NAL PROPOSAL No. 36

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A Proposal To Study Small Angle p-p Scattering At Very High Energies

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ABSTRACT

We propose to measure small angle p-p scattering by using a thin foil and a hydrogen jet target to intercept a small fraction of the beam without interference with the acceleration process. The measurements are based on the detection of the slow recoil proton and will yield the energy dependence of (a) the slope of the p-p nuclear diffraction peak, (b) the real part of the nuclear scattering amplitude, (c) the diffractive excitation of isobars. The proposed technique is energy independent and will provide data over the entire energy region from 25 GeV to the highest energy achieved by NAL. Total accelerated beam intensities of 10^{11} to 10^{12} protons/pulse are quite adequate. The equipment is presently under development and could be fully operational by June 1971.

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I. INTRODUCTION

We propose to measure p-p scattering at very small momentum transfer by an energy independent technique from ~25 GeV to the highest energy attainable at NAL. The experiment is based on the measurement of the angle and energy of the slow recoil protons from a hydrogen jet target in the NAL main ring; thin foils (~1 micron or less) can also be used except at the lowest momentum transfers. This technique, which has been successfully used at Serpukhov[1], is ideally suited to early operation at NAL for the following reasons:

a) The method, and thus the apparatus as well, is energy independent and can provide results up to any energy without modifications.

b) A large set of energies can be covered simultaneously by appropriate time labeling of events during the acceleration cycle of the synchrotron.

c) Multiple traversals of the internal beam allow the use of very thin targets as well as beam intensities as low as 10^{11} to 10^{12} protons/pulse.

d) The apparatus is small and does not require external beam extraction or beam transport.

e) The experiment can be run without interfering with machine testing or normal operation since the target would remove only a small fraction of the beam.

f) The experiment is capable of giving important results at an early date.

g) Finally, while one could consider measurements of p-p scattering in an external beam detecting the forward scattered proton, the angular and energy resolution required to reach the coulomb interference region becomes exceedingly difficult to achieve as the energy increases. It is our belief that, quite independent of the advantages mentioned in (a) to (e) above, the technique we propose is inherently more accurate.

The main goals of the experiment are:

a) A measurement to ±1% of the slope of the nuclear diffraction peak as a function of energy. These measurements will cover the region from $0.01 < |t| < 0.12$ and can be accomplished with either the foil or jet target.

b) A measurement of the scattering in the region of interference between coulomb and nuclear amplitudes. This data should yield the ratio of the real to the imaginary part of the scattering amplitude both in sign and magnitude to an accuracy of 0.01 to 0.02. This ratio will be measured as a function of energy. In view of the recently reported deviations from the expected behavior of the total cross sections, exact knowledge of the real part of the nuclear scattering has become exceedingly important. These measurements must be made in the region $0.001 < |t| < 0.01$ and thus necessitate the use of the jet target.

c) Measurement of the excitation of isobars in the forward direction. In particular our technique is applicable to the study of "diffraction dissociation" phenomena for the proton, either via the nuclear field or the coulomb field.

II. PHYSICS JUSTIFICATION

The main goals of the experiment have been enumerated in the last three paragraphs of the previous section. Here, we wish to elaborate and amplify on this discussion.

1. The Slope of the p-p Nuclear Diffraction Peak

Proton-proton elastic scattering exhibits a sharp diffraction peak in the forward direction, the slope of this peak becoming steeper as the incident energy increases. In a simple "optical" model this behavior would indicate an increase in the effective radius of the interaction; in the Regge model, if only a single trajectory is exchanged, the slope is expected to increase as ln s. In Fig. 1 we show the latest results from the Serpukhov experiment[1] which seem to support the Regge model.

A knowledge of this slope at NAL energies is of great interest since many theoretical models predict an asymptotic limit rather than continued shrinkage. Furthermore, if we extrapolate linearly to the energy region of 200 - 500 GeV the existing data suggest a slope higher than 13 $(GeV/c)^{-2}$. This value would be larger than the slope for $\bar{p}p$ diffraction measured at 12 GeV/c and for which the diffraction pattern is known to expand (anti-shrink). Thus, if the diffraction peaks for pp and $\bar{p}p$ are to have a common limit as $E \rightarrow \infty$ either the rate of change of the pp slope must decrease at small t, or the $\bar{p}p$ slope must change its behavior and begin to shrink. Existing data therefore suggests that important changes may occur in the energy region between 100 - 500 GeV.

Finally, in the context of the Regge model the slope of the vacuum trajectory is of fundamental importance. Without exact knowledge of this slope the predictive power of the model is greatly reduced except for those reactions where vacuum exchange is forbidden. In the past, the estimates for the slope of this trajectory have varied from 1.0 $(GeV/c)^{-2}$ to zero and now back to ~ 0.4 $(GeV/c)^{-2}$. The uncertainty in the value is due to the contributions from other trajectories which cannot easily be isolated in the energy region below 30 GeV. On general theoretical grounds, secondary trajectories such as the P', ρ, ω, etc. should not contribute appreciably at energies > 80 GeV allowing a unique determination of the slope of the vacuum trajectory.

We expect to measure the slope of the nuclear scattering to an accuracy of 0.01 and, since this quantity will be measured at many energies, a detailed analysis of its energy dependence will result.

2. The Real Part of the Scattering Amplitude

The real amplitude is obtained from measurements of the interference between the coulomb amplitude (which is predominantly real) and the nuclear amplitude, (hence its real part). Due to final state interactions there is a phase shift in the coulomb wave functions and this introduces a correlation calculated by Bethe[2].

In Fig. 2 we show the expected behavior of the coulomb, nuclear and interference term contributions at 200 GeV/c. The ratio of real to imaginary nuclear amplitudes has been taken as

$$\alpha = \frac{\mathrm{Re}\ (p\text{-}p)}{\mathrm{Im}\ (p\text{-}p)} = -0.2$$

which is the value measured[3] at 20 GeV/c. If the existing values of α are extrapolated to 200 GeV/c as 1/p, one obtains $\alpha = -0.02$ which is near the limit of our accuracy.

The accuracy of our measurement should be between 0.01 and 0.02 in the absolute value of α, and will depend mainly on our ability to establish the proper relative normalization between different t values. The energy dependence of α should be of great value in eliminating possible deviations (statistical or others) of the individual measurements.

3. <u>Isobar Production and "Diffractive Dissociation" of the Proton</u>

In Fig. 3 we show the kinematics of the recoil proton for p-p elastic as well as for N^* (1688). It can be seen that within the same range of recoil energies several high mass isobars can be reached, even though the recoil angle recedes from 90° towards the forward direction. If the isobar can be produced by vacuum exchange, then the forward direction is favored. Therefore $I = 1/2$ $J^P = 1/2^+, 3/2^-, 5/2^+$, etc. states will be detected from the missing mass distribution of the recoils and the energy dependence of this excitation can be studied.

An interesting additional possibility of this technique which could become the basis for a future proposal for an extension of this work is the use of heavy gas targets. Since the momentum transfer (q - minimum) required to reach a state of mass m_x is

$$q_{min} = \frac{m_x^2 - m_p^2}{2p}$$

the large incident energy reduces q_{min}, allowing coherence even for large masses. For example, helium or organic gases could be used in the jet in which case dissociation of the proton into states of higher mass may become observable. We expect to supply an addendum discussing the physics possibilities in more detail in the near future.

