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Neutron Spectra from 647- and 800-MeV Proton Bombardment of Hydrogen and Deuterium

by

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NEUTRON SPECTRA FROM 647- AND 800-MeV PROTON
BOMBARDMENT OF HYDROGEN AND DEUTERIUM

by
Christopher Wayne Bjork

ABSTRACT

Zero degree neutron spectra for the inclusive reactions $p(p,n)$ and $d(p,n)$ were obtained at the Clinton P. Anderson Meson Physics Facility (LAMPF) with the aid of a multiwire proportional chamber spectrometer which momentum analyzed charged particles produced in a liquid hydrogen radiator target in the zero degree neutron beam. Spectra were obtained for bombarding proton kinetic energies of 647 and 800 MeV. The primary targets were liquid hydrogen and liquid deuterium. The spectra were corrected for inelasticity in the hydrogen radiator target upstream of the spectrometer. Neutron momenta were measured to as low a value as 385 MeV/c. The cross sections were normalized by the n-p charge exchange elastic cross sections and by the primary proton flux as measured by a toroid current monitor.

The strongly peaked $p(p,n)$ spectra are well explained via the $p(p,n)p\pi^+$ reaction primarily through the production of the N_{33}^* (Δ^{++}) resonance. However, there is evidence for n-p final state interactions as well. Calculations have shown the roles of the N_{33}^* resonance and the n-p final state interactions in these $p(p,n)$ spectra.

The $d(p,n)$ spectra exhibit a strong quasi-elastic charge exchange peak influenced by the final state p - p interaction in the reaction $d(p,n)2p$. The $d(p,n)$ spectra also show a broad bump at lower neutron momenta qualitatively similar to the $p(p,n)$ spectra. The $d(p,n)$ spectra at lower momenta are nearly explained by nucleon-nucleon single pion production via the N_{33}^* resonance but it appears that higher order contributions involving nucleon-nucleon and nucleon-pion interactions are required as well. The $d(p,n)2p$ reaction provides an intense, nearly monoenergetic neutron beam for use as a probe, primarily of the n - p interaction, at medium energies.

The $d(p,n)$ and $p(p,n)$ measurements provide zero degree neutron momentum distributions which are very useful in furthering the knowledge about pion production near the N_{33}^* resonance. These data provide a challenge to the theoreticians to explain pion production in the two and three nucleon initial states.

C H A P T E R I

INTRODUCTION

The Clinton P. Anderson Meson Physics Facility (LAMPF) of the Los Alamos Scientific Laboratory (LASL) was built to probe the mysteries of nuclear and particle physics at projectile energies up to 800 MeV. One of the several tasks underway at LAMPF is the measurement of the scattering properties among protons, neutrons, and deuterons. The experiments to be described below give new information on the inelastic processes in nucleon-nucleon collisions. They have also provided a process for production of neutron beams that enable further nucleon-nucleon studies to be carried out.

Production of neutrons at zero degrees from p-p and p-d collisions represents a primary process in interactions of the LAMPF beam with the simplest atomic nuclei. In both cases very little data exists on these processes at medium energies. Neutron production in p-p collisions is associated with the fundamental inelastic process in the nucleon-nucleon interaction, namely pion production, which proceeds primarily through the $\Delta(1236)$ resonant state. Neutron production in p-d collisions proceeds from a three-body initial state, which may be viewed, however, as arising from quasifree two-body interactions. There are two well defined energy regimes involved. At the high energy end of the neutron spectrum, it appears that the neutrons result from

quasifree p-n scattering with the proton in the deuteron acting as a spectator. At lower energy, well separated from the high energy neutrons, the neutron spectrum reflects, in the simplest conception, neutron production from quasi-free p-p and p-n collisions with associated pion production.

The emission of the highest energy neutrons from the $d(p,n)2p$ reaction near zero degrees via quasifree scattering is enhanced by the final state interaction of the two protons in a low energy state. Such considerations were given by Gluckstern and Bethe¹ as early as 1951. Calculations by Cromer² in 1962 and Phillips³ in 1963 also indicated the favorable nature of the reaction as regards the production of monoenergetic neutrons. In 1960 Larsen⁴ used a liquid deuterium target bombarded by 710 MeV protons to produce a very low intensity neutron beam at a scattering angle of 7° to the incident proton beam. Larsen's beam had an energy width of 14 MeV full width at half-maximum (FWHM) and an integrated laboratory cross section of 15.41 ± 0.75 mb/sr. Results of this thesis indicate that this value is too low. In 1966 Measday⁵ used liquid deuterium at the Harvard 160 MeV cyclotron to obtain a neutron beam which peaked at an energy of about 152 MeV with a width of 6.6 MeV FWHM. This beam had a low energy tail (i.e. neutron kinetic energies ≥ 35 MeV) which was 16 ± 3 % as intense as the neutron peak.

Measurements of the spectrum of neutrons from p-d collisions have not been made above about 150 MeV. It is of interest to confirm

the existence of a monoenergetic group of high energy neutrons produced by n-p quasifree charge exchange scattering. The width of the distribution relates to the influence of kinematic effects and of the p-p final state interaction. This latter effect is known to exist at lower energies. The magnitude of the integrated cross section of the high energy neutron peak relates to an inhibition in the $d(p,n)2p$ reaction as compared to free n-p charge exchange scattering.

In contrast to the existing lower energy neutron spectra from the $d(p,n)$ reaction, two structures are expected at LAMPF energies. The one mentioned above is the high energy neutron peak. The other is a broad bump at lower neutron energies, in which neutrons are associated with pion production probably via quasifree p-p and p-n interactions in the deuteron. Very little information of this kind has so far been available. By measuring $p(p,n)$ spectra in addition to $d(p,n)$ spectra in the pion production region one hopes to gain insight into p-p, p-n, and p-d pion production. Such few nucleon systems should yield data which will be of great benefit to the forthcoming theories of nucleon-nucleus pion production.

Relatively little information is known about the $p(p,n)$ process. The dominant reaction between two protons resulting in an observed neutron is the reaction $p(p,n)p\pi^+$. This reaction has been studied by detection of the pion alone⁶ and by bubble chamber measurements⁷ in which both of the final state charged

particles are observed. The bubble chamber data were used to deduce neutron spectra integrated over all angles of neutron emission but give the neutron spectra to low statistical accuracy. By contrast the results given in this thesis were limited to zero degrees only, but give the neutron spectra to good statistical accuracy.

The $p(p,n)p\pi^+$ process derives its importance from the fact that the residual proton and pion interact strongly through the $\Delta(1236)$ resonance which has spin and isospin equal to $3/2$. The measured neutron spectra, especially at 800 MeV, confirm this fact. The 800 MeV spectrum has a relatively sharp peak in contrast to the predictions of phase space alone. The elementary nature of the process has stimulated calculations by the LASL medium energy theoretical group, which confirm the role of the Δ . Not anticipated by the theory is evidence for an n-p final state interaction which shows in both spectra, but with special force at 647 MeV. Such effects are more difficult for the theory to handle.

The early efforts in generating monoenergetic neutron beams encouraged the design and construction of a high power liquid deuterium target to be placed in the Nucleon Physics Laboratory of LAMPF. It was placed in the proton beam inside a well shielded cave. After the proton beam passed through the target the beam was bent and buried in a heavily shielded beam stop. The copious production of neutrons in the p-d collisions in all directions was

then utilized by appropriate collimation to form neutron beams. The zero degree neutron beam, measured in this work, has proved to be an excellent probe for future n-p scattering measurements. The high energy neutron peak is very narrow in energy spread, very intense, and well separated in energy from the lower energy pion-associated neutrons. Similar neutron beams are planned for use at TRIUMPF and at the upgraded synchrocyclotron at CERN.

The $d(p,n)$ and $p(p,n)$ neutron spectra provide a self-consistent set of data which should be useful to the understanding of the few nucleon problems.

C H A P T E R I I

EXPERIMENTAL METHOD

The measurements of $p(p,n)$ and $d(p,n)$ zero-degree neutron spectra described here were performed at LAMPF. A proton beam from the LAMPF accelerator was transported through the neutron production target, then through a 60° bend and into a heavily shielded beam stop. The area around the target was well shielded and a collimator at zero degrees to the incident proton beam was used to define a zero-degree neutron beam. The neutron beam impinged upon a liquid hydrogen radiator target producing predominantly elastically scattered protons which were then momentum analyzed in a multi-wire proportional chamber magnetic spectrometer.

A. PROTON BEAM

Figure 1 is a schematic drawing of LAMPF, a one-mile long high intensity proton linear accelerator. Although LAMPF is designed for simultaneous acceleration of H^+ and H^- beams for use in different experimental areas, in the present work only an H^- beam was accelerated. A 750 keV beam of H^- ions is provided by one of three Cockroft-Walton injectors shown at the extreme left in Figure 1. The beam is then transported by a series of bending magnets and quadrupole magnets into the 201.25 MHz drift-tube linear accelerator where it is accelerated to an energy of 100 MeV. The beam then enters the half-mile long 805 MHz side-coupled cavity linear accelerator for its ultimate acceleration to full

LOS ALAMOS MESON PHYSICS FACILITY

Figure 1

energy. The accelerator has been designed to deliver a beam of maximum energy of 800 MeV and maximum average intensity of one milliampere. The measurements described here, which were carried out during the first full year of LAMPF operation, were typically performed with about 12 microamperes of average beam intensity in the accelerator, with about 2 microamperes of average beam intensity through the neutron production target. Energies of 800 MeV (full LAMPF energy) and 647 MeV (in which the last 11 modules of the accelerator are turned off) were used. The beam has a macro-pulse structure of duration of typically 400 microseconds and repetition rate of 120 Hz established at the injector. This makes the macroduty factor of the machine equal to 4.8% ($120 \times 400 \times 10^{-6}$). There is also a micropulse structure of one pulse every 5 nanoseconds (reflective of the 201.25 MHz frequency in the drift-tube linac) with each pulse having an FWHM of .25 nanosecond.

Figure 2 shows the LAMPF experimental area. The H^- beam enters at the left of the figure from the accelerator and enters the beam switchyard where about 90% of the beam is stripped to H^+ by a carbon foil and transported on to the main experimental area (Area A) as protons. The remainder of the H^- beam is bent to the northeast towards the High Resolution Spectrometer (Area C) and the Nucleon Physics Facility (Area B). Successive carbon strippers allow the beam to be split and injected simultaneously to Area C (protons), to the neutron production target, designated LD₂ target in Figure 2 (protons), and to the extreme eastern side of

Figure 2

Area B (H^- ions). This last beam line is designated the external proton beam line (EPB). In the present work no beam was allowed into Area C, and only a few nanoamperes into EPB; thus, nearly all of the H^- beam from the beam switchyard was injected into the LD_2 target. In Figure 2, just northeast of the Line B and EPB split, a black rectangle, 3 black squares, and another black rectangle can be seen just upstream of the LD_2 target. These represent, respectively, LB-BM-04, LB-QM-1, LB-QM-2, LB-QM-3, and LB-BM-05 (LB=Line B, BM=Bending Magnet, and QM=Quadrupole Magnet). These 5 magnets are responsible for focusing the beam onto the window of the neutron production target. The beam position and spread were monitored by means of two beam profile monitors, or wire scanners, LB-WS-04, positioned just downstream of LB-QM-3, and LB-WS-06, positioned about 40 cm upstream of the LD_2 target window. The beam was centered onto the neutron production target window and focused until a maximum spread of 1 cm, vertically or horizontally, was obtained. Since the LD_2 target window has an opening of 3.2 cm horizontally, this focus was adequate for all of the measurements.

Figure 3 shows, in more detail, a plan view of the layout of the experiment in the western half of Area B. The beam entering at the left has just passed, in succession, LB-BM-05, a titanium foil placed in the vacuum system for hydrogen safety, LB-CM-02 (a toroid current monitor), and LB-WS-06. After passing through the neutron production target, the proton beam is

Figure 3

transported by the two 15° bending magnets (LB-BM-06 and LB-BM-07) and the 30° bending magnet (LB-BM-08) to the beam stop.

B. NEUTRON COLLIMATION AND SHIELDING

Since neutrons are produced copiously in every direction in the neutron production target via (p,n) reactions, extensive shielding and collimation are required to produce a useful neutron beam. Figure 3 shows the massive steel primary shielding and some of the concrete block secondary shielding. Between the detection apparatus (at the right of the figure) and the production target there is a wall of steel about 3.7 meters thick (about 20 attenuation lengths for an 800 MeV neutron). Concrete blocks about 0.91 meter thick are stacked next to the steel wall to absorb low energy neutrons and charged particles and so reduce the back-ground radiation near the detectors. A roof covers the LD₂ cave (the space including the LD₂ target and the three bending magnets) and the nuclear chemistry cave (the space just upstream of the proton beam stop). This roof consists of 1.52 meters of steel with 0.91 meter of concrete on top of the steel.

