NAL PROPOSAL NO. 4

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NEUTRON-PROTON DIFFRACTION SCATTERING AND NEUTRON TOTAL CROSS SECTIONS UP TO 200 GEV

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ABSTRACT

We propose to use the 0° neutral beam planned for Experimental Area 2 to measure differential cross sections for np elastic scattering in the diffraction region over the energy range of from 40 to 200 GeV and also total cross sections for neutrons on protons, deuterons, and other nuclei over the same energy range.

The proposed experiments would use techniques previously developed by the authors in similar experiments at the Bevatron and the AGS. Most of the apparatus already exists. The two experiments could be run in the same beam, either simultaneously or sequentially. The experiments are simple and place very modest demands on accelerator performance.

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II. Physics Justification

The np elastic scattering experiment will measure cross sections with good accuracy at least out to 2 $(GeV/c)^2$ and at incident neutron energies up to ≈200 GeV. There is a good chance that no np experiments will take place at Serpukhov before turnon at NAL because of the lack of a suitable neutral beam. The NAL experiment would then extend our previous studies of np elastic scattering at the AGS[1a] by a factor of approximately 7 in neutron energy. Such measurements of elastic differential cross sections are basic to any theory of strong interactions at high energies. Major points of interest are a comparison of pp and np cross sections, possible shrinkage of the diffraction peak, or possible structure in the diffraction peak such as that found by Allaby et al.[2] near $t = 1.5(GeV/c)^2$ in pp scattering at 19.3 GeV/c.

The np and n-nucleus total cross section measurements would yield total cross sections to ≈2% accuracy over the energy range 40 to 200 GeV. We note that direct measurements of np total cross sections with a neutron beam eliminate the uncertainty in the np total cross sections caused by the uncertainty in the screening corrections if a pd-pp subtraction is used. (This uncertainty is especially serious when extrapolating present experience to such high energies because of the possibility of coherent inelastic effects as discussed by Pumplin and Ross[3].) Furthermore a comparison of np, pp and nd (or pd) total cross sections allows an experimental determination of the screening correction which would serve as a test for the existence of effects like those considered by Pumplin and Ross.

The energy dependence of the n-nucleus cross sections would also provide a test for such effects. These can be done very simply with very little running time. The data analysis can be done very quickly so that these total cross section measurements will be almost immediately available to give a "preview" of possible new effects at very high energies which can be investigated in other experiments soon after turnon.

Another very important aim of the experiment is to gain experience with high-energy neutral beams at NAL. In addition to those proposed here, there are several very interesting experiments that could be done with a neutron beam at NAL. Since they are somewhat more difficult and less certain to succeed they might be considered "second generation" experiments. Two such experiments which have been considered by Longo[4] and Jones[5] in NAL summer studies are np charge-exchange scattering and neutron diffraction dissociation ($n + \text{nucleus} \rightarrow n^* + \text{nucleus}$). Our group is currently studying np charge-exchange scattering up to 30 GeV at the AGS and plan an exploratory experiment to determine the feasibility of neutron diffraction dissociation measurements in the near future. These experiments are of great theoretical interest, and prospects for extending them to NAL energies are good.

Both the total cross section and the diffraction scattering experiment would make use of a total absorption spectrometer to measure the neutron energy. Our group has pioneered in this technique in previous experiments at the AGS[6] and Bevatron[7] and also in cosmic ray experiments[8]. At high energies the potential energy resolution of such devices is very good ($\sim\pm 4\%$ at 200 GeV)[9], and we believe they will find many important applications at NAL. Another significant goal of the experiment is therefore to develop and gain experience with total absorption spectrometers at NAL energies.

III. Experimental Arrangement

A. Neutron beam

The main requirement for the neutron beam is that the takeoff angle be small, $\leq$2mr. It is our understanding that a small-angle neutral beam will be available in Experimental Area 2. The desirability of a small takeoff angle has been emphasized by Jones[5] and Longo[4]. The main advantage is the much higher flux of neutrons near 200 GeV in the smaller angle beams. Fig. 1 shows a comparison of expected neutron spectra at 0 mr and 3 mr from Jones' paper[5]. This assumes the inelastic neutron spectrum is similar to that for inelastic protons which is estimated on the basis of the Hagedorn-Ranft model.

Details of the neutron beam will be considered in conjunction with NAL staff. Available neutron fluxes should be more than adequate. With a 1" diameter aperture at 1000 ft. we estimate a neutron flux of $\sim 10^7$ neutrons (between 160 GeV and 200 GeV) per 10^{12} protons. This is at least an order-of-magnitude more than needed so that a means for varying the size of the defining collimator should be provided.

