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CRYSTAL CALORIMETERS IN PARTICLE PHYSICS¹

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Abstract

We review the principal design characteristics of large high precision crystal electromagnetic calorimeters now in operation, or under development for the next generation of accelerator and collider experiments in high energy physics. The unique physics capability of these detectors is the result of their high electron and photon energy resolution over a wide energy range, uniform hermetic coverage and fine granularity over a large solid angle, and clean electron and photon identification. In order to maintain the high resolution *in situ*, the principal requirements to the crystals are radiation hardness and precision calibration. This has led to BaF₂, CeF₃ and undoped CsI as the leading candidate crystals for use at multi-TeV hadron colliders, and the choice of CsI(Tl) for several lower energy experiments.

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1 Introduction

Total absorption shower counters made of inorganic scintillating crystals have been known for decades for their superb energy resolution and detection efficiency. In high energy physics, large arrays of scintillating crystals have been assembled for the precision measurement of the energy and angle of photons and electrons. The discovery potential of crystal calorimeters was first demonstrated by the Crystal Ball detector [1], through its study of radiative transitions and decays of the Charmonium family (Figure 1 [2]). Over the last decade, following the Crystal Ball and CUSB [3] experiments, larger crystal calorimeters have been constructed, and their use has been a key factor in the successful physics programs of the L3 experiment at LEP [4], CLEO II at CESR [5] and the Crystal Barrel at LEAR [6]. Crystal detector arrays of this type also have been designed and are under development for the next generation of high energy physics experiments aimed at the study of CP violation, including KTeV at Fermilab [7]), and the SLAC [8] and KEK [9] B Factory detectors.

In addition, crystal calorimeters containing 10^4 to more than 10^5 elements have been designed and studied intensively by a large sector of the high energy physics community planning experiments for multi-TeV hadron colliders, including the late Superconducting SuperCollider (SSC) in the U.S. [10, 11] and the Large Hadronic Collider (LHC) at CERN in Europe [12, 13]. Although some of these crystal detector designs [10, 11, 13] are no longer under consideration for use in an experiment, significant advances in our understanding of the physics capabilities of these detectors, and key advances in crystal detector technology took place in the course of their development. We therefore include these designs in this review. At the time of this writing, a crystal calorimeter is actively being considered as an option for the CMS electromagnetic calorimeter at the LHC.

The unique physics capability of a crystal calorimeter is the result of its high electron and photon energy resolution over a wide energy range, uniform hermetic coverage, fine granularity over a large solid angle, and clean electron and photon identification. The combined energy resolution and position resolution of these detector systems results in the greatest available efficiency (and signal/background ratio) for the reconstruction of multilepton, lepton-photon and multiphoton invariant masses, and in clean separation of electrons from jets and single hadrons. A well-designed crystal calorimeter has greater sensitivity than sampling calorimeters (where the detection medium is interleaved with, or embedded in a matrix of inert material) for detecting multibody final states containing low-mass resonances (such as π^0 , η , and η'), or yet-to-be-discovered high-mass particles such as the Higgs in the “Intermediate Mass” range between 80 and 170 GeV. Experiments that include large crystal calorimeters thus have advantages in isolating rare new physics events from “Standard” physics backgrounds. This is demonstrated in Figure 1 for the Crystal Ball NaI(Tl) calorimeter.

In order to maintain the high resolution and the resultant sensitivity to new physics *in situ*, the key detector requirements are radiation hardness and precision calibration, in addition to high speed, mechanical robustness, and a stable readout with high linearity and large dynamic range. For experiments that are required to operate in the high-rate high-radiation environment of multi-TeV hadron colliders, very high speed (triggering within the typical beam-crossing time of 25 nsec) and radiation resistance up to the 10 Mrad range are among the principal design requirements. This has led to the choice of BaF₂, CeF₃, or other new high density fluorides as the leading candidate crystals. At lower energies, high luminosity experiments searching for rare B, K, or τ decays, or performing precise CP violation measurements through the study of B and K final states containing e^+e^- pairs, single or multiphotons (including π^0 's and

η 's), have chosen CsI(Tl) (CLEO II, Crystal Barrel, SLAC and KEK B Factories) or undoped CsI (KTeV). This offers a mechanically robust relatively low cost solution to the requirements of high light output, a minimum of material in front of and between the crystals, radiation hardness up to the 10 krad range, and moderate to high speed.

Section 2 describes the main properties of commonly used inorganic heavy crystal scintillators related to shower containment and performance. Section 3 presents the parameters of the major crystal calorimeters that have been built, or designed for future experiments. The achievable performance of crystal calorimeters and the contributing factors to the resolution are summarized in Section 4. Section 5 is devoted to radiation damage, which is a key issue for the highest energy experiments. The readout considerations for a crystal calorimeter are summarized in Section 6. Section 7 addresses the important issue of calibration. A brief summary of the physics discovery potential of crystal calorimeters in future experiments at multi-TeV hadron colliders is given in Section 8.

Figure 1: An inclusive photon spectrum measured at the ψ' by the Crystal Ball experiment at SLAC, showing nearly all the principal radiative transition lines of the Charmonium system simultaneously [2]. The upper inserts show the background subtracted signal from η_c and η_c' states.

2 Inorganic Crystal Scintillators

Table 1 [14, 15, 16, 17, 18] lists the basic properties of commonly used heavy crystal scintillators: NaI(Tl), CsI(Tl), undoped CsI, BaF₂, CeF₃ and BGO (Bi₄Ge₃O₁₂). Except for CeF₃, all other crystals are available on the market in large scale mass production. The crystals' expected price/cm³ listed in the table corresponds to typical quotations for an order for large crystals totaling 10⁶ and in some cases more than 10⁷ cm³.

The choice of crystal for a calorimeter is governed by the characteristics, and related considerations summarized below.

Material Properties: Density, melting point, speed of growth, breaking stress, machinability (cleaving), quality of crystal structure, flatness and crystal structure of polished surfaces, and hygroscopicity. These factors affect the production rate, net yield and price. They also determine the minimum thickness of support material that must be placed in front of and between the crystals, which may affect the energy resolution.

Shower Containment: Radiation length (X_0) and Moliere radius (R_M). Dense crystals with a shorter X_0 , require a smaller crystal depth for longitudinal containment of high energy electromagnetic showers. $23 - 25 X_0$ is sufficient for most applications, up to the TeV range. Tail suppression to high accuracy (as in KTeV), requires $27 X_0$ or more at energies above 100 GeV. Lateral containment is controlled by R_M . 93% of the energy deposited near the longitudinal position of the shower peak is contained within a perpendicular distance of $\approx 1.5R_M$ from the line along the direction of an incident photon.

Scintillation Properties: Light frequency, decay speed, and temperature dependence. Scintillators in the far UV (such as BaF_2 's fast component) must be read out by photosensors with special photocathodes and/or windows. Sufficiently long light attenuation lengths for uniform response along the crystal (often limited by the efficiency for reflection at the surfaces) are more difficult to achieve for wavelengths below 300 nm. High speed is an advantage for operation at multi-TeV hadron colliders, particularly for triggering the detector in a single beam-crossing. However, the readout must be able to match this speed, leading to a preference for low capacitance (~ 10 pf) vacuum photodevices unless the experiment's magnetic field is too high. Stability of response, and calibrations precise to $< 0.5\%$, are easier to achieve if the light output is temperature independent (as in the case of the BaF_2 fast component).

Radiation Resistance: Stability of response up to doses of ~ 10 Mrad at multi-TeV hadron colliders, and ~ 10 krad at a B Factories, are required for a stable response, and hence for a high resolution.

We briefly review the main characteristics of the commonly used crystals. As summarized below BaF_2 and CeF_3 are particularly well-suited for use at future multi-TeV hadron colliders.

- **NaI(Tl):** high light yield; emission well-matched to bialkali cathode; highly hygroscopic and thus difficult to handle.
- **CsI(Tl):** high light yield; emission well-matched to solid state photodiodes; high plasticity and resistance to cracking (mechanically robust); slightly hygroscopic: careful surface treatment is needed; radiation damage still under study [19, 17].
- **Pure CsI:** relatively fast; emission matched to bialkali cathodes; otherwise the

same as CsI(Tl) (but may be more difficult to grow).

- **BaF₂**: the fast component is the fastest scintillator and is temperature independent [20]; intrinsically radiation hard up to the Mrad range [21], but commercial available samples suffer from different levels of damage [22, 14]; radiation damage is annealable with visible light [23].
- **CeF₃**: relatively new scintillator [24]; relatively fast; light yield nearly temperature independent [18]; emission matched to bi-alkali cathodes; smaller X_0 and R_M than BaF₂; radiation damage is under study [18, 25].
- **BGO**: very high density and short X_0 , R_M ; emission well-matched to photodiodes; not hygroscopic and easy to handle; radiation damage (up to the krad range) [26, 27] can be reduced by Eu doping [28].

In addition to the crystals listed in Table 1, three other heavy crystals have recently been studied. PbWO₄ (lead tungstate) [29], PbF₂ [30] and Ce-doped lutetium oxyorthosilicate (Lu₂(SiO₄)O or LSO; i.e. Lu_{2(1-x)}Ce_{2x}(SiO₄)O [31].

