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NOTICE

PORTIONS OF THIS REPORT ARE ILLEGIBLE.**It has been reproduced from the best available copy to permit the broadest possible availability.****COMPENSATION EFFECTS IN HADRON CALORIMETERS[†]**T. A. Gabriel and B. L. Bishop
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Abstract: The pros and cons of utilizing a fissionable material such as ^{238}U to compensate for the nuclear binding energy losses in a hadron calorimeter are discussed. Fissionable material can return some lost energy to the particle cascade in terms of low-energy neutrons and gamma rays, but electromagnetic sampling inefficiencies (often called transition effects) and the detection medium which tries to convert this energy to a useable signal are just as important.

Introduction

As long as leakage and sampling fluctuations are small in a hadron calorimeter, the resolution and the ratio of the electron signal to the hadron signal (e/h) at a fixed energy will generally be dominated by shower fluctuations and losses associated with nuclear binding energy. This assumes, of course, that the active medium can detect all types of radiation on an equal basis and that the behavior of the active and passive media are similar. In practice, however, the active and passive media exhibit different characteristics when exposed to similar types of radiation and the active medium, in general, be it plastic scintillator, liquid argon, etc. do not produce similar signals for the same energy deposition by different particles and is not equally sensitive to low-energy neutrons and gamma rays. For calorimeters which utilize iron or low atomic weight (A) material as the passive material, the energy distribution in the particle cascade for medium GeV (1-20) incident hadrons is approximately distributed equally between the produced protons, neutrons, charged pions, and neutral pions. If Pb, Ta, or U is used as the passive material, the energy distribution is shifted more toward the produced neutrons, and, in addition, the energy spectra of all particles become softer. For calorimeters utilizing low A material the majority of the signal is from charged particles which are produced in the passive material and which pass through the active region. For calorimeters utilizing high A material, the signal from charged particles produced in the passive material, though suppressed, is still present. To fully utilize the sizable fraction of energy left in the cascade in terms of low-energy neutrons (≤ 50 MeV), the detection medium itself must be sensitive through internal collisions to these particles. Particles above ~ 50 MeV can produce other charged particles (and neutrals) in the passive material which can be detected. One way to detect the low-energy neutrons is through nuclear recoil in the active medium, of which hydrogen is the most logical candidate. In the low MeV range (≤ 50 MeV), hydrogen has a large cross section for neutron interaction and, in addition, from just kinematical considerations allows for the largest energy transfers. Even with sizable energy transfers to the active medium most material produces signals substantially below those expected from electrons which deposit the same amount of energy. However, without a direct coupling of the neutrons to the active region, a reduction in the e/h ratio seems unlikely.

For electrons incident on various calorimeters, similar general statements can be made. By changing from a low Z passive medium (i.e., Fe) to a higher Z passive material (i.e., Pb or U), the energy spectra of the particles becomes softer. For a Fe-plastic calorimeter or Fe-liquid argon calorimeter, the average energy deposited in the active region can be calculated fairly accurately by the following ratio

$$\frac{dE/dx|_{1-\min x_t} \cdot E_{\text{incident}}}{dE/dx|_{1-\min x_t} + dE/dx|_{\text{Fe}-\min x_{\text{Fe}}}}$$

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where $dE/dx|_{\min}$ is the energy loss at minimum and x is the thickness of the passive or active medium. However, this expression does not work at all well for a calorimeter using Pb or U as the passive medium and can overestimate the energy deposition by as much as ~ 30 -40%. This reduction in signal aids the e/h ratio. The softer spectrum produced by the high Z material is absorbed in the high Z material at a much faster rate than would be expected from such a simple formula. The detection of the signal in the active medium is for both cases (high and low Z) predominantly from high-energy electrons and positrons passing through and very little from direct interaction in the active medium itself.