B. The np diffraction scattering experiment

Fig. 2 shows the proposed layout for the elastic scattering experiment. The neutron beam is incident on a hydrogen target. The forward scattered neutrons are detected in an arrangement of spark chambers interspersed with steel plates and scintillators, shown in detail in Fig. 2A. This array serves two purposes. The vertex of the neutron's interaction in the steel plates at the upstream part of the array gives a point on the neutron trajectory which, when connected to the point of interaction in the hydrogen target, gives the neutron scattering angle. The whole array also functions as a total absorption spectrometer (TAS) so that the summed pulses from the scintillation counters give a measure of the neutron energy. Extrapolating from our previous experience at the AGS[6] and the Bevatron[7] we anticipate an energy resolution $\approx\pm 6\%$ at 100 GeV and $\pm 4\%$ at 200 GeV. This is more than adequate for our needs. This array would be mounted on rails so that it could be moved to cover different ranges of t.

The recoil proton from the hydrogen target would be detected in a standard wire-chamber spectrometer. This gives the proton momentum and angle. Since the only unknown is the incident neutron energy, we have a 3-constraint fit to the hypothesis of an elastic scattering. This will provide a very powerful means of discriminating against inelastic events. With this and the anti shield around the hydrogen target to further reduce inelastic background we expect to be able to make measurements to $t \geqslant 2(\mathrm{GeV})^2$. As in our previous experiments[1] we would simultaneously measure cross sections over the whole range of incident neutron energies with the events later binned according to energy.

Except for the anti shield around the target and the use of the TAS incorporated into the neutron detector, the technique is identical to that employed by our group at the AGS[1a] and the Bevatron[1b] to study np elastic scattering. The technique extrapolates very nicely to higher energies, and in many respects the experiment becomes easier. The identification and measurement of the neutron vertices becomes simpler and the greatly improved energy resolution of the TAS provides a very effective means for measuring neutron energies. The increased neutron fluxes available at higher energies allows the use of a smaller diameter neutron beam with correspondingly better resolution in neutron scattering angle.

The use of a neutron detector with good energy resolution has an important advantage in normalizing the data. The number of events (per monitor count) at a given setting is proportional to the product of the cross section, the number of beam neutrons, and the neutron detector efficiency. The product of the number of beam neutrons (per monitor count) and the detector efficiency can be measured directly for each incident neutron energy range by placing the neutron detector in the beam. Thus the cross sections can be normalized in a straightforward manner.

C. The total cross section experiment

Figure 3 shows the proposed layout for the total cross section experiment. The standard transmission technique is employed. The neutron detector is a total absorption spectrometer, which could be the same as that used for the diffraction scattering except that the spark chambers would not be used. The TAS would be preceeded by a converter plate and transmission counters as shown. Cross sections would be measured for each transmission counter and the results extrapolated to "zero solid angle" in the usual way.

Again the techhique extrapolates very nicely from AGS energies and again there are significant advantages at higher energies. The improved energy resolution of the TAS allows the <u>simultaneous</u> measurement of cross sections over a very wide range of neutron energies with $\approx 5\%$ energy resolution. The higher beam fluxes make possible the use of a very small diameter beam which allows measurements at very small four-momentum transfers (much smaller than feasible with charged particles because of the absence of Coulomb scattering) so that the correction to the cross sections for the finite solid angle subtended is very small.

Both the total cross section and the diffraction scattering experiment have been discussed by Longo[4] and Jones[5]. It is interesting to note that it would be quite easy to extend the total cross section experiment to 500 GeV if a 500 GeV proton beam, even of very low intensity (10^{10} to 10^{11} protons per pulse), were available in Area 2.

IV. Apparatus

All of the spark chambers for the diffraction scattering experiment would be wire chambers with magnetostrictive readout. The chamber array for the neutron detector already exists and is presently being set up as a gamma detector at the Berkeley cyclotron. This array, as used for gamma detection, consists of 60 wire planes (30 gaps) interspersed with lead plates. The readout technique employed can handle a large number of sparks per plane, limited only by the size of the pulses from the magnetostrictive lines. These chambers have been tested extensively and perform very well. Spurious sparks with no tracks in the chambers are very rare even at high operating voltages. This chamber array was designed in such a way that it is a simple matter to replace the lead plates with steel plates, more suitable for a neutron detector.

We have our own HP 2115A computer with software for reading out the chambers and monitoring their operation. We also have programs available for the determination of gamma vertices from the spark locations. These can be modified fairly easily to find neutron vertices.

We also have a TAS currently in operation at the AGS. With small modifications it can be incorporated into the neutron detector.

