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COMPARISON OF SOME RECENT DATA ON p-NUCLEUS INTERACTIONS WITH THE HAGEDORN-RANFT MODEL PREDICTIONS

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I. Introduction

Problems of radiation shielding and the like, i.e., wherever internuclear cascades are important, have for the past year or so been analyzed using the Hagedorn-Ranft (HR) model[1] for particle production[2]. The HR model was chosen after careful consideration. It is presently the only one furnishing extensive predictions on particle yields from p-nucleus collisions and which furthermore could be adapted (albeit in crude fashion) to incident particles other than protons. Because of the important role the particle production model plays in such calculations it is necessary to compare the HR model predictions with experimental data. Recently some results have been reported from emulsion studies and counter experiments. While this sample is too limited to yield definitive conclusions, it is still worthwhile to make these comparisons.

It should be briefly recalled that the HR model explicitly pertains to proton-proton collisions and contains a number of parameters determined by data fitting. Some time later Ranft[3] readjusted these parameters to fit the 19.2 GeV/c p-nucleus data of Allaby et al[4]. It follows from this procedure that particle spectra so generated will retain many features of p-p particle spectra (e.g., symmetry in a p-p center of mass) no longer obeyed in p-nucleus collisions. Likewise specific nuclear effects (e.g., coherent particle production) will not be well represented in the spectra.

A few additions and modifications were made to the HR model before applying it to shielding-type problems. These are briefly listed below and appear in more detail elsewhere[2].

(1) Additional low energy nucleons are added to the HR spectra. Their differential yields were taken from the parametrization of Ranft and Routti[5] of the intranuclear cascade calculations of Bertini[6]. These nucleons have kinetic energies up to a few hundred MeV.

(2) Each inelastic particle-nucleus collision creates a certain amount of nuclear excitation. The dominant excitation mechanism is via emission of low energy ($\lesssim$ 30 MeV) nucleons and nuclear fragments.

(3) Neutrons (not explicitly treated by HR) have the same relative spectra as protons. The total number of nucleons emerging from the collision (belonging to the HR component) is normalized to two. The total number of protons is (1+Z/A).

(4) The pion spectra are normalized so as to conserve energy in the collision (assuming the π^o production cross-sections are equal to the average of those of π^+ and π^-). The normalization constants so determined are fairly close to unity except at low incident energies.

(5) Particles other than nucleons and pions are presently not included. However, by enforcing energy conservation in the above manner the effects of such particles (e.g., in terms of radiation hazards) are not completely neglected.

The results presented here are obtained using the parameters as they appear in the "Atlas" of Grote, Hagedorn and Ranft[1]. The extra normalization discussed above (depending upon target, incident momentum and particle type) is stated explicitly for each case treated here (see figure captions). This might be of interest when using the HR model to estimate target yields.

Results obtained with hydrogen targets are not included. While they are no doubt of more fundamental importance they are of lesser interest from the applied point of view adopted here.

II. Comparison with Emulsion Studies

Results of a number of emulsion experiments performed at 200 GeV have been reported[7]. These include: average number of "shower tracks", $\langle n_s \rangle$, and the average number of "heavy tracks" $\langle N_h \rangle$, per inelastic event as well as the angular distribution of shower tracks. (Roughly, a proton leaves a shower track in the emulsion above 400 MeV kinetic energy and a charged pion above 50 MeV. Below these values they leave heavy tracks.)

The emulsion data ($\langle A \rangle \simeq 70$) are compared with predictions of HR for Cu ($A \simeq 64$). The latter are rather insensitive to nuclear mass. It is further assumed that all charged pions and protons contribute to n_s. The comparison of $\langle n_s \rangle$ versus incident momentum is shown in Fig.1. It appears that the HR model underestimates the number of shower tracks produced, more so the higher the incident momentum.

For the average number of heavy tracks the model used in shielding calculations[2] predicts $\langle N_h \rangle \simeq 10$ while experimentally $\langle N_h \rangle \simeq 7.5$ is observed. Both values remain essentially constant above ~ 5 GeV/c incident momentum.

The comparison of the angular distribution (in the forward direction) of shower particles is presented in Fig.2 in the form of a $dN/d\theta$ vs θ plot. It can be seen that the disagreement is at worst a factor of two, except possibly at very small angles. It should be pointed out that for angles

$\lesssim$ 10 mrad the emulsion data suffer somewhat from low event rates and poor experimental resolution. There may also be systematic errors present in this angular region[8].

At high energies the model underestimates the multiplicity of shower tracks rather seriously. The angular distributions, outside the dubious small-angle region, are quite well matched in shape and it appears that the model underestimates the angular distribution of shower tracks about uniformly.

The implications of these results for shielding calculations are rather difficult to assess. The aim of the latter is to predict particle fluxes and momentum spectra of particles emerging from thick targets. These particles are usually many generations removed from the incident ones. Looking at Fig.1, the HR model together with forced energy conservation will predict fewer energetic particles in the first generation, but since these are more energetic each will produce more particles in the next generation. The key to how well the model will perform in this respect, particularly at high energy, lies in the angular distribution of the energy carried off by cascade propagating particles. Presently, little is known about this.

As Fig.1 shows, the average number of shower tracks predicted is closer to measured value at lower incident momenta. The same appears to hold for their angular distribution. Fig.3 shows the angular distribution for 60 GeV/c π^- on emulsion[9]. Ignoring again the small angle region, the fit is definitely better than for 200 GeV/c protons Presumably around 20 GeV/c, where the model was matched to experiment, the fit can be expected to be better yet.

III. Comparison with data of Baker et al.

Baker et al[10] measured particle yields at 3.6 mr from a beryllium target (1/8" x 1/8" and 12" long) both for 200 GeV/c and 300 GeV/c incident protons. Of the various particles measured p, π^+ and π^- are of interest here. Since a target of this length (about one interaction length) is quite commonly used, it is worthwhile to calculate specifically the effect of finite target length. This was performed using the program CASIM[2] and keeping a separate tally of secondaries and of all higher generations. (The yield of secondaries only could equally well be calculated from the differential yield per nucleus with straightforward corrections for absorption). Figures 4 and 5 show the comparisons. The data points carry errors in excess of 30%, mainly overall normalization. Because the calculations essentially lump all particles other than nucleons into the pion spectra the sums of π's and K's of like charge are also shown. Apart from measurements very near the incident momentum (say above ~ 170 GeV/c at 200 GeV/c), the largest deviation occurs for π^- of ~ 35 GeV/c where the calculation overestimates the yield by a factor of ~ 2.5. Generally the fits are quite good.