The use of uranium, as first suggested by Fabjan and Willis¹ offers a way to compensate on an event-by-event basis for fluctuations and losses due to nuclear binding energy. This reduction can be explained in the following way. If the particle cascade generated by an incident hadron in the calorimeter is strongly electromagnetic through the production of π^0 's, etc., there will be only a slight amplification of the energy in terms of low-energy fission neutrons and gamma rays in the cascade due to the small photofission cross section and due to a reasonably small number of secondary hadronic particles, especially neutrons. However, if the particle cascade is strongly hadronic, there will be a reasonably large amplification of the cascade energy available due to hadronic induced "fast" fission, and to a lesser extent, neutron capture leading to the emission of capture gamma rays. Energy can be returned to the system, but if the active medium is not very sensitive to this type of energy very little benefit can be gained. If plastic is chosen as the active medium, signals from proton recoil due to low-energy neutron collisions should be detected even considering saturation effects. However, low-energy gamma rays will rapidly be absorbed by the uranium minimizing their effect. If liquid argon is chosen as the active medium signals from low-energy neutron collisions with the argon atoms will be greatly suppressed due to saturation effects and small energy transfers. The low-energy gamma rays again will be rapidly absorbed in the uranium, but liquid argon with its higher Z

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and larger density should fair much better than the plastic with regard to the detection of low-energy gamma rays. It appears that high-energy particle detector systems have come full circle; i.e., the age-old problem of detecting low-energy neutron and gamma rays with equal ease in the same detector. Presented in the following sections are a description of the calculational techniques used in the CALOR computer code network and a summary of calculational results which support many of the statements given in this introduction.

These results come from two studies which have recently been underway. One, conducted by J. E. Brau and T. A. Gabriel at the University of Tennessee, is an optimization of the uranium liquid-argon calorimeter for SLD.² This work has led to an appreciation for the role of electromagnetic sampling inefficiencies in the hadronic calorimeter. The second study, by A. DiCiaccio, M. Goodman, R. Wilson and T. A. Gabriel, has been an investigation of calorimeters using TMS as the active region in preparation for the UA-1 upgrade.

Method of Calculation

The calculational procedures used here are similar to those used in previous CALOR calculations.³ A flow diagram of the codes is given in Fig. 1. The three-dimensional, multi-media, high-energy nucleon-meson transport code (HETC)⁴ has been used, with modifications, to obtain a detailed description of the nucleon-meson cascade produced in the devices considered in this paper. This Monte Carlo code takes into account the slowing down of charged particles via the continuous slowing-down approximation; the decay of charged pions and muons; inelastic nucleon-nucleus and charged-pion-nucleus (excluding hydrogen) collisions through the use of the intermediate energy intranuclear-cascade-evaporation (MECC) model ($E > 3$ GeV); and inelastic nucleon-hydrogen and charged-pion-hydrogen collisions via the isobar model ($E < 3$) and phenomenological fits to experimental data ($E > 3$ GeV). Also accounted for are elastic neutron-nucleus collisions ($E < 100$ MeV); and elastic nucleon- and charged-pion collisions with hydrogen.

The types of particle collisions included in the calculations are elastic, inelastic and charge exchange. This model incorporates the diffuseness of the nuclear edge, the Fermi motion of the bound nucleons, the exclusion principle, and a local potential for nucleons and pions. The density of the neutrons and protons within the nucleus (which is used with the total cross section to determine interaction locations) are determined from the experimental data of Hofstadter. Nuclear potentials are determined from these density profiles by using a zero-temperature Fermi distribution. The total well depth is then defined as the Fermi energy plus 7 MeV. Following the cascade part of the interaction, there is excitation energy left in the nucleus. This energy is treated by using an evaporation model which allows for the emission of protons, neutrons, d , ^3He , α , and T . High-energy particle-induced fission is accounted for during this phase of the calculation by allowing it to compete with evaporation. Whether or not a detailed fission model is included has very little effect on the total number of secondary neutrons produced from the high-energy collisions.

