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A PROPOSAL TO STUDY ELASTIC PROTON-PROTON SCATTERING IN THE RANGE $0.1 < |t| < 3\ (\mathrm{GeV/c})^2$ FROM 50 TO 500 GeV AT NAL

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ABSTRACT

We propose measuring the pp elastic scattering cross sections for incident momenta between 50 and 500 GeV/c and for $0.1 \lesssim |t| \lesssim 3.0\ (\mathrm{GeV}/c)^2$. The experiment will be performed in the P-West area and will employ a liquid hydrogen target and the existing 2.4 GeV/c recoil spectrometer. In addition, the forward scattered protons will be detected in a high spatial resolution, small angle hodoscope which will permit separation of elastically scattered protons from the inelastic background.

I. INTRODUCTION

We propose making a high statistics study of the energy dependence of the p-p elastic scattering cross section. The measurements will be made at beam momenta of 50, 100, 200, 300, 400 and 500 GeV/c and will cover the region $0.1 \lesssim |t| \lesssim 3.0\ (\mathrm{GeV/c})^2$. The detection system will include the 2.4 GeV/c recoil spectrometer and its instrumentation, which is presently being assembled in the Proton-West area in preparation for Experiment 63.[1] In addition, a small angle, high spatial resolution scintillation counter hodoscope will be used in coincidence with the spectrometer detectors to tag those events for which the scattering angles are consistent with elastic scattering kinematics. There are several characteristics of the proposed experiment which make it especially appealing:

1) In the Proton Laboratory, as distinct from the Meson Laboratory, it will be possible to explore the elastic reaction up to 400 or 500 GeV incident energy. The ISR data[2] indicate that there is little further energy dependence beyond this. Thus a single measurement, covering the entire transition energy range from existing AGS and PS energies up to the "asymptotic" regime, is clearly extremely interesting.

2) The experiment employs primarily equipment and facilities which now exist or are being built. The only exceptions are the small angle hodoscope and modifications of the beam pipe downstream of the spectrometer.

3) The acceptance of the recoil spectrometer and the expected P-West beam intensities are adequate to provide good statistics over the full $|t|$ range proposed. In addition, the beam intensity and target thickness will both be measured accurately (hopefully to 1 or 2%) thereby permitting good absolute measurements and perhaps more important, an accurate extraction of the s dependence of the data. Indeed, special toroids have already been built and tested and will record the beam intensity to 1%, independent of energy.

4) Measurements in the Proton-West laboratory have shown sufficiently low background rates with scintillators of roughly the size of interest in this proposal. Thus, we do not anticipate difficulties in operation of a hodoscope at the small angles proposed herein.

II. GENERAL PHYSICS MOTIVATION

The p - p elastic differential cross sections measured at the ISR[2] for $1.0 \lesssim |t| \lesssim 4.0\ (\mathrm{GeV/c})^2$ have two extremely interesting features (Figure 1):

1) The cross sections $d\sigma/dt$ at any given t at 500 GeV/c and 1500 GeV/c are essentially equal.

2) The shoulder in $d\sigma/dt$ observed between ~10 and 30 GeV/c has, by 500 GeV/c, developed into a pronounced dip.

A high statistics study of the cross section in the NAL energy range could be very revealing. The development of the diffractive dip from the low energy shoulder and the s dependence of its position and depth are of special interest.

At lab momenta below ~ 30 GeV/c, $d\sigma/dt$ at constant $|t|$ (~ 1.5 $(GeV/c)^2$ for example) has a fairly pronounced energy dependence[3] (~ $1/s^3$). The ISR results indicate that the NAL energy range of 50 to 500 GeV covers the transition from a power law description of the cross section to the asymptotic energy independent region.

We intend making a careful study of the s and t dependence to high accuracy for this reaction over the full energy range available. The justification for doing this experiment does not lie in proving or disproving any particular model. Rather, the fundamental nature of this reaction together with the obvious changes which must take place in the NAL energy range demand that the highest quality data be obtained.

III. EXPERIMENTAL DESIGN CONSIDERATIONS

In designing this experiment, two approaches have been considered:

1) Detection of the recoil proton alone.

This would require improvement of the characteristics of our spectrometer allowing detection of the recoil proton with high resolution in terms of both production angle and momentum.

2) Application of a coincidence technique.

This would involve detection of the recoil proton using the existing spectrometer with its moderate resolution and detection of the forward scattered proton with high spatial resolution.

We shall refer to these two approaches as systems I and II. The choice of system depends on consideration of inelastic backgrounds. Allaby et al.[3] have observed sizable production cross sections for the low mass (1400 to 2200 MeV) nucleon isobars at 24 GeV/c. For example, $d\sigma/dt$ for $N^*(1400)$ production for $1.0 \leq |t| \leq 1.5$ $(\mathrm{GeV/c})^2$ may be half of the elastic cross section. It is difficult to estimate the s dependence of the N^* cross sections at NAL energies but the available data[3] at $s < 50$ GeV^2 indicate that the diffractively produced N^*'s and the elastic cross section have similar s dependence. In the NAL energy range, the elastic cross section for $|t| \simeq 1.5$ $(\mathrm{GeV/c})^2$ falls by about a factor of forty. A worst case analysis would involve the assumption that the $N^*(1400)$ cross section did not fall at all with energy. This would give a ratio of $N^*(1400)$ to elastic cross section at $|t| = 1.5$ $(\mathrm{GeV/c})^2$ and 500 GeV of 20 to 1. We base the following discussion on the more optimistic assumption that the ratio is unity. We shall show that in this case:

a) System I.

