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THE URANIUM-SCINTILLATOR DEVICE

S. David Smith, BNL * **

The calorimeter subgroup of the 1977 ISABELLE Summer Workshop strongly recommended investigation of the uranium-scintillator device because of its several attractive features: (1) increased resolution for hadronic energy, (2) fast time response, (3) high density (i.e., 16 cm of calorimeter per interaction length), and, in comparison with uranium--liquid argon detectors, (4) ease of construction, (5) simple electronics, and (6) lower cost.

The AFM group at the CERN ISR became interested in such a calorimeter for substantially the same reasons, and in the fall of 1977 carried out tests on a uranium-scintillator (U-Sc) calorimeter with the same uranium plates used in their 1974 studies of the uranium--liquid argon (U-LA) calorimeter.¹ The chief disadvantage of the scintillator test was that the uranium plates were too small to fully contain the hadronic showers. However, since the scintillator and liquid argon tests were made with the same plates, direct comparison of the two types of devices could be made.

The original U-LA measurements were extrapolated to predict the performance of a full-sized U-Sc calorimeter on the basis of actual measurements of hadronic shower leakage into a surrounding iron--liquid argon calorimeter. Fig. 1 is a schematic diagram of the two devices.

Energy containment, resolution, and compensation were studied² at 10 GeV. The results are summarized in Table 1 and

Table 1		
Containment and Resolution for 10-GeV/c π^-		
	U-LA (Dec. 1974) *	U-Sc **
Containment (%)		
π	82 $\pm$ 4	73 $\pm$ 4
e	100	100
Resolution, σ , for stack (%)		
π	20	17
e	-	3.8
Signal(el) <u>theor</u>		
Signal(el) <u>meas</u>	1.35 $\pm$ 0.05	1.31 $\pm$ 0.04

* 250 gaps, 1 absorption length $\approx$ 11.9 cm, containment measured.

** 188 gaps, 1 absorption length $\approx$ 14.0 cm, containment calculated on basis of U-LA measurement.

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Fig. 1. Uranium--liquid argon calorimeter (top),
and uranium-scintillator calorimeter.

compared with the old U-LA test data. The containment for the U-Sc module is evaluated from containment measured in the U-LA module, with account taken of the slightly different absorption length and number of gaps (the number of gaps for the U-Sc version was chosen to be consistent with the planned R807 calorimeter). The resolution measured for hadrons (π^-) in the U-Sc stack is consistent with the U-LA resolution; if anything, slightly better. The expectation of a resolution of $\sigma \approx 12\%$ for a module fully containing the hadronic shower seems justified. The electron resolution of $\sigma = 3.8\%$ was measured at high rates in the presence of a strong π^- background and may also be broadened by photon statistics.

It has become customary to relate the measured electron signal to a "theoretical" signal derived from a calorimeter calibration based on energy loss dE/dx . For the LA module, the calibration was done by measuring the absolute charge produced by the electron shower in liquid argon with an error indicating the range of systematic effects. For the scintillator module the dE/dx calibration was obtained from the μ -signal. The result given in Table 1 is averaged over several energies from 2 to 10 GeV, with an error reflecting the averaging and some systematic effects. It is comparable with the U-LA value.

The degree of compensation through U fission and the response linearity to hadrons are summarized in Table 2.

Table 2
Energy Dependence of Hadron Signal and Uranium Fission Compensation

E (GeV):	4	6	8	10
$s_{\pi}/s_{\mu} E$	0.59	0.60	0.62	0.61
s_{π}/s_{μ}^e	0.73	0.73	0.74	0.75
s_{π}/s_{μ}^e (extrapolated)	1.03 ± 0.05	1.02 ± 0.05	1.00 ± 0.05	1.03 ± 0.05

Linearity is expressed via the ratio pion signal/beam energy and is normalized to the μ -signal, s_{μ} . Within measurement errors this ratio is constant, whereas a slight decrease in containment with increased beam energy might be expected to cause it to drop. Fission compensation is expressed through the ratio of the pion signal to the electron signal at the same energy. For perfect compensation this ratio should be 1. The raw measurements are given as s_{π}/s_e (extrapolated) with values consistent with 1. This, of course, is assuming that the radially leaked energy is compensated much the same as the 75% of the shower core - a perhaps questionable assumption, which will have to await the large prototype test for verification. However, the results on compensation in the U-Sc module are fully consistent with the old U-LA results. Thus, the prospects for a uranium-scintillator calorimeter are promising, though tests with a full-scale calorimeter are necessary to lay to rest all questions associated with shower leakage.

