Experiment 231: Revised Proposal

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p-p and p-d Elastic and Inelastic Scattering
in the New C0 Internal Target Laboratory

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Abstract

We propose an experiment to measure p-p and p-d elastic and inelastic scattering in the new C0 Internal Target Area. These measurements will cover the t-region from 0.2 up to 10 (GeV/c)² for p-p elastic scattering and up to 5 (GeV/c)² for p-d elastic scattering. Incident beam energies from 8 to 500 GeV will be continuously covered. A magnetic spectrometer will be used to measure the angles and momenta of the recoil particles. In the higher t-region a forward hodoscope (or a forward magnetic spectrometer in later stages of the experiment) will be used to identify elastic from inelastic events. For absolute normalization we will install solid state detectors, which will cover both the Coulomb and nuclear scattering regions.

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I. Introduction

In July 1973 we submitted experimental proposal 231 "p-p and p-d Elastic and Inelastic Scattering in the High t-region in the New Internal Target Laboratory."

In this proposal we planned to do p-p and p-d elastic and inelastic scattering using a hydrogen and deuterium jet target at the B0 straight section, which we assumed would be expanded into a bigger internal target area at that time.

During the 1973 Summer Study, the subject of expanding an internal target area was discussed. As a result of the discussion, D. Jovanovic, E. Malamud, V. Nikitin, and A. Kuznetsov¹ have proposed construction of a modest experimental hall at C0 which might house the recoil spectrometer proposed in Exp. 231. In light of these developments, we reexamined our proposal and concluded that the experiment was feasible in the new C0 laboratory and certain improvements were possible with only minor modifications. At that time we wrote a letter to urge the start of construction at C0 and the approval of our experimental proposal.

During this time Exp. 36 was finished and Exp. 186 was started in the present C0 area using the jet target. In Exp. 36 members of our collaboration measured the slope parameter, b , and the ratio of the real to the imaginary part of the scattering amplitude for p-p elastic scattering.^{2,3} The diffraction excitation of nuclear resonances in p-p collision at incident proton energies from 175 to 400 GeV were also measured.⁴ In Exp. 186 we are measuring p-d elastic and inelastic scattering up to $|t| = 0.2 \text{ (GeV/c)}^2$, and these data are being processed now.

It is now clear that the jet target has been very fruitful to investigate not only elastic scattering but also to study inelastic scattering. The jet target has also been used by other experimental groups to measure the $p+p \rightarrow p+X$ inclusive reaction and the $p+p \rightarrow \gamma+X$ reaction.⁵ In the internal target area we have the added advantage that all incident energies are readily available up to the maximum machine energy. The s-dependence of the reactions can be determined easily.

We believe that a large variety of physics can be studied in the expanded internal target laboratory. Using a magnetic spectrometer as the basic apparatus, a series of experiments which require only minor modifications or additions to the apparatus may be done.

As a first experiment we wish to measure p-p and p-d elastic and inelastic scattering in two phases (I and II). Members of our collaboration have already studied the low t-region (up to $|t| \approx 0.2 \text{ (GeV/c)}^2$) with solid state detectors; this experiment would extend the t-region to $|t| = 10 \text{ (GeV/c)}^2$ for p-p scattering and to $|t| = 5 \text{ (GeV/c)}^2$ for p-d scattering.

In the first phase, we should like to measure the t-range from 0.2 to 5 (GeV/c)^2 for p-p scattering and up to 3 (GeV/c)^2 for p-d scattering. During Phase I we will use the recoil magnetic spectrometer and install a scintillation counter hodoscope in the forward direction. With this hodoscope we will study rates and investigate the power of coplanarity and opening angle constraints. This study will pave the way for extending the measurements to t values larger than 5 (GeV/c)^2 and will also improve the lower t measurements.

In Phase II we will use a forward magnetic spectrometer to extend the measurements to $t = 10 \text{ (GeV/c)}^2$ for the p-p reaction and to 5 (GeV/c)^2 for the p-d reaction.

We will install an absolute monitor system using solid state detectors to measure the elastic scattering in the nuclear scattering region and also in the Coulomb scattering region. Thus, we will have the ability to absolutely normalize the data. Whenever we have beam energy higher than over 400 GeV, we will use these detectors to measure the total p-p cross section. Using the same equipment, we will also investigate the oscillatory behavior of the pp elastic diffraction slope in the small t-region, as recently suggested by Tsarev.⁶

Most of the equipment which we propose can be used for many future experiments, including these same experiments extended to 1000 GeV when the proposed energy doubler comes into operation. The new C0 laboratory will be used by many other experiments, and will be the first experimental area for the beam from the energy doubler.

