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SEARCH FOR FAST PARTICLES PRODUCED AT LARGE LAB ANGLES AT NAL

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A Proposal Submitted by

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ABSTRACT — An experiment is proposed to look for charged particles emitted at large lab angles that are normally forbidden kinematically. These particles if found would correspond to hitherto unobserved events such as "spectator" quarks emitted in direct quark interactions and production of particles with imaginary mass values ("tachyons"). The detection system will consist of wire-chambers, dE/dx and time-of-flight counters. The basic hardware is under construction and the final system will be ready for test runs at a lower-energy machine in six months. The detection telescope will view interactions of the primary proton beam from backward(in lab) directions and our first choice experimental site is the straight section B with a thin internal target. We would like to use the highest available beam at NAL and since our beam transport and intensity requirements are very minimal, we will be able to run parasitically during the tuning periods of the NAL machine in the next year. The machine time required for this experiment is about three months.

I. INTRODUCTION

In the general reaction $P_a + M_t = P_b + P_x$, where the subscripts a, t, b and x denote the incident, target, detected final state and "missing" final state particles, respectively; the missing mass squared is given by $M_x^2 \approx 2M_t E_a - 2E_a E_b + 2E_a E_b \cos\theta$ where θ is the lab production angle of particle b and $E_a \sim 200-500$ GeV and $E_b \approx |\vec{P}_b|$. It is readily seen that for $\theta \approx 180^\circ$ the missing mass becomes imaginary unless $M_t > 2E_b$ (or $M_t > E_b$ for $\theta \approx 90^\circ$) and any presence of backward particles with energy greater than a few GeV in lab would imply hitherto unknown reactions (assuming a hydrogen target). We consider several possible reactions which may produce backward particles in lab.

A. Quark Interactions

If quarks really existed it would be probable that some high energy ($E_a \sim 500$ GeV) interactions involve "quasi-free" quark targets and an appreciable number of "spectator" quarks may be emitted with low momentum and more or less isotropically in lab. Therefore, detection of less-than-minimum ionizing particles produced at backward angles would be a new and perhaps the best way of looking for quarks at NAL.

Numerous attempts have been made during the last decade¹ to find the quarks but only a few marginally positive evidences²⁻³ have been reported so far. It is interesting to note that the quark "candidates" in these evidences seem to have the following features:

- (1) The quarks were closely associated with large air showers,
- (2) The quark mass was of the order of 10 GeV and the sea-level momentum was small ($\gamma\beta \sim 1.0$)²,

- (3) The quarks were not parallel to the shower axis and they are consistent with having been produced locally (e.g., in the shielding, magnet, lower atmosphere, etc.),
- (4) The observed quark frequency is consistent with an effective quark production cross-section of the order of one mb, and
- (5) The quarks were strongly interacting with a cross-section of one mb or so.

It should be noted that these features of quark production (if true) would "explain" some of the negative results reported by various cosmic ray groups.^{1,4}

Quark searches done at proton machines⁵⁻⁷ were so far sensitive only to high momentum and forward (0° to 20°) quarks produced presumably in reactions such as $NN \rightarrow NN\bar{q}q$, $\pi N \rightarrow N\bar{q}q$, etc.⁸ The latest machine experiment⁵ places an upper limit of about 10^{-40} cm^2 on the quark production cross-section if $M_q \approx 4-5 \text{ GeV}$ and if quarks were produced with large momentum in forward directions. Figure 1 gives a summary of the maximum "sensitivity" achieved in various machine experiments. The solid curves in the figure represent the best estimates on the quark-anti-quark ($q\bar{q}$) pair production cross-section as quoted in Ref. 1. It should be noted that if $q\bar{q}$ pairs are indeed produced in the same manner as $N\bar{N}$, $Y\bar{Y}$, etc., then the sensitivity reached in the proton machine experiments was either marginal or well above the predicted quark production cross section. Indeed, if one takes $M_q \approx 6 \text{ GeV}$, one gets $\sigma_{q\bar{q}} \approx 10^{-50} \text{ cm}^2$!!

On the other hand, it is quite probable that an appreciable number of quarks may be produced in exactly the same manner in which "spectator" protons are produced in particle interactions in, e.g., deuterium. Thus an

incident particle may interact with a quasi-free quark with the two "spectator" quarks are emitted⁹ more or less isotropically in lab. The effective quark production cross section then would be given by $\sigma_q \approx \eta \sigma_{qh}$ where σ_{qh} is the total quark-hadron interaction cross section and η is the "incoherence" factor (i.e., a measure of the extent of the validity of the impulse approximation). This factor would be small near the threshold but should increase with E_a . Various estimates of σ_{qh} are given in Table I.

One may estimate a lower limit of the average Fermi momentum of spectator quarks using the usual quantum mechanical arguments, namely $h/p_q \approx 2r_N$. Thus, taking the nucleon "radius" $r_N \approx 0.8$ fermi, one obtains $p_q \sim 0.8$ GeV/c. On the other hand, if one simply takes (in the absence of anything better to do!) the expression for nucleon Fermi momentum distributions in light nuclei, one would have $F(p_q) \sim p_q^3/(M_q BE + p_q^2)^2$. With $M_q \approx 6$ GeV and $BE \approx 10 - 20$ GeV, the most probable value of p_q would be about 10 GeV/c.