Buried in the steel shielding wall are six 155 mm diameter gun barrels which serve as collimator holders. Two of these are shown in Figure 3, one at 0° (used in the measurements described here) and another at 37° , as measured with respect to the proton beam incident upon the neutron production target. There are also gun barrels at 7° , 14° , 21° , and 27° . Steel slugs (20 per barrel) were fabricated with lead sleeves poured to match the rifling of

the gun barrels to be used as tight-fitting inserts in the six barrels. All but the 0^0 barrel were filled with these slugs during the zero-degree (p,n) measurements. The 0^0 barrel was filled with slugs having a 2.54 cm diameter cylindrical hole centered on the gun barrel axis. The resulting zero-degree collimator was, therefore, 3.66 meters long and 2.54 cm in diameter. It was surveyed to be within 0.4 milliradian of the zero-degree line as defined by the proton beam wire scanners. The neutron detection apparatus (M1 through W4 in Figure 3) was set up downstream of the zero-degree neutron collimator. M1 is the sweep magnet to clear charged particles from the neutron beam. LH₂ is the liquid hydrogen radiator target. W1 through W4 are the four multiwire proportional chambers. M2 is the spectrometer magnet. The nominal bend of an 800 MeV proton is 22^0 in the spectrometer.

C. NEUTRON PRODUCTION TARGET

The neutron production target⁸, often referred to as the LD₂ target, since deuterium is usually used for neutron production, is shown schematically in Figure 4.

It consists of a counter-current heat exchange, forced convection loop, which can be filled with liquid hydrogen or deuterium, and its associated gaseous helium refrigerator. Note, also, the solid target wheel at the bottom of the figure. The circle with the dot in the center indicates that the proton beam would be coming out of the paper if the target were placed in the beam. The

Figure 4

whole apparatus can be driven up and down so that one can place either the window of the loop or the solid target wheel into position in the proton beam. The loop and solid target wheel are lowered into a vacuum jacket which is itself part of the vacuum system of the proton beam line. The loop is cooled via a heat exchanger which is part of a closed gaseous helium refrigeration system consisting of two surplus air compressors (used to compress the helium to about 50 psig), filters to remove compressor oil from the helium, copper tubing to transmit the warm helium to and from the Cryovac helium refrigerator³ (Figure 5) where the helium is cooled to about 20°K, and vacuum jacketed, aluminized mylar insulated transfer lines to transmit the cold helium to and from between the refrigerator and the loop heat exchanger. As shown in Figure 4, the loop contains the heat exchanger on the right side, and on the left side the window, the heaters and an electric fan which provides the forced convection in a clockwise direction of the fluid in the loop. The gaseous helium flow is such that there is counter-current heat exchange between the loop fluid and the helium refrigerant. The loop is precooled before an experimental run with helium inside the loop. When the refrigerator and loop are cold the helium is purged from the loop and the desired gas, hydrogen or deuterium, is brought in under about 10 psig pressure until enough condenses to nearly fill the loop (about halfway up the horizontal tube which completes the top of the loop). The fan forces the fluid past the heat exchanger, through the window

Figure 5

region where the proton beam heats the liquid, past the heaters which are adjusted to compensate for the difference between the refrigeration power and the beam heating rate, and finally again past the heat exchanger. Notice the two tubes in Figure 4, one from the top of the loop and the other from the bottom, which are used to pass the fluids into and out of the loop. They are open at the top of Figure 4, but, in reality, are connected to a system of remotely activated solenoid valves for control of helium, hydrogen, and deuterium.

During an experimental run, just after filling with hydrogen or deuterium, helium, under about 10 psig pressure, is admitted simultaneously into both of these tubes causing a gas and liquid dynamic thermal equilibrium to develop between the liquid hydrogen or deuterium and its vapor together with some partial pressure of gaseous helium. This results in what is called subcooling of the liquid (typically of about 4°K), which means that there is sufficient partial pressure of helium such that the entire volume of liquid would have to rise in temperature the number of degrees of subcooling in order for the vapor pressure of the liquid to equal the operating pressure (part vapor and part helium). Operating with helium in a closed system this way allows one to prevent local boiling and cavitation as the proton beam traverses the liquid. Also shown in Figure 4 are the three parahydrogen vapor bulb thermometers, one in the top section, one near the window, and one near the bottom of the loop. Also indicated is the loop

pressure sensor which consists of a hypodermic stainless steel tube welded onto the loop and open to the inside of the loop. It passes up through the vacuum jacket to the outside and terminates at a precision pressure transducer which gives a D.C. voltage output proportional to the absolute pressure it senses. Each of the vapor bulbs are connected by similar tubes to individual pressure transducers. Before a run, the vapor bulbs are evacuated, the transducer output voltages are adjusted to zero, the output voltages are calibrated by a precision pressure gauge for various hydrogen pressures, and the bulbs are finally charged to about 250 psig, which is sufficient to insure the formation of liquid hydrogen at the lower temperatures encountered during a run. Chromic oxide is used in the vapor bulbs as a catalyst to insure the formation of liquid parahydrogen. Accurate tables of parahydrogen vapor pressure versus temperature are then used to determine the temperatures in the loop. We believe that these sensors allow us to determine the density of the liquid to better than a per cent, since there are accurate tables of density of both liquid hydrogen and deuterium for various pressures and temperatures.

The schematic diagram near the bottom of Figure 5 shows some of the elements of the refrigeration cycle. The helium cool-down part of the refrigeration cycle consists of compression of the helium, removal of compressor oil, cooling via relatively cold helium on its way back to the compressors, further cooling

in a liquid nitrogen cooled heat exchanger, purification, further cooling by helium just returned from the loop and finally expansion cooling brought about by a turbine suspended in a helium gas bearing which revolves at 4000 revolutions per second under the expansion of the cold pressurized helium. The helium warm-up (or loop cooling) phase of the refrigeration cycle consists of passage of the cold helium from the turbine via one of the transfer lines to the loop, passage through the loop heat exchanger, return to the refrigerator through the other transfer line, passage through the two heat exchangers already mentioned to cool fresh helium from the compressors and finally return to the compressors.

The transfer lines extend horizontally from the top of the refrigerator to a position above the target loop assembly mounted in the vacuum jacket of the Line B vacuum system. The transfer lines make a 90° bend downward so that they may be connected to the loop heat exchanger. The transfer lines have bellows sections near the refrigerator and at the 90° bend section above the target loop so that they can flex under the nearly 50 cm of vertical motion required to move from the solid target "in-beam" position to the loop window "in-beam" position. The transfer lines have bayonet joints and rely on the compression of warm rubber O-rings to make the vacuum seals.

Figure 6 shows a photograph of the target loop and shield plug assembly hanging vertically (its ordinary operation orientation) on its work stand. The large cylinder at the extreme top of

Figure 6

Figure 6 is the shield plug which supports the rest of the target. Notice the 45° bevel at the bottom of the shield plug. This matches a bevel on the inside of the vacuum jacket in Line B, thus providing a mounting place so that the loop may be inserted into the vacuum jacket reproducibly without surveying each time one wishes to work on the loop. A vacuum seal is made between the shield plug and the vacuum jacket by a rubber O-ring. All of the tubes and electrical wires from the loop and solid target wheel pass upward through the shield plug. The shield plug is filled with lead shot for shielding against 90° scattered particles. The shield plug also provides the mechanical support for the lifting mechanism which moves the loop up and down as required. Figure 6 has the same orientation as the schematic diagram of the loop (Figure 4). The long shiny aluminum window is located on the left-most of the two vertical stainless steel tubes of the loop. Notice the burn mark on the exit window of the target left by the proton beam. Figure 7 shows a close-up photograph of the window section of the target loop. The stainless steel loop window section has a flange on each side (proton beam entrance and exit) cut with a groove for an indium wire seal between the body of the cell and the 0.14 cm thick aluminum windows which are held in place by the stainless steel pressure ring. The Allen-head countersink screws enable application of uniform torque around the entire sealing surface. One successively torques the sealing plate screws until an ultimate torque of 35 oz-in is obtained on every screw. The

Figure 7

window opening is 3.2 cm wide and 15.24 cm long. The long narrow style was chosen so that one could place the proton beam at several places on the window by moving the loop up and down thus prolonging the life of the windows. The entrance and exit windows are 10.63 ± 0.10 cm apart after correcting for the bulging of the windows due to the fact that there is a vacuum outside of the windows. This length of liquid deuterium at a density of 0.168 gm/cm^3 results in a 4.26 MeV energy loss for 800 MeV protons. At an average beam current of one microampere (typical of the runs involved in these measurements) the beam heating power is 4.26 Watts. The Cryovac refrigerator, with its original compressor, was designed to provide 1000 Watts of refrigerating power at 30°K . The present system has been tested to provide 250 Watts at 20°K . Therefore, if Line B ever carries 20 microamperes average, the beam heating power will be 85 Watts and the refrigerator should easily handle it.

The loop is partially shielded from radiation by cylindrical copper sheet metal plates kept at 77°K by liquid nitrogen. The tubes that carry the liquid nitrogen and the support structure for the copper plates are located around the loop structure as can be seen in Figure 6. One can also see some of the hypodermic tubes from the vapor bulbs and loop pressure sensing point. At the bottom of the loop is the solid target wheel assembly, complete with its electric motor and the assorted targets on the moveable wheel. There are five spots for targets on this wheel. During

these measurements they contained slabs of carbon, beryllium, and aluminum as well as a loop dummy cell (for subtraction of neutron yield from the aluminum entrance and exit windows in the $p(p,n)$ and $d(p,n)$ measurements). One space was left empty to be used during beam tuning, for entrance into Area B and for nuclear chemistry experiments being performed in the nuclear chemistry cave just downstream from the LD_2 cave. The loop target has worked very reliably and should provide an excellent source of medium energy neutrons for years to come.

D. LIQUID HYDROGEN RADIATOR TARGET

The liquid hydrogen radiator target, or LH_2 target, is shown schematically in Figure 8 and in place in the zero-degree neutron beam in Figure 9. The target consists of a CTI model 1022, 10 Watt, two-stage, helium expansion refrigerator, a mylar target flask-reservoir system for the liquid hydrogen, and a vacuum jacket for insulation. Helium at about 250 psig from the compressor enters the drive unit and through a two-stage expansion refrigerator scheme warms up by removing heat from the refrigerator's surroundings within the vacuum jacket and is returned to the compressor at about 60 psig. The helium is again compressed and cooled by a gas-to-air heat exchanger on the compressor. The refrigerator actually has two separate refrigeration heads. The one after the first stage is at about $77^{\circ}K$ and the other after the second stage is in the operating range of 15° to $24^{\circ}K$. The cold head after the second stage is in good thermal contact with the

10 cm

Figure 8

Figure 9

liquid hydrogen system. The liquid hydrogen system consists of a closed reservoir vessel attached by two tubes to a closed mylar target flask. The target flask is a cylinder of mylar plastic sheet of 0.013 cm thickness with spherical end domes of the same thickness of mylar glued together with a cold-resistant epoxy resin cement. The shape of the flask is closely approximated by the drawing in Figure 8. The axis of the flask is colinear with the axis of the zero-degree neutron beam. At the top of the flask a connection is made to one of the tubes connecting the flask to the reservoir. This tube contains the target valve, a helium actuated valve used for emptying liquid hydrogen from the flask. The other tube connects the bottom of the flask to the reservoir. This tube coils around the wall of the flask (around the back side in Figure 8) and continues up to the reservoir. Not shown in the hydrogen system are the two carbon resistor liquid hydrogen level sensors, one located on each tube about 1 cm from where each tube is attached to the target flask. Also not shown are the valves and connections which allow hydrogen in and out of the reservoir to the outside. Surrounding the target flask is a vacuum jacket with a 360°, 0.013 cm thick cylindrical mylar window, glued to an open cylinder at the top for attachment to the rest of the vacuum system and glued to a cylinder closed at one end at the bottom. A special supporting bracket is used to keep the mylar vacuum jacket from collapsing when the system is evacuated. This jacket allows one to observe charged particles leaving the LH₂ up to a laboratory

angle of 110° to the right of the neutron beam (out of the paper in Figure 8 would be 90° to the right) with only two thicknesses of mylar, the target flask wall and the vacuum jacket wall, between the liquid hydrogen and the outside.