PbWO₄ is a very dense (8.28 g cm⁻³) material with the shortest radiation length (0.85 cm) and Moliere radius (2.2 cm). Its scintillation light is peaked at 440 and 530 nm [29] with a decay time of 10 and 40 ns. The main shortcoming of this material is its low light yield (10-15 photoelectrons/MeV measured with a bi-alkali photocathode) and strong temperature dependence of the scintillation light (-1.9%/°C), in addition to the radiation damage observed [29, 32]. It is now under study by the CMS collaboration at CERN as an alternative to CeF₃, in their consideration of a crystal electromagnetic calorimeter option.

PbF₂ is another dense material (7.77 g cm⁻³, $X_0 = 0.93$ cm $R_M = 2.21$ cm) but it is not a scintillator in its common form. Attempts to dope PbF₂ or to grow another

form of the crystal with a different structure [33] to make it scintillate have not been successful. It thus does not really belong in this section – it has to be used as a Cherenkov radiator – but it is mentioned because of the substantial work that has been carried out to make it a low cost scintillator.

LSO is also dense (7.41 g cm^{-3} , $X_0 = 1.14 \text{ cm}$, $R_M = 2.3 \text{ cm}$; similar in these respects to BGO). Its scintillation light is peaked at 440 nm (a good match to bialkali cathodes), with a decay time of 40 ns. Its light output is 75% of NaI(Tl). It has also been tested to be radiation resistant to 100 Mrad [34]. The main obstacles to large scale use of LSO, however, are a very high melting point ($> 2,000^\circ\text{C}$) and very high price ($\sim 100 \text{ \$/cc}$ for crystals produced during R&D). A similar material is Ce doped GSO, $\text{Gd}_2(\text{SiO}_4)\text{O}$ [35], which has similar desirable properties and practical drawbacks.

Table 1: Properties of Some Heavy Scintillators

	NaI(Tl)	CsI(Tl)	Pure CsI	BaF ₂	CeF ₃	BGO
Density (g cm ⁻³)	3.67	4.51	4.51	4.89	6.16	7.13
Melting Point (°C)	651	621	621	1280	1460	1050
Radiation Length (cm)	2.59	1.85	1.85	2.06	1.68	1.12
Moliere Radius (cm)	4.8	3.5	3.5	3.39	2.63	2.33
Interaction Length (cm)	41.4	37.0	37.0	29.9	26.2	21.8
Refractive Index*	1.85	1.79	1.95	1.50	1.62	2.15
Hygroscopic	Yes	slightly	slightly	No	No	No
Luminescence (nm)	410	550	565	310	340	480
(Peak Wavelength)			315	220	300	
Decay Time (ns)	230	1000	35	630	30	300
			6	0.9	9	
Relative Light Output**	100	45	4	20	3.5	13
			2	4	3.5	
Price (\$/cc)	1-2	2	3	2.5	3***	7

* at the wavelength of the emission maximum.

** measured with a PMT with a bialkali cathode.

*** expected mass-produced price, now in the R&D stage.

3 Crystal Calorimeters

Tables 2 and 3 list the main parameters of major crystal calorimeter projects of the recent past (Crystal Ball), present (L3, CLEO II, Crystal Barrel) and future (KTeV, B Factories, CMS). Figure 2 shows the crystal arrangement of the L3 BGO calorimeter as an example. The BaF_2 calorimeter design for the GEM experiment [11] at the SSC, and the CeF_3 calorimeter design for the L3P experiment at the LHC [13] are included for completeness. The inner radius of the detector, crystal type, number of calorimeter elements and the depth in radiation lengths are listed. The magnetic field, photosensor, gain of photosensor, readout dynamic range and the energy-equivalent noise in MeV per channel. In addition, we list the parameters $\mathbf{a}_0$ and $\mathbf{a}_1$, which represent the contributions to the energy resolution (at 1 GeV) from photoelectron statistics and noise respectively, as discussed in Section 4.1. For crystal calorimeters at future multi-TeV hadron colliders, the transverse segmentation also is listed.

The details of the design of each crystal calorimeter are governed by its physics goals, which are usually related to precision measurements of photons and electrons. Examples are: detection and study of radiative transitions of the J/Ψ and Υ families (Crystal Ball); new states decaying to leptons and photons, precision electroweak tests (L3); searches for new resonances decaying to multiple π^0 , η and ω (L3, Crystal Barrel); Υ transitions, τ branchings to multi- π^0 and η final states, and rare B and τ decays (CLEO); K^0 mesons and rare decays, and precise CP violation measurements (KTeV); B mesons and rare decays, and CP violation (SLAC and KEK B Factories); and the origin of electroweak symmetry breaking and Higgs boson detection (CMS, GEM and L3P). The crystal choice, crystal depth and segmentation are adapted to these physics goals, especially to optimize the mass resolution and/or background rejection.

At low energies (below a few hundred MeV), the large light yields (photoelectrons/MeV) from NaI for the Crystal Ball and from CsI(Tl) for the CLEO II, Crystal Barrel and the B Factory detectors, and to a lesser extent from BGO for L3, are needed to achieve good energy resolution. Figure 3 [36] shows the χ_b signal in the inclusive photon spectrum from the decay $\Upsilon(3S) \rightarrow \gamma\chi_b(2P)$, obtained by CLEO II as an example. Because CLEO II uses silicon photodiodes (Si PD), the noise below 200 MeV is predominantly due to electronic noise. Minimization of the inactive material in the front of calorimeter and between the crystals also is required to maintain the resolution at low energies.

At high energies (above few tens GeV), the energy resolution of a crystal calorimeter is dominated by systematics. To achieve a systematic accuracy of less than 0.5%, the crystals must have enough depth to reduce the rear leakage to the few percent level, and they must be radiation resistant so that light response uniformity can be maintained within $\approx 5\%$ over the length of the crystal. The intrinsic mass resolution (without radiative tail) for a 90 GeV photon pair or an e^+e^- pair which has been achieved by L3 is below 1%, and is expected to be in the 0.5% range once improved calibrations are implemented (see Section 7). The CMS, L3P and the GEM projects have aimed at a mass resolution of $\approx 0.4\%$ for a photon pair from $H^0 \rightarrow \gamma\gamma$. In the case of KTeV, the crystal depth ($27 X_0$) also is dictated by the requirement that the energy resolution function have a sufficiently small tail, such that an absolute systematic uncertainty level of 0.02% in the γ energy-scale can be attained, following extensive calibration [7].

The inner radius of a crystal calorimeter is a tradeoff between the required performance and cost. A larger radius would provide better 2γ separation, and thus higher efficiency of π^0 reconstruction and/or rejection, but with a larger volume of crystals

and hence increased cost. The lateral segmentation is a tradeoff between position resolution (see Section 4.2), which improves with finer segmentation, and the number of readout channels. Longitudinal segmentation of the crystals would provide an angular measurement for high energy isolated photons (see Section 4.3). This would be advantageous at future hadron colliders to determine the vertex of the photon pair at high luminosities in the $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ range, where multiple minimum-bias events will overlap with the event of interest at every bunch crossing, but at the price of a much larger number of crystal pieces and readout channels.

The choice of photosensor and its gain are governed by the magnetic field, the crystal type (e.g. by the wavelength of the scintillation light) and by the energy-equivalent noise per channel. Operation in a magnetic field excludes the possibility of using most multistage vacuum phototubes. The photosensor choices include solid state photodiodes, vacuum diodes or triodes (VPT) [37], or proximity-focused few stage grid mesh tubes recently developed by Hamamatsu [38]. For multi-TeV hadron colliders, the sensor also must be radiation hard. Finally, the dynamic range and precision of the readout must cover both the high energy electrons or photons used to extract the physics signals of interest, and the much lower energy particles used for calibrations.

Table 2: Crystal Calorimeter Parameters

Experiment	C. Ball	L3	CLEO II	C. Barrel	KTeV
Accelerator	SPEAR	LEP	CESR	LEAR	FNAL
Inner Rad. (m)	0.254	0.55	1.0	0.27	-
B-Field (Tesla)	-	0.5	1.5	1.5	-
Crystals (k)	0.672	11.4	7.8	1.4	3.3
Crystal Type	NaI(Tl)	BGO	CsI(Tl)	CsI(Tl)	CsI
Crystal Depth (X_0)	16	22	16	16	27
Light Output (p.e./MeV)	350	1,400	5,000	2,000	40
Photosensor	PMT	Si PD	Si PD	WS*+Si PD	PMT
Gain of Photosensor	Large	1	1	1	4,000
Noise/Channel (MeV)	0.05	0.8	0.5	0.2	Small
Dynamic Range	10^4	10^5	10^4	10^4	10^4
a_0^{**} (%)	<0.1	0.3	0.2	<0.1	<0.1
a_1^{***} (%)	0.2	0.1	0.05	0.07	0.5

* Wavelength Shifter.

