

Homogeneous scintillating LKr/Xe calorimeters

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Recent R&D work on full length scintillating homogeneous liquid xenon/krypton (LXe/Kr) cells has established the essential properties for precision EM calorimeters: in-situ calibration using α 's, radiation hardness as well as the uniformity required for $\delta E/E \approx 0.5\%$ for e/γ 's above 50 GeV.

1. Introduction

Precision electron/photon detectors are needed at many of the future high energy and/or high luminosity particle accelerators (SSC/LHC), relativistic heavy ion collider (RHIC), B-factories, ϕ -factories and Charm-factories, where it is important to measure photons and

electrons precisely in order to reconstruct the invariant mass of the Higgs, heavy quarks as well as to demonstrate the existence of the quark-gluon plasma states. Such a precision electron/photon detector has vast potential usage of astrophysics, nuclear physics, and high energy physics.

Scintillating LXe/Kr detectors are precise, fast, ra-

diation hard, with the capability to distinguish π^0 's from isolated γ 's and to precisely measure the three dimensional energy distribution of particle showering.

In comparing with crystal detectors, LXe/Kr detectors are radiation hard; they can be calibrated and are easy to have longitudinal segmentation; liquids fill up the entire cell, leaving no clearance near the walls (made of 200 μm thick Kapton and copper) separating the cells. Noble liquids saturate at two orders of magnitude higher energy density than crystals like NaI, BGO or BaF_2 .

This disadvantage of LXe/Kr detectors is obvious: LXe/Kr needs purifiers, cryogenics, leak proof containers with precise temperature or pressure control. How to get the UV light out has been a difficult problem in the past. It is also true for all large liquid detectors, that longitudinal uniformity in light collection, is especially difficult to achieve since most liquids do not have much total-internal reflections. This report describes our R&D work using full length scintillating LXe/Kr prototype detectors, showing the above problems are solvable.

2. General properties of LKr / Xe scintillators

The scintillation light of liquid xenon for electrons and photons is fast (decay time ~ 20 ns, see ref. [1]) and intense. The photoelectron yield for LXe was determined using 5.49 MeV α 's [2-5]. The measured pulse height of photoelectrons corresponds to 4×10^4 electrons with a resolution, dominated by the electronic noise of the amplifier, of 6.6% (3 μs gate time) and 17% (20 ns). The temperature dependence of the scintillation yield, in the temperature region around -108°C is about $-0.4\%/^\circ\text{C}$.

Scintillation properties of solid and liquid Kr were investigated in earlier works [6,7]. A recent experiment (see ref. [8]) has determined the attenuation length of the liquid krypton for 150 nm scintillation light in LKr to be 100 ± 10 cm for refraction index = 1.4, or 200 ± 20 cm for refraction index = 1.3. This is significantly better than what was observed for LXe and will make the uniformity in LKr easier to achieve than LXe. The photon yield for liquid krypton was determined for 5.157 MeV α 's. It corresponds to $(3.7 \pm 0.4) \times 10^4$ electrons with a resolution 16% (FWHM) at 1 μs shaping time.

Recent work using windowless UV photodiodes [3-5,9-11] has shown there are large windowless silicon photodiodes to detect UV light in LXe and LKr/LAr (mixed with 5% LXe); both diodes and amplifiers work well inside LXe, LKr and LAr; the effective quantum efficiency $> 30\%$, including the effect of reflection. When α 's stop directly in the diode, the width of the pulse height distribution is $\pm 0.2\%$ with 1 μs gate time (fig. 1), and 1% with 20 ns.

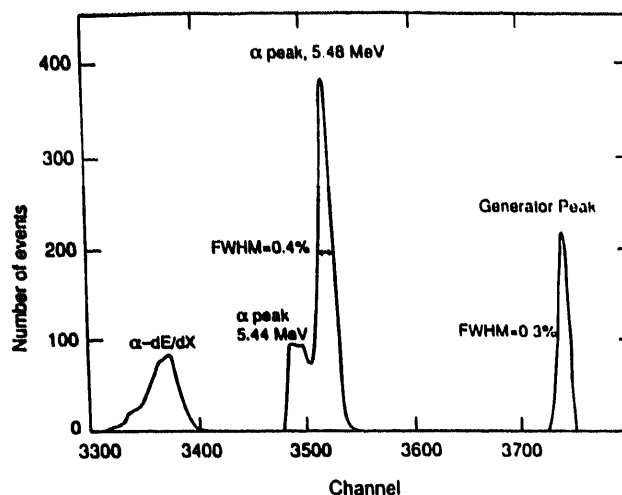


Fig. 1. Calibration using 5.44 MeV α 's directly hitting a UV photodiode. The signals are (from left) α passing through the metal grids, signal and test pulse (to measure the number of photoelectrons in the signals). A resolution of 0.2% per α has been achieved and is stable over weeks.