To fill the target with liquid hydrogen one evacuates the vacuum jacket, evacuates and purges with gaseous hydrogen the reservoir and target flask with the target valve open and cools down the refrigerator to about 20°K with the hydrogen system pressurized to about 5 psig by means of a regulated supply of hydrogen to condense on the cold end of the refrigerator and drip down and cool the rest of the hydrogen system. The liquid hydrogen will flash at first as it touches the warm parts of the hydrogen system (the tubes and target flask) but will remain liquid eventually when all of the hydrogen system is below the boiling point of hydrogen. The first indication of this occurs when the level indicator at the bottom of the target flask shows that it is immersed in liquid hydrogen. One continues to supply hydrogen gas until the level sensor at the top of the flask shows that it is under liquid. One then closes off the supply of hydrogen and adjusts a resistive heater located on the cold head of the refrigerator to balance the refrigeration power of the 10 Watt refrigerator. To aid against radiative warm-up of the target flask there is a copper heat shield connected to the 77°K cold head of the refrigerator and also a few thin layers of aluminized mylar wrapped around the flask. This mylar is visible in Figure 9 and completely surrounds the

target flask. This adds only about 0.001 cm to the flask and vacuum jacket total thickness of 0.026 cm of mylar to be penetrated by the particles exiting the liquid hydrogen. Since the charged particles one observes coming from the liquid hydrogen radiator target may come from reactions in the mylar as well as from the liquid hydrogen, a background subtraction is necessary. This is accomplished by accumulating radiator target empty data. One simply closes the target valve and raises the resistive heater wattage slightly. Some of the liquid hydrogen will vaporize and the vapor pressure will increase to the point where the vapor will push the liquid in the flask out of the bottom tube and up into the reservoir. The flask is about 13.2 cm long over the average cross section of the neutron beam and is about 10 cm in diameter. Its volume is about 1 liter. The reservoir has a volume of 1.5 liter, so there is adequate room for all of the liquid in the flask to be stored in the reservoir during a radiator target empty run. One usually needs to adjust the heater to stabilize the system and keep the liquid in the reservoir. Of course, the flask contains gaseous hydrogen at about 20°K but since the density ratio of liquid hydrogen to gaseous hydrogen at 20°K is about 50 to 1 one makes only a 2% error on a background subtraction.

E. MULTIWIRE PROPORTIONAL CHAMBER (MWPC) SPECTROMETER

Figure 10 shows a schematic drawing to scale of the plan view of the neutron detection apparatus. It is oriented with respect to the horizontal line, which is the axis of the zero-degree

Figure 10

neutron beam. The first apparatus at the left, just at the end of the neutron collimator, are the left and right neutron monitor telescopes, shown in more detail on the left side of Figure 11. Next, in line downstream along the neutron beam is the sweep magnet, M1, an H-frame magnet with a 7.62-cm gap and a central field of 16 kilogauss capable of bending an 800 MeV proton through an angle of about 15° . The polarity of the current in this magnet is adjusted so that the central field is directed toward the earth, thus bending positively charged particles to the left (towards the top of Figure 10), out of the way of the rest of the apparatus. The next element in the system is the anticoincidence scintillation counter, S0, followed by the liquid hydrogen radiator target (LH_2) used as a converter of the beam neutrons into protons via (n,p) charge exchange elastic scattering. The hydrogen monitor telescope, shown in more detail on the right side of Figure 11, is shown viewing the LH_2 target in Figure 10.

Other charged particles such as electrons, pions, and deuterons are also emitted from the LH_2 target. Many of the charged particles moving forward are capable of then traversing the multi-wire proportional chamber (MWPC) spectrometer¹⁰ whose major elements are MWPC's W1, W2, W3, and W4, scintillation counters S1 and S2, and the dipole spectrometer bending magnet, M2. The dominant field of M2 is directed away from the earth so that positively charged particles will be bent to the right and thus have a chance of traversing W3 and W4 if they have already passed W1 and W2. All

Figure 11

the wire chambers have vertical and horizontal sensing wires with 2 mm wire spacing, each of which can detect with nearly 100% efficiency the passage of a minimum ionizing particle near it. The spectrometer is used to detect the passage of a charged particle through the MWPC's and to record the coordinates of the struck wires. The coordinates are then used together with the measured magnetic field of M2 to reconstruct the orbit and determine the momentum of the charged particle. Plastic bags filled with helium were placed between all of the wire chambers to reduce multiple Coulomb scattering. A master coincidence to signal a valid event consists of:

$$\overline{S0} \cdot S1 \cdot 3/4 (W1X, W2X, W3X, W4X) \cdot 3/4 (W1Y, W2Y, W3Y, W4Y) \cdot S2R \cdot S2L$$

which means no signal from S0 (the absence of a charged particle in the neutron beam), signals from the fore and aft scintillation counters of the spectrometer, S1 and S2 (note that both the left and right phototube signals in S2, S2L and S2R, are required), a signal from at least three out of four of the horizontal wire planes (X planes) and from at least three out of four of the vertical wire planes (Y planes). Such a coincidence then indicates that an uncharged particle has interacted in the liquid hydrogen radiator target producing a charged particle which has traversed the spectrometer triggering scintillators, S1 and S2, and 6 out of 8 of the wire planes. The above wire plane coincidence requirement allows the orbit and momentum of the charged particle to be constructed analytically from the coordinates of the struck wires and the

measured magnetic field of M2. The minimum requirements to determine such an orbit and its accompanying momentum are the horizontal coordinates in any three of the wire chambers and the vertical coordinates in any three of the wire chambers together with a complete knowledge of the magnetic field in the bending region of the spectrometer between chambers W1 and W4.

In operation, the spectrometer detects a valid event; inhibits further triggers; records data about the event including scintillation counter pulse heights, time-of-flight from S1 to S2, and encoded struck wire positions; and re-enables the electronics to collect further data. We use, therefore, event by event data acquisition.

1. Current Integration and Neutron Monitors

Event by event data acquisition with a certain amount of inhibition time means that the neutron detector (the radiator target and the MWPC spectrometer) has a live time of less than 100%. In order to determine a (p,n) cross section, we must measure the live time during a run and also measure the number of protons that passed through the neutron production target during the run.

a. Toroid Current Monitor

The proton flux through the neutron production target is measured by the toroid current monitor, LB-CM-02, which consists of a magnetic toroid placed around the proton beam pipe just upstream of the neutron production target. As previously mentioned, the beam has a microstructure of 0.25 ns bursts, 5 ns apart, with

a macrostructure envelope of 400 microseconds duration, pulsed at a rate of 120 Hz. Beam passing through the toroid induces an electromotive force in the one-hundred turn loop wrapped around the toroid. The amplitude of the EMF is proportional to the proton flux passing through the toroid. The signal is amplified by the preamplifier at the toroid and passed by a twisted pair cable to a signal processor module. 60 Hz pickup is eliminated by this module and the signal, nearly D.C. over the length of the macropulse, is fed through a precision resistor into an ORTEC 439 integrator. The integrator produces a digitized pulse train whose frequency is proportional to the integrated current. A potentiometer is used to zero out any D.C. offsets in the signal processor. A pulsed calibration unit is used to supply a D.C. current through a single turn of wire through the toroid (to simulate a beam) for the duration of the macropulse. One measures the frequency of pulses from the current integrator and calculates the average calibration current defined as the product of the measured peak calibration current during the macropulse times the macroduty cycle (macropulse length in seconds times repetition rate in Hz). The ratio of the average calibration current times the number of protons per unit charge to the frequency of current integrator pulses is then equal to the so-called electronic calibration given as the number of protons per current integrator pulse.

In June, 1974, the electronic calibration was measured and compared to a value given to us by the nuclear chemists from group

CNC-11 (chemistry-nuclear chemistry) of the Los Alamos Scientific Laboratory. The chemists measured the total number of protons that passed through an aluminum foil by measuring the activation gamma ray activities from decay of several nuclides such as fluorine-18, sodium-22, and sodium-24. During the activation of the aluminum foil we measured the total number of current integrator pulses. The nuclear chemistry calibration (number of protons as determined by the activation divided by the number of current integrator pulses collected during the activation) was 1.03 times larger than the electronic calibration just before the activation. The nuclear chemistry calibration was:

4.20×10^{11} protons per current integrator pulse

The chemists believe their value is good to about 5% absolute. Therefore, the electronic calibration is within their error.

b. Left and Right Neutron Monitors

The live time of the system is measured by the left and right neutron monitor telescopes, shown in plan view in Figure 11. The first element at the left is an anti-coincidence scintillation counter, A, 15.24 cm by 25.40 cm by 0.16 cm thick. Next is a polyethylene radiator, CH₂, 3.18 cm in diameter (0.64 cm larger than the 2.54 cm diameter collimator) and 2.54 cm long. The left arm consists of scintillation counters L₁ and L₂ separated by 4.57 cm of copper. The right arm, consisting of counters R₁ and R₂ with the same thickness of copper, is oriented to be the mirror image of the left arm in a vertical plane containing the zero-degree

neutron beam axis. L_1 , L_2 , R_1 , and R_2 are all plastic scintillators 7.62 cm by 7.62 cm by 0.32 cm thick. The lines on Figure 11 drawn through the centers of each arm make an angle of 25° with the neutron beam axis. The respective counters L_2 and R_2 define the solid angle of each of the two range telescopes. The solid angle with respect to the center of the CH_2 radiator is 0.071 sr. A left monitor count is defined by the coincidence $\bar{A} \cdot L_1 \cdot L_2$, which indicates that an uncharged particle reacted in the radiator producing a charged particle that penetrated L_1 , the 4.57 cm of copper, and L_2 . Similarly, a right monitor count is registered for every $\bar{A} \cdot R_1 \cdot R_2$ coincidence. (n,p) elastic kinematics for scattering of the incident neutrons with the protons in the hydrogen atoms of the CH_2 yields the result that neutrons above 255 MeV will give 25° protons with kinetic energies above 207 MeV, the kinetic energy of protons whose range is 4.57 cm of copper. Therefore, the left and right monitors see neutrons over most of the spectrum measured by the spectrometer (from 80 MeV up to 800 MeV). These monitors do not see low energy neutrons which may result as secondaries in the shielding wall. Therefore, if the density of the neutron production target remains constant, the left and right counting rates should track with the current integrator rate, since the neutron flux in the collimator is proportional to the product of the proton beam flux, the neutron production target density, and the cross section for (p,n) reactions in the production target. We usually gated the current integrator and the left and right

monitor by the macropulse beam gate from the accelerator. By forming the ratio of left plus right monitor to current integrator and checking this ratio from run to run, one can check the validity of this argument. We found that the analyzed particle yields such as protons or deuterons in a given momentum bite tracked, when the statistics were adequate, with left plus right yields to better than a per cent. However, in a contiguous series of runs, the left plus right to current integrator ratio varies by, typically 2 to 3 %. The variation in this ratio between run cycles weeks or months apart was often even worse. This variation was sometimes as much as 10%. Therefore, we used the left and right monitors as our relative normalization standard among a series of runs in which the neutron production target was held fixed, even though the current integrator was used for absolute normalization. We calculated the average value of the left plus right to current integrator ratio among the runs and used this ratio together with the most reliable current integrator calibration to determine the normalization.

