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MONTE CARLO SIMULATIONS OF CALORIMETER RESPONSE

A. Van Ginneken

Fermi National Accelerator Laboratory*

The study of cascades in large targets is useful for a variety of applications. From one point of view these applications can be divided into two groups: (a) those fully described by the average behavior of the cascades and (b) those requiring information on the fluctuations about the average. Examples of problems of the first group are radiation protection, target heating, etc. The second group includes the topic of energy resolution of hadron calorimeters. Of course there are a number of questions connected with calorimeters for which knowledge of the averages can be quite useful.

Quite recently a new Monte Carlo (MC) program CASIM[1], has been completed. This program calculates the information required for problems of the first type and applies to Fermilab incident energies. By making use of weighting and averaging this program is far more efficient and covers a wider range of problems than comparable analog MC codes. A collection of such calculated results useful for calorimeter design appear in Ref. 2. Figs. 1 and 2 are explicit examples of this.

A program which only calculates averages has nonetheless considerable overlap with a program calculating the distributions.

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*Operated by Universities Research Association Inc. under contract with the U. S. Energy Research and Development Administration.

In addition, before CASIM came into use, shielding problems and the like at Fermilab relied on a version of J. Ranft's program FLUTRA[3], an analog MC program readily adapted to study calorimeter response[4]. Motivated then by the availability of these codes CASIM is presently being rewritten to apply to fluctuation problems. This is a progress report stating our approach. Results and comparisons with experiment will be reported at a later date.

The modification of FLUTRA will be referred to as CALOR I and that of CASIM as CALOR II (or briefly I and II). Since II is believed to be the better approximation, more attention will be devoted to it. A description of CALOR I as well as results obtained with this program have been reported earlier[4].

PARTICLE PRODUCTION MODEL

Of singular importance in simulating hadronic cascades is the treatment of particle production in hadron-nucleus interactions. In both I and II the particles considered are nucleons and pions. By enforcing energy conservation the general effects of K's and other particles are not completely neglected but are approximated by the effects of extra pions (and, in I, also nucleons).

The production model of I is a modification of the Trilling formulae. In II it consists of the Hagedorn-Ranft model adapted to p-nucleus and π-nucleus collisions along with an extra term representing low energy "knock-out" nucleons. Both are fully described in Refs. 1 and 3 respectively.

The Trilling formulae are readily cast in a form convenient for random sampling in the standard way. The same is not true for the Hagedorn-Ranft model. However CASIM includes a scheme of approximate unbiased random sampling and this can be exploited for the present application. The procedures used to achieve this are sufficiently general so that, with only minor modifications, any other hadron production model (within limitations of computer time and storage) could be substituted. The ability to use models of particle production other than those convenient for random sampling (or those specially created for this purpose) removes an important limitation. As more data on particle-nucleus model become available an update of the Hagedorn-Ranft model parameters appears highly desirable. Perhaps extra terms can be added to describe typical nuclear effects such as coherent production and quasi-elastic scattering. Perhaps in the future a sufficiently detailed prescription of particle-nucleus interactions may emerge from one of the current (qualitative) models[5].

Both production models used (Trilling and Hagedorn-Ranft) represent inclusive distributions. In programs calculating only average quantities these distributions can be used directly. In fact, since the inclusives result from averaging over the exclusive distributions it is more efficient and much simpler to use the inclusives even if a set of fully exclusive distributions were available. However, to calculate fluctuations, the inclusive distributions are clearly insufficient. A possible approach would be to estimate second (and higher) moments of the distribution of the quantities sought (e.g., energy deposition at a given depth in the calorimeter). Even if one were able to identify and estimate the dominant correlations between all the particles of the cascade it appears to become a formidable bookkeeping effort. This approach may still be the only viable one in certain cases such as for unusually large calorimeters or at extremely high energies. For the present however an analog MC approach has been taken. Both in CALOR I and II the inclusive distributions are supplemented by energy conservation for each MC event. Further, in II (a) leading particles and (b) momentum conservation (in the high momentum limit) are introduced.

