FERMILAB PROPOSAL No. 305

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PROPOSAL TO STUDY THE COHERENT DISSOCIATION OF NEUTRONS

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May 22, 1974

Stage II of
Proposal FL 27

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PROPOSAL TO STUDY THE COHERENT DISSOCIATION OF NEUTRONS

Abstract

At Fermi Laboratory energies, neutrons can be coherently excited by nuclei with appreciable cross section. By coherent we mean that the target nucleus recoils as a single entity without excitation. This neutron excitation can occur either by γ absorption in the nuclear Coulomb field (Coulomb dissociation) or by Pomeranchukon exchange with the nucleus (diffractive dissociation). Both channels lead to the formation of $\pi^- p$ 2-pronged events. The two coherent processes can be identified and separated by their characteristic variation with neutron energy, momentum transfer, Z-dependence, effective mass and angular correlations. The former process (Coulomb) is dominated by Δ^0 (1236) production while the latter (diffractive) is dominated by N* (1470) production. Stage I of Experiment 27 has demonstrated that the experimental equipment can trigger cleanly on 2 prong events and that the two coherent processes can be observed and separated. Stage II of Experiment 27 has a number of goals which can be gathered into three broad categories:

I Measuring of the total neutron and anti-neutron cross section on a number of elements as function of the incident momentum by using Coulomb excitation as a tool for detecting neutrons and anti-neutrons.

II Studying the diffraction dissociation of neutrons off a proton target, as a function of incident energy, momentum and effective mass. A hydrogen gas target will be used for this purpose.

III Measuring the relative phase and spin dependence of the Coulomb and diffraction dissociation processes by using a partially polarized neutron beam and a variety of targets.

PHYSICS JUSTIFICATION

I. Status Report For Experiment 27

We summarize the accomplishments resulting from our equipment debugging run of November, 1973, and describe our first production run which took place during the recent running period in Spring, 1974.

Calendar Year 1973

Our equipment was set up in the M3 beam line at the Meson Laboratory during late summer of 1973. A run for debugging equipment and taking preliminary data was made in November, 1973. Analysis of the preliminary data was carried out and the results were reported at NAL (April 15, 1974) and at the Washington Meeting of the APS (April 22, 1974).

The findings from the run indicated that the data are essentially of the fine quality we had expected. We noted, in particular, that the $n \rightarrow p\pi^-$ dissociation studies for neutron momenta in excess of ~ 150 GeV/c were of excellent quality. The data at lower energies, however, appeared to have some contamination from three-body fragmentations of the neutron (i.e., $n \rightarrow p\pi^-\pi^0$ or $n \rightarrow \pi^+\pi^-n$). In addition, as a result of the revised configuration chosen for the experimental set up (e.g., the reduced distance between the target and analyzing magnet, chosen so as to increase the solid angle subtended by the magnet aperture and consequently our sensitivity to large-mass $p\pi^-$ systems), we found some difficulty in resolving sparks in the spark chamber nearest to the target box. As a result of this difficulty we built a more elaborate vertex-defining spark chamber just downstream of the production target. (Because of an accident during the clean-up period following the fire at the Meson Laboratory, we also had to replace one of our 5-plane 2 square-meter spark chambers, which was completely destroyed by a member of the clean-up detail.)

Spring 1974

The newly installed vertex-defining spark chamber provided the additional spatial information and accuracy required for an unambiguous reconstruction of the $p\pi^-$ tracks produced in the target. This improvement of the apparatus was particularly important for obtaining the best possible resolution at small values of t'.

During four weeks of data taking we collected ~ 600,000 triggers on various nuclei, ranging from Be to U. From an analysis of a small sample of the triggers we find that ~ 70% of these events correspond to acceptable $n \to p\pi^-$ dissociations. Consequently, we have aquired ~ 400,000 $p\pi^-$ dissociations of neutrons on nuclei. We have thus far processed only a small fraction of the data because we are still improving our reconstruction and spark-fitting techniques.

In addition to the study of neutron dissociation in the Spring, 1974 running period, we also performed a test of our method for measuring neutron-nucleus total cross sections. A series of nuclear targets were rotated periodically (under computer control) into the beam line at a point ~ 600 feet upstream of our thin Pb dissociation target. The ratio of the neutron dissociation rates with and without the upstream transmission targets provided direct measure of the total cross section for neutrons on nuclear targets.

The stability of the neutron flux for these studies was monitored using H. Haggerty's telescope of counters, the rates of which were found to be consistently proportional to those of our own neutron flux monitor. Approximately 200,000 triggers were recorded in ~ 4-5 days.

The Preliminary Data

Figure 1(a-c) displays the t' distributions for $n \to p\pi^-$ dissociation on C, Cu and Pb for neutron momenta in the range of 170 GeV/c to 230 GeV/c. We see the characteristic fall off in t' expected for coherent production from nuclei. Much of the cross section near t' = 0, particularly in Pb, can be attributed to Coulomb production of $p\pi^-$ systems. Figure 2 is taken from our proposal of February, 1971 and shows the expected distribution in t' for $n \to p\pi^-$ dissociation on Cu. Figure 3, which displays the $p\pi^-$ mass spectra at small values of t', clearly indicates the qualitative differences in the data as a function of Z. In Pb, Coulomb production (dominated by Δ (1236)) is far more copious than nuclear excitation of N* systems, while the opposite is the case in C (refer to Figure 4). Because of the expected Z^2 -dependence for the Coulomb excitation of the neutron, we can essentially ignore the small amount of γ -exchange in C. The difference in the $p\pi^-$ low-mass region between the Pb and C data, shown in Figure 5, is seen to closely resemble the shape expected for the $p\pi^-$ mass spectrum assuming that the difference in the shapes of the mass spectra is due to Coulomb production in Pb.

If Coulomb Δ production is the dominant process in Pb then an M-1 transition would require that the Δ decay proceed via a

$1 + 3/2 \sin^2 \theta$ dependence (in the t-channel). Figure 6 displays the Pb data for the Δ region ($t' < 0.002$ GeV ^{2}, and $M < 1.35$ GeV) and for the N* region ($0.002 < t' < 0.005$ GeV^2, and $1.35 < M < 1.5$ GeV). Clear differences between the two regions are apparent, and for each region the data are consistent with expectations from naive prejudices.(once small geometrical corrections are included).

Figure 7 displays our preliminary data for neutron total cross sections on nuclei. These results are based on ratios of triggers rather than on ratios of reconstructed events and could, consequently, be biased.

II. Physics Goals

The goals of the experiment are to make a number of fundamental measurements to elucidate the nature of the dissociation process and to measure neutron total cross sections. These measurements can be catagorized as follows.

1. $n + p \rightarrow N^* + p$ (Diffraction Dissociation)
   a) The cross section for the production of the various N*'s will be measured on hydrogen as a function of energy from 50 to 300 GeV/c. Based on observations between 10 and 30 GeV/c, it is expected that the diffractive cross section is relatively energy independent. Our measurements will extend the data to 300 GeV/c to test this conjecture.

   b) The t dependence of the differential cross section of the various N*'s will be measured from 50 to 300 GeV incident energy.

c) A search will be made for the production of high mass N*'s.

d) The mass dependence of the slope of the diffraction pattern will be measured to very high accuracy.

2. $n + A \rightarrow N^* + A$ (Relative Phase and Spin Dependence in Coulomb and Diffractive Dissociation)

a) The t dependence of the $n \rightarrow p\pi^-$ excitation will be measured for a variety of nuclei using a partially polarized neutron beam.

b) Interference effects between diffraction dissociation and Coulomb excitation will be studied to extract the phase of the nuclear diffraction process.

3. Total Cross Section

The total cross section on a variety of elements will be measured to better than 2% precision for 20 GeV/c intervals over an energy range from 50 to 300 GeV. These measurements will use the diffraction process to detect neutrons. This set of measurements, to be done early in the run, will extend the sample of data already taken in Stage I.

A high statistics measurement of the energy dependence of σ_T(n-A) is important in the light of rising total cross sections at FERMILAB energies, and a measurement of the A dependence would provide a necessary extention of low energy work in the determination of the scattering amplitude.

At a latter stage of the experiment we expect to install transmission targets of liquid hydrogen and deuterium to measure the np and nn total cross sections. This effort will depend on the results of the experiments presently making total cross section measurements and on our success in finding the anti-neutron components in the beam. We expect the integrated anti-neutron component to be 0.1% of the neutron flux but at 50 GeV it may be as high as 5%, although decreasing rapidly with energy. Even over an energy range from 50 to 100 GeV measurements of the total cross sections for np, nn, $\bar{n}p$ and $\bar{n}n$ are highly desirable.

APPARATUS NEEDED

I Immediate Improvements to Apparatus

To ascertain with greater accuracy the low-energy part of our data, and to improve the background rejection at the high-energy end of the neutron spectrum, we are building two detectors. One of these is a neutron detector/calorimeter 4 inches x 4 inches in cross sectional area. The calorimeter consists of 24 units of 1 inch thick slabs of iron sandwiched between 1/8 inch scintillator pieces. This detector is ready for use and will provide rejection of $n \to n\pi^+\pi^-$ dissociation background. (The small solid angle covered by the calorimeter will suffice for rejection of background in the coherent peak.) The other item we are building is a γ detector. A sketch of this device is given in Figure 8. The unit consists of eight layers of 1/4 inch lucite strips, with 36 strips per plane (sensitive area will be 72 inches x 30 inches), sandwiched with 1/4 inch Pb sheets as shown in the Figure. All eight layers of lucite for any particular transversely-positioned set of strips will be viewed through a single photo-tube. This detector will be extremely valuable for rejection of $n \to p\pi^-\pi^0$ dissociations at high energies, and will in fact, provide a useful sample of such events for study (see next item).