4. Comparison with Other Planned Experiments

As mentioned earlier, a similar experiment is in progress at Serpukhov; however the energy is limited to 70 GeV. The CERN storage rings can reach the energy region considered here and p-p elastic scattering is proposed. The small angle region will be very difficult to reach at the ISR and in addition normalization problems will tend to complicate the type of precision measurements considered here.

III. EXPERIMENTAL ARRANGEMENT

1. Kinematic Considerations and Resolution

For elastic scattering the kinetic energy, T, of the recoil proton is related to the momentum transfer by $q^2 = -t = 2\,mT$ where m is the mass of the proton. Thus we need to detect protons in the energy region

$$0.5 < T_p < 60 \text{ MeV}$$

and the recoil angular region

$$90^\circ > \theta_p > 80^\circ$$

if we want to cover the interference region and the part of the diffraction peak that lies below $|t| < 0.12\ (GeV/c)^2$; (see Figs. 2 and 3). In view of the small recoil energies thin targets must be used, particularly in the interference region.

The angular resolution required to obtain a recoil mass resolution Δm is

$$\Delta \theta_r \simeq \frac{m \, \Delta m}{p_o \sqrt{t}} \quad . \tag{1}$$

To resolve the elastic peak completely from one pion production Δm must be less than 0.14 BeV. In the worst case at 500 BeV/c and $|t| = 0.1 \, (\mathrm{BeV/c})^2$, an angular resolution of about 1 mrad would be required. The internal beam angular divergence is much smaller than this value.

The energy resolution to obtain a mass resolution Δm is

$$\frac{\Delta T}{T} = \frac{4m^2 \, \Delta m}{p_o \, |t|} \quad . \tag{2}$$

At 500 BeV/c the detectors should be capable of about 1% energy resolution near $|t| = 0.1 \, \mathrm{BeV/c}^2$ for Δm equal to one pion mass. This resolution can be obtained with existing solid state detectors.

To obtain satisfactory measurements in the cross section slope parameter b it is also necessary to have good resolution in t. Our calculations indicate that satisfactory t resolution for 1% measurements on the slope can be achieved if the mass resolution requirements are met.

Equations (1) and (2) are plotted in Fig. 4, exhibiting clearly the two basic features: (a) the required mass resolution decreases linearly with incident proton energy; (b) for fixed incident proton energy, the required mass resolution decreases with increasing t.

The angular resolution depends on both the detector size and the interaction size at the target. In the arrangement shown, with either hydrogen jet or foil target, both the size of the detector and the interaction region can be $\lesssim$ 5 mm, which gives

$$\Delta\theta = \frac{5 \text{ mm}}{2.5 \times 10^{+3}} = \pm 2 \text{ mrad} .$$

The energy resolution of readily available detectors is ±0.5%. Thus the angular uncertainty completely dominates the mass resolution. In column 6 of Table I we give the missing mass uncertainty for the proposed apparatus. One-pion mass is resolved for most combinations of energy and momentum transfer. In general, the rate for such processes (excluding resonance production) is known to be much smaller than the elastic rate at lower energies so that the background should be small. The Serpukhov data support this view. The resonant states of the proton are resolved at all energies.

2. The Experimental Arrangement

The experimental arrangement is shown in Fig. 5. A "tee" is added to the vacuum pipe of the main ring, providing a 2.5 meter path into 10 solid state detectors. The detectors are arranged to cover recoil proton angles from 80-90 degrees and are situated inside the vacuum chamber. The chamber is tapered and reaches 30 cm at its widest point to accommodate the 10 degree angular range.

Two three-counter telescopes upstream from the target and on either side of the main ring vacuum pipe monitor the incident proton intensity. The angle of the telescope with respect to the beam direction and the counter size will be chosen to produce an appropriate rate for this purpose. In addition, the circulating current is monitored at the 1% level by a standard harmonic induction monitor. We note that for 10^{11} circulating protons, the current is 1 mA. If necessary, scintillation counters placed outside the vacuum chamber and directly behind the solid state detectors can be used to veto fast particles passing through the detectors.

Detectors: Totally depleted silicon surface barrier detectors, 5 mm in diameter and 2 mm thick are available and sufficient to cover the energy region up to 18 MeV. "Practically" detectors of this kind operated "warm" give an energy resolution of ±0.1% on 5.4 MeV α-particles. They may be cascaded to extend the energy region covered. Silicon drifted detectors with rectangular geometry are also available. Since the proton may enter the sensitive region perpendicular to the drift direction, it is not difficult to obtain detectors which present as much as 2 cm range to the incident proton, sufficient to cover the entire energy region envisioned in this experiment. These detectors can also be operated warm, and the energy resolution is more than adequate for our purposes. Some combination of surface barrier detectors should suffice in the low energy region ($85^{o} < \theta_R < 90^{o}$ - see Table I) and the more expensive drifted silicon detectors will be required only in the last 2-3 energy bins. The choice of detectors is being studied experimentally both at Rochester and NAL, and the final configuration will depend on the results of these experiments. Figures 7a and 7b show typical resolution curves we have obtained with alpha sources.

Columns 1 - 5 of Table I summarize the location, central t value, Δt acceptance, central recoil angle, and kinetic energy of the recoil proton at the elastic peak for each of the 10 detectors.

Target: We propose the use of two types of targets (a) a thin polyethylene or parylene foil and (b) a hydrogen gas jet. The foil target will be of a thickness of 0.5 to 1 micron and has the advantage of simplicity of construction and of high density ($\sim 10^{18}$ protons/cm^2). We have been successful in spinning a 4 micron thick mylar foil in vacuum at 3600 rpm and propose to use the same technique for the thinner targets. The foil was shaped in the form of a blade and was stretched by its own centrifugal force. Figure 6 is a photograph of the foil in operation.

By varying the width of the foil any appropriate duty cycle can be selected. It is possible to keep the target out of the beam region during injection. The foil target is adequate for the study of the nuclear scattering and of the diffractive isobar excitation. It has the advantage of a very well defined interaction region (in one place) and a relative ease in absolute normalization. The problems of hydrogen depletion and radiation damage will be studied at AGS energies.

The hydrogen jet target on the other hand has densities of the order of 3×10^{16} hydrogen molecules/cm^3 and has a thickness of 5 mm, but is free from the carbon background. The jet is necessary for the interference region measurement, and will be pulsed for approximately 250 msec during each machine cycle.

A hydrogen jet based on the work of Nikitin[6] is being designed and will be constructed by Rochester. The initial pressure is 10 atmospheres and the jet is formed in a Laval nozzle, after precooling to liquid nitrogen temperature. For efficient pumping it appears that a liquid helium collector will be required.

It is important not only to know the jet density but also the effective fraction of the beam interacting with the jet. The latter is energy dependent in view of the damping of the betatron oscillations; thus a direct measurement of the effective interaction density is required. We propose to achieve both a relative and absolute normalization by collecting the knock-on-electrons ejected by the passage of the beam through the hydrogen jet; initial calculations indicate that more than adequate current can be collected to provide stable monitoring.

3. Event Rates

The differential cross section for scattering a recoil proton into a solid angle $d\Omega_R$ (θ_R, ϕ_R) is related to the cross section for scattering a fast proton into $d\Omega_f$ (θ_f, ϕ_f) by

$$\frac{d\sigma}{d\Omega_R} = \frac{2m\sqrt{t}}{P_o^2} \frac{d\sigma}{d\Omega_f} \qquad (3)$$

where

$$\frac{d\sigma}{d\Omega_f} = \frac{P_o^2}{16\pi^2} \sigma_T^2 e^{-bt} \qquad (4)$$

P_o	=	Incident proton momentum
m	=	Proton mass
σ_T	=	Total pp cross section
$b(P_o)$	=	Slope of the diffraction peak
t	=	Square of the four momentum transfer to the target proton.