We would prefer to run the total cross section and diffraction scattering experiment sequentially so that the same neutron detector could be used for both. However, the TAS is a relatively inexpensive device (~$3000 replacement cost) and its potential for future experiments at NAL is great enough that we would be quite willing to build a second one if necessary.

It would be helpful if we could obtain some fast electronics and other general purpose equipment such as power supplies and scalers from an equipment pool at NAL. We would also need access to a "large" computer (e.g., - PDP-10) to do some preliminary analysis of the data during the run.

Our requirements on accelerator operation are minimal. By having a defining collimator whose size can be changed we can accommodate a large range of proton intensities, and it should be possible to operate at levels down to 10^{11} protons/pulse. We would need as long a spill as possible, though a short spill can be tolerated at the cost of more running time.

Our magnet requirements are very modest indeed. Several sweeping magnets, which can have a very small bore, are needed. The magnet for the proton spectrometer can be anything from about 18"x36" to about 48"x48". The larger magnets of course would improve our rate of collecting data.

Members of our group would work closely with NAL staff in the beam design. The costs of installing the neutron beam should be considerably less than that for any of the charged beams, and operating costs are almost insignificant.

We wish to emphasize that our requirements are quite flexible. The experiments we have in mind are simple in principle and modest in scale and therefore able to accommodate to restrictions on floor space, availability of equipment, and the uncertainties in the operation of a new accelerator.

Facilities and equipment required:

Magnets - Several bending magnets for sweeping magnets. A very small aperture is possible. One magnet for proton spectrometer, minimum size 18"x36"x6" gap.

Beam - Small angle neutral beam preferably 0°. Neutron flux $\sim 10^6$/pulse.

Proton beam target - A light nucleus such as beryllium is preferred.

Neutron beam targets - Hydrogen target ≈12" long for elastic scattering experiment. Hydrogen target ≈4' long for total cross sections.

Other equipment to be supplied by NAL - Collimators for neutral beam, some fast electronics would be desirable but not essential. On-line computer, spark chambers, and counters would be supplied by us.

Running time requested:*

<u>Elastic scattering</u> - 200 hours tuneup and 200 hours run.

<u>Total cross sections</u> - 100 hours tuneup and 200 hours run; most of this could be concurrent with elastic scattering. Some running at machine energies below 150 GeV is desirable.

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* Due to the many uncertainties in accelerator operation and the many options available as far as emphasis and accuracy of the measurements, the estimate should only be considered indicative. We have in mind a fairly modest experiment. The scope and emphasis of the measurements will be decided in consultation with the NAL Program Committee.