Recoil proton detection with $\pm 0.1\%$ momentum resolution and arbitrarily good angular resolution is insufficient to separate the elastic from inelastic background.

b) System II.

A coincidence technique provides a clean separation of the elastic scattering from inelastic processes.

We first consider the situation of a high resolution recoil spectrometer, namely system I. Figure 2 shows a calculated mass spectrum for a spectrometer with a momentum resolution of $\pm 0.1\%$ and arbitrarily good angular resolution at $|t| = 1.5\ (\mathrm{GeV}/c)^2$ and 500 GeV/c. Clearly, the separation of the elastic from the inelastic background requires a momentum resolution which is significantly better than $\pm 0.1\%$ and in addition a thorough understanding of the tails of the resolution function. It should be emphasized that this is the most interesting kinematic region, namely the region of the dip in the elastic cross section at high energy. We conclude, therefore, that this technique may not be adequate.

We consider now system II in which a coincidence measurement is made. In this case, we use the kinematic constraints to eliminate the resonant and nonresonant background. We expect the most difficult background to be due to production of the low mass nucleon isobars, in particular the $N^*(1400)$, (1520), and (1688) which have significant production cross sections and whose production angles are nearly identical to those for elastic scattered protons. The distribution of the nucleon direction in the $N^* \rightarrow N\pi$ and $N\pi\pi$ decays is peaked at 0° and 180° in the cms[4] so that the laboratory decay distribution will peak directly under the true elastic events. In order to subtract the inelastic background we must have an angular resolution for the fast forward proton of about 0.1 mr at 500 GeV/c and 5 mr at 100 GeV/c. Figure 3 shows the calculated distribution of events in a coincidence hodoscope at 500 GeV assuming equal cross sections for elastic scattering and $N^*(1400)$ production. In addition, the more massive isobars, which are included within the recoil spectrometer mass resolution, are estimated to have an integrated cross section twice as large as the elastic. We have also included a nonresonant background which is assumed to have a cross section roughly equal to the resonance production cross section. A signal to noise ratio of about 15:1 is obtained.

In summary, a comparison of Figs. 2 and 3 shows conclusively that the cleanest identification of elastic scattering at these energies is by means of the coincidence technique rather than improvement of the resolution of our spectrometer. Even if the inelastic background was an order of magnitude worse than we have estimated we would still obtain rather clean separation of the elastic cross sections in all cases. Of course, at other momentum transfers or less than 500 GeV the elastic peak should be able to be separated more easily from the background.

IV. EXPERIMENTAL METHOD

Figure 4 shows a schematic of the proposed apparatus in the P-West area. The 2.4 GeV/c spectrometer will require no modifications whatsoever. The kinematics for the recoil proton, which are very insensitive to the incident momentum, are shown in Fig. 5. To cover the region $0.1 \lesssim |t| \lesssim 3.0$ $(\text{GeV}/c)^2$, we will detect recoil protons in the region $47^\circ \leq \theta_{recoil} \leq 80^\circ$ with momenta $0.3 \leq p_{recoil} \leq 2.4$ GeV/c. The resolution of the spectrometer within this range is approximately

$$\frac{\Delta p_{recoil}}{p_{recoil}} \simeq \pm 0.5\%$$

$$\Delta\theta_{recoil} \simeq \pm 1 \text{ mr}$$

The momentum acceptance is about ± 4% and the solid angle acceptance is 2×10^{-4} ster. Figure 6 shows the laboratory angle of the forward scattered proton as a function of $|t|$ at several beam momenta. The forward scattered proton will be detected in the angular range from ~ 1 mr to 40 mr.

We propose building two small hodoscopes of about 15 elements each to detect the forward scattered proton. They will be located at different downstream locations and will be movable remotely. The distances from the target to the hodoscope locations are somewhat flexible and depend upon beam quality and logistics. One hodoscope (H1) will probably be located 40' from the target and cover the angular region from ~ 5 to 40 mr. The second hodoscope (H2) will be located at 175' and cover the angles from 1 mr to 6 mr. At the smallest angle in each case, the central counter will be no closer to the beam than ~ 2.1".

As indicated in Fig. 4 special beam pipes will be required. In past P-West beam tests, small scintillators (~ 1 in^2) have been operated within a few inches of the beam with no particular problem. We are confident that with the expected improvements in the beam quality, counters with areas $\lesssim 1/10 \text{ in}^2$ can be operated with little difficulty.

The sizes of the counters within each hodoscope must be large enough to "cover" the spectrometer acceptance and the beam size at the target, and yet small enough to provide adequate angular resolution for background subtraction purposes. For the given hodoscope locations, there is an optimum angular range and element size for each hodoscope. The geometry for H2 is sketched in Fig. 6. The horizontal dimension of the hodoscope elements is determined by the beam divergence (± 0.05 mr) and spot size (±1.5 mm) and the horizontal angular acceptance of the spectrometer (± 2.5 mr). The vertical dimension of the elements is determined principally by the azimuthal acceptance of the spectrometer (± 20 mr). The sketch shows a fifteen element hodoscope. At 500 GeV the central counter alone will detect the elastic events. The horizontally adjacent counters insure that the elastic peak is centered on the central element. The 8 vertically adjacent elements are the background detectors. They each correspond to roughly 0.1 mr from the target. At 300 GeV/c, the hodoscope must be at larger angles (i.e. further from the beam) so that the elastics will spread vertically into the counters adjacent to the central counter. This does not deteriorate the ability to subtract the resonance background since the required angular resolution becomes larger.