For the purposes of this estimate we have assumed Ref(0) = 0. Substituting equation (4) into (3) with σ_T = 40 mb we obtain

$$\frac{d\sigma}{d\Omega_R} \approx \frac{90\sqrt{t}\ e^{-bt}}{2\ m} \quad \frac{mb}{steradian} .$$

We take

$$b \cong 13\ (GeV/c)^{-2} \text{ at } P_o = 200\ GeV/c.$$

With the detectors and geometry described in the previous section

$$\Delta\Omega_R = \frac{3.12 \times (2.5)^2}{(2.5)^2 \times 10^{[illegible]}} \cong 3 \times 10^{-5} \text{ steradians/detector.}$$

For a typical [illegible] of [illegible]

$$\Delta\sigma = \frac{90 \times [illegible] \times 10^{[illegible]}}{1.38} \times 3.3 [illegible] \times 10^{[illegible]} = 2 \times 10^{-5} \text{ mb/detector.}$$

Energy selection is achieved by time binning of events during the acceleration cycle. Time bins of 10 msec [illegible] to an energy interval of 1.0 GeV and therefore provide more than adequate resolution in incident energy. For the jet target we will be restricted to [illegible] 15 such energy bins per cycle, while for the foil target the [illegible] energy region could be scanned during each cycle.

<u>Rates with Foil Target:</u> Assuming 10^{12} circulating protons, target density of 10^{18} protons cm^{-2} [illegible] a duty factor of 1/20 [illegible] angular [illegible] of [illegible] $10^{[illegible]}$ we obtain

$$10^{12} \times \frac{10\ \text{msec}}{20\ \mu\text{sec}} \times \frac{1}{20} \times 10^{18} \times 2 \times 10^{-32} = 0.5\ \text{counts/pulse}$$

[per detector - per energy bin].

Hence, a total of

$$0.5 \times 10 \times 200 = 1000\ \text{elastic counts/pulse.}$$

Depending on the background such a rate is close to the limit of our data acquisition rate.

For an estimated 10^4 counts/detector - energy bin, a few days of running at 10^{12} will suffice to complete the measurements up to 200 GeV/c with the foil.

<u>Rates with Hydrogen Jet</u>. Assuming 10^{12} circulating protons, target density of 8×10^{16} protons/cm^3, a 0.5 cm diameter of the jet and an average beam size (vertical) across the jet of 1.0 cm, we obtain

$$10^{12} \times \frac{10\ \text{msec}}{20\ \mu\text{sec}} \times [illegible] \times 10^{16} \times 2 \times 10^{-32}$$

$= 0.10$ counts/pulse [per detector - per energy bin]

rearranged however to 15 [illegible] per pulse. Hence

$$0.10 \times 10 \times 15 = 15\ \text{elastic counts/pulse.}$$

4. <u>Estimate of Running Time</u>

On the basis of the above estimates, we feel that the essential time required for the proposed experiment in the region 25 to 200 GeV/c is

	Test	Data Run
Foil Target	2 days	3 days
Hydrogen Jet	7 days	10 days

We wish however to emphasize that the experiment should not interfere with machine testing or the regular operation of the external beam. We would hope therefore that the apparatus could be left in place for an extension of the measurements to higher energies.

IV. APPARATUS

In this section we discuss in some more detail the equipment to be used, its location in the main ring, and our plans for implementing the proposal.

1. Location of Equipment and Interaction with the Machine

From a technical point of view the location of the experiment around the accelerator circumference appears to be relatively unimportant. We firmly believe that the location of the experiment can and must be determined on the basis of the accelerator requirements. The same is true for the specific orientation of the apparatus since all azimuthal angles are equivalent; thus the detector assembly can be placed in such a way as not to interfere with traffic and operations in the ring.

We have considered several locations for the experiment. As possibilities for further study we suggest:

a) To place the target in the short straight section F - 22 and to place the apparatus in the booster transfer gallery below the booster transfer beam pipe. A hole would have to be drilled to connect the target with the apparatus. The transfer gallery should be a relatively inactive area since one end is plugged and it offers the advantage of being very close to the cross gallery; thus close liaison could be maintained with accelerator operations.

b) To place the target and apparatus in long straight section A where either side of the beam would be available. Operation in this area may be difficult since section A may be very busy during the initial phases of accelerator operation. We therefore would prefer any one of the other free long straight sections; a communications link will then be established with the control room.

The computer and electronics detection equipment can be placed in an access room. When the jet is in use, the pumping and cryogenic equipment may have to be located in the main ring tunnel. The detector bank can be placed in or near the vertical plane since this offers minimal interference. Appropriate positive action interlocks will be built into the apparatus in order to protect the machine in case of failures of our equipment. We also foresee the installation of quick action valves which should be able to isolate the target area from the beam vacuum chamber, both in case of emergencies but also in order to make repairs or to remove part of the apparatus.

We have considered the radiation problem. For the foil target and assuming a total cross section of 40 mb per nucleon, the relative beam loss is, pessimistically,

0.5%

for a full acceleration cycle of [illegible] sec. This is of the same order as the beam loss in the residual vacuum of the machine, and in any case can be controlled by [illegible], the duty cycle of the foil target.

For the jet target the relative beam loss is more than an order of magnitude lower and thus unimportant. The jet is designed so that the vacuum in the target region can be maintained at 10^{-5} torr.

2. <u>Data Reduction</u>

The data will be acquired on a Honeywell DDP - 516 computer connected on-line to the equipment. This computer has presently 8K of fast memory (1.2 μsec), magnetic tape, and hardware multiply-divide. Several interfaces have been built and used with it. An on-line link to a larger computer could increase the capabilities of the system but is by no means essential to the experiment. In either case we contemplate further off-line analysis of the data stored on the magnetic tapes. The appropriate analog to digital converters for encoding the pulse height information exist and will be added to the system. Data analysis should be straightforward since geometrical event reconstruction is not required.

3. Implementation of the Program

We feel that the manpower requirements are appropriately met by the group submitting the present proposal. Furthermore, 2-3 additional staff and students from Rockefeller University will join the group shortly.

We propose to test the apparatus at the AGS in the winter of 1970 and we are confident that the full system can be operational in June of next year. As mentioned earlier, we are presently proceeding with the design and model testing of the necessary equipment. We have already carried out a number of tests on various parts of the apparatus including current monitors, detectors and target elements. Our time table calls for an operational model before the end of 1970.

However, in view of the intimate connection of the apparatus with the main ring, we foresee that the construction and location of our vacuum chamber will have to be closely coordinated and approved by the appropriate NAL staff.

TABLE I

Distance x cm[††]	t $(GeV/c)^2$	Δt $(GeV/c)^2$ [*]	T MeV	$\pi/2 - \theta_R$ mrad	ΔM_x (MeV) For E_{in} in GeV 50	200	500	Events/10^4 pulses/ Energy Bin[†]
4	0.0009	0.0002	0.5	16				215 [**]
9	0.0045	0.0005	2.4	36				
13	0.0096	0.0008	5.1	52	10	40	100	
18	0.018	0.0010	9.6	72				
23	0.030	0.0013	16	92				
27	0.042	0.0015	22	108	20	80	200	330
32	0.059	0.0018	31	128				
37	0.079	0.0022	42	148				
42	0.102	0.0024	54	168				
46	0.120	0.0026	64	184	35	140	350	500

* Acceptance of detector, full width.