The sharp peak in the proton spectra near the incident momentum at 200 GeV/c (Fig. 4a) is likely associated with (quasi) elastic scattering and diffractive excitation off initially bound target nucleons. From the way the HR model for p-nucleus collisions is obtained it cannot be expected to fit this feature.

The calculation also underestimates the high momenta π^- yield (Fig. 4c). This is again not surprising in view of the rather cursory treatment of the kinematical cut-off in the HR model[11]. Effects of finite step size in the numerical integration also become apparent.

Neither of the discrepancies occuring at high momenta are likely to have significant effects on the outcome of shielding calculations. The comparisons as plotted in Figures 3 and 4 actually show the equivalent of the energy carried off by the particles as a function of momentum.

The discrepancy of π^- can be seen to occur where this quantity is down by more than two orders of magnitude from the broad peak at ~ 50 GeV/c. The effects of the protons in the high momentum peak are not much different from the incident protons themselves and their omission should not have any serious consequences.

IV. Comparison with data of Cronin et al.

Cronin et al[12] measured particle yields at 77 mr from targets of beryllium (3.14" long x 1/4" diam.) and titanium (2.23" x 1/4") for 300 GeV/c incident protons, and from tungsten (0.85" x 1/4") at 200, 300 and 400 GeV/c. (The angle of 77 mr corresponds roughly to $\pi/2$ radians in a nucleon-nucleon center of mass frame at these energies.) The comparisons with the HR model are shown in Figs. 5 through 9 for the particle yields of interest here (p, π^+, π^-). The ordinates have been chosen to be $p \frac{dN}{d\Omega dp}$ since this is more convenient for the present purpose. The data points carry an overall scale uncertainty of 50% in addition to statistical and other known systematic errors. The measurements actually extend to higher values than are reproduced here (70 GeV/c for Be and Ti, 120 GeV/c for W).

It is obvious that the calculation underestimates the experimental values at high momenta by a wide margin. Thick target effects appear also appreciable although it is difficult to state this with certainty since the HR model diviates so much at the high momenta it cannot be relied on to estimate this effect. (Cronin et al. used also a 2.0" x 1/8" tungsten target. For this longer and thinner target the spectrometer accepts a large faction of the particles from the side of the target, which reduces thick target effects. Because of variations in beam conditions etc. no reliable differences between targets could be observed). The consequences for shielding calculations from these comparisons must be found at the rather low momenta and here the comparisons are more satisfactory. Typically, below about 20 GeV/c, the calculation overestimates proton yields and underestimates π^- yields while π^+ yields are reproduced fairly accurately. The plots show that truly large deviations begin to occur only at levels involving on the order of 1% of the energy carried off by the different particles. This is unlikely to cause great difficulties for shielding calculations.

In view of the large scale uncertainty and the lack of data points below 10 GeV/c it is difficult to state whether this comparison corroborates the result of the comparisons with emulsion work viz., that of an underestimate (by a factor of ~ 2 at 77 mr) of the total number of shower particles.

Acknowledgment

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Figure Captions

Fig.1 Average multiplicity of shower particles versus incident proton momentum.

—— emulsion studies

--- Hagedorn - Ranft (as used in shielding programs)

The extra normalization constants (see text) which multiply the HR predictions range from N_p=1.56, N_π=1.28 at 10 GeV/c to N_p=0.94, N_π=1.06 at 300 GeV/c.

Fig.2 Angular distribution of shower particles produced by 200 GeV/c protons in emulsion.

O Hébert et al. (Ref 7)

— Hagedorn - Ranft (N_p=0.98, N_π=1.12)

Fig.3 Angular distribution of shower particles produced by 60 GeV/c π^- in emulsion.

⊙ Gierula et al. (Ref 9)

— Hagedorn - Ranft (N_p=1.06, N_π=1.27)

Fig.4 Particle yields at 3.6 mr for 200 GeV/c protons incident on a beryllium target (a) protons (b) π^+ (c) π^-.

O data of Baker et al. (Ref 10)

● data of Baker et al. with $K^+(K^-)$ added to $\pi^+(\pi^-)$

--- secondaries only, Hagedorn - Ranft

—— total yield of thick target (N_p=0.84, N_π=1.01)

Fig.5 Same as Fig.3, for 300 GeV/c incident protons (N_p=0.81, N_π=0.96).

Fig.6 Particle yields at 77 mr for 300 GeV/c protons incident on a beryllium target (a) protons (b) π^+ (c) π^-.

O data of Cronin et al. (Ref.12)

● data of Cronin et al. with $K^+(K^-)$ added to $\pi^+(\pi^-)$.

--- secondaries only, Hagedorn - Ranft

—— total yield of thick target (N_p=0.81, N_π=0.96)

Fig.7 Same as Fig.6. 300 GeV/c p on Ti. (N_p=0.90, N_π=1.04).

Fig.8 Same as Fig.6. 200 GeV/c p on W. (N_p=1.06, N_π=1.22).

Fig.9 Same as Fig.6. 300 GeV/c p on W. (N_p=1.03, N_π=1.16).

Fig.10 Same as Fig.6. 400 GeV/c p on W. (N_p=1.02, N_π=1.12).

