Scintillating Liquid Xenon Calorimeter

M. Chen et al.[1]

Scintillating LXe EM Calorimeter

A Introduction

Liquid Xenon (LXe) is radiation hard and its scintillation light for electrons/photons is fast (decay time 20 ns, cf. [1]) and intense (4×10^7/GeV at 170 nm, cf. [2]). The inherent large signals naturally result in excellent total energy ($\sigma(E)/E < 0.5\%$) and dE/dx measurements.

The scintillation signals from nuclear spallation (e.g. slow protons) produced in hadron-nucleus inelastic scattering, are yet faster (decaytime of a few ns) and more intense (7×10^7/GeV)([2]) than that of an electron. It is thus possible to use a short gate (about 15 ns) to enhance the π signal relative to the electron signal to compensate the nuclear binding energy loss and achieve $e/\pi=1$.

Using three layers of thin photodiodes and fast amplifiers submersed in LXe, one can use 3-D shower profiles to determine a photon vertex of ~ 0.7 cm. This is useful in selecting the correct vertex of photons at high luminosities when multi-events occur in a single crossing. The longitudinal shower profile is also a measurement of the rear energy leakage thus can be used to improve the energy resolution by adding a correction term, dependent on the back/front energy ratio, $E_3/(E_1 + E_2)$ (Figure I.1). The total energy and the pre-shower (first layer) measurements together can yield a π/e suppression better than 10^{-4}.

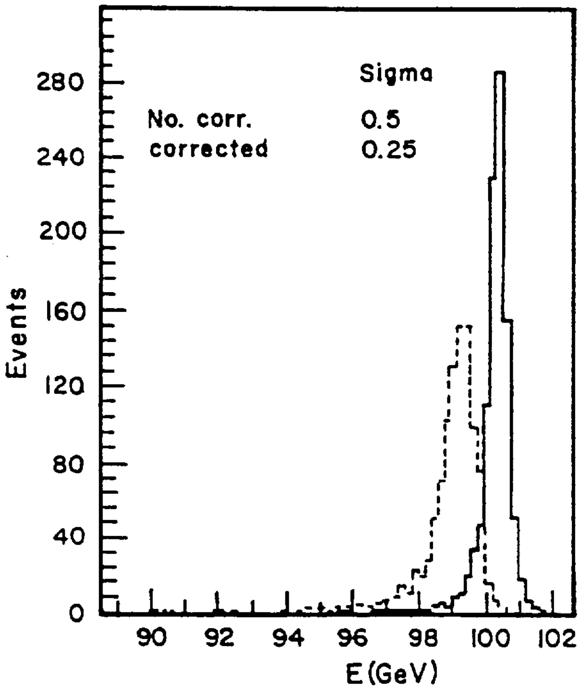

Figure I.1: Distribution of the total energy for 100 GeV electron showers in 22 X_o of LXe. The dashed histogram is the sum of energy of 3 diodes (0.5% σ and 1.2% rms), while the solid includes the correction due to back/front energy ratio (0.25% σ and 0.7% rms). Similarly, for 100 GeV photons, the resolutions are 0.6% σ and 1.9% rms without correction and 0.3% σ and 1% rms with correction.

B LXe EM Calorimeter

Using multi-layers of UV-photodiodes and fast amplifiers submersed directly in LXe to measure the scintillation light from LXe, one can thus detect photons and electrons with an EM energy resolution of < 0.5%; as well as a photon vertex determination of ~ 0.7 cm and a spatial resolution of their impact points to ~ 1 mm by measuring their three dimensional shower profiles.

Such a detector could contains $\approx 2 \times 10^4$ LXe cells. A typical cell of the xenon EM shower counter contains photodiodes, UV reflectors, and amplifiers as described in the following:

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B.1 UV photodiodes

We have developed large windowless UV sensitive silicon solid-state photodiodes covered by gold meshes, which are insensitive to magnetic fields and have a quantum efficiency > 50%. The diodes are 400 μm thin so that < 0.1% of the signal of an EM shower is due to particles passing through the diodes. This makes hermetical calorimeters with 3-D shower measurement possible.