Because of the Fermi motion the effective mass of a quark as seen by the incoming particle may be very large and high energy particles (normal dE/dx) may also be emitted in backward directions in addition to the spectator quarks discussed above. The "quark" event reported in ref. 2 seems to show one Fermi quark and a normal ionization particle going backward in lab.

B. Tachyon Production

High energy particles may be emitted at "forbidden" angles if particles with imaginary mass (tachyons)¹⁰ are produced. Attempts to find tachyons have until now been of limited extent. Tachyon searches have been made in low energy photoreactions¹¹ and also in bubble chamber pictures¹² with negative results.

Tachyons may be produced in reactions such as $N + N \rightarrow N + N + T$ and due to the negative mass square of tachyons (T), high energy nucleons may be emitted at large lab angles. For example, in the extreme case that one of the nucleons remains stationary in lab, the other nucleons may be scattered backward ($\theta = 180^\circ$) if the tachyon is produced in the forward direction. Then the energy of the scattered nucleon would be $E_b = (4M^2 + m^2)/4E_a$ where M is the nucleon mass and m^2 is the negative square of the tachyon "mass."

Experimental observations of large angle and high energy particles in lab would constitute strong evidence for (but not proof of) the existence of tachyons, but more detailed examinations of the interactions in which backward particles are emitted will be required for any conclusive search for tachyons.

In the proposed experiment, we will search for high energy backward (normal dE/dx) particles and more definitive experiments will be proposed in the secondary beam area if we find any positive evidence for tachyons in this experiment to warrant for further search for them.

C. Other Possibilities

It is very unlikely but nevertheless it is possible that the incident particle interacts with a group of nucleons as a whole in a high Z target. In such a case, large angle and high energy particles may be emitted in lab.

Fig. 2 gives an estimate of the solid angle for particles that are produced isotropically in the production CM system with velocity larger than that of the CM system. As is well known, the solid angle involved is very small for a target mass less than 20 GeV. However, these particles may be backward-peaked in the CM system in which case the "effective" solid angle would be much larger than that implied in the figure.

High energy interactions in high Z nuclei produce a large flux of low energy (about 20 MeV average kinetic energy) protons and neutrons nearly isotropically in lab¹³. But these thermal nucleons will not be detected in our system.

High energy back-angle particles from interactions with heavy nuclei if they exist at all will not disturb our quark dE/dx signals except to reduce the maximum sensitivity. However, they will fake tachyon production in the present experimental set-up. Use of a hydrogen target should eliminate this particular background but one would still have to cope with the backward particles (with normal dE/dx) which may be produced in interactions with quasi-free quarks.

II. Experimental Methods

The main objective of the proposed experiment is to detect relatively fast (beta of 0.5 to 1.0) fractionally charged particles. We plan to detect these particles through their less-than-minimum dE/dx in liquid scintillators. A secondary objective of the experiment is to look for normal dE/dx particles emitted at large lab angles with high momentum (two or more GeV/c). This part of the experiment will constitute a preliminary phase of a later experiment to look for tachyons at NAL.

The basic logic of the detection system is shown in Fig. 3. It should be noted that both the normal and quark events will be detected concurrently in the system.

A. Detection System

The system is designed to measure: (1) the energy deposited by charged particles in liquid scintillators, (2) the particle velocity, and (3) the number and the direction of particles triggering the system. The solid angle acceptance of the system is defined by a set of plastic scintillators, P_1 to P_5 . The plastic scintillators are also used for the time-of-flight of the particles. The paired counters P_1 and P_2 and the pair P_3 and P_4 are separated by about 5 meters.

The array of six liquid scintillation counters (about $5 \times 50 \times 50 \text{ cm}^3$ each) is used for the dE/dx measurement. Each counter is viewed by four phototubes and pulses from these tubes are mixed per counter and ADC'd into the PDP-8 computer.

The magnetostrictive wire-chambers S_1 to S_6 are used to count the number of particles passing through each liquid scintillator. They are also used

to ensure that the detected particle originates in the target.

The PDP-8 computer (Indiana State University) has 8,192 words of memory, two magnetic tape drives and a storage CRT unit. The computer is expected to read in the ADC-bits (time-of-flight, dE/dx , and wire-chamber data) in less than one msec per event. This is comparable to the wire-chamber dead-time. During the interval between beam pulses, some routine tests on the performance of the system will be made. All pertinent data will be recorded on magnetic tapes for off-line data analysis.

The wire-chambers and their interface to the computer are being constructed at Indiana State University and the basic detection-logic system is being designed at ISU and the Ohio State University with the help of Mr. C. Rush (an electronics engineer). We expect to have the basic system ready in six months for testing and debugging, initially with cosmic rays but later on with an accelerator beam at a lower-energy machine.