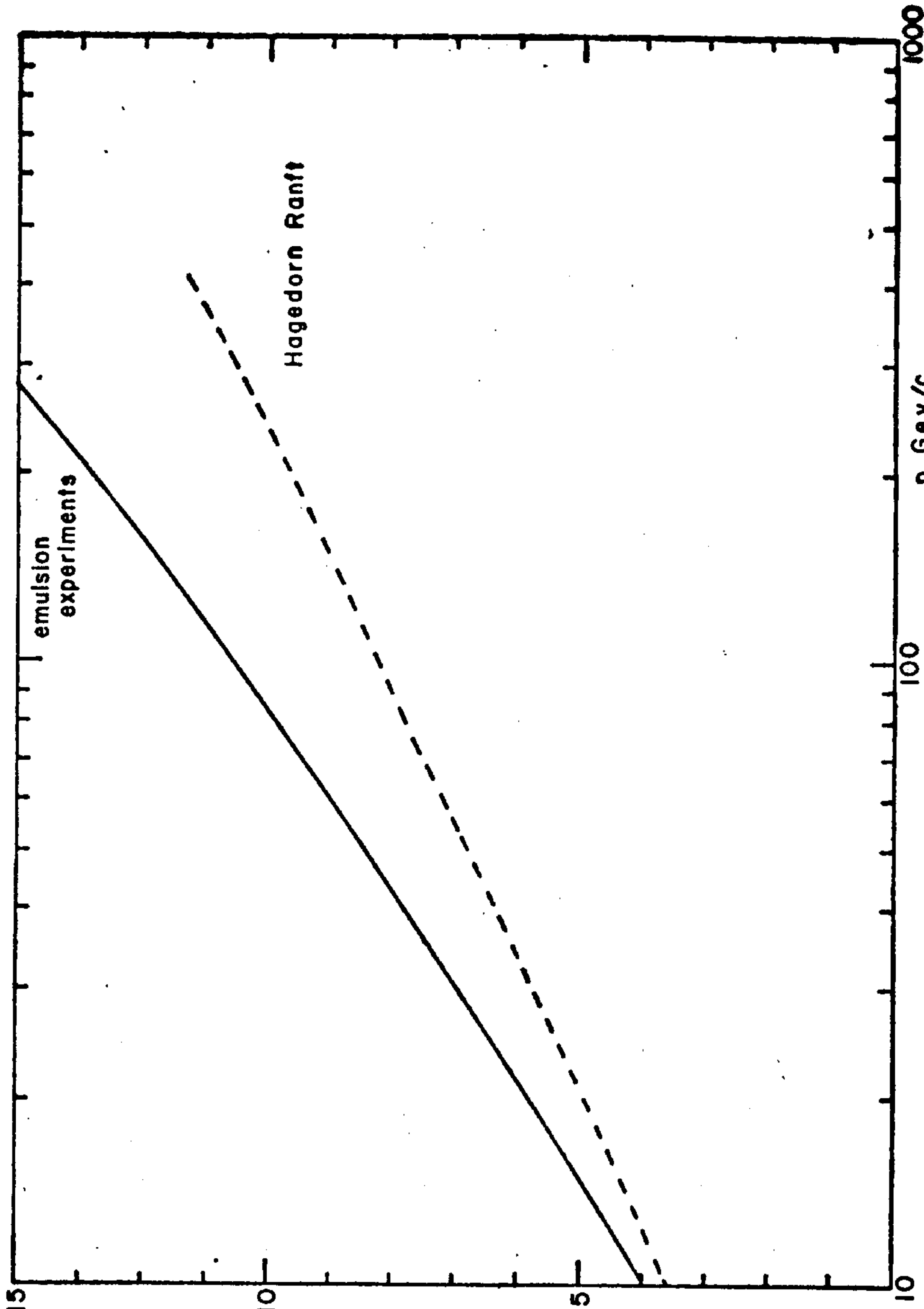
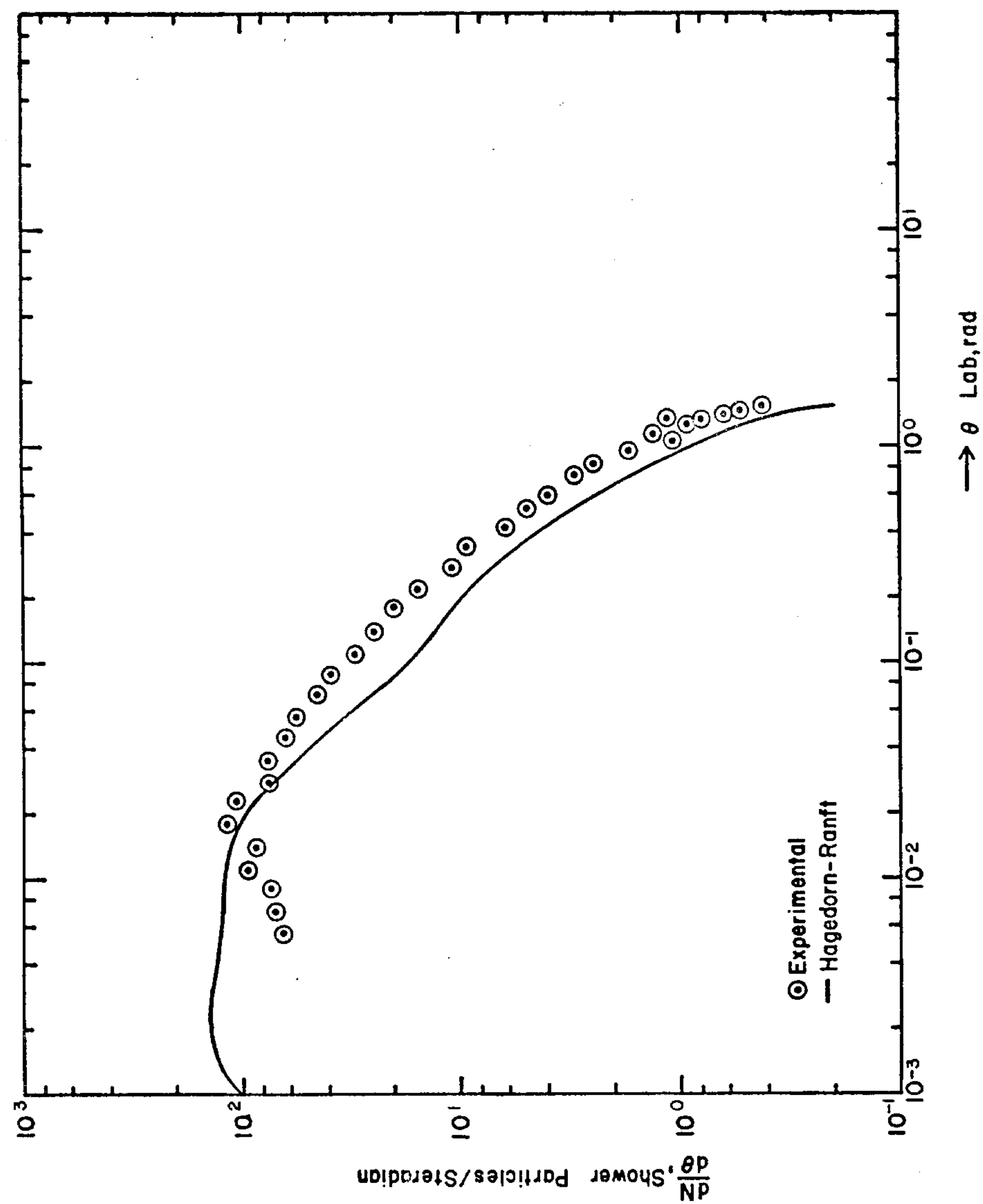