This inherently large light output naturally results in excellent total energy ($\sigma(E)/E \approx 0.5\%$) and dE/dx measurements. The intrinsic energy resolution of a LXe detector equipped with full size (5 cm diameter) silicon photodiodes was measured using ion beams from the Ring Cyclotron at Riken, Japan [3,5]. The observed energy resolution was 0.6% rms for 1.64 GeV ^{14}N , and 0.7% for 2.65 GeV ^{40}Ar . The charge observed is 2.91×10^7 electrons for 2.65 GeV ^{40}Ar .

3. Measurements of LXe calorimeter cell

3.1. Prototype liquid xenon detector

A full length (66 cm) vacuum insulated noble liquid cell (4 liters) (fig. 2) was built to investigate uniformity of calorimeter cells.

Purification with impurities less than a few parts per million is accomplished by a series of molecular sieve and hydrox getter purifiers. The flow rate of gaseous xenon is ~ 5 l/min during purification. All components of the gas and detector systems (except the photodiodes) are bakeable to 100°C .

The cell walls are used to reflect UV light and do not mechanically support the weight of the liquid. We have tested UV reflectors made of Kapton, Al, glass plates, and Cu clad printed circuit board (290 μm thick) coated with Al and MgF_2 and obtained reflectivities in the range 85-90%.

All reflective and support materials of the UV mirrors are known to be sufficiently radiation hard. MgF_2 is radiation hard up to 10^7 rad. As seen in fig. 3 the radiation damage effect in the transmission efficiency

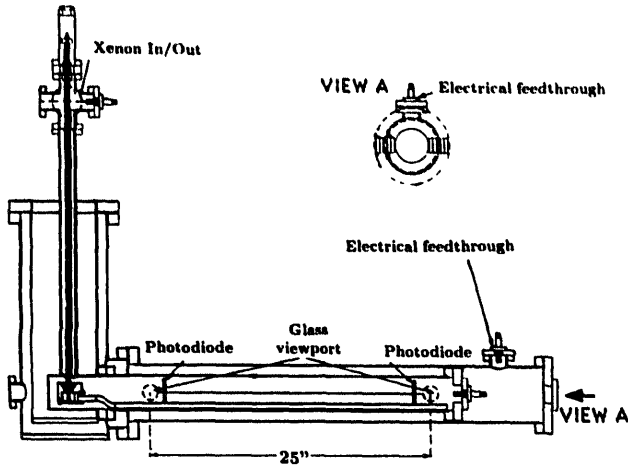


Fig. 2. Schematic of a full length liquid xenon/krypton cell for uniformity tests with mirrors and diodes.

of 170 nm UV is not visible ($< 1\%$) for 1500 μm thick window. Our mirror is $< 1 \mu\text{m}$ thick, so the effect of radiation damage is $< 1/1500$ of 1%. Kapton is hard up to $5 \times 10^{8-9}$ rad. Silicon diode can be calibrated and the leakage current is negligible at -100°C . The frame of the diode is either ceramic or Kapton, both are radiation hard.

Assuming a reflectivity of 0.88 at 170 nm [12] for most of the mirrors and darkening the ~ 1 cm nearest the diode, Monte Carlo studies for a 30 cm long section show uniformity better than the average for the L3-BGO crystals which have proven excellent energy resolution.