The basic components of the PDP-8 software for our system already exist and we plan to do an exhaustive simulation study of various backgrounds in the on-line as well as the off-line computers in order to optimize our detection system. Therefore, the detection system described in this proposal will most likely be different from the "final" version of the system.

In view of the absence of any reliable estimate on radiation backgrounds in the proposed experimental site, the plastic counters, P_1 to P_5 , will be used as an independent system to survey the radiation backgrounds in the very first phase of this experiment. This survey should allow us to optimize the shielding and it should also ascertain the feasibility of using the Straight Section B for this experiment.

C. Expected Event "Rate"

If our quark production model is correct and if the "incoherence" factor is not too small at the NAL energies and if the quark-nucleon interaction cross-section is not much smaller than the values given in Table 1, then one would expect a fairly hot flux of quarks at NAL.

The expected quark flux per pulse is given by:

$$N_q = \sigma_{qh} N_o N_p \rho^t \Delta\Omega \eta \epsilon / 4\pi \quad \text{, where}$$

N_q : quark flux per pulse.

σ_{qh} : quark-hadron interaction cross section: we take it to be 10^{-30} cm^2 .

N_p : proton flux per pulse, about 10^{10} ppp.

N_o : Avogadro's number, 6×10^{23} nuclei/gram mole.

ρ^t : target thickness, 100 grams/cm², effective.

$\Delta\Omega$: 2.5×10^{-3} steradian.

η : "incoherence" factor, 10^{-2} (a wild guess).

ϵ : over-all inefficiency and contingency factor, 10^{-1} .

Therefore, we would expect about one quark in every ten pulses. If one assumes one pulse per minute, we would have about 50,000 quarks per year.

In case of negative results, we would like to run for about three months (parasitically, of course). This will give us a sensitivity of about 10^{-35} cm^2 for quark detection. As shown in Fig. 1, this sensitivity is comparable to that achieved in the quark search experiments done at lower energy machines.

III. NAL Requirements

A. Beam

Beam energy: as high as possible - ideally, 500 GeV or higher.

Beam intensity: 10^{10} ppp and one pulse/min. or faster.*

Beam shape: any shape (emittance); flat-topping preferred.

Beam purity: not required.

*This is for an internal target in the straight section B.

B. Shielding

Our equipment will come with some thin (one or two cm-thick Cu) shielding. This shielding will be adequate only for low energy charged particles and photons and we expect the NAL to provide the main shielding for neutrons and high energy particles. For the use of an internal target (our first choice), we will provide some additional shielding blocks for low energy neutrons. These shielding blocks will be in small modular units for maximum mobility inside the tunnel.

C. Experiment Site

First Choice - Straight Section B: A possible layout for our equipment in this area is shown in Fig. 4. A low intensity beam and a thin target are to be used. The equipment (including shielding) will be made very compact and mobile so as not to block the traffic in the area.

Second Choice - Highest energy external beam. The layout would be the same as in Fig. 4. Since our beam requirements are very minimal, we will be able to use essentially any high energy beam, used or otherwise. We should be able to use tired and old beams just prior to a beam dump with a moderate amount of shielding.

D. Shelters

We will need some form of shelter for our electronics equipment. The equipment (including PDP-8) will need air-conditioning. We would like to place the equipment as close to the counters as possible. Of course, we expect to monitor the control equipment continuously and some working space for two to three experimenters should also be included in the shelter. If necessary, we will provide our own shelter (a trailer) at NAL.

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Table I. Estimates on σ_{qh}^*

σ_{qh} (cm ²)	Source
$\pi (h/M_q)^2 \sim 10^{-29}$	Adair and Price ^a
$\sigma_N (M_\pi/M_q)^2 \sim 10^{-29}^{**}$	Dardo et al ^b
$\sigma_N (M_\pi/M_q) \sim 10^{-27}$	composition of jet particles
$1/3 \sigma_N \sim 10^{-27}$	Dooher ^c
$\sim 10^{-27}$	McCusker et al ^d
$\sim 10^{-27} - 10^{-26}$	Chu et al ^e

* We assume $M_q \approx 6$ GeV.