Average Multiplicity of Shower Particles
0
5
10
15
p, Gev/c
10
100
1000
emulsion experiments
Hagedorn Ranft

Fig. 1


dN/dθ, Shower Particles/Steradian
θ Lab, rad
Experimental
Hagedorn-Ranft
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10^2
10^1
10^0
10^-1
10^-3
10^-2
10^-1
10^0
10^1

Fig. 2

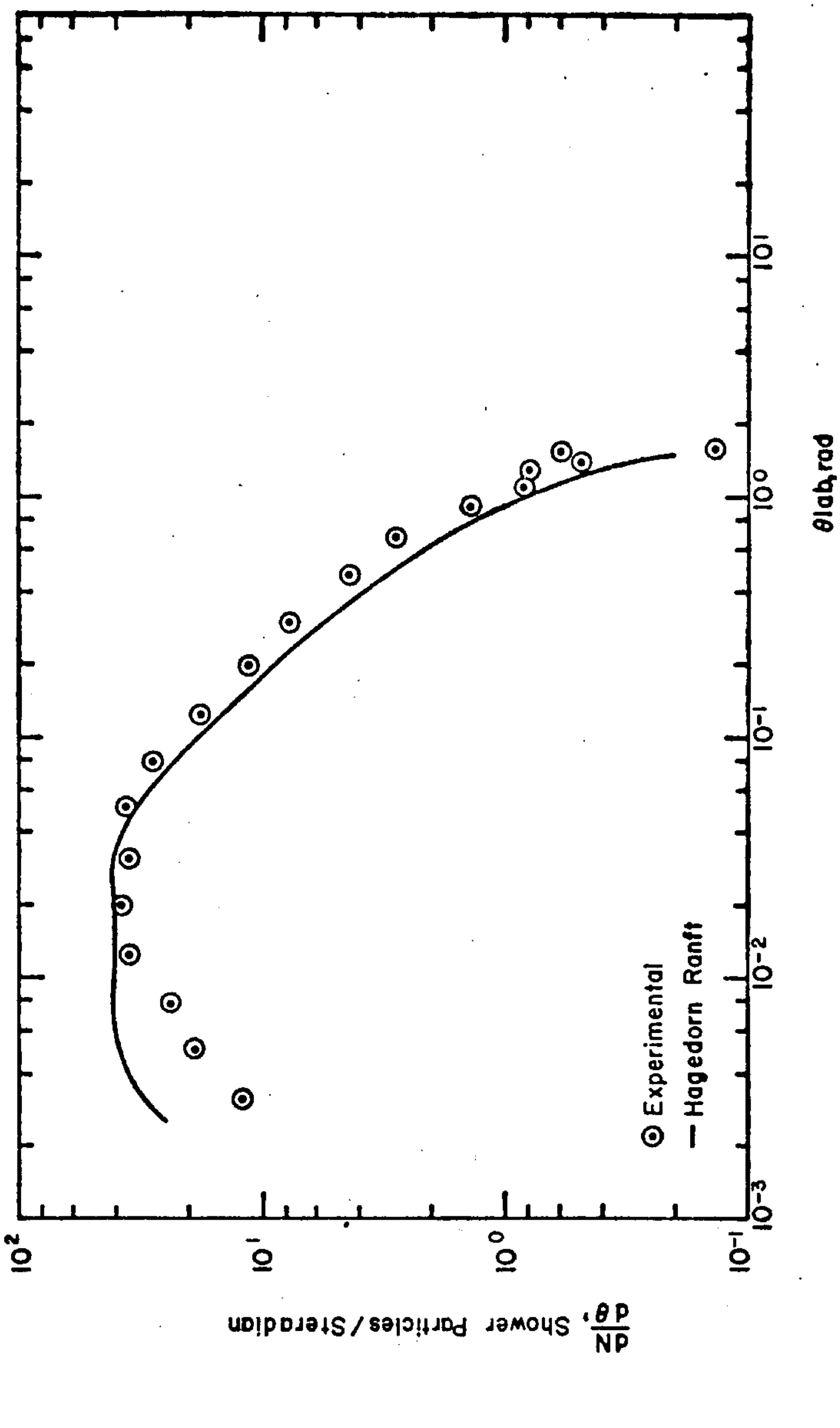
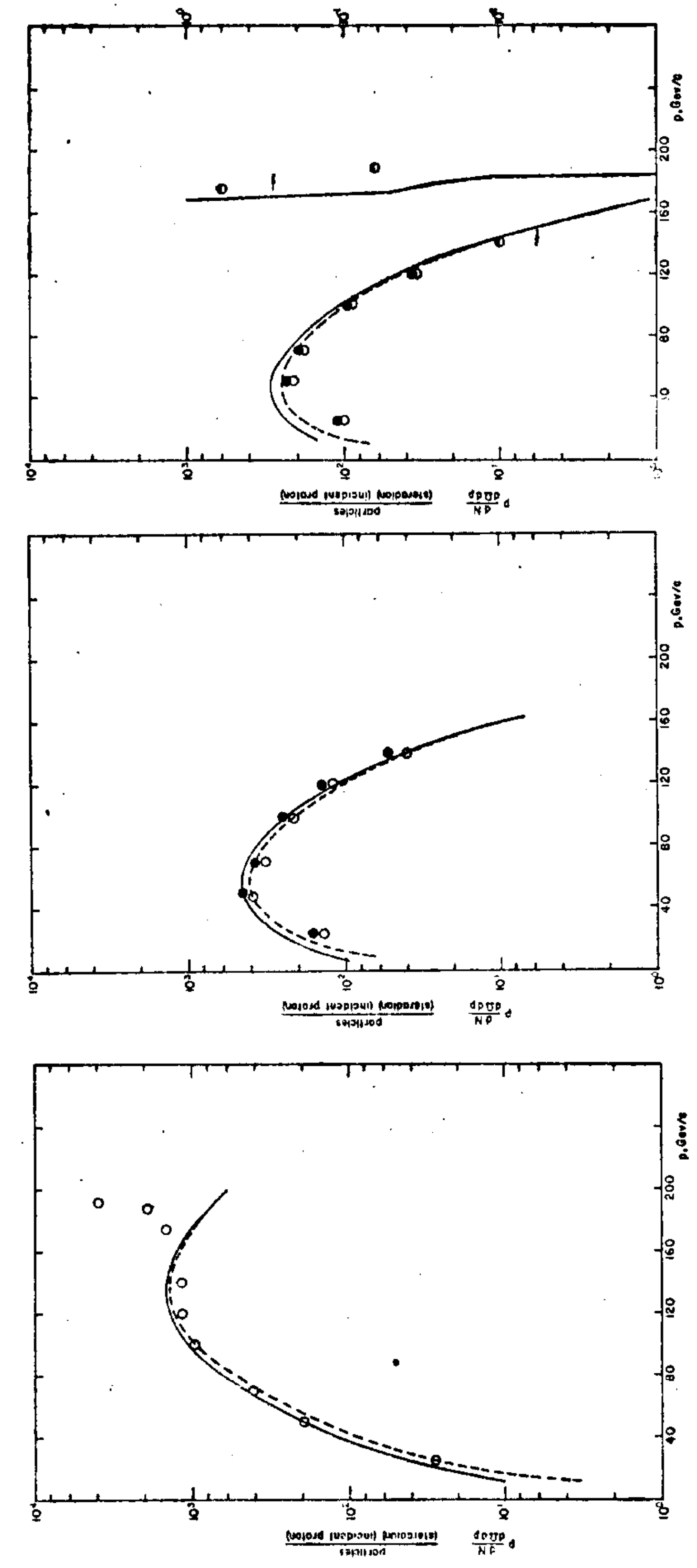

