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Calculated Hadronic Transmission Through Iron Absorbers

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Neutron Physics Division

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Through Iron Absorbers*

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CALCULATED HADRONIC TRANSMISSION
THROUGH IRON ABSORBERS

T. A. Gabriel
B. L. Bishop

Abstract

The transmission of hadrons through iron absorbers is investigated for a variety of experimental configurations, and incident particle types (protons, and charged pions) and energies (0.8 GeV/c to 100 GeV). The results obtained are consistent with available experimental data.

I. INTRODUCTION

In many high energy experimental devices such as muon range detectors, calorimeters, wire proportional counters, etc., it is necessary to know not only the average signal from any counter for a given incident particle type and energy but also the probability that a given counter or series of counters will produce a signal when constrained by some bias. Presented in this paper are a series of calculations for which the transmission of hadrons through iron absorbers are investigated for a variety of experimental situations, and incident particle types (protons and charged pions) and energies (0.8 GeV/c to 100 GeV). Whenever possible the calculated data are compared to experimental data. Improvements in the calculational procedures have been implemented for these results which include the use of a newly developed high energy intranuclear cascade model (HECC) to provide high energy (> 3 GeV) nonelastic nuclear collision data for neutrons, protons, and charged pions. The description of the calculation is described in Section II, and the results are presented and discussed in Section III.

II. DESCRIPTION OF THE CALCULATIONS

The calculational procedures used here are basically the same as those described in Ref. 1. Only those changes that have been implemented for these calculations are described in any detail. The three-dimensional, multi-media, high-energy nucleon-meson transport code HETC² has been used, with modifications, to obtain a detailed description of the nucleon-meson cascade produced in the devices considered in this paper. 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; nonelastic nucleon- and charged-pion-nucleus (excluding hydrogen) collisions through the use of the intermediate energy intranuclear cascade (MECC)³-evaporation model ($E \lesssim 3$ GeV); nonelastic nucleon- and charged-pion-hydrogen collisions via the isobar model³ ($E \lesssim 3$ GeV) and phenomenological fits to experimental data ($E \gtrsim 3$ GeV)⁴; elastic neutron-nucleus collisions ($E < 100$ MeV); and elastic nucleon- and charged-pion collisions with hydrogen. In past applications high energy ($\gtrsim 3$ GeV) non-elastic charged pion- and nucleon-nucleus-collision data have been obtained by the use of a scaling model⁵ that takes data generated at ~ 3 GeV by MECC and scales it to all higher energies. Since then the high energy intranuclear cascade code (HECC)⁶ has become available and can now be used to generate this nonelastic collision data. This model (HECC), in addition to containing the effects of a diffuse nuclear surface, the Fermi motion of the bound nucleons within the nucleus, the exclusion principle, and a local potential for nucleons as did MECC, also takes into account a localized reduction in the density of the nucleus during the development of the particle cascade and the sequencing of the events correctly with time. The high energy nucleon- and pion-nucleon production of pions within the nucleus is taken into account via the phenomenological fits to experimental data mentioned earlier.⁴ A complete incorporation of this model (HECC) into HETC will not be completed until a much later date. Until then, data generated by HECC for iron and carbon at energies of 5-, 10-, 20-, 40-, 80-, and 160-GeV for incident neutrons, protons, and charged pions have been placed in a data base for use by HETC. The scaling model is used to fill in all intermediate energies

above ~ 3 GeV. Results obtained by using the scaling model have been excellent for scaling of energies on the order of 2 to 5. As other elements are needed additional data bases can be created until HECC is fully included into HETC.

In previous calculations similar to the one presented here, neutrons are transported if their energy is above 10 MeV. For neutrons below 10 MeV it was assumed that they deposited their energy at their point of origin or their energy was prorated between different areas on a gram-thickness basis. To obtain a better smearing of this usually small amount of energy and to prevent isolated localized energy pulses, the cutoff energy in HETC for this paper was set at 2 MeV at which point the neutrons then deposited all of their energy.