Similar arguments indicate that the hodoscope H1 should have elements roughly 3/8" long by 1/4" high. At 100 GeV/c and small $|t|$ the elastic events appear in 1 counter, while at large $|t|$ they populate two counters. At 50 GeV/c and at $|t| \sim 3\ (\mathrm{GeV/c})^2$, four counters would detect the elastic protons, and the angular resolution is again sufficient to allow reliable background subtractions.

V. RATES

The elastic scattering rate is given by

$$N_{e\ell} = N_b \, N_t \, \frac{d\sigma}{dt} \, \Delta t \, \frac{\Delta\phi}{2\pi}$$

where

N_b = beam protons

N_t = target protons

= $0.42 \times 10^{23}/\text{cm}^2$ for a 1 cm long liquid hydrogen target.

Δt = t acceptance bite of the spectrometer

= $2M \, p_r \sin\theta_r \, \Delta\theta_r$

where the subscript r refers to the recoil proton

$\Delta\theta$, $\Delta\phi$ = spectrometer horizontal and vertical angular acceptances

= 5 mr and 40 mr respectively.

The following table shows the rate of elastic events assuming a beam of 10^{12} p/pulse and elastic cross sections interpolated between the PS[3] data and the ISR data.[2]

TABLE I

$\|t\|$ $(GeV/c)^2$	Δt	$d\sigma/dt$ $\left(\frac{cm^2}{(GeV/c)^2}\right)$ 500 GeV	100 GeV	Rate (events/ machine cycle) 500 GeV	100 GeV
0.3	0.005	4×10^{-27}	5×10^{-27}	5400	6700
0.8	0.008	2×10^{-29}	5×10^{-29}	43	108
1.2	0.010	3×10^{-31}	1×10^{-30}	0.81	2.4
2.0	0.013	1×10^{-31}	6×10^{-31}	0.35	2.1
3.0	0.016	4×10^{-32}	9×10^{-32}	0.17	0.39

In the small $|t|$ range it will be necessary to take data with a beam intensity of about 10^{10} p/pulse. The beam intensity will be increased as the measurements extend out to the larger momentum transfers.

SUMMARY AND CONCLUSIONS

We have outlined in this proposal a method of measuring the pp elastic scattering cross sections over the entire NAL energy range and over a rather broad $|t|$ interval. We have demonstrated the feasibility of the experiment with respect to both data rates and expected signal to noise ratio.

The requirements from the National Accelerator Laboratory are two fold. The Proton Laboratory will be required to install a special beam pipe. The total beam times required to obtain 1 to 3% statistics at 30 values of $|t|$ at each energy are shown in the table.

In addition, we request 60 hours of testing and checking.

Intensity / Beam Energy	Less than 10^{10}	10^{10}-10^{11}	10^{11}-10^{12}	Total (hours)
50	1	1	8	10
100	1	1	10	12
200	1	1	15	17
300	1	1	25	27
400*	1	1	70	72
500*	1	1	100	102
Total	6	6	228	240

*Assumes 12 sec machine cycle.

REFERENCES

[1]The 2.4 GeV/c recoil spectrometer is expected to be operational by the summer of 1974.

[2]Results presented by C. Rubbia, XVI International Conference on High Energy Physics, Batavia, September 1972.

[3]Allaby, Diddens, Robinson, Klovning, Litt, Rochester, Schlüpmann, Wetherell, Amaldi, Bioncastelli, Bosio, and Matthiae, Nucl. Phys. B52, 316 (1973).

[4]Pickup, Robinson, and Salant, Phys. Rev. 125, 2091 (1962). Fickinger, Pickup, Robinson, and Salant, Phys. Rev. 125, 2082 (1962).

FIGURE CAPTIONS

Fig. 1 ISR results of the ACGHT Collaboration (Rubbia et al.) from Reference 1 and some low energy data.

Fig. 2 Calculated mass spectrum expected from a recoil spectrometer with $\Delta p/p = 0.1\%$, $\Delta\theta/\theta = 0$, at $t = 1.5$ $(GeV/c)^2$ at 500 GeV/c. Equal cross sections for $N^*(1400)$ production and elastic scattering have been assumed.