The source distribution for the electromagnetic cascade calculation, which consists of photons from neutral pion decay, (electrons and positrons from muon decay),⁵ deexcitation gamma rays from inelastic nuclear collisions, and fission gamma rays, is provided by HETC (or by a related code). Since the discrete decay energies of the deexcitation gammas are not provided by HETC, but only the total energy is known, individual gamma energies were obtained by uniformly sampling from the available energy until it was completely depleted. The transport of the electrons, positrons, and gammas from the above sources was carried out using the EGS system.⁶

Neutrons which are produced below 20 MeV are transported using the MORSE^{7,8} Monte Carlo transport code. The neutron cross sections used by MORSE were obtained from ENDFB/IV. Gamma rays (including those from capture, fission, etc.) produced during this phase of the calculations are stored for transport by the EGS code. The MORSE code was developed for reactor application and can treat in detail fissioning systems. This ability is very important since a majority of the fission compensation results from neutrons with energies less than 20 MeV. Time dependence is included in MORSE. Since HETC and EGS do not have a timing scheme incorporated, it has been assumed that no time has passed for this phase of the particle cascade. Therefore, all neutrons below 20 MeV are produced at $t = 0$. General time cuts used in the MORSE code are 50 nsec for plastic and 100 nsec for liquid argon.

The nonlinearity of the light pulse or charge collected due to saturation effects is taken into account by the use of Birk's law

$$\frac{dL}{dx} = \frac{dE/dx}{1 + kBdE/dx} \quad (2)$$

The resulting curves corresponding to several particles at low energies for the medium indicated are shown in Fig. 2 for $kB = 0.01$ g/cm²/MeV. For electrons at all energies, it is assumed that $kB = 0$.

Fig. 1. Flow diagram of the CALOR system.

The intranuclear-cascade-evaporation model as implemented by Bertini is the heart of the HETC code.⁵ This model has been used for a variety of calculations and has been shown to agree quite well with many experimental results. Even when agreement is not very good, the results produced by this model can lead the user to make correct decisions. The underlying assumption of this model is that particle-nuclear interactions can be treated as a series of two-body collisions within the nucleus and that the location of the collision and resulting particles from the collision are governed by experimental and/or theoretical particle-particle total- and differential-cross-section

⁵Usually not of interest in calorimeter calculations because of lifetime.

Fig. 2. Scintillation light or charge collected vs. charged-particle energy for several different types of particles.

Calculational Results

Three basic types of calorimeters utilizing liquid argon, tetramethylsilane ($\text{Si}(\text{CH}_3)_4$, TMS), and plastic as the active medium are considered. The passive materials will be iron, lead, uranium, or a mixture.

Uranium-Liquid Argon Hexagonal Calorimeter: The hexagonal calorimeter of reference 1 consists of 5.1 interaction lengths of central modules of uranium-liquid argon (1.7 mm uranium plates and 2 mm argon gaps) surrounded and backed up by iron-liquid argon modules. This geometry has been approximated with cylindrical geometry in the same way as in reference 9. Fig. 3a shows the calculated energy distribution for 5 GeV hadrons incident upon this hexagonal uranium calorimeter. The energy detected in each module has been individually weighted to account for the fraction of the energy loss appearing in the liquid argon and the weights for the iron sections have been increased by 20% as in reference 1. This distribution shows a resolution of $\sigma/E = 0.22$ when fit to a Gaussian distribution starting at the half-peak point on the low energy side. This corresponds to a resolution of $\sigma/E = .50\sqrt{E}$.

This calculation can be compared to the test data reported in reference 1. These results have been widely interpreted as demonstrating hadronic resolutions of about $30\text{--}35\%/\sqrt{E}$ for a uranium liquid argon calorimeter, but in fact they do not for a full calorimeter. The results presented in that paper are based on showers for which the first interaction occurs in module B. Module B begins after the 1.7 interaction lengths of module A, meaning that a small factor ($<20\%$) of the showers have this characteristic. Figure 3b shows the energy distribution for the showers of Fig. 3a which have their first interaction in region A or region B. The resolution is much better ($\sigma/E = 0.16$) but should not be interpreted as the overall resolution of the calorimeter. Notice, less than 20% of the selected interactions occur in region B, as was the case in the data reported in reference 1. The above statements should not be interpreted as meaning that uranium calorimeters do not offer promise, only that liquid argon is not the best detection medium for utilizing the benefits of uranium fissioning.

