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The CALOR93 Code System

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ABSTRACT

A brief history and description of the CALOR93 code system which is used for detector (calorimeter) design and analysis, in particular and radiation transport in general, is presented.

I. INTRODUCTION

The purpose of this paper is to describe a program package, CALOR93, that has been developed to design and analyze different detector systems, in particular, calorimeters which are used in high energy physics experiments to determine the energy of particles. Calorimeters are an important tool in high-energy experimental physics. One's ability to design a calorimeter to perform a certain task can have a strong influence upon the validity of experimental results. The validity of the results obtained with CALOR93 has been verified many times by comparison with experimental data. The codes (HETC93, SPECT93, LIGHT, EGS4, MORSE, and MICAP) are quite generalized and detailed enough so that any experimental calorimeter setup can be studied. Due to this generalization, some software development is necessary because of the wide diversity of calorimeter designs.

The CALOR code system for analyzing detectors for high energy physics research was first distributed in the early 70s.[1] At that time, the code system consisted of HETC,[2] ELPHO, and SPECT, and was considered to be a benchmark for particle cascade calculations. HETC is the high energy transport code for protons, neutrons ($E \geq 20$ MeV), charged pions and muons. This code was originally designed for accelerator shielding studies, but it soon become apparent that the code which is mostly analog in its makeup could be used in detector studies; i.e., calorimeter design. ELPHO is an old obsolete electromagnetic transport code which can operate as a stand-alone code or can track the gamma rays and $e^{\pm}$ generated in HETC ($\pi^{o} \rightarrow \gamma + \gamma$, $\mu^{\pm} \rightarrow e^{\pm} + \nu + \bar{\nu}$, $A \rightarrow A' + \gamma$'s). SPECT is not a transport code but analyzes data generated by the HETC code. Energy deposition data is calculated by this code, and in a user-written subroutine, is stored in appropriate data arrays. For scintillator or ionization systems, saturation and/or recombination effects can be included during the SPECT analysis using the LIGHT program.

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During the middle and latter 70s, with the introduction of high-Z materials into calorimeters, Pb, W, U, etc., low-energy neutrons and gamma rays become an important topic in hadronic shower development.[3] To better understand the importance of these low-energy particles, the MORSE[4] Monte Carlo code was added to the CALOR system to track low-energy neutrons generated during the transport of the high-energy particles in HETC. Many calorimeter studies[5] at this time were carried out with this code system; i.e., HETC, ELPHO, SPECT, and MORSE. Studies of many different calorimeters revealed discrepancies between calculated and experimental data and, in addition, inadequacies in code methods. Generally, each of these discrepancies could be traced to one or another of the codes.

The ELPHO code could not satisfactorily explain many physical phenomena, for example, the e/μ ratio, electromagnetic detector resolution, high-Z material shower suppression, etc., and therefore was discarded in favor of the EGS[6] system which included a much more complete description of the physics in electromagnetic showers and could satisfactorily explain the above quantities. The use of the EGS system started during the latter part of the 70s and early 80s. The CALOR code system – HETC, EGS, SPECT, and MORSE – continued in use until the present and now is continually undergoing additional updates and improvements.

Since MORSE is not an analog transport code, it could only be used to approximate energy deposition at each collision site. This deficiency and others have now been overcome by the creation of a new analog transport code MICAP[7] which can, if necessary, replace the MORSE code in any of the calculations.

It had already been confirmed by comparison with data that the old CALOR code system could not accurately reproduce detector resolutions and radial shower spreads at very high energies ($\gtrsim$ 30 GeV). This discrepancy was traced to the high-energy collision model that is used in HETC. This collision model, which scales data generated at 3 GeV to higher energies, underestimated at energies $\gtrsim$ 20-30 GeV the amount of energy going into the electromagnetic channel and progressively overestimated the hadronic component. The collision model was originally developed for shielding studies and, fortunately, this type of error would lead to a slight overestimation of the amount of shielding necessary; i.e., the error is on the conservative side. To correct this deficiency, a new high-energy collision model based on the work of Capella and Tran Thanh Van[8,9] was incorporated into the HETC code. With the completion of this task, CALOR93 has been a firm theoretical base ranging in energy from approximately 20 TeV to 10^{-3} eV and will be able to satisfy many problems associated with SSC detector design and radiation damage and protection studies.

