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WHY WASTE ALL THOSE MIPS ON COMPENSATION STUDIES?

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ABSTRACT

In a high-energy hadronic cascade some fraction F_{π^0} of the energy appears in electromagnetic cascades, with most of the transfer to the electromagnetic channel occurring through π^0 production. *Most of the statistical fluctuations and all of the energy dependence* in calorimeter response arise from this transfer. The process is uninteresting for purposes of understanding compensation, and F_{π^0} may be found on an event-by-event basis by means of truncated high-energy transport calculations. The subsequent fraction appearing as visible energy (ϵ_e) may be calculated without reference to the original hadronic cascade. Detailed transport to very low energies is necessary to find the corresponding hadronic efficiency (ϵ_h), but comparatively few events are needed if F_{π^0} is explicitly factored out. Most of the usual calculation time can be avoided by doing the problem in this piecemeal way. A hadronic cascade in a uniform calorimeter is completely characterized by F_{π^0}, ϵ_e, and ϵ_h.

1. Introduction

Compensation calculations consume enormous amounts of computing time. This is because the program follows every last neutron to its death, and every photon and electron to a low-energy threshold. Since the number of particles to be transported increases almost linearly with incident hadron energy, the problem is exacerbated when energy dependence is desired. We believe that 90% or so of this time is totally wasted, and that with careful understanding of the details the waste can be avoided. Moreover, the energy dependence need not cost extra time.

We consider the response of a uniform calorimeter to an incident high-energy hadron with energy E. By "uniform" we mean that the structure of the calorimeter (usually a sandwich structure) is the same from front to back, and that the dimensions are sufficient to contain the cascade. In addition, plate thickness is small compared with the interaction length of a ~1 MeV neutron (of order 10 cm), but not necessarily small compared with a radiation length.

We submit that *most of the statistical fluctuations and all of the energy dependence* arise from the transfer of energy to the electromagnetic channel, for the most part through π^0 production. Although these fluctuations are of eventual importance to resolution and compensation studies, they may be understood, trivially and without substantial computer time, with runs of HETC (or FLUKA, or ...) in which the low-energy cutoff can be as high as the π^0 production threshold.

After the transfer of a fraction F_{π^0} of the energy to the electromagnetic sector,† the world divides into two parts:

1. Energy $E_{EM} = F_{\pi^0}E$ produces a signal (visible energy) $\epsilon_e E_{EM}$ in the calorimeter.
2. Energy $E_h = (1 - F_{\pi^0})E$ produces a signal $\epsilon_h E_h$ in the calorimeter.

In either case, the details depend upon the calorimeter structure. The ratio of the two conversion efficiencies ϵ_e/ϵ_h (similar to Wigmans' intrinsic e/h) is the single parameter needed to describe the energy-dependent compensation properties the calorimeter[1]. By themselves, ϵ_e and ϵ_e describe sampling efficiency and hence carry much of the information about sampling contributions to the resolution. An overview of this logic is shown in Fig. 1.

The computation time is saved simply by scoring ϵ_e and ϵ_h directly. This approach also yields additional information. For example, does a given change in calorimeter structure most affect the electromagnetic or hadronic sector?

The approach is hardly new; the authors of HETC have been using parts of it for more than a decade[2]. However, some elements are new, particularly in the context of calorimeters with composite plates, and it is still true that most practitioners burn hours of CPU time making unnecessary global calculations.

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† We reserve f_{π^0} for the energy transfer to the electromagnetic sector in a single collision.

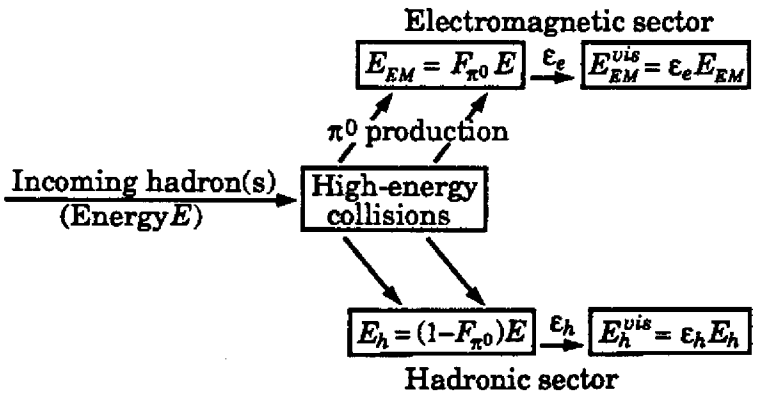

FIG. 1. Logic flow in a hadron-induced cascade in a calorimeter. Transfer of energy to the electromagnetic sector occurs in many high-energy collisions. ϵ_h (ϵ_e) is the efficiency with which energy in the hadronic (electromagnetic) sector is converted to visible energy, or output signal. Included are all effects of saturation, gate width, *etc.*