As previously mentioned, the left and right monitors are also used to determine the spectrometer live time. This is done by scaling the left and right monitors in two ways. The first, as described above, is by gating them only with the beam gate. Since the neutrons in the collimator are created by protons from the accelerator and the proton beam is gated by the macropulse, this type of gating insures a left and right rate proportional to the neutron beam from the collimator. The other type of gating includes,

in addition to the same beam gate, inhibition of the left and right monitor scalars by the spectrometer inhibit between valid events. Therefore, the live time is given by the ratios L_g/L_u or R_g/R_u where the "g" stands for gated (meaning inhibited when the spectrometer is inhibited) and where "u" stands for ungated (meaning only the macropulse beam gate is present). Remember that the beam gate is applied throughout these experiments. These two ratios tracked one another to within a few tenths of a per cent.

c. Hydrogen Radiator Monitor Telescope

The hydrogen monitor is shown in plan view on the right side of Figure 11. It is a differential range telescope consisting of four thin plastic scintillation counters labelled H_1 through H_4 . There are also two copper absorbers, the first between H_2 and H_3 , and the second between H_3 and H_4 . H_1 , H_2 , and H_3 are all 10.16 cm wide, 20.32 cm high and 0.16 cm thick. H_4 is 15.24 cm wide, 25.40 cm high and 0.16 cm thick. The centerline of the telescope is oriented at 45° to the left of the neutron beam axis, chosen to provide clearance between the telescope and the edge of the housing of MWPC W1 and because the (n,p) elastic cross section is nearly constant around 45° (see Figure 10). A valid event in this monitor is defined by the coincidence $H_1 \cdot H_2 \cdot H_3 \cdot \bar{H}_4$. In other words, to be counted by the hydrogen monitor, a charged particle leaving the LH₂ radiator target must have sufficient momentum to trigger H_1 and H_2 , penetrate the first section of copper, and trigger H_3 , but, must not penetrate the last piece of

copper and be seen by H_4 . The copper between H_2 and H_3 is 3.43 cm thick, the range for a 175 MeV proton. The copper between H_3 and H_4 is 3.81 cm thick, the range for a 186 MeV proton. Therefore, the hydrogen monitor differential range telescope is sensitive to protons with kinetic energies between 175 and 361 MeV. On the basis of kinematics for elastic (n,p) scattering at 450 MeV the protons detected in the hydrogen monitor correspond to neutrons in the energy range of 356 to 888 MeV. Most of these are quasi-elastic neutrons when deuterium is in the neutron production target. This was the situation during the (n,p) differential cross section measurements which will be discussed later in the context of normalization of the (p,n) spectra. The hydrogen monitor, together with the left and right monitors, was used to keep track of the liquid hydrogen radiator target since the rate in the hydrogen monitor is proportional to the neutron flux times the liquid hydrogen density. The hydrogen monitor is used when the target valve on the radiator is closed to decide when the radiator flask is empty. Typically, the hydrogen monitor rate is 13 times greater with liquid hydrogen in the radiator flask than with gaseous hydrogen in the flask.

As mentioned earlier, the current integrator output varied with respect to the left and right rates. It varied in the same way with respect to the hydrogen monitor during radiator target full runs. The hydrogen and left and right monitors tracked each other to within statistics. Thus, the calibration of the current

integrator was not constant. Such variations in the calibration can occur if the current in the bending magnet, LB-BM-04, about a meter upstream of the current monitor toroid, LB-CM-02, is altered during beam tuning. The stray field of this magnet is sufficient to upset the zero-offset on the current integrator system, causing faster or slower counting by the ORTEC 439 current integrator, depending on whether the offset is positive or negative, respectively.

2. Scintillation Counters

The scintillation counters in the spectrometer, S0, S1, and S2, are used in a fast coincidence for timing purposes; a valid signal is $\overline{S0} \cdot S1 \cdot S2R \cdot S2L$. S0 is 10.16 cm wide, 10.16 cm high and 0.079 cm thick with an adiabatic light pipe on an RCA 8575 phototube, the tube used on all scintillators in this experiment. S0 is used to veto any charged particle which may still be present in the neutron beam downstream of the sweep magnet from causing an event in the spectrometer. S1, shown schematically in Figure 12, is 15.24 cm wide, 15.24 cm high and 0.079 cm thick. The tent-type light reflecting system is used to transmit as much light as possible from scintillations in S1 to the phototube cathode. The scintillator and tent faces are suspended above the large plexiglass light-pipe by the ends of the tent which are made of thin aluminum. The tent faces consist of 0.013 cm thick aluminized mylar to reflect light toward the light pipe and are wrapped on the outside with single layers of 0.038 cm thick black plastic tape. One tries to maximize the light input from each scintillation into the

Figure 12

phototube while minimizing the amount of material present in the neutron beam. This tent-wrapped counter had a typical pulse height resolution of 60% whereas an adiabatic light pipe version with the same scintillator had a resolution of only 150%. S2 is 81.28 cm wide, 40.64 cm high and 0.318 cm thick. On each end of S2 is an adiabatic light pipe cemented to the face of a phototube. S2 is large because it must be able to see every particle which has been detected by W4, the largest wire chamber.

The scintillation counters in this experiment are all thin (0.079 cm to 0.318 cm). They must detect protons with energies from about 100 to 800 MeV, nearly minimum ionizing. Singles rates may range as high as 10^7 events per second. Therefore, one needs a photomultiplier tube with high gain, 10^7 to 10^8 , and one must try to use a base which will prevent gain slump at high rates. The design and testing of a base and magnetic shield assembly for the twelve stage RCA 8575 photomultiplier tube are discussed in Appendix A. The performance of the scintillation counters was monitored during the experiment by on-line display of pulse height histograms for S1, S2R, and S2L, as will be discussed under the heading of Data Acquisition Electronics. In these experiments one must be sure that a discriminator setting is not cutting off valid events of low scintillator pulse height. Before every run, a plateau curve was measured for each counter (Scintillator or MWPC) to insure as high an efficiency as possible as a function of high voltage. Of course, we were careful to limit the high voltage to

be just safely on plateau so that noise pulses didn't trigger the system unduly. Our on-line measurements convinced us that the scintillation counters, S1 and S2, were at least 98% efficient at all times.

3. Multiwire Proportional Chambers

The multiwire proportional chamber spectrometer, described in detail in Reference 10, consists of scintillation counters S1 and S2, MWPC's W1, W2, W3, and W4, and the spectrometer magnet, M2 (see Figure 10). All of these elements are rigidly fastened to a common framework supported by a movable magnet stand under M2. A pivot under the liquid hydrogen radiator target allows the spectrometer to rotate about the center of this target. The magnet stand has four air pads capable of levitating the twenty-one ton magnet so that it can be pushed to the desired angle. This allowed us to measure angular distributions in (n,p) elastic scattering from 0° to 60° . In the (p,n) spectral measurements, where the spectrometer is kept at 0° , the planes of W1 and W2 are normal to the zero-degree neutron beam axis and approximately centered up and down and left and right with respect to this axis. The W3 and W4 planes are normal to a line which defines the nominal bend angle of 22° to the right of the neutron beam axis. Their up-down orientation is symmetric with respect to this 22° bend line. Their right-left orientation was chosen on the basis of early experimentation with the spectrometer, to maximize the acceptance of the spectrometer for particles leaving the liquid

hydrogen radiator in a cone about the zero-degree neutron beam axis.

The multiwire proportional chambers are of the Charpak type¹¹. They have 2 mm signal wire spacing and 1 mm high voltage wire spacing. They are nearly 100% efficient and have high rate capability. Figure 13 shows a scale drawing representing chambers W1 through W3, all identical. They are comprised of seven G-10 fiberglass-epoxy laminate planes each 4.7 mm thick. Associated with each signal plane are two high voltage planes, one on either side of the signal plane. The printed circuit boards for signal or high voltage connections are cut from 2.35 mm thick copper coated G-10 laminate and are bonded with an epoxy resin into depressions milled into the appropriate G-10 planes. The W4 chamber is made similarly to W1 through W3 but it has 6.35 mm thick G-10 laminate planes. The thickness of the planes was chosen by stress testing the laminate so that negligible deformation would occur when the wires were under tension across the open area of the planes. Chambers W1 through W3 can have 96 horizontal and 192 vertical signal wires with an open area of 19.9 cm by 39.1 cm. Chamber W4 can have 192 horizontal and 320 vertical signal wires with an open area of 39.1 cm by 64.7 cm. W1 and W2, being close to the radiator target, need not be full size, and are used with a limited number of active wires. The number of active wires used is shown in Table 1.

TABLE 1

ACTIVE WIRES IN THE MWPC'S

<u>Chamber</u>	<u>No. Horizontal</u>	<u>No. Vertical</u>	<u>Sum</u>
W1	64	96	160
W2	96	128	224
W3	96	192	288
W4	192	320	<u>512</u>
Total			1184

The magic gas mixture, developed at CERN, consisted of 74.3 volume % argon, 25.0 volume % isobutane, and 0.7 volume % freon 13 B1 (di-bromo, di-fluoro methane) and was flowed under a pressure of a few centimeters of water through the chambers in parallel and into the atmosphere. The argon, before mixing with the other gases, was bubbled through methylal at -12°C as a measure to increase the effective lifetime in high-radiation fields.

The chambers act similarly to a Geiger counter. When an ionizing particle passes through the chamber an electron shower develops and drifts away from the negatively charged high voltage planes and is detected by a nearby signal wire (at approximately ground potential) with its associated electronics. Each signal wire is an independent detector, making an MWPC position sensitive. The isobutane in the gas mixture tends to quench the electron discharge and thus tends to lower pulse heights but also to reduce the multiplicity of adjacent wire response to a single discharge. In

an active chamber, that is, one detecting several particles a second, free radicals from breakup of the freon and isobutane can polymerize on the wires, forming an insulating layer. This tends to decrease the efficient lifetime of a chamber. The methylal prevents migration of the radicals to the wires by providing the neutralizing electric charges required. Therefore, the life of the chamber should be increased with the use of methylal.

Figure 14 shows our prototype MWPC in its housing. This chamber had 64 signal wires vertically and 64 signal wires horizontally with 2 mm spacing. The G-10 laminate planes were 4.76 mm thick, the same as W1 through W3. However, it had only three high voltage planes. The center high voltage plane was shared between the signal planes. No difference was observed between the configuration in which the wires of both high voltage planes seen by a signal plane were either parallel or perpendicular to the signal wires. Some problems were experienced, however, in the configuration where the wires of one high voltage plane were parallel and the other perpendicular to the signal wires. Therefore, in W1 through W4 each signal plane was accompanied by its own pair of high voltage planes, both oriented with the wires perpendicular to the signal wires.

Figure 14 gives a good representation of the MWPC chamber, its associated electronics, and its housing. A cover plate has been removed from the housing to allow us to photograph the contents in Figure 14. The chambers W1 through W4 each had similar

Figure 14

housings in the experiment with openings only to expose the active areas of each chamber. During the experimental runs, we checked the chambers for uniform response across the active area, usually with a Bi^{207} beta source. The chambers were on a whole nearly 99% efficient. However, sometimes there were a few dead or shorted signal wires. These were not much of a problem in the (p,n) spectral measurements, where we accepted events out to a polar scattering angle of 0.038 radian, thus sampling several wires in each plane. The usual coincidence ratio techniques were used to determine the overall efficiencies of each wire plane for each run. These were generally well above 99%. As mentioned earlier, the chambers were plateaued as a function of applied high voltage before each running cycle using the actual particles produced by neutrons in the radiator target.

4. Data Acquisition Electronics

Figures 15 and 16 are, respectively, a block diagram of the data collection system and a schematic diagram of the fast logic and analog electronic system. The system detects, inhibits, and records events sequentially.

Some of the important elements in the system are the amplifier-logic cards attached to the MWPC signal wires. In Figure 14 one can see some of the amplifier-logic cards plugged into the chamber and into the chamber housing. Each of these cards has eight individual circuits attached to eight consecutive signal wires. Each of these cards is called a module in the

Figure 15

Figure 16

encoding scheme. Therefore, a module consists of eight adjacent signal wires. The main features of the amplifier-logic cards include amplification and shaping of the millivolt sized pulses arising on the signal wires from an electron shower, formation of a fast discriminator output signal from the OR-ed function of any input which exceeds threshold, initiation of a monostable delay, and setting of a flip-flop unit if a Write Gate pulse is received from the triggering electronics of the spectrometer before the end of the monostable delay time. This delay is about 680 ns in our system, chiefly due to the 67 meter long signal cables between the spectrometer and the electronics trailer where we monitor the experiment.

The master gate signal, indicating the presence of an event, has the coincidence requirement:

$$\overline{S0} \cdot S1 \cdot S2R \cdot S2L \cdot 3/4(W1X \ W2X \ W3X \ W4X) \cdot 3/4(W1Y \cdot W2Y \cdot W3Y \cdot W4Y)$$

The master gate signal has the following functions: it initiates inhibition of the system; it initiates analog to digital conversion of pulse heights in S1, S2R, and S2L as measured by fast linear gates and analog to digital conversion of the time spectrum between S1 and S2L as measured by a time-to-amplitude converter; it sends out the write gate signals to the chambers to set the flip-flops on the struck wires; and it sends the EVENT signal to the scratch pad memory.