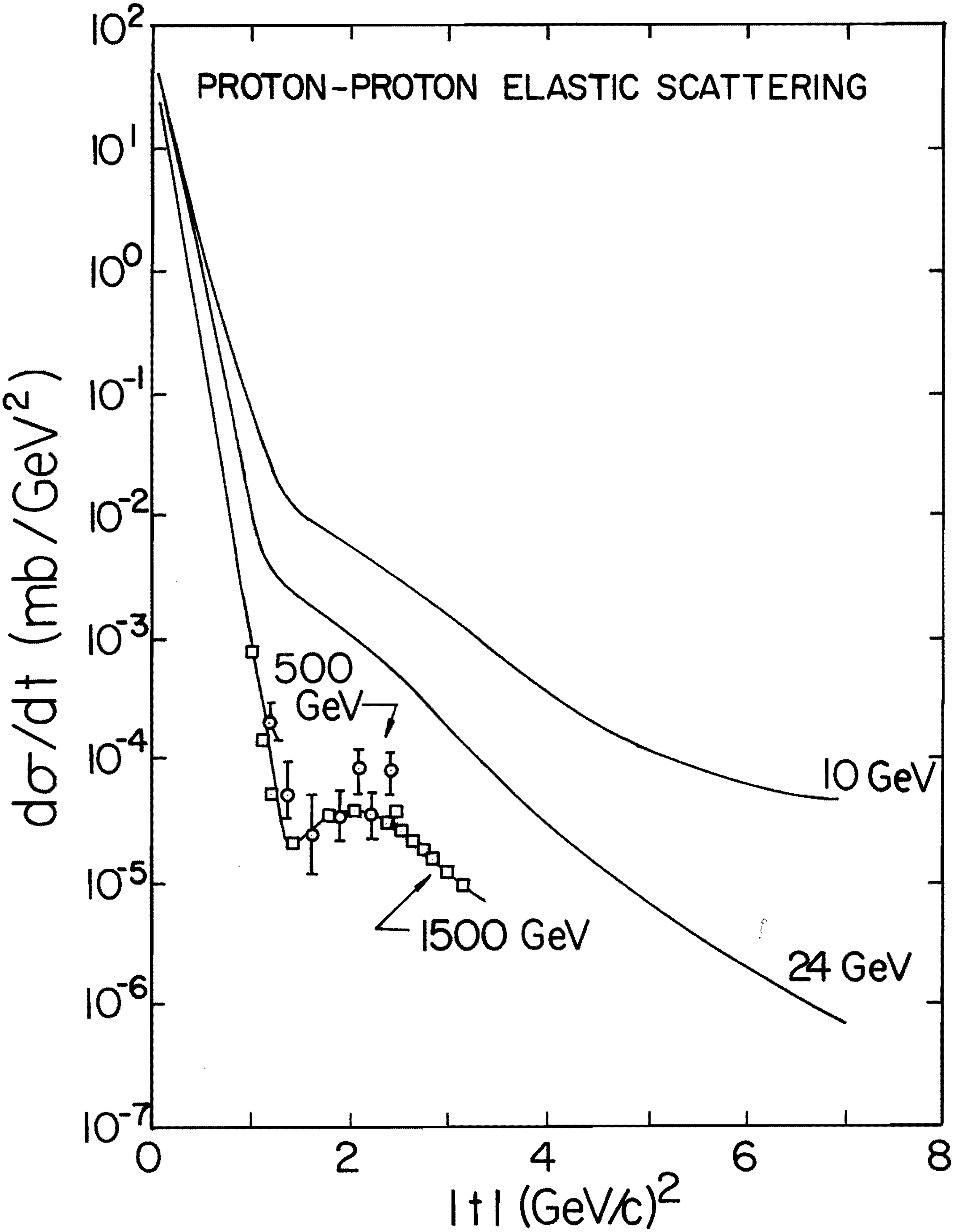
Fig. 3 Calculated distribution of hodoscope events in coincidence with the recoil spectrometer. The $N^*(1400)$, $N^*(1520)$, and $N^*(1688)$ production cross sections are assumed individually equal to the elastic cross section, and a non-resonant component is included.

Fig. 4 Layout sketch showing the apparatus in P-West. The locations of the hodoscopes are indicated as H1 and H2.

Fig. 5 Kinematics for the recoil proton in pp elastic scattering.

Fig. 6 Kinematics for the forward scattered proton in pp elastic scattering.

Fig. 7 Cross sectional sketch of the downstream hodoscope H2. The 15 hodoscope elements are each 0.25 x 0.25 in^2.



PROTON-PROTON ELASTIC SCATTERING
dσ/dt (mb/GeV²)
10²
10¹
10⁰
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
500 GeV
1500 GeV
10 GeV
24 GeV
0
2
4
6
8
|t| (GeV/c)²