In the mid 80s, a paper was presented detailing the underlying mechanisms of compensating calorimetry.[10] From previous presentations and publications,[11,12] it was recognized at that time that this new understanding would be met with much skepticism within the high-energy physics community. At that time, the following critical points were deduced following substantial analysis of various calorimeter systems utilizing the CALOR system:[13]

1. prior to later experimental confirmation, it was pointed out that current designs of uranium liquid argon calorimeters were not fully compensating;[10,11,12,14,15]

2. the importance of the hydrogen content in the active medium to couple the low energy neutrons to the output signal was stressed;[10,11,12,14,15]

3. the significant role of "electromagnetic sampling inefficiencies" (which are the result of preferential photon absorption[16] and electron multiple scattering in the high-Z inactive material [12,15]) in reducing the ratio of electron to hadron response was explained;[10,11,12,14,15]

4. the importance of the saturation of signal in the regions of high density energy deposition was emphasized;[10,11,12,14,15,] and

5. these new understandings led us to "predict that a lead calorimeter may also give EM/HAD ≈ 1",[17] where EM/HAD is the ratio of average electron-to-hadron response for the same incident kinetic energy, hereafter referred to as the e/h ratio. In other words, a compensating lead calorimeter was predicted.

As a result of these predictions, experimental programs (for example,[18] SLD and DO uranium liquid argon and uranium-scintillator tests) directed their efforts at proving or disproving the above conclusions. After much experimental testing and reviewing, as well as additional analytical efforts,[19,20] during the past several years, this skepticism has evolved into a general acceptance by the community of this new understanding of compensating calorimetry.[21]

This new enlightenment was a direct result of having in hand a code system, CALOR,[13] which contained as good a description of the current physics of calorimetry as possible. However, there is still substantial room for improvements in all calorimeter code systems. Current and future improvements in these code systems will provide additional returns through better designs of calorimeters, as well as a better understanding of the physics processes at SSC energies.

II. A BRIEF DESCRIPTION OF THE CODES IN THE CALOR SYSTEM

A flow diagram of the codes in CALOR is given in Fig. 1. The three-dimensional multimedia high-energy nucleon-meson transport code HETC93[22] is used, with modifications, to obtain a detailed description of the nucleon-meson cascade produced in absorbers.

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 an intermediate-energy intranuclear-cascade evaporation (MECC) model ($E < 3$ GeV), a scaling model ($3\ \mathrm{GeV} < E \lesssim 15$ GeV), and a multi-chain fragmentation model ($E \gtrsim 15$ GeV), and inelastic nucleon-hydrogen and charged-pion-hydrogen collisions via the isobar model ($E < 3$ GeV), and a fragmentation model ($E > 3$ GeV). Also accounted for are elastic neutron-nucleus ($E < 100$ MeV) collisions, and elastic nucleon and charged-pion collisions with hydrogen.

The intranuclear-cascade-evaporation model as implemented by Bertini is the low energy heart of the HETC code.[23] This model has been used for a variety of calculations and has been shown to agree quite well with many experimental results. The underlying assumption of this model is that particle-nucleus 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 collisions are governed by experimental and/or theoretical particle-particle total and differential cross-section data. The types of particle collisions included in the calculations are elastic, nonelastic, 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 sections to determine interaction locations) are determined from the experimental data of Hofstadter.[23] 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, excitation energy remains in the nucleus. This energy is treated by using an evaporation model which allows for the emission of protons, neutrons, d, ^{3}He, α and t. Fission, induced by high-energy particles, 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.