Experimental
Hagedorn Ranft
θlab, rad
dN/dθ, Shower Particles/Steradian
10^-3
10^-2
10^-1
10^0
10^1
10^2

Fig. 3


p, Gev/c
particles
(steradian) (incident proton)
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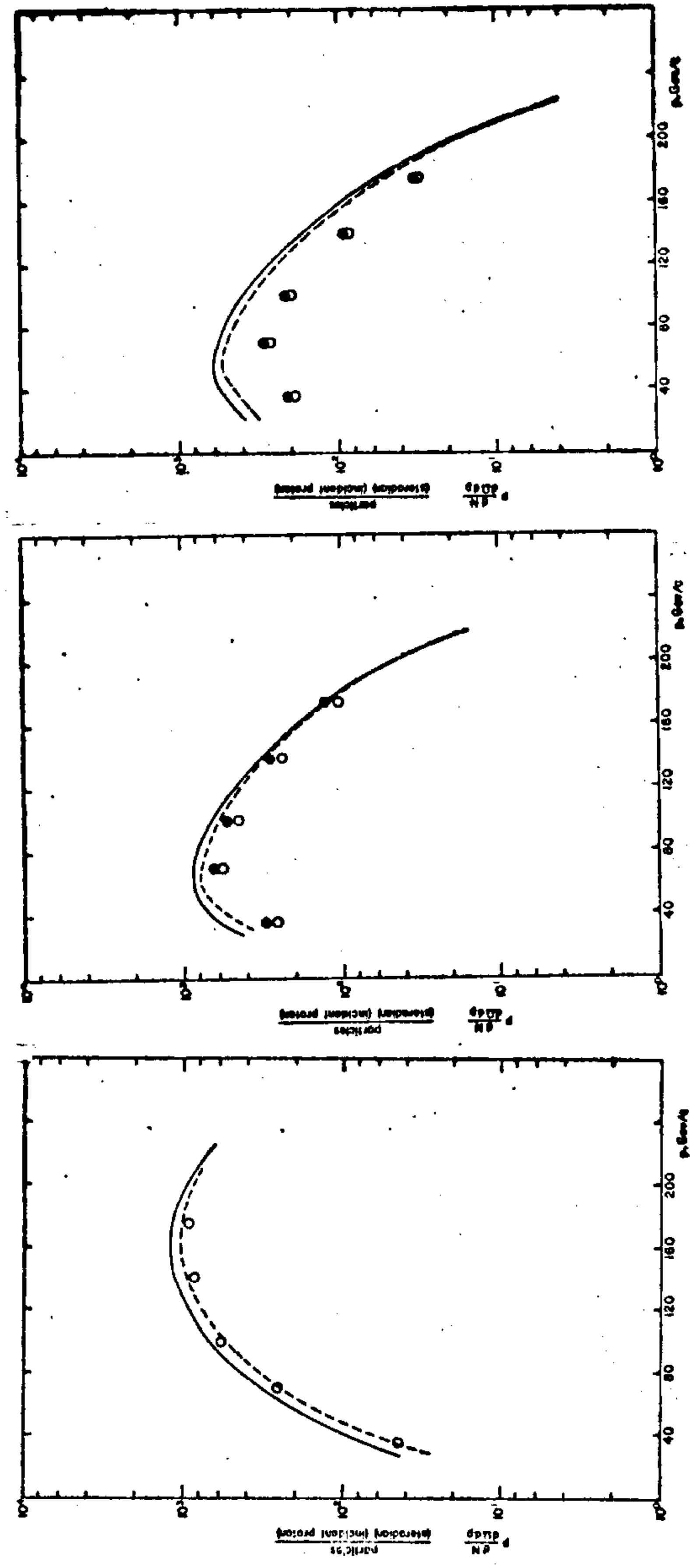
80
120
160
200

(c)

(b)

(a)

Fig. 4



(a) (b) (c)