Fig 1

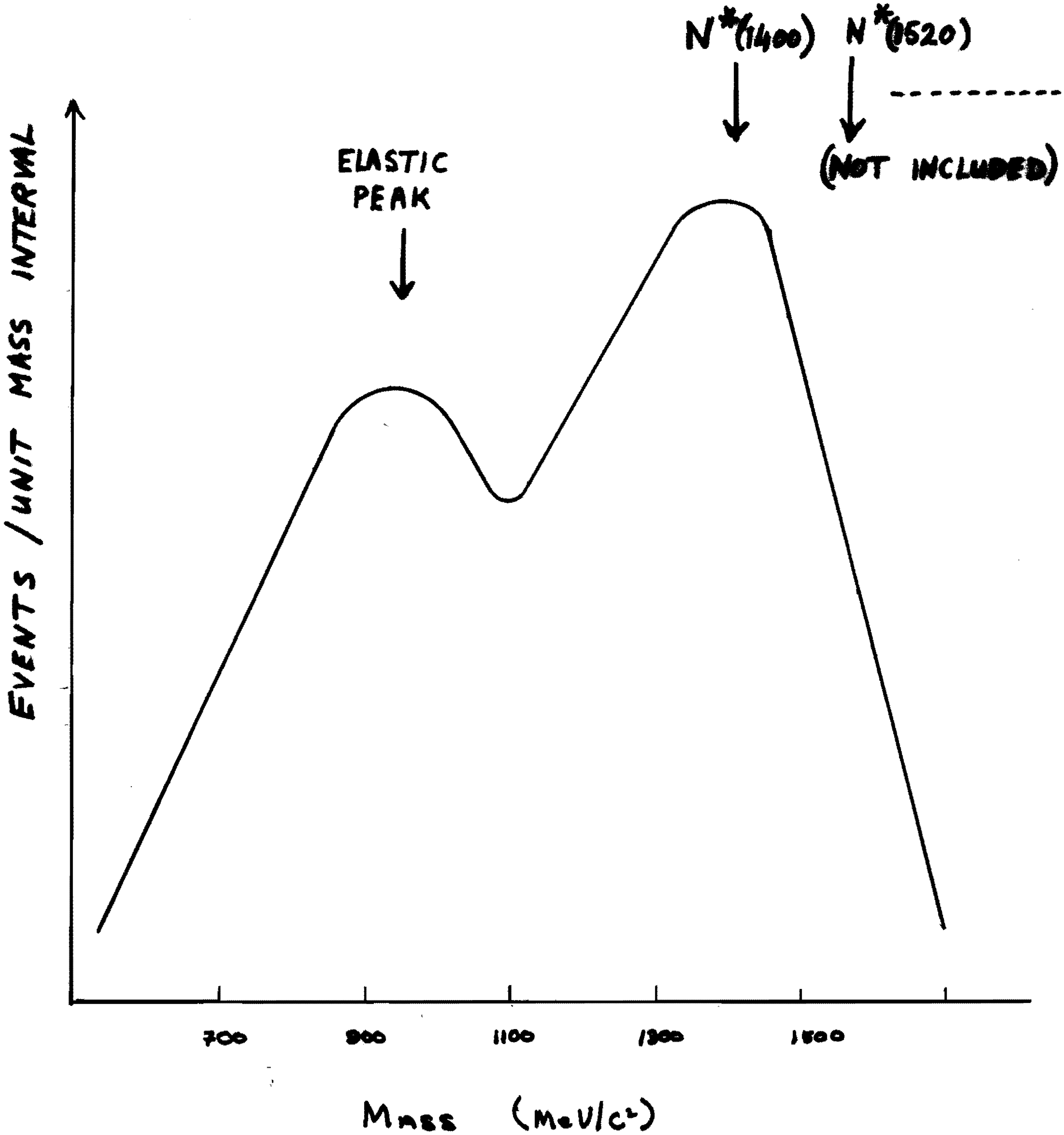

N*(1400)
N*(1520)
(NOT INCLUDED)
ELASTIC PEAK
EVENTS / UNIT MASS INTERVAL
700
900
1100
1300
1500
MASS (MeV/c²)