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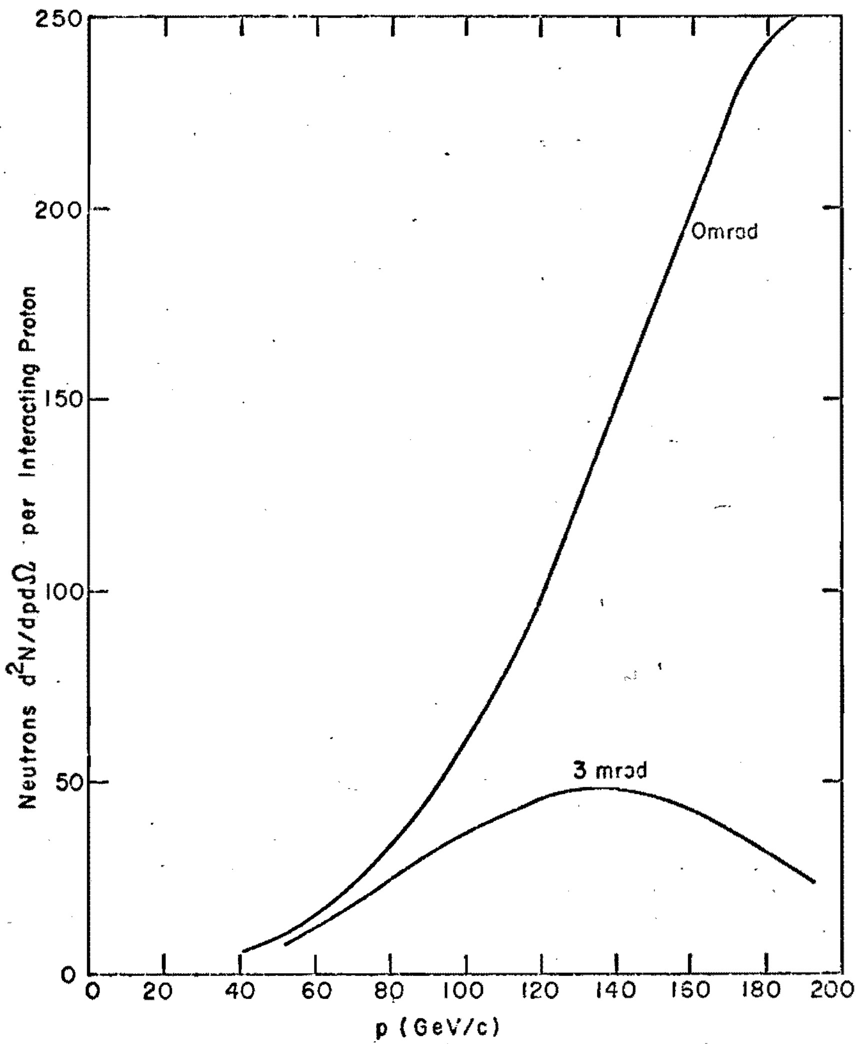
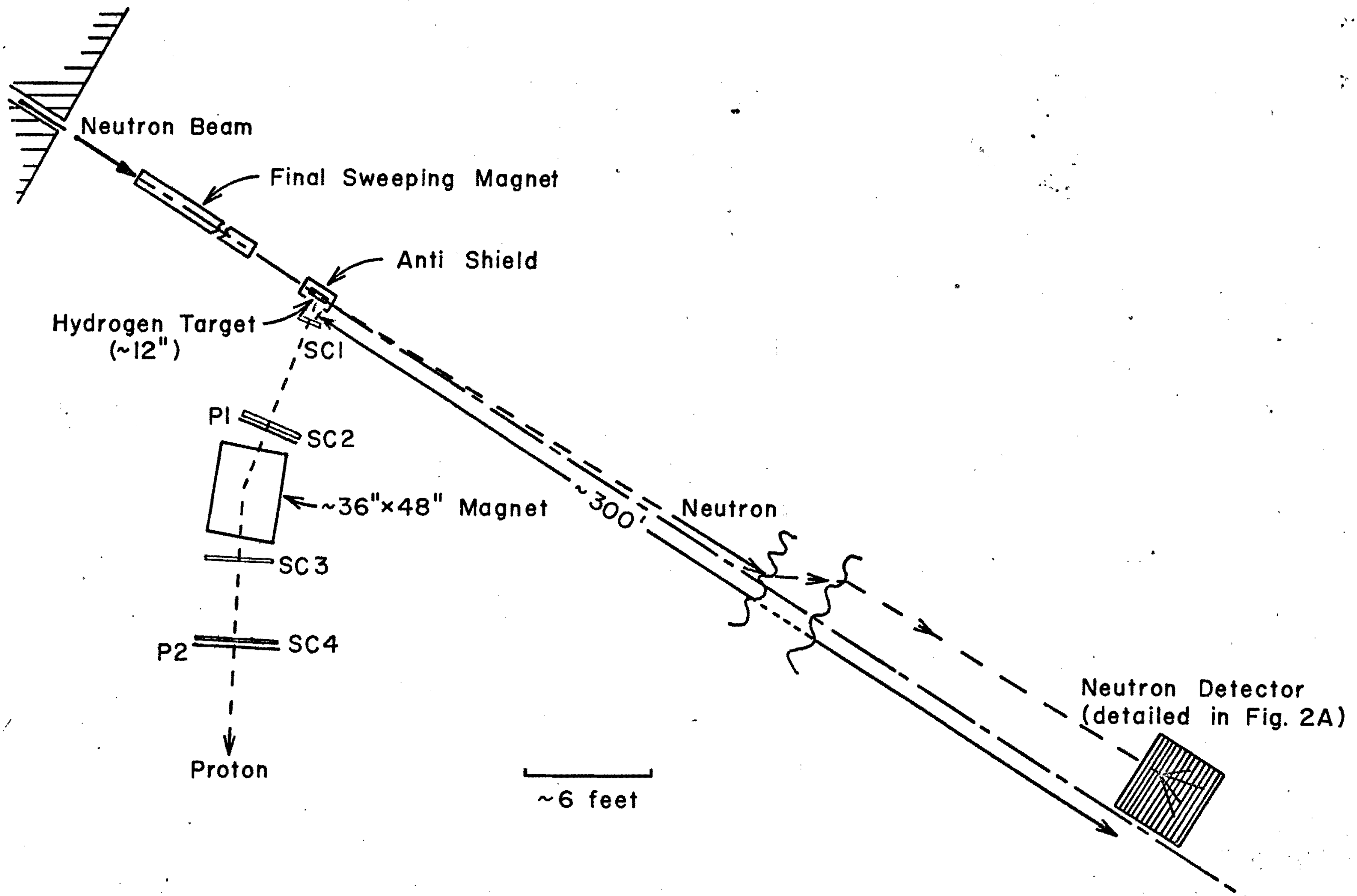