** $\sigma_N \sim 40$ mb, nucleon interaction cross-section

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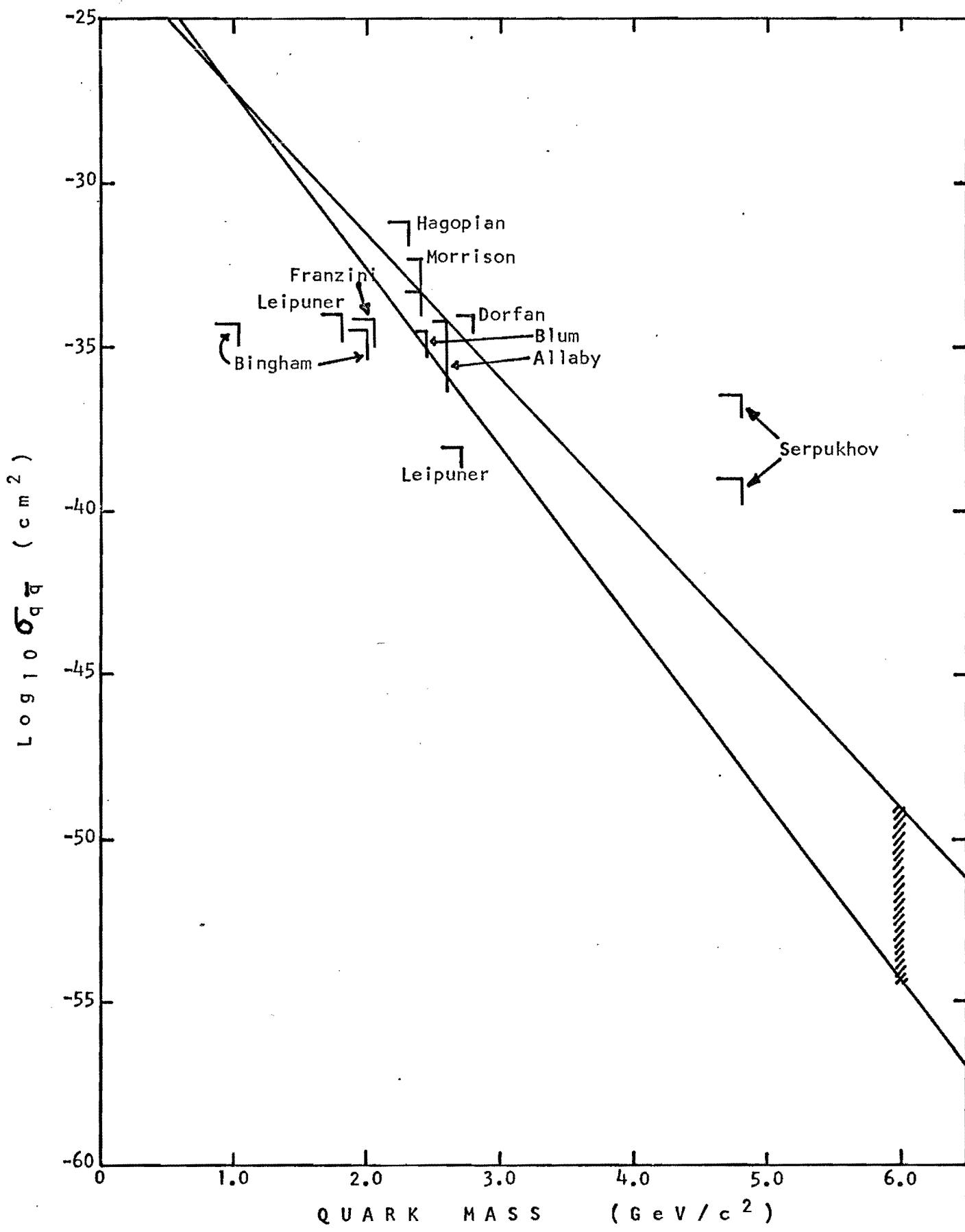


