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Electromagnetic shower development in uranium and tungsten: a comparison
of data from a silicon sampling calorimeter

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Abstract: Longitudinal electromagnetic shower development has been studied in uranium and tungsten using a sandwich calorimeter with silicon as the active medium. Data were taken with incoming electron energies of 2, 4, and 6 GeV. The silicon detectors were operated with depletion layers of both 200 and 70 μm . The energy resolution of the calorimeter was not reduced by more than 10-15% when the detectors had depleted layer widths of 70 μm .

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1. Introduction

Recently, construction has begun on several new colliding beam machines. These include the e^+e^- machines LEP and SLC; and the ep machine HERA. In addition, a high energy $p\bar{p}$ collider SSC has been proposed. A calorimeter at any of these machines must have excellent energy resolution for both electrons and hadron jets. Furthermore, it has to satisfy strict requirements concerning compactness and granularity.

Because of the high energies involved, sandwich calorimeters are a logical choice for experiments at colliders. The use of silicon detectors as active samplers allows calorimeters to be made highly compact and granular.

To achieve the best possible energy resolution such a calorimeter must have the same response to pions that it has to electrons. Thus for pions the calorimeter must compensate for energy lost in nuclear break-up induced by the strong interaction. This important characteristic, "compensation", has only been achieved so far with uranium as the showering medium ([1] and references therein, [2]). The mechanism by which uranium compensates is not completely understood. It has been surmised that fission amplifies the response of the calorimeter to the hadronic component of a shower [3]; however, it has also been suggested that uranium may instead reduce the response to the electromagnetic component. In particular, a Monte Carlo comparison [4] of electromagnetic showers in uranium-liquid argon and iron-liquid argon calorimeters predicts more observed energy for uranium than for iron with equal radiation length structures. With equal absorption length structures the reverse is predicted. Also, both neutrons and photons are emitted in fission processes and can contribute to the compensation mechanism. Their relative importance is a complicated function of the physics involved and of the calorimeter design. Data on longitudinal shower development are lacking, so it is not known whether compensation occurs at particular depths in the shower, or whether it depends on the sampling frequency, or signal collection time.

As a first attempt in answering these questions, we have studied the longitudinal shower development of 2, 4, and 6 GeV electrons in a silicon sampling electromagnetic calorimeter. Data were taken with both uranium and tungsten absorbers and with the silicon detectors operated with depleted layer widths of both 70 and 200 μm .

2. The experiment

The silicon detectors and their associated electronics oriented to calorimetry [5],[6] as well as the electromagnetic calorimeter [7] have been described previously.

In this experiment the calorimeter contained 24 radiation lengths of either uranium or tungsten. A silicon detector was located after each two radiation lengths of absorber. Each detector was placed in the calorimeter so that the junction side faced towards the beam.

The experiment was performed in the t_9 beam at the CERN-PS with incoming electrons of energies 2, 4 and 6 GeV. A gas Cherenkov counter, filled with helium at 1.4 bar, was used to select electrons. A beam scanner, consisting of a scintillator counter of 0.5×0.5 cm² area, insured that only those electrons impinging on the middle of calorimeter triggered. Before and after each period of data taking the calorimeter was calibrated and the electronics equalized using an Am^{241} α source [7]. A pedestal run was taken before each data run.

Each silicon detector was read out individually to its own ADC channel. An on-line sum was also performed, thus measuring directly the overall energy response and resolution of the calorimeter in the various operating conditions.

3. Data analysis

Fig 1 shows the energy response of the calorimeter as a function of the incoming electron energy. The data show the linear response seen at high energies [7]. The linearity is observed for the detectors operated with depleted layer widths, X_d , of 200 and 70 μm , and employing both uranium and tungsten as showering media; however, independent of the X_d values, the mean sensed energy is about 11% higher when uranium absorbers are used. Also, the ratio of the mean sensed energies at different depletion widths and with fixed absorber, $\epsilon(X_d=200\mu\text{m})/\epsilon(X_d=70\mu\text{m})$, does not depend on the incoming electron energy, but is about 8-11% greater than the cor-

responding ratio of the depleted layer widths.¹ The increase in energy detected for uranium compared to tungsten is due to an augmented energy deposit beyond the shower maximum. The slight increase of the energy detected at $X_d=200\mu\text{m}$ is similarly due to increased energy deposited in the final detectors (Fig 2).

In Table 1, the energy resolution obtained as a function of the electron energy, for $X_d=200$ and $70\mu\text{m}$, and for both U and W data are given. The data show that for $X_d=70\mu\text{m}$ the energy resolution is degraded by not more than 10-15%. The errors are largely the result of calibration uncertainties [7].

The longitudinal shower development is also in agreement with our high energy data in showing a two component structure which can be parametrized by [7]

$$\varepsilon = \varepsilon_0(t/2)^a \exp(-bt) + \varepsilon_1 (t/2)^c \exp(-m(t-x_1)-y_1) \quad [\text{MeV}]$$

where t is the thickness of the passive material in units of radiation lengths. a , b , c , m , x_1 , and y_1 are dimensionless parameters which vary at most logarithmically with the incident energy E :

$$a=a'+a'' \ln E, \quad b=b'+b'' \ln E, \quad c=c'' \ln E, \quad m=m'' \ln E, \quad x_1=x_1'+x_1'' \ln E.$$

ε_0 and ε_1 are normalization constants proportional to the depleted layer width (i.e. $\varepsilon_{0,1} \propto (X_d/200)$) [7]. Table 2 gives the results of a fit for the parameters.