Fig. 1. The neutron spectrum (taken from the inelastic proton spectrum of Awschalom and White) at 0 and 3 mrad production, for 200-GeV protons on a Be target.



np Elastic Scattering Experiment

Figure 2

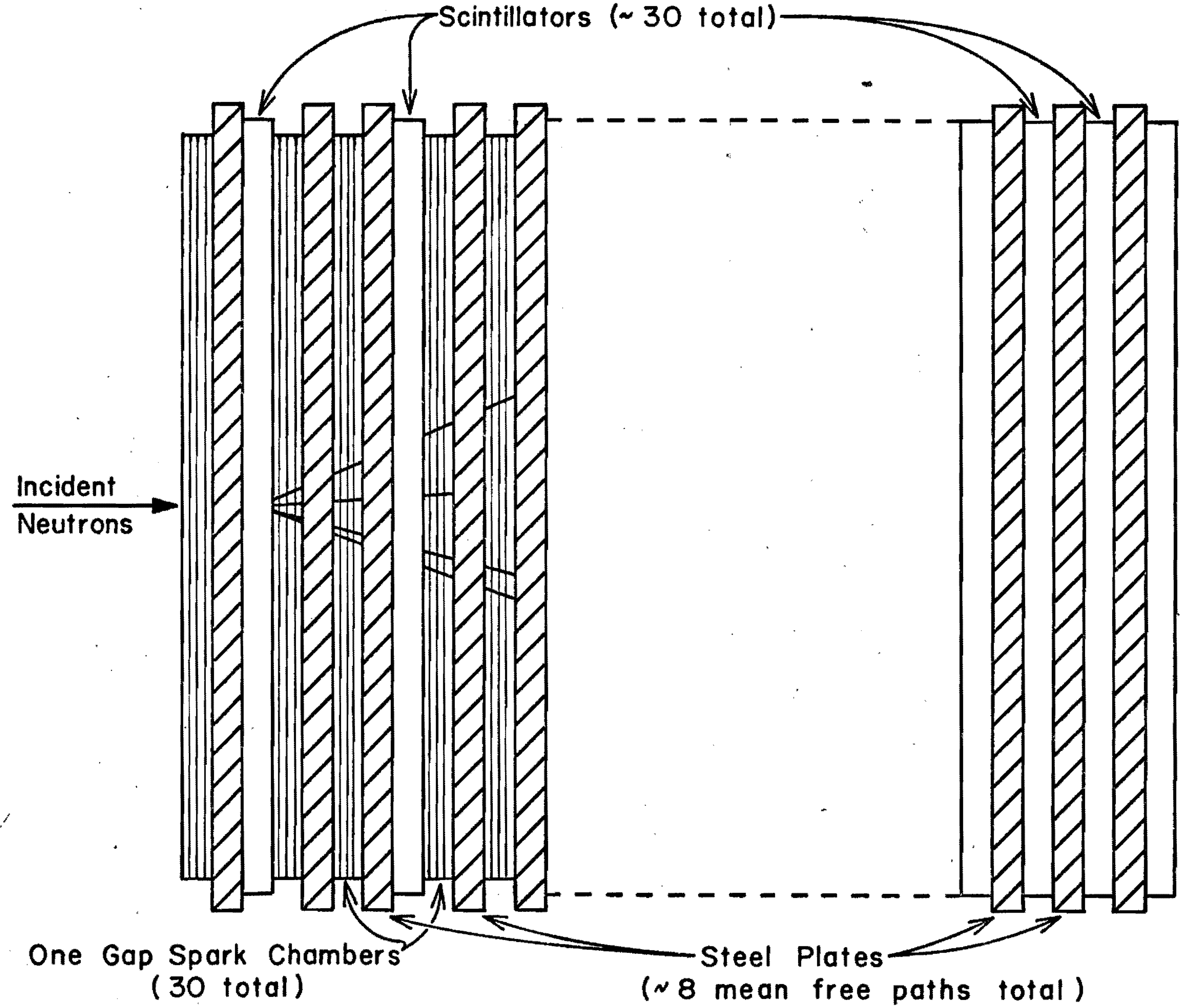


Figure 2A – Neutron Detector (Schematic)

