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A Calorimeter for High-Energy Heavy Ions^{*}

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Abstract

A total absorption hadron calorimeter for use with high-energy heavy ions is described. The calorimeter's response to 2.1 GeV/nucleon ions from ^2H to ^{20}Ne is linear in mass (and thus in total kinetic energy). The RMS resolution ranges from 54% for ^2H to 8.5% for ^{20}Ne .

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1. Introduction

Hadron calorimeters have been used extensively in high energy physics to measure the energies of very high energy particles.¹⁻⁸ The principal advantages of hadron calorimeters are their compactness and large dynamic range of operation. A calorimeter a few meters thick can measure the energies of the highest energy hadrons that can be produced with the current generation of accelerators. The compactness of calorimeters enables them to cover a large solid angle. A calorimeter is also attractive for studying high-energy neutrino interactions^{6,7} since it serves as both target and detector. Drawbacks of hadron calorimeters are their modest energy resolution, $\sigma/E \geq 10\%$, and limited particle discrimination.

The use of hadron calorimeters to measure the energies of high-energy heavy ions has until now been applied only to cosmic ray measurements.⁹ We want to show that hadron calorimeters show promise of becoming a useful survey tool in the field of high-energy heavy ion physics.

The most violent relativistic heavy ion collisions result in the complete destruction of the target and projectile nuclei. This means, for example, that $^{238}\text{U} + ^{238}\text{U}$ collisions, which will soon be possible at the LBL Bevalac, will have multiplicities $M \approx 500$, more than half of which are neutrons. Experiments to measure and identify every particle would be almost impossible. With such high multiplicities collective properties of the final state, such as the outgoing energy flux, become statistically meaningful. Calorimeters may well prove the best tool for such measurements.

We have constructed and tested a hadron calorimeter for use with relativistic heavy ion projectile fragments. Relativistic heavy ion projectile fragments are confined within a few degrees of the beam direction and have fragment energies within a few percent of the beam energy/nucleon.¹⁰ We tested our calorimeter with a beam of 2.1 GeV/nucleon ^{20}Ne from the LBL Bevalac and with projectile fragments with $Z = A/2$ which were magnetically separated and charge-identified with a scintillator placed in front of the calorimeter.

II. Description of the Calorimeter

The calorimeter is shown viewed from above in Fig. 1. It consists of five identical aluminum modules (labeled C1-C5 in Fig. 1) each having a 20" x 20" square cross section and a thickness of 10-3/4". Figure 2 shows the interior of one of the modules as viewed through one of its two lucite windows. Each module contains twelve 1/2" thick steel plates separated by 1/4" thick standoffs. The void between the plates is filled with Nuclear Enterprise 235H, oil-based liquid scintillator. Each module is viewed through the Lucite windows by two 5" diameter RCA 4525 phototubes (labeled PT in Fig. 1), one on each side of the module. The phototubes view the window from the end of a 15" long hollow shroud (labeled LG in Fig. 1), covered on the interior with a highly reflecting aluminum foil. The shroud provides the spatial uniformity of light collection of a long Lucite lightguide, at a small fraction of the cost. Although the use of shrouds and Lucite windows reduces somewhat the amount of light collected, photon statistics does not limit the resolution of the calorimeter.

The 1/2" thick steel calorimeter plates were cadmium plated to

avoid contamination of the oil by rust, which would degrade light transmission. Since the oil-filled gaps are thin, some form of light piping of the light from within the gaps is necessary to obtain reasonable spatial uniformity of light collection. We did this by epoxying 0.001" Teflon to the faces of the steel plates and the interior surfaces of the calorimeter boxes. We chose Teflon (see ref. 6) because of its small refractive index, $n = 1.35$, compared to the index for liquid scintillator, $n = 1.47$. Light incident on the scintillator-Teflon interface at angles $\theta \geq 66^\circ$ is totally internally reflected and guided out the scintillator-filled gap. The Teflon film has a thin layer of aluminum evaporated on to it on the surface that is epoxied to the steel plate. The aluminum film makes the epoxy adhere to the Teflon. The aluminum coating also serves as a mirrored surface. The mirrored surface allows the UV light of scintillation to have sufficient path length in the scintillator to be waveshifted. A summary of the properties of the calorimeter is given in Table 1.

III. Testing of the Calorimeter

We tested the spatial uniformity of light collection in a single module, using small plastic scintillators to select cosmic ray muons with various trajectories through the module. The average muon signal was found to vary with position by less than 10% for sample points at least 2" from any edge.

The complete calorimeter was set up in the focus region of the beam-40 0° spectrometer at the LBL Bevalac. The 0° spectrometer is designed to produce and focus "beams" of projectile fragments. With no target in place the primary beam of 2.1 GeV/nucleon ^{20}Ne was

focused on a 3" x 3" square trigger paddle centered on the front of the calorimeter. When a target was put in place, projectile fragments with mass-to-charge ratio $A/Z = 2$ were focused on the detector along with the primary ^{20}Ne beam. By charge-identifying the projectile fragments with a second scintillator in front of the calorimeter it was possible to calibrate the calorimeter simultaneously with a variety of 2.1 GeV/nucleon nuclei from ^2H to ^{20}Ne .

