SIMULATION OF NUCLEAR-ELECTROMAGNETIC CASCADES IN IONIZATION CALORIMETERS*

W. V. Jones

Department of Physics and Astronomy
Louisiana State University
Baton Rouge, Louisiana 70803

ABSTRACT

Monte Carlo simulations of the development of nuclear-electromagnetic cascades in ionization calorimeters have been underway for several years. The model used is based as much as possible on experimental observations. Results of the calculations have been compared with several experiments using both accelerated beams and cosmic rays. The basic physics principles used in the model as well as the general method of performing the calculations are described. Examples of the agreement of the calculated results with experimental data are given.

1. INTRODUCTION

The Monte Carlo simulations described herein were originally begun as part of a balloon experiment to measure the energy spectra of cosmic ray protons and alphs particles over the energy range 30 - 500 GeV.[1] The apparatus included an ionization calorimeter composed of iron absorber and plastic scintillator detection layers. The calorimeter was calibrated with 10, 20, and 28 GeV protons at the Brookhaven Alternating Gradient Synchrotron (AGS).[2] It was essential to extropolate the calibrated response to the higher cosmic ray energies. This was achieved by using a one-dimensional model of the cascade process. However, it was clear that three-dimensional calculations would be necessary for detailed agreement with measurements.[3] It was also recognized that a proper simulation should consider the alternating layers of different materials in order to properly account for transition effects when electromagnetic cascades pass from the basic heavy absorber to the lighter scintillators.

The cascade model and the method of simulation have been modified extensively since the original presentation.[3] The calculations are now completely three-dimensional. They are done specifically for sandwich type detectors and they follow each individual particle down to essentially its rest energy. Cascades for almost any primary particle from gamma rays, electrons, pions, and nucleons up to iron nuclei can be calculated. The calorimeter can be comprised of almost any arrangement of any materials for which the basic physical properties are known.

2. PHYSICS PRINCIPLES

The basic physics involved in the calculations can be divided roughly into three classes: (1) electromagnetic interactions, (2) hadron interactions, and (3) heavy nuclei interactions. Space does not permit a presentation of the specific formulas and distributions used. Hopefully it will suffice to state the major processes considered. Generally, all the parameters considered are energy and material dependent although approximations are frequently used to simplify or speed-up the calculations.

Electromagnetic Interactions. The processes included for electrons are (1) bremsstrahlung, (2) soft collision ionization, (3) delta ray production, and (4) multiple coulomb scattering. For gamma rays the process considered are (1) pair production, (2) compton scattering, and (3) the photoelectric effect. The original part of the program for the electromagnetic cascade treatment was written by R. J. Kurz of the NASA Johnson Space Center (JSC).[4] Some refinements, including the treatment of the photoelectric effect were made by C. D. Orth also of JSC.[5] The program has since been modified by Louisiana State University (LSU) to provide three-dimensional calculations of electromagnetic cascades. Generally speaking the cross sections used are calculated from theoretical formulas at high energies, while at low energies tabulated values are used.

Hadron Interactions. The process included in hadron interactions are primarily (1) the interaction mean free path, (2) inelasticity, (3) multiplicity, (4) longitudinal and transverse momenta of the secondaries, (5) nuclear disintegration of the target nucleus, (6) ionization energy loss, and (7) coulomb scattering. The model is based primarily on cosmic ray measurements at very high energies and on accelerator measurements at low energies. For energies less than a few GeV, empirical fits to tabulated multi-pion channel cross section data are used. No appreciable refinement of the program has been made during the last two years. Consequently, we have not yet taken full advantage of the results coming from FNAL, although some of the early results are used.

Heavy Nuclei Interactions. The most important physical processes used for the interactions of heavy nuclei are (1) fragmentation of the projectile nucleus and (2) secondary particle production by nucleon fragments during the interaction. Presently the model uses the semi-empirical fragmentation parameters published by Shapiro's group at the U.S. Naval Research Laboratory. The new information coming from studies of nucleus-nucleus interactions using heavy ion beams at the Bevatron have not yet been introduced into the model.