The parameters a and b are in approximate agreement for all the data sets. Thus for t less than 12-14 the shape of the longitudinal shower development does not depend on either the absorber, uranium or tungsten, or the depleted layer width, X_d . At greater depths a second component is

¹ The effective sensitive layer width is greater than the space charge region X_d . Measurement has shown [8] that for $1\mu\text{s}$ of shaping time (about what is used in our electronics) the sensitive layer is extended by about $25\mu\text{m}$. If this is taken into consideration, the ratio of the mean sensed energies is about 13-14% larger than the corresponding ratio of the effective sensitive layer widths.

present in the shower decay. As can be seen from the table, this component depends on both absorber type and silicon detector depletion.

At $X_d=70\mu\text{m}$ a large percentage of the silicon is passive, so the orientation with respect to the beam of the detector junctions could be important. To look for such an effect, we also took data at 4 GeV, exposing the rear side of the detectors to the beam, for $X_d=70\mu\text{m}$ and $200\mu\text{m}$ and with tungsten as absorber. To within errors, no change in the shower development profile was noted.

Electrons and photons with energies near and below the critical energy might be responsible for the observed behaviour. Early in the shower, when the average particle energy is large compared with the critical energies, the shower development shape is approximately independent of absorber and depletion width. Later, low energy phenomena contribute to the shower development. These include: the large photofission cross-section of uranium (for U^{238} $\sigma_{\text{max}} = 110\text{mb}$ at $E = 14 \text{ MeV}$ [9]), the difference in critical energies between uranium and tungsten, the non-linear relationship between total electron range and kinetic energy, the high sensitivity of silicon as a low energy photon detector. As a result, one expects, late in the shower development, a complicated dependence of deposited energy on absorber material and depletion width X_d .

4. Conclusions

The mean detected energy with uranium as absorber is about 11% higher than with tungsten. The mean detected energy at $X_d=200\mu\text{m}$ is about 7-10% higher than expected when a linear increase with X_d is assumed. The linear energy response, which was seen at high energies, is confirmed in the 2-6 GeV electron energy range for both uranium and tungsten absorbers, and for both $X_d=200$ and $70\mu\text{m}$ depleted layer widths of the silicon.

The energy resolution is degraded by no more than 10-15% by employing detectors operated with depleted layer widths of $70\mu\text{m}$.

The longitudinal shower development indicates that more energy is sensed deeper in the shower with uranium as absorber or with $X_d=200\mu\text{m}$. Such additional energy produces a non-linear proportionality between the deposited energy and the depleted layer width.

The use of silicon detectors in hadronic calorimetry might allow the investigation of the extent to which the compensation mechanism is related to photons emitted in the fission process. The use of a hydrogenic material in front of the devices might also extend the investigation to the neutrons emitted during fission.

Table 1:

Energy resolution $\sigma(E)/E$ in %

	U	U	W	W
E(GeV)	$X_d=200\mu\text{m}$	$X_d=70\mu\text{m}$	$X_d=200\mu\text{m}$	$X_d=70\mu\text{m}$
2	16.9 ± 0.6	19.9 ± 1.8	19.6 ± 1.1	20.2 ± 1.5
4	12.8 ± 0.9	15.3 ± 1.7	12.8 ± 1.1	14.6 ± 1.6
6	11.1 ± 0.8	12.2 ± 1.4	10.7 ± 1.1	11.6 ± 1.8

Table 2:

Longitudinal shower development parameters

	U	W	U	W
Parameter	$X_d=200\mu\text{m}$	$X_d=200\mu\text{m}$	$X_d=70\mu\text{m}$	$X_d=70\mu\text{m}$
a'	2.3 ± 0.2	2.2 ± 0.1	2.3 ± 0.1	2.3 ± 0.2
a''	0.6 ± 0.3	0.6 ± 0.1	0.3 ± 0.1	0.5 ± 0.1
b'	0.50 ± 0.04	0.52 ± 0.02	0.53 ± 0.04	0.56 ± 0.03
b''	0.02 ± 0.04	0.02 ± 0.02	-0.04 ± 0.02	-0.03 ± 0.02
c''	0.3 ± 0.2	0.3 ± 0.1	1.2 ± 0.9	-0.2 ± 0.2
m''	0.04 ± 0.02	0.06 ± 0.01	0.15 ± 0.02	0.02 ± 0.02
x_1'	23 ± 14	50 ± 6	95 ± 78	64 ± 41
x_1''	-4 ± 3	13 ± 2	-55 ± 47	-5 ± 13
y_1	28.1 ± 0.2	3.9 ± 0.2	7 ± 2	4 ± 1

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FIGURE CAPTIONS

Fig 1 : Mean energy detected by the calorimeter vs the incoming electron energy for uranium with a silicon depletion layer of 200 μm ($\blacksquare$); for uranium with a silicon depletion layer of 70 μm ($\square$); for tungsten with a silicon depletion layer of 200 μm ($\bullet$); for tungsten with a silicon depletion layer of 70 μm ($\circ$). The full lines are the least squares fits to the data.

Fig 2 : The electromagnetic longitudinal shower development at 2, 4, and 6 GeV for (a) tungsten with a silicon depletion layer of 70 μm ; (b) tungsten with a silicon depletion layer of 200 μm ; (c) uranium with a silicon depletion layer of 70 μm ; (d) uranium with a silicon depletion layer of 200 μm .

Fig 1

Fig 2a

Fig 2b

Fig 2c

Fig 2d