We are also rebuilding our large spark chamber which was accidentally destroyed in December, 1973. This chamber, in conjunction with the γ detector, will provide us with a π^0-measurement capability sufficiently powerful to examine the coherent production of $p\pi^-\pi^0$ systems. We expect the π^0 detector to be built in the summer of 1974.

II <u>New Equipment to Extend the Scope of the Experiment</u>

We are completing the construction of a high-pressure hydrogen gas target to be used for measuring neutron dissociation from hydrogen. We expect the hydrogen target to be ready by June, 1974.

From the Fermi Laboratory we shall be seeking modifications to the collimator to produce a polarized beam and eventually a liquid hydrogen deuterium transmission target for installation in the Meson Lab tunnels. (In Appendix II we resubmit a note on the design of a polarized neutron beam.)

III <u>Summary of New Apparatus and Finances</u>

Beam and Equipment:

1. The experiment will use the neutral beam M3 in the Meson Laboratory. It will be equipped with appropriate sweeping magnets, collimators, etc.
2. Experimental equipment will be located as it was for Experiment 27.
3. Fermi Lab will provide as additional equipment:
   a) Fast electronics from PREP amounting to $27,000
   b) Housing and venting for high pressure hydrogen gas target.

c) Modifications to collimator and appropriate remote controls to produce polarized beam.

d) 3,500 pounds of lead in sheet form.

e) 2 elevating tables.

f) Liquid H_2, D_2 transmission target.

4. The experimenters will provide as equipment additional to the already existing wire planes, counters and computer.

   a) High pressure hydrogen gas target and recoil detector. (Northwestern, Rochester and Fermi - $20,000).

   b) Neutron detector (Northwestern - $4,000).

   c) Shower detector (Northwestern, Rochester and Fermi - $15,000).

   d) Wire spark chamber (Northwestern, Rochester and Fermi - $2,500).

   e) Additional memory for PDP-15 computer (Rochester - $2,500).

5. Fermi Physics Department contributions to the above are:

   a) Engineering consultation, drafting and parts testing ~ 100 man hours.

   c) Assembly space, phototubes ~ $5,000.

   d) Assembly facilities and equipment - $1,000.

   e) Analysis time at Argonne - 360 - $10,000.

6. In addition, the Universities of Massachusetts, Northwestern, and Rochester will provide analysis time on their respective University computers totaling $30,000.

SCOPE OF THE EXPERIMENT

The experiment is presently set up in the M3 beam line and was recently fully operational. It is recognized that there are other experiments using the beam line and it is expected that our experiment will be interleaved with the running of the other experiments on a basis of about one month every four months through calendar 1975. On this basis we would expect to start running this summer on the high Z total cross section measurements. The neutron calorimeter will be added for this early running. The preparation of the high pressure hydrogen gas target for diffraction studies is being pressed and we expect to install and check it out towards the end of this running period.

For the fall running period we would install and check out the π^0 detector and then use the hydrogen gas target to carry out the diffraction dissociation studies. By spring we could install the polarized beam apparatus which in itself is fairly simple but which imposes sophisticated requirements on the software analysis. Next summer we would expect to carry out the liquid hydrogen transmission target measurements.

FIGURE CAPTION

Fig. 1 a), b) and c) t' distribution of the $p\pi^-$ system observed in the reaction $n + A \rightarrow p\pi^- + A$ for C, Cu and Pb targets.

Figure 2 t' distribution expected for the reaction $n + Cu \rightarrow p\pi^- + Cu$ for Coulomb dissociation, nuclear diffractive dissociation and incoherent N* (1470) production.

Figure 3 Effective mass distribution of the system $p\pi^-$ diffractively produced on C, Cu and Pb targets.

Figure 4 Expected Z dependence of the Coulomb and nuclear diffractive cross sections for the reaction $n + A \rightarrow A + p\pi^-$.

Figure 5 Effective mass distribution of $p\pi^-$ produced on Pb and C, normalyzed for masses above 1.6 GeV. Lower curve: the difference histogram of the two mass distributions compared to that expected for pure Coulomb production off Pb (solid line).

Figure 6 Angular distribution of the $(p\pi^-)$ in the low t' -region (Coulomb) and large t' - region (nuclear diffraction).

Figure 7 A - dependence of the neutron - nucleus total cross section estimated from trigger rates. (Indicated errors are only statistical.)

Figure 8 Scheme of equipment constructed (calorimeter) or under construction (spark chamber and shower counters) for detecting the diffractive channels $n \rightarrow n\pi^+\pi^-$ and $n \rightarrow p\pi^-\pi^0$.

FIGURE 1a

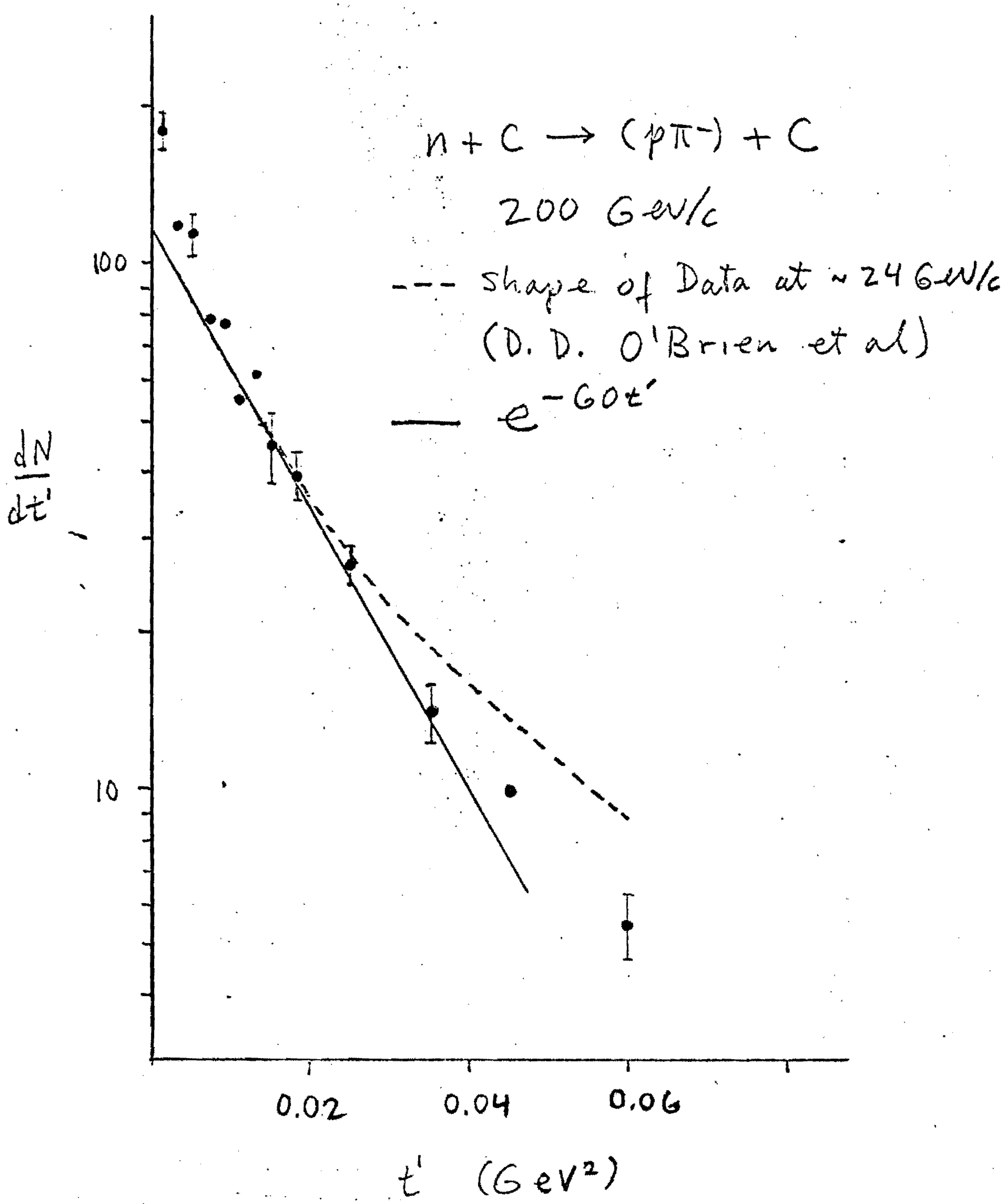

n + C → (pπ⁻) + C
200 GeV/c
--- shape of Data at ~ 24 GeV/c
(D. D. O'Brien et al)
— e^{-60t'}
100
10
dN/dt'
0.02
0.04
0.06
t' (GeV²)