The results of reference 1 also include an Fe/Ar calorimeter of similar geometry to the U/Ar case. Figure 4 shows the calculated

Fig. 3a and b. Pulse height distribution for 5 GeV protons incident on the hexagonal uranium-iron-liquid argon calorimeter.

energy distribution for 5 GeV hadrons. The Gaussian fit gives a resolution of 0.20 in good agreement with the value reported in Fig. 11 of reference 1. Note that this is comparable to the U/Ar case when all showers are retained, although the contribution of sampling fluctuations to the U/Ar case are slightly larger.

The e/h (electron/hadron) ratios have been calculated for both the uranium/iron and the all-iron hexagonal calorimeters of reference 1. The values calculated (as shown in Table 1) are 1.1 and 1.5 compared with the reported measurements of 1.1 and 1.5, in good agreement. The principal mechanism responsible for reducing e/h in uranium liquid argon is the electromagnetic sampling efficiencies, not fission.

The AFS Uranium Calorimeter: Another calorimeter (the AFS at the ISR) has obtained $\sim 35\%/\sqrt{E}$ resolution with uranium using scintillator, so the obvious question is how can that be if the liquid argon case does not. To address this question, the Oak Ridge code

Table 1. Ratio of Electron to Hadron Pulse Height (e/h) at 5 GeV.

	e/h (data)	e/h (Monte Carlo)
Iron-Liquid Argon [*] Hexagonal Calorimeter	1.5 [†]	1.7 1.5 [†]
Uranium/Iron Liquid Argon Hexagonal Calorimeter	1.1 [†]	1.2 1.1 [†]
AFS all uranium-plastic	1.11	0.9 (1.02) [‡]
AFS 50/50 iron/uranium-plastic	1.22	1.0 (1.12)
AFS all iron-plastic	1.48	1.4 (1.53)

^{*}kB chosen such that a 5 MeV α in liquid argon gives the same signal as a 1.25 MeV e.

[†]First interaction site restricted.

[‡]kB = 0.01 gm/cm²/MeV (kB = 0.02 gm/cm²/MeV).

Fig. 4. Pulse height distribution for 5 GeV protons incident on the hexagonal iron-liquid argon calorimeter.

was applied to the AFS calorimeter. This calorimeter consists of thin uranium plates separated by scintillator. The AFS collaboration has also reported results of tests with varying mixtures of copper and uranium plates¹⁰ and results of a test of a copper catcher,¹¹ an all copper/scintillator calorimeter. Copper was unavailable for the calculations, but iron has much similar properties and has therefore been substituted. The uranium and uranium/iron calorimeters were 60 cm x 120 cm in cross section and of lengths specified in reference 9. Two uranium cases have been calculated. The all uranium calorimeter contains 3.81 absorption lengths (395 mm of uranium and 337.5 mm of scintillator). The "50/50" mix of iron and uranium has 161 mm of uranium, 265 mm of iron, and 290 mm of scintillator. A third case was done to simulate reference 10. This "iron catcher" has a cross section of 64.2 cm by 50 cm (somewhat smaller than the uranium calorimeter). It has a depth of 75 cm. Figures 5a-c and 6a-c show the resulting calculations with superimposed Gaussian curves fitted in the same way as the data was fit by the authors of references 10 and 11. The data are for two different values of kB. Here we see a resolution of 0.15 (or 33%/√E) for the all-uranium case. The resolution is slightly worse for the higher saturation value. Table 2 compares the resolutions determined from the Monte Carlo

energy distribution with those of the published data. The agreement is remarkably good. One might wonder to what extent the restricted surface area of the all-iron-plastic calorimeter is responsible for its worse resolution. Calculations were carried out in which a surface area of 60 cm x 120 cm (the same as the AFS uranium calorimeter) was used and the resolution is still much worse than the uranium cases, being 0.22.

For comparison to the uranium liquid argon case it is interesting to consider the resolution for showers occurring in a restricted region of the calorimeter. When the first interaction was required to occur at a depth of 25 cm to 50 cm the calculated resolution became 0.13, or somewhat better than the overall resolution.