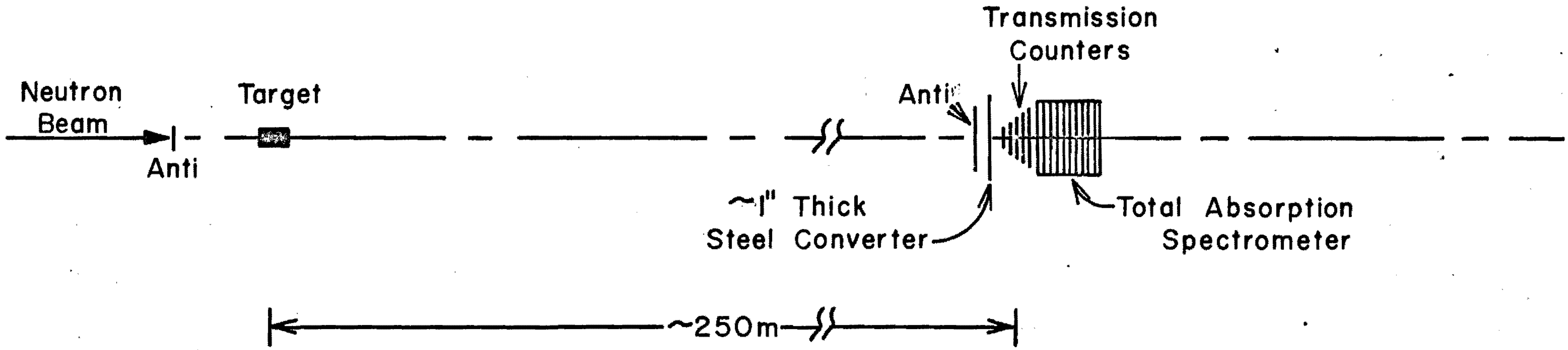


Figure 3 — Total Cross Section Experiment
(Schematic)

Neutron Small-Angle Elastic Scattering

A Supplement to Experiment 4

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Introduction

Experiment 4 is currently set up and operating satisfactorily in beam M3 in the Meson Area; with suitable beam conditions and an operating hydrogen target, significant data acquisition should commence very soon.

This supplemental proposal stems from the observation that these same apparatus, targets, and beam can be used with very minor modification to study very small angle neutron elastic scattering in a range of four momentum transfer totally inaccessible with charged hadrons due to coulomb scattering.

Physics

It was observed several years ago[1] that pp elastic scattering showed evidence of a break in the slope of the diffraction peak near $-t \simeq .1(\mathrm{GeV}/c)^2$. Subsequent ISR measurements confirmed this break and emphasized the necessity for careful measurements down to the smallest accessible values of $|t|$.[2] Neutron experiments by our group confirmed that this phenomenon is restricted neither to protons nor to high energies.[3] However coulomb scattering in the pp system is equal to nuclear (strong interaction) scattering at $|t| \cong .002(\text{GeV/c})^2$, and in view of the rapid $|t|^{-2}$ dependence of the coulomb scattering, critical information cannot be gathered on the pp interaction for $|t| \leqslant .005(\text{GeV/c})^2$.

There are several motivations for studying the hadronic elastic scattering at very small t. First, there is the obvious question of whether the exponential slope seen over the range $.005 < |t| < .1(\text{GeV/c})^2$ extends to still smaller $|t|$, or whether there might be yet another change in slope. In view of the possibly rising pp total cross sections, it is of interest to search for evidence of a more diffuse outer "cloud" of the nucleon interaction, which may become more opaque at higher energy. Second, the elastic scattering on heavier nuclei would allow a systematic determination of nuclear radius as functions of atomic number and energy. Combined with the systematic search for the A and E dependence of total cross section in Experiment 4A, these data will provide a more complete picture of the strong interaction in nuclear matter at these high energies. This kind of information is totally inaccessible to the ISR. Third, it should be possible to observe the interaction of the neutron magnetic moment with the nuclear coulomb field. Although this effect should be accurately predictable, it has not been observed to date.

Beam and Detector

The neutron beam at 1 mr. production from a tungsten target in the proton beam has a spectrum given in Figure 1 and an intensity of about 250 neutrons/(sterad proton), based on the SEM monitor of proton flux incident on the target . It has not been possible to date to make a definitive measurement of the calorimeter energy resolution; however brief runs with no bending magnets energized in the M3 beam which provide a mixed beam of elastic protons together with pions, inelastic protons, and neutrons gives the spectrum of Figure 2, suggesting that our detector resolution is no worse than 20% F.W.H.M., and may indeed be better. Since the elastic scattering cross section near 0° is proportional to p^2, the neutron spectrum effective in elastic scattering is enhanced by this factor in the data collected in this experiment.