** Noise contribution to the energy resolution (at 1 GeV).

*** Photoelectron statistics contribution to the energy resolution (at 1 GeV).

Table 3: Parameters of Recently Designed Crystal Calorimeters

	BaBar	KEK BF	CMS	(GEM)	(L3P)
	SLAC	KEK	LHC	SSC	LHC
Inner Rad. (m)	1.0	1.25	1.3	0.8	2.9
$\Delta\eta$	-	-	0.02	0.04	0.01
B-Field (Tesla)	1.0	1.0	4.0	0.8	2.0
Crystals (k)	10.0	8.9	43.2	15.0	129.6
Crystal Type	CsI(Tl)	CsI(Tl)	CeF ₃	BaF ₂	CeF ₃
Crystal Depth (X_0)	18	16	25	24.5	23.2
Light Output (p.e./MeV)	10,000	5,000	300	30	50
Photosensor	Si PD	Si PD	Si PD	VPT	VPT
Gain of Photosensor	1	1	1	12	10
Noise/Channel (MeV)	0.06	0.1	20	3	20
Dynamic Range	10^4	10^4	10^5	10^5	10^5
a_0^* (%)	<0.1	<0.1	6	1	6
a_1^{**} (%)	0.03	0.03	0.2	0.6	0.5

* Noise contribution to the energy resolution (at 1 GeV).

** Photoelectron statistics contribution to the energy resolution (at 1 GeV).

Figure 3: Inclusive photons in hadronic events measured by CLEO II, showing the χ_b signal from the decay $\Upsilon(3S) \rightarrow \gamma \chi_b(2P)$ [36].

4 Crystal Calorimeter Performance

This section summarizes the systematic factors that may limit the energy, position, angle and time resolution of a crystal calorimeter. It also presents the resolutions that may be achieved by proper control of systematics.

4.1 Energy Resolution

The energy resolution of an electromagnetic calorimeter can be parametrized as:

$$\left(\frac{\Delta E}{E}\right)^2 = \left(\frac{\mathbf{a}_0}{E}\right)^2 + \left(\frac{\mathbf{a}_1}{\sqrt{E}}\right)^2 + \mathbf{b}^2 \quad (1)$$

where $\mathbf{a}_0$ is the contribution from electrical noise, summed over the readout channels within a few Moliere radii around the center of the lateral shower distribution, and $\mathbf{a}_1$ is the contribution from the photoelectron statistics, related to the photon yield of the crystal and the area the end face of the crystal that is covered by the photosensor. The systematic, or constant, term $\mathbf{b}$ has three main contributions:

$$\mathbf{b}^2 = \mathbf{b}_G^2 + \mathbf{b}_C^2 + \mathbf{b}_n^2. \quad (2)$$

Here $\mathbf{b}_G$ represents the geometry effect, including shower leakage from the back, side, and front (albedo), and absorption of part of the shower in the inactive material in front of and between cells. The typical lower limit of $\mathbf{b}_G$ is 0.3 to 0.4%, and it may become larger at both lower and upper ends of the energy range of interest. $\mathbf{b}_C$ represents the inter-calibration error between crystals. Depending on the calibration method(s) used, the typical lower limit on this term is 0.3%. $\mathbf{b}_n$ is the contribution from non-uniformities in the crystal response (due to intrinsic attenuation length, reflector efficiency variations as a function of position, or radiation-induced nonuniformities). This term contributes to the resolution because the shower depth and

width distributions vary from event to event, for particles of the same incident energy, due to random fluctuations in the development of an electromagnetic shower.

An additional contribution to the energy resolution is from the overlap of particles from different physics events, within the gating time of the detector. This is known as “pile-up noise”, which is a particular problem for crystal calorimeters at very high luminosity ($10^{34} \text{ cm}^{-2} \text{ s}^{-1}$) hadron colliders such LHC. A detailed discussion of pile-up noise can be found in references [12] and [13]. One way to reduce the pile-up noise contribution is to place the crystal calorimeter at a large distance from the beam line, at the expense of a large crystal volume [13].

Compared to the effects mentioned above, the intrinsic resolution due to fluctuations in shower development, assuming a perfectly uniform very large single crystal, are negligible in the energy range of interest for high energy physics experiments.

4.1.1 Noise and Sampling Terms

At low energy, the dominant contributions to the energy resolution are the electronic noise term ($\mathbf{a_0}/\mathbf{E}$), and the pile-up noise in the case of very high luminosity, which decrease quickly with increasing energy. The sampling term ($\mathbf{a_1}/\sqrt{\mathbf{E}}$) dominates in the range of medium to high energies, up to the high energy limit where the systematic term ($\mathbf{b}$) becomes dominant. The values of the coefficients $\mathbf{a_0}$ and $\mathbf{a_1}$ for various crystal calorimeter systems are listed in Tables 2 and 3. Each table entry is calculated analytically using the energy-equivalent noise (in MeV) per readout channel, the light output per unit energy deposited (photoelectrons/MeV), and assuming a summation of 3×3 channels to form an electromagnetic cluster representing an electron or photon.

The energy-equivalent electronic noise also determines the lower limit of the “energy reach” of a crystal calorimeter, as well as the resolution and photon identification efficiency at the low energy end. For a given type of crystal, this term is determined by the choice of photosensor. In the case of a solid state photodiode, the noise is controlled by the diode’s area and thickness, and the fraction of the rear crystal face covered. A larger collection area corresponds to a larger signal per unit energy, but also a larger electrical noise, caused by the larger capacitance and leakage current.

The thickness of a diode also determines the (relatively large) equivalent energy of a particle passing through the diode. This may have a significant effect on the resolution in the case of very high luminosity, or in the case of crystals which are not deep enough to fully contain a high energy electromagnetic shower.

4.1.2 Constant Terms

The resolution at the high energy end is limited by systematics. The requirements and means of controlling the terms b_n and b_C are discussed later in this section and in Section 7 respectively. Once a sufficiently precise intercalibration and uniform light response are achieved, however, the ultimate energy resolution of a crystal calorimeter is determined by the shower leakage and absorption term b_G . This term can be reliably estimated by a “realistic” GEANT [39] simulation which includes an accurate geometrical representation of the calorimeter support structures, the crystal wrapping material and air gaps between crystals. The simulation parameters must be set to allow tracking of the particles down to energies around 0.1 MeV (and to 10 keV for photons in some cases). The same simulation can be used to study b_n , by incorporating non-uniformities in the response to deposited energies as a function of the location in the crystal. This is discussed further below.

A typical example which has been studied in detail with a GEANT simulation [14] is a BaF_2 matrix consisting of 121 (11×11) crystals, as proposed for the L^* and GEM experiments. Each crystal has the shape of a truncated pyramid with the dimensions: $3 \times 3 \text{ cm}^2$ in the front, $5 \times 5 \text{ cm}^2$ at the back and 50 cm long. The effects included in the simulation are: (1) $250 \mu\text{m}$ carbon fiber wall between crystals, (2) transverse shower “leakage” because of summing a limited number of crystals (3×3 or 5×5) in the formation of an electromagnetic cluster, and (3) 0.3 radiation lengths of aluminum, representing the beam pipe, the central tracker and the carbon fiber mechanical support, at the front of the BaF_2 calorimeter. Particles were shot uniformly over the front surface of the central crystal of the array. The energies deposited in each crystal, in the carbon fiber walls between crystals, in the aluminum and leaking out sideways were recorded. The result of this simulation for electrons with different energies (5, 10, 20, 50, 100, 200 and 500 GeV), in terms of σ of the peak, defined as the full width at half maximum (FWHM) divided by 2.35, is listed in Table 4. This GEANT simulation predicts a constant term not less than 0.3%. For very high energies, the systematic contribution is somewhat larger, caused by rear leakage because of limited calorimeter depth.

The light response uniformity at the level of a few percent over the length of the crystal, except for the first few and the last few radiation lengths, is important to maintain high resolution of a crystal calorimeter. This uniformity also is needed to maintain good linearity over a large dynamic range. The effect of light response uniformity also can be estimated by incorporating a light uniformity response function into the GEANT simulation. Figure 4 [14] shows the GEANT predictions for the energy fraction (top figure) and the intrinsic energy resolution (bottom figure) calculated by summing the energies deposited in a 3×3 BaF_2 subarray of the crystals, as a function of the light response uniformity. In this simulation, the light response (Y)

of the crystal was parametrized as a normalized linear function:

$$Y = Y_{25} [1 + \delta(z/25 - 1)] \quad (3)$$

where Y_{25} represents the light response at the middle (25 cm) of a 50 cm long BaF_2 crystal, δ represents the deviation of the light response uniformity, and z is the distance from the small (front) end of a tapered crystal. To maintain a b_n term of less than 0.5%, the δ value is required to be less than 5%. A detailed study using many different functional forms of the light response nonuniformity, in addition to a linear dependence, confirmed this conclusion quantitatively [40].

Light response uniformity can be achieved by using special wrapping or coating techniques. For a tapered crystal with its 6 faces polished, there are two counterbalancing factors which affect the light uniformity over the crystal length: the light attenuation (both bulk attenuation and losses at each reflection) and an “optical focusing” effect. The optical focusing effect can be understood in terms of Liouville’s theorem: as the crystal gets larger and a bundle of light rays thus is allowed to expand, the individual rays within the bundle tend to become more parallel to the long axis of the crystal. While light attenuation causes a decrease of the response with increasing distance from the photosensor, the optical focusing effect leads to higher light collection efficiency and thus increasing response with distance. For a 24 cm long BGO crystal, the second factor dominates: a strong increase of the light response (up to a factor of 2.4) at the small end compared to the large end was observed for L3 crystals which had all sides well-polished [4].