The source distribution for the electromagnetic-cascade calculation, i.e., photons from neutral-pion decay, electrons and positrons from muon decay, and de-excitation gamma rays from nonelastic nuclear collisions, is provided by HETC. The transport of the de-excitation gamma rays has been added as a new feature for the same reasons as stated above for low energy neutrons. Since the discrete decay energies of the de-excitation gamma are not provided by HETC, but only the total energy, individual gamma energies were obtained by uniformly sampling from the available energy until the energy was completely accounted for. The transport of the electrons, positrons, and gammas from the above sources was carried out as described previously.¹

Saturation effects associated with plastic or liquid scintillators has as before been taken into account and unless specified differently the results presented include this effect.¹

Four different geometries have been considered in this paper. The first geometry is shown in Fig. 1. Not shown in this figure is a plastic scintillator (1.91 cm thick, and that is referred to as number 6), which completely covers the top of the device. Scintillators 1 and 6 will be used as "anti" counters. The second geometry is a solid iron block, semi-infinite in length and infinite in lateral extent. Boundaries within the block have been defined at 10 cm depth intervals, and at radii of 5-, 10-, 20-, ∞ cm. The third and fourth geometries are the same except for their lateral dimensions. Geometry III is given in Table I.

Table I

Description of Geometry III

Cross Sectional Area = $152.4 \times 152.4 \text{ cm}^2$

70 unit cells* each cell consisting of

Fe	10.16 cm in thickness
H ₂ O	0.635 cm
Plastic	0.635 cm
Mineral Oil	1.270 cm
Plastic	0.635 cm
H ₂ O	0.635 cm

*The Fe thickness for the first cell is only 8.16 cm in thickness.

For this device the pulse height signal is taken from the mineral oil.

The cross sectional area of geometry IV is $25.40 \times 35.56 \text{ cm}^2$.

ALL DIMENSIONS ARE IN cm

Fig. 1. Diagram of Geometry I. The plastic scintillators are numbered from 1 at the front to 5 at the back. Not shown is scintillator 6, which completely covers the top of the device.

Since oxygen has not been included in the data base, high energy particle collisions with oxygen in HETC were assumed to be the same as with carbon. Since oxygen represents a small fraction of the total material and of the number of high energy collisions, this is a good approximation.

III. RESULTS, COMPARISON WITH EXPERIMENT, AND DISCUSSION

Unless otherwise specified, the data presented here are for a zero width, zero angular spread beam incident on the front center of the device. No constraints have been placed upon the position when the primary particle first interacts, i.e., the primary interacts according to the expression $e^{-\Sigma(E)z}$ where Σ is the inverse mean free path as a function of particle energy E .

A. Geometry I

The probability that counters 2-5 will fire independently of all other counters when 0.8-, 1.0-, 1.5-, 2.0-, 2.5-, 3.0-, and 3.5-GeV/c $\pi^\pm$ are incident as a function of the energy pulse or equivalent particle (e.p.) level at which counters will fire are given in Figs. 2-5. As defined in this section, 1 e.p. = 4.0 MeV in effective energy deposition in the scintillator. The dashed lines are hand drawn and are to help guide the eye. As the energy bias is increased, there is a rather sharp transition at the one equivalent particle level, which is usually the minimum level at which "punch through" is defined. This is most pronounced for the lower momentum values and counter numbers, and is due to the "punch through" of the incident particle. Also for the lower momentum values there is an apparent difference between incident $\pi^\pm$. However, this difference decreases with increasing energy. The difference between $\pi^\pm$

Fig. 3. Probability that counter 3 will fire independently of all other counters as a function of the energy pulse level at which the counter will fire and of the type and energy of the incident particle.

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Fig. 4. Probability that counter 4 will fire independently of all other counters as a function of the energy pulse level at which the counter will fire and of the type and energy of the incident particle.

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Fig. 5. Probability that counter 5 will fire independently of all other counters as a function of the energy pulse level at which the counter will fire and of the type and energy of the incident particle.

for counter 4 at 2.0 GeV/c is attributed in part to statistical fluctuation and π^- capture.

Shown in Fig. 6 is the probability that the anti-counters 1 and 6 will fire when $\pi^\pm$ are incident at various momenta. Counter 1 gives a measure of the albedo while counter 6 gives an estimate of the leakage. Since counter 1 has a $2.54 \times 2.54 \text{ cm}^2$ hole in the center to allow entrance of the incident particle, this data does not include the energy deposited by the primary $\pi^\pm$. If in an experimental configuration counter 1 was used to accept only those incident particles that enter through the $2.54 \times 2.54 \text{ cm}^2$ hole, then it is possible if the bias level is set at 1 e.p. to reject $\sim 15\%$ of the "collimated" 2.5- or 3.5-GeV/c π^- because of the albedo.