Leading particles are included quite naturally in II since the Hagedorn-Ranft model treats them separately. Momentum conservation is introduced as follows: For each (pion producing) collision, after removing the excitation energy, low energy nucleons and leading particles, the remaining invariant mass, M, is determined. For very small values of M it is taken to represent a single π (with mass M). For values in the mass region of the ρ meson it is assumed to decay into two π's. For still higher masses (in the A_1-A_2 region) it is assumed to decay into a π and a $\pi\pi$ system (with a mass approximately that of the ρ). Above this region the π momenta are chosen from the inclusive distribution. Decay angular distributions are assumed to obey

$$P(x) = a + (1-a)(n+1)x^n \tag{1}$$

where $x = (P_z/P_{max})$ in the rest frame of M with the z-axis along the direction of the incident particle. The particles so generated are "subtracted" from the inclusive distribution i.e., when later selected randomly they are then discarded. A similar scheme is used in FLUTRA (and in CALOR I) with respect to energy conservation. The quantities a and n in (1) as well as the specific limits on M can either be fixed in strict adherence to the model i.e., chosen to put the least strain on the inclusive distribution or they can be used as parameters to be fixed by comparison with data. For the low energy nucleons emerging from the collision, momentum conservation is not enforced.

Even with the inclusion (in II) of a low energy nucleon component a low momentum cut-off is imposed in these calculations. This is because of the large amount of information required to track these low energy particles. Because they deposit relatively small amounts of energy there is, for most applications, also less need to do so.

A comparison of the Hagedorn-Ranft model used in II with data on p-nucleus collisions at Fermilab energies shows no gross discrepancies which would affect the present type of calculations[6]. A similar comparison has not been performed for the Trilling formulae, however at high energy it appears to seriously underestimate the average multiplicity.

ENERGY DEPOSITION

In both I and II the energy deposition of the cascade can be divided into four components, briefly described below. More information can be found in Refs. 1 and 3.

(a) Electromagnetic showers initiated by photons from π^0 decay. Each photon is transported over a randomly selected distance to where an e^+e^- pair is formed. The energy of each electron is then deposited according to an empirical prescription which reproduces the average energy deposition. Fluctuations in the energy deposition of each of these four electrons are ignored. The justification lies in (1) the larger number of particles in the electromagnetic cascade, (2) the fact that the radiation length is considerably shorter than the collision length for most calorimeter absorber materials.

(b) Ionization losses of charged particles (p,π^+,π^-).

(c) De-excitation of struck nuclei. This is described by simple prescriptions for (i) amount of excitation energy created in a collision, (ii) the number and energy of the "evaporation" nucleons and fragments (and the energy spent in removing these particles from the nucleus), (iii) the spatial dependence of the energy deposition of these evaporation particles.

(d) Nucleons which are below the low momentum cut-off of the calculation are treated much like the evaporation particles in (c). For pions allowance is made that a fraction of the rest-mass will be deposited near the point of where they are stopped.

CALORIMETER RESPONSE

Normally the geometry is a cylinder or a block but any arbitrary geometry can be treated. The calculation may also be performed for several sizes of a cylinder or block simultaneously. This can be done approximately by computing for a very large calorimeter and then truncating to the desired sizes (i.e., assuming the propagation of the cascade is uniformly forward and radially outward). Alternatively it can be done rigorously by means of correlated sampling. The advantage of calculating several sizes at once is that the relative difference in response between two calorimeters is calculated much more accurately than by using independent MC runs.

The cylinder or block is divided into a large array (50 x 50) of elementary volumes. The scintillators are assumed to be infinitesimally thin and do not perturb the cascade.

Each of the four components of energy deposition are adjusted for differences between absorber and scintillator in dE/dx, excitation energy, etc. The 50 x 50 matrix of energy deposited (expressed per unit thickness of scintillator) is written on tape after each primary particle has been fully treated. A second program analyzes the tape for the response of any one scintillator or of any combination of scintillators.

The program CALOR I has been compared with data[7] at 8, 18 and 250 GeV and shows the fits going from excellent (at 8 GeV) to poor (at 250 GeV)[4]. While the model leaves considerable room for improvement this appears less worthwhile now with CALOR II being readied.