Why is the AFS calorimeter so much better than the uranium liquid argon? The answer lies in the transfer of the fission energy and low-energy neutrons from spallation reactions from the uranium through the sampling medium to an electrical signal and the role of saturation in this process. Table 3 shows the fraction of the measured energy appearing in each of the four categories tallied. The low-energy neutrons transfer much less energy to electrical signal in the liquid argon than in the scintillator. The mechanism behind this is saturation. For a given density of ionization in the two media, the scintillator has much larger saturation, but the hydrogen which is scattered in the scintillator by the neutrons gives lower dE/dx losses (less dense ionization) than those resulting from scattered argon ions in the liquid argon.

The e/h ratios for the AFS calorimeter have been examined to see how they compare with the data. Values of 0.9 have been calculated at 2 and 5 GeV for kB = 0.01 gm/cm²/MeV while the reported experimental ratios are 1.1. The Monte Carlo shows slightly lower e/h values, or more compensation, than the data. This is probably due to several factors. The kB of the plastic used in the experiment is larger. By increasing the kB value to 0.02 gm/cm²/MeV the e/h ratio can be improved without totally destroying the agreement between the calculated and experimental resolutions (see Tables 1 and 2).

Iron-TMS, Lead-TMS, and Uranium-TMS Calorimeters: The calculations presented here represent data that are being prepared for the design of the UA-1 calorimeter upgrade.[†] The total available

[†]At this time the UA-1 upgrade will probably use U-plastic. The authors would like to thank C. Rubbia for pointing out the need for these calculations.

AFS SIMULATION

Fig. 5a, b, and c. Pulse height distribution for 5-GeV negatively charged pions incident on the a) uranium plastic, b) 50/50 iron/uranium-plastic, and c) all iron-plastic calorimeter ($KB = 0.01$ gm/cm²/MeV).

AFS SIMULATION

Fig. 6a, b, and c. Pulse height distribution for 5-GeV negatively charged pions incident on the a) uranium plastic, b) 50/50 iron/uranium-plastic, and c) all iron-plastic calorimeter ($KB = 0.02$ gm/cm²/MeV).

Table 2. Comparison of Energy Resolutions at 5 GeV.

Calorimeter	$\sigma/\sqrt{E}$ (%)	
	AFS Data ^a	Monte Carlo [†]
All uranium-plastic	33 ± 1	33 (37)
50-50 iron/uranium-plastic	38 ± 1	37 (39)
All iron-plastic	48,52	52 (56,52) [‡]

^aFitted to data in range 2-10 GeV.[†]Determined at 5 GeV. $kB = 0.01 \text{ gm/cm}^2/\text{MeV}$ ($kB = 0.02 \text{ gm/cm}^2/\text{MeV}$).[‡](By Gaussian fit, by FWHM/2.36).

Table 3. Fractional Detected Energy for 5 GeV Protons in the Calorimeters.

	Fractional Energy	
	Hexagonal U-LA	AFS All Uranium-Plastic
Primary and secondary π , p , μ and nuclear-recoil and evaporated-charged particles produced by all p and π , and neutrons with $E > 20 \text{ MeV}$	0.65	0.49
Neutrons with energy $< 20 \text{ MeV}$	0.02	0.27
Deexcitation and fission gamma rays	0.11	0.06
Electromagnetic from π^0 decay	0.22	0.18

space in which a uranium calorimeter can be placed is rather limited. However, some of the results are still interesting because of the response of TMS, which contains large amounts of hydrogen, to the various types of energy contained in the particle cascade. The geometry used in the calculations are U or Pb or Fe of 0.2 cm thickness followed by TMS of 0.2 cm thickness for a total depth of 44.8 cm. Behind the front calorimetry is an iron plastic calorimeter utilizing unit cells of 5 cm Fe plus 1 cm plastic repeated 14 times. The lateral extent is, for all practical purposes, infinite.

For the various geometrical configurations and energies studied, including various saturation levels, the results for the energy resolutions are shown in Table 4. Since containment of the particle cascade in the uranium section does not exist, excellent resolution can not be expected. The 1 GeV run has a smaller resolution. For the 1 GeV case very little of the energy is deposited in the back iron-plastic calorimeter. Therefore, the resolution of a uranium-TMS device for this geometry is expected to be about $0.37/\sqrt{E}$ or comparable to the AFS calorimeter.