The scratch pad memory, the CAMAC input gate, the micro-programmed branch driver (MBD), the PDP-11 computer and its

magnetic tape unit form a many-buffered memory string for handling and recording the data from the wire chambers. The PDP-11 functions as the central processor establishing the programmable interface in the MBD which then controls data flow between CAMAC and the PDP-11. The EVENT signal starts the reading in of the encoded wire chamber data stored in the flip-flops of the wires struck during the event. The scratch pad interrogates the chambers in order from W1 through W4 and stores the 16-bit words, each corresponding to a module of signal wires that had one or more wires struck during the event. The 16-bit system is based on the PDP-11 16-bit word system. In the case of the wire chamber encoding, the upper two bits give the chamber number (0 to 3 corresponding to W1 to W4). The next three bits give the address of the super module. A super module is a group of eight adjacent modules. Remember that a module is a group of eight adjacent signal wires. Therefore, a super module is a group of 64 adjacent signal wires. The next three bits give the address of the module within the super module which contains struck wires. This takes care of the upper eight bits of the word. These eight bits thus give the address of the module containing struck wires. The lower eight bits of the word give the hit pattern of the eight adjacent wires making up the module. This encoding allows up to eight super modules per chamber or 512 wires per chamber. W4 uses this maximum allotment. After the scratch pad has collected the last wire chamber word, the inhibit is lifted from the system by the MBD via the output

register in CAMAC. The analog data from the ADC's is read into the MBD via the octal scalar in CAMAC, event by event. This occurs during the time the scratch pad is reading in the wire chamber data. The wire chamber data is read into the MBD via the CAMAC input gate during beam off periods, the 7.93 milliseconds between 400 microsecond macropulses. The MBD then transfers the data into the PDP-11, which sends it to magnetic tape in one thousand word blocks whenever it is full. The details of the data handling program, DAISY-11, are given in Reference 13. Also present in CAMAC are several scalars for accumulating counts continuously between the start and stop of a run. These count the left and right monitors, the current integrator, hydrogen monitor, singles in all the counters and various coincidences including the master gates. A priority interrupt register in CAMAC is used chiefly to keep the system inhibit on until the ADC's have finished conversion and the analog data is in the MBD. The data on the magnetic tape, in the form of 16-bit words, has the format tabulated in Table 2. TRF is a time-of-flight spectrum from a time-to-amplitude converter whose stop pulse comes from the RF pulse structure of the beam (a pulse every 5 nsec) and whose start pulse is from S1. The coincidence buffer word contains 16 switches telling which wire planes are included in the event. NMWPC is the number of MWPC addresses present in the event, one for each module having at least one struck wire. Notice that the last word of an event is the zero tagword. This acts as the delimiter between events on the tape.

TABLE 2

DATA TAPE FORMAT

<u>Word Number</u>	<u>Upper Eight Bits</u>	<u>Lower Eight Bits</u>
one	pulse height in S1	T12 (time-of-flight from S1 to S2L)
two	pulse height in S2L	pulse height in S2R
three	spare	TRF (incident neutron time-of-flight)
four	coincidence buffer	
five	blank	NMWPC
six	first MWPC address	
.	. . .more MWPC addresses. . .	
.		
five+NMWPC	last MWPC address	
six+NMWPC	tagword (all zeros)	

The on-line program, DAISY-11, not only starts, stops, and handles the data from the run; but can perform several tasks for keeping track of the experiment as it proceeds. A certain fraction of the events, the so-called ideal events, in which only one module is present from each of the eight wire planes, is stored on the RK05 disk of the PDP-11 for on-line analysis. All data is sent to the magnetic tape for off-line analysis later, but the ideal subset can be interrogated via commands from the Tektronix 4010 Graphic Terminal to display various parameters during data acquisition. One can display several parameters during data acquisition. One can display histograms of parameters such as the

pulse heights, times-of-flight, particle momenta through the spectrometer, horizontal projection of the hit positions in W1 and W2 projected back to the symmetry plane of the hydrogen radiator target, and the vertical projection of the W1 and W2 hit positions. Two-parameter displays are also available on the screen of the Tektronix 4010. Examples of photos actually taken from the 4010 are shown in Figure 17. These were taken for a high momentum run at 647 MeV with liquid deuterium in the neutron production target and liquid hydrogen in the radiator target. The photo at the upper left corner represents the two-parameter plot of the vertical and horizontal projections of the struck wire positions in W1 and W2. It therefore shows a profile of the neutron beam in the symmetry plane of the radiator target. The two-parameter display at the upper right shows momentum plotted vertically and time-of-flight between S1 and S2 plotted horizontally. The momentum as used on-line is actually a quantity represented by the reciprocal of the horizontal bend angle. The upper right photo has two groups of particles, deuterons to the right and protons to the left. Notice how they merge at high momenta and how some mistiming occurs, indicated by the horizontal line of events across the picture. More will be said about this later. The lower photo in Figure 17 contains single parameter histograms of the pulse height distribution in S1 (labelled S1 in the photo), the pulse height distribution in S2R (labelled A2 in the photo), the pulse height distribution in S2L (labelled A3 in the photo), and the

Figure 17

time spectrum for the time-of-flight between S1 and S2 (labelled T12 in the photo). Since S1 and S2 are thin plastic scintillators, they show the usual dE/dx form of a pulse height distribution encountered with nearly minimum ionizing particles. T12 shows two peaks, for deuterons to the right and protons to the left. The pulse height histograms were used on-line to set the discriminators on the scintillation counters so that no events were cut off by too high a discrimination level, or, if you please, too low an anode pulse height from the phototube. The pulse height from a scintillation counter in this experiment is measured from a pick-off on the eleventh dynode of the twelve stage RCA 8575 phototubes. The trigger signal from the counter is obtained from the anode of the phototube. Therefore, we would routinely put a 6 db attenuator between the anode and its discriminator to cut the anode pulse height by a factor of 2 in voltage into 50 ohms. If pulse height spectra from dynode 11 were the same with and without the attenuator, then we were confident that the discriminator was not cutting off any events.

Summarizing, the data acquisition proceeds with a start signal at the 4010 which clears all scalars, displays, and flip-flops in the wire chambers and begins data acquisition. The data is stored on the magnetic tape and the ideal subset is also stored on the disk. Displays of data in the ideal subset can be requested on the 4010 to oversee the experiment, on-line. A preset counter, on the current integrator scalar, for example, can be used to stop

the run. One can also stop the run at any time from the 4010. This stop command writes a trailer record on the magnetic tape which contains the contents of all the scalars that have been counting since the run start command. There is a command on the 4010 which will print out this trailer record on the DECWRITER of the PDP-11 also. This provides a hard copy of the pertinent data such as the total accumulation of counts from the left and right monitors (gated and ungated), the hydrogen monitor, and the current integrator; as well as the total number of master gate triggers (number of events) and the other singles and coincidences of the system for the run.

The magnetic tape is the finished product of the experimental run. It contains the scalar, pulse height, time-of-flight and wire chamber data from the run. It serves as the input to an off-line computer program on the LASL Control Data Corporation (CDC) model 7600 computer which generates the physical parameters, principally the momentum, from the data, event by event.

5. 18D36 Spectrometer Magnet

In order to calculate the momentum from the measured hit positions in the wire chambers, an accurate map of the magnetic field between W1 and W4 is required as input data to the CDC 7600 program. The spectrometer magnet is known as the 18D36 magnet. It is a dipole magnet with a gap of six inches (15.24 cm), a pole piece length of thirty-six inches (91.44 cm), and a pole piece width of eighteen inches (45.72 cm). The pole width, length, and

dipole nature give the magnet its name, 18D36. It is a pancake coil magnet obtained from the Princeton-Pennsylvania Accelerator by LAMPF. Figure 18 shows the experimental set-up corresponding to the same layout as is shown in Figure 10. It provides a good view from left to right of the sweep magnet, M1 (Eurydice), the radiator target (LH₂), W1, W2, the 18D36 magnet, W3, W4, and S2. The pancake coils of the 18D36 are clearly visible. Many man-hours were required to measure the fields of this magnet. Figure 19 shows the results of the magnetization measurements both for the central vertical field (B_y) and the $\int |B_y| dz$ versus the current in the coils. The Z-axis is defined to be the symmetry axis through the gap of the 18D36 magnet, parallel to the 36-inch edge of the pole piece, with the positive direction pointed away from W2 and towards W3. The Y-axis passes vertically from the center of the lower pole face through the upper pole face. The positive X-axis is therefore directed 11° to the right of "up" in Figure 10. The current in the coils was measured by a nulling voltmeter across a shunt in series with the magnet and also by means of a direct current transducer. Good agreement between the two were obtained. The central field was measured by a Skandatronics nuclear magnetic resonance (NMR) gaussmeter with a proton probe. The $\int |B_y| dz$ was measured with a flip-coil set-up described in Appendix B. Notice that the curves in Figure 19 are linear only up to 200 amperes in the coils of the 18D36. Therefore, we found it necessary to map the magnet at 200, 400, 600, and 800 amperes in order to interpolate

Figure 18

Figure 19

between maps and obtain magnetic field values for any current up to 800 amperes. The 800 ampere current setting (the highest allowed by the power supply) in the 18D36 will bend an 800 MeV proton through an angle of 22° , which we assigned to be the nominal bending angle for the spectrometer. The details of the magnet mapping are presented in Appendix B.

CHAPTER III

DATA REDUCTION

The raw experimental data resides on the data tapes in the form of digitized analog signals and encoded wire addresses. Several steps are required to extract the pertinent physical distributions such as, in this work, the (p,n) cross section for zero-degree neutrons as a function of the neutron's momentum.

The first step involves determination of the physical parameters, event by event, such as momentum, polar scattering angle, and azimuthal scattering angle. This is accomplished by means of the FORTRAN program TEWA, developed by our group and used on the CDC 7600 computer. The output of this program is a magnetic tape consisting of several G-vectors, written one after the other. Each G-vector contains the physical parameters for an event as determined in TEWA. Thus, there is a one-to-one correspondence between each event as written on the data tape and each G-vector as written on the output, or G-tape, in chronological order.

The next step in the data reduction process is to take a block of this G-data and sort through it to obtain the distributions in single parameter histograms and two-parameter scatter plots. This is accomplished with the use of the program KIOWA, a utility program in FORTRAN on the CDC 7600 computer developed at the Lawrence Berkeley Laboratory¹⁴ and modified by us for our

application. KIOWA allows one to obtain a plot of momentum versus time-of-flight from which one can identify a particle type. One can then histogram the momenta for a given particle and any of several other valuable parameters. In the (p,n) spectral measurements, the neutron yields are measured by detecting protons in the spectrometer arising from elastic (n,p) scattering in the liquid hydrogen radiator target. Therefore, measurement of the proton yield in each proton momentum bin, obtainable with KIOWA, can be translated into a neutron yield from the (p,n) reaction at the neutron production target in a corresponding neutron momentum bin. Since the neutron yield is proportional to the (p,n) cross section, one has almost accomplished the task of determining the cross section.

Further details involve background subtractions including neutron production target empty, liquid hydrogen radiator empty, and radiator target inelastic data. Finally, normalization involving the (n,p) elastic cross section for the scattering in the radiator target, the proton beam flux measurement in the neutron production target, and the solid angle determination of the neutron beam collimator is required.

A. PROGRAM TEWA MOMENTUM DETERMINATION

The program TEWA is single event oriented. The data tape, as discussed previously, has a tagword equal to zero delimiter between each event. TEWA recognizes the contents of a single event from between two of these tagwords and executes. The G-vector for

this event is written to the output file of TEWA and TEWA goes on to the next event.

The first step in execution of an event consists of passing on the numerical value for each digitized piece of analog data to its corresponding component of the G-vector. Next, the wire chamber addresses are decoded to determine which wires detected the passage of the charged particle through the spectrometer. Sometimes several adjacent wires in a given plane are found to have been active during the event. Such a group is given the name cluster. TEWA determines the hit positions in each plane by determining the coordinates of the centers of gravity of the clusters in that plane. There may be one or more hit positions in each plane. Multiple clusters in a plane require special treatment as will be discussed later. Single clusters in each plane triggered during the event can give one and only one trajectory for the charged particle responsible for the event.

Determination of the orbit and the momentum for events with single clusters in each plane will now be discussed with the aid of Figure 20. This figure schematically shows, in plan view similar to Figure 10, the pertinent horizontal parameters used in TEWA. Vertical displacements are not very important and tests have shown the fitting of the vertical trajectories to be unnecessary. The magnet-centered coordinate system has been discussed previously under the context of the magnet measurements for the 18D36 spectrometer magnet. In reality, W1 and W2 are normal to the zero-degree

Figure 20

neutron beam. Similarly, W3 and W4 are normal to the nominal bend angle line 22° to the right of the zero-degree neutron beam. All wire planes are drawn parallel for simplicity in Figure 20. Simple use of analytical geometry in TEWA translates the cluster centers in the wire planes to the rectangular coordinates in the magnet-centered coordinate system. The start plane in the orbit determination is defined to be the midplane between W1 and W2. The end plane is defined to be the midplane between W3 and W4. Figure 20 shows the horizontal bend angle, α , between the two straight solid lines. These lines would be the ones determined by the W1X with W2X hit positions and W3X with W4X hit positions, respectively. In the start plane one finds the incoming x-coordinate, x_i , and the horizontal component of the direction cosine of the incoming trajectory, dx/dz_i . In the end plane one finds the outgoing x-coordinate, x_o , and the horizontal component of the direction cosine of the outgoing trajectory, dx/dz_o . These parameters thus comprise the information on the measured trajectory. The fitted trajectory and its momentum are then determined by a procedure involving Runge-Kutta integration and a χ^2 minimization procedure.