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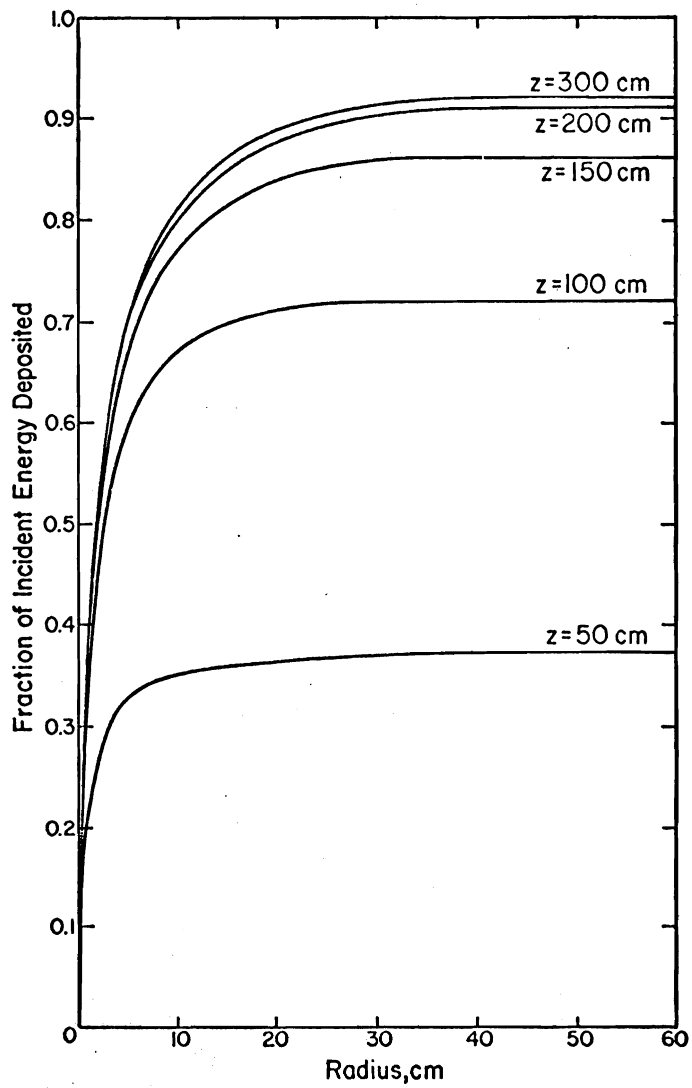

Fig. 1. 300 GeV/c protons incident on a solid iron cylinder. Fraction of the incident kinetic energy deposited as ionization, plotted as a function of radius for various cylinder lengths. The beam of 0.3 cm x 0.3 cm cross section is centered on the cylinder axis.

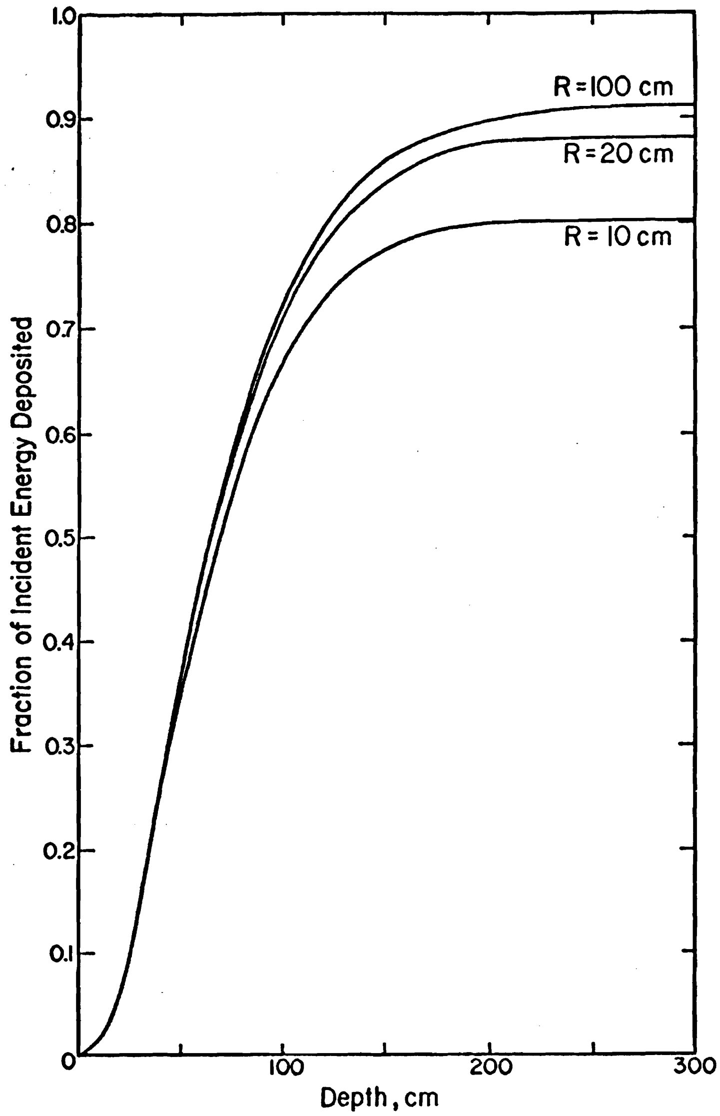

Fig. 2 Fraction of the incident kinetic energy deposited as ionization plotted as a function of length for various cylinder radii, for the same case as in Fig. 1.