In general, uniform light response has been obtained by treating at least part of the crystal surface to avoid total internal reflection that continues over many bounces – effectively “trapping” part of the light in the crystal – and to instead scatter the light diffusely, randomizing the direction of light rays within the crystal. Common

techniques are (1) depolishing the lateral crystal faces in a nonuniform and carefully controlled manner (Crystal Ball) [41], (2) coating all surfaces of the crystals with a highly reflective diffuse reflector, such as a 40-50 μm thick coating NE560 white paint NE560 (L3 BGO calorimeter) [4], or (3) teflon or aluminized mylar wrapping (KTeV CsI calorimeter) [7].

Figure 5 shows the light response uniformity of a 40 cm long CsI crystal with teflon wrapping measured by KTeV [7]. A deviation of 2.1% over the crystal length is achieved. Figure 6 shows light response uniformity of 96 BGO crystals measured with a cosmic test bench. Note, a slight negative response at the front end was designed to compensate the rear leakage of the L3 BGO calorimeter caused by limited length of $22 X_0$ [4].

In some cases, the required depth of a calorimeter element exceeds the commercially available length of a single crystal. In these cases (e.g. the GEM BaF_2 and the CMS CeF_3 calorimeters) several pieces of crystals may be glued together, or otherwise joined to form a unit. It is essential in these cases to find a glue with good transmission at the wavelength of the scintillation light, to make a bond with sufficient light transmission efficiency as well as mechanical strength. Figure 7 shows the transmittance measured for 500 μm thick layers of various adhesives. For the case of BaF_2 , where the fast scintillation light is in the 200 nm range, a thin layer (tens of microns) of KE103 glue has been demonstrated to provide a transmission efficiency above 97% [14], as well as high radiation resistance [42].

4.1.3 Summary of the Energy Resolution

Taking the BaF₂ calorimeter as an example, Table 4 shows all of the contributions described in Section 4.1, and the expected overall energy resolution. An inter-calibration accuracy of 0.4% has been assumed (see Section 7 for a discussion). Assuming the light response uniformity ($\mathbf{b_n}$) is under control, the dominant contributions to the energy resolution at the high energy end are the intercalibration term $\mathbf{b_C}$ and the shower leakage and absorption term $\mathbf{b_G}$. The resultant expected energy resolution is shown in Figure 8b. This resolution is compared to the simple parametrization $2\%/\sqrt{E} \oplus 0.5\%$ in the figure (solid line).

For comparison, Figure 8a shows the energy resolution of 4,000 BGO crystals (one half-barrel) measured at the CERN SPS test beam (2 – 50 GeV), using the LEP injector (180 MeV) and at CESR (100 MeV) [4]. In the energy range beyond 20 GeV, the dominant contributions to the energy resolution are the systematic terms described above. The resolution of the L3 BGO calorimeter in the figure also is compared to the parametrization $2\%/\sqrt{E} \oplus 0.5\%$ (solid line).

4.2 Position Resolution

High resolution position reconstruction, and hence precise determination of the angles of electrons and photons, is needed if the energy resolution of a crystal calorimeter is to be fully utilized to provide precisely reconstructed invariant masses of resonances decaying to photons or electrons. This is a key issue in the difficult case of the search for the intermediate mass Higgs through its rare decay mode $H \rightarrow \gamma\gamma$ [44].

The position of the impact point of an electron or photon on the front face of a calorimeter, or at another reference plane, may be reconstructed from the pattern of

energies deposited in a cluster of crystals. The simplest technique is the center of gravity method, where the centroid of an electromagnetic shower is computed as a linear combination of the energies deposited in the crystals:

$$X_{cg} = \sum_i (X_i E_i) / \sum_i E_i \quad (4)$$

where E_i is the energy deposited in the i^{th} row along the x-direction, and X_i is the x-coordinate of the center of the i^{th} row at the reference plane. The summation can be carried out over the (approximately) square subarray of 25 (Σ_{25}), 9 (Σ_9) or 5 (Σ_5) crystals centered on the crystal which has the maximum energy deposition. Because of the finite cell size, the measured position X_{cg} is biased towards the center of a cell, such that a uniform flat input distribution in x results in a reconstructed X_{cg} distribution with a characteristic s-shape. One needs to apply corrections to unfold the s-shape, to obtain an accurately reconstructed position X_{rec} .

Since the center of gravity method actually calculates the shower center near the shower peak, it is important to note that the above algorithm is accurate only for a calorimeter with a projective geometry and a particle passing through the geometric origin. Otherwise, the algorithm defines an accurate position only for showers with average depth. An additional shower depth-related correction is needed for showers that start early or late, which can be determined by the energy in the hadron calorimeter, or by the energy sharing among the segments of a longitudinally segmented calorimeter.

Figure 9 [43] shows the relation between X_{cg} and X_{rec} , calculated by using a GEANT simulation with 5,000 Bhabha events at the Z peak, i.e $\sqrt{s} = 91.16$ GeV, versus the actual simulated impact point X_{in} for the L3 BGO calorimeter. The correction applied to obtain the reconstructed coordinates was a simple polynomial function. The simulation shows that summation over 9 or 25 crystals provides a reconstruction

accuracy with a position resolution of ≤ 0.65 mm, while summation over 5 crystals provides a slightly degraded accuracy of ≤ 0.85 mm. This result agrees very well with the Bhabha data obtained by L3 at LEP [43]. A GEANT simulation, for the KTeV CsI calorimeter with 5 cm and 2.5 cm blocks, shows that 1.4 and 0.8 mm position resolution can be achieved for these two block sizes, as shown in Figure 10 [7]. This position resolution does not degrade the two photon invariant mass resolution provided by a crystal calorimeter at multi-TeV hadron colliders, provided that the origin of the photon can be determined by using the central tracker [44].

In general, the position resolution of a calorimeter depends on its structure, especially the lateral cell size. The intercalibration among the cells also has an important effect, especially if the calibration is not controlled to the level of 1% or better. The optimum lateral cell dimension is a compromise between good position resolution and the total number of readout channels, which is reflected in the cost. Good position resolution as well as a good knowledge of the transverse shower shape, which are needed for e/π and double γ separation, favor a small cell size, while shower containment in a few cells favors a larger size. A cell dimension in the neighborhood of approximately one Moliere radius (R_M) is usually taken, corresponding to $\approx 75\%$ of the shower energy deposited in the center cell. For example, the front face of an L3 BGO crystal has a dimension of $0.86R_M \times 0.86R_M$, while the CLEO II CsI(Tl) and CMS CeF_3 designs have dimensions of 1.4 and 1.0 R_M respectively.

4.3 Angular Resolution

For some applications, such as the $H \rightarrow \gamma\gamma$ search at multi-TeV hadron colliders [44], it is important to measure the photon direction as well as the energy. The most accurate measurement of the photon direction can be achieved by using the event vertex

position determined by the central tracker, and the shower position determined by using the center of gravity method described in Section 4.2. At very high luminosity, however, the efficiency of Higgs vertex determination would be degraded by the pile-up of multiple event vertices in a single bunch crossing. An alternative method thus is to provide an angle measurement with the electromagnetic calorimeter itself, known as “photon pointing”. This is a necessary feature for crystal calorimeters operated at LHC. (Note that in a collider experiment, the beam profile is small and the beam location is accurately known in a plane perpendicular to the direction of the incoming beams. It is only the vertex position along the direction of the beams that is smeared out by the bunch length. Photon pointing is thus needed only to determine the polar angle of electrons or photons accurately with respect to the beam line.)

To measure the photon direction, one must measure the lateral shower position at two depths. Two possible approaches have been designed and studied: one simply segments the crystal into pieces of $8 X_0$ in front and $17 X_0$ at the back, or one uses a fine-grained position detector at a depth of $4\text{--}5 X_0$ and combines this with a measurement of the shower position in the crystal segments at the back. Although the second approach provides a better angular resolution, the first approach has the advantage of simpler mechanical design. For the first approach, one can further split the front crystal into several pieces to provide better angular resolution. One of the CMS calorimeter designs, for example, has the front segment of each calorimeter cell split into four crystal pieces [12], matched to one much larger piece in the back of the cell. It should be pointed out that the first approach only works with sufficient precision for high energy photons, such as the >20 GeV photons at future hadron colliders. For low energy photons, because of the limited shower length, the energy resolution and shower fluctuations in each segment, the number of longitudinal segments required may too large to be practical.

A simple parametrization of the angular resolution is $\delta\theta(\text{mrad}) = a/\sqrt{E}$, where E is in a unit of GeV. GEANT simulations of CMS CeF_3 crystal calorimeter designs have shown that $a = 60$ mrad can be achieved by using a front crystal split into four pieces, and $a = 50$ mrad can be obtained with a precise position detector located at $5 X_0$ depth [45]. This is illustrated in Figure 11. The angular resolution tends to improve if the position detector is located closer to the front, such as at $4 X_0$ instead of $5 X_0$ [45].

4.4 Time Resolution

Time resolution is not important for crystal calorimeters used in a low rate environment. At e^+e^- colliders, for example, the total cross-section is low; even at the B Factory luminosity of $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$, the event rates are below the kHz level. The typical light pulse shaping (or gated integration) times for the L3 BGO calorimeter, for the CsI(Tl) calorimeter at CLEO II, and for the SLAC and KEK B factories, are thus in the range of a few microseconds. At multi-TeV hadron colliders, because of the 100 mb level total cross-section, very fast rise time and short decay times are very important both for triggering and precision energy measurement.