† Approximately 1 day of running at 200 GeV repetition rate with hydrogen jet.

** Nuclear only. At $t = 2 \times 10^{-3}$ coulomb and nuclear cross sections are approximately equal.

†† Distance from 90° line to counter center. (Fig. 5)

REFERENCES

[1] G. G. Beznogikh et al., Phys. Letters 30B, 274 (1969).

[2] H. Bethe, Ann. Phys. 3, 190 (1958).

[3] K. J. Foley et al., Phys. Rev. Letters 19, 857 (1967).

[4] See for example: L. Stodolsky, Phys. Rev. 144, 1145 (1966); G. Bellettini et al., Nucl. Phys. 79, 609 (1966).

[5] See for example: S. M. Berman and S. D. Drell, Phys. Rev. 133, 791 (1964), also Y. Nagashima and J. Rosen, University of Rochester Preprint UR-875-295.

[6] L. S. Zolin et al., "Forming and Trapping of a Gaseous Hydrogen Jet in a Vacuum", Joint Institute for Nuclear Research, Report No. 13-3425, Dubna, 1970. (BNL-TR-343).

LIST OF FIGURES

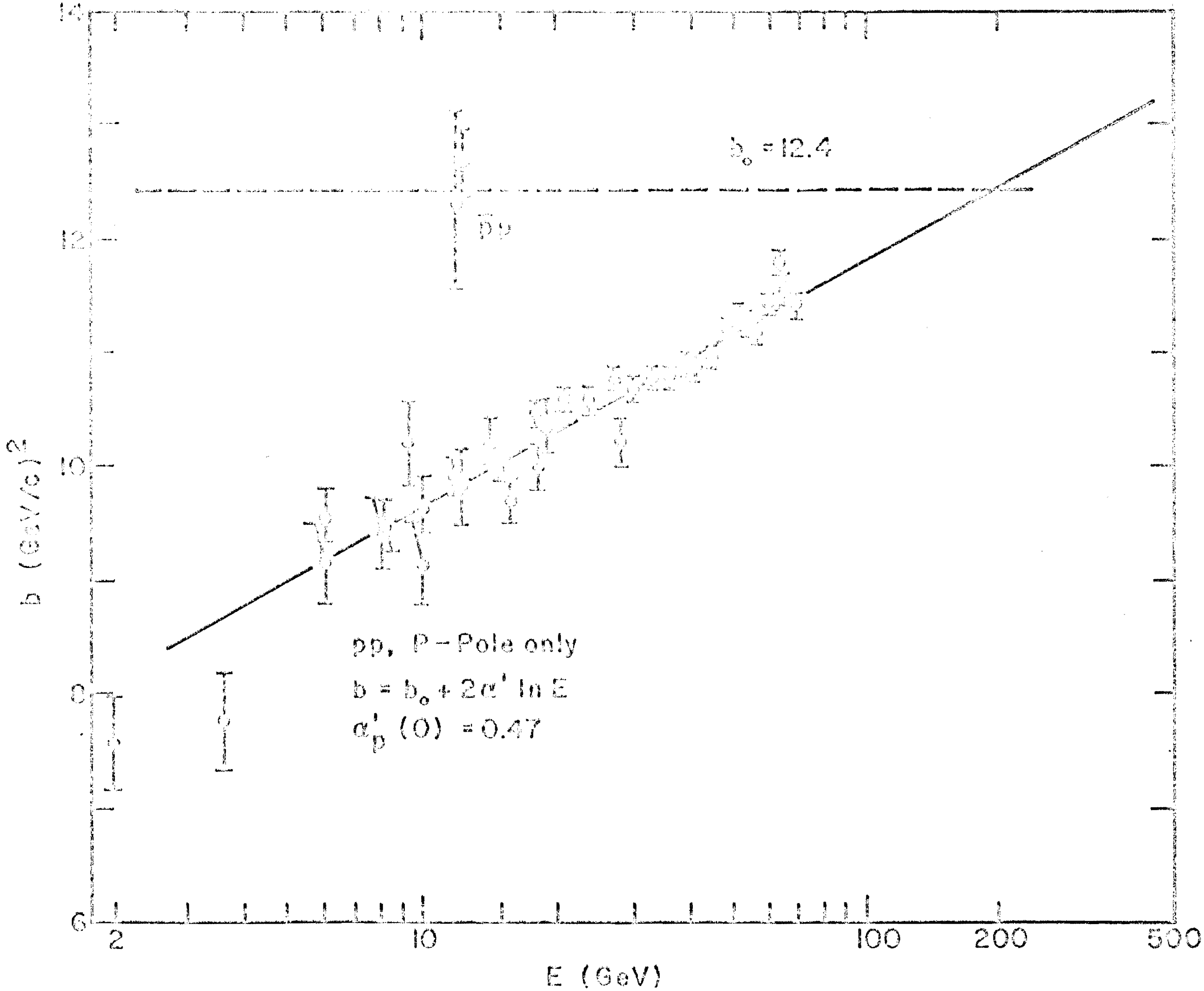
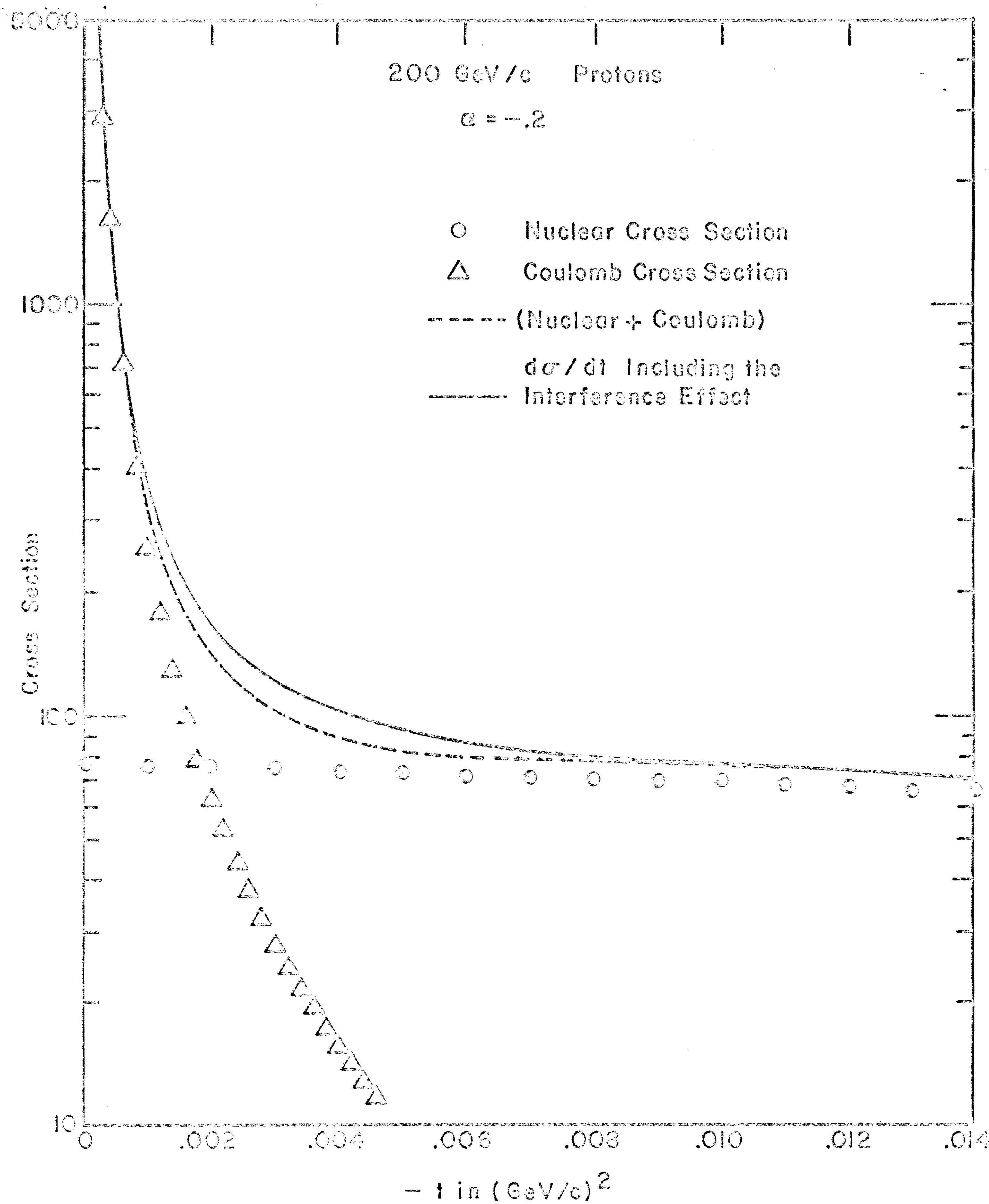