Fig. 5

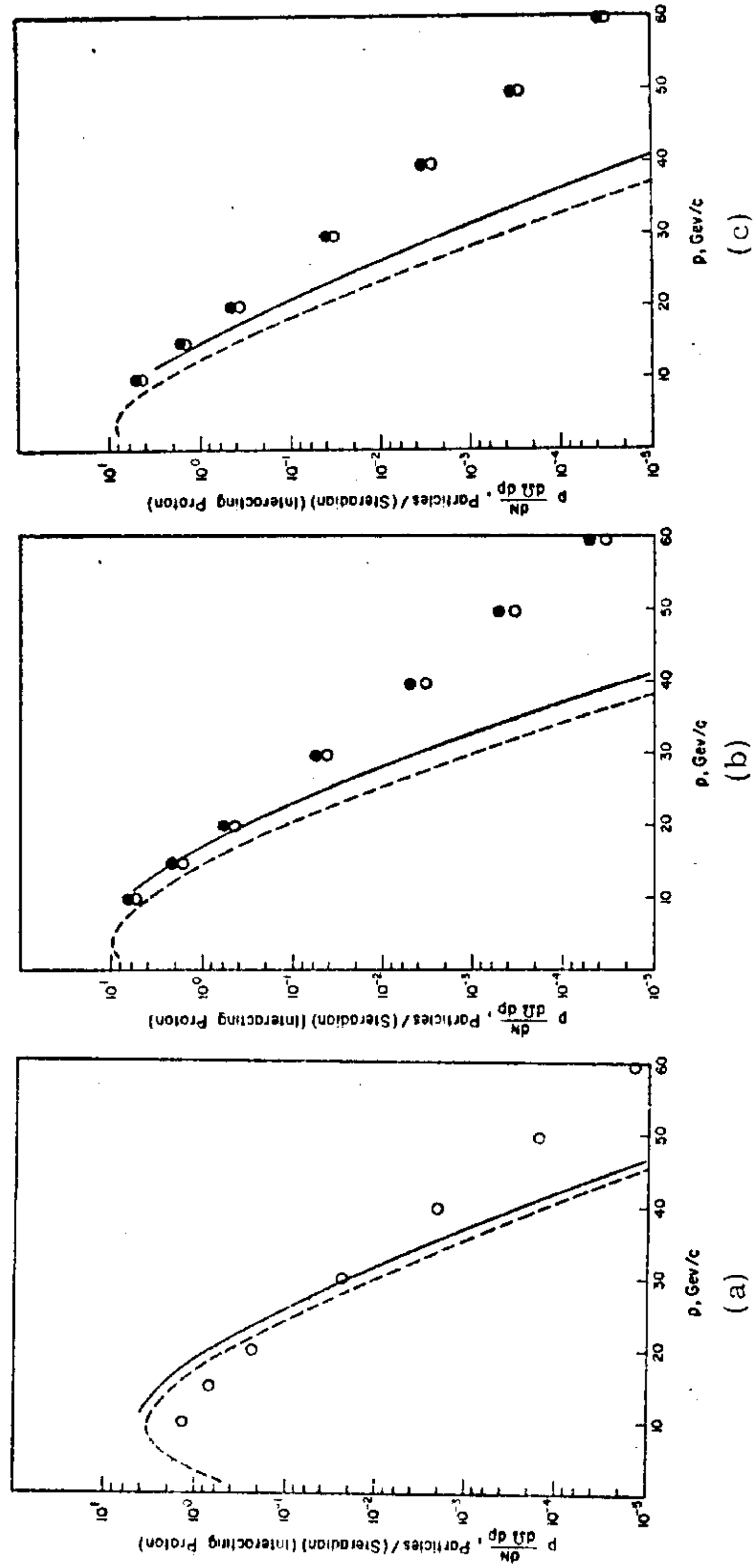

p dN/dΩ dp, Particles / (Steradian) (Interacting Proton)
p, Gev/c
(a)
(b)
(c)