The leakage current from the diodes is less than 10 nA at −108°C. It may increase by three orders of magnitude after heavy doses of radiation and the noise due to leakage current is still negligible.

B.2 Fast amplifiers

Fast amplifiers operate in LXe directly and have a peaking time of 10 ns for the largest size diode (5 cm diameter). The detector yields < 0.5% energy resolution for 2.5 GeV ^{27}Al ions. The fast amplifiers can be positioned behind the largest diode, attached to the cooling lines outside the active xenon region.

B.3 UV reflecting cell walls

We have constructed 3 x 3 UV reflectors using 100 μm aluminum foils, welded flat piece by piece using electron guns, and then expanded into shape. These metal reflectors also serve as Faraday shields for individual cells to reduce cross talk and noise.

Assuming a reflectivity of 0.88 at 170 nm, which was achieved by large system of Al coated mirrors [8], Monte Carlo studies show excellent uniformity (see Figure I.2) for the following configurations:

1. Using a single photodiode and darkening the nearest ~ 1 cm of the reflector, the signal corresponds to 40% light collection.
2. Using two photodiodes, S_1 and S_2, at either end, The composite signal, $\frac{S_1 S_2}{S_1+S_2}$, corresponds to ~ 60± 1.5% light collection efficiency over the full section. The uniformity of this configuration is insensitive to the exact values of reflectivity or attenuation length used.

The resultant uniformity is better than the average of the L3-BGO crystals, which has been proven to have excellent energy resolution. Reflectivity of mirrors is currently measured using a VUV spectrometer at Osaka University.

C Results from Tests on Prototype Detector

The properties of prototype scintillating liquid xenon detectors using diodes and amplifiers developed at Waseda/MIT are described in the following sections and summarized in Table I.1.

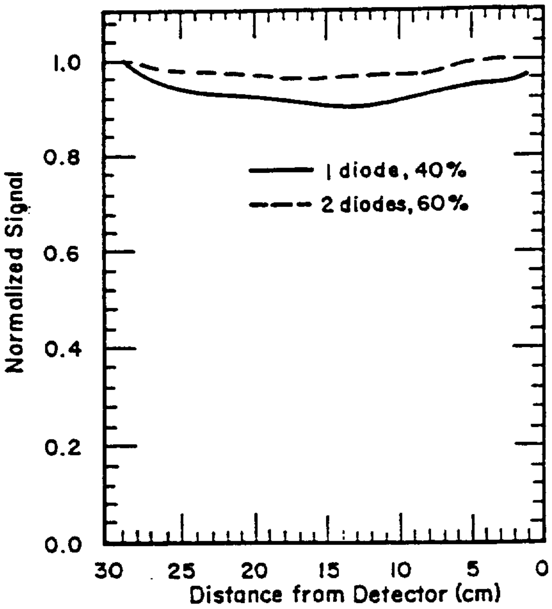

Figure I.2: Monte Carlo studies of the signal uniformity as a function of distance from the large end of a 30 cm long section of a 66 cm long, truncated pyramid reflector cell with a normal reflectivity of 0.88.

Table I.1: Physical properties of liquid xenon with our diode/amplifiers

photoelectrons/GeV	10^7, including Q.E. and acceptance
calibration	5.49 MeV α
saturation	100 times higher than NaI
$\sigma(E)/E$	< 0.5% for E > 2.5 GeV

D Calibration using α Particles in situ

We determine the photoelectron yield and study calibration methods for LXe detectors using 5.49 MeV α's [3]. 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% (slow) and 17% (fast amplifiers). The temperature dependence of the scintillation yield, in the temperature region between −110°C and −75°C, was about −0.4%/°C, three times smaller than that of the BGO.

When α's are allowed to stop directly in the diode, the width of the pulse height distribution is 0.5% with 3 μs gate time and 1.5% with 20 ns [4]. This high resolution demonstrates the excellent uniformity of the photodiodes, both home made and from Hamamatsu. Both diodes and amplifiers work well at low temperature.