As shown in Table 1, the fastest scintillation response can be obtained from BaF_2 , which has fast scintillation components with a decay time of less than 1 ns. BaF_2 crystals, however, also produce a slow component with a 600 ns decay time, and an intensity that is 5 times higher. In triggering, the slow component's effect may be suppressed electronically, by sampling the output of each channel just before, and a few fast-decay-time constants after the start of a pulse [46]. The intrinsic slow component, however, would limit the dynamic range of the photosensors, and would lead to pileup noise that degrades the energy resolution. An alternative method

of suppressing the slow component is lanthanum doping of the BaF_2 crystals [47]. Doping at an appropriate concentration of lanthanum reduces the slow component by a factor of five, while it has no effect to the intensity of the fast components.

The BaF_2 fast components also may be selected by using the spectral difference between the fast and the slow components. The light emission spectrum of the fast component is mostly below, while the slow component is mostly above a wavelength of 240 nm. Figure 12 shows the scintillation spectrum (dashed line) of a BaF_2 crystal and the quantum efficiencies of (1) a bialkali and (2) a UV-selective ‘solar-blind’ Cs-Te photocathode for vacuum phototube, and (3) a silicon photodiode. The solar blind Cs-Te cathode, which has enhanced sensitivity below 240 nm, is well-matched to BaF_2 ’s fast components. Figure 13 shows pictures of the scintillation light pulses recorded using a bialkali photocathode (a and e), a Cs-Te photocathode (b and f), a K-Cs-Te cathode (c and g) and a Rb-Te cathode (d and h). The K-Ce-Te and Rb-Te cathodes were developed by Hamamatsu specifically for BaF_2 readout [48]. They have a measured rise-time (from the results illustrated in the figure) of 2.3 nsec.

Were a Si photodiode to be used as a readout device, the rise-time would be 10-15 nsec caused by large capacitance of the Si PD. As shown in Figure 12, however, the Si PD has a factor of six higher quantum efficiency at 220 nm. An interference filter with peak transmittance at 220 nm and with a width of 30 nm (as tested at Caltech), could be used together with a Si PD to suppress the slow component while maintaining a better photoelectron yield.

Table 4: Energy Resolution (%) of a BaF₂ Calorimeter

E (GeV)	5	10	20	50	100	200	500
Electrical Noise	0.4	0.2	0.1	0.04	0.02	0.01	0.004
Photoelectrons	0.2	0.14	0.1	0.063	0.045	0.03	0.02
GEANT (b_G)	0.60	0.43	0.32	0.30	0.30	0.30	0.36
Intercalibration (b_C)	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Total	0.85	0.63	0.53	0.51	0.50	0.50	0.54

Figure 4: The relative mean energy fraction and the energy resolution for electromagnetic clusters of 3×3 crystals, as a function of the light response uniformity, calculated with a GEANT simulation [14]. See text for the definition of the parameter δ that characterizes the light response uniformity.

PD has a factor of six higher quantum efficiency at 220 nm. An interference filter with peak transmittance at 220 nm and with a width of 30 nm (as tested at Caltech), could be used together with a Si PD (as proposed by the authors) to detect the signal.

Figure 5: Light response uniformity of a 40 cm long CsI crystal with teflon wrapping [7], showing 2.1% overall uniformity.

Figure 6: Light response uniformity of 96 L3 BGO crystals with NE560 white paint [4], showing a slightly lower response at the front that compensates the rear leakage of high energy showers in the 22 X_0 BGO crystals.

Figure 7: Transmittance of 500 μm thick layers of various grease and glues [14]. The typical layer thickness used to couple the photosensors to the crystals in calorimeters is 10 to 50 μm .

Figure 8: Energy Resolutions of (a) a 4000 crystal half-barrel of the L3 BGO calorimeter, measured in test beams at the CERN SPS (2 – 50 GeV), the LEP injector (180 MeV extracted beam) and CESR (100 MeV) [4], and (b) a BaF₂ calorimeter, as shown in Table 4. The solid curves represent the simple parametrization $2\%/\sqrt{E} \oplus 0.5\%$.

Figure 9: Correlation between the positions measured with the center of gravity method (X_{cg}) and the reconstructed positions (X_{rec}) versus the “actual” positions (X_{in}) from a GEANT simulation. The simulated results are from 5,000 $Z \rightarrow e^+e^-$ decays in the L3 BGO calorimeter [43].

Figure 10: Position resolution of the KTeV CsI calorimeter, obtained by a GEANT simulation, for 5 and 2.5 cm blocks [7].

Figure 11: Angular resolution as a function of photon energy for the CMS CeF_3 calorimeter, obtained by GEANT simulations for the two design approaches using longitudinal segmentation, and a position detector at $5 X_0$ in depth [45], as described in the text.

Figure 12: BaF₂ scintillation spectrum and quantum efficiencies of (1) a bi-alkali photocathode, (2) a UV-selective 'solar-blind' Cs-Te photocathode and (3) a silicon photodiode.

Figure 13: BaF_2 scintillation light pulses observed by a bi-alkali cathode (a and e), a Cs-Te cathode (b and f), a K-Cs-Te cathode (c and g), and a Rb-Te cathode (d and h). The rise time of the scintillation light pulse in these pictures was entirely dominated by the 2.3 ns rise time of the PMTs. On an expanded scale (a, b, c and d) the full width at half maximum of the fast scintillation light is measured to be 4 to 6 ns. The optical suppression factors (F/S) for the slow component, defined as the number of photoelectrons in the fast components (F) divided by the number of photoelectrons in the slow component (S)⁸⁹, are also shown in the figure.

5 Crystal Radiation Damage

All known large crystal scintillators are affected by radiation damage [49]. The principal damage phenomenon, observed in all mass-produced crystals, is the appearance of absorption bands, caused by color center formation. The absorption bands reduce the transmission of scintillation light through the crystals to the photosensors, and hence the apparent light yield following irradiation. Additional effects observed in some crystals include reduced intrinsic yield of scintillation light, increased fluorescence (afterglow), and phosphorescence (spontaneous light emission over a long period). For crystals to be used in a high radiation environment, such as at multi-TeV hadron colliders, it is important that a crystal's scintillation mechanism not be damaged and that the radiation-induced phosphorescence does not affect the read-out signal. By choosing crystals such as BaF_2 or CeF_3 , these criteria can be met. However, the increased radiation-induced absorption (equivalently: a reduced light attenuation length), changes the light response uniformity, and thus may degrade the energy resolution.

5.1 Radiation Damage Phenomena

The radiation-induced color center formation, and the decreased absorption length, usually is related to impurities and/or structural defects in the crystals. The impurities may be present as substitutional or interstitial trace element atoms in the lattice, or they may occur as molecular ions, or microscopic color center complexes containing many atoms. Based on the extensive literature on high purity silicon crystals, and the specific studies of BaF_2 scintillators carried out by Charles Evans and Associates for the GEM Collaboration [52], it is known that the impurities also

may lead to macroscopic structures which have a high density of trace-element rich color center complexes clustered together. These structures form inclusions which are visible under a low power microscopic, and in some cases to the naked eye.

A study of (1) the trace element content and distribution in the crystals, (2) the quality of the crystal structure, and (3) the density and structure of the inclusions in a series of crystal samples was carried out for BGO in 1981-85 [26, 27, 28], and for BaF₂ from 1988-93 [21, 22, 14]. This data was cross-correlated with the degree of radiation damage in a series of doped and undoped crystal samples. This led to greatly improved processing technology for both types of crystals. As a result of the improved control of raw materials, crystal growth and annealing methods, crystals with greater radiation resistance were produced, especially for BaF₂. Studies of the radiation damage problem for pure and doped CsI [19, 17], CeF₃ [25] and PbWO₄ [32] are also underway.

Studies of BGO indicate that key impurities at the sub-ppm level may cause severe damage [27, 50]. Figure 14 [27] shows the relative light output as a function of time after irradiation with a 2.5 krad dose, for BGO samples doped with different dopants. This data led to the conclusion that impurities in the BGO crystal can be categorized in three classes: (1) "harmful" impurities which cause permanent or severe damage (Cr, Mn, Fe and Pb), (2) "less harmful" impurities which cause some damage (Co, Ga, Mg and Ni) (3) "harmless" impurities which cause no discernible damage (Al, Ca, Cu and Si) at the typical trace impurity levels found in standard-quality crystals. The figure also illustrates that different doped and undoped BGO crystal samples recover at different rates, with characteristic recovery times ranging from hours to weeks.

For BGO crystals, it was discovered that europium doping improved the radiation

resistance by accelerating the recovery from the damage at room temperature. Figure 15 [28] shows the relative pulse height as a function of time after a radiation dose of 2.5 krad from a ^{137}Cs γ -ray source for four BGO crystals doped with different levels of europium: 0, 5, 10 and 100 ppm by weight for the samples labeled BGO0, BGO1, BGO2 and BGO3 in the figure. The damage level is shown in terms of the parameters A_F and A_S from a fit to a function of $1 - A_F e^{-t/\tau_f} - A_S e^{-t/\tau_s}$. It is clear that the damage level ($A_F + A_S$), especially the slow recovery component decreases with increased europium doping. The Eu-doped BGO crystals are used in the rings of crystals in L3's BGO endcaps closest to the beam line, where the dose is higher than the barrel, and in the luminosity monitors which are closest to the beams.