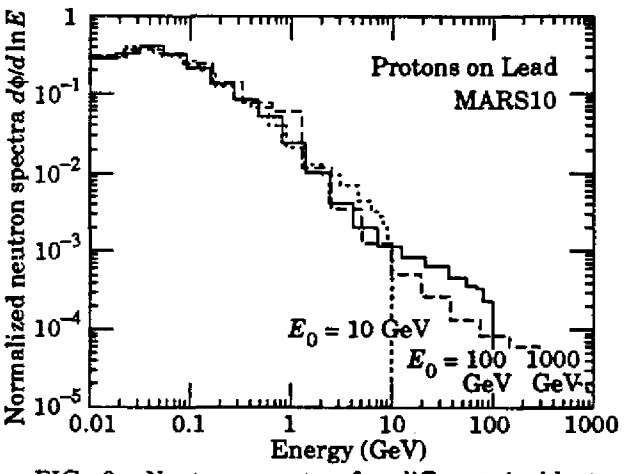

FIG. 2. Neutron spectra for different incident proton energies, as obtained by N. V. Mokhov using MARS10 simulations[3]. Normalization is adjusted to emphasize identity in shape below the beam energy cutoff. The apparent peak at ≈50 MeV is an an artifact of the low-energy cutoff in the code.

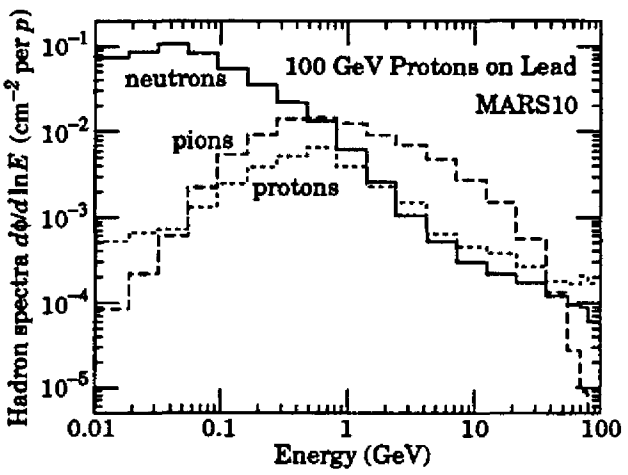

FIG. 3. Spectra of neutrons, protons, and charged pions in cascades induced by 100 GeV protons in lead, as calculated by N. V. Mokhov using MARS10[3].

2. Universal low-energy hadron spectrum

The underlying concept of a universal low-energy hadron spectrum has been discussed elsewhere[1], but we reiterate it here because of its importance to the present discussion. In a high-energy* hadronic cascade in a uniform medium, the spectra of the low-energy hadrons are totally independent of the energy and species of the incident hadron. This situation is illustrated in Figs. 2 and 3, in this case from MARS10 calculations[3]. Figure 2 shows the neutron spectra in proton-induced cascades in solid lead. Within statistics and an overall normalization the spectra are identical up to the incident energy, and only a negligible contribution to the integral comes from neutrons above the lowest incident energy. Figure 3 shows the spectra of the commonest hadrons for 100 GeV incident protons on lead; below a few hundred MeV the charged hadrons range out, so most of the energy is carried by neutrons.

While its importance in calorimetry is only beginning to be appreciated, the universal spec-

* By "high energy" we mean sufficiently high that mass effects are unimportant: $E \approx p >> m$. For practical purposes, this seems to mean $E \gtrsim$ 10 GeV.

trum concept has long been familiar to those doing shielding calculations, and was discussed by Gabriel and Santoro more than 20 years ago[4].

3. Implications for the hadronic sector

The normalization factor for spectra at different energies is $E(1 - F_{\pi^0})$. The exact functional form of $\langle 1 - F_{\pi^0} \rangle$ is not important in the present context, but we have argued elsewhere that it behaves as a weak negative power (≈ -0.14) of the energy[1]. What *is* important is that the number of neutrons and other low-energy hadrons is enormous compared with the number of high-energy π^0's. This, together with the universality of the spectrum, has two serious consequences:

1. For a modest number of incident hadrons, fluctuations in hadronic response are dominated by fluctuations in F_{π^0}. It has been usual to run long enough to average out such fluctuations. Since F_{π^0} can be recovered explicitly on a run-to-run or even an event-to-event basis, this seems grossly inefficient. Instead, run until $\epsilon_h = E_h^{vis}/E_h$ (see Fig. 1) becomes stable.

