NAL PROPOSAL No. 7

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A Proposal to Measure $\pi^{\pm}p$ and p-p Differential Elastic Scattering Cross Sections from 50 to 170 GeV/c

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I. Introduction

Since the time of Rutherford the study of elastic differential cross sections has brought us the most compelling evidence for the structure of the atom. High energy elastic scattering experiments indicate that the nucleon scatters particles as if it were a diffuse disk with a radius of approximately 10^{-13} cm. The exact shape, angular width, and energy dependence of the forward elastic scattering cross sections depend on the quantum numbers of the colliding particles in a way not yet understood. In particular, at presently available accelerator energies the proton-proton forward differential cross section shows a marked shrinkage in width as a function of incident beam energy while pion-proton cross sections show no perceptible change. This single fact alone has caused much theoretical anguish and colored our ideas about strong interactions at high energies.

It is natural to try to investigate these shrinkage effects at NAL energies as soon as possible. By measuring the slopes of the differential cross sections versus momentum transfer at several beam energies, we can find out whether the quantitative differences between π^+p, π^-p, and pp scattering persist. The present experimental data for these slopes is shown in Fig. 1. It is interesting to note that the present data on slope measurement of $\pi^{\pm}p$ elastic scattering do not exhibit a consistent behavior.

At the same time more detailed questions may be answered by measuring elastic scattering. For example, at present energies the π^+p and π^-p differential cross sections intersect at a momentum transfer of about $0.2(GeV/c)^2$. In Regge language these elastic cross sections are dominated by the P, P', and ρ trajectories and since the ρ amplitude contributes with opposite sign for π^+p and π^-p scattering, this "cross over" effect can check the predictions of any reasonable Regge model which satisfies the charge exchange data.

As shown in Figures 2 and 3 the characteristic shapes of the πp and pp cross sections change markedly for momentum transfers greater than $-t = 0.6(GeV/c)^2$. Beyond this point the cross sections do not fall as precipitously with momentum transfer as an extrapolation of the forward diffraction peak would indicate. In πp scattering the elastic cross sections in this "secondary" region of momentum transfer become comparable to other two body processes which exchange non-zero quantum numbers so that it is likely that purely diffractive effects are no longer dominant. At higher energies where individual channels become less important it might not be surprising if the cross section in this secondary region would continue to decrease with energy, with the extrapolation of the forward diffraction peak as a possible lower bound. If this is true the differential cross section in this secondary region will reach extremely small values.

In this introduction we have tried to indicate some of the questions which would be answered by measuring πp and pp elastic scattering at NAL. More specifically we are proposing to measure these cross sections for 5 incident beam momenta of 50, 80, 110, 140, and 170 GeV/c and for momentum transfers between $-t = 0.1(\text{GeV/c})^2$ and $-t = 4.5(\text{GeV/c})^2$. The lowest energy was chosen to overlap data expected to be available in the future from Serpukhov and the highest energy is the point beyond which we believe the incident pion flux will become a limiting factor (assuming 200 GeV operation). The upper bound for the pp measurements will be determined solėly by the beam transport system.

We propose to detect both the forward fast particle and the recoil proton. This method sets a lower limit to the momentum transfer of $-t \doteq 0.1(\text{GeV/c})^2$. For momentum transfers less than this value the recoil proton has insufficient energy to escape the hydrogen target and be detected. The maximum momentum transfer is limited by the geometry of the recoil proton spectrometer. This spectrometer has been designed to accept protons at angles of 40° to 80° with respect to the incident beam. The 40° limit fixes the maximum observable momentum transfer to $-t = 4.5(\text{GeV/c})^2$ independent of beam energy. For reasons already given we expect that this momentum transfer range will be more than adequate to match the cross section sensitivity of this apparatus.

In the diffraction peak region the cross sections are expected to be large so that high statistical accuracy may be obtained in a few hours running time. We propose to test the existence of shrinkage in the diffraction peak by measurements of the slope parameter to an accuracy of 0.5% at all energies. The existing data on slope parameters is typified by errors of 3 to 4%. To achieve accuracies of 0.5%, energy dependent systematic errors must be well understood and minimized insofar as possible. The angular acceptance for the elastic events in this region will be determined by the recoil proton spectrometer. Since the kinematics of the recoil proton are essentially independent of the incident beam energy, we expect that there will be negligible systematic error in measuring the cross section slope parameters as a function of energy.