To summarize, the physics which we propose to study is as follows:

1. Elastic p-p in the t-region of 0.2 to 5 (GeV/c)² for energies from 8 to 500 GeV and elastic pd scattering to $|t| = 3$ (GeV/c)² (Phase I).
2. Inelastic p-p and p-d scattering in the same region as above (Phase I).
3. The inclusive reactions $pp \rightarrow pX$ and $pd \rightarrow dX$ with the recoiling proton and deuteron momentum up to 6 GeV/c (Phase I).
4. Elastic p-p scattering in the t-region from 5 to 10 (GeV/c)² for energy from 8 to 500 GeV (Phase II).

Since we will install the solid state detector system for absolute normalization, the following physics will also be investigated using the system:

5. Total p-p cross section up to 500 GeV.
6. The presence of fine oscillatory structure in the diffraction peak for the p-p reaction below $|t| = 0.2$ (GeV/c)².

II. Physics

Elastic scattering may be divided into regions according to the t-range covered as shown in Table 1 for p-p elastic scattering and Table 2 for p-d elastic scattering. The data are divided according to their phenomenological behavior. Regions 1 and 2, for p-p and p-d, will be measured in Experiment 36 and 186. We will extend these measurements in the new internal target laboratory to higher t and higher s-regions.

A. p-p Scattering

Elastic p-p scattering at very high energy and at high- t up to $5 (\text{GeV}/c)^2$ has been measured at the ISR and reported⁷ as shown in Fig. 1. There is extensive data below 30 GeV, but there is not enough data between 30 GeV and ISR energies. We can measure elastic scattering in the NAL energy range and thereby provide this fundamental data in the gap between 30 GeV and ISR energies.

The most prominent feature of the ISR data may be the dip around $1.3 (\text{GeV}/c)^2$ as shown in Fig. 1. This had not been observed at lower energies, although a kink in the cross sections exists there. This dip was predicted by many models.⁸ According to theory, this dip is partially filled at low energy where the real part of the scattering amplitude is large. Exp. 36 finds the ratio of the real to the imaginary part of the scattering amplitude to cross zero at $280 \pm 60 \text{ GeV}$, as shown in Fig. 2. Therefore, we should be able to observe this dip and its s -dependence at NAL energies. Its relation to the real part of the scattering amplitude will be studied.

An interesting prediction for the shape of the dip has been published by Phillips and Barger,⁹ who did a model independent analysis of the data in terms of two exponential amplitudes with a relative phase. The steeper exponential has normal Regge shrinkage and phase, while the other does not shrink. Shown in Fig. 3, their picture predicts the deepest dip near 175 GeV.

It turns out that the position of the first dip is relatively stable against small changes because it is a diffraction zero determined mainly by the opacity and size of the absorbing material. However, the height of the

second maximum varies enormously according to different models. For example, the Chew-Yang model predicts a 250% rise in $d\sigma/dt$ at $t = -1.8$ $(\text{GeV}/c)^2$ while Regge models do not predict any rise for the height of the secondary peak. Measurements in this region will distinguish between these models.

The theory also predicts a second dip around $|t| = 5 \sim 8$ $(\text{GeV}/c)^2$. If this dip exists, our counting rate is high enough to find it. The internal target has an advantage over the ISR as far as counting rate is concerned. As is described in a memo by E. Malamud,¹⁰ the interaction rate per second for $\sigma = 40$ mb is 10^4 for the ISR with a 10 ampere current, while that of a jet target is 7×10^8 with a proton density of 5×10^{-7} g/cm² and a beam intensity of 10^{13} ppp. Thus, our rate is about 10^5 higher than that of the ISR. We will have better statistics and will be able to measure into the higher t -region where the cross section is smaller. The data of Fig. 1 ends around $|t| \approx 5$ $(\text{GeV}/c)^2$. We will be able to extend these results to $|t| \approx 10$ $(\text{GeV}/c)^2$.

B. p-d Scattering

The differential cross section for p-d elastic scattering was measured up to 2 $(\text{GeV}/c)^2$ at CERN using the PS up to 24 GeV/c.¹¹ This result is shown in Fig. 4. The dip around $|t| = 0.3$ has been investigated at lower energies extensively in other laboratories. Recently, Glauber has suggested that it may be due to the strong dependence on polarization of the deuteron spin and the d-state admixture.¹² Beyond 2 $(\text{GeV}/c)^2$ no data exists even at low energy. Only the NAL machine has the capability to investigate this region.

At $|t| \geq 1$ GeV^2 the double scattering term in the p-d scattering amplitude dominates. At small t this term is determined mainly by elastic rescattering (elastic Glauber corrections). However, at higher energies inelastic

contributions become more and more important. This inelastic contribution to the Glauber corrections can be determined by our measurements. They are important for the Glauber theory itself and also as a source of information on inelastic processes.

From the p-d elastic scattering we can also deduce information about p-n scattering.¹³

C. Isobar Production

In the previously mentioned measurements of p-p and p-d elastic scattering, we will measure the momentum spectrum of the recoil protons. With sufficient resolution we can measure the cross sections for isobar production.