The main conclusions from the investigations of radiation damage in BaF_2 crystals are:

- As in BGO, the damage of BaF_2 is caused by the formation of color centers, which introduce a self-absorption of the scintillation light. There is no damage to the scintillation mechanism itself.
- There is no permanent damage in BaF_2 caused by doses from photons, neutrons or other hadrons (such as protons, pions or kaons). At room temperature, the recovery of the damage is extremely slow (characteristic times of many months to years). However, all damage recovers fully after thermal annealing at 500°C in an inert dry atmosphere for three hours. UV light also has been found to be effective in removing the radiation damage.
- The radiation damage of BaF_2 shows clear saturation, in both transmittance and light yield at the photosensor, after an initial dose of 100 krad or less. This means that additional doses of Megarads result in no further change in

transmittance, once saturation has been reached. The saturation phenomenon indicates that the number of color centers is relatively few, as expected for damage controlled by trace impurities.

- The damage has no dependence on the radiation dose rate.
- The basic radiation damage mechanism is understood. Impurities (such as rare earths) [51, 52], defects (inclusions) [53, 52], oxygen [53] and OH^- (U and O⁻ substitutional centers) [54, 55] are responsible.

Figure 16 [14] shows (a) the transmittance before and after 1 Mrad γ -ray irradiation and (b) the relative light output measured for three 25 cm long BaF_2 crystal produced at the Shanghai Institute of Ceramics (SIC) in early 1991 (SIC102), early 1992 (SIC302) and July 1992 (SIC402). The progressive improvement of the quality of production BaF_2 crystals is clearly seen from the figure.

5.2 Optical Bleaching *in situ*

The improvement of the intrinsic radiation resistance, by purification of the raw materials and the use of optimized growth and annealing cycles, is a very difficult, time-consuming and expensive process. As shown in Figure 16, the light attenuation length of 25 cm long BaF_2 crystals currently produced at SIC and Beijing Glass Research Institute (BGRI), after 1 Mrad of saturated irradiation is 42 cm [57]. This did not meet the GEM specifications (95 cm attenuation length) as of August 1992. A technique for annealing BaF_2 crystals *in situ*, i.e. optical bleaching, was proposed by a BaF_2 Expert Panel, which was specially organized by the SSC Laboratory to evaluate the radiation damage problem of BaF_2 , and assist in setting research directions for the development of BaF_2 crystals to be used at multi-TeV hadron colliders [56].

Following the Panel's recommendations, five independent measurements on optical bleaching were carried out by BNL [58], Caltech [23], LLNL [59], Tsinghua and McGill Universities [60] and West Virginia University [61].

It was found that the optical bleaching with visible light was effective in removing the radiation damage. Studies also were performed to characterize the spectral behavior, required light intensity, and rate of bleaching. The damage effect was found to be annealable with very low light intensities carried over silica fibers [58], and at wavelengths as long as 700 nm [23]. The light intensity required to restore the crystals to a stable light attenuation length of at least 150 cm — well beyond the GEM specifications — was determined [23] to be in the range of mW/cm².

Figure 17 shows a practical implementation of optical bleaching through a 2 m long $\phi 0.6$ mm fiber, in a test setup. The crystal was simultaneously irradiated with a dose of 130 rads/hr, and illuminated with a calibrated bleaching light power through the fiber of 1.6 mW (integrated from 200 to 500 nm) from a 150 W xenon lamp. This modest amount of bleaching light resulted in a stable attenuation length of 170 cm [14], well in excess of the required value of 95 cm. The large opening angle of the light cone from the fiber (60°), and the reflection of the bleaching light at crystal surface, ensure that the entire crystal is uniformly illuminated. For a large crystal calorimeter, the fiber system could be very similar to the xenon flasher system used to monitor the L3 BGO crystals described in Section 7.3.

It also has been determined that the color center density in BaF₂ crystals follows a simple dynamical model of color center creation and annihilation [23]. If both the creation and annihilation processes exist at the same time for one kind of color center, the density obeys the equation

$$dD = -aIDdt + (D_{all} - D) bRdt \quad (5)$$

where D is the optically bleachable color center density, a is a constant in units of $\text{cm}^2 \text{mW}^{-1} \text{hr}^{-1}$, I is the light intensity in mW cm^{-2} , D_{all} is the total density of traps related to the optically bleachable color centers in the crystal, b is a constant in units of krad^{-1} , R is the radiation dose rate in units of krad hr^{-1} , and t is the time in hours. The solution of Equation 5 is

$$D = D_0 e^{-(aI+bR)t} + \frac{bRD_{all}}{aI + bR} [1 - e^{-(aI+bR)t}] \quad (6)$$

where D_0 is the initial value of the bleachable color center density. For each value of I and of R , and for one kind of color center, an equilibrium between annihilation and creation will be established at an optical bleachable color center density (D_w) of

$$D_w = \frac{bRD_{all}}{aI + bR} \quad (7)$$

The data points in Figure 18a show the measured transmittance and 18b shows the corresponding light attenuation length during series of test runs [57]. The light attenuation length corresponding to D in Equation 6, calculated taking the conditions of each run into account, is shown as the solid line in the figure. The parameters a , b and D_{all} were determined from previous measurements to be: $a = 0.68$ and $0.95 \text{ cm}^2 \text{j}^{-1}$ for $D < 0.08$ and > 0.08 respectively, $b = 0.65 \text{ krad}^{-1}$ for accumulated dose < 5 krad, and $D_{all} = 0.73 \text{ m}^{-1}$. The agreement between the data and the model is very good.

5.3 Summary

In conclusion, a crystal to be used for constructing a precision calorimeter must have a long and stable light attenuation length under irradiation, particularly in the high radiation environment of multi-TeV hadron colliders. One approach is to improve

the intrinsic radiation resistance by reducing the impurities and defects in the crystal. This, however, usually results in a very expensive crystal fabrication technique. It is thus important to understand the correlation between damage and impurities in the crystals, and between damage and the details of the crystal growth process. A high quality crystal can only be produced with raw material of sufficient purity, special preparation and handling methods for the material, and a corresponding carefully controlled growth technique. This is a cross-disciplinary research project, often requiring a collaboration between physicists and materials scientists.

An alternative approach is to eliminate the radiation damage by either thermal or optical annealing. Recent studies on optical bleaching [23] show that optical bleaching is a practical solution for a BaF_2 calorimeter that would function stably, and with high resolution, at a multi-TeV hadron collider. Based on the experience with BaF_2 , there is reason to believe that once crystals of sufficient quality are produced, that the optical bleaching technique could be applied to some other types of crystals as well.

Figure 14: Relative pulse height as a function of the time after irradiation with a 2.5 krad dose, for BGO crystals doped with different dopants.

Figure 15: Relative pulse height as a function of the time after a 2.5 krad γ -ray dose for four BGO crystals doped with different levels of europium: 0, 5, 10 and 100 ppm by weight for BG00, BG01, BG02, and BG03 respectively.

Figure 16: (a) Transmittance and (b) relative light output, measured for three 25 cm long BaF_2 crystal produced at SIC in early 1991 (SIC102), early 1992 (SIC302) and July 1992 (SIC402), after a 1 Mrad γ -ray dose. The improvement of the intrinsic radiation resistance of the crystals over time is shown.

Figure 17: Schematic view of bleaching light propagation in a BaF_2 crystal, in the test setup used at Caltech.

Figure 18: (a) Measured (points) and calculated (solid line) transmittance and (b) the light attenuation length (LAL) of crystal SIC302, during a series of tests with simultaneous ^{60}Co irradiation and 450 nm light illumination.

6 Readout Electronics

As discussed in Section 3, the front end readout – the type and gain of photosensors and the preamplifiers – are directly related to the performance of a crystal calorimeter. The choice of photosensor is affected by the following factors: the magnetic field of the detector, the scintillation light yield and wavelength of the crystal, and the energy-equivalent noise per readout channel. Tables 2 and 3 list some of the principal performance-related parameters of the photosensors for various crystal calorimeters.

The traditional photosensor is the vacuum photomultiplier tube (PMT) (Crystal Ball, CUSB and KTeV) with the advantages of high gain, low noise, low capacitance and high radiation resistance up to neutron fluences in the range of $10^{14} \text{ cm}^{-2}\text{s}^{-1}$ [62]. The spectral response of different photocathodes is also a useful feature for a vacuum photosensor. Solar-blind photocathodes [37] have been used, for example, to help select the fast scintillation components of BaF_2 , as shown in Figure 12.

Because of these factors, some crystal calorimeters designed for multi-TeV hadron colliders have chosen vacuum photosensors. As an example, a design simulation [46] has shown that with a low gain vacuum photosensor of 20 pF capacitance, a charge-equivalent noise of ~ 1000 electrons (including the effect of pileup from additional tracks in the same event) could be achieved with a shaping time of approaching 1 bunch-crossing time, for the BaF_2 calorimeter. This corresponds to an energy-equivalent noise of $\approx 3 \text{ MeV/channel}$.

Because the presence of a magnetic field on the photosensors, most of the calorimeters now in operation or recently designed (CLEO II, L3, Crystal Barrel, and B factories) have chosen large area (few cm^2 and few hundred pF capacitance) silicon photodiodes (Si PD). Because of their low gain a preamplifier with sufficiently low noise, high

gain and good linearity over a large dynamic range is required. Except for the case of high-rate hadron colliders, the decay time constant of the preamplifier pulse is usually chosen in the millisecond range, and the pulse is shaped by a pole-zero circuit connected to the ADC. To minimize the noise, the typical shaping time (in these lower rate applications) is a few μs . Figure 19 [5] shows the example of the CLEO II front end electronics. Each crystal is read out by four photodiodes and four preamplifiers to provide redundancy. Analog signals from clusters of contiguous crystals are summed with individually adjustable gain factors, and the signals are then fed to the first level of energy trigger.