2. Since the spectral shape is independent of energy, the computer just grinds its gears repeating exactly the same thing if the calculation is repeated at a different energy. This is equally pointless; again, the change is in F_{π^0} rather than in anything of interest. This is implied by the very idea of an energy-independent "intrinsic h."

The visible hadronic energy is scored by many programs. Some is actually scored in the high-energy transport code itself (energy loss by spallation products, expenditures in unbinding nuclei, *etc.*). Also included is nonlinear response of sensitive materials (Birk's law), which often introduces large uncertainties. Most of the energy is carried by low-energy neutrons, which are transported with a low-energy code such as CALOR. Neutrons moderate before undergoing (n, γ) captures, so that ϵ_h is time dependent. The γ's from the capture reactions are transported by EGS. Since the number of these γ's scales with energy in the same way as do low-energy hadrons, we classify them as part of the hadronic rather than electromagnetic sector. Similarly, as a matter of bookkeeping rather than correctness, we assign neutrinos and muons to the hadronic sector.

4. Electromagnetic sector

The photons are mostly from π^0 decay, but electrons from fast decays as well as photons from η decay and other prompt processes are also included. These are usually transported with EGS. For our uniform calorimeter, ϵ_e may be found without any reference to the hadronic cascade. For example, one might transport 10 GeV electrons or photons having a distribution of starting points which roughly matches the hadronic cascade profile. The fainthearted might want to use the photons and electrons as supplied by the high-energy transport code, but even in this case not many events are needed to establish ϵ_e to sufficient accuracy.

The shift of interest from neutrons to the electromagnetic sector represents an interesting new development in calorimetry[5,6,7]. Basically, one can take advantage of the Z dependence of the low-energy photon part of electromagnetic energy deposition. For example, suppose the absorber plates consist of lead clad with iron. Electromagnetic energy is preferentially deposited in the lead, and the "transition energy" is absorbed in the iron rather than appearing as visible energy in the sensitive region. Such effects can be tuned to achieve shifts in ϵ_e of up to 15%. In the present context, we note that since plate *rearrangements* do not affect ϵ_h, changes can be calculated with good accuracy with fairly modest EGS calculations.

5. Choice of energy

There are two awkward points connected with the choice of incident hadron energy:

1. If the energy is low compared to the particle mass, then different species behave differently. A pion and proton with the same kinetic energy give different responses because the pion's mass. Even at 1 GeV, ionization energy loss competes with nuclear interaction. Calorimeter response to a very low-energy proton (say 100 MeV) can be understood entirely in terms of its ionization energy loss. The concept of F_{π^0} only makes sense above the π^0 threshold, and makes even more sense when a multistep cascade occurs.

2. High-energy transport programs currently in use (*e.g.* HETC) have trouble in the 3–5 GeV range. This is because they make a transition

at this energy from a simple intranuclear cascade model to a treatment of hadron-nucleus collisions which is more appropriate at high energies. The transition is not smooth and one or both treatments must be inaccurate in this region. An appearance of smoothness can be achieved by randomizing the crossover energy, but this only hides the problem.

The solution seems to be to choose the incident hadron energy substantially above 10 GeV, say 30 or 50 GeV. If this is done, one is saved by the fragmentation function: The distribution of collision products peaks sharply at very low energies, with very few of the particles having energies in the crucial few-GeV range.

There is one point about which we remain confused: Above about 10 GeV, the ratio of hadron to electron responses (Wigmans' e/π ratio) falls smoothly with energy and is well-described by our power-law description of $\langle 1 - F_{\pi^0} \rangle$. Yet for a 10–20 GeV incident particle, practically all of the collision products are in the very low energy region where the description is difficult. This objection often comes up in connection with jets, where, in a way, the first collision has occurred before the hadron hits the calorimeter. Stated differently, an incident jet is not very much different from the debris after the first hadronic collision in the calorimeter.

The explanation seems related to F_{π^0} itself. The energy dependence of "e/π" above $\approx$10 GeV has to do only with π^0 production. The low-energy collision products might themselves produce π^0's, but do not transfer a large fraction of their energy in this way. They are firmly part of the hadronic sector.