The equation of motion for a charged particle moving in a magnetic field is:

$$\vec{f} = q(\vec{v} \times \vec{B}) = m(d\vec{v}/dt)$$

which, using a line element dl along the trajectory in the direction of the unit vector $\hat{u} = \vec{v}/v$, may be written:

$$d^2\vec{r}/dl^2 = q(\hat{u} \times \vec{B})/P$$

where P is the magnitude of the particle's momentum. Using the rectangular coordinates of Figure 20 and formally integrating, one finds, for the x coordinate:

$$dx/dl = (A'_x/P) + (dx/dl_i)$$

and

$$x = (A'_x/P) + (dx/dl_i)l = x_i$$

for which, if

$$M = B_z \sin\theta \sin\phi - B_y \cos\theta$$

with θ and ϕ being the polar and azimuthal angles of $\hat{u}$, one has:

$$A'_x = q \int_0^1 dl' M(l')$$

and

$$A_x = q \int_0^1 dl' \int_0^1 dl'' M(l'')$$

Taking the equation above for dx/dl and multiplying by dl/dz one obtains:

$$dx/dz = (A'_x/P)(dl/dz) + (dx/dz_i)(dz_i/dl_i)(dl/dz)$$

dl/dz is always near one for our geometry. The product of the last two factors in parentheses in the second term is never more than a couple of percent away from unity and it can be neglected. Then, if one redefines A'_x to be $A'_x(dl/dz)$, one obtains to a good approximation:

$$dx/dz = (A'_x/P) = (dx/dz_i)$$

Likewise, redefining A_x to be $A_x - A'_x(dx/dz_i)$, but making no

approximations, one obtains:

$$x = (A_x/P) + (z-z_i)(dx/dz_i) + x_i$$

Now, the Runge-Kutta numerical integration method can be used to determine the trajectory for a given guess of the momentum, P_0 , as based on the bend angle and the value of the magnet setting as well as the starting values x_i and dx/dz_i . The magnetic field map for each of the current settings 200, 400, 600, and 800 amperes is stored on a magnetic tape. Runs comprising all the data in this work came from the 18D36 current settings of 100, 145, 200, 240, 300, 400, 600, and 800 amperes. The 190, 145, 200, and 240 ampere runs were analyzed using the 200 ampere map. The 100 and 145 ampere runs correspond to the linear region of the magnetization curve and were analyzed with a simple linear scaling of the 200 ampere map. The 240 ampere data required a scaling of the 200 ampere map based on the $\int |B_y| dz$ ratio from 240 to 200 amperes. The 200, 400, 600, and 800 ampere runs were analyzed with their respective field maps. The 300 ampere runs were analyzed with the 400 ampere map scaled down by the $\int |B_y| dz$ ratio from 300 to 400 amperes. A separate three-dimensional matrix (one dimension per coordinate direction) is established by TEWA for each of the three components of the magnetic field from the data of a field map. The Runge-Kutta procedure requires the knowledge of the magnetic field at each numerical integration point along the trajectory. Linear interpolation between adjacent field map grid points is used to determine the values of the magnetic field components as

required by the Runge-Kutta procedure. When the integration is complete, that is, the trajectory has reached the end plane, the exit values x_2 and dx/dz_2 are determined. These are not shown in Figure 20.

The values of A_x and A'_x can be calculated from:

$$A_x = P_o [x_2 - x_1 - (z - z_1)(dx/dz_1)]$$

$$A'_x = P_o [(dx/dz_2) - (dx/dz_1)]$$

The trajectory is tested to see what correction must be made to P_o to improve the fit. Assume:

$$1/P = \rho + 1/P_o$$

where P is the "true" momentum and ρ is the correction. Assume, also, that the measurements by W1X and W2X of x_1 and dx/dz_1 are inaccurate by amounts ξ and η , respectively. One can then form a χ^2 from the model variances of the system, the measured positions and slopes for the event, and the Runge-Kutta exit values. Calling $z_o - z_1 = L$, the result is:

$$\begin{aligned} \chi^2 = & (\xi^2/\sigma_1^2) + (\eta^2/\sigma_2^2) + (1/\sigma_{1p}^2)(x_2 + A_x\rho + L\eta - x_o)^2 \\ & + (1/\sigma_{2p}^2)[(dx/dz_2) + A'_x\rho + \eta - (dx/dz_o)]^2 \end{aligned}$$

To minimize χ^2 , the derivative of χ^2 with respect to ρ , ξ , and η is set to zero and matrix methods using Cramer's rule determine the values of ρ , ξ , and η which simultaneously minimize and determine χ^2 . One can then calculate the corrected momentum to be:

$$P = 1/[\rho + (1/P_o)]$$

The model variances in the system are obtained from the

notion that a signal wire has uniform response to a charged particle passing within a half-wire spacing on either side of the wire and no response for a particle farther away. Let s be the wire spacing, equal to $2n$ mm, where n is equal to the number of adjacent wires contributing to a cluster in a plane. Then the response function, $f(x)$, is given as a constant, k , between $-n$ and $+n$ mm from the wire:

$$\int_{-n}^{+n} f(x) dx = 1 = k(2n)$$

which defines:

$$f(x) = k = 1/2n \text{ mm}^{-1}$$

Therefore, the mean square deviation of a track from the center of the cluster is given by:

$$\langle x^2 \rangle = \int_{-n}^{+n} (1/2n) x^2 dx = n^2/3$$

Therefore the root mean square deviation, set equal to Δx , is given by $n/\sqrt{3}$, or $s/\sqrt{12}$. This is the variance, σ , of a constant distribution of width s .

Suppose x_1 and x_2 are the x -positions in mm for the cluster centers in wire planes W1X and W2X, respectively. Suppose they both are associated with clusters containing n adjacent wires (90% of the time $n = 1$). Since:

$$x_i = (x_1 + x_2)/2$$

then:

$$\Delta x_i = \sqrt{\Delta x_1^2 + \Delta x_2^2} / 2 = n/\sqrt{6}$$

The model variance σ_1 is set equal to Δx_i . For 1000 mm between W1X and W2X:

$$dx/dz_i \approx (x_2 - x_1)/1000$$

Then:

$$\Delta(dx/dz_i) = \sqrt{\Delta x_1^2 + \Delta x_2^2} / 1000$$

The model variance σ_2 is set equal to $\Delta(dx/dz_i)$. Similarly, σ_{1p} is the variance associated with x_o . σ_{2p} is the variance associated with dx/dz_o . However, σ_{1p} and σ_{2p} are increased a bit due to a multiple Coulomb scattering correction for the spectrometer based on the Rossi-Greisen formula¹⁵ for protons with a momentum, P_o , the guessed momentum for the event.

Experience has shown that it is usually not worthwhile to iterate the procedure and determine another trajectory from the corrected momentum and the corrected start plane values. $(x_i + \xi)$ and $(dx/dz_i + \eta)$. The convergence is so good that the corrected values after the first integration differ less than 0.5% from the final fit values. The dot and dash curve in Figure 20 represents the fitted trajectory after a single integration having the corrected start plane values, the guessed momentum, P_o , and end plane values of x^* and dx/dz^* .

The procedure just described is useful only for a single cluster present in each plane. Since we require only 3/4 of the horizontal and 3/4 of the vertical planes to detect an event, we must be able to reconstruct events with fewer than all planes.

This is done with the aid of the symmetry plane of the magnetic field. This plane is indicated in Figure 20. Experience has shown that this plane corresponds to a z-coordinate value of about -1 cm. Since the four wire chambers are in nearly zero magnetic field regions, the value of z for which the straight line from W1 and W2 approaches most closely the straight line from W3 and W4 is about the same as the z-coordinate of the symmetry plane. For events with only three X-planes present, a straight line between the two planes present on one side of the magnet is constructed. The intersection of this line with the symmetry plane is located. The line between this intersection point and the remaining measured position in the third plane is reconstructed. There then exists incoming and outgoing straight line trajectories that intersect in the symmetry plane from which a momentum can be determined. The χ^2 value for such a reconstructed event will only be useful as a measure of the goodness of fit to the points actually measured provided the variance value given to the missing point is large enough.

Some of the multiple cluster data can be handled with reconstruction methods, namely those events where no more than one X-plane or where no more than one Y-plane contains multiple clusters, provided the other planes each have a single cluster. These are called reconstructed multiple cluster events. In these kinds of events the multiple cluster planes are considered to have no information and the remaining single cluster planes are used to

reconstruct the incoming and outgoing tracks as described above.

Other types of multiple cluster events, those with more than one X-plane or Y-plane having multiple clusters can only be treated by forming each possible track from all the clusters in all the planes and stepping through these combinations to obtain fits to each one. These events are called higher order multiple cluster events. The events of this type are predominantly due to a single real track plus background hits due to noisy wires or ambient radiation. Some are due to two real tracks. For example, a neutron incident on hydrogen can give a negative pion and two protons in the final state. It is conceivable that the two protons could each form a track in the spectrometer. Therefore, information on the two tracks with the lowest χ^2 is saved in an extended G-vector (one with about twice as many components as the usual one), the one with the lowest χ^2 coming first.

In addition to the momentum and the digitized analog data, other physical quantities are entered by TEWA as components in the G-vector. Among these are the wire number hit positions in each wire plane (including all reconstructed planes), the X- and Y-projections in the symmetry plane of the radiator target, the horizontal bend angle α , the vertical bend angle β , the polar scattering angle θ , the azimuthal scattering angle ϕ , the value of χ^2 for the fitted track, the path length along the fitted track, and the value of the z-coordinate at the point of closest approach of the incoming and outgoing straight line tracks. These values

are output by TEWA onto the G-tape along with a trailer record containing the scalar information for the run as it exists on the data tape. The G-tape can then be sorted by the KIOWA program so that the event number distributions of any of the parameters can be perused.

B. PROGRAM KIOWA DATA SORTING

KIOWA allows us to obtain histograms and scatter plots from among the components of the G-vectors as generated in TEWA.

1. histograms and Scatter Plots

A histogram is defined to be a plot of the weighted number of events from the sample set of data which have a value for the parameter being histogrammed within a particular bin range for that parameter. The user of KIOWA is allowed to give the lowest value for the parameter to be examined and the bin size for that parameter. The maximum allowed number of bins was 120 in our application, based on the width of standard computer printout. Therefore, the largest value for the parameter is equal to the lowest value plus 120 times the bin range. The weight attached to each event having a parameter inside the range of one of the bins can also be set by the user. KIOWA then plots the histogram on a sheet of computer printout by adjusting the vertical scale. It also prints the weighted numerical contents of each bin. For example, a typical histogram perused in these experiments was the wire number hit position in the wire plane W1X. One typically would set the bin size for this parameter to be one, since on the average 90% of

the events contain wire plane clusters with only a single wire struck. The weight of each event was usually set to be one. The resultant graph showed a flat-topped Gaussian shaped distribution centered about the wire number corresponding to the zero-degree neutron beam axis. This corresponds to the fact that most of the events measured by the spectrometer are the result of knock-on charged particles generated by the neutron beam in the liquid hydrogen radiator target.

One can specify a negative weight if one wishes to do a background subtraction. Typically one will assign a positive weight to a radiator target full run and a negative weight to a radiator target empty run and execute the data from these two runs in one KIOWA job. The resultant histograms will then be the net data from the liquid hydrogen in the radiator provided the absolute values of the two weights are in a ratio corresponding to the inverse ratio of their respective left plus right gated neutron monitor counts.

The scatter plots in KIOWA are in a sense three-dimensional displays of two parameters simultaneously. They are very similar to the two-parameter displays available on-line with the Tektronix 4010. One can specify 50 bins vertically for one parameter and 100 bins horizontally for the other parameter. These limits are again dictated by the size of a computer printout sheet. If an event has a value of the first parameter in bin A and a value of the second parameter in bin B, then the (A,B) grid point in the

two-dimensional space of these parameters will be incremented by one. When KIOWA is ready to print a scatter plot, it uses the numbers 1 through 9 to indicate that a given grid point has 1 through 9 events, respectively, as its contents. KIOWA uses the letters of the alphabet A through U to specify contents from 10 through 30 events, respectively. KIOWA uses the letter V to show that a grid point contains 31 or more events. Therefore, scatter plots are useful to determine the extent of distributions in any two-parameter space as chosen by the user, but the scatter plots are not useful as a quantitative tool to measure contents unless all grid points contain 30 or fewer events.