Fig. 6

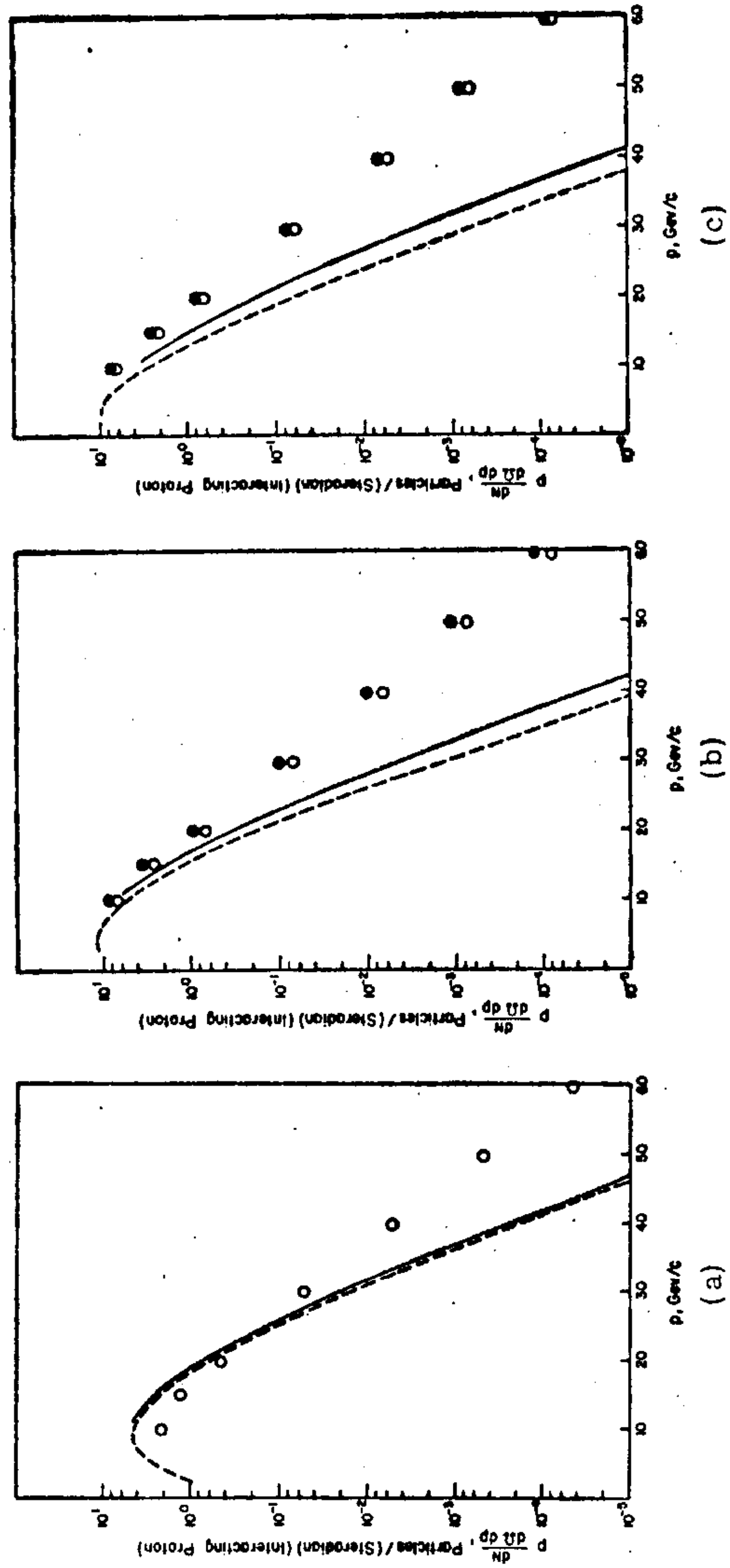

p, Gev/c
p $\frac{dN}{d\Omega\, dp}$, Particles / (Steradian) (Interacting Proton)
(a)
(b)
(c)