Evaluation of the Model. As is shown below the agreement of the calculations with measurements using ionization calorimeters is quite good. However, it has been pointed out that some of the latest results from FNAL and the Bevatron have not yet been incorporated into the model. Therefore, it is likely that compensating errors in the model lead to fortuitous agreement. It is our philosophy that the model should incorporate the most recent accurate physical data. Whenever one of the many physical parameters used in the model is made to approach the true physical situation, tighter limits can be placed on the less well known parameters.

3. METHOD OF CALCULATION.

As stated above the computer program is designed primarily for performing a realistic simulation of cascade development in ionization calorimeters consisting of alternating layers of heavy absorbers and scintillators. The layers may have arbitrary dimensions, thickness and cross-sectional area, which is specified as input to the program. The number of different types of absorbers, as well as the total number of layers, is limited only by the dimensions of the storage arrays allocated in the program. In case of a single-absorber device, e.g., a block of CsI, all layers are taken to be of the same material.

The program keeps track of the life history of each particle in the cascade, throughout all layers. At each layer boundary the energy, trajectory, etc. for each particle is known. Input to the program specifies which layers correspond to the ionization detection layers (scintillators). Experimental configurations of modular design, such that more than one scintillator is used to obtain a single output signal, can also be readily specified. The number of "equivalent particles" in the cascade can be determined from the energy deposited in the detection layers exactly as is done in calorimeter experiments. For comparison of the calculation with experiments which count the actual number of particles, e.g., track counting in emulsions, one can use the true number of particles crossing the layer boundaries.

4. COMPARISON OF RESULTS WITH MEASUREMENTS.

Results of the calculations have been compared with most of the major experiments using calorimeters, both in calibrations at accelerators and in cosmic ray measurements. In order to illustrate results of the calculations at various stages of development of the program, we will begin by showing comparisons with measurements using the original one-dimensional program and proceed toward the latest comparison with results from an FNAL exposure.

Figure 1 illustrates the agreement of the original one-dimensional calculations with measurements performed at the Brookhaven AGS.[3] This figure shows the frequency distribution of the sum of particles (ΣN) recorded by all scintillators of a small iron calorimeter.[2] The important features are the agreement in shape of the distribution and a shift in scale. The scale shift was attributed to the limitations of the one-dimensional treatment. This belief was not based solely on this figure, but rather on several other characteristic differences. Figure 2 shows that when the calculations were made three-dimensional the scale shift disappeared and satisfactory agreement resulted.

Figure 3 shows a comparison of the calculations using the three-dimensional model, but not the slab-configuration, with cosmic ray measurements of L. W. Jones' group at Echo Lake.[6] Shown here are the cascade development curves as a function of depth in a large iron calorimeter. This comparison provided reassurances that the model could be relied upon for extrapolations of accelerator calibrations to higher cosmic ray energies.

Figure 4 shows one of the first comparisons with experimental data after the slab-configuration technique was used in the calculations.[7] This comparison shows the agreement of the cascade development curves with the NASA Goddard Space Flight Center measurements using an iron calorimeter at the Brookhaven AGS. Each iron module contained two scintillators. The total depth of the calorimeter was about 4 λ (proton mean free paths).

Figures 5 and 6 compare results (solid curves) of the present model with measurements (data points) in a tungsten calorimeter.[8] The measurements were carried out by LSU and the Max Planck Institute for Extraterristrial Physics (MPI) during the summer of 1974. In Fig. 5 are shown the cascade development curves for proton interactions occurring near the front end of the calorimeter. The 100 GeV data is estimated to have about

50% pion contamination while the 300 GeV data is essentially pure protons. For some reason, not yet understood, there is a normalization difference in the calculations and the data at 300 GeV shown in this graph. The data are preliminary and the normalization may be in error.[8] There may also be a discrepancy in the peak at the cascade maximum. If the first interactions are not restricted, the cascade curves are relatively smooth and the agreement is better. The explanation for having the pronounced peak in the curves for tungsten but not in the previous curves shown for iron lies in the greater inelasticity for tungsten, coupled with the greater ratio of the interaction length to the radiation length.