In recent years, a large amount of experimental and theoretical work has been done, and more reliable models are now available for the description of high energy (≥5-10 GeV) hadron-proton and hadron-nucleus collisions. In particular,

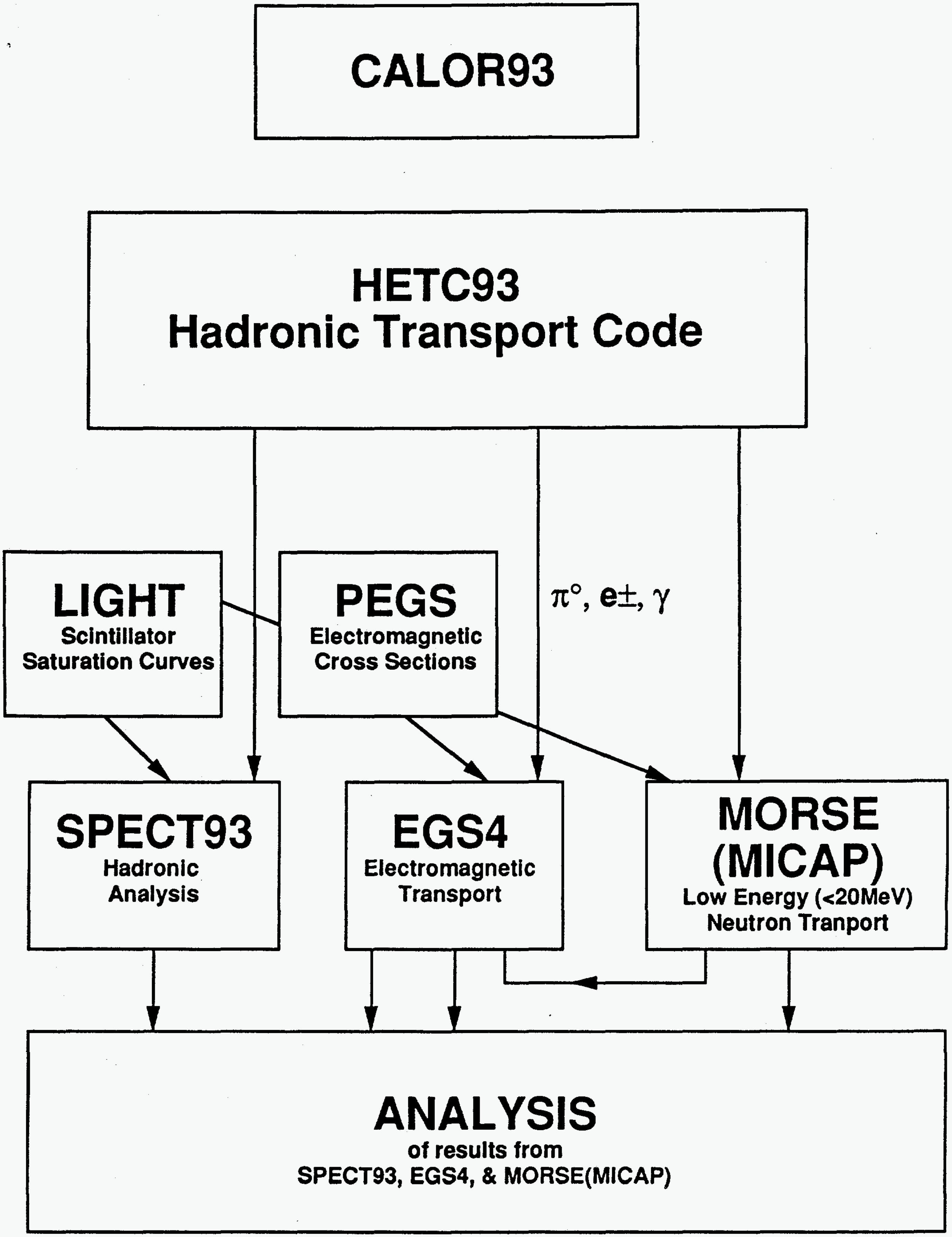

Fig. 1 Codes in CALOR

a multi-chain fragmentation model of hadron-nucleus collisions has been developed and implemented into a Monte Carlo code by J. Ranft et al.,[24] following the work of A. Capella and J. Tran Thanh Van. The version of the model that is used in the work reported here, with some modifications, is that provided by the transport code FLUKA87. The modifications that have been made are mostly those necessary to predict such things as residual nuclei and excitation energies.[25] This information is needed in HETC for evaporation calculations which yield the production of low-energy neutrons, protons, deuterons, alpha particles, etc.