Figure 1

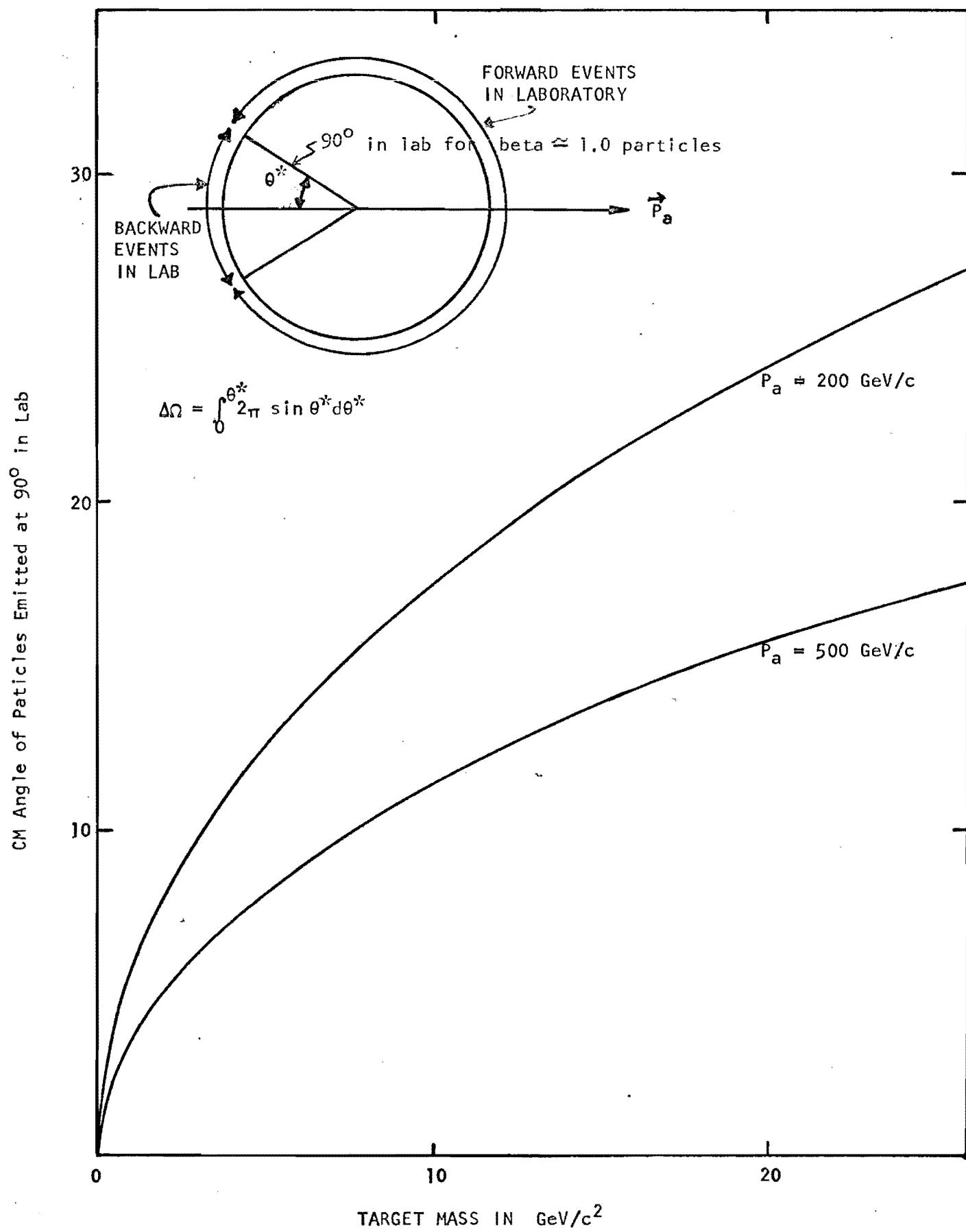


Figure 2

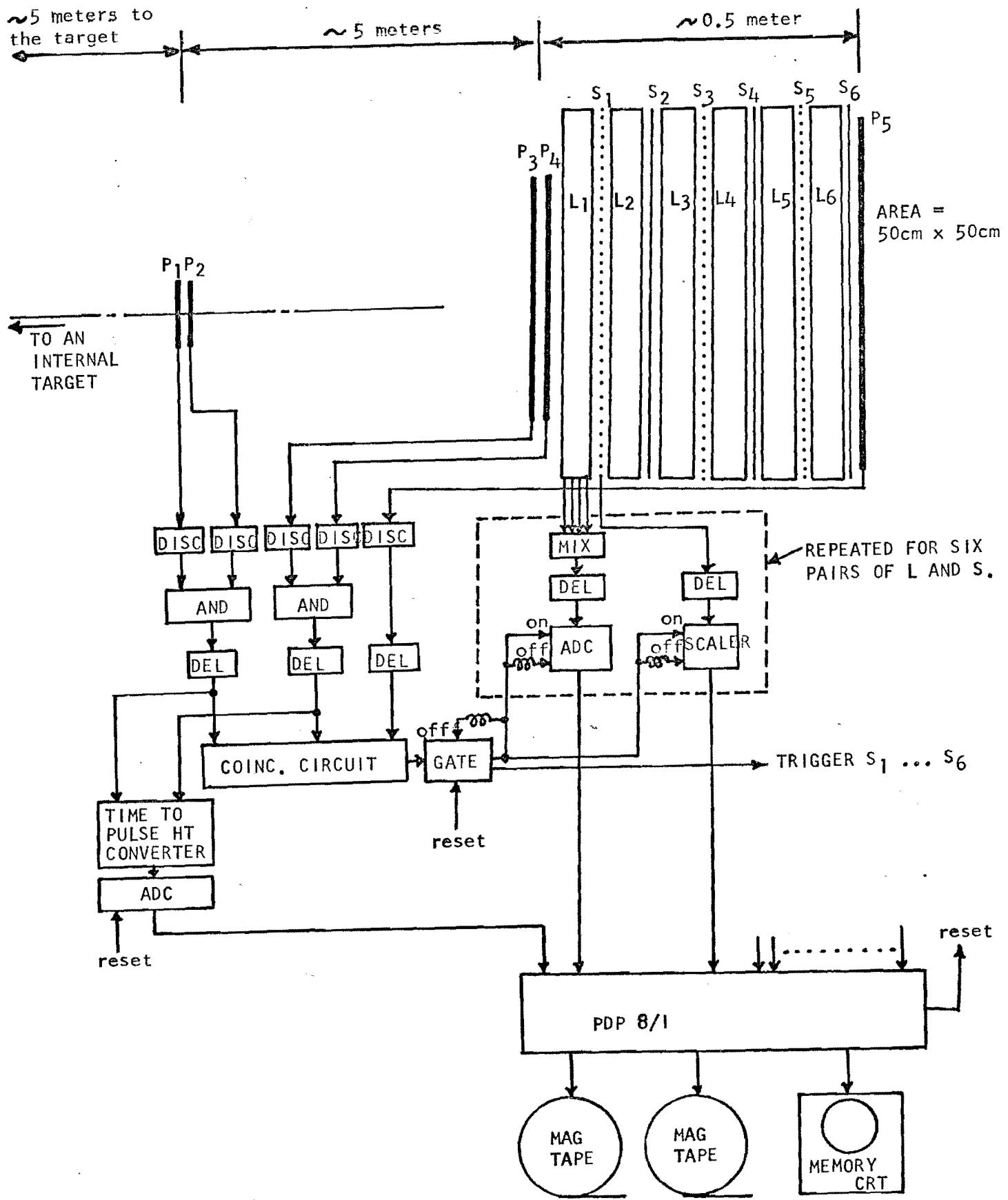


Figure 3

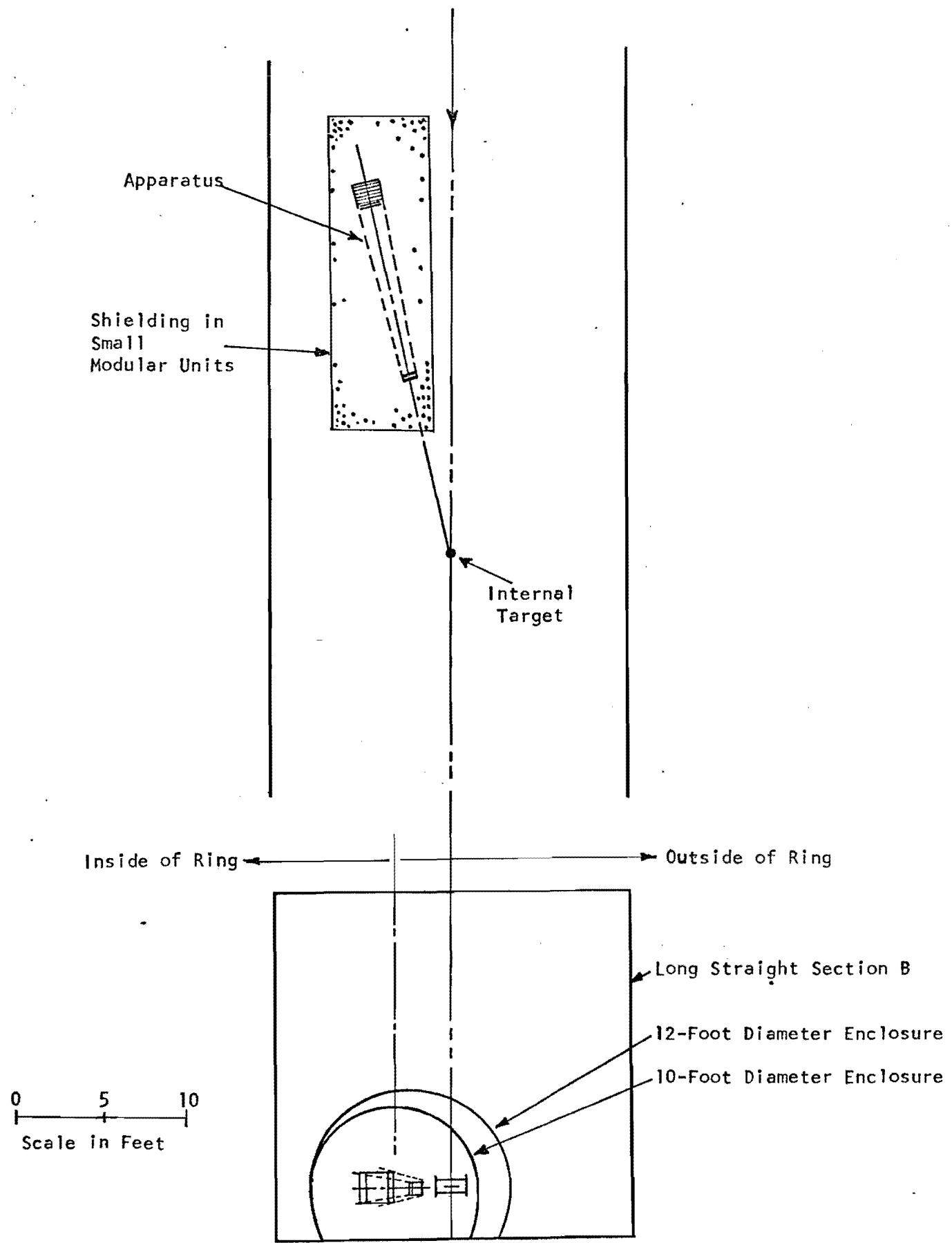


Figure 4

A QUARK WAY TO ASYMPTOPIA*

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Abstract: A phenomenological quark model of the behavior of the hadron-hadron interaction cross sections at intermediate and "asymptotic" energies is proposed. The model gives nearly constant cross sections at intermediate energies and increasing cross sections at asymptotic energies. Some implications of the model and their experimental tests are discussed.

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The surprising results on the behavior of the meson-nucleon total cross sections at the Serpukhov energies¹⁾ and certain inconsistencies in the cosmic-ray data at energies above 100 GeV²⁾ seem to forebode the coming of still more surprises with the construction of new proton machines with another order of magnitude increase in the available energy.