Although it is obvious that elastic scattering experiments will be among the simplest done at NAL, there are still a host of experimental problems which must be solved. In this proposal we have tried to discuss these problems and present reasonable solutions which will insure accuracy and reliability. Most of these solutions have been reached by conservative extrapolation of our experience with past experiments of this type.

II. Experimental Design

Three items are of particular importance:

1. The experimental design must include sufficient rejection against inelastic processes to allow measurements down to cross sections at least as low as 100 nanobarns/$(\text{GeV/c})^2$.

2. The experimental design must clearly identify and distinguish pions from kaons and protons in the incident beam up to the full beam energy.
3. The statistical and systematic errors of the measurements must be small enough to obtain definitive data on the slopes of the cross sections in the diffractive region (i.e., $|-t| < 1.0(\text{GeV/c})^2$.

A. Identification of Elastic Events

A system capable of measuring the small elastic differential cross sections at large momentum transfers requires some special design considerations in order to operate at NAL energies. In the past, one of the conventional methods of measuring elastic cross sections relied upon the determination of the momentum of the fast forward particle. Elastic scattering events are selected by calculating the missing mass of the recoil particle.

For forward elastic scattering the missing mass error is related to the scattered particle momentum error by the equation:

$$\frac{\Delta M^2}{M^2} = \frac{2P_{inc}^2 \, \Delta P_{scat}}{M_P E_{inc} P_{scat}} \simeq 2P_{inc} \, \frac{\Delta P_{scat}}{P_{scat}} \left(P_{inc} \text{ in GeV/c}\right)$$

The formula shows that as the incident beam energy increases the momentum resolution must become proportionally better in order to preserve the missing mass resolution. At 200 GeV/c a momentum resolution of better than 0.2% would be required to just resolve the proton mass from the N*(1238). Since the magnetic field length required for a given momentum precision increases linearly with the particle momentum, a simple scaling up of this type of single arm spectrometer will not be economical at NAL energies.

We propose to measure the angles and momenta of both scattered particles. We will use this information to provide a three constraint fit for every event; namely, coplanarity, opening angle, and transverse momentum balance. We will neglect to first order the fourth constraint of longitudinal momentum balance. The transverse momentum balance is the requirement that the algebraic sum of the transverse momenta of the recoil and scattered particles equal zero in an elastic collision. The experimental precision of this constraint is set by the momentum precisions available for the two particles. The precision of the transverse momentum balance is dominated by the measurement error for the recoil proton and is expected to be at most 1.7%.

The expected angular resolution of the recoil proton spectrometer is 3 mr. Using the relation:

$$\frac{d\theta_{scat}}{d\theta_{recoil}}\,\delta\theta_{recoil} \approx \delta\theta_{scat}$$

where $\delta\theta_{recoil}$ and $\delta\theta_{scat}$ are the angular errors for the directionof the recoil particle and the forward scattered particle respectively, one sees that $\delta\theta_{scat}$ must be 0.05 mr or less. When similar calculations are made for the coplanarity angles we find that the incident beam direction should be determined to ~ .05 mr in both horizontal and vertical planes.

The ability of the system to reject inelastic events depends upon the tightness of each of the three constraint conditions. To a good approximation we can extrapolate the effects of these constraints from "low" energy experiments to NAL energies, since the kinematics of the recoil particle are essentially energy independent. In a previous experiment by this group at 5 GeV/c[1], inelastic event rejection was sufficient to achieve a cross section sensitivity of 100 nanobarns/$(GeV/c)^2$. This was obtained with an angular resolution of about 5 mrad for the opening angle and coplanarity, compared with 3 mrad for this proposed experiment.

For the third constraint, the transverse momentum balance, there is no direct comparison to the missing mass constraint of the "low" energy experiment mentioned above. In that experiment the missing mass precision was approximately $\frac{\Delta M^2}{M^2} = 10\%$. For this proposed experiment the transverse momentum error of 1.7% will probably give significantly better rejection than was possible with the lower energy experiment.

From these considerations we expect that the proposed experiment will be able to measure elastic cross sections at least as low as 100 nanobarns/$(GeV/c)^2$.

One other question so far unconsidered is the momentum transfer resolution of the system. With the system described the momentum transfer at 200 GeV/c will be defined to $\pm 0.01 (GeV/c)^2$

in the diffraction region and to $\pm0.04(GeV/c)^2$ for $-t = 4(GeV/c)^2$. This precision will be proportionally better at lower beam energies.