The α spectra are very stable and, therefore, can serve as a reliable calibration for the experiments. One can use two α sources, (one situated in LXe and the other on the diode), and cosmic μ for calibration, after the detectors have been calibrated in beams Figure I.3.

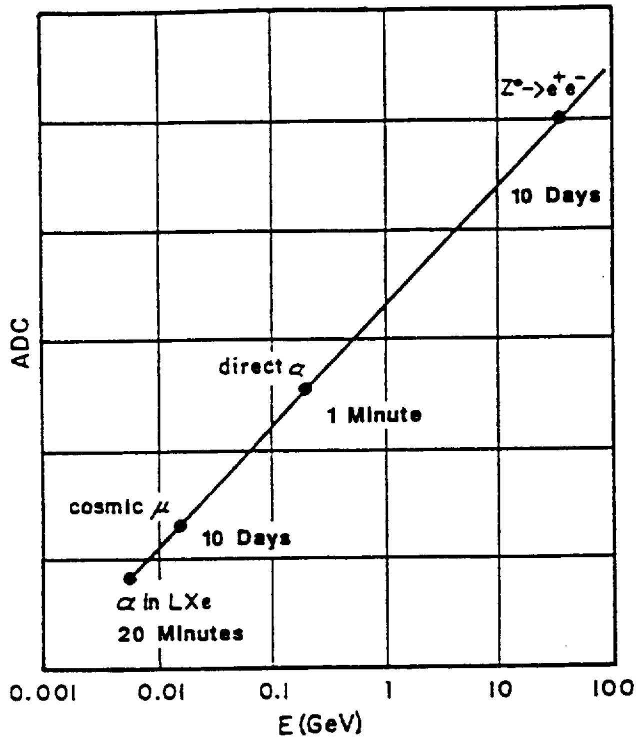

Figure I.3: Calibration of liquid xenon detector using α particle in LXe and direct on the diodes, cosmic μ's, based on our measurements, and monitored by the expected $Z \rightarrow ee$ events. Estimated time needed to reach 0.5% calibration accuracy is indicated for each data set.

E Energy Resolution measured with Heavy Ion Beams

We determine the intrinsic energy resolution of a scintillating LXe detector equipped with full size (5cm diameter) silicon photodiodes using heavy ion beams from the Ring Cyclotron at Riken, Japan. The observed energy resolution was 0.6% RMS for 1.64 GeV ^{14}N, and 0.68% for 2.65 GeV ^{40}Ar. The charge observed is 2.91×10^7 for 2.65 GeV ^{40}Ar.

To estimate the intrinsic resolution of LXe detectors, and to test the reliability of the detectors, we baked the same diode used for the above measurements until the quantum efficiency of the diode has dropped to 50% of its previous value. We repeated the measurement using 2.47 GeV ^{27}Al ions 2 months after the previous Ar ion tests. Indeed the charge observed is reduced to 1.36×10^7 electrons. The measured energy resolution without corrections improves slightly to 0.5% with 40 ns gate, due to better beam collimation.

(Figure I.4)

These results demonstrate that the measured energy resolution is mainly due to beam energy spread, not electronics or intrinsic photon statistics: the actual intrinsic energy resolution of LXe detectors is still much better than what are quoted above.

F Purification System

Ypsilantis (cf. [1]) showed that the attenuation length of LXe is >> 20 cm. We have studied the effect of impurity by filling up two full size scintillating liquid xenon cells with commercial grade xenon and found that scintillation works well even without any purification. We have built an 65 cm long single cell, completed with UV reflector, full size diodes and fast amplifier to be tested in heavy ion beam in order to determine uniformity and attenuation length.

G Xenon Availability

Four commercial companies: Air Liquide, Matheson, Spectra Gases and Union Carbide, have submitted letters that each of them can produce up to 15 m^3 of new LXe by 1999 at a price of about 2.5 M\$/m^3 of LXe.