In this note we briefly discuss a phenomenological model of the behavior of the hadron-hadron interaction cross sections at "high" energies. We divide the behavior into three phases. First, the low energy phase (phase-I) where the cross sections are mainly controlled by the presence of resonance channels³⁾; or, in terms of the quark model, the interactions occur via bound states of the quarks. In this phase the cross sections decrease with energy³⁾. In the second phase (phase-II), the quark bindings begin to dissolve as the interaction energy increases and the hadrons become more and more "ionized"⁴⁾. Naively speaking, the ionization energy would be equal in the CM system to the sum of masses of the quarks excited into real and/or virtual continuum states and the ionization process most likely occurs over a wide range of the interaction energy. And in the third phase (phase-III), we have asymptopia where hadrons are completely ionized and hadron-hadron interactions are via free or quasi-free quarks. Here we adopt the Cheng-Wu model⁵⁾ which predicts that the total cross sections increase with energy. We assume that free or quasi-free quarks act like Lorentz-contracted pancakes whose radius and interaction strengths both increase with energy⁵⁾.

The hadron interaction cross sections in the energy region below 30 GeV are known to fall roughly as $1/\sqrt{s}$ where s is the square of the effective

mass of the interaction. However, the recent results of the Serpukhov experiments¹⁾ show that π^- , K^- and possibly \bar{p} cross sections on nucleons behave roughly as constants in the energy region above 30 GeV. The possibility of increasing cross sections at high energies has been discussed by several cosmic ray workers⁶⁾. For example, the flux of the nucleons having no shower accompaniment at mountain altitudes has been observed to be much less than what is expected from the attenuation of nucleons in air and this "anomalous" flux of the leakage nucleons can be explained in terms of an increased cross section⁶⁾. This is in contradiction with the expectations of the conventional description of the high energy behavior of hadron interactions^{7,8)}.

We make the conjecture with Horn⁴⁾ that the physical mechanism responsible for the resonances is also responsible for the decrease in the total cross sections and the fact that the decrease in the cross sections stops or becomes more gradual is a reflection of the "ionization" of hadrons. For example, one may interpret the observed flattening of the π^-p total cross section at $\sqrt{s} \approx 7.5$ GeV as being due to the excitation of one quark ($M_q \approx 6$ GeV) into a quasi-free or free state. In the present scheme, the behavior of the cross sections at phase-II energies is given by the composite of the decreasing contributions from the residual resonance channels and the increasing contributions from the free or/and quasi-free quarks. Thus, the cross sections in this phase would stay relatively constant as indeed observed in the Serpukhov experiments¹⁾.

Recently, Cheng and Wu⁵⁾ have made the prediction that at "asymptotic" energies (i.e., our phase-III region), the hadron-hadron total cross sections will be given by $2\pi R^2$ where the effective radius (i.e., the range of the interactions) of hadrons R increases with energy \sqrt{s} . These authors pre-

dict $R = R_0 \log H$ where R_0 is a constant independent of energy and $H \sim s/(\log s)^2$. Furthermore, Cheng and Wu assert that at extremely high energies hadrons act like Lorentz-contracted pancakes which have two general regions: (1) a black core whose radius R increases with energy as given above and which becomes more absorptive with energy and (2) a partially absorptive "fringe" which extends further out than R . We assume specifically that at very high energies ($\sqrt{s} \gg$ "total" ionization energy) hadrons are completely ionized into a system of quasi-free or free quarks and that the effective size of these quarks is given by the Cheng-Wu formula; we assume that the hadron-hadron interaction cross sections at these energies are given by the additivity hypothesis⁹⁾ whereby the forward scattering amplitude for the hadron-hadron interactions is given by the sum of all possible two-body quark-quark scattering amplitudes.

Naively speaking, one may expect the beginning of phase-III energies to be about 400-500 GeV corresponding to the ionization energy of five or six quarks. Fig. 1 shows the Cheng-Wu growth as a function of the quark interaction energy \sqrt{s} which would be less than the hadron interaction energy, the difference being roughly equal to the quark "ionization" energy. And it is very likely that in this energy range, the contributions from the resonance channels may still be appreciable and the effective increase in R is probably rather moderate for a hydrogen target as seen in Fig. 1.

We note that the Cheng-Wu effects⁵⁾ may be "amplified" by several times in hadron-nucleus interactions. This amplification would come out because of the sizable increase in s in nucleus interactions. The exact mechanisms by which the nucleus provides the additional energy are not known¹⁰⁾ but we

take the view that the energy increase in one form or another reflects the recoil (partial or total) of the nucleus. We consider two plausible means by which the nucleus transfers energy to the interaction: (1) the so-called linear cascade which increases the effective mass of the incoming particle and (2) the Cheng-Wu growth of particle size which increases the effective mass of the target particle.