B. Beam Particle Identification

We propose to use gas threshold Cherenkov counters to resolve pions from kaons and protons in the beam. Recent results on the performance of a high resolution threshold counter at IHEP[2] suggest that it is possible, with some simple improvements in that design, to build counters that work satisfactorily up to 180 GeV/c. A single counter will be approximately 40 m long and have a diameter of about 40 cm. Light collection in these counters will involve a single reflection by a spherical mirror onto a phototube inside the radiating gas. The counters will use helium gas at less than atmospheric pressure. In order to separate pions and kaons at 180 GeV/c and 60 GeV/c pressures of .094 atm and .94 atm would be required respectively. In order to investigate more fully the properties of such a device we intend to build and test a prototype at the ZGS this fall.

C. Statistical Accuracy of the Slope of the Diffraction Peak

Since one of the primary aims of this experiment is to measure shrinkage effects accurately in the diffractive scattering region, we must consider the statistics of slope measurement.

Under the assumption that the cross section in the $-t = 0.1(\text{GeV}/c)^2$ to $0.6(\text{GeV}/c)^2$ region can be represented by a simple exponential, an analysis by R. Peierls[3] is applicable for determining the slope parameter.

With this method of analysis and a background as large as 10%, which far exceeds what we anticipate, we would expect the error in the slope parameter, b, to be given by

$$\frac{\delta b}{b} \cong \sqrt{\frac{3.5}{N}}$$

where N is the total number of measured events within the diffraction peak. In the diffraction region the data rate with 10^5 particles/pulse in the beam would be 25/pulse. With this rate we could measure the slope of a diffraction peak to 0.5% in half a day.

III. Description of the Experimental Apparatus

The spectrometer system for this proposed experiment is shown in Fig. 4. It consists of a high momentum spectrometer in the forward direction to analyze the scattered beam particle and a low momentum, large angle spectrometer to analyze the recoil protons emitted at 40 to 80 degrees with respect to the beam direction. Wire spark chambers are placed before and after the spectrometer magnets to determine the particle trajectories. The trigger for these wire spark chambers will be provided by scintillation counters placed in the two arms of the spectrometer and will include several veto counters which will detect particles from unwanted multiparticle final states. The target is a 12" long flask of liquid hydrogen maintained by a small cryogenic refrigerator.

A. The Forward Spectrometer

The momentum dispersion for the forward spectrometer is provided by an 8" high x 24" wide x 144" long picture frame magnet with a total effective field of 2700 kg-in (68.5 kg-meters). The particle trajectory before bend is defined by a set of wire spark chambers at the upstream face of the analyzing magnet and the event origin is obtained from the beam counters and the recoil track. The trajectory after the bend is determined by two more sets of wire spark chambers with a 600" spacing between sets. Our experience with wire spark chambers indicates that in practice the spark localization error is about 0.032" for each gap. Using 4 chambers per set and 600" separation between sets we obtain a bend angle resolution of 0.06 mr, which provides a momentum resolution of $\frac{\Delta P}{P} = 0.5\%$ at 200 GeV/c. The spectrometer magnet will accept particles emitted at horizontal angles of -5 mr to +25 mr with respect to the incident beam. The wire spark chambers will be made insensitive near the beam and will be active for positive horizontal angles only.

In past experiments we have found it convenient to be able to direct the incident beam through the wire spark chamber spectrometer. The direct beam allows an automatic survey of exact chamber positions by triggering the chambers with the spectrometer magnet at zero field, as well as a convenient measurement of spark chamber efficiency. For these reasons we propose to include a small steering magnet upstream of the hydrogen target which will be able to steer the beam into the active region of the forward spectrometer. This feature will save time during the initial set up.

B. The Recoil Spectrometer

The recoil proton momentum dispersion is provided by a large magnet designed specifically for spark chamber experiments. This magnet has pole face dimensions of 30" x 84" and will provide a 480 kg-inch field integral (12 kg-meters) with a 26" gap spacing. The particle trajectory is determined by 6 wire spark chambers spaced 4" apart between the target and magnet and another set of 6 chamber on the far side of the magnet spaced 8" apart. This system will have a 3 mr bend angle resolution and consequently a momentum resolution $\frac{\Delta P}{P}$ = 1.7% at 2 GeV/c. The azimuthal angular acceptance of the system is limited by the magnet gap height of this recoil spectrometer and is not limited by the aperture of the forward spectrometer over the kinematic region of interest. The recoil trajectory aids in localizing the event interaction point to the region inside the hydrogen target, something which is very difficult to do with the forward particle trajectory alone.