Recently, we measured the light collection efficiency using cosmic μ 's through different parts of a 62 cm long LXe or LKr cell with dark mirror coated with a thick layer of MgF_2 (about 600 μm). We found that the efficiency for LKr follows the solid angle covered by the photo detector as seen by the μ 's, while that for

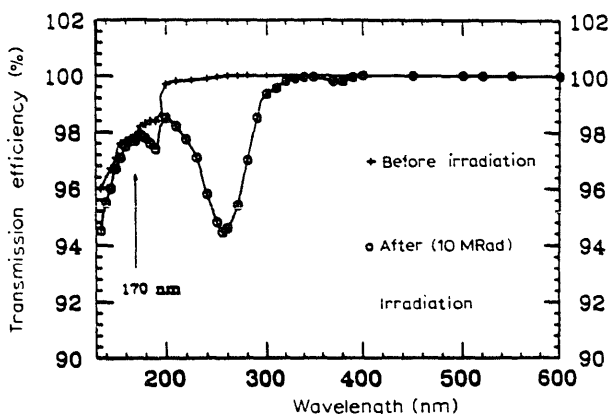


Fig. 3. Measured transmission efficiency of a 1500 μm thick MgF_2 window as a function of the wavelength before and after 10 Mrad of radiation from ^{60}Co , showing the radiation damage effect for 170 nm UV is negligible ($< 1\%$).

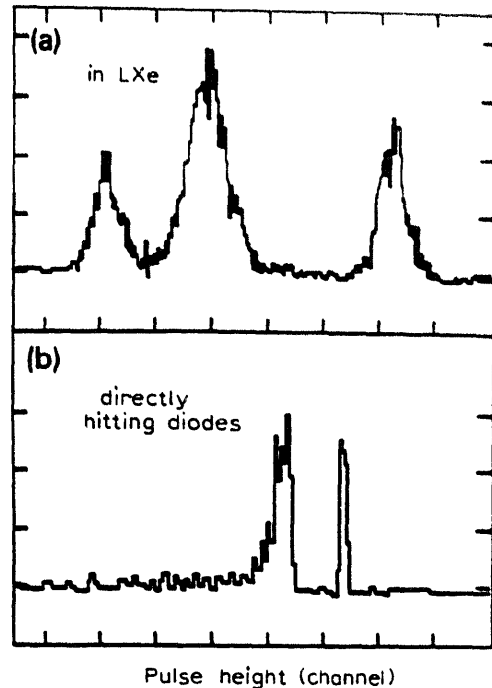


Fig. 4. 5.48 MeV α 's signals detected using a UV photodiode and fast amplifier: with the α particles stopped in (a) liquid xenon (scintillation signal) and (b) in the diode directly. The signals in (a) are (from left) pedestal, signal and test pulse (to measure the number of photoelectrons in the signals) while the pedestal is suppressed in (b).

LXe is flat, which shows that the index of refraction of LXe is larger than that of MgF_2 (1.45). A fit to the data results a value between 1.55 to 1.6 for the index of refraction of LXe at 170 nm. It means that LXe scintillation light has total internal reflection against mirrors coated with thick (> 4 wavelengths) MgF_2 .

3.2. In situ calibration using α 's

The measured energy depends on the gain of the electronics (ADC-amplifiers), the quantum efficiency of the diode, scintillation yield of liquid xenon and the reflectivity of the UV reflector (see ref. [13]). To achieve 0.5% resolution, all of them have to be calibrated. One can use α , cosmic μ or RFQ for calibration, after the detectors have been calibrated in beams. We prefer the calibration scheme using two α sources, one situated in LXe to calibrate the complete detector system using LXe scintillation light, and one situated on the front surface of the diode to calibrate the electronics system using the direct hits of α 's (fig. 4 and fig. 1).

The gains of the electronics (ADC-amplifiers) can be readily calibrated using direct α hits on the diodes, which produce the equivalent of about 300 MeV energy in liquid xenon, due to a factor of five lower W -value and higher collection and quantum efficiencies. Our data shows the peak position can be mea-

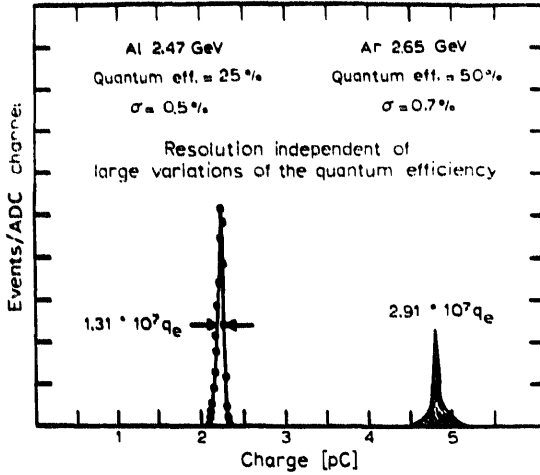


Fig. 5. Measured numbers of photoelectrons for 2.65 GeV Ar ions (solid); and 2.47 GeV Al ions with 50% reduced quantum efficiency (points), showing that the resolutions are not limited by photoelectron statistics.

sured to an accuracy of 1.5% with a fast amplifier. Therefore a few hundred hits/diode yields 0.15% accuracy.