FIGURE 1b

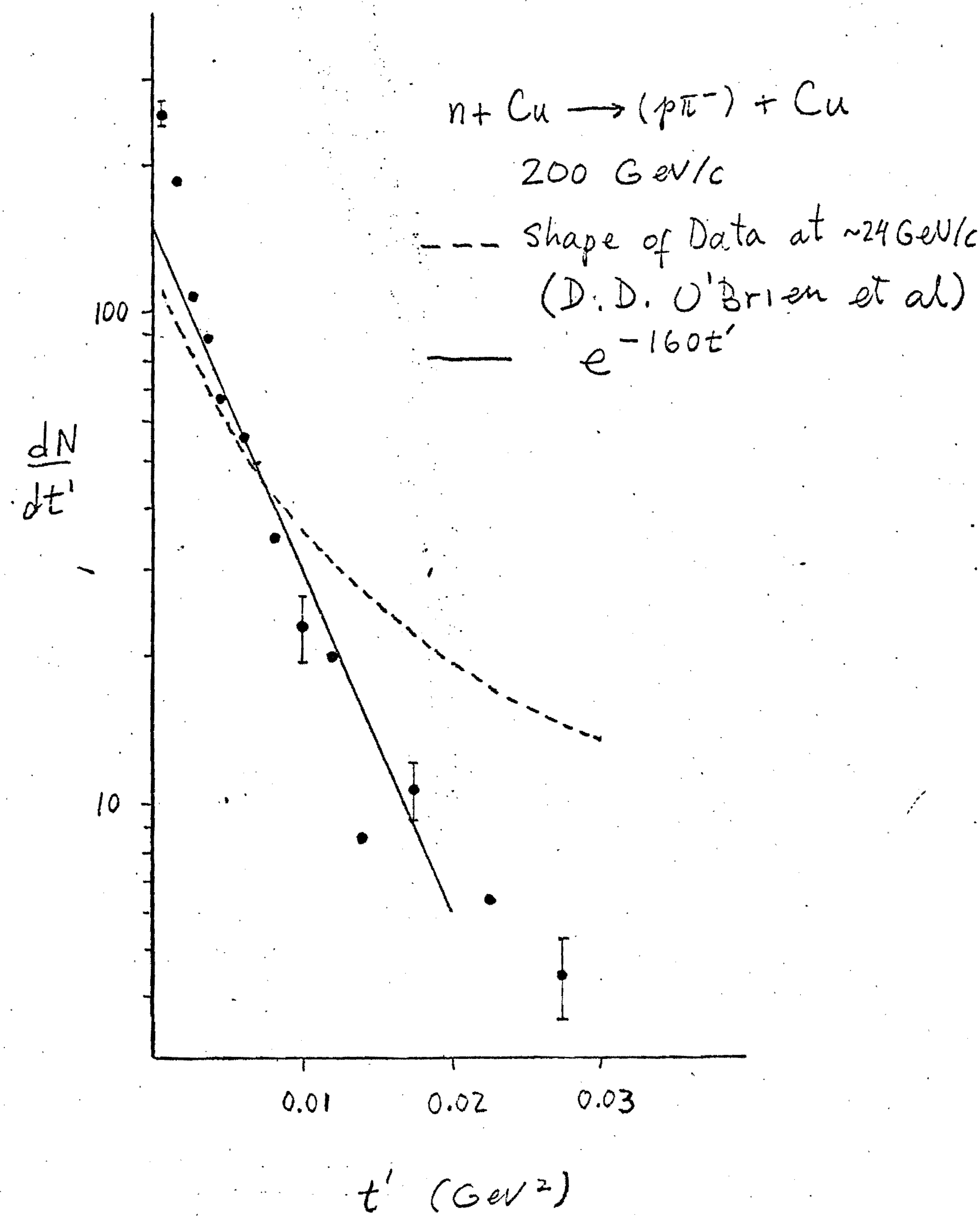
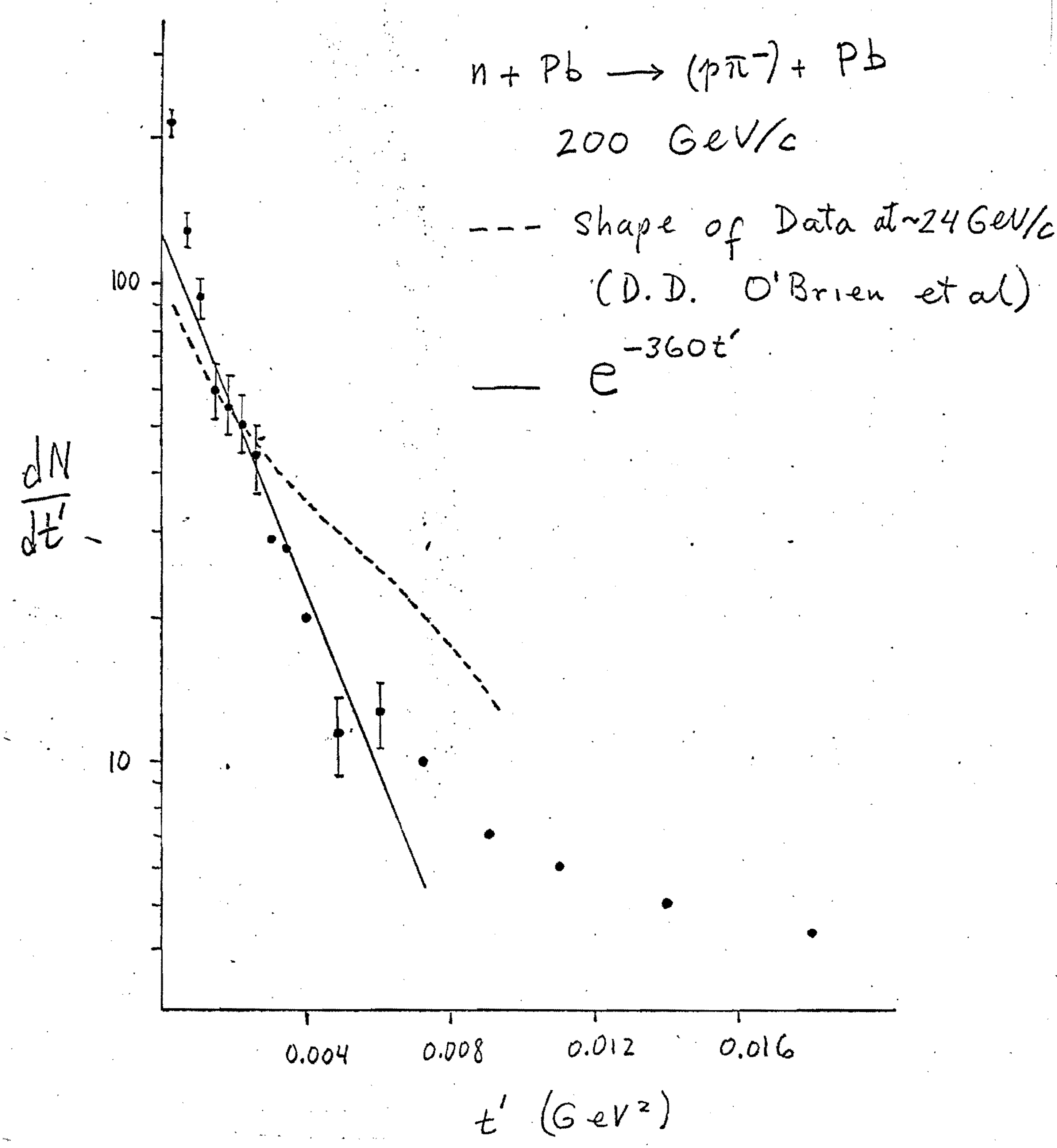

n + Cu → (pπ⁻) + Cu
200 GeV/c
--- Shape of Data at ~24 GeV/c
(D. D. O'Brien et al)
—— e^{-160t'}
dN/dt'
100
10
0.01
0.02
0.03
t' (GeV²)

FIGURE 1c



n + Pb ⟶ (pπ⁻) + Pb
200 GeV/c
--- Shape of Data at ~24 GeV/c
(D. D. O'Brien et al)
— e^{-360t'}
100
10
dN/dt'
0.004
0.008
0.012
0.016
t' (GeV²)