There have been some important developments in photosensors recently. Proximity-focused few stage grid mesh tubes have been developed by Hamamatsu [38], which function in a magnetic field up to 1 Tesla, but with relatively high cost. A similar approach is the microchannel plate (MCP) which also has appropriate gain, speed and in some cases relative immunity to magnetic fields. The principal problems of MCPs are their high cost and relatively fast ageing. On the other hand, the solid state equivalent of PMTs [63], and large area Avalanche Photodiodes (APD) [64] have reached figures of noise, stability, and gain that makes them very competitive as photosensors, especially for lower energy measurements. The intrinsic temperature dependence ($-2\%/^{\circ}\text{C}$), however, must be taken into consideration when APDs are chosen as the photosensor.

As shown in Table 2 and 3, it is not unusual to find a dynamic range in a range of 10^5 , which is extremely difficult to achieve. Indeed, most crystal calorimeters built to date do show small nonlinearities of a few percent over their energy range, which adds to the difficulty of overall detector calibration. A logarithmic amplifier could reduce the dynamic range and simplify the design after the front end. However, the accuracy

of such amplifiers and their low speed make them unsuitable. Most designs therefore include a “split” in the electronic readout chain for each channel, followed by several parallel branches with different gains and hence different (overlapping) energy ranges. Note that the large dynamic range requirement can be met with ADCs of sufficient speed and linearity. The issue in a large system with many thousands of channels thus becomes one of cost, or of careful design and some R&D.

Figure 19: Block diagram of the CLEO II front end electronics and signal shaping [5]. For reasons of redundancy individual preamplifiers have been used for each of the four photodiodes reading out one crystal. The mixing of the four signals and the suppression of malfunctioning readout branches is performed by a computer-controlled mixer stage.

7 Calibration Techniques

Once crystals of sufficient depth, light output, uniformity of response, speed and radiation resistance are chosen to meet the needs of a particular experiment, the precision of the calibration performed *in situ* is the dominant factor in determining the resolution for electron and photon measurements during running. Although all of the individual cells of a crystal calorimeter may be calibrated in a test beam at several different energies to provide a set of initial calibration constants before installation [4], the change in response over time differs from one calorimeter element (crystal, photodetector, readout chain) to the next. Calibrations *in situ* therefore are required to track down the evolution of each channel independently. The time evolution may depend strongly on the position in the calorimeter, where radiation damage could degrade the light uniformity and thus the resolution. Figure 20 shows the radiation-induced change in the response, and the longitudinal response profile, of an L3 BGO crystal situated near the LEP beam line.

The task of calibration can be divided into two parts: (1) finding the absolute energy scale of the calorimeter (absolute calibration) and (2) measuring the channel-to-channel relative gains (intercalibration). The accuracies in these two procedures affect the mean value of the measured energy, as well as the resolution. In many cases, every means of calibration at the disposal of the experiment (and additional methods invented for this purpose in the case of L3) must be used to obtain and maintain a sufficiently precise calibration *in situ*. Figure 21 shows the energy range and the corresponding time required to complete a calibration, for the various calibration techniques used by the L3 BGO calorimeter. No single technique can, by itself, guarantee sub-1% calibration of the many thousands of channels at any given time, over the full energy range. A variety of different techniques must be combined

to provide a sufficient level of understanding and control of systematics.

In this section, we discuss *in situ* calibrations using (1) high energy physics processes, (2) low energy γ rays produced by radioactive sources and radiative capture nuclear reactions, and (3) light flashers.

7.1 Physics Processes

Calibration *in situ* using physics processes is the most commonly used method, since it covers the right energy range and it does not require additional hardware. Methods based on physics-processes include (1) electrons or photons of known energy, (2) electron or photon pairs which can be used to reconstruct a known invariant mass, (3) low energy electrons with momentum accurately measured by a magnetic spectrometer, and (4) minimum ionizing particles which penetrate a crystal with measured path length.

At e^+e^- colliders “Bhabha” scattering (e^+e^- elastic scattering) produces electrons of close to the beam energy, and is widely used as a high energy calibration point. Some care has to be taken to understand and unfold the effects of initial and final state photon radiation (bremsstrahlung) that broaden the electron energy distribution and produce a tail on the low energy side. Crystal Ball has been able to find high energy corrections to their low energy calibration on a channel-by-channel basis, by using Bhabha events [1, 41]. The rate of such events in L3, on the Z peak, is too low at the present LEP luminosity (~ 6 electrons/crystal/year on average for the barrel) to be used as the basis of an inter-calibration. There are enough of these events in L3, however, to establish the high energy scale with negligible statistical error, once crystal-to-crystal differences and time drifts have been corrected by other methods.

Photons from radiative dilepton-events also can be used as a calibration source, by precisely measuring the leptons and using the beam energy constraint in e^+e^- collisions. As an example, CLEO II's absolute calibration normalization is set by using photons from the processes $e^+e^- \rightarrow e^+e^-(\gamma)$, $e^+e^- \rightarrow \gamma\gamma$, $e^+e^- \rightarrow \gamma\gamma\gamma$ and $e^+e^- \rightarrow \pi^0 X$, although it can intercalibrate the whole calorimeter using Bhabha events alone in about one week [5]. The photon calibration provides CLEO II with their best measurement of photons for calibration over the entire energy range from few MeV to 5 GeV. The need for calibration as a function of energy is demonstrated by the fact that CLEO II observes an energy dependent shift between electrons and photons. This is illustrated in Figure 23 [5].

Invariant mass reconstruction by using photon or electrons pairs from a boson with known mass is also a powerful calibration tool. In general only the global energy scale is determined by this method. The Crystal Barrel experiment, however, has a high enough rate of π^0 's so that they are able to calibrate each crystal of the calorimeter in about one day of data taking, with a statistical error of $\pm 0.5\%$ using this method [6]. Studies of crystal calorimeter calibration at the SSC, by reconstructing the Z mass in $Z \rightarrow e^+e^-$ decays, show that an accuracy of 0.3% can be achieved with less than one month of running at a luminosity of $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ [14]. This iterative procedure needs a set of initial calibration constants accurate to $\sim 20\%$, which could be provided by measuring the energy deposition of minimum ionizing particles crossing the crystals longitudinally.

In most of the modern collider detectors, a momentum measurement is available for charged particles before they enter the electromagnetic calorimeter. The reconstructed momentum for isolated electrons, where the corresponding electromagnetic shower is well-separated from the energy deposited by other particles, therefore pro-

vides an alternative energy reference that may be used for calibration. Since the momentum measurement degrades while the calorimetric energy measurement improves with increasing energy, this technique is generally useful only for relatively low energy particles. In practice in many cases, (as on the Z^0 resonance at an e^+e^- collider for example) the isolation requirement and the restriction to low momentum tracks limits the effective rate of useful events, so that this technique may serve only as a check on the calorimeter resolution.

Both cosmic rays and a substantial fraction of the charged particles emerging from high energy interactions may be used as a source of minimum ionizing tracks. For detectors with pointing geometry final state particles might traverse one crystal longitudinally while a cosmic ray track generally leaves energy in many crystals. In order to use these tracks to perform a calibration, the path length of the track traversing the crystal must be known precisely, so that the expected energy deposited in a crystal can be calculated with sufficient accuracy.

L3 uses its large precise muon spectrometer to measure the path length of cosmic rays penetrating a crystal. The multiple scattering in the ~ 7 interaction length hadron calorimeter between the muon spectrometer and the electromagnetic calorimeter, however, reduces the tracking precision. Only muons of momentum above 10 GeV and crossing the crystals from opposite (non-contiguous) lateral faces are used. For these tracks the path length inside the crystal is only slowly dependent on the impact point. The energy distribution observed has a shape dominated by Landau fluctuations [65], with an rms width of 18%, and the energy deposited is typically 20 MeV. L3 can collect $\approx 130,000$ useful crystal hits per day during dedicated running periods, so that a few months of dedicated data-taking time is needed to determine the peak position for every crystal with a precision of 1%. This technique is thus not practical,

considering that the calorimeter response in each channel may change significantly during this long period.

Studies of monitoring each individual crystal's gain using charged particles from high energy interactions at multi-TeV hadron colliders show that a precision of 0.3% could be achieved in a few hours, using a dedicated trigger at a rate of more than 1 kHz at a luminosity of $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ [40]. A higher rate dedicated trigger also could be implemented (at higher cost).

7.2 Radioactive Sources and Radiative Capture Reactions

Low energy γ -rays from radioactive sources or from radiative capture reactions are often used as a low energy calibration source. This is particularly important for those crystal calorimeters where physics processes do not occur at a high enough rate for a frequent calibration, as in the L3 BGO calorimeter. Radioactive sources are relatively inexpensive and very small in dimension, so that they can be directly mounted on each crystal to monitor the calorimeter continually during its lifetime. Using this technique CUSB has been able to intercalibrate their detector, and to fix the absolute energy scale with 5 GeV electrons (from $e^+e^- \rightarrow e^+e^-$) and with π^0 decays [3]. Disadvantages of the use of radioactive sources are the limited energy range, and the necessity of triggering on a signal that is random in time relative to the beam-crossing time.