2. Particle Identification

KIOWA is used for particle determination via a plot of momentum versus time-of-flight between S1 and S2. This time-of-flight, T12, is measured between phototubes S1 and S2L. The plot is similar to the on-line display in Figure 17. Since particles are bent to the right in the spectrometer, a particle with a low momentum traversing the spectrometer will pass through S2 farther from S2L than a particle with a higher momentum. Transit time for an 800 MeV proton with a speed of 84% the speed of light through the 4.9 meter path between S1 and S2 is about 19 ns. Light transit time from the center of S2 to either end is about 1.6 ns. Therefore, both the S1 to S2 and S2 hit position to S2L transit times increase with decreasing momentum.

A special version of KIOWA corrects the time-of-flight of

a particle from S1 to S2 for time-walk due to pulse height correlation in S1 and S2L as well as for light transit time in S2. The W4X position is used to determine the distance of the particle hit position in S2 from S2L. A typical timing resolution of 1.8 ns FWHM before correction was reduced to about 1.0 ns with this correction for a proton group around 800 MeV. The special version of KIOWA incorporates the use of χ^2 minimization in a space of linear parameters. First, the variables S2L pulse height and W4X position are inserted in the following expression where $S2L = x_1$ and $W4X = x_2$:

$$Y(x_1, x_2) = a + b_1 x_1 + b_2 x_2 + c_1 x_1^2 + c_2 x_2^2 + d_1 x_1 x_2 + d_2 x_1^2 x_2 + d_3 x_1 x_2^2 + d_4 x_1^2 x_2^2$$

Next, let TOF_i be the channel number from the T12 time spectrum for the i th event. Let:

$$K_0 = L/(c\alpha)$$

where L is the path length from S1 to S2, c is the speed of light, and α is the time-to-amplitude converter, TAC, calibration in seconds per channel. In relativistic kinematics:

$$1/\beta = c/v = \sqrt{1 + m^2/p^2}$$

where v is the velocity of the particle, m is the mass, and p is the momentum. The quantity T_i is formed for event i :

$$T_i = TOF_i - K_0(1/\beta_i)$$

Then χ^2 is formed from a sample of N events:

$$\chi^2 = (1/N) \sum_{i=1}^N [T_i - Y(x_1, x_2, i)]^2$$

where i indicates that S2L and W4X are taken for the i th event.

χ^2 is minimized with respect to the nine parameters of the Y function. T_i is then set equal to:

$$T_i - Y(S2L, W4X, i) + T_0$$

where T_0 is approximately equal to the average of T_i over the sample of N events. T_i now has a value corrected for time walk in S2L and light transit time variation in S2.

Let x be the value of S1 pulse height channel number. The following function is formed, where $S1 = x$:

$$Z(x) = \sum_{n=0}^4 a_n e^{nxb}$$

where b is fixed. The following χ^2 expression is then minimized with respect to the 5 parameters a_0 through a_4 :

$$\chi^2 = (1/N) \sum_{i=1}^N [T_i - Z(x, i)]^2$$

where T_i is the corrected value from the S2L and W4X correction.

This is done by passing through the same set of N events a second time. The final value of T_i is then set equal to:

$$T_i(\text{uncorrected}) - Y(S2L, W4X, i) - Z(S1, i) + 2T_0$$

where

$$T_i(\text{uncorrected}) = \text{TOF}_i - K_0(1/\beta_i)$$

In practice, one runs this special KIOWA version for a run typical of a sequence of runs containing the data for a particular

experiment. The 14 parameters for the Y and Z functions can then be used for all the runs provided the TAC calibration was not adjusted.

In the standard KIOWA version, one accomplishes particle identification on a plot of the corrected time-of-flight versus momentum. Loci are constructed which show how particles with unit positive charge and masses 400, 1400, and 2040 MeV would move in the space of time-of-flight versus momentum based on the relativistic equation:

$$1/\beta = \sqrt{1 + m^2/p^2}$$

If an event in this space corresponds to a mass ≥ 2040 MeV, it is identified as a massive particle (i.e. more massive than a deuteron). Very few of these particles are seen in the (p,n) spectral measurements since most of the interactions in the radiator target involve a neutron beam and a hydrogen target. If the event's mass, m, satisfies $1400 \leq m < 2040$ MeV, it is identified to be a deuteron. If the event's mass, m, satisfies $400 \leq m < 1400$ MeV, it is identified to be a proton. If its mass is < 400 MeV, it is identified to be a pion.

The proton and deuteron identifications are unambiguous except in momentum regions of the spectrum where the rate is very high and S1 or S2L is responsible for mistiming in the T12 time spectrum. This can be seen in the T12 versus momentum plot in Figure 17. The data in Figure 17 are for a d(p,n) spectral measurement at 0° with an 18D36 magnet current setting of 600 amperes

which allows the spectrometer to view the quasi-elastic neutron peak near the kinetic energy of the incident proton beam of 647 MeV. This was run number 1375 as we numbered the runs. One can see in this photo the horizontal bar near the top which shows several events scattered across the full window of the TAC. Remember, momentum is plotted vertically and T12 horizontally. The ratio of deuterons to protons in the momentum range where mistiming occurs in run 1375 is about 0.6%. Therefore, all mistimed events are assumed to be protons and one corrects the yield of protons by adding on all mistimed events to the yield of protons as identified by the 400 MeV and 1400 MeV mass loci. This boosts the proton yield in the mistimed momentum band by a factor of 1.014.

The particles identified to be pions (i.e. their masses are less than 400 MeV) may also be muons or positrons but in the (p,n) spectral measurements one is concerned only with the protons and deuterons. Therefore, further particle identification is not required.

To insure the goodness of the time-walk fit throughout a set of runs, one examines the KIOWA scatter plot of time-of-flight versus momentum to see if the particle groups remain between the appropriate loci as defined above. One also examines a plot of particle mass versus momentum. This should show groups of constant mass no matter what the value of momentum. One can also examine a histogram of particle mass. This shows a clear distinction among the deuteron, proton and "pion" groups. Each

group is approximately Gaussian in shape. In Run 1375 the number of proton events with $680 \leq m < 1160$ MeV was 23745. The number of events with $1160 \leq m < 1560$ MeV was 98. The number of deuteron events with $1560 \leq m < 1920$ MeV was 3419. This shows the good separation between protons and deuterons.

3. Spectrometer Acceptance Determination

The acceptance of the spectrometer has been determined empirically with the use of plots of proton recoils in various momentum bites. Figure 21 shows reduced photos of the KIOWA scatter plots of polar scattering angle, θ , versus the wire hit positions in W3X or W4X, as the case may be. The plots correspond to looking upstream through the wire chambers. Therefore, the 600 ampere 18D36 magnet plots are displaced to the left of the 300 ampere plots as one looks at Figure 21. These plots are subject to a cut of $\sin\theta\sin\phi \leq 0.02$ which sets a limit on the vertical extent of any track. The finite size of the neutron beam and the gap of the 18D36 magnet are used to determine the limiting value of 0.02 on $\sin\theta\sin\phi$, so that there is negligible probability that an event will strike the pole pieces if $\sin\theta\sin\phi \leq 0.02$. Consider plots (a) and (b) in Figure 21. These show that right-scattered events, $(\pi/2) \leq \phi \leq (3\pi/2)$, start running off the edge of W3 at values of $\theta > 0.03$ while they still lie within the acceptable region of W4. Conversely, particles scattered to the left, that is, $0 \leq \phi \leq (\pi/2)$ or $(3\pi/2) \leq \phi \leq (2\pi)$, don't escape W3 until $\theta > 0.05$ nor do they escape W4 until $\theta > 0.065$. This shows that W3 limits the acceptance of the

Figure 21

spectrometer for both left-scattered and right-scattered particles. The plots (c) and (d) show a larger θ -cutoff for right-scattered particles but a lower θ -cutoff for left-scattered particles than do plots (a) and (b) even though all of these plots correspond to the same momentum band. This just says that the lower current bends the particles through a smaller bend angle. Comparing plots (a) through (d) with plots (e) through (h), respectively, shows how much farther to the right lower momentum particles are bent for the same magnet settings. Several such plots were generated for various momentum bands and magnet current settings. The magnet current dependence can be removed by scaling the momentum by the value of $\int |B_y| dz$ along the symmetry axis of the magnet for the current setting considered. The maximum values for θ for left- and right-scattered particles can then be determined from the plots.

Figure 22 shows a plot for the right and left limits on θ versus the momentum as scaled by $\int |B_y| dz$ including the restriction $\sin\theta\sin\phi \leq 0.02$. A particle has negligible chance of missing a wire chamber if it has momentum and scattering angles consistent with the acceptable region lying between the loci of the plotted points. The scaling of momentum by $\int |B_y| dz$ (called $\int B \cdot dl$ in Figure 22) is certainly correct since the points for the four 18D36 magnet currents all lie along the same loci. The connected points at $\theta_{\text{left}} = 0.07$ and at $\theta_{\text{right}} = 0.065$ correspond to absolute limits on θ due to MWPC W2.

Figure 22

The six-sided polygon bounded by the continuous line segments in Figure 22 corresponds closely to the acceptance region used in the zero-degree (p,n) spectral measurements. θ is restricted to be less than 0.04 by the horizontal line segments. Let P_L and P_U be the lower and upper momentum limits, respectively, defined by the vertical lines. The dashed lines through the polygon subdivide it into the right triangles A and C and into the kite-shaped region B.

In KIOWA, during the analysis of the (p,n) measurements, regions A, B, and C were defined by software for each magnet current used. If W was the weight assigned to a run, based on the number of monitor (current integrator and/or left and right monitor) counts, then an event was entered into a momentum histogram with a weight, W, if it was within region B or with a weight, 2W, if it was within either regions A or C. If an event was not within any of the three regions, it was not counted in KIOWA. The rationale for this way of counting comes from the fact that region B includes all values of ϕ , that is, the boundaries of region B correspond to equal values of θ_{left} and θ_{right} for each momentum between P_L and P_U . Regions A and C, however, exist wholly on one side of the zero-axis for θ in Figure 22. Therefore, it is necessary to double-count events in regions A and C to make up for the fact that only half of the allowed range of ϕ is accepted for events with θ and momentum corresponding to regions A and C. We, of course, are using the fact that the cross section for n-p

interactions in the radiator target leading to charged particles at scattering angles θ and ϕ is dependent only on the polar scattering angle θ .

Our software restrictions in KIOWA determine exactly the solid angle acceptance of the spectrometer and no special Monte Carlo or any other such acceptance determination is required.

4. MWPC Hit Position Randomization

Early KIOWA analysis showed that granularity existed in the histograms of θ , ϕ , vertical bend angle, β , horizontal bend angle, α , and, consequently, momentum, P , since momentum is so dependent on horizontal bend angle. This granularity in the distributions had a periodicity which reflected the 2 mm wire spacing in the MWPC's. Therefore, a randomization procedure was used in which the hit positions in all eight planes (some of them reconstructed for non-perfect events) were allowed to move up to ± 1 mm with equal probability under the direction of a random number generator which gives the randomized hit positions. This randomization is based on the notion that signal wire response is constant up to ± 1 mm from the wire and zero farther away. The randomized positions then are used to calculate the randomized values θ_r , ϕ_r , α_r , and β_r . The randomized momentum, P_r , is calculated from the formula:

$$P_r = \alpha_r P / \alpha$$

where α is the original bend angle, P is the original fitted momentum calculated by TEWA and α_r is the randomized horizontal bend angle. This formula results from the fact that for a given

value of $\int |B_y| dz$, the momentum is inversely proportional to the bend angle to first order.