The production of isobars having masses of 1236, 1400, 1520, 1688, and 2190 MeV in p-p reactions has been investigated quite extensively up to $|t| = 6 \text{ (GeV/c)}^2$ and $P = 24 \text{ GeV/c}$.¹⁴ These results show that the differential cross sections for the 1520, 1688, and 2190 isobars have relatively small slope parameters ($b = 3 \sim 5$) and that they are comparable to that for elastic scattering around $|t| = 1 \text{ (GeV/c)}^2$ as shown in Fig. 5. Moreover, the cross sections for producing these isobars are roughly s-independent up to 24 GeV/c.

At momenta less than 25 GeV/c where the bulk of data on isobars exists, both elastic and inelastic cross sections have a break at $|t| \sim 1.4 \text{ (GeV/c)}^2$, as shown in Fig. 5. It is known that at larger s this kink becomes a dip for elastic scattering. It will be extremely interesting to learn also what happens to isobars.

As shown in Fig. 9, our mass resolution on the recoil particle using only the recoil arm is good enough to separate the isobars at 100 GeV beam energy for $0.2 \leq |t| \leq 10 \text{ (GeV/c)}^2$. At higher beam energies the separation of isobars becomes more difficult, especially between the 1520 and 1688

isobars. Thus, we expect to measure isobar production cross sections certainly at 100 GeV and perhaps up to 300 GeV in incident energy.

III. Experimental Setup

The angles and momenta of recoiling particles are measured by a magnetic spectrometer using proportional chambers. At higher beam energies and the extremes of the t -region we wish to study, the resolution of the recoil spectrometer alone is insufficient to give a clean separation of elastic and inelastic scattering. Thus, it will be necessary to use at least a forward hodoscope in order to give a clean separation between elastic and inelastic scattering. In Phase I of this experiment a hodoscope will be placed in the forward direction to measure the angles of forward scattered particles; in Phase II a forward magnetic spectrometer will be used to measure both the momenta and angles of the forward particles.

A. Recoil Particle Spectrometer

We propose to make a magnetic spectrometer with two bending magnets and a wire proportional chamber system to measure the momenta and angles of recoil particles. In Fig. 6 this recoil spectrometer is shown in one of the tentative versions of the expanded CO internal target laboratory. This spectrometer subtends about 0.94 msr with a polar angle coverage of about 2.8° in the laboratory system. Its resolution is good enough for measurements of p-p and p-d elastic and inelastic scattering over a wide range in t without the use of a forward hodoscope or momentum spectrometer.

The spectrometer consists of two bending magnets, four vertical proportional chamber planes, two horizontal proportional chamber planes, a Cherenkov counter, and scintillation counters. The relative position of these components to the target and beam line is also shown in Fig. 6. The system is mounted on a carriage which may be rotated about the jet target.

The first two wire proportional chamber planes, W1 and W2, with vertical wires spaced at 1 mm, define the recoil angles to an accuracy of about ± 0.1 mrad. The recoil particle trajectory will be extrapolated back to the target to check that it originated in the target.

There is a chamber, W3, between the two magnets, and another similar chamber, W4, 4.5 meters downstream from the second magnet. These chambers have one millimeter wire spacing vertically and two millimeters spacing horizontally.

A possible design of a recoil spectrometer bending magnet is shown in Fig. 8A. This is almost a C-shaped magnet having only a thin yoke on the beam side which acts as a magnetic shield for the main ring and gives structural strength. We plan to operate these magnets at 18 kilogauss. With this field 2.9 and 6.3 GeV/c protons, corresponding to $|t| = 4$ and 10 (GeV/c)^2 , will be bent in the horizontal plane by 32.1° and 14.7° respectively. The momentum resolution, $\Delta p/p$, will be about 0.05% and 0.063% respectively. Also, we are considering the use of two superconducting magnets (24-8-72), which are being developed in the Research Division, if they are available to us. As there is already a He liquefier in C0 area, the operation of these superconducting magnets must be easily started here.

The solid angle defining counter S1 is at the end of the spectrometer as is a second scintillation counter, S2. An absorber and a Cherenkov counter are placed between them. A signal derived from the coincidence of S1 and S2 will be used to register events into the computer. In addition, a coincidence is required with the RF structure of the main ring beam to

avoid events not originating in the target. Pulse height in the Cherenkov counter will be recorded and used to help eliminate background due to pions.

The p-p and p-d elastic scattering kinematics are shown in Fig. 7 for 300 GeV incident energy. At large fixed angles, the t-value of elastic scattering changes very little for incident energies from 100 to 500 GeV. The spectrometer, set at recoil angles between 30° to 90° , will cover the t-region of interest at different incident energies.