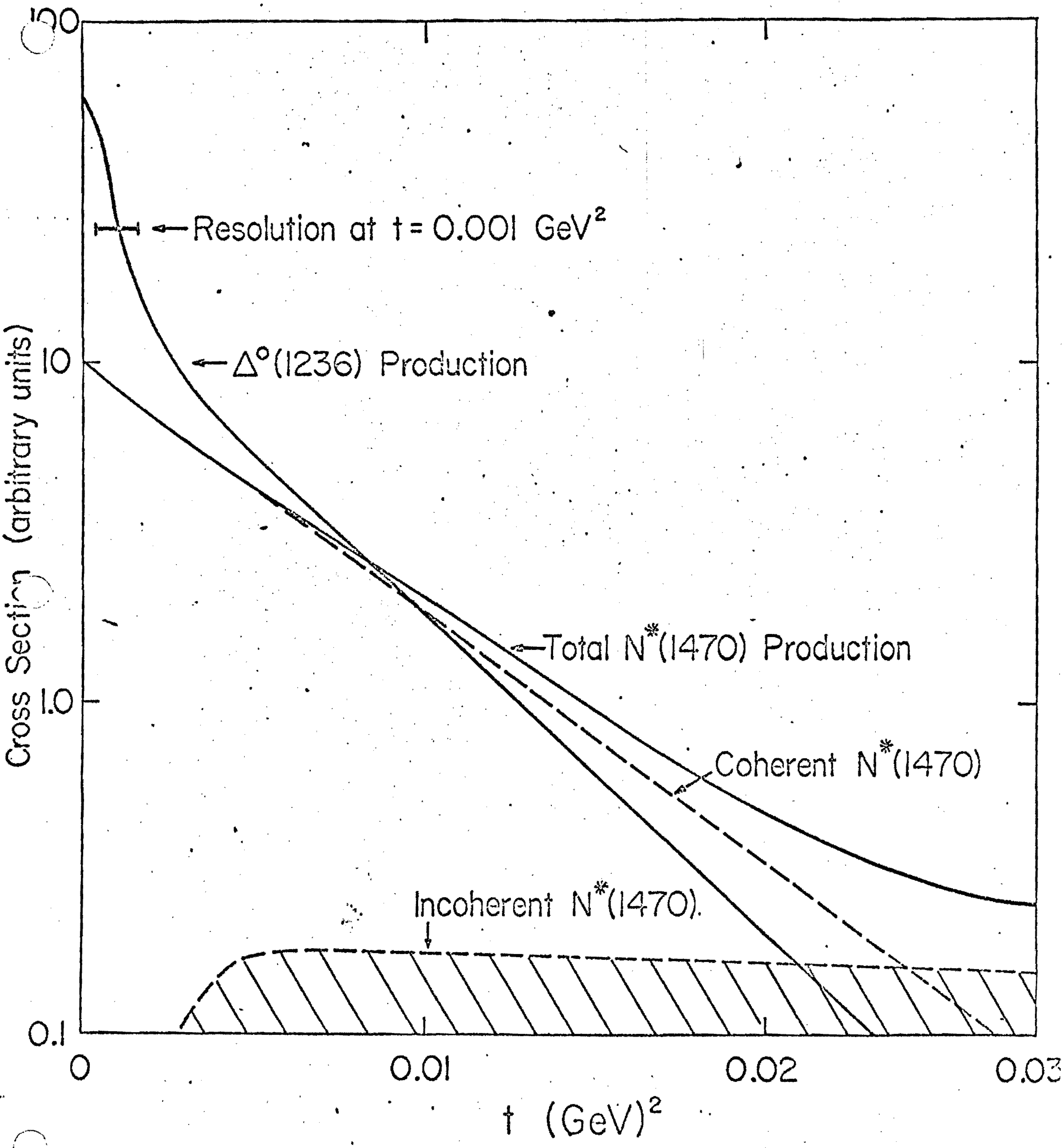
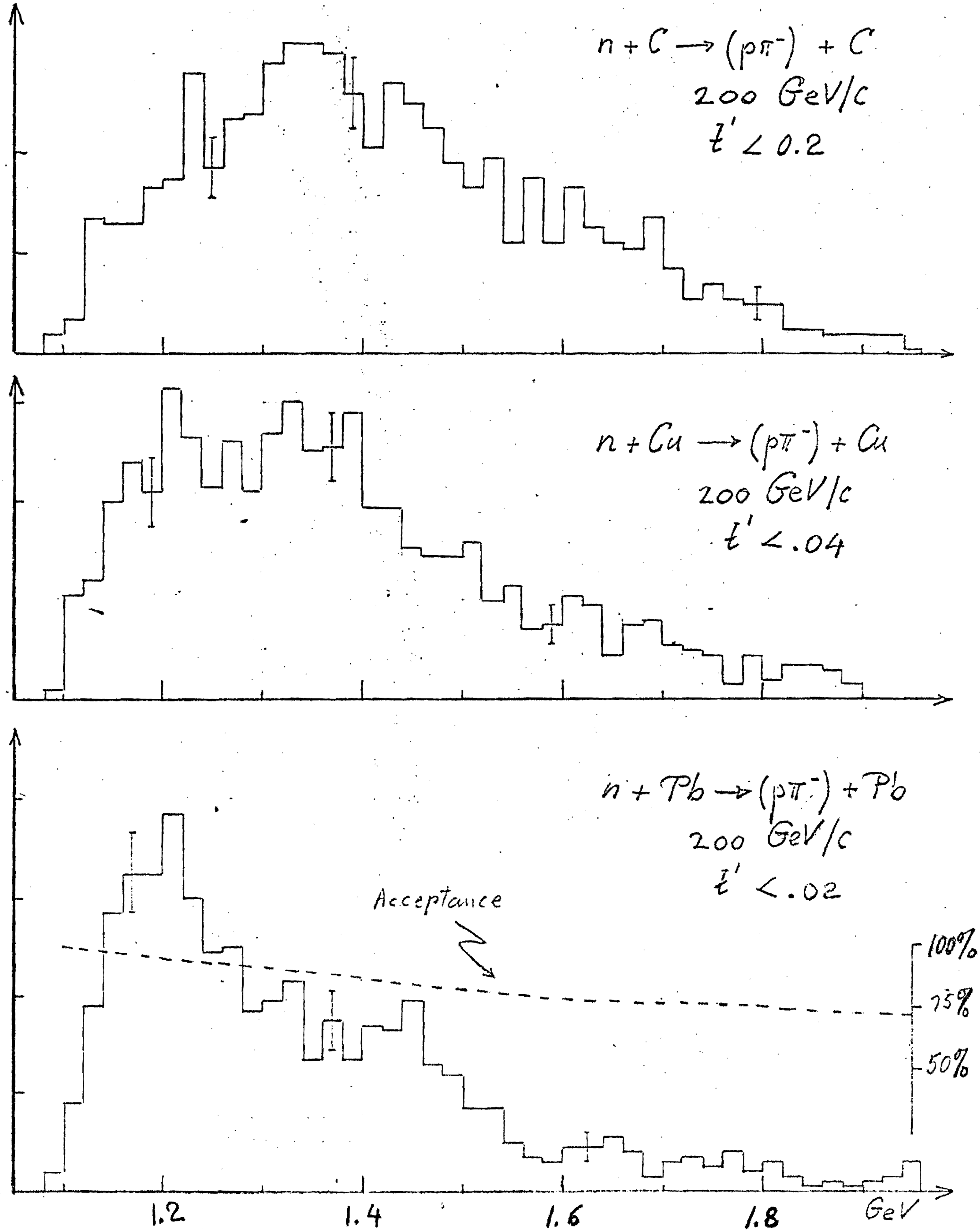


Fig. 2 Dissociation from Cu at 100 GeV

FIGURE 3



n + C → (pπ⁻) + C
200 GeV/c
t' < 0.2
n + Cu → (pπ⁻) + Cu
200 GeV/c
t' < .04
n + Pb → (pπ⁻) + Pb
200 GeV/c
t' < .02
Acceptance
100%
75%
50%
1.2
1.4
1.6
1.8
GeV