14
12
10
8
6
b (GeV/c)^2
b_o = 12.4
$\bar{p}p$
pp, P-Pole only
$b = b_o + 2\alpha' \ln E$
$\alpha'_p(0) = 0.47$
2
10
100
200
500
E (GeV)

Figure I



200 GeV/c Protons
a = -.2
Nuclear Cross Section
Coulomb Cross Section
(Nuclear + Coulomb)
dσ/dt Including the Interference Effect
Cross Section
5000
1000
100
10
0
.002
.004
.006
.008
.010
.012
.014
- t in (GeV/c)²

Figure 2

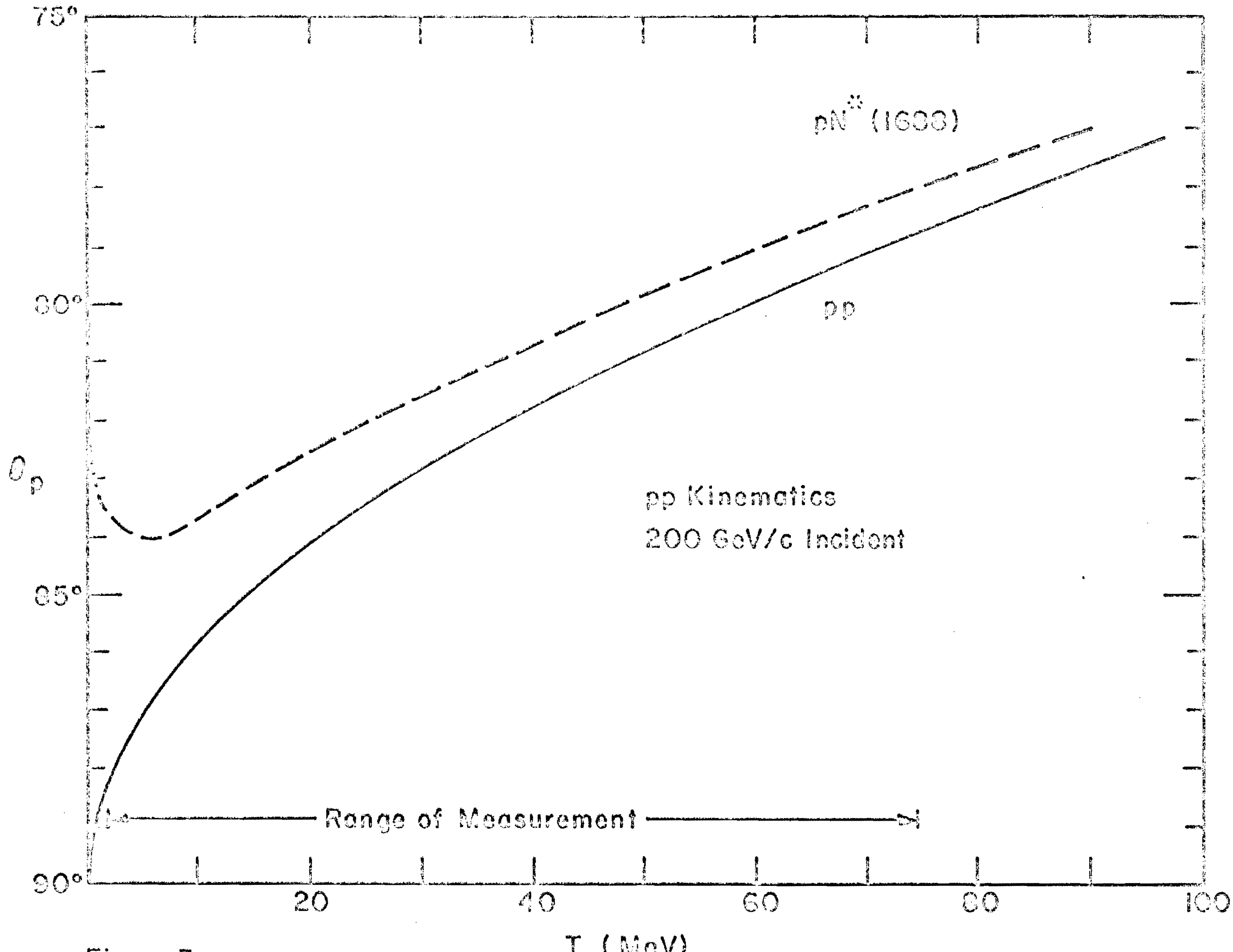
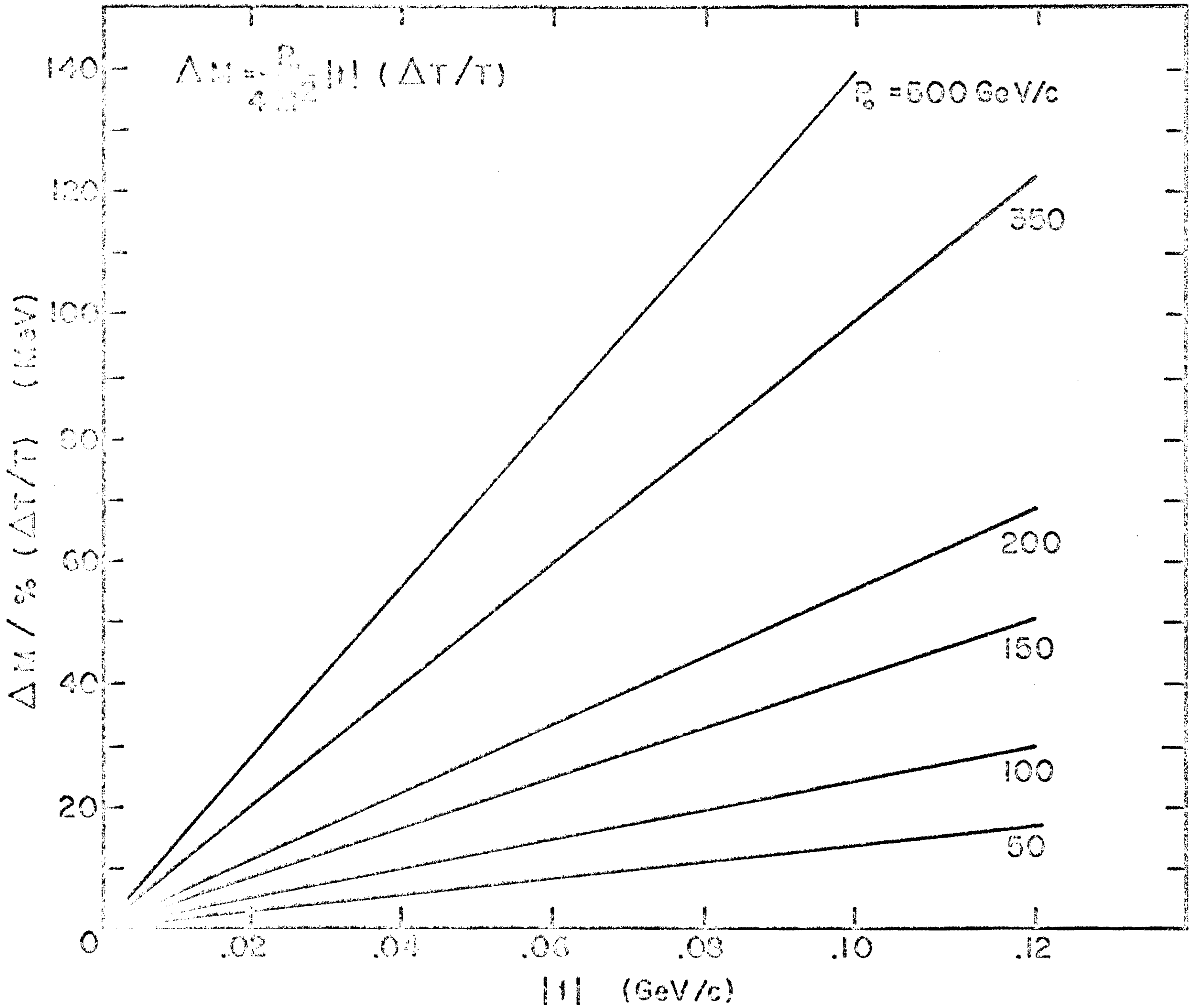
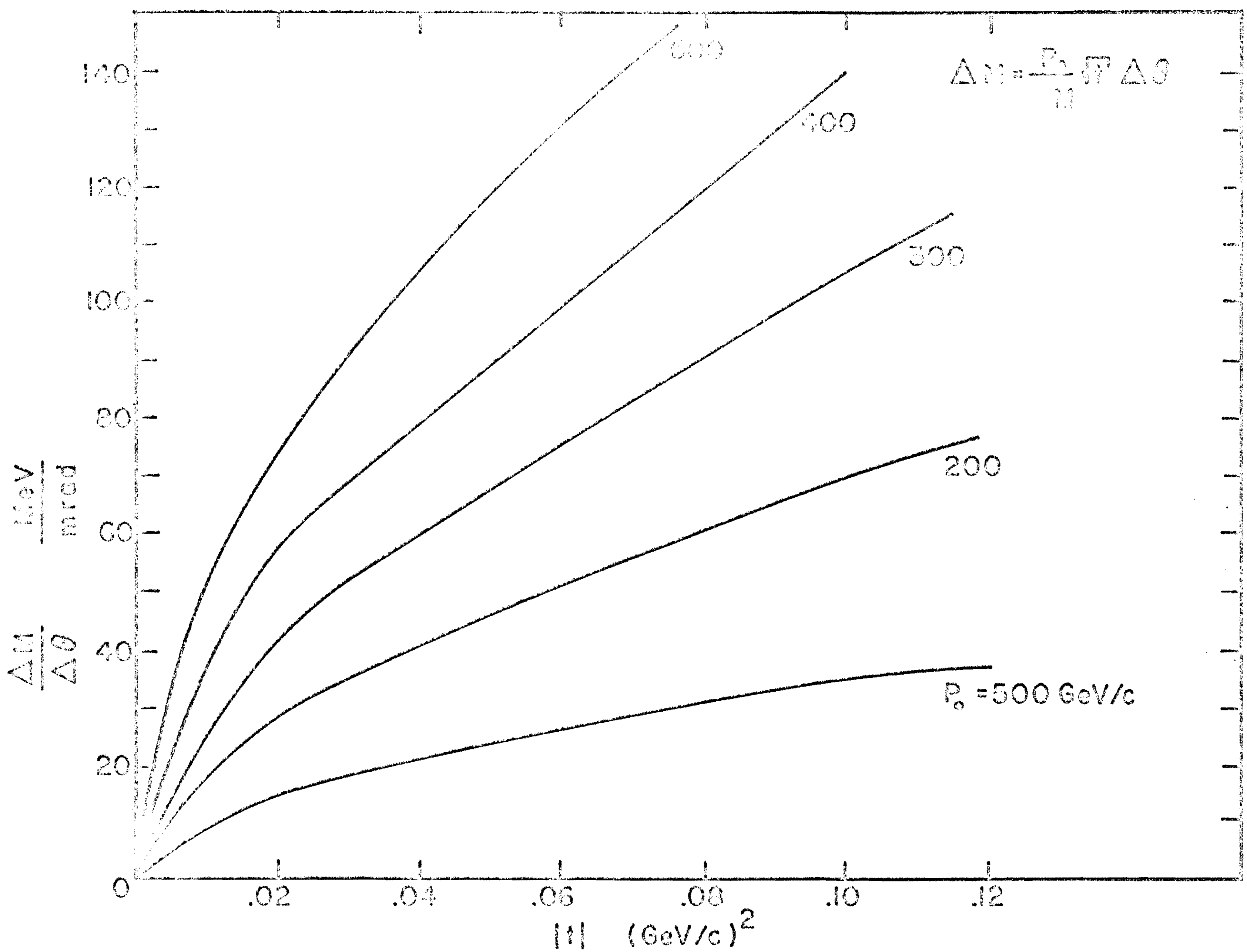

75°
80°
85°
90°
θ_p
pN^* (1688)
pp
pp Kinematics
200 GeV/c Incident
Range of Measurement
20
40
60
80
100
T (MeV)