The Experiment

A hodoscope of ten small counters, each 3/4" x 2" (approximately 2 x 5 cm^2) has been built. These would mount behind an iron converter plate and ahead of the calorimeter. The counters are adjustable vertically, so that they may constitute a continuous hodoscope of 7.5 inches or a spaced hodoscope of 15 inches. The detector is located about 650 feet (200 m) from the hydrogen and solid target station, so that each counter subtends an angle of $10^{-4} \times 2.5 \times 10^{-4}$ steradians, and the array covers a range of 10^{-3} to 2×10^{-3} radians (depending on whether close-packed or spaced). At 100 and 200 GeV, the apparatus thus covers a range of 0.0001 to 0.04 and 0.0004 to 0.16$(GeV/c)^2$ in $|t|$ respectively. One might think that an array of annular rings would be the ideal configuration for this experiment, however the one-dimensional hodoscope is very suitable. If the scattering is represented by a pure exponential in $|t| = p^2\theta^2$, then $d\sigma/d\Omega = K \exp(-Bp^2\theta^2) = K \exp(-Cr^2)$; or $d\sigma/d\Omega = K \exp(-Cx^2)\exp(-Cy^2)$. If the width of each counter element is constant in x, then the x dependence factors out and the counts in each y counter element determine the slope C. To the extent that the scattering deviates from a pure exponential the exact detector geometry may be unfolded to extract $d\sigma/d\Omega$ and $d\sigma/dt$. In practice the narrow width in x of each counter will facilitate any unfolding. The calorimeter energy resolution will also be carefully determined from proton calibrations and will also be unfolded. Beam halo will be subtracted by taking data with targets in and out of the beam.

In practice, each detected event will be recorded on tape with the calorimeter pulse height, the y-address of the appropriate hodoscope element, and the target status. Suitable anticoincidence counters of course constrain the geometry and help assure the event elasticity. Systematic non-uniformities in the separate counters and in the calorimeter response can be eliminated by translating the entire detector assembly in the y-direction (relative to the beam axis).

Data Rate

The limiting data rate will be for hydrogen, and as that case is also the most interesting we will consider it as an illustration. In general (for totally imaginary elastic scattering)

$$\frac{d\sigma}{d\Omega} = \left(\frac{p\sigma_T}{4\pi\hbar}\right)^2 e^{-Bp^2\theta^2};$$

$$\left(\frac{d\sigma}{d\Omega}\right)_{0°} = \left(\frac{p\sigma_T}{4\pi\hbar}\right)^2.$$

For $\sigma_T = 40$ mb, $(d\sigma/d\Omega)_{0°} \cong 2.5 \times 10^{-22}$ cm^2/sterad and $\cong 10^{-21}$ cm^2/sterad for p of 100 and 200 GeV/c. Each hodoscope element subtends a solid angle of 2.5×10^{-8} sterad, and the 4-foot liquid hydrogen target contains about 9 g cm^{-2} of hydrogen, so that each hodoscope element (not in the direct beam) will receive a count for each 3×10^4 (100 GeV) to 7×10^3 (200 GeV) beam neutrons. It is convenient to operate our neutron beam at a flux of about 10^4 neutrons per pulse into a spot less than one cm diameter at the detector. By operating at this flux we could collect one event per channel or about 10 events total per pulse. At 10^4 pulses per day, one week of data collection would suffice for excellent hydrogen data including target out subtraction.

We believe that we should be able to collect adequate data on hydrogen plus heavy elements in one month of good operating conditions.

Status of Experiment

The counters, electronics, and programs are now operating in Experiment 4A. The only change required will be the replacement of the front counter assembly now on the neutron detector with the hodoscope array, which is already assembled and tested. The targets, counting area, computer, and all other components would remain as in Experiment 4A.