6. Summary: a procedure

We summarize the above discussion in the form of a recipe for obtaining ϵ_e, ϵ_e, and ϵ_e/ϵ_h for a uniform calorimeter:

1. Dig into the code far enough to be able to extract F_{π^0} and enough energy-deposition categories to be able to tally E_{EM}^{vis} and E_h^{vis}.

2. Using 30 or 50 GeV incident pions, calculate F_{π^0}, E_{EM}^{vis} and E_h^{vis} for each event. Runs at a different (higher) energy should yield approximately the same statistical significance when the number of events is chosen to require same execution time.

3. Sum appropriately, then divide to obtain ϵ_e and ϵ_h. Find the error in ϵ_e/ϵ_h either from the variances of F_{π^0}, E_{EM}^{vis} and E_h^{vis}, or from the variance of ϵ_e/ϵ_h as calculated from a number of subsets of the data.

4. The properties of F_{π^0} (energy dependence of the mean, the variance) can be studied by a truncated calculation, using the high-energy transport code alone. More events are needed, but the cascades are not followed below the π^0 production threshold. Given $\langle F_{\pi^0} \rangle$ and ϵ_e/ϵ_h, the electron-to-hadron response ratio ("e/π" ratio) is completely specified.

Additional time-saving procedures are also available:

1. Turn off EGS for the electromagnetic sector (but not its incidental use in the hadronic sector), and calculate ϵ_h as above. Further time savings might be possible using a slightly more dangerous extension: Since the neutron interaction length is large compared with the plate thickness, replace most of the calorimeter by a homogenous structure with average composition and density. Occasional sensitive layers can be used to sample E_h^{vis}.

2. In either case, make a separate run using only EGS. Use *e.g.* 10 GeV photons with origins distributed roughly according to an average hadronic shower profile. Alternatively, use a file of photon (electron) energies and origins from a high-energy transport run; this does not add significantly to the running time. Obtain ϵ_e from E_{EM} and E_{EM}^{vis}.

7. Dagwood sandwich calorimeters

Many people are considering configurations in which the metal plates in a simple sandwich calorimeter are replaced by layered plates—for example, lead plates with iron cladding. In such cases:

1. The hadronic sector is very insensitive to order, and considerable time can be saved by replacing the composite plate by one with average density and composition.

2. A reordering (such as placing both the iron sheets on the same side of the lead) does not affect ϵ_h, so only the EGS half of the calculation is

necessary after reordering. In particular, ϵ_e can be calculated with considerably more certainty than ϵ_h. This means that the *change* in ϵ_e/ϵ_h produced by a plate rearrangement can be calculated with much more confidence than ϵ_e/ϵ_h itself.

8. Camels

Unfortunately, real-life calorimeters are unlikely to satisfy our definition of "uniform." At a minimum, they will probably have (a) an electromagnetic compartment with a thickness of about 20 radiation lengths or a little less than 2 nuclear interaction lengths, (b) a high-quality hadronic compartment which contains most of the cascade, and (c) a low-quality "catcher" which contains most of the remainder.

F_{π^0} develops "early," in the sense that most of the energy transfer to the electromagnetic sector happens in the first few hadronic collisions. This means that an uncompensated catcher causes little problem. Exactly where to make the transition will be decided by future simulations and beam tests. The goal of the simulations will be to understand F_{π^0} and its fluctuations as a function of depth.

A compensation difference between the electromagnetic section and the front hadronic section causes more serious problems, since (a) hadronic response depends upon where the first interaction occurs, resulting in resolution degradation, and (b) a jet deposits E^{vis} early and hence produces a signal which is systematically different from that of a hadron.

In any case, the methods proposed in this paper are still applicable. One calculates ϵ_e/ϵ_h for a large version of each section, and then scores F_{π^0} separately in each section; from these quantities the average, or effective, ϵ_e/ϵ_h may be found for an ensemble of single hadrons or jets. The situation is not quite equivalent, since the low-energy hadronic spectrum is affected by the proximity of a boundary. Subject to checking, we believe this causes minor response differences within about 10 cm of the boundaries, which has little impact on the total response.

9. Conclusions

Runs of abbreviated complexity are done to establish the average and distribution of F_{π^0} as a function of energy. EGS runs, specialized to the particular calorimeter structure but which have nothing to do with a particular hadron energy, establish ϵ_e. The full CALOR[8] structure or its equivalent is used to obtain the response to the hadronic component of a small number of events.

The discussion would be more convincing if the claimed gains were fully documented. However, we have successfully used the F_{π^0} behavior by itself in several compensation studies[9,10], and implicit separation of the ϵ_e part of the problem has been done by Mockett[5] and Foster[7].

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