Figure 3



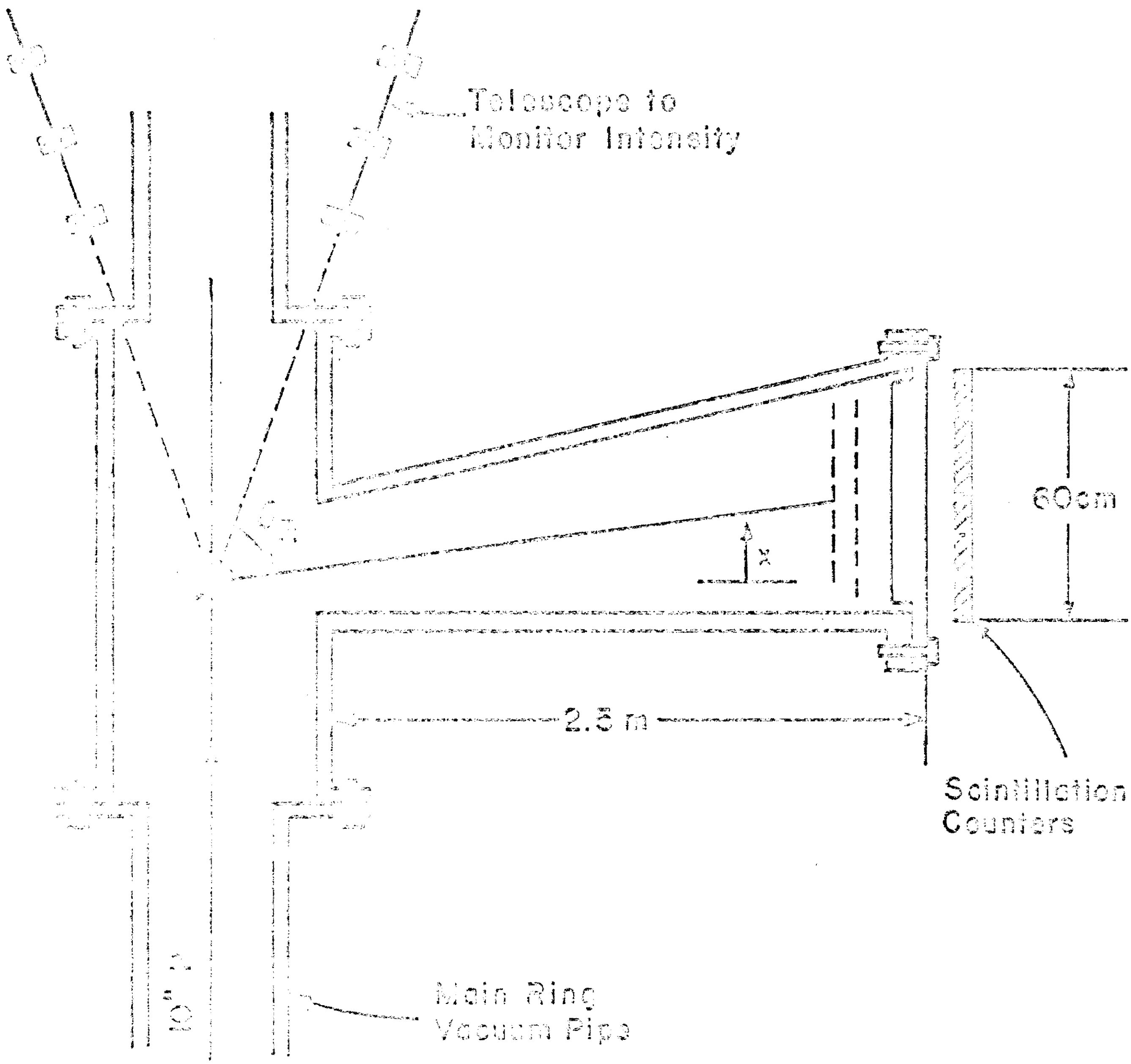
$\Delta M = \frac{P_0}{4m^2}|t|(\Delta T/T)$
P_0 = 500 GeV/c
350
200
150
100
50
ΔM / % ($\Delta T/T$) (MeV)
0
20
40
60
80
100
120
140
.02
.04
.06
.08
.10
.12
|t| (GeV/c)

Figure 4a



140
120
100
80
60
40
20
0
.02
.04
.06
.08
.10
.12
|t| (GeV/c)²
ΔM/Δθ MeV/mrad
600
400
300
200
P₀ =500 GeV/c