FIGURE 2

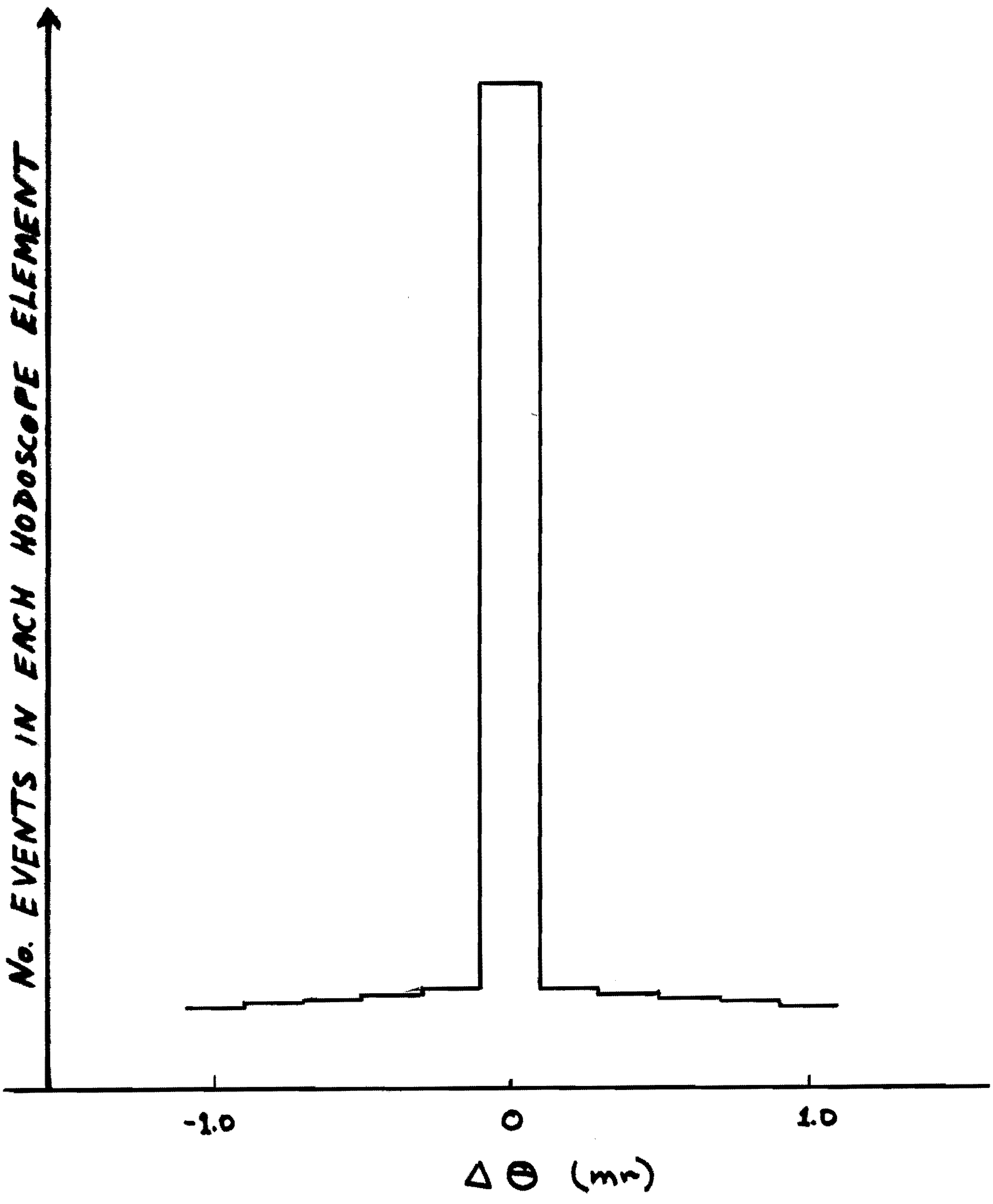


FIGURE 3

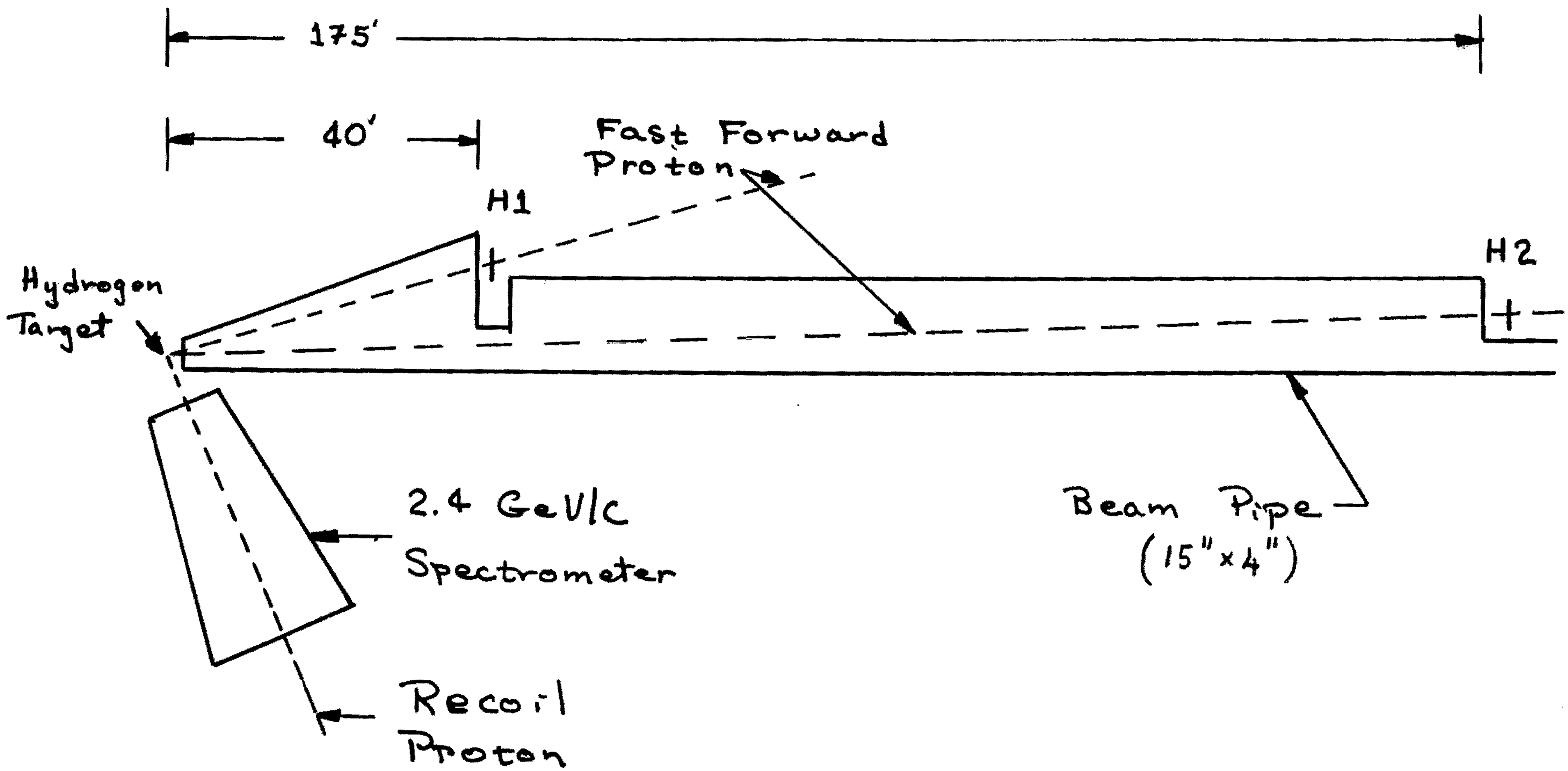

175'
40'
Fast Forward
Proton
H1
H2
Hydrogen
Target
2.4 GeV/c
Spectrometer
Beam Pipe
(15" x 4")
Recoil
Proton