B. Mass Resolutions

Measuring only the recoil proton, the missing mass squared of the forward scattered particle is given by

$$M^2 = m_o^2 + 2m_r^2 + 2m_r(E_o - E_r) - 2(E_o E_r - p_o p_r \cos \theta_r).$$

Here the subscripts o and r refer to the incident and recoil particles respectively. Thus, the missing mass resolution can be estimated by taking

$$\Delta M^2 = \left[\left(\frac{\partial M^2}{\partial p_o} \right)^2 (\Delta p_o)^2 + \left(\frac{\partial M^2}{\partial p_r} \right)^2 (\Delta p_r)^2 + \left(\frac{\partial M^2}{\partial \theta_r} \right)^2 (\Delta \theta_r)^2 \right]^{\frac{1}{2}}.$$

The results of our calculations are shown in Fig. 9A for p-p elastic scattering and Fig. 9B for p-d elastic scattering. We have taken into account multiple scattering in the vacuum chamber windows and proportional chambers and also the position measurement error in the chambers. The rise in ΔM^2 at low t is due to an increase in multiple scattering while at higher t the rise is due to the momentum resolution.

Fig. 9 shows that the resolution of the recoil spectrometer alone is sufficient to give a good separation between elastic and inelastic scattering. If, for example, we take $\Delta M^2 \leq 0.7 \text{ (GeV)}^2$ ($\Delta M \approx 0.37 \text{ GeV}$) as the mass

resolution necessary to separate the elastics from $N^*(1520)$, from the standpoint of resolution only we can measure from $t = 0.1, 0.2$, and 0.8 (GeV/c)^2 at incident energies of 100, 300, and 500 GeV respectively.

Of course, the use of a forward hodoscope (Phase I) or forward magnetic spectrometer (Phase II) will make the separation between elastics and inelastics cleaner by allowing the use of coplanarity and elasticity constraints. Because we cannot move the forward spectrometer arbitrarily close to the beam there is an acceptance cutoff in $|t|$ beyond which we cannot use the forward system for measuring lower values of $|t|$. For example, this cutoff occurs at $|t| = 0.25, 0.9$, and 2.1 (GeV/c)^2 for incident beam energies of 100, 300, and 500 GeV respectively.

C. Forward Hodoscope (Phase I)

In Phase I a scintillation counter hodoscope will be placed in the forward arm so as to allow the imposition of coplanarity and opening angle constraints. This hodoscope would be placed 20m from the jet target.

At 400 GeV/c the forward proton from the decay of the 1400 MeV N^* is allowed within a cone of $\sim 1 \text{ mr}$ away from the N^* direction. Thus in order to reduce the background from these events we should have angular resolution at least 10 times better than this cone angle, or $\sim 0.1 \text{ mr}$. This implies hodoscope elements whose dimension is $\sim 0.25 \text{ cm}$. We will accomplish this with 25 counters 0.75 cm wide with one-third overlap giving 49 bins of $\sim 0.1 \text{ mr}$ and $\sim 5 \text{ mr}$ for the forward particle.

A single counter following this hodoscope will cover the azimuthal bite of the recoil spectrometer while accepting only $\sim 0.1 \text{ mr}$ in the dip angle.

D. Forward Particle Spectrometer (Phase II)

As is shown in Fig. 10, the forward scattered particles at fixed angle have increasing momentum and t -values as the circulating beam energy increases. Therefore, the system at a fixed position with a fixed current measures elastic scattering for one energy only. The laboratory angle for the forward scattered particle at $|t| = 4 \text{ (GeV/c)}^2$ is 6.9, 5.2, and 4 mr for 300, 400, and 500 GeV beams respectively.

The system consists of three bending magnets and four sets of scintillation counter hodoscopes. At 300 GeV the front end of the first magnet is placed 19.1 meters downstream from the jet target in order to cover the t -region from 4 to 10 $(\text{GeV/c})^2$. The current in the magnets as well as the position and angles of the magnets will be adjusted to accept only the elastically scattered protons. The momentum acceptance, which should be about 0.5%, can be easily achieved and the necessary horizontal acceptance is 2 mr. The solid angle is defined by the recoil spectrometer.

The scintillation counter hodoscopes are before the first magnet, between magnets, and after the last magnet in the forward spectrometer. There are also some anticoincidence counters to veto particles scattered from the steel surface and from the outside. Each hodoscope consists of twelve horizontal and six vertical scintillation counters. With the information from the forward spectrometer the coplanarity and elasticity of the events will be determined, and we can select the elastically scattered protons from the background. If necessary, proportional chambers will be installed near the end of the forward spectrometer to improve resolution. For completeness we show the layout of the forward spectrometer for a different energy in Fig. 11.

The magnets are similar to the main ring magnets as far as aperture and length are concerned. The steel core is shaped like the recoil spectrometer, as shown in Fig. 8B. The outside dimensions will be about 28 inches high and 27 inches wide.

The first magnet has an aperture 1.5 inches high and 9.75 inches wide with a 16 turn coil. The inside yoke is $1/4$ inch thick and the coil is 2.39 inches wide. Therefore, the particle can go through the magnet at a minimum distance of 2.64 inches from the outside surface. The second and third magnets have an aperture 2.0 inches high and 8.73 inches wide and 24 turn coils.