The correlated probabilities that counter 2 will fire and counter 1 will not, and counters 2 and 3 will fire and counter 1 will not are given in Fig. 7. These are compared to the cases when counter 1 is ignored. As expected, except for the very low pulse levels, there are very little differences between the cases when the bias is turned on or left off.

The counting statistics in % for the data in Figs. 2-7 can be obtained approximately from the following expression:

$$\pm 2.24\%/\sqrt{\text{probability}}.$$

B. Geometry II

In contrast to the previous results presented in which the signal was taken from energy deposition in a plastic scintillator, the data presented in this section reflect a straightforward particle count, i.e., how many charged particles cross the boundary. Presented in Fig. 8 are the expected average number of charged particles crossing

Fig. 6. Probability that counters 1 and 6 will fire independently of all other counters as a function of the energy pulse level at which the counter will fire and of the type and energy of the incident particle.

Fig. 7. Correlated probabilities that various counters will or will not fire as a function of the energy pulse level at which the counters will fire and of the type and energy of the incident particle.

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Fig. 8. Average number of charged particles crossing various boundaries in Fe when 3-, 6-, 10-, and 15-GeV π^- and 2.21 GeV p are incident.

various boundaries in Fe when 3-, 6-, 10-, and 15-GeV π^- and 2.21-GeV p are incident. For the cases involving incident pions the average peak value of the number of charged particles is approximately the same as the incident particle energy, i.e., for 15-GeV incident π^- the average peak value should be ~ 15 particles.

The probabilities that x or more charged particles will cross various boundaries in Fe are given in Figs. 9-13 for the particle types and energies shown in Fig. 8. By comparing (see Fig. 10, Δ 's) the data for the 3-GeV π^- case in Sec. B with the 3-GeV/c π^- case in Sec. A, the relative merit of using energy deposition to define number of particles can be ascertained. Except for the 4 or more particle data they agree quite well. The differences between these data are due to several factors including the angular distribution of charged particles, neutrals, and large energy depositions by medium low-energy charged particles. Also shown in Fig. 10 are some experimental data points⁷ for 4.0 GeV/c incident π^- and p.

So far, these data have been integrated over all radial intervals. The effect of smaller radial intervals is shown in Fig. 14 for 10-GeV π^- incident. These data still include the secondary effect (largest at the larger depths) that charged particles born at larger radii can return to smaller radial positions thereby increasing the interradsial values slightly.

The particle pulse height distribution at a depth of 40 cm in Fe for 15-GeV π^- incident is shown in Fig. 15. Large values for the number of charged particles can be obtained.

Fig. 9. Probability that x or more charged particles will cross various boundaries in Fe when 2.21-GeV protons are incident.

Fig. 10. Probability that x or more charged particles will cross various boundaries in Fe when 3.0 GeV π^- are incident.

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Fig. 11. Probability that x or more charged particles will cross various boundaries in Fe when 6.0 GeV π^- are incident.

Fig. 12. Probability that x or more charged particles will cross various boundaries in Fe when 10.0 GeV π^- are incident.

Fig. 13. Probability that x or more charged particles will cross various boundaries in Fe when 15.0 GeV π^- are incident.

Fig. 14. Effect of smaller radial intervals on the average number of charged particles and on the probability that 1 or more charged particles will cross various boundaries in Fe when 10. GeV π^- are incident.

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Fig. 15. Particle pulse height distribution at a depth of 40 cm in Fe for 15-GeV π^- incident.

The average number of charged particles as a function of depth in Fe and as a function of the angle of emergence at a boundary relative to the beam direction for 3- and 10-GeV π^- incident is shown in Fig. 16. As can be implied from Fig. 16 and can be seen in Fig. 17, the angular distribution of the charged particles is rather strongly forwardly peaked.

C. Geometries III and IV

The average energy deposition both with (nonlinear) and without (linear) saturation effects in the mineral oil for 5-, 10-, 20-, 50-, and 100-GeV π^- incident on both geometries are presented in Figs. 18-22. The effect of saturation is quite evident. Also shown are the equivalent particle levels for the nonlinear data (1 e.p. = 2.42 MeV, nonlinear; 1 e.p. = 2.49 MeV, linear). The nonlinear pulse height distributions for 5- and 10-GeV π^- incident are shown in Fig. 23.