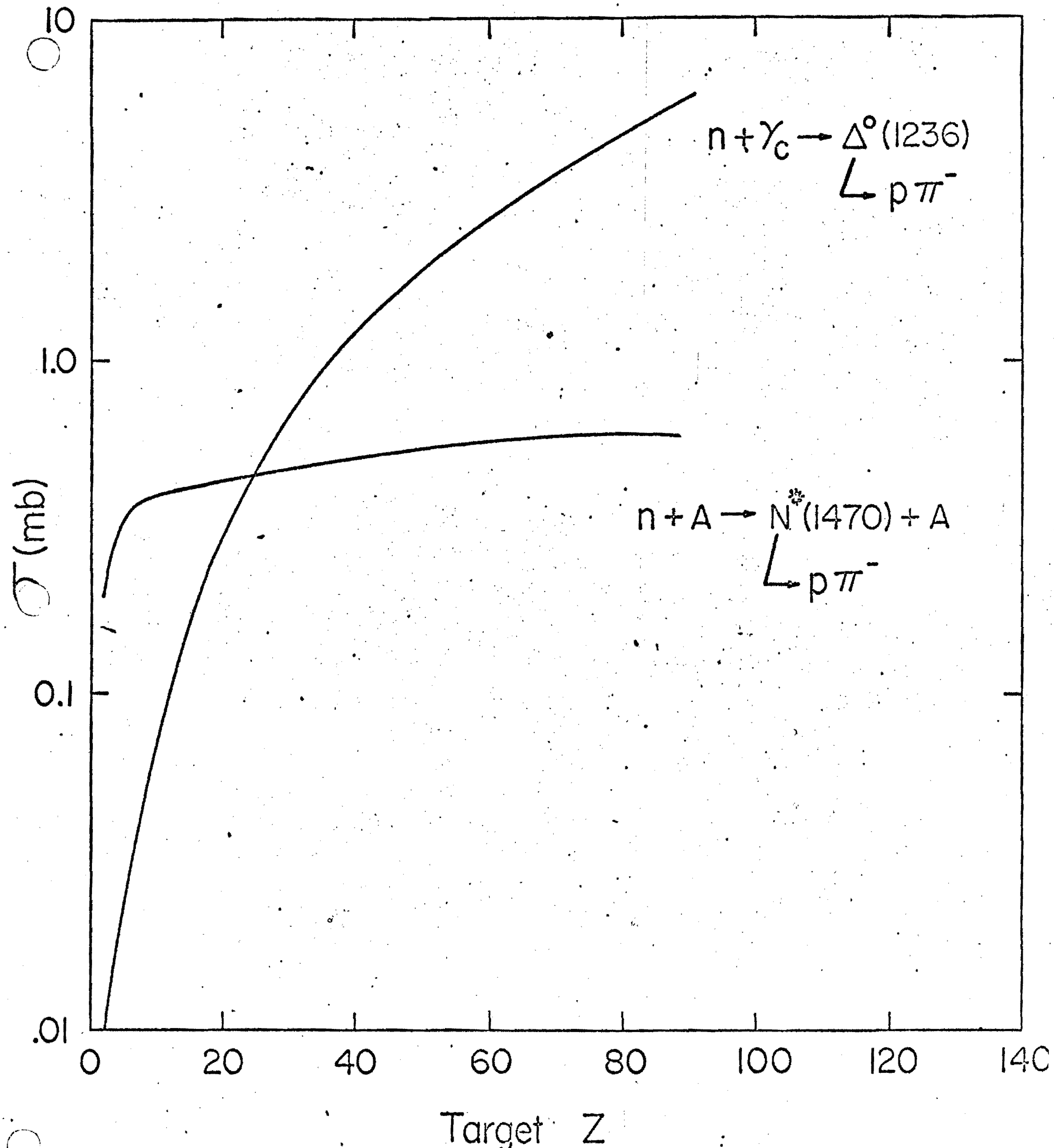
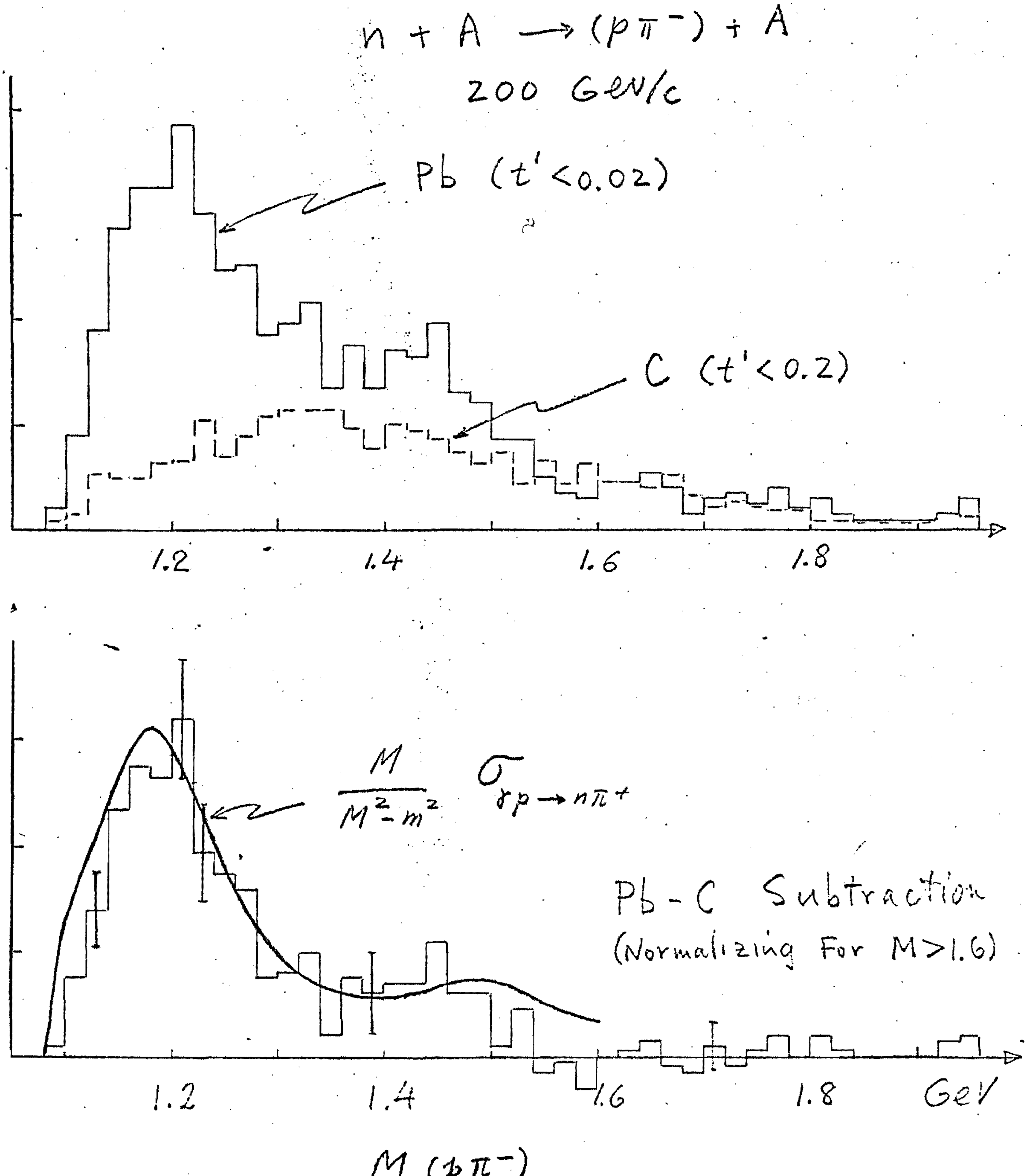
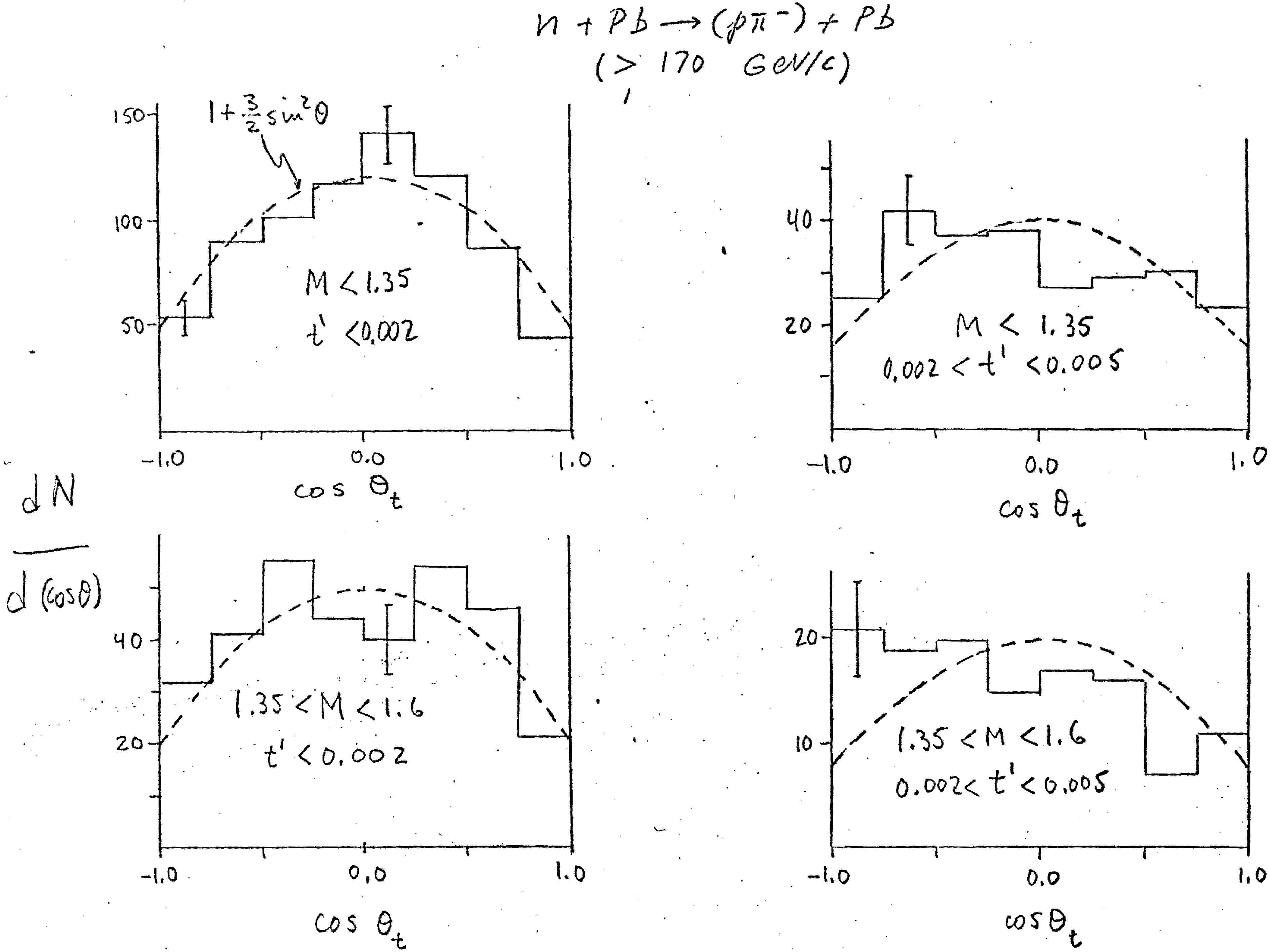


Fig.4 Dissociation Cross Sections at 100 GeV

FIGURE 5



n + A → (pπ⁻) + A
200 GeV/c
Pb (t'<0.02)
C (t'<0.2)
1.2
1.4
1.6
1.8
M/(M²−m²) σ γp→nπ⁺
Pb−C Subtraction
(Normalizing For M>1.6)
1.2
1.4
1.6
1.8
GeV
M (pπ⁻)



n + Pb → (pπ⁻) + Pb
(≳ 170 GeV/c)
1 + 3/2 sin²θ
M < 1.35
t' < 0.002
M < 1.35
0.002 < t' < 0.005
1.35 < M < 1.6
t' < 0.002
1.35 < M < 1.6
0.002 < t' < 0.005
dN / d(cosθ)
cos θ_t