Figure 4b



not to scale

Figure 8

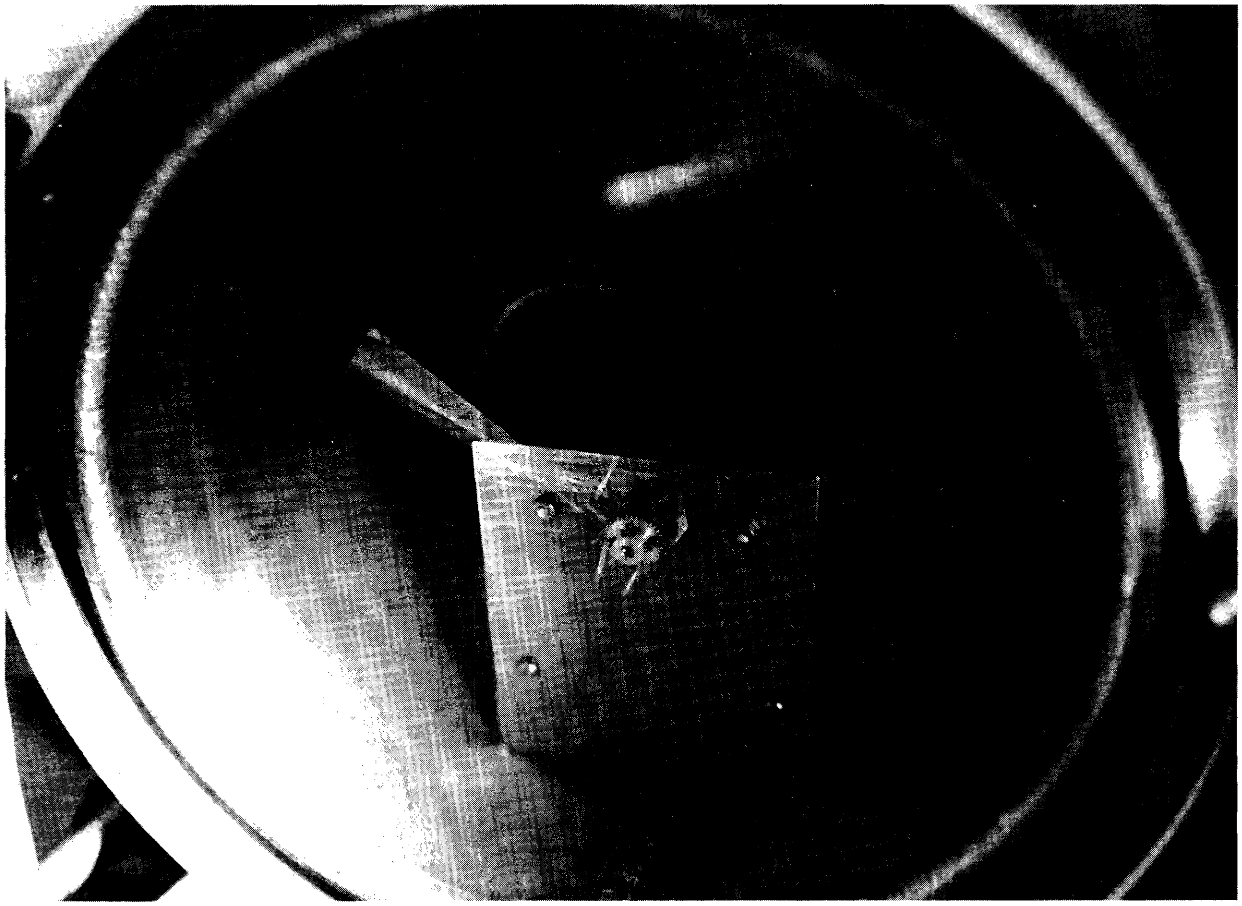
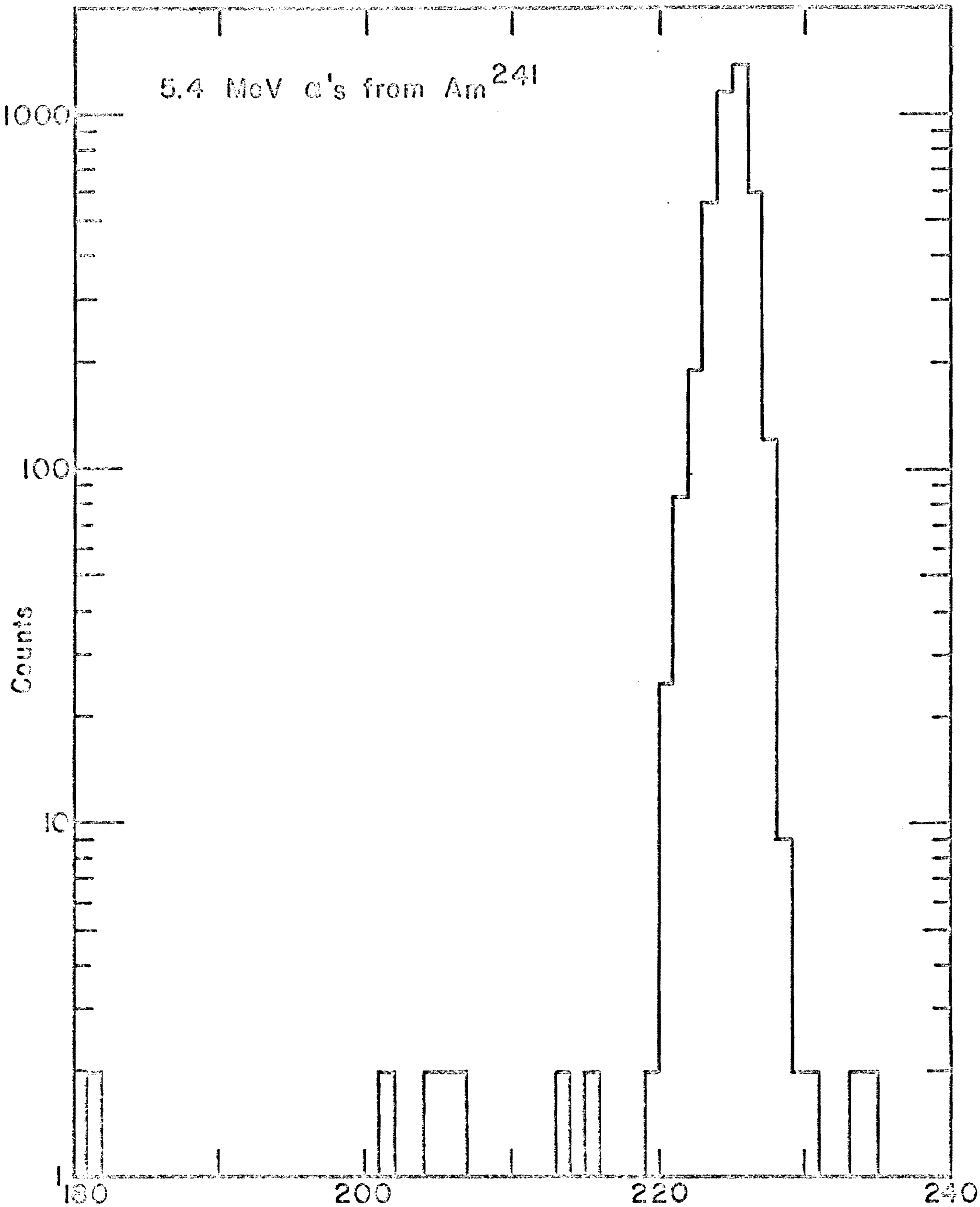
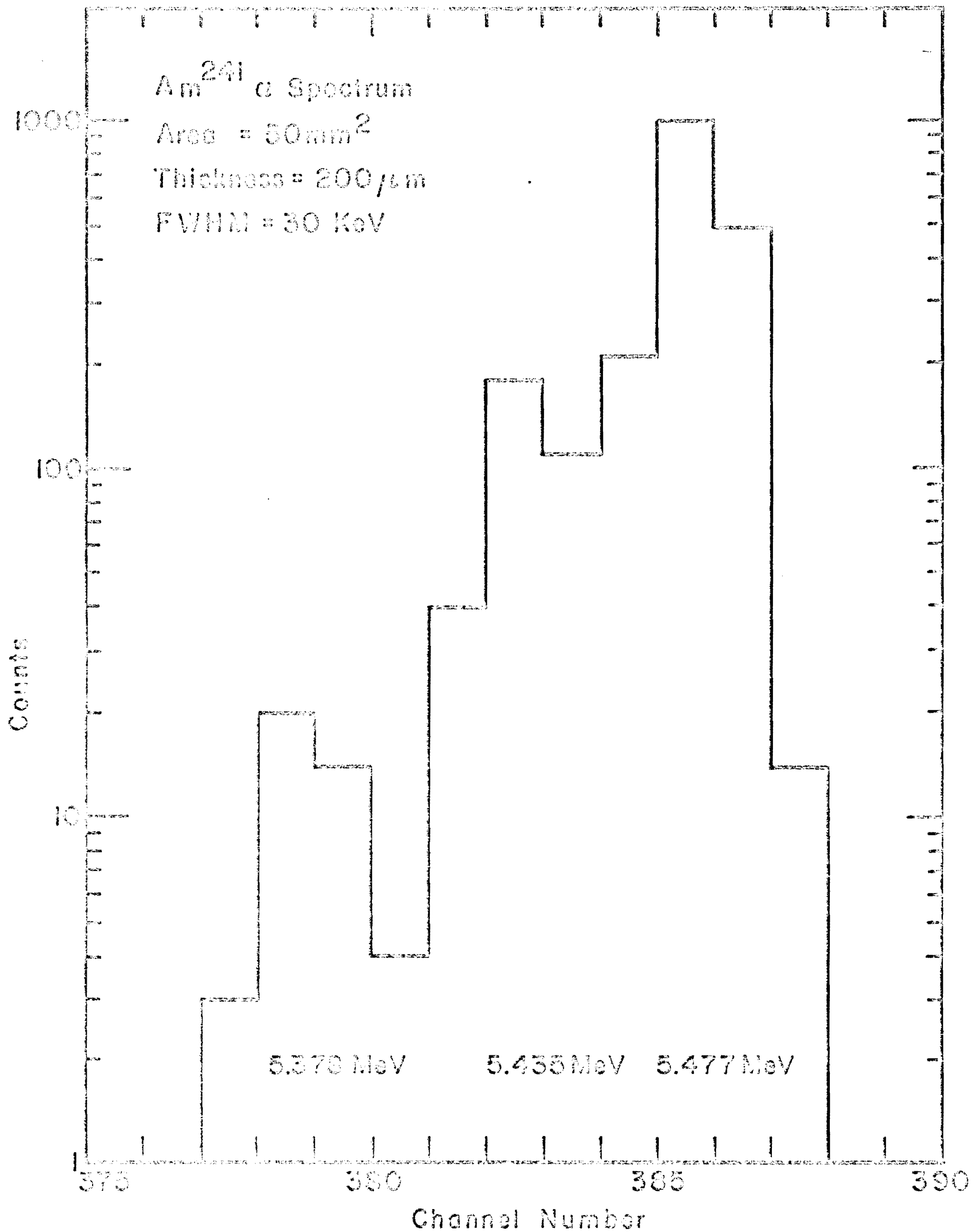


Fig. 6



5.4 MeV α's from Am^{241}
1000
100
10
1
Counts
180
200
220
240
Channel Number

Figure 7a



Am^{241} α Spectrum
Area = 50mm^2
Thickness = 200 μm
FWHM = 30 KeV
1000
100
10
1
Counts
5.378 MeV
5.435 MeV
5.477 MeV
375
380
385
390
Channel Number

Figure 7b