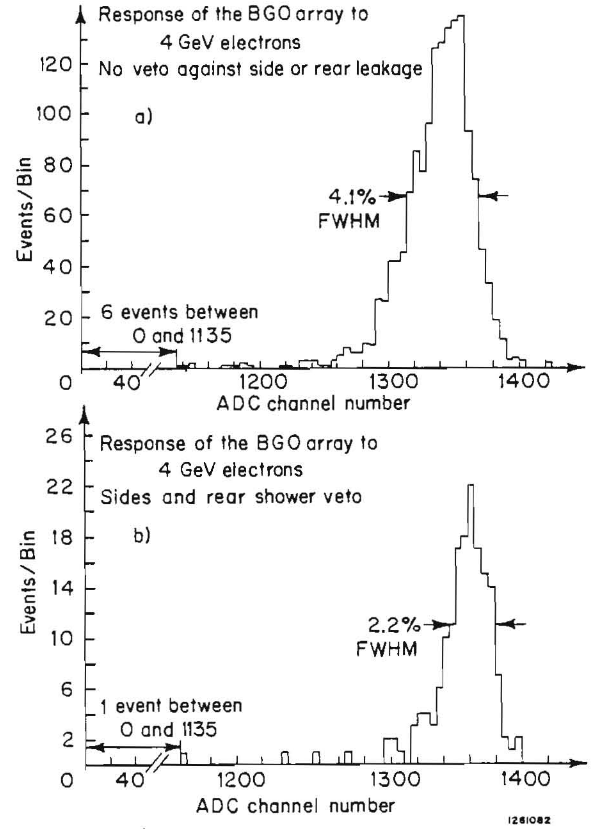

Fig.2a,b Pulse height spectra for the measurement number 2a and 2b of table 3.

Table 4. e/hadron rejection ratio for BGO test calorimeter

P_{inc}	Rejection	Comment
1 GeV (π-)	(1$\pm$0.5)/550	cluster of 9
	(1$\pm$1)/1100	central slab alone
3.5GeV(π-)	(1$\pm$0.3)/1200	central slab alone
3.5Gev(π+)	(1$\pm$0.3)/2600	central slab alone
4 GeV(π-)	(1$\pm$0.3)/900	cluster of 9
	(1$\pm$0.7)/3250	central slab alone
10 GeV (π-)	(1$\pm$0.6)/1300	cluster of 9

Several large scale (but compact) BGO detectors are now being planned or considered. The LEP proposal L3 (ref.5) would use a barrel like geometry with interior radius of 50 cm, an interior length of 1 meter, and 1400 liter volume. A more modest device (25 cm inside radius, 400-500 liters) is being studied as a detector for Upsilon spectroscopy at CESR. In both cases the interior cavity would contain a drift chamber and the whole EM calorimeter would be embedded in a magnetic field. The limited radius available for magnetic tracking is a strong impetus toward the development of small drift chambers with extremely good spatial resolution, perhaps operating in magnetic fields of 15-20 kG. The extent to which precise EM calorimetry can be combined with respectable momentum measurement for charged tracks will depend on how far resolution at high magnetic field can be pushed.

References

1. G.Blanar et al.,'Bismuth Germanate, a novel material for electromagnetic shower detectors', Max-Planck-Institut Munchen, MPI-PAE/Exp.El.94 (1981).
2. G.Blanar et al.,'Photodiode readout for scintillating crystals of BGO and NaI(Tl)', submitted to Nuclear Instruments and Methods, also Max-Planck Institut Munchen, MPI-PAE/Exp.El.99(1981).
3. M.Kobayashi et al.,KEK Preprint 82-9, July 1982.
4. H.Dietl et al.,MPI report to be published.
5. Letter of Intent for a LEP experiment (L3).
6. R.L.Ford and W.R.Nelson, SLAC-210 report, Stanford 1978.
7. O.H.Nestor and C.Y.Huang, Bismuth Germanate, a high Z gamma ray and charged particle detector. Harshaw Chemical Company.
8. Hitachi data sheet No.S-021(1981).