C. Beam

We have planned upon a secondary particle beam with a momentum capability of up to 180 GeV/c and a positive or negative pion intensity of 10^6 particles/burst over as much of the momentum range as possible. By introducing a horizontal and vertical beam hodoscope or a proportional chamber after the last quadrupole of the incident beam and a beam defining counter before the hydrogen target, we can obtain the required beam angular resolution of ±0.05 mr in the incident beam. The horizontal hodoscope would have 30 scintillation counter elements and the vertical hodoscope 20 elements with a typical element width of 1/8". The necessary beam momentum resolution of $\frac{\Delta P}{P} = \pm 0.2\%$ could be obtained by placing two momentum defining counters at the foci.

D. The Electronic Logic

The wire spark chamber trigger will be derived from several scintillation counters which will detect the incident particle and the two scattered particles. The spectrometer length is so great that any scintillation counter placed at the rear will not be able to transmit a signal back to the target area in less than 0.3 μsec after an interaction has occurred. This time delay is approximately the lifetime of the ion tracks in a spark chamber and would seriously impair chamber performance if included in the triggering scheme. For this reason any counter used for the chamber trigger cannot be much farther from the hydrogen target than the forward spectrometer magnet.

The beam counter logic will include signals from two Cherenkov counters to identify incident particle type and two hodoscopes to determine the incident beam position and direction. The scattered particles will be detected with an eight counter hodoscope for the recoil in coincidence with a single counter for the fast forward particle. During data taking we will limit the on-time for the small momentum transfer counters in order to avoid being swamped with these events. Anticoincidence counters, particularly in the forward hemisphere, will veto events with multiparticle final states. Some of these veto counters will also be faced with lead sheets to convert and anti γ's from π^o decay.

In addition the signals from a Cherenkov counter downstream of the forward spectrometer will be recorded to help identify the reaction type. For signal transit time reasons this information cannot be used in the spark chamber trigger.

All of the spark chamber data and most of the counter information will be input to a dedicated computer via a temporary data buffer. The computer must have a memory equivalent to 16K x 18 bits in order to handle the data rate.

E. Data Rate

In the region of the diffraction peak where the cross section is large there should be little problem in accumulating good statistics in a short time. At the larger momentum transfers ($-t \simeq 3(\mathrm{GeV}/c)^2$) we can only guess the magnitude of the cross section; it might be very low. We take the viewpoint that we will follow the differential cross section down to a level of less than 100 nanobarns/$(\mathrm{GeV/c})^2$. Assuming a 12" hydrogen target, 10^6 useful beam particles/machine pulse and 10^4 machine pulses/day, we estimate that a cross section of 100 nanobarns/$(\mathrm{GeV/c})^2$ would yield 20 events/day in a Δt bin $.2(\mathrm{GeV/c})^2$ wide. Thus we could get reasonable statistics in 8 days for very small cross sections and very good statistics everywhere else. In order to measure the elastic π^+p, pp, and π^-p cross sections at 5 different incident energies, we will require about 80 days of running time plus several days to install equipment, time counters, etc.

IV. Apparatus Logistics

If this experiment were to be done at a time when NAL has established its experimental program on a solid footing there is no doubt that all the required apparatus would be easily available. However, we feel that this is one of the first experiments that should be done and a serious attempt should be made to perform it, even if all the necessary components are not yet in existence at NAL. It is most likely that at the actual time of performance of the experiment, some of the equipment will have been procured by NAL and some will have to be borrowed from other laboratories. We believe that as the time draws near these arrangements can be worked out satisfactorily.

A. Spark Chambers, Electronics, and Related Equipment

These parts of the apparatus are either similar to or identical with equipment now in existence. Their availability will pose no problem inasmuch as the construction of such equipment is well within the group resources.

B. On-Line Computer

The PDP-15, such as that being obtained at NAL, would be adequate for this experiment. The necessary spark chamber buffer equipment is commercially available. If this computer system could not be made available, equipment such as the EMR-6050's in use at ANL, could be pressed into service as replacements.

C. Hydrogen Targets

We assume that NAL will establish a system for supplying experimental hydrogen targets. The target proposed is very simple and should present no challenge. If expedient, a target now in use at ANL could be used.

D. Cherenkov Counters

Two counters will be needed in the beam. An additional counter would be useful but not essential for the forward secondary. We have done preliminary design work on these counters and plan to test a prototype at ANL soon. It is expected that they will become part of the general NAL facilities.

E. Steering Magnet

This magnet will be built at the University of Michigan specifically for the experiment.