FIGURE 6

σ_T (n + A)

includes all momenta 0-300 GeV/c with

<P> ~ 240 GeV/c

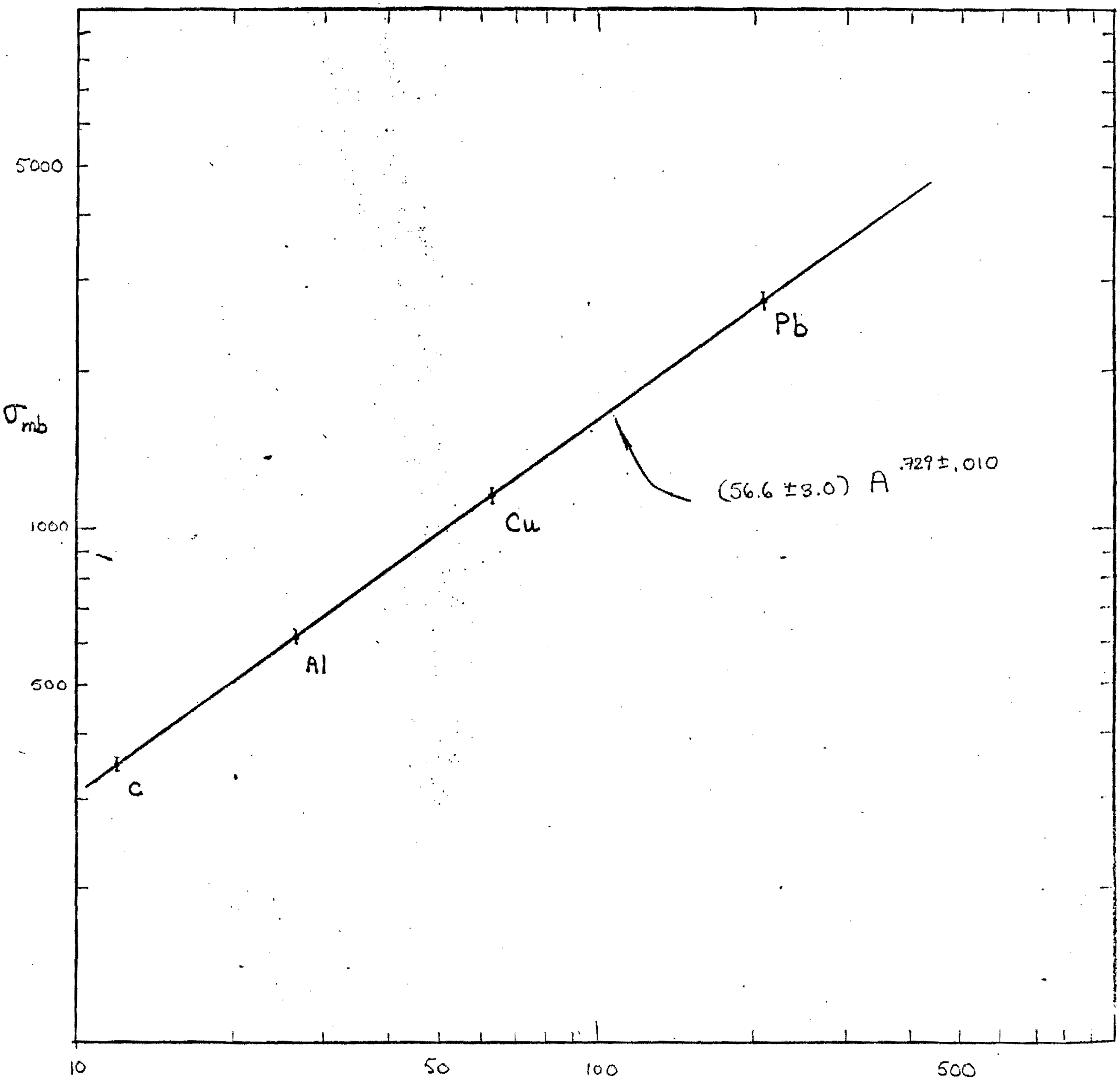
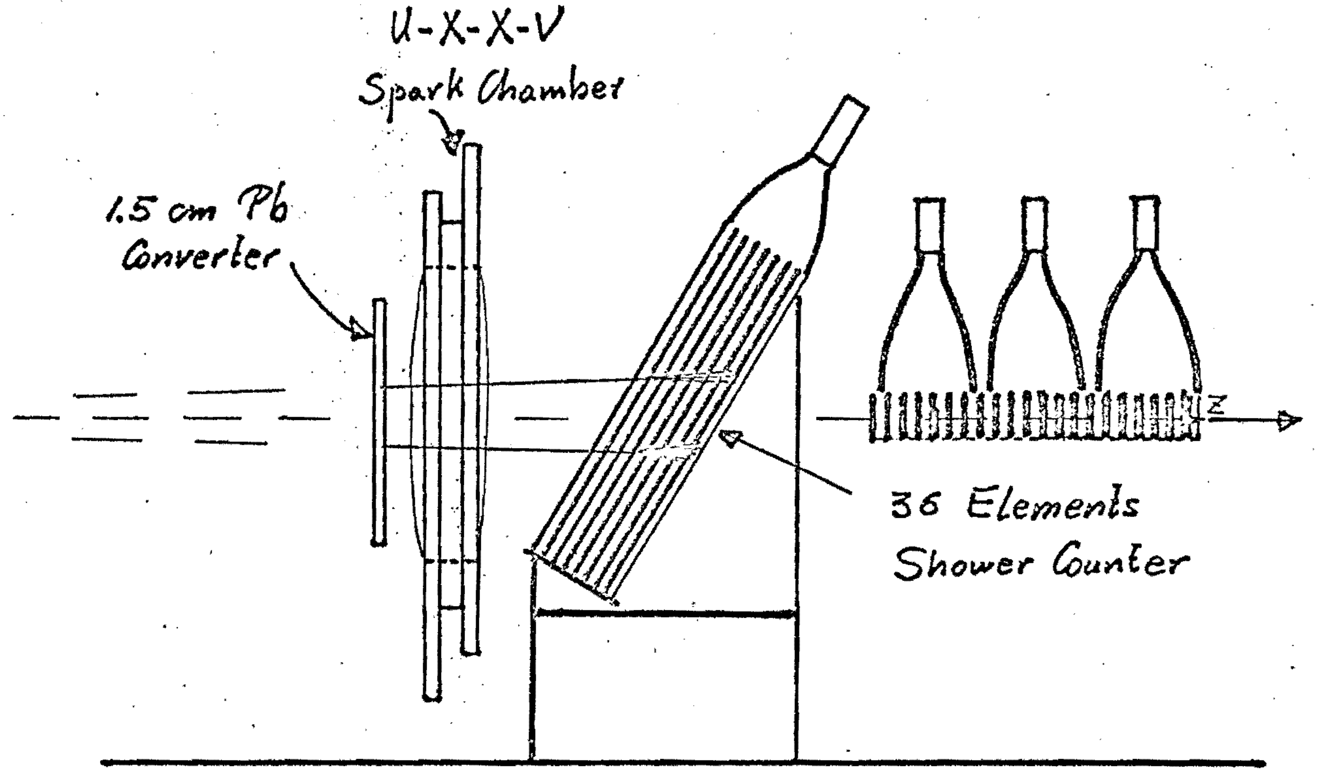