The breakdown by energy deposition in the TMS region is shown in Table 5. The first row of numbers is the contribution resulting from high-energy charged hadrons, except those produced by neutrons below 20 MeV. The second row of numbers indicates the energy due to recoiling protons (and heavy ions) due to fission neutrons. The third row indicates the contribution due to gamma-rays from slow fission and nuclear excitation. The fourth row of numbers indicates energy in the high-energy electromagnetic channel; this includes both fast fission gamma-rays and those resulting from π^0 decay. The energy due to recoil protons increases as A increases

from Fe to Pb, and this large increase in the observed energy in combination with a decrease in electron signals at the same incident energy causes a transition from undercompensated to overcompensation, at least at the indicated level of saturation. Since the number of spallation neutrons is proportional to A , this contribution begins to dominate the total energy deposition in the TMS for large A . Although providing a few percent of the total energy deposited in the TMS, the contribution due to low-energy gamma-rays is not dominant. The neutron induced proton (and heavy ion) recoils dominate the total energy for high A , and the large fluctuations in this energy deposition dominate the energy resolution.

On the last line, the e/p ratio which includes the contribution due to the existing rear calorimeter is given. The energy deposition in the rear Fe/plastic scintillator calorimeter was added to the energy deposition in the uranium/TMS front calorimeter by a procedure which determined the sum of the energy in front and back sections in such a way that the overall energy resolution for all histories in a given run was minimized. The e/p ratio was determined by fitting the distribution of e/p with a Gaussian. The quoted values are the Gaussian centers. The errors on e/p were determined by calculating the errors on the fitted parameters. The errors on e/p are < 0.1 for all the cases studied.

The effect of various values of kB on the e/h ratio are shown in Fig. 7. For the Fe/TMS case, complete compensation is not obtained. For U/TMS or U/Fe/TMS, it is possible, depending on the saturation level of TMS, to overcompensate or undercompensate. The best results on kB obtained so far indicate a value of $\sim 0.02 \text{ gm/cm}^2/\text{MeV}$.¹² If this value holds, complete compensation appears

Table 4. Energy Resolutions in TMS Calorimeters for Incident Protons.

Calorimeter ^a	Energy (GeV)	kB gm/cm ² /MeV	$\sigma/\sqrt{E}$ (%)
U/TMS	5	5.45×10^{-4}	0.52
	1	5.45×10^{-4}	0.37
U/Fe/TMS	5	0.	0.45
	5	5.45×10^{-4}	0.45
	5	2.10×10^{-3}	0.40
Pb/TMS	5	5.45×10^{-4}	0.51

^aPlus iron-plastic calorimeter at rear. kB = 0.01 gm/cm²/MeV for the plastic.

Table 5. Fractional Detected Energy and e/h Ratios in the TMS Calorimeters for 5 GeV Protons^a

	Fe/TMS	U/TMS	Pb/TMS
Primary and secondary π , p, μ and nuclear-recoil and evaporated-charged particles produced by all p and π , and neutrons with E>20 MeV	0.57	0.27 (0.32) [†]	0.41
Neutrons with Energy <20 MeV	0.22	0.61 (0.56)	0.43
De-excitation and fission gamma-rays	0.024	0.039 (0.033)	0.024
Electromagnetic from π^0 decay and fast fission gamma-rays	0.18	0.072 (0.086)	0.13
e/h	1.3	0.51 (0.61)	0.92

^akB = 5.45×10^{-4} gm/cm²/MeV.

[†]No slow fission neutrons.

Fig. 7. Electron to proton pulse ratio at 5 GeV as a function of saturation.

unlikely with TMS. In addition, the energy associated with low-energy neutrons will for the most part be lost and will not dominate the detectable energy. One final point, the use of hydrogen to detect the low-energy neutrons is self-defeating. Energy removed from the neutrons by collisions with hydrogen rapidly decrease the neutron energy below the 0.5 MeV fission threshold of ²³⁸U. This leads to a suppression of fission energy which can be returned to the system.

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