The maximum energy photon easily available from a long-lived radioactive source is the 2.6 MeV line of ^{228}Th . The 0.66 MeV line of ^{137}Cs and the 1.17 and 1.33 MeV lines of ^{60}Co (which are typically measured as one peak in large crystals) are more commonly used [66, 3]. In many cases, including all calorimeters using Si PD readout, the signals from radioactive sources are much too close to the pedestal, or even “in

the noise”, so that they are not useful as a means of calibration.

Photons with energies an order of magnitude higher can be produced using radiative capture reactions, by bombarding a target mounted inside the calorimeter with a proton beam of suitable energy. This technique has been pioneered by Crystal Ball [66] with the use of a Van de Graaf accelerator to produce the proton beam. It is now used by L3 in a more sophisticated implementation, with a Radiofrequency Quadrupole (RFQ)-based accelerator system [67], as shown in Figure 24.

While Crystal Ball used a set of reactions producing photons from 2.2 MeV to 17.6 MeV, L3 concentrates on the 17.6 MeV line from the reaction

This is the highest energy attainable with non-refrigerated targets (the reaction $p + {}^3_1\text{H} \rightarrow {}^4_2\text{He} + \gamma$ yields 21.6 MeV but requires a cryogenic tritium target). A synchronized trigger is provided by pulsing the proton beam and hence the photons to be detected. Since most of the 14 m long beam transport line and the lithium target are in a 0.5 T magnetic field, a neutral hydrogen beam is produced by stripping an electron away from the H^- ions outside of the magnetic volume, using a low pressure (5×10^{-4} Torr) nitrogen gas cell. RFQ calibration runs in 1993, with limited statistics, resulted in a resolution of 0.99% for 45 GeV electrons from Bhabha scattering events (after unfolding the radiative tail). With the higher beam intensity on target expected in 1994, the overall calibration precision is expected to be improved below this figure. At the design intensity of the RFQ beam, 1% precision could be reached in a single calibration run of approximately one hour.

An extension of this technique [68] uses the high cross section of the reaction

to produce a large number of 6.1 MeV photons for each RFQ bunch (a few microseconds long). The photons pile up in the calorimeter readout gate, resulting in an effective energy of several GeV in each crystal. This technique, that is particularly suitable for crystal calorimeters at multi-TeV hadron colliders, has been shown to achieve an accuracy of 0.4 % in a few minutes for the L3 BGO system [68].

7.3 Light Pulsers

A light pulser system is a useful tool to monitor the transmittance of a crystal, the reflectivity of the crystal wrapping or coating and its readout response. As discussed in Section 5, the scintillation mechanism of most crystals is not damaged by irradiation. The light pulser thus can serve as another means of intercalibration.

The example of the L3 Xenon flasher system [69] is illustrated in Figure 25. A light pulse is produced by a high intensity Xenon flash lamp. The pulse is filtered to roughly reproduce the BGO scintillation light spectrum. The light is then transported by a set of optical fibers to the individual crystals of the calorimeter and to various intensity monitoring devices. Usually some diffusing medium is inserted in the optical path, to ensure uniform light distribution between fibers. Fibers are selected to be radiation resistant and some of the intensity monitoring devices are located as close as possible to the calorimeter, so that possible fiber aging can be detected. In general no attempt is made to provide a source of stable intensity, rather the intensity is precisely measured on a pulse to pulse basis by photodiodes and phototubes maintained in a controlled environment.

The light pulser system is fast and easy to operate, and so it is very useful to track changes in the detector response over short periods of time. Since the relative amount of light carried by each fiber is not *a priori* known to the system the initial inter-

calibration has to be found using a more absolute technique, such as a test beam run. Subsequently changes in the intercalibration (particularly those associated with overall light transmission through the crystals to the photosensor, and the relative gain of each readout chain) can be tracked. A precise set of temperature sensors also must be used, and tracked over time, as the scintillation light yield is a function of temperature (with a coefficient of $-1.6\%/^{\circ}\text{C}$), while the light pulser system does not check the scintillation efficiency of the crystals.

The L3 calorimeter was initially intercalibrated using a test beam. Since then it has been continuously monitored using the light flasher system. By combining the results of the Xenon light flasher system with Bhabha events, a resolution of 1.22% at 45 GeV was obtained after ≈ 3 years of L3 running.

Figure 20: a) Longitudinal crystal response to a constant energy deposition by minimum ionizing particles in the L3 BGO. b) The normalized difference of response between two cosmic ray runs taken 5 months apart. The data plotted are for a crystal exposed to radiation damage from the LEP beam. The damage is more severe in the front part of the crystal.

Figure 21: Time-Energy “phase space” for the calibration sources used in L3.

Figure 22: Energy resolution (FWHM) obtained from a test beam and from nuclear reactions, for a prototype of the Crystal Ball calorimeter.

Figure 23: The correction factor for absolute photon energy calibration, measured using different physics processes in CLEO II as a function of the photon energy [5].

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Figure 24: Layout of the L3-RFQ calibration system.

Figure 25: Conceptual schematics of the L3 Xenon light pulser system. PFB: primary fiber bundle. SFB: secondary fiber bundle. F: attenuation filter. SF: Spectral filters. (1) Fiber from the other lamp system. (2) Fibers from other mixers.

8 Conclusion: Physics with Crystal Calorimetries

The high resolution and uniform hermetic coverage of homogeneous crystal calorimeter systems has given past and present experiments unique physics discovery potential. Over the last two decades, large calorimeters of this type have achieved resolutions meeting or approaching their design values. The only limitations have been traced to the calibration quality, which fundamentally rests with the availability of sufficient physics calibration processes, combined with quick precise monitoring methods, and possible radiation damage.

The special physics capabilities of these detectors is clearly illustrated through the search for the Higgs boson – the key missing piece of the otherwise highly successful “Standard Model” of the fundamental interactions – in the mass range between 80 and 180 GeV in multi-TeV hadron colliders [44].

Figure 26 shows the $\gamma\gamma$ invariant mass spectra obtained with 10^4 pb^{-1} (1 “standard SSC year”) for Higgs signals of 80, 100, 120, 140 and 160 GeV, superimposed on the irreducible background (a, b, c) and the background subtracted spectra (d, e, f). Three energy resolutions are shown in the figure: $(2/\sqrt{E} \oplus 0.5)\%$ (for a crystal calorimeter), $(7.5/\sqrt{E} \oplus 0.5)\%$ (for a liquid argon calorimeter) and $(15/\sqrt{E} \oplus 1.0)\%$ (for a sampling calorimeter). The irreducible background is from direct production of photon pairs not associated with the Higgs, predominantly from gluon-gluon scattering.

Figure 27 shows the significance obtainable in a Higgs search as a function of the integrated luminosity, expressed in units of standard SSC years (SSCY), for Higgs masses of 80, 90, 100, 120, 140, 150 and 160 GeV. In this figure the significance is plotted as a band for each energy resolution. The upper edge of the band corresponds

to the irreducible $\gamma\gamma$ background only, while the lower edge of the band takes into account the background due to hadron jets misidentified as photons. The advantage of a crystal calorimeter's resolution, in searching for the Higgs in this difficult mass region, is clearly shown in these two figures.

To reach and maintain this resolution, speed, radiation hardness, and precision intercalibration *in situ* are among the primary requirements at future multi-TeV hadron colliders. Recent extensive R&D by the BaF₂ Collaboration has demonstrated that mass-produced crystals of sufficient quality could be obtained, and stable uniform response and the intrinsic resolution could be achieved (through optical bleaching) to meet these requirements. Based on the knowledge gained during the BaF₂ program (as discussed above), and recent studies of other scintillating crystals by SIC, BGRI, Caltech, and member groups of the CMS and Crystal Clear collaborations, we believe that a precision crystal calorimeter could have a key role to play in the physics program of the next generation of hadron colliders. In order to achieve the requisite stability and uniformity of response during running, for crystals denser and thus potentially more cost-effective than BaF₂, further R&D is required.

$M_H=80,100,120,150$ GeV Background Subtracted

Figure 26: $\gamma\gamma$ invariant mass spectra obtained with 10 pb^{-1} (1 SSCY) for Higgs signals of 80, 100, 120, 140 and 160 GeV, superimposed on irreducible background (a, b, c) and background subtracted (d, e, f). The energy resolutions corresponding to three calorimeter types are shown: $(2/\sqrt{E} \oplus 0.5)\%$ (BaF_2), $(7.5/\sqrt{E} \oplus 0.5)\%$ (liquid Ar) and $(15/\sqrt{E} \oplus 1.0)\%$ (sampling).

Significance of $H \rightarrow \gamma\gamma$

Figure 27: The significance of the $H \rightarrow \gamma\gamma$ signal as a function of the integrated luminosity (in SSCY) for Higgs masses of 80, 90, 100, 120, 140, 150 and 160 GeV, and for the resolutions: $(2/\sqrt{E} \oplus 0.5)\%$ (BaF₂), $(7.5/\sqrt{E} \oplus 0.5)\%$ (LAr) and $(15/\sqrt{E} \oplus 1.0)\%$ (Sampling).

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