FIGURE 7


U-X-X-V
Spark Chamber
1.5 cm Pb
Converter
36 Elements
Shower Counter
Z

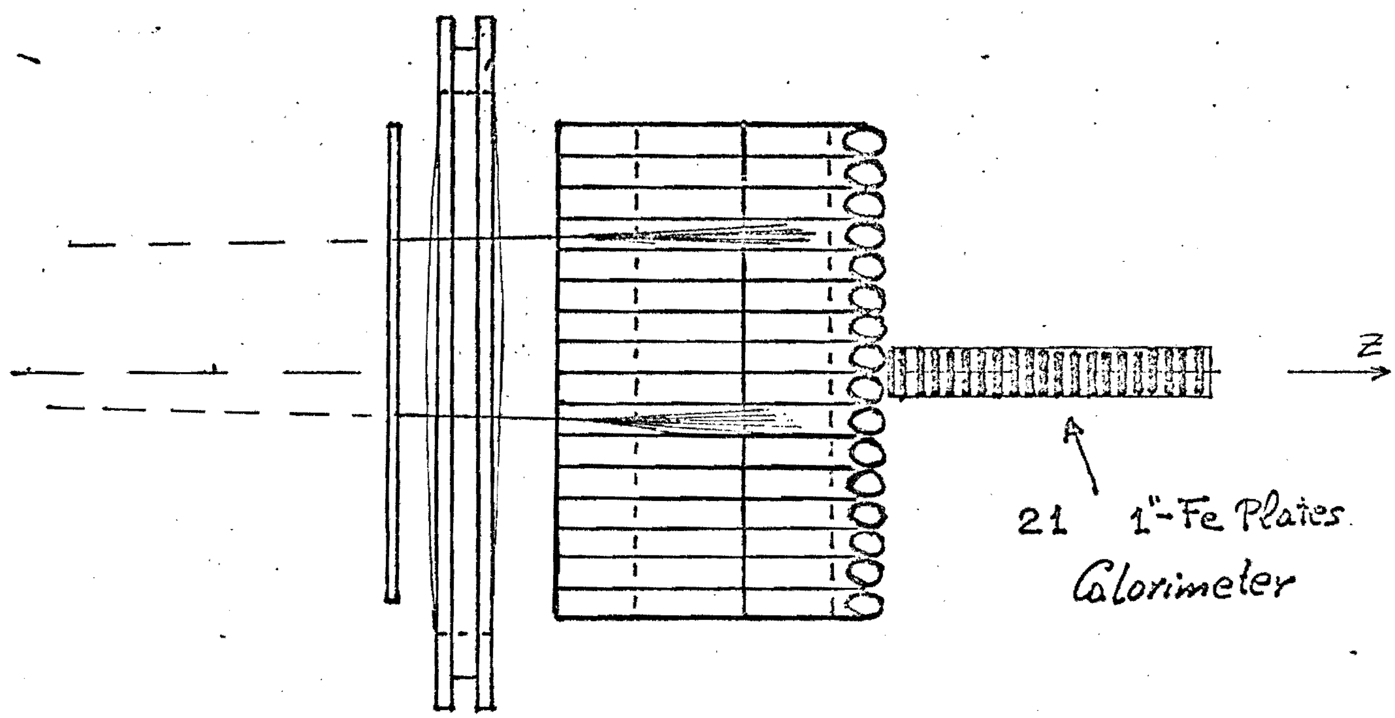

Z
21 1"-Fe Plates
Calorimeter

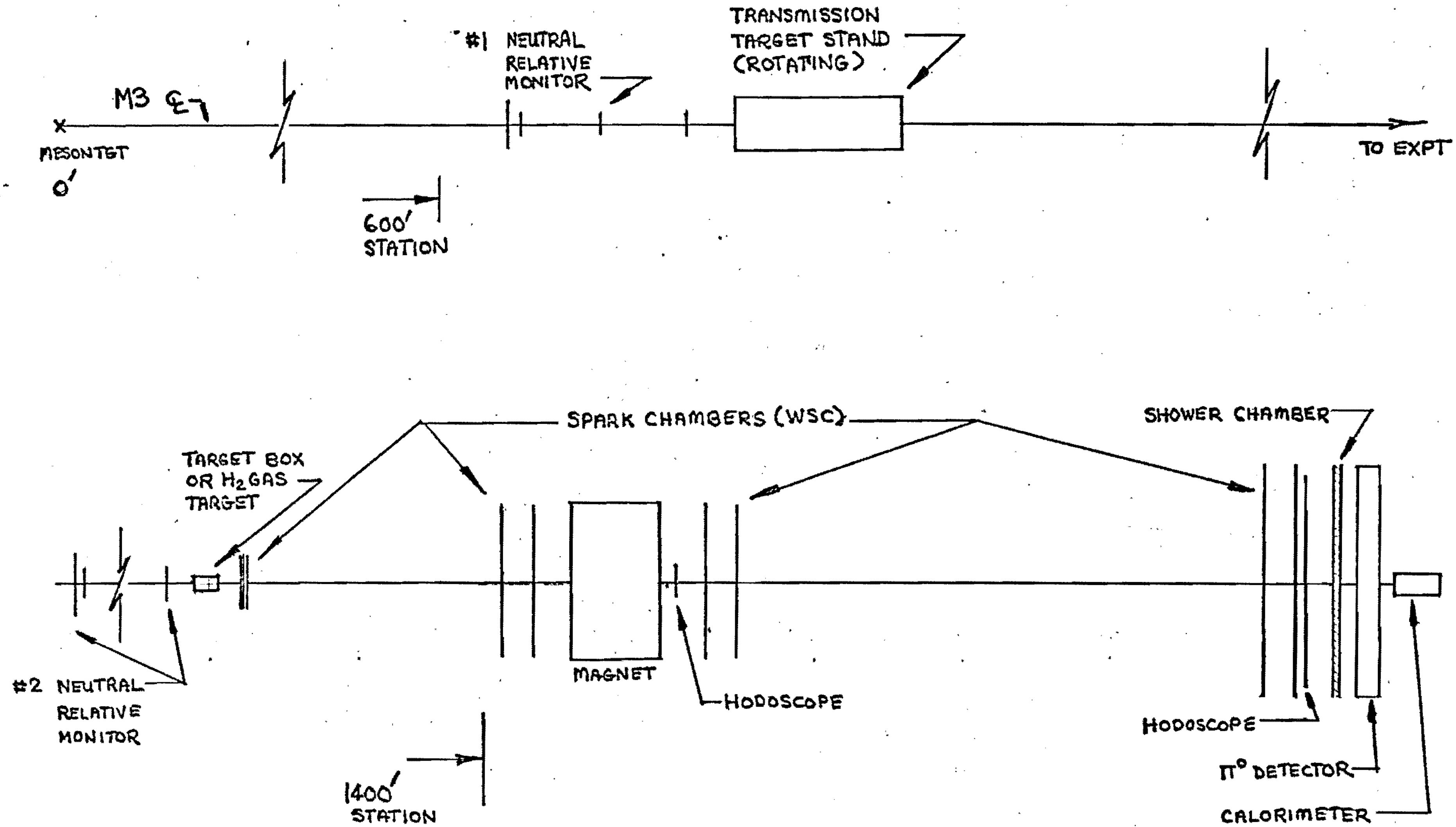
FIGURE 8

APPENDIX I

Experimental Layout

Figure AI-1 shows the experimental layout. The M-3 neutral beam is incident on the Target Box or the H_2 Gas Target. Downstream of the Target Box is a wire spark chamber spectrometer using 4 sets of chambers and a magnet. Scintillation counters are arranged to trigger the wire chambers when two and only two charged particles are produced in the target. This triggering system which is based on an array of anti-counters around the target has worked very successfully.

To make total cross section measurements a transmission target is placed in the beam at Z = 600' and the target box and spectrometer are used as a neutron detector. To study diffraction dissociation the target box is replaced by a hydrogen gas target which incorporates in the gas volume counters to detect recoil protons. To make a polarized beam the collimator at Z = 300' is modified. The spectrometer remains as it is since it has sufficient aperture to deal with the larger diameter polarized beam.



AI - 1

E27 LAYOUT (SCHEMATIC)

APPENDIX II

Design of a High Energy Polarized Neutron Beam For FNAL

Abstract

A simple procedure for polarizing a high energy neutron beam is proposed. A specific arrangement appropriate to the M3 beam line is described. The design characteristics are: $> 10^5$ neutrons/10^{12} interacting protons on target, effective energy range (150-300) GeV, mean polarization 20-25%.

If neutrons scatter elastically at very small angles from a nuclear target there are two coherent channels or mechanisms for such scattering.

1. Nuclear diffraction scattering
2. Magnetic scattering - the magnetic moment of the neutron experiences a magnetic force due to the moving coulomb charge of the nucleus Ze.

The scattering distribution is given by

$$\frac{d\sigma}{dq^2} = \pi e^{-bq^2} \left[\frac{\sigma_T}{4\pi} + \frac{Z\,\alpha\,\mu}{M_N\,q}\,(\vec{\sigma}\cdot\hat{n})\right]^2 \qquad (1)$$

where

q^2 = (momentum transfer)^2 = $p^2\theta^2$

b = slope parameter of the nuclear diffraction pattern ($\approx$ 400 (Gev)$^{-2}$ for Pb)

σ_T = total cross section ($\approx$ 3200 mb for Pb)

α = fine structure constant

μ = magnetic moment in nuclear magnetons = -1.91

M_N = mass of the neutron

$\vec{\sigma}$ = 2 x spin vector of the neutron

$\hat{n}$ = normal to the scattering plane = $\hat{p} \times \hat{p}'$

A number of approximations all good to high accuracy have been employed

(i) Ultra-relativistic approximation.

(ii) The diffraction form factor has been parameterized in the usual form e^{-bq^2}. This is quite reasonable for $bq^2 \leq 1$. For simplicity the charge form factor has been set equal to the nuclear form factor. b_{charge} is a bit smaller than b and a small correction could be incorporated if desired.

(iii) The optical theorem has been used to replace f(0) by Im[f(0)] = $\frac{k\sigma_T}{4\pi}$.

The magnetic term is intrinsically imaginary and interferes with Im[f(0)]. We have neglected $\{Re[f(0)]\}^2$. Although the complex scattering amplitude for neutrons has not been measured, we anticipate that it behaves similar to that of the proton. A real part as large as 10% would constitute a sub 1% correction to our present considerations.

Some intuitive feeling for the above formulae can be obtained by recalling the well known expression for the high energy scattering of charged hadrons and replacing the usual Coulomb amplitude factor $2Z\alpha/q^2$ by

$$i\,\mu\,\left(\frac{q}{2M_n}\right)\,(\vec{\sigma}\cdot\hat{n})\,\frac{2Z\alpha}{q^2}$$

Such a magnetic term is usually neglected in a discussion of the small angle scattering ($q/M << 1$) for charged hadrons.

[We thank Professor R. Oakes for showing us an elegant and simple way of deriving the convariant magnetic amplitude in terms of the well known coulomb amplitude.]

Equation (1) is of the form $A+B(\vec{\sigma}\cdot\hat{n})$ so that scattering at small angles introduces polarization into an otherwise unpolarized incident beam. This technique for polarizing neutrons is really quite old having been proposed in 1948. ["On the Polarization of Fast Neutrons" - J. Schwinger, Physical Review 73, 407 (1948)]
By fast neutron, Schwinger meant 1 mev so that his formulation is not directly appropriate to NAL energies. The successful exploitation of the nuclear spin orbit interaction in polarization studies at low and medium energies has resulted in the languishment of Schwinger's proposal.

Let q^* = the value for which the diffractive and magnetic amplitudes are equal.

$$q^* \equiv \frac{4\pi\ (Z\alpha)\ \mu}{\sigma_T\ M_N} = 1.87\ \text{mev/c} \qquad (2)$$

Then

$$\frac{d\sigma}{dq^2} = \frac{\sigma_T^2}{16\pi}\, e^{-bq^2} \left(1 + \frac{q^*}{q}\vec{\sigma}\cdot\hat{n}\right)^2$$

$$\text{Polarization} = \frac{2qq^*}{q^2 + q^{*2}}$$

A specific scheme developed for the M_3 beam line (1.75 mr. neutral beam) is sketched in Figure 1. A partially polarized beam is produced with the profile properties shown in Figure 2. Table I lists the beam properties estimated on the basis of Equation (1).

Consider Figure 1. The beam is collimated to 4 mm diameter at 113 m from the production target. A collimator and plug (> 6 interaction lengths) is carefully positioned at 320 m so as to block the primary beam. Precision collimators and remote controls are called for. After this alignment a 2 cm Pb scattering target is placed after the first collimator. This target is ≈ 20% of an interaction length so that ≈ 10% of the primary beam elastically scatters. The beam characteristics described in Figure 2 and Table I results.