These magnets are connected in series and are excited by the same power supply to a magnetic field of about 18 kG with 3500 Amp. The resistance of the first and second magnets will be about 17 and 26 m Ω . The maximum total power consumption for these three magnets will be about 850 kW. These are conventional magnets, but they could be made with superconducting wire to save power.

The main ring vacuum pipe at C0 will be shifted inward by one inch relative to the center line connecting the upstream and downstream quadrupole magnets. The injected beam will be centered in this pipe with local low field correction magnets. However, the high energy beam will be set to run 2 inches from the outer surface of the 6 inch pipe as shown in Fig. 8B. As the extraction septum in A0 is set at 3 cm outside the center line and the abort target in D0 is set at 1.5 inches, this would not seem to be a problem.

The use of a local magnetic field beam bump at high energy will be considered. With this modification the beam will be shifted outward to make a lower t-region accessible in the coincidence experiment.

E. Monitor

We will install a vacuum guide at right angles to the main ring beam line, which is about 5 meters long and covers laboratory angles roughly from 90 to 80 degrees. At the end of it will be installed solid state detectors which will be used to monitor small angle elastic events.

An experimental setup and procedure similar to those of Experiment #36 will be used, except with better precision for the measurement of the Coulomb interference region. The setup is shown in Fig. 12.

We will use 10 discrete solid state detectors in the t -range from 0.01 to 0.15 (GeV/c)² and 6 detectors in the t -range from 0.001 to 0.01 (GeV/c)². Electronics which are similar to those used for Experiment #36 or #186 will be employed. The experimental procedure is quite established now. The measured shape of $d\sigma/dt$ around the Coulomb-nuclear interference region is shown in Fig. 13.

As an option we may consider using position sensitive detectors, which give energy and position information at the same time for each event. Some of the data from Experiment #36 was taken with such detectors and is now being processed. The position sensitive detectors were developed in the last few years, and will give a spatial resolution of better than 0.5 mm over their 5 cm width.

F. Counting Rates

The counting rate, N , per jet pulse is given by the following equation:

$$N = N_b N_t \frac{d\sigma}{dt} \Delta t \frac{\Delta\phi}{2\pi}$$

where N_b is the number of circulating protons available during a pulse of the jet and N_t is the number of target particles. The azimuthal acceptance,

$\Delta\phi$, and the t -acceptance, Δt , are determined by the recoil spectrometer since the forward hodoscope (Phase I) and forward spectrometer (Phase II) are large enough to accommodate all forward particles from elastic scattering events which are detected by the recoil spectrometer. Using estimated $d\sigma/dt$ values from presently available data, N is given in Table 3.

The present density of the jet is about 5×10^{-7} g/cm³ in a beam interaction region of about 1 cm, giving $N_t = 3 \times 10^{17}$ proton/cm² available as our target. Within a main ring cycle the jet duration is about 200 ms for 3 or 4 jet pulses and one second for a single pulse. For the lower t -values we plan to operate the jet during the ramp and for higher t -values we may use the flat-top or front porches of the main ring ramp.

The presently available beam intensity in the main ring is about 4×10^{12} protons/pulse, which should eventually increase to the design intensity of 5×10^{13} proton/pulse. For these calculations we have assumed 1×10^{13} protons/pulse which may be a conservative value in the latter part of 1974. During a 200 ms jet pulse the main ring beam circulates 10^4 turns around the ring, giving an available beam during a jet pulse $N_b = 10^4 \times 10^{13} = 10^{17}$ proton/pulse. We plan to operate at least one jet at low energy and another at higher energy for which the forward hodoscope or spectrometer is adjusted. When feasible, we will operate 2 or 3 jets, during flat-top.

It is possible that the counting rates listed in Table 3 can be increased by a factor of 50 in the near future with increases in the jet density and beam intensity. The Russian members of our collaboration are presently exploring the possibility of increasing the jet density by reducing the jet velocity and using solid hydrogen or deuterium. With such modifications the jet density may be increased by a factor of 10

or more. This, coupled with an increase in beam intensity to 5×10^{13} proton/pulse, could increase our listed counting rates by a factor of 50 or more in the near future.

IV. Background Rate

There are two types of background: one target associated and the other not. The background which does not come from the target was measured in May 1973 at 300 GeV to be about 16 minimum ionizing particles/cm²/sec/ 10^{10} circulating protons at 3.5 feet from the beam line.¹⁵ Thus, at 13 cm from the beam line and with 10^{13} circulating protons, the corresponding number is 1.3×10^5 particles/cm²/sec. Although this rate is tolerable for the forward hodoscope, it will be reduced by at least an order of magnitude. First of all, the experimental area at C-0 will be designed more carefully so as not to restrict the circulating beam. Secondly a beam scraper at A17 and beam collimators at D-0 will be used.