FIGURE 4

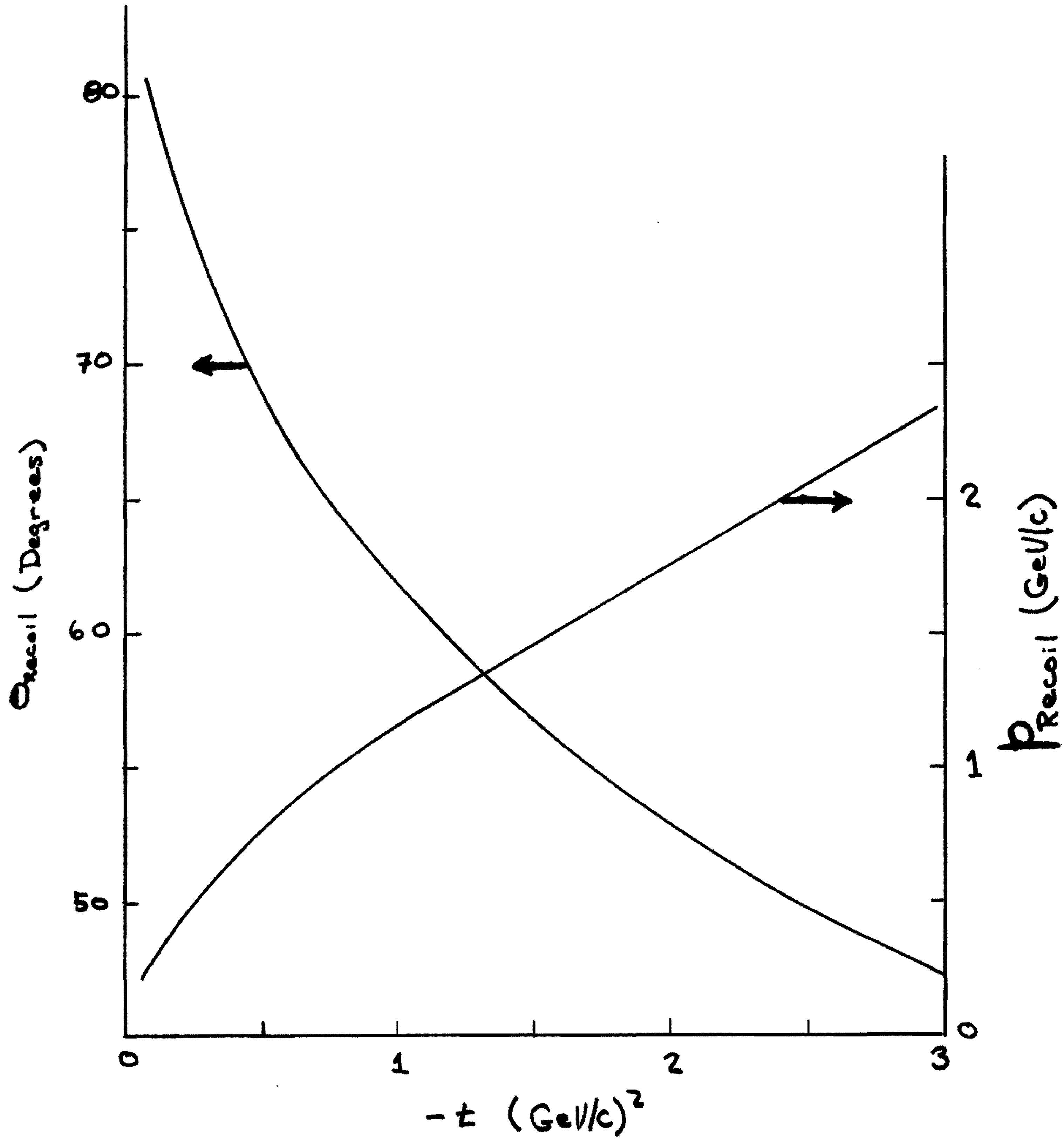


FIGURE 5

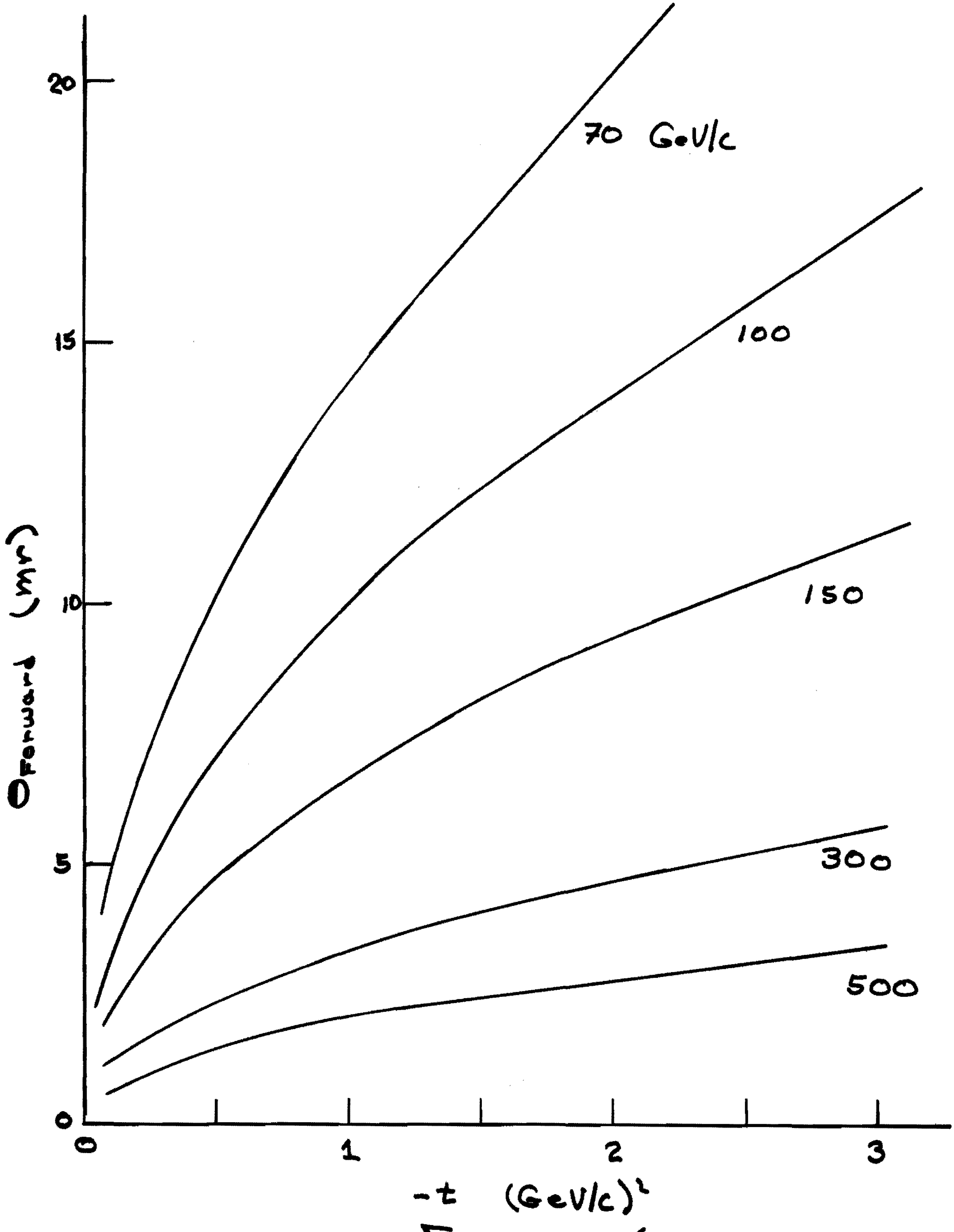