Given in Table II are the integral linear and nonlinear energy deposition and equivalent number of singly ionizing particles. As can be seen in the table under the column labeled "(L/N)", as the energy increases the cascade becomes more electromagnetic and the saturation effect decreases. Also, the leakage associated with geometry IV becomes smaller. This decrease is due to two factors. First, the cascade becomes more strongly forward peaked thereby decreasing the lateral leakage; secondly, the cascade becomes more electromagnetic and needs less material to contain it. For comparison, experimental data are provided also in the table.

Fig. 16. The average number of charged particles as a function of depth in Fe and as a function of the angle of emergence at a boundary relative to the beam direction for 3- and 10-GeV π^- incident.

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Fig. 17. Angular distribution of charged particles at 10-, 40-, and 70-cm depths in Fe for 3-GeV and 10-GeV π^- incident.

Table II

Hadronic (π^-) Shower Energy Deposition in Two Calorimeters
Expressed in Terms of Integrated Linear and Nonlinear
Energy Deposition in the Mineral Oil Scintillators
and in Terms of Equivalent Number
of Singly Ionized Particles

<u>Geometry III^b</u>						
Kinetic Energy (GeV)	Linear Energy Deposition (MeV)(L) and Equivalent Par- ticles (L/ ΔE^a)			Nonlinear Energy Deposition (MeV) (N) and Equivalent Particles (N/ ΔE^a)		
	L/N	L	L/ ΔE	N	N/ ΔE	
5	1.32	86.9	34.9	65.8	27.2	
10	1.27	178.	71.5	140.	57.9	
20	1.23	355.	143.	288.	119.	
50	1.19	874.	351.	734.	303.	
100	1.17	1769.	710.	1513.	625.	
<u>Geometry IV^b</u>						
5	1.20	61.8	24.8 (29%) ^c	51.4	21.2 (22%) ^c	18.2 $\pm$ 4 ^d
10	1.19	134.	53.8 (25%) ^c	113.	46.7 (19%) ^c	52.7 $\pm$ 5 ^d
20	1.15	284.	114. (21%) ^c	247.	102. (15%) ^c	106. $\pm$ 5 ^d
50	1.12	704.	283. (19%) ^c	628.	260. (14%) ^c	269. $\pm$ 5 ^d
100	1.11	1466.	589. (17%) ^c	1324.	547. (12%) ^c	538. $\pm$ 5 ^d

^a ΔE = 2.42 MeV for nonlinear
= 2.49 MeV for linear.

^bThe signal is taken from the mineral oil. Geometry IV: same as
Geometry III except cross sectional area - 25.4 x 35.56 cm².

^c% decrease relative to Geometry III.

^dExperimental values, Ref. 8 with restricted initial primary interaction
site.

Given in Figs. 24-28 are the probabilities that a given counter will fire as a function of the signal required to fire the counter. Again, the data presented here for the 5-GeV π^- Geometry III case are consistent with the data in Sec. B when compared to the 6-GeV π^- case there.

Fig. 18. Average energy deposition with (nonlinear) and without (linear) saturation effects in the mineral oil for 5-GeV π^- incident.

Fig. 19. Average energy deposition with (nonlinear) and without (linear) saturation effects in the mineral oil for 10-GeV π^- incident.

Fig. 20. Average energy deposition with (nonlinear) and without (linear) saturation effects in the mineral oil for 20-GeV π^- incident.

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Fig. 21. Average energy deposition with (nonlinear) and without (linear) saturation effects in the mineral oil for 50-GeV π^- incident.

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Fig. 22. Average energy deposition with (nonlinear) and without (linear) saturation effects in the mineral oil for 100-GeV π^- incident.

Fig. 23. Pulse height distributions for 5- and 10-GeV π^- incident.

Fig. 24. Probabilities that a given counter will fire as a function of the signal required to fire the counter when 5-GeV π^- are incident.

Fig. 25. Probabilities that a given counter will fire as a function of the signal required to fire the counter when 10-GeV π^- are incident.

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Fig. 26. Probabilities that a given counter will fire as a function of the signal required to fire the counter when 20-GeV π^- are incident.

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Fig. 27. Probabilities that a given counter will fire as a function of the signal required to fire the counter when 50-GeV π^- are incident.

Fig. 28. Probabilities that a given counter will fire as a function of the signal required to fire the counter when 100-GeV π^- are incident.

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