An interesting special feature of uranium calorimetry is the background noise due to its natural radioactivity. On the basis of our measurements we would expect mean anode currents of $\sim 10 \mu A$ for phototube gains of 2×10^5 and 300 photoelectrons/GeV, or in more natural units ~ 1 MeV/ns/tube. Note that these currents are much larger than typical dark currents or even the average currents

due to particle fluxes that will occur at the ISR. This current is a direct measure of the calorimeter gain, and it suggests an attractive method for calibration monitoring of the large number of phototubes involved.

Use of the wavelength-shifting technique for light collection seems to be essential for the U-Sc device. In order to obtain the improved resolution via the fission compensation, a sampling thickness of ~ 2 mm uranium to a depth of at least 160 layers is indicated. We aim for about 2 photoelectrons per minimum ionizing crossing in order that photon statistics not seriously degrade the electron resolution. With wavelength-shifting techniques, this can be accomplished by reading out both sides of a 20-cm-width scintillator with acrylic scintillator thicknesses as low as 2.5 mm.² This would give a total scintillator output area of 1600 cm² per 20 cm calorimeter edge. Without the wavelength-shifting readout, elaborate and unwieldy light pipes would be required, making segmentation in more than one transverse dimension difficult. Also it would require about 300 cm² of photocathode (> 2 5" tubes) area per 20 cm of calorimeter edge to match the performance of two 2" tubes in the wave-shifting design.

The test described above was done with normal Plexipop⁴ with BBQ-doped acrylic wavelength shifter.⁵ This leads to rather long phototube pulses (~ 80 -ns gates are required for charge integration). We have subsequently tried calorimetry with scintillator similar to plexipop but without the primary POPOP waveshift additive. This allowed us to avoid one stage of wave shifting altogether and to use faster POPOP wave bars in place of the BBQ, thus achieving faster signals and improved light output due to the better spectral matching of POPOP light to photocathode sensitivity. Pulse lengths of 30 ns are obtained.⁶ There remains, however, a pronounced and long tail ($\sim \mu$ sec time constant), which seems to be present at varying levels in all scintillators we have tested.⁷

A special problem associated with wavelength-shifting calorimetry is non-uniformity of response as one observes particles striking closer to the wave bar. In a geometry where the wave bar is parallel to the incident particle direction, the largest effect is due to the Cerenkov light generated in the wave bar by leakage of showers from the edge of the calorimeter. Two basic approaches must be used to overcome this problem: (1) maximize the response of the calorimeter (photoelectrons/GeV) to showers completely contained, and (2) reduce the amount of Cerenkov light that can be generated by shower leakage into the wave bar. Step (1) requires fine sampling with optimal light collection, and may even eliminate the use of low light yield Plexiglas scintillators. (Plexiglas is already suspect for use at ISABELLE because of its susceptibility to radiation damage.³) Step (2) relies on minimizing the total volume of wavelength-shifting materials as well as adding chemicals to strongly absorb Cerenkov light emitted at wavelengths shorter than the scintillator wavelengths before it can be wave-shifted to wavelengths within the photocathode's sensitive range.

More subtle sources of non-uniformity remain, however. Reading out both ends of the scintillator will cancel out attenuation non-uniformities to first order, giving good uniformity if the distance between the two ends, w , is short compared with the attenuation length. However, as one approaches the scintillator edge, the attenuation is quite non-exponential. The short-wavelength end of the scintillation spectrum is generally determined by self-absorption of the scintillating material itself, thus nearer and nearer the edge the device becomes increasingly sensitive to light affected by shorter and shorter attenuation lengths. In principle this problem can be overcome by careful optimization of an ultra-violet-absorbing additive to the wavelength-shifting bar. Thus the wavelength bar can be made blind to light emitted at wavelengths outside the region of uniform transparency in the scintillator. This approach fits nicely with the requirements of Step (2) above.

Even if these effects are removed, a faster than exponential dependence will remain, due to solid-angle effects, regardless of geometry. This is because light emitted at an angle θ with respect to the normal to the output surface must travel a proportionally longer distance and thus see an effective attenuation length of $x_0 \cos \theta$, where x_0 is the attenuation length. Thus, when the light is generated a long distance from the edge, x , only light at small θ is important, but, at $x \ll x_0$, larger angles become important. The integral over solid angle yields the attenuation:

$$A(x) \propto \int_1^{\sec \theta_c} e^{-\tau x/x_0} - (d\tau/\tau^2)$$

where θ_c is the largest θ for which the light can be captured in the wave shifter. For the simplest case of a polished scintillator output edge, $\sin \theta_c = 1/\eta$, where η is the scintillator index of refraction. Thus, the requirement for uniformity becomes more stringent, $w \ll x_0 \cos \theta_c$.

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