The effect of the accidental rate due to particles coming from the target can be estimated for the forward spectrometer including the first forward hodoscope as follows. This hodoscope is more seriously affected than the recoil spectrometer. We estimate the background rate at the $|t| = 4 \text{ (GeV/c)}^2$ setting at 300 GeV. As there is a maximum of 1113 beam bunches in the main ring, we have $N_b = 10^{10}$ proton/bunch for a beam intensity of 10^{13} ppp. The interval between beam bunches is about 20 ns and the total number of reactions during a bunch is estimated from a total cross section of 40 mb as follows:

$$N_b N_t \sigma_{\text{tot}} = 10^{10} \times 3 \times 10^{17} \times 40 \times 10^{-27} = 120$$

The multiplicity measured by the bubble chamber is about 8.9 at 303 GeV, and the projected distribution in one dimension is shown in Fig. 12, where the events are grouped in 0.5 mr bins.¹⁶ Therefore, we have about 1000 charged particles coming from a jet target associated with a single beam bunch. The maximum

number of particles going through the aperture of the first useful magnet opening (which is 4 mr horizontally and 1.5 inches high) is estimated to be less than 0.6%. Thus, on the average, six particles may go through this opening; we can easily select the elastic scattered proton from the information given by the following counter hodoscopes. As these 1000 charged particles may produce many low energy daughter particles when they finally hit vacuum chambers and magnets, it is preferable to use a vacuum tube and also to place the counter hodoscope so that the back scattered particles reach the hodoscope out of phase with the scattered particles of interest, e.g., 10 ns later. The number of muons was measured in the C0 area by Experiment 120.¹⁷ They observed 500 μ /jet (=200 ms)/ 10^{12} proton at 250 GeV with a counter of 2/3" x 2/3" placed at 16 mr and at 32 feet downstream from the jet. This gives 2.5×10^{-3} /bunch (=20 ns)/ 10^{13} proton/2 msr at 16 mr. This number will not cause difficulty for this experiment.

VI. Comparisons with Other Experiments

In the future, elastic scattering will be measured at NAL using external beams. However, we can measure the elastic scattering of p-p and p-d in the main ring in a very flexible and efficient way. There are several advantages of the internal target experiment over external target experiments for these reasons:

1. It is possible to select the incident beam energy freely from the injection energy to the highest extraction energy. Thus, the s-dependence measurement can be done easily and in a bias free way.
2. The internal target has the first access to the highest machine energy, because no external beam line is needed. When the energy doubler becomes operational, this experiment will have immediate access to this new energy without awaiting a new beam transport system.

3. The target is thin, so that the multiple scattering of the recoil particle is small compared to that of a liquid hydrogen target. Therefore, elastic scattering may be measured using only the recoil spectrometer over a large range of t (see Fig. 9).
4. For the same reason as in 3, the mass resolution is much better than in experiments using regular hydrogen targets. Thus, the isobars can be easily studied.
5. The luminosity for the internal target is comparable to that of the external beam. For the internal target with three pulses of 200 ms width and a beam intensity of 10^{13} ppp, $L = N_b N_t = 10^{13} \times 3 \times 10^4 \times 5 \times 10^{-7} \times 6 \times 10^{23} = 0.9 \times 10^{35}$. For the external beam with 4×10^{11} ppp and 4" long liquid hydrogen target we have:

$$L = N_b N_t = 4 \times 10^{11} \times 2.54 \times 0.071 \times 6 \times 10^{23} = 1.7 \times 10^{35}.$$
6. At the internal target the incident beam has no pion contamination; identification of incident particles using Cherenkov counter is therefore not necessary.
7. This experiment can be done parasitically with respect to external experiments. Therefore there is always more machine time available.
8. Power consumed by this experiment is minimal since no external beam line is required.
- A. How do these unique features translate into a better experiment?

Because of the items C and D mentioned above it is possible to design a recoil spectrometer which has sufficient resolution to separate elastics and diffractively produced N^* 's up to large values of t (e.g., at 200 GeV our design is fully capable of these measurements up to 10 (GeV/c)^2).

Because of this resolution it is possible in the internal target area to cover the t range from 0.2 to 10 $(\text{GeV}/c)^2$ with one experiment, whereas such a capability is not presently available in the approved experiments. Hence, the attendant relative normalization difficulties encountered when attempting to compare different experiments is no longer a problem.

This is truly a unique feature in that all other presently approved experiments (except E-96) require double arm capability in order to isolate elastic scattering. Single arm mass resolution alone is insufficient, and hence the inelastic spectrum is not studied well by these experiments. In the case of E-96 the t region covered is out to ~ 1.5 $(\text{GeV}/c)^2$ and the highest beam energy at which elastic scattering may be studied is ~ 200 GeV/c .