Because the calorimeter was segmented it was possible to look at the longitudinal development of the heavy ion shower. Figure 3 shows the fractional longitudinal containment $C(N)$ of the shower energy by the first N modules of the calorimeter for 2.1 GeV/nucleon ^{20}Ne ions. The containment $C(N)$ is defined by the expression

$$C(N) = \frac{\sum_{i=1}^N \bar{S}(i)}{\sum_{i=1}^5 \bar{S}(i)}$$

where $\bar{S}(i)$ is the average signal in the i th module. The fractional containment of the entire calorimeter $C(5)$ is defined in the expression for $C(N)$ to be $C(5) \equiv 1$. The actual containment of the entire calorimeter can be estimated from Fig. 3 to be about 98%.

The RMS fractional resolution of the calorimeter for 2.1 GeV/nucleon ^{20}Ne ions was $\sigma/E = 8.5\%$. This resolution is comparable to the best resolution, $\sigma/E \approx 10\%$, previously obtained for hadrons of comparable total kinetic energy $E \approx 40$ GeV. Figure 4 shows the RMS resolution of the calorimeter as a function of the number of modules included in the sum. The effect of partial containment on the resolution of the calorimeter is clearly demonstrated. The resolution of the calorimeter with all five modules summed appears to be only

slightly degraded by incomplete containment.

The resolution of the calorimeter was also measured for several projectile fragments of ^{20}Ne with $Z = A/2$. These results are listed in Table 2. Ions which were very low in yield or were not cleanly separated from adjacent charges are not listed. The fractional resolution of the calorimeter is shown to improve dramatically with increasing ion mass or total kinetic energy of the incident ion. The resolution improves with increasing energy roughly as $\sigma \propto E^{-0.8}$ which is more rapid than is expected ($\sigma \propto E^{-0.5}$) if resolution is limited by the statistics of shower development. The calorimeter's resolution is comparable to that obtained with protons of the same total kinetic energy for calorimeters of similar design.^{2,11}

The average signal in the calorimeter is shown in Fig. 5 as a function of incident ion mass. Since the ions have the same energy/nucleon the signal is expected to be proportional to the incident ion mass for an ideal calorimeter. The calorimeter response is in fact quite linear. The RMS deviation from the straight line in Fig. 5 is $\sigma_m \approx 0.35$ amu, with no apparent systematic departure from linearity.

IV. Limitations of Heavy Ion Calorimetry

When using calorimeters with ions heavier than ^{20}Ne or at lower beam energies, one might expect to encounter nonlinearities in calorimeter response. Unlike high-energy protons, heavy ions lose a significant fraction of their energy by ionization before fragmenting. For example, 20% of the energy of a 2.1 GeV/nucleon ^{20}Ne ion is lost by ionization in a distance equal to one interaction length. This presents a difficulty because a calorimeter's response to primary ionization typically

differs from its response to a hadron shower. In the case of a high-energy proton's shower the signal is only 70-80% of that due to an equivalent amount of ionization energy loss by a fast, singly-charged particle.¹¹ In addition, the response of scintillators to relativistic heavy ions is known to saturate with increasing ionization.¹² These combined effects tend to cancel, which explains why we find no observable non-linearity of the calorimeter's response to 2.1 GeV/nucleon ions up to ^{20}Ne , but may well lead to non-linearities for heavier ions.

V. Summary

We have studied the response of a segmented hadron calorimeter to 2.1 GeV/nucleon heavy ions ranging in mass from ^2H to ^{20}Ne . The calorimeter's response was found to be a quite linear function of ion mass (and thus of total kinetic energy) over this range. The RMS resolution ranges from 54% for ^2H to 8.5% for ^{20}Ne . The calorimeter's resolution is comparable to that obtained with protons of the same total kinetic energy for calorimeters of similar design.

This work was supported by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics, Division of the U.S. Department of Energy under Contract No. W-7405-ENG-48.

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Table Captions

Table 1. A summary of physical properties of the calorimeter.

Table 2. Table of the RMS fraction resolution of the calorimeter
for various 2.1 GeV/nucleon ions.

Table 1

Dimensions:	20" wide, 20" high, 53-3/4" deep
Composition:	Steel-liquid scintillator Alternating 1/2" steel - 1/4" scintillator
Segmentation:	5 equal longitudinal segments each containing 12 steel plates
Weight:	1900 kg.
Length in proton int. lengths:	~6
Length in ^{20}Ne int. lengths:	~10
Length in g/cm^2 :	690

Table 2

<u>Ion</u>	<u>RMS Resolution (%)</u>
^2H	54
^4He	30
^{12}C	14
^{14}N	15
^{16}O	12
^{20}Ne	8.5

Figure Captions

- Figure 1. Schematic top view of calorimeter, consisting of five identical modules (C1-C5), shown with lightguides (LG) and phototubes (PT) attached.
- Figure 2. Side view of a single module with lightguide and window removed. The hatched bands are steel plates viewed on edge.
- Figure 3. Plot of containment $C(N)$ of the first N modules as a function of N , for a 2.1 GeV/nucleon ^{20}Ne beam.
- Figure 4. Plot of the RMS fractional resolution of the first N modules of the calorimeter as a function of N , for a 2.1 GeV/nucleon ^{20}Ne beam.
- Figure 5. Plot of the average signal in the calorimeter for various 2.1 GeV/nucleon ions as a function of ion mass.

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FIGURE 1

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FIGURE 2

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FIGURE 3

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FIGURE 4

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FIGURE 5