Figure 6 shows a comparison of the Monte Carlo predictions with the 300 GeV measurements for the energy resolution as a function of the calorimeter depth. Here energy resolution is taken to be ratio of the normal standard deviation to the mean of the distributions of measured ionization energy. The data points represent the measurements while the curve has been drawn through the calculated points. This figure is also for protons which interact near the front end. It is seen that there is good agreement between the calculations and the data. Similar agreement has been found for 5, 10, and 15 GeV pion data from a Stanford Linear Accelerator Center (SLAC) exposure of the same calorimeter.

5. DISCUSSION.

In conclusion it can be said that the Monte Carlo model has given rather good agreement with measurements in several absorbers. It is somewhat surprising that as the model has been refined the agreement with data has not improved greatly. However, the model can now be used to answer certain detailed question which the cruder calculations could not address. Perhaps the complex cascade process smears out the effects of errors in the model. A close look at small discrepancies in certain details of comparisons with data can help in perfecting the model.

The attempt to make the calculations as realistic as possible has resulted in an expensive program, as far as computer time is concerned. Consequently, work is currently underway to determine ways of speeding up the calculations without significantly sacrificing the accuracy of the calculations or losing details which are important for experiments. The basic procedure for accomplishing this is to store all the relevant information from individual events on disk or magnetic tape, and then randomly select one of a set of these stored events whenever a secondary particle has properties similar to those of the set. This procedure has been used successfully in simulating cascades initiated by heavy nuclei. Cautious approximations are necessary in building high energy cascades from low energy calculations because of the almost continuous distribution of angles and energies encountered. The slab configuration complicates the situation also. Nevertheless, orders of magnitude of computer time may be saved, at the expense of storage space, with negligible sacrifice in accuracy of the calculations.

6. REFERENCES.

*Supported in part by NASA contracts NAS5-11426, NAS5-23174, NAS5-20883, NAS9-10986, NASA Grant No. NGR 19-001-012, and by the U.S. National Science Foundation.

1. W.K.H. Schmidt, K. Pinkau, U. Pollvogt, and R.W. Huggett, Phys. Rev. 184, 1279 (1969).
2. W.V. Jones, K. Pinkau. U. Pollvogt, W.K.H. Schmidt, and R.W. Huggett, Nucl. Instrum. Methods 72, 173 (1969).
3. W.V. Jones Phys. Rev. 187, 1868 (1969).
4. Now at TRW Systems, Redondo Beach, California 90278.
5. Now at Space Sciences Laboratory and Lawrence Berkeley Laboratory, University of California, Berkeley, California 90278.
6. G.D. DeMeester, Ph.D. Dissertation, University of Michigan (1971).
7. H. Whiteside, C.J. Crannell, H. Crannell, J.F. Ormes, M.J. Ryan, and W.V. Jones, Nucl. Instrum. Methods 109, 375 (1973).
8. D.L. Cheshire, R. W. Huggett, W.V. Jones, W.K.H. Schmidt, and M. Simon, "Response of a Tungsten Calorimeter to FNAL Proton Beams," Paper contributed to this Conference.