We cannot overemphasize the importance of having all energies simultaneously available. Many of the important questions in high energy pp scattering require measurement of a slowly varying energy dependence. The internal target laboratory is ideal for such measurements. The kinematics of the recoil particle vary only slowly as the incident momentum is varied, thus making systematic error minimal. The hydrogen jet may be pulsed several times during the ramp. Thus, in one machine cycle, data at several energies may be accumulated. The relative normalization of the various energies is thus made much more reliable than when these data must be accumulated during periods which may be separated by days. We believe this feature of our experiment to be very important when the energy dependence sought can be as slow as logarithmic.

Finally, it is worthy of note that all this is accomplished with what is essentially a simple apparatus requiring detection of particles only up

to 6 GeV/c in the recoil arm. The simplicity of the apparatus, in our view, will tend to make the apparatus reliable, stable, and easy to understand; the data will hopefully also have these same properties.

B. Comparison with Approved Experiments:

1. Exp. 7 Summary

This experiment measures elastic scattering of π , K and p up to 200 GeV/c and out to t-values of ~ 3 (GeV/c)². The low lying N^{*}'s may be accessible with only the forward spectrometer up to incident energies of ~ 80 GeV/c.

2. Exp. 63 Summary

This experiment is primarily a particle production survey detecting particles with lab momentum < 2.4 GeV/c for incident protons in the 50-500 GeV/c range. Elastic scattering is not emphasized; however, we may assume that this experiment will measure elastic pp scattering out to $t \sim 1.5$ (GeV/c)².

3. Exp. 96 Summary

The high resolution - high momentum spectrometer in the meson area will be used to study elastic $K^\pm$, p, and $\bar{p}$ scattering from protons and deuterons. The incident momentum accessible is from 50 to 200 GeV/c while the t-range accessible is up to ~ 1.5 (GeV/c)². In addition, the inelastic spectrum will be studied up to $M_x \approx 2$ GeV.

4. Exp. 177 Summary

pp elastic scattering will be measured at 200 and 400 GeV. A double arm spectrometer is employed to measure the differential cross section for t-values between 4 and 20 (GeV/c)².

5. Exp. 231 (this proposal) Summary

pp and pd elastic will be measured for beam energies between 8 and 500 GeV. These measurements will cover the t-region from 0.2 to 10 (GeV/c)² for pp elastic scattering and 0.2 to 5 (GeV/c)² for pd elastic scattering. In addition, the single arm resolution is sufficient to measure diffractively produced N^{*}'s to large t-values also. This capability does not presently exist in the above approved experiments. In addition the single particle production spectra can be studied for lab momenta up to ~ 6 GeV/c for $\pi^{\pm}$, p, $\bar{p}$, and $K^{\pm}$ using Cherenkov counters and time-of-flight.

VII. Apparatus

We are assuming the construction of the C0 internal target area will be started in the spring of 1974. Allowing six months for construction of this area, we expect the experimental area will be ready for occupation in the fall of 1974. While the experimental area of the C0 straight section and the service building are under construction, we will work on preparations for the experiment.

The major items which should be made or purchased during that time are:

1. Recoil spectrometer magnets
2. Forward spectrometer magnets
3. Power supplies for spectrometers
4. Cooling system for spectrometers
5. Fast logic circuits
6. Proportional chamber system including Camac and its interface
7. Scintillation counter hodoscopes
8. On-line PDP-11 system
9. Solid state detector monitor system

We request NAL to supply the spectrometer magnets and power supplies as well as the cooling system. Purdue University will build the proportional chambers and all scintillation counters. NAL will supply fast logic circuits, the readout electronics for the chambers, the PDP-11, and Camac and its interface. Dubna will provide electronics for the monitor system and make a new jet target, if needed.

VIII. Experimental Procedure

We think we can build or have all the experimental equipment except the forward spectrometer magnets in six months. The existing superconducting magnets (24-8-72) may be available as recoil spectrometer magnets. Therefore, we can start Phase I of this experiment without any trouble.

In Phase I we will study p-p and p-d elastic and inelastic scattering in the lower t-region up to 4 (GeV/c)² with continuous incident energies using only the recoil arm and forward counter hodoscope. For this phase of the experiment we need about 400 hours of running time.

In the Phase II, using both the forward and recoil spectrometers, we will measure p-p elastic scattering in the high t-region with 200, 300, 400 and possibly 500 GeV beams. This experiment needs about 600 hours of running.

Thus, we are requesting a total of 1,000 hours of running time for all experiments. Within one month after we move into the new area, we will be able to start the experiments. Members of our collaboration started the C0 Internal Target Area and also helped carry out other experiments. This has provided a driving force in C0 and we expect to provide a similar driving force in the new C0 Internal Target Area.

IX. Possible Future Experiments

The elastic scattering experiment we propose to do should be the first experiment in the new Internal Target Area; it will provide data essential to understanding the apparatus for further experiments. Using the same equipment and with some modifications the apparatus can also do the following experiments.

A. $p+p \rightarrow p^{\pm} + \text{anything}$

B. $p+p \rightarrow \pi^{\pm} + \text{anything}$

These two reactions will be very interesting to study over the entire s-range. We can do these experiments by adding suitable Cherenkov counters to the recoil arm.