In order to use this beam the subsequent physics experiment must be of such nature that the transverse position of the neutron interaction point is measured. Only then is a scattering plane defined. The study of the spin structure of diffractive dissociation is ideally matched to the polarization capability. The detection of the coherent $\pi^- + p$ final state automatically provides the interaction transverse coordinates to better than mm accuracy.

The beam thru the 4 mm hole at 113 m should be $\sim 10^7$ n (150-300 Gev)/ pulse -10^{12} protons interacting on target. Some 10% of these will be scattered. According to Table I $\sim$ 20% (of the 10%) will be used at the experimental end and a mean polarization of (20-25)% will exist. Thus > (10^5/pulse) neutrons will be available. This is quite sufficient for a high statistical accuracy study of coherent dissociation.

In our previous studies, we measured 23 Gev proton coherent dissociation at B.N.L. We collimated the beam flux to $\sim$ 70k/pulse. In an 80 hour experiment we recorded $\sim$ 900k triggers for 9 elements. Some 200k coherent events survived various selection criteria. We expect to do better at N.A.L.

Considerable phenomenological theory work needs to be done in order to systematize the studies we have in mind. We do know that some polarization must be manifest as a result of the interference between Coulomb and Diffractive dissociation.

Table I

E(Gev)	$q_{av}(\frac{mev}{c})$	Polarization %	*Useful fraction of scattered beam (%)
300	21.8	17	30
250	18.1	21	22
200	14.5	26	15
150	10.9	34	9

*fraction = $[e^{-b\,p^2\theta_{min}^2} - e^{-b\,p^2\theta_{max}^2}]$

$b = 400\ (\text{Gev})^{-2}$

$\theta_{min} = 3.6\text{x}10^{-5}$

$\theta_{max} = 1.1\text{x}10^{-4}$

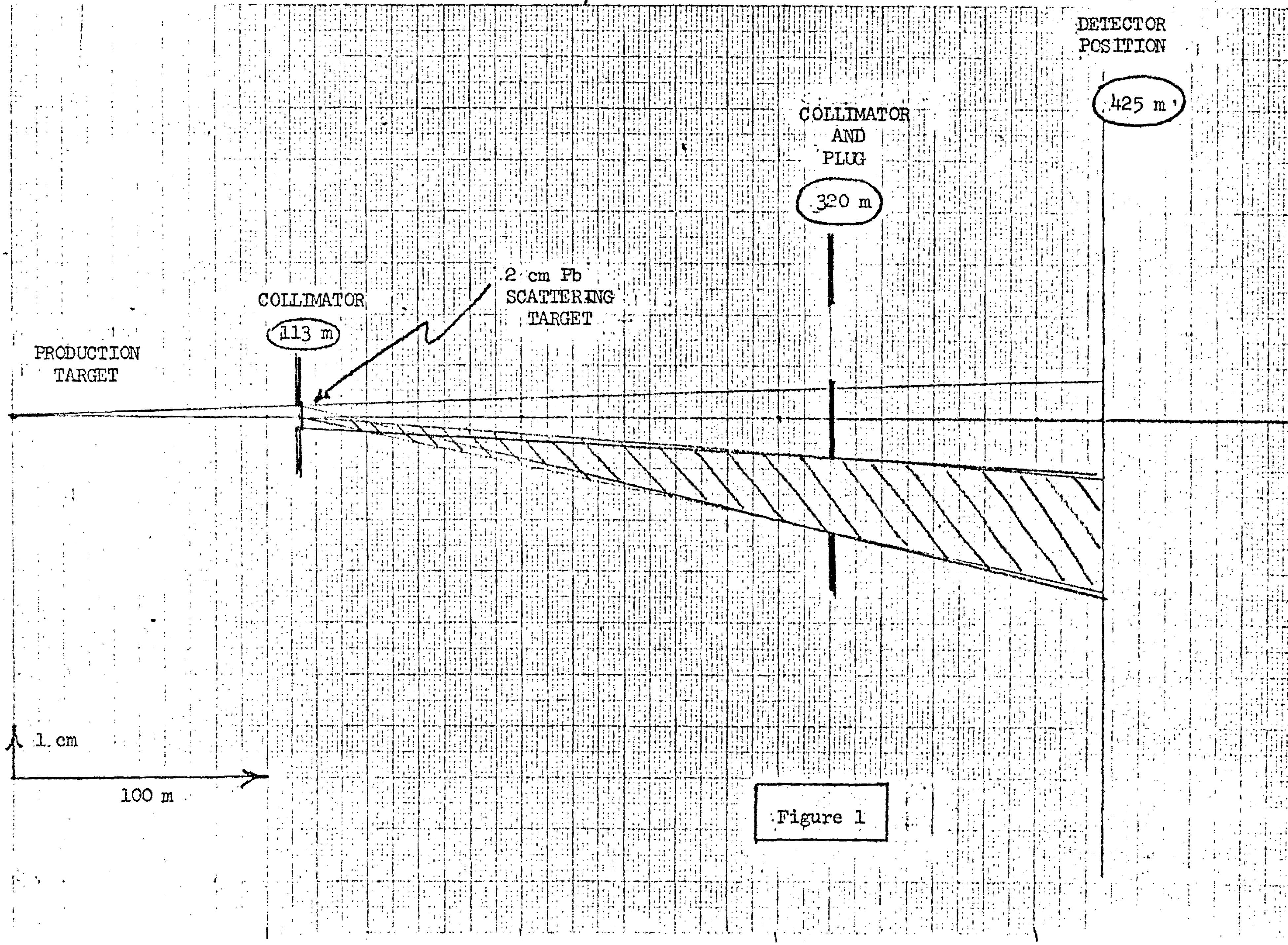
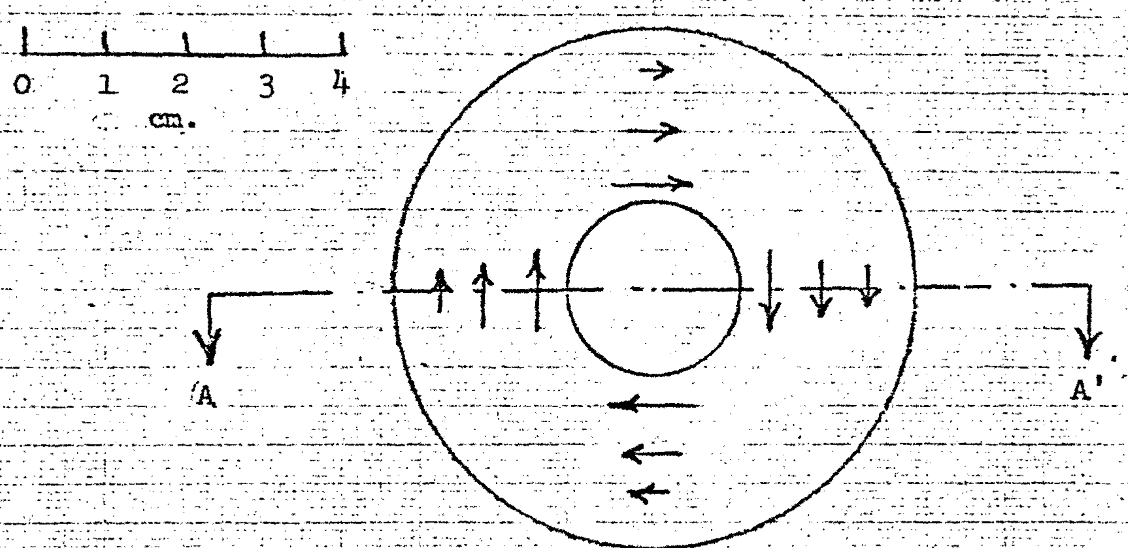

DETECTOR
POSITION
425 m
COLLIMATOR
AND
PLUG
320 m
2 cm Pb
SCATTERING
TARGET
COLLIMATOR
113 m
PRODUCTION
TARGET
1 cm
100 m

Figure 1



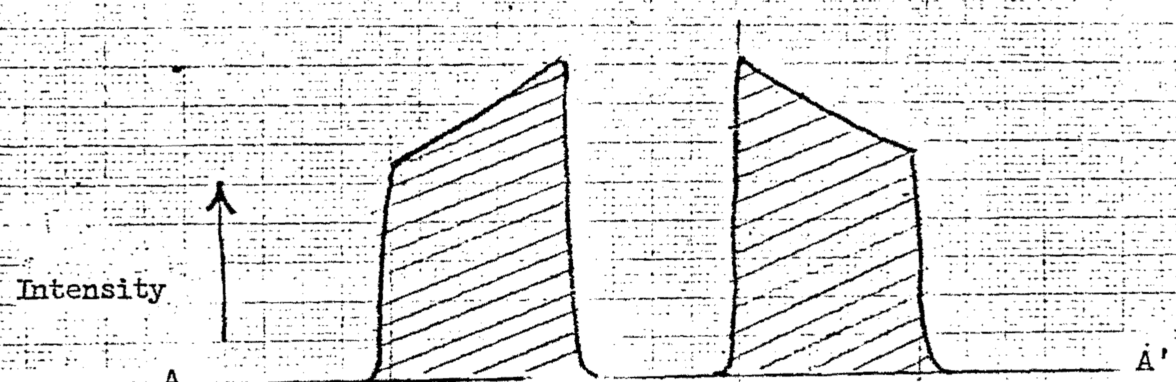


Figure 2. The upper figure displays the beam profile and the spin polarization orientation looking upstream.

The lower figure is a section profile.