We can calibrate the overall effect, including electronics-LXe-reflectivity, using UV light produced by α 's in liquid xenon. As described below, the resolution of α signals in LXe is 17% for fast amplifiers and 6% for slow amplifiers. Using fast amplifiers we need 10000 events to determine the peak position to $17\% / \sqrt{10000} < 0.2\%$. With slow amplifiers, we need 1000 events/diode to determine the peak position to $6\% / \sqrt{1000} < 0.2\%$. We do not have to do this calibration very often, since we expect the UV reflectors, once in place, would at most change slowly over long time period.

As seen in fig. 1, a resolution of 0.2% per α has been routinely achieved and the signals are stable to 10^{-3} over weeks. This demonstrates how the LXe detectors can be calibrated in situ.

To estimate the intrinsic resolution of LXe detectors, to demonstrate the calibration method and to test the reliability of the detectors, we baked the same diode used for the above measurements [3,4] until the quantum efficiency of the diode, calibrated using α 's dropped to 50% of its previous value. We repeated the measurement using 2.47 GeV ^{27}Al ions two months after the previous Ar ion tests. Indeed the charge observed is reduced to 1.36×10^7 electrons (fig. 5), exactly corresponding to the decrease in quantum efficiency. The measured energy resolution without corrections improves slightly to 0.5% with 40 ns gate, due to better beam collimation.

3.3. Longitudinal uniformity

Longitudinal uniformity is the most difficult problem for large precision scintillating liquid detectors. This difficult arises, because the indices of refraction of most liquids are not much higher than that of wall of the container, and total internal reflection is rare for liquid detector.

To achieve sufficient uniformity in LXe and LKr detectors, we make use of the following effects:

- Focussing effects using tapered cells, which makes light produced at far distance more parallel to the cell axis than these produced near the diodes;
- Tiny light collimator in the form grids, situated in front of the diodes, to enhance the acceptance of light produced at far distance relative to these produced near the diodes;
- E -field near the diode, which reduces the amount of light due to recombination and thus light yield by a factor of two at 200 V/cm. When the front surface of the diode is at negative high voltage, it produces an E -field over the region of a few mm, sufficient to suppress the light yield near the diodes.

The light collimators, situated next to the diode, are made of fine grids coated with Al and are grounded.

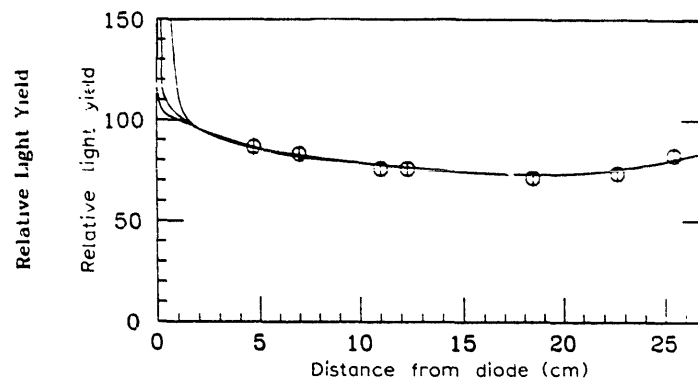


Fig. 6. The measured light collection acceptance, using cosmic μ 's, versus the distance to the diode, in a 27 cm long mirror system. Three Monte Carlo curves, corresponding to different light collimators from top to bottom (8×8 grid and 12 mm deep; 32×32 grid and 3 mm deep, and 128×128 grid and 1 mm deep), showing the nonuniform region near the diode decreases as the number of grids increases.

In general, the smaller the grid size, the smaller the nonuniform region near the diode is. The optimum depth of light collimators is also directly proportional to the grid size. We studied the light collection uniformity using cells with light collimators made of 1×1 , 8×8 and 32×32 grids, as described in the following.