On the basis of certain similarities between the nucleon-induced events in nuclei of widely varying A , Kaplon and Ritson¹¹) have made the observation that most of the particles produced in high energy nuclear interactions are well collimated and they interact simultaneously in the subsequent collisions. In the extreme case ("Kaplon-Ritson" limit) where the entire energy $\sqrt{s_0}$ of the initial collision is incident simultaneously on a target, the CM energy $\sqrt{s_1}$ of the new collision would be increased according $s_1 = s_0 + 2E_0 M_t + M_t^2$ or $s_n = s_0 + 2E_0(nM_t) + (nM_t)^2$ for the n -th successive collision. It is seen that the CM energy is nearly doubled for $n=3$ if the incident energy E_0 is 200 GeV assuming a stationary nucleon target. A more realistic form of the linear cascade may be interactions in which the incoming particle imparts a small longitudinal momentum recoil Δ_{11} to the target¹²). In such peripheral collisions, the major part of the collision energy may stay concentrated both in time and in space as the linear cascade progresses through the nuclear matter. In these collisions, the CM energy would increase according $s_1 \approx s_0 + 2E_0 \Delta_{11}$ or in the n -th successive collision $s_n \approx s_0 + 2E_0(n\Delta_{11})$ where the recoil momentum is assumed to be less than the target mass.

In contrast to the linear cascade in which the effective mass of the incident "particle" grows through multiple interactions, the Cheng-Wu growth of the size of the interacting particles would mean an effective increase

in the target mass. Because of the Lorentz-contraction and the Cheng-Wu growth of the particle size, the target nucleus would look like a large black disc to the incoming particle and a sizable fraction of the nuclear mass may participate in the reaction as a single unit.

Since the two mechanisms described above would "bootstrap" each other, a sizable fraction of hadron-nucleus interactions in the 200-500 GeV energy range may involve the entire nuclear mass as the target and we assert that in these reactions the incoming particle ionizes and creates a local "sea" of free or quasi-free quarks. It is probable then that many of these quarks are emitted in the laboratory system more or less isotropically with a relatively low energy. We note that in the 200-500 GeV reaction $p + Cu \rightarrow 3q + Cu$, quarks can be emitted with a 20 GeV/c momentum at $\theta_L = 180^\circ$ or with a momentum of 40-50 GeV/c at $\theta_L = 90^\circ$. The laboratory momentum distribution of quarks on the basis of the phase space available in the reaction is shown in Fig. 2. One may visualize the situation in which the momentum distribution (curves I and II in the figure) is made of a gaussian-like (isotropic in angle) distribution peaked at 20-30 GeV/c and a skewed distribution similar to the proton target distribution (curve IV in the figure). Dynamically, this situation would correspond to emission of "spectator" quarks with Fermi momenta and to scattering of the interaction quarks which presumably participate more actively in the interaction than the spectators.

6) Grigorov et al. have measured the proton- C^{12} total inelastic cross section in their Proton series experiments. The actual quantity measured was the ratio of the flux of singly arriving protons with a given integral energy with and without a 30.6 g/cm^2 graphite absorber in a calorimeter. The attenuation of protons obtained in this way would correspond to a difference between the total cross section and the elastic or quasi-elastic cross sec-

tion. The observed value shows an increase of about 20% in going from 20 GeV to 500 GeV. This value is an order of magnitude less than the increase one would expect from the present model if pure phase-III is assumed. However, we believe that because of certain technical problems, the Russian data indicate only a portion of the actual increase in the cross section¹³⁾ and it suffices to make the observation that the Russian results indicate a sharp rise in the cross section above 100 GeV.

Several high energy cosmic-ray pictures in a bubble chamber¹⁴⁾ and in emulsions¹⁵⁾ seem to show possible examples of phase-III interactions in which particles with a momentum as large as 10 GeV/c are emitted at large angles in the laboratory system. Other possible evidences for phase-III interactions have been discussed by Kaufman and Mongan¹⁶⁾ and Smorodin²⁾. These authors interpret, among others, the apparent discrepancy between the satellite-observed and the EAS-based data on the energy spectrum of the primary cosmic-ray nucleons as being due to production of "passive" or "less-ionizing" particles at energies above a few hundred GeV.

Finally, we note that a simple experimental test of the present model (phase-III interactions) would consist of looking for fast ($p > 2-3$ GeV/c) particles (preferably, "less-ionizing" particles) at large laboratory angles in high-energy hadron-nucleus interactions. At large angles ($\theta_L \geq 90^\circ$), one has the important advantages of being able to use low-energy particle detection techniques and of coping with much lower energy backgrounds.

We wish to thank Prof. Jay Orear for stimulating our interest in this subject.

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Figure Captions

Fig. 1. The Cheng-Wu growth of the range of quark interactions as a function of the energy available in the CM of the quark interactions. The range of the interaction energy available for hadron interactions is also shown for free nucleon targets and for Cu targets. The quark interaction energy would be roughly equal to the hadron interaction energy minus the "ionization" energy.

Fig. 2. The phase-space laboratory momentum distribution of the quarks (M_q is assumed to be 6 GeV) produced in a Cu target by 200 and 500 GeV nucleons (curves I and II, respectively). Curves III and IV show similar quantities for 500 GeV nucleons incident on a hydrogen target.