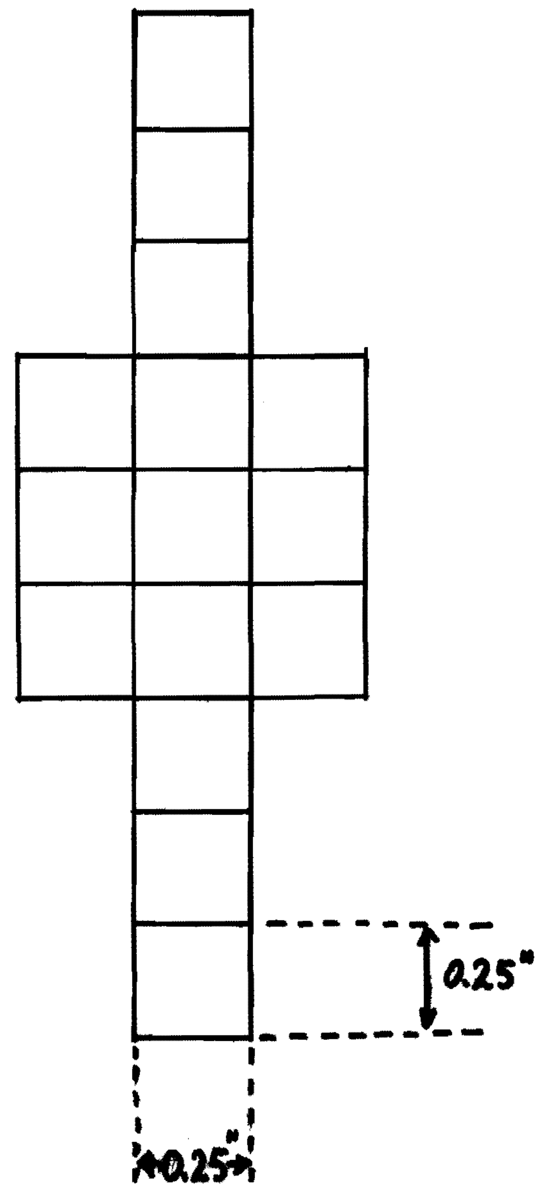


FIGURE 6



HODOSCOPE(H2) SKETCH

FIGURE 7