F. Large Magnets and Power Supplies

The magnet parameters as specified in the proposal are not absolute requirements. We are confident that the experimental magnets to be procured by NAL will certainly include magnets similar to the ones we have described, which will be entirely suitable for this experiment. To the extent that NAL cannot supply these components because of an accelerated schedule of machine construction, it seems reasonable to expect that a loan of magnets and power supplies could be arranged with ANL. In particular a recoil spectrometer magnet of the type SCM-105 (three of which exist at ANL) can be made readily available together with its power supply.

V. Other Experiments That Can Be Done With This System

Our proposal to measure $\pi^{\pm}$+p and p-p elastic scattering differential cross sections is only the first of a series of experiments for which this detection system might be used. By adding certain pieces of equipment other groups could study a variety of processes.

A. $K^{\pm}$+p and $\bar{p}$-p Forward Elastic Scattering

Improved mass definition of the incident particle might be needed. Threshold Cherenkov counters with better velocity resolution of a DISC counter could accomplish this. Otherwise no change in the target, magnets, counters, or wire chambers would be required. The same t range would be accessible.

B. Polarization Studies

Replacement of the liquid hydrogen target with a polarized target would permit the study of polarization effects in elastic scattering.

C. Backward Elastic Scattering of Pions and Kaons

These baryon exchange processes can be studied by identifying the forward fast proton. If the baryon exchange cross sections do not continue to drop as fast with energy these processes could be measured at NAL with this apparatus.

D. Quasi-Two Body Inelastic Processes

The comparatively large angular acceptance of the two arms of our proposed spectrometer plus magnetic analysis in both arms permits studying reactions in which one of the detected particles is the decay product of a nucleon resonance or a meson resonance.

E. "Missing-Mass" Studies

For this general class of experiments the two arms of the system could be used simultaneously though independently. "Bump hunting" for resonances will probably be fruitless at these energies. However, a very important set of investigations could be carried out to test the theories of Feynman, Yang and of Cheng and Wu by measuring cross sections of the type $\pi+p \rightarrow \pi+$"anything" and $p+p \rightarrow p+$"anything".

Further usefulness of a detection system would seem an important consideration at NAL. We think that the proposed system can be used with some small modifications for a variety of experiments.

References

1. D. R. Rust et al., "Structure in 5 GeV/c π^+p Elastic Scattering at Large Angles," ANL/HEP 7006 (also Phys. Rev. Letters, to be published).

2. Yu. P. Gorin et al., "High Resolution Cerenkov Threshold Counter," p. 20, (IHEP. 69-63) Bibliog. 11., July 1969.

3. R. Peierls, Proc. Roy. Soc. (London), A149, 467 (1935).

Figure 4. SPECTROMETER LAYOUT

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Addendum to Proposal 7

When experiment 7 was designed we proposed to do $\pi^{\pm}$-p and p-p elastic scattering. While we were obviously aware of the interest in doing $K^{\pm}$-p and $\bar{p}$-p scattering we felt unsure of having suitable Cerenkov counters available to clearly separate the particles at the time we would run. As a result we did not propose to measure these.

In the past 3 months two developments have changed the situation. First we have built and tested (at the Cornell synchrotron) a threshold counter for use at NAL. From that test we have concluded that the quantum efficiency of the new RCA 31000M phototubes is a factor of 2 higher than that of tubes previously available. Second, the total cross section experiment has definitely been assigned to run before us and it will supply some of the Cerenkov counters needed. We are therefore confident that we can run $\pi^{\pm}$, $K^{\pm}$ and $p^{\pm}$ differential cross sections.

We propose to take data on all three reactions <u>simultaneously</u> so that we are not requesting additional accelerator time. This will mean that the statistical accuracy of $K^{\pm}$-p and $\bar{p}$-p will be poor at the larger t values in the experiment. However the small t data will be interesting. The additional effort needed to run these other reactions is minimal since the Cerenkov counters will be in operation anyway, and we normally record the condition of each Cerenkov counter on magnetic tape with our other data.

In addition we will be recording data on N* resonance production as a function of t. To take this data simultaneously is unavoidable. To what extent the data will be of sufficient accuracy and sufficiently free of background to be physically interesting we cannot predict because of the unknown size of the cross section. The same is true of the $\pi^{+}+p \rightarrow K^{+}+\Sigma^{+}$ reaction where at best we will get a rough size for the reaction.

We would like to emphasize that we are not requesting additional accelerator time. The apparatus will be available if someone wants to take higher statistics $K^{\pm}$ and $\overline{p}$ data. We only feel that data which is so easily obtained and is of considerable physical interest should not be thrown away.

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