H Future Beam tests

The present development program is aiming at the measurements of fully contained high energy electron showers using a 5×5 LXe cells in 1991, and (with a hadron calorimeter behind) fully contained 100 GeV pion showers using an 11×11 LXe cells in 1992, in order to:

- determine e/π ratio,
- determine the energy resolution, uniformity, linearity of xenon detectors with both electron and π beams,

I Conclusion

We summarize our recent results in the following:

- photodiodes: α and heavy ion tests with home made full size photodiode and amplifiers submersed in LXe, show:
  1. quantum efficiency > 50%
  2. 10 ns peaking time
  3. $\sigma(E)/E < 0.54\%$ at $E > 2.5$ GeV.

  Therefore 3-D shower measurement becomes possible.
- Calibration: LXe detectors have large output (> 10^7 photo-e/GeV) and thus can be calibrated using α's in situ. This calibration method has been verified using heavy ion beams.
- Uniformity: Monte Carlo studies show high uniformity can be achieved.

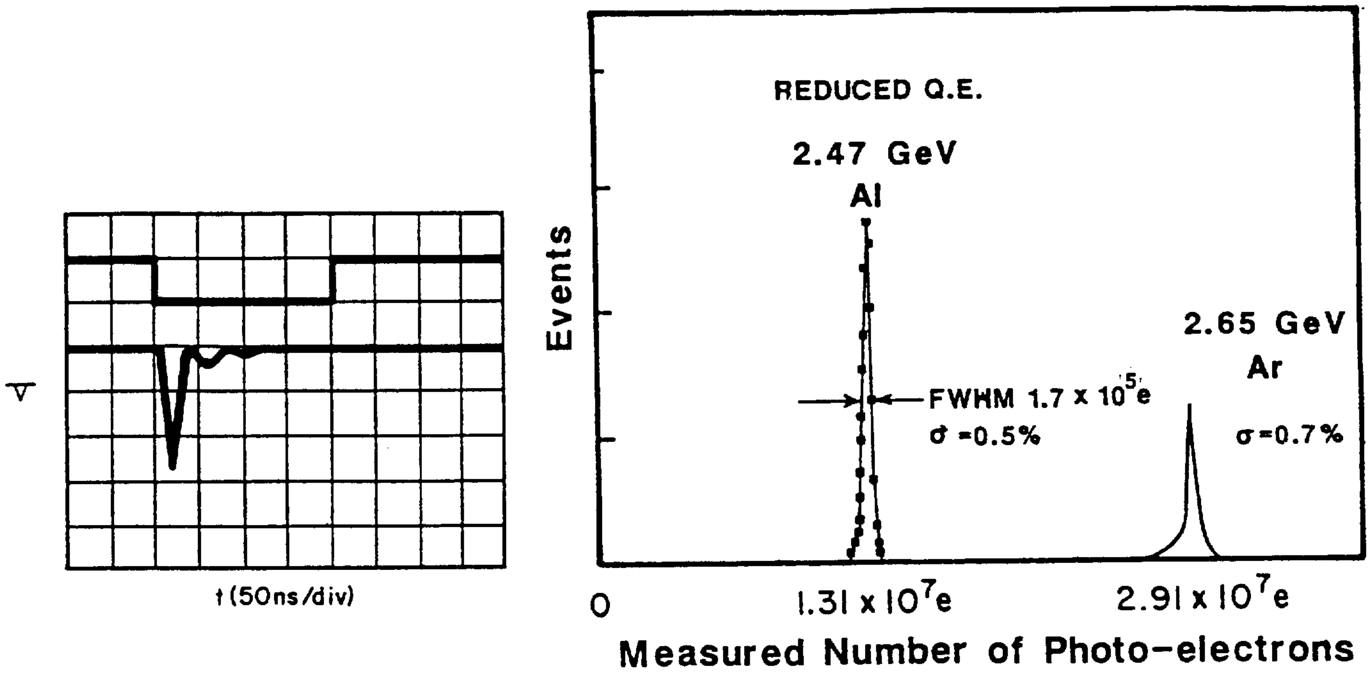

Figure I.4: a. Output pulse shape from a full size diode and fast amplifier; b. Measured photo-electrons for 2.65 GeV Ar ions and 2.47 GeV Al ions with 50% reduced quantum efficiency, showing the measured resolution is limited by beam energy spread.

- The potential new production of xenon is sufficient.

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