Fig. 7

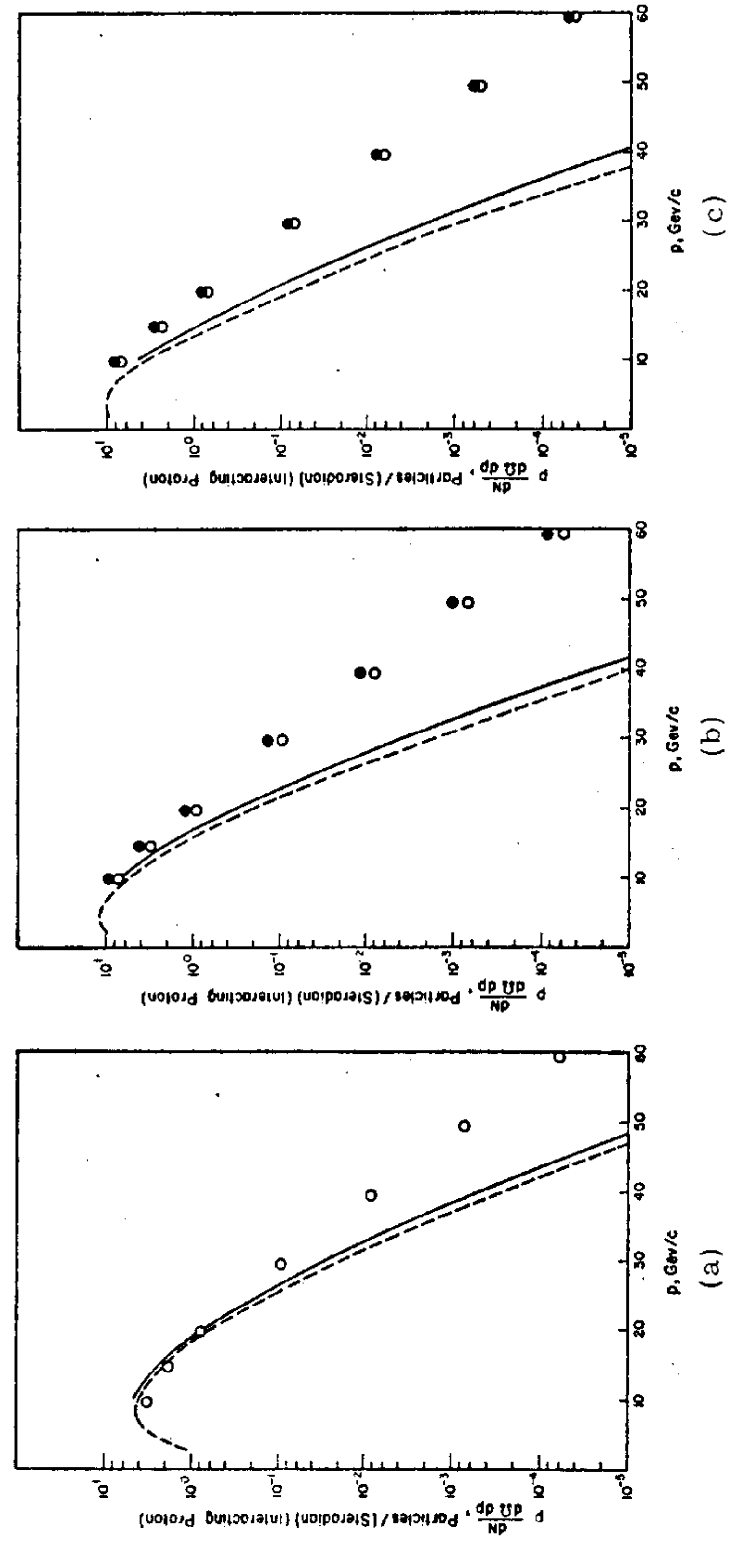


Fig. 8

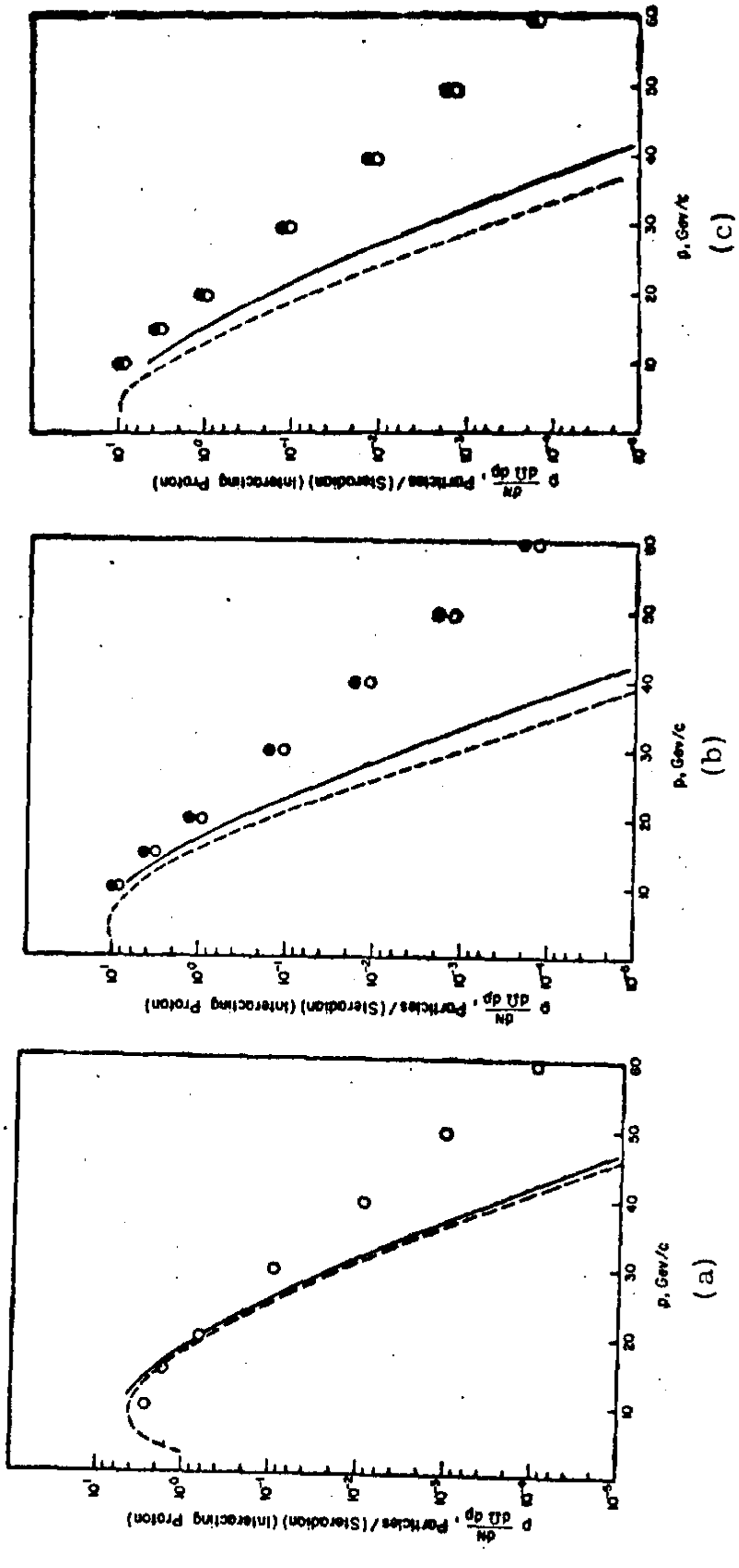


Fig. 9

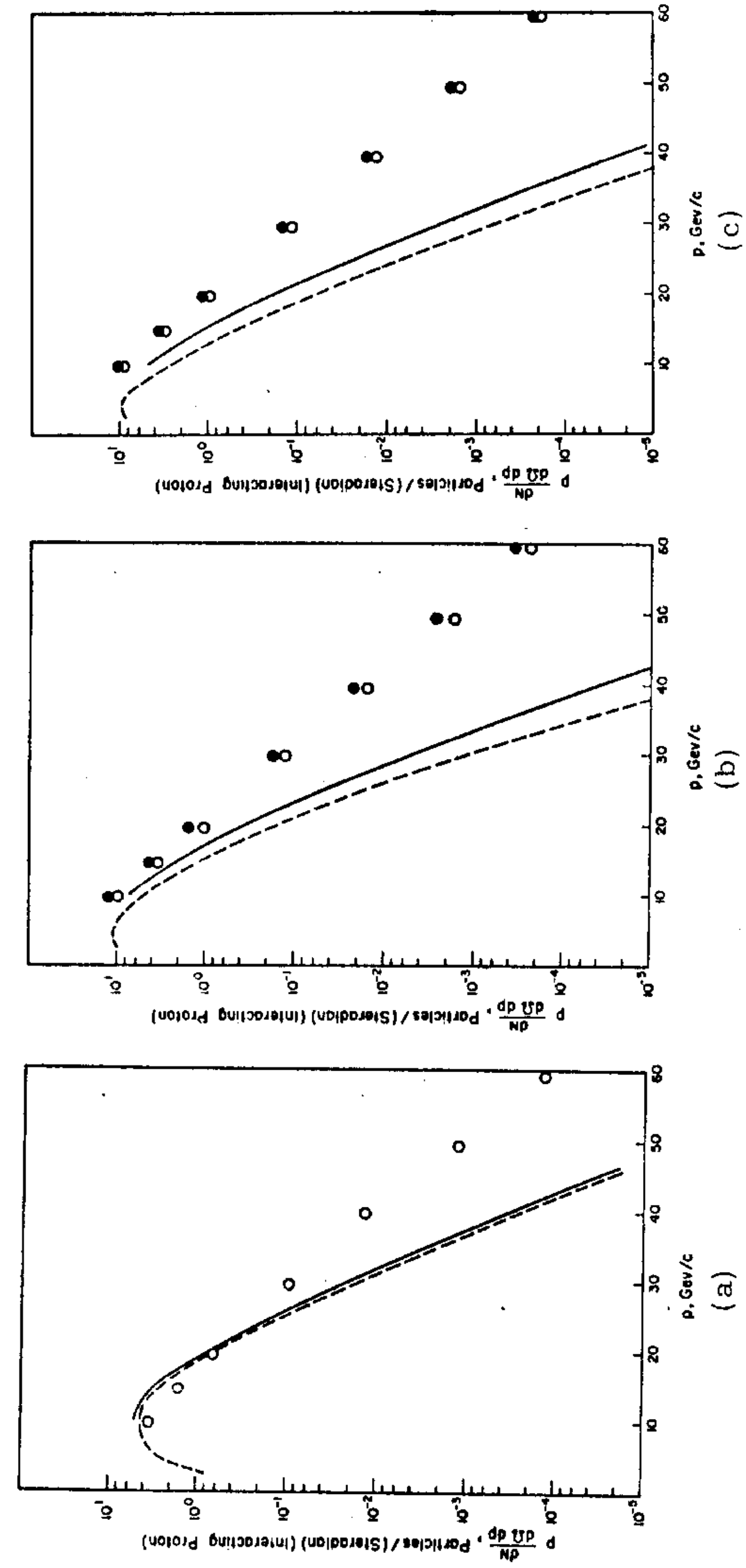

p, Gev/c
p dN/dΩ dp, Particles / (Steradian) (Interacting Proton)
(a)
(b)
(c)

Fig. 10