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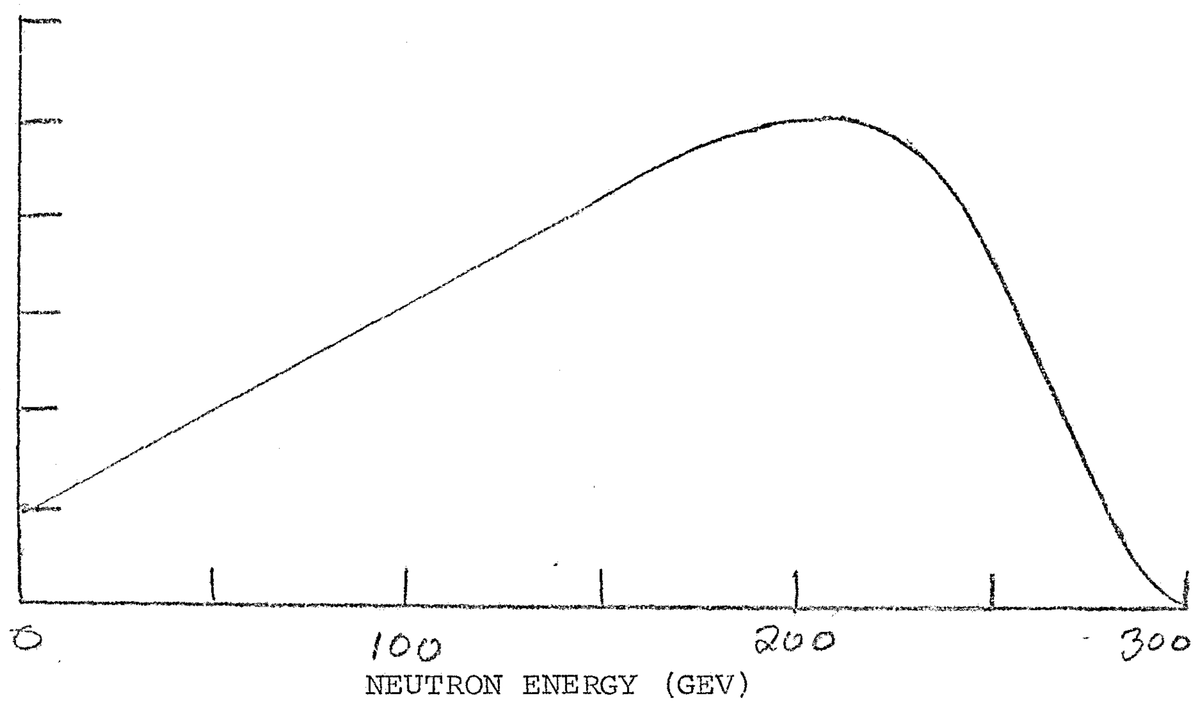

Figure 1. Neutron energy spectrum from 300 GeV protons incident on a tungsten target. The neutron production angle is 1.0 mr. (The neutron detector resolution function is not unfolded.) The energy scale is deduced from calibration with 300 GeV protons (Figure 2).

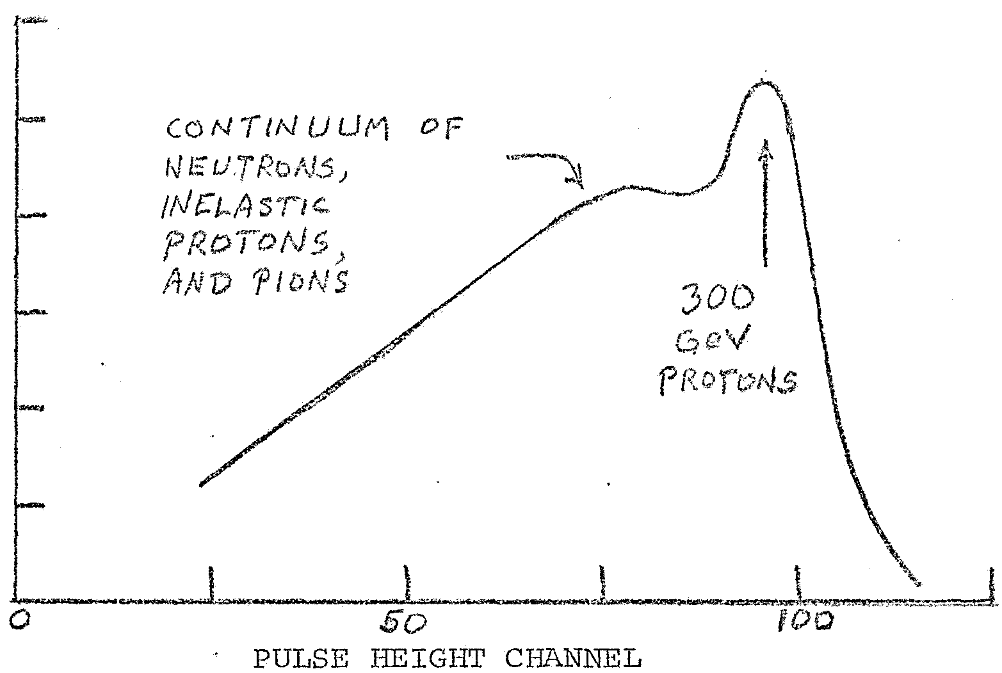

Figure 2. Pulse height spectrum from the calorimeter in the M2 beam channel with no magnets energized. The beam presumably contains diffraction-elastic protons together with a continuous spectrum of inelastic hadrons similar to the neutron spectrum of Figure 1.