At high energies, a complete intranuclear cascade does not develop when a nucleon is hit by a hadronic projectile inside the nucleus. The time-scale governing typical hadronic interactions is very long and therefore the most energetic secondaries are actually produced as the jet decays beyond the target nucleus and therefore have no chance of re-scattering.

Fragmentation of the jets in the jet C.M.S. is carried out with possible formation of 180 stable particles or resonances.[26] The resonances decay with either two-body isotropic decay or three-body decay. Experimental decay products and branching ratios are input[27] to the code so that all quantum numbers are conserved. In this way, exclusive events are generated, and correlation studies can be carried out. All particles produced in the fragmentation of the jets are assumed not to interact with the nucleus.

The source distribution for the electromagnetic cascade calculation is provided by HETC; it consists of direct photon production from hadron-nuclear collisions, photons from neutral pion decay, electrons and positrons from muon decay (although this is usually not of interest in calorimeter calculations because of the long muon lifetime), de-excitation gamma rays from nonelastic nuclear collisions and fission gamma rays. Since the discrete decay energies of the de-excitation gammas are not provided by HETC and only the total energy is known, individual gamma energies are obtained by uniformly sampling from the available energy until it is completely depleted. The transport of the electrons, positrons, and gammas from the above sources is carried out using the EGS system.[6]

Neutrons which are produced with energies below 20 MeV are transported using the MORSE[4] or MICAP[7] Monte Carlo transport codes. The neutron cross sections used by MORSE or MICAP are obtained from ENDFB/V. 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. The MICAP code was developed specifically for detector analysis. Both codes can treat fissioning systems in detail. This ability is very important since a majority of the fissions results from neutrons with energies less than 20 MeV. Time dependence is included in MORSE and MICAP, but since neither HETC nor EGS has a timing scheme incorporated, it is generally assumed that no time passes 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 or MICAP codes are 50 ns for scintillator and 100 ns for TMS or Argon.

The non linearity of the light pulse, L, in scintillator due to saturation effects is taken into account by the use of Birk's law[28] where the light emission per unit path length is given by

$$\frac{dL}{dx} \propto \frac{dE/dx}{1+k_B dE/dx},$$

and k_B is the saturation constant and dE/dx is the ionization and excitation energy loss per unit path length. For plastic scintillator k_B is generally between 0.01- and 0.02-g cm^{-2} MeV^{-1}. A similar law is assumed to apply to the charge collected in ionization detectors. This takes into account the loss of signal resulting from recombination effects in the ionization column.[29] For electrons at all energies, it is assumed that $k_B = 0$.

The Cerenkov response can be obtained from the following equations:

$$\frac{dI}{dx} = \frac{4\pi^2 e^2 Z^2}{hc^2} \Delta\nu \left(1 - \frac{1}{\beta^2 n^2}\right)$$

where

$\frac{dI}{dx}$ = the number of photons emitted per unit path length,
$\Delta\nu$ = the frequency interval of the photons,
Z = the charge of the particle,
β = the velocity of the particle relative to light velocity c,
n = the index of refraction of the medium in the frequency interval considered,
dE/dx = the ionization and excitation energy loss, and
e,h,c = the electronic charge, Plank's constant, and the speed of light, respectively.

The non uniformity of light collection can be taken into account by weighting the light pulse by spatially-dependent weight factors. These factors can be determined experimentally or calculationally using Monte Carlo techniques.

III. SUMMARY

CALOR93, like it predecessors will continue to produce detailed radiation transport information for calorimeter designers as well as for shielding designers and will continually be updated for future calculations.

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