The relative light collection uniformity has been measured in the LXe cell, using cosmic μ 's and α 's. The results are shown in fig. 6. The geometry of the mirrors, representing the second and the third sections of a LXe cell, is $(2.4 \times 2.4 + 3.5 \times 3.5) \times 27 \text{ cm}^3$ and the entire length is coated with 99.999% pure Al and then a MgF_2 layer. Near the diode, we use a light collimator, made of either an 8×8 grid, each of a size of about $3 \times 3 \times 12 \text{ mm}^3$, or an 32×32 grid, each of a size of about $1 \times 1 \times 3 \text{ mm}^3$.

The LXe has been purified using an oxysorb and a molecular sieve of size $13 \times$, and a Ti getter. The detector is constantly calibrated by an Am α source situated near the diode. The trigger of cosmic muons are done by using 9 sets of scintillation hodoscopes, situated directly above and below the LXe cell to define the positions where the cosmic rays passing through the LXe cell to about 1 cm.

4. Composed energy resolution

Using the measured uniformity curve and the measured quantum efficiency of UV-diodes, we used the GEANT Monte Carlo program to simulate the charges generated at the diodes by high energy electron showers inside the full dimensions (7×7 cells) LXe detector, which is yet to be beam tested. The geometry of the mirrors in each cell is $(3 \times 3 + 4.3 \times 4.3) \times 62 \text{ cm}^3$, with three layers of diodes situated at 8 cm, 35 cm and

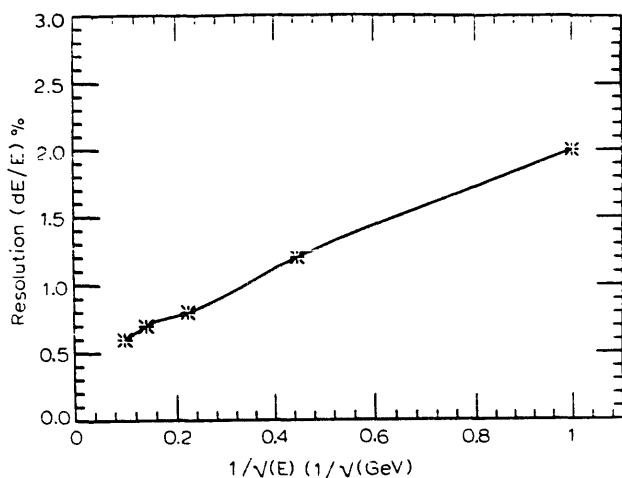


Fig. 7. Predicted energy resolution, $\delta E/E$ in %, of a 7×7 scintillating LXe cell using the measured uniformity curve and quantum efficiency by GEANT Monte Carlo program.

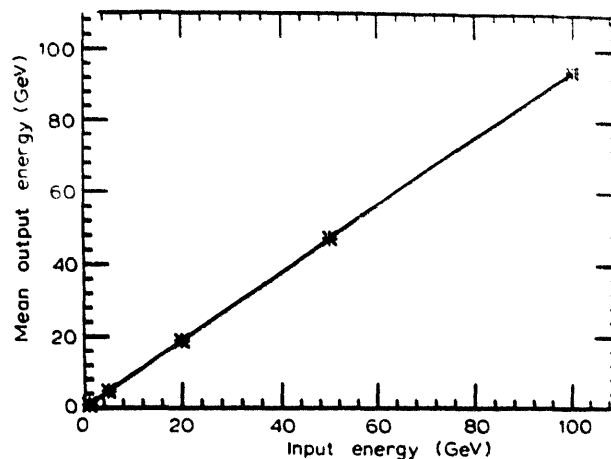


Fig. 8. Predicted linearity between incoming electron energy and output charge, normalized at 100 GeV, from a 7×7 scintillating LXe detector using the measured uniformity curve and quantum efficiency by GEANT Monte Carlo.

62 cm positions. The total measured energy is the weighted (independent of energy) sum of the charges observed by the three layers of diodes.

The resultant energy resolution and linearity are shown in fig. 7 and 8, respectively. As seen, an energy resolution $\delta E/E$ about 0.5% for $E > 50 \text{ GeV}$ and excellent linearity ($< 0.5\%$ above 1 GeV) are predicted. The results are not very sensitive to the uniformity due to a cancellation among the nonuniform effects of the three sections, when the shower maximum position fluctuates. It is well known that if only one diode per cell were used, the linearity and $\delta E/E$ would have changed significantly when the slope of the uniformity changes by more than 6% (see ref. [14]). This is another reason why 3 diodes per cell is preferred.

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