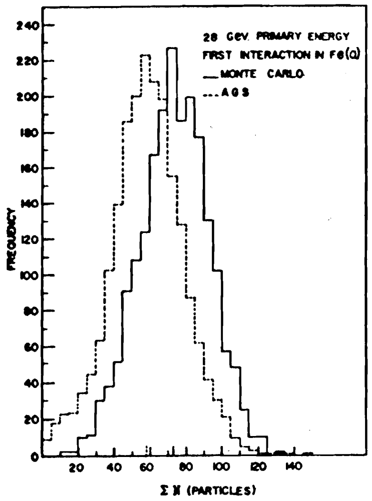

Fig. 1

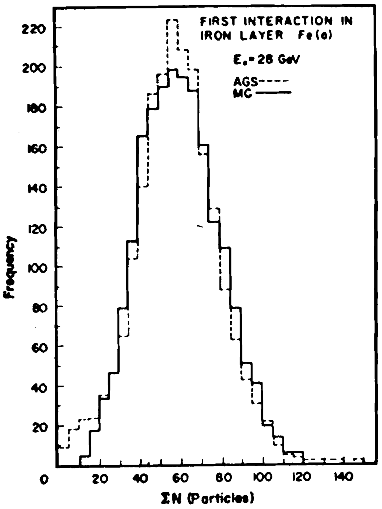

Fig. 2

Fig. 2

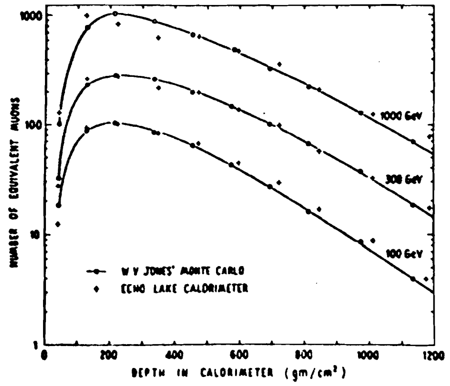

FIG. 29 COMPARISON OF THE AVERAGE SHOWER CURVES WITH THE MONTE CARLO RESULTS OF W. V. JONES.

Fig. 3

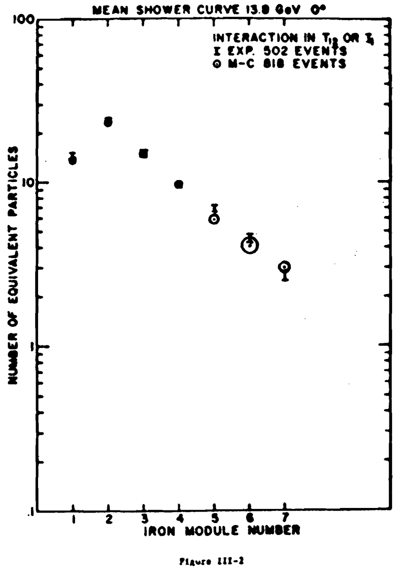

Fig. 4

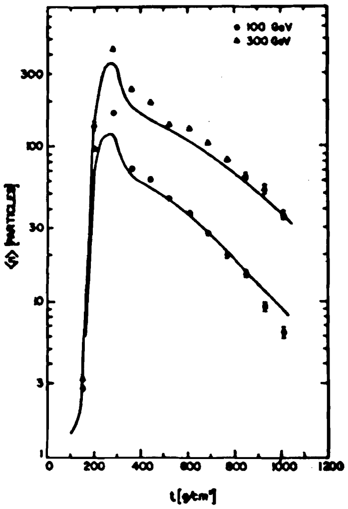

Fig. 5

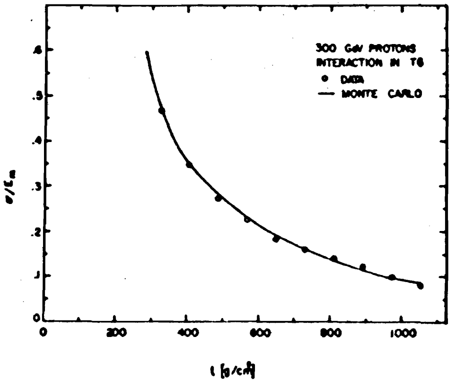

Fig. 6