C. Elastic scattering from some nuclei

Elastic scattering from some nuclei can be measured using the same equipment by observing the recoil nuclei with the low momentum spectrometer.

D. Polarization measurement

A carbon polarizer can be placed after the first magnet of the recoil spectrometer in order to measure the left-right asymmetry with use of an extra set of wire chambers. A polarization measurement in the region around the dip at $|t| = 1.3 \text{ (GeV/c)}^2$ should help provide an understanding of the mechanism responsible for the dip.

E. $p+p \rightarrow \pi^+ + d$

F. Particle Production Experiment

Using the recoil spectrometer and adding Cherenkov counters, we can measure the production rate of $\pi^{\pm}$, $K^{\pm}$, and other particles at large angles.

X. Manpower

In addition to the physicists listed on the title page, we expect one or more people from NAL and at least one graduate student from Purdue University to join the experiment when it is approved.

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Appendix I

The Difference between the Old Concept of an Internal Target Laboratory and the Internal Target Area Using Jet Target

The present and planned Internal Target Area is quite different in nature from what was conceived as an Internal Target Laboratory six years ago as a general facility. With the invention of the gas jet target at Dubna and with subsequent very successful experiments at the Dubna and Serpukhov accelerators, the Internal Target Area of NAL was started two years ago and already many experiments have been finished.

In the old conception, we were going to use a solid beryllium target or some other material as an internal target to make a diffractively scattered proton beam and secondary particle beams in the main ring. Subsequently these beams might have been extracted. In this conception, we would have used as much equipment as needed for an extraction system in the transfer hall and a much more complicated control system might have been required. As we would have to use a solid target, the radiation loss might have been very heavy and the operation of this area might have been very complicated, and it might have affected the operation of the synchrotron tremendously. Also many downstream main ring magnets might have been exposed to scattered particles and made highly radioactive.

In the present internal target area we have been doing experiments using the jet as a target without interacting with the circulating beam too much. Only one tenth of a percent or less of the circulating beam intensity is lost. The operation is fairly simple and we do not detect any noticeably high radiation effects on downstream magnets. The interaction with the operation of synchrotron has been minimal.

Yet four experiments have been finished and another four experiments are going on now. There are already several published papers on the slope parameter b and the ratio α of the real part to imaginary part of the scattering amplitude for p-p elastic scattering on the $pp \rightarrow pX$ inclusive reaction, and on the γ spectrum from pp and p-nucleus reactions.

The present internal target area has been very useful and fruitful for studying high energy physics in the early stages of the NAL accelerator. We think the usability of this area will be much enhanced by the addition of the extended internal target area.

List of Figures

1. Proton-Proton Elastic Scattering
2. Ratio of Real Part to Imaginary Part of Scattering Amplitude
3. Phillips and Barger Differential Cross Section Prediction for Proton-Proton Elastic Scattering
4. Proton-Deuteron Elastic Scattering
5. Isobar Production at 24 GeV/c
6. Layout of Experiment in the Expanded CO Internal Target Laboratory
7. Kinematics of Recoil Particles for Proton-Proton and Proton-Deuteron Elastic Scattering
- 8A. Cross Section of Recoil Magnet
- 8B. Cross Section of Forward Magnet
- 9A. Missing Mass Squared Resolution as a Function of $|t|$ for Proton-Proton Elastic Scattering
- 9B. Missing Mass Squared Resolution as a Function of $|t|$ for Proton-Deuteron Elastic Scattering
10. Kinematics of Forward Scattered Proton in Proton-Proton Elastic Scattering
11. Position of Forward Spectrometer
12. Setup of Monitor System
13. Differential Cross Section in the Coulomb Nuclear Interference Region

TABLE 3

Calculated Counting Rates for Experiment 231

We have assumed a jet density of 5×10^{-7} gm/cm³, a 200 msec jet pulse, and a 1 cm interaction region.

	$ t $ (GeV/c) ²	$\frac{d\sigma}{dt}$ [cm ² /(GeV/c) ²]	Δt (GeV/c) ²	θ (Degrees)	$\Delta\phi$ (Radians)	No. of Events Jet Pulse	No. of Events day
pp Elastic Scattering	1	1.5×10^{-30}	0.24	61.7	0.022	37.1	1.28×10^6
	2	4×10^{-32}	0.41	52.8	0.024	1.90	6.55×10^4
	4	3×10^{-33}	0.78	42.9	0.028	0.32	1.10×10^4
	10	$\sim 1 \times 10^{-36}$	2.21	30.2	0.038	3.90×10^{-4}	13.5
pd Elastic Scattering	1	6×10^{-30}	0.39	74.9	0.020	223	7.7×10^6
	2	1×10^{-31}	0.56	69.1	0.021	5.52	1.91×10^5
	4	$\sim 5 \times 10^{-35}$	1.11	61.8	0.022	5.8×10^{-2}	2.00