In practice, in KIOWA, one selects particles with the restriction that the momentum, P , satisfies $(0.95)P_L \leq P \leq (1.05)P_U$. The randomization is then performed event by event. The randomized values of momentum, P_r , polar scattering angle, θ_r , and azimuthal scattering angle, ϕ_r , are then subjected to the restrictions:

$$P_L \leq P_r \leq P_U, \sin\theta_r \sin\phi_r \leq 0.018, \text{ and } \theta_r \leq 0.038$$

The decreased limits on $\sin\theta_r \sin\phi_r$ and on θ_r insure the randomized values were calculated only for events which lie within regions A, B, and C in Figure 22. With the restrictions imposed on θ_r and ϕ_r one can calculate the geometric efficiency of the spectrometer for events within regions A, B, and C. The geometric efficiency, $\epsilon(\theta)$, is given by the fraction of the azimuthal angle accepted for a given value of θ :

$$\epsilon(\theta) = 1 \text{ for } \theta \leq 0.018$$

$$\epsilon(\theta) = (2/\pi)\arcsin(0.018/\theta) \text{ for } 0.018 \leq \theta \leq 0.038$$

5. Energy Loss Correction

The selected, randomized, and particle identified events in KIOWA require one more correction before one can extract the momentum histograms from which spectra can be generated. This correction involves energy loss experienced by the charged particles produced in the hydrogen radiator target before the deflections by the magnetic field begin to influence the trajectories. This correction is based on the Bethe equation¹⁶ for

the rate of energy loss by ionization of a particle containing z protons, in a material of atomic number Z , and atomic weight A , in units of MeVcm^2/gm :

$$(dE/dx)(1/\rho) = -4\pi z^2 (NZ/A) (e^2/mc^2)^2 (mc^2/\beta^2) \cdot \{\log_e [2mc^2\beta^2/I(1-\beta^2)] - \beta^2\}$$

where

$$(e^2/mc^2) = r_o = 2.8178 \times 10^{-13} \text{ cm}$$

$$mc^2 = 0.511 \text{ MeV}$$

$$N = 6.0225 \times 10^{23} \text{ atoms/mole}$$

$$\rho = \text{density of material in gm/cm}^3$$

$$I = 9.1Z(1+1.9Z^{-2/3})\text{eV}$$

$$\beta = v/c \text{ ratio for the ionizing particle}$$

I involves the ionization and excitation potentials in the atom of the material.

This equation is applied for the components of the spectrometer between the center of the liquid hydrogen radiator target and the final window of W2 before the particle enters the 18D36 magnet. The rationale for this choice involves the method of momentum determination with this spectrometer. The fitted momentum, in a sense, includes any energy loss between W2 and W3 since the trajectory is fitted between the two straight line paths as determined by W1 to W2 and W3 to W4. Therefore, one assumes that the spectrometer correctly determines the momentum of the particle as it leaves W2. One then increases the momentum of the particle by successively applying the Bethe equation from W2 back to the

center of the hydrogen radiator target through the various materials present. This is accomplished with a DO LOOP in KIOWA whereby the β of the particle increases for each pass of the Bethe equation corresponding to a particular material. The materials include the copper signal wires in W2, the tungsten high voltage wires in W2, the mylar windows of W2, the predominantly argon gas within W2, the helium between W2 and W1, the materials in W1 (identical to those in W2), the air between W1 and the radiator target, the plastic of S1 and the radiator, and finally, the hydrogen in the radiator. Since, on the average, a neutron moves halfway through the hydrogen before scattering with a proton, the hydrogen contribution to the energy loss is calculated using one-half of the length of the radiator flask to determine the effective thickness in gm/cm². This thickness is multiplied by the Bethe equation result to obtain the energy loss due to the hydrogen. Another detail involves the use of the density of liquid hydrogen at 20°K (0.07 gm/cm³) in the determination of the effective thickness of the radiator contents for radiator target full runs and the use of the density of gaseous hydrogen at 20°K (0.0014 gm/cm³) for the radiator target empty runs.

In terms of increases in momentum, this correction boosts proton momenta by 3.3 MeV/c at 1400 MeV/c and as much as 24.2 MeV/c at 400 MeV/c. The boost increases with decreasing particle momentum. The corresponding values for deuterons are 7.9 MeV/c at 1400 MeV/c and 113 MeV/c at 400 MeV/c. The (p,n) spectral

measurements involve proton momenta between about 380 and 1450 MeV/c and deuteron momenta between 1400 and 1600 MeV/c (for normalization of the (n,p) elastic scattering data via the $p(n,d)\pi^0$ reaction to be discussed later). The largest relative momentum change due to energy loss involved in the (p,n) measurements is about 6% at the low proton momenta near 400 MeV/c. This relatively small percentage probably would be little changed by corrections to the Bethe equation for variations in the ionization and excitation function I due to differing materials and proton momenta. Therefore, no further energy loss corrections were applied to the data other than the ones just described.

C. PROTON RECOIL SPECTRUM CONSTRUCTION

The randomized and energy loss corrected events were histogrammed as to particle type in histograms of momentum. The complete spectra were pieced together from several runs using a typical momentum bin spacing of 10 MeV/c. The proton momentum histograms and deuteron momentum histograms were constructed from hydrogen radiator target full and empty runs using the left plus right gated neutron monitor yields to set the weights per event as previously discussed in Section B, Subsection 1, of this chapter. Subtractions for neutrons generated by the aluminum windows of the neutron production target loop were also employed by normalizing with respect to the average value of the current integrator yield as determined by the appropriate ratios of left plus right ungated neutron monitor yields to the current integrator yields for the

neutron production target full and empty runs. The production target empty runs were actually runs using the dummy cell with windows identical to those on the neutron production target loop. Typical percentage subtractions were $\approx 7\%$ for radiator empty from radiator full with the neutron production target full and $\approx 1\%$ for the dummy cell from the neutron production target full, both having the radiator full of liquid hydrogen. A few runs with the dummy cell and the radiator empty were taken, but the yields were less than a per cent of the foreground.

One, typically, combines runs taken with the same setting of current in the 18D36 spectrometer magnet to obtain a net momentum spectrum of proton recoils for that current setting. The proton momentum spectrum gives the normalized yields and statistical errors in the yields for each momentum bin. If N is the absolute number of counts in a bin for a given run (i.e. weight = 1), then $\pm\sqrt{N}$ is assumed to be the statistical error in the yield, N , as is the usual convention. If the run is histogrammed in KIOWA with a weight, W , then the relative error in the same bin is assumed to be $\sqrt{N}/N$ and the absolute error will be $\pm W\sqrt{N}$. Suppose a foreground run has a bin with a weighted yield of N_1 and a weighted absolute error of $\pm\Delta N_1$ and a background run has a weighted yield of N_2 and a weighted absolute error of $\pm\Delta N_2$ in the same bin. The net spectrum will then have a yield of

$$N = N_1 - N_2$$

in that bin and an error of $\pm\Delta N$, where:

$$\Delta N = \sqrt{\Delta N_1^2 + \Delta N_2^2}$$

The aforementioned statistics are calculated in KIOWA so that the statistical errors in all foreground and background runs analyzed together in a single KIOWA job will be reflected in the errors on the yields in the net momentum spectra.

A complete momentum spectrum of proton recoils requires the piecing together of the net proton spectra from several settings of the 18D36 magnet. Table 3 shows the momentum limits allowed by the acceptance polygon in Figure 22 for various settings of the 18D36 current.

TABLE 3

ACCEPTABLE MOMENTA FOR VARIOUS 18D36 MAGNET CURRENTS

<u>Current</u>	<u>Lowest Momentum</u>	<u>Highest Momentum</u>
800 amperes	1146 MeV/c	1964 MeV/c
600	1050	1800
400	903	1549
300	768	1316
240	635	1089
200	537	921
145	390	668
100	269	461

Consider the proton recoil spectrum from neutrons generated by the p(p,n) reaction at 647 MeV. This spectrum extends to an upper momentum limit of about 1100 MeV/c. It required the piecing together of runs from magnet settings of 400, 240, 145, and 100 amperes. There exist three momentum overlap regions in these data between 400 and 240, 240 and 145, and 145 and 100 amperes, respectively. In each of these overlap regions the data from the

two current settings were averaged to obtain the final proton yields. The ratio of the yield from one current to the yield from the neighboring current in the same overlap momentum region differed from unity only up to about 10%, the largest deviations occurring for the lower currents. These deviations are probably due to a small loss of events due to multiple cluster events which were not analyzed. The averaging between adjacent currents corrects somewhat for these small deviations.

Let N_a and $\pm\Delta N_a$ be the yield and error, respectively, in an overlap momentum bin for the current setting (a). Let N_b and $\pm\Delta N_b$ be the yield and error, respectively, in the same momentum bin for the current setting (b). We assume here that N_a and N_b are both normalized to the same number of ungated neutron monitor counts. Then the statistical average contents of the bin, N , and its error $\pm\Delta N$, are given by:

$$\Delta N = \Delta N_a \Delta N_b / \sqrt{\Delta N_a^2 + \Delta N_b^2}, \quad N = \Delta N^2 [(N_a / \Delta N_a^2) + (N_b / \Delta N_b^2)]$$

The piecing together just described determines a spectrum of proton recoil yield as a function of momentum. However, one wishes to determine the neutron spectrum from (p,n) reactions by using the proton recoil spectrum generated by the neutrons via (n,p) scattering in the radiator target. Therefore, in KIOWA we also calculate the incident zero-degree neutron momentum assuming (n,p) elastic kinematics and using the randomized values of proton momentum and polar scattering. Histograms of such neutron momenta

are nearly identical to the proton momentum histograms. One then wishes to apply the cross section for (n,p) elastic charge exchange scattering to known elastic proton recoils. The proton recoil spectra as constructed above, however, contain protons from the $p(n,p)p\pi^-$ and the $p(n,p)n\pi^0$ reactions as well as from the (n,p) elastic scattering. The pion production reactions above are predominantly responsible for the inelasticity present in the proton recoil spectra.

D. INELASTIC PROTON RECOIL SUBTRACTION

Since our spectrometer system only detects a single charged particle per (n,p) scattering event, we are not able to determine if a detected proton came from (n,p) elastic scattering or from a pion-associated reaction.

To correct our measurements for the presence of the unwanted pion-associated protons, a series of runs occupying several days of experimental time and many days of analysis were undertaken using the chopped beam facility at LAMPF.

1. Chopped Proton Beam Operation

The microstructure of the LAMPF beam, as previously discussed, consists of pulses 5 ns apart with widths of 0.25 ns, FWHM. The chopped beam facility consists of two pairs of parallel electrodes on either side of the H^- beam in the transport section of beamline between the Cockroft-Walton injector and the drift-tube linac. The energy of the beam in this region is 750 keV. The parallel plate electrodes can be driven with an oscillating

potential to provide an oscillating electric field perpendicular to the H^- beam. The oscillating field will deflect the beam from its nominal axis. The two pairs of electrodes follow one another down the beamline with the second oriented to give an electric field perpendicular to the electric field of the first as well as perpendicular to the H^- beam. Farther downstream in the beamline is a circular aperture across which the proton beam can be swept. The plates are usually driven with an RF frequency of 12.578125 MHz, exactly 1/16 of the 201.25 MHz responsible for the 5 ns micropulse structure (4.9689 ns to five significant figures). When both sets of plates are used the beam oscillates in an ellipse across the aperture. If one uses a D.C. bias such that the beam intercepts the aperture once per revolution around the ellipse, then the frequency of pulses getting through the aperture will be 12.578125 MHz, or one pulse in 16, or one pulse every 79.503 ns. If one just sweeps the beam across the aperture with RF on just one set of plates then one gets one out of every 8 micropulses through the aperture, or one pulse every 39.7515 ns. This second method with just one set of plates was employed by us to obtain data on the inelastic events. The average beam intensity would be only 1/8 of its usual value if all of the beam were chopped in this way. Since other experimenters required nearly full intensity only the first 40 microseconds (10%) of each 400 microsecond macropulse was chopped in this way. This cut the average beam by only 8.25%. We gated our electronics by the 40 microsecond gate instead of the

whole 400 microsecond macropulse so that we only accepted events from the chopped portion of the beam. This made our average beam 1/80 of its usual value of 1 to 2 microamperes. The valid event rate in the spectrometer was one to two events a second compared to the usual 100 to 150 events a second. Therefore, it took a long time to just record as much data as we did. We also had to tune up the beam chopping system frequently to keep it in synchronization with the linac.

2. Neutron Time-of-Flight Determination

With a beam of about one pulse every 40 ns, one can unambiguously distinguish neutrons with kinetic energies between 110 and 800 MeV over a flight path of 11.25 m (the distance from the neutron production target to S1) provided one can tag these neutrons in time. This comes about from the fact that an 800 MeV neutron takes 44.6 ns to negotiate the 11.25 m flight path and a 110 MeV neutron takes 84.1 ns. Therefore, a 110 MeV neutron produced in one pulse could almost be overtaken by an 800 MeV neutron produced by the pulse 40 ns later.

We set up a time-to-amplitude converter (TAC) which had a string of pulses 40 ns apart, generated from the RF signal of the accelerator, input to the stop terminal of the TAC. The master gate signal, with the timing of S1, was input to the start terminal of the TAC. The output of the TAC was digitized by one of the ADC's just as the S1, S2R, and S2L pulse heights and T12 TAC spectrum are digitized and this new TAC spectrum, known as TRF,

was placed as an analog word on the data tape event by event along with the other analog words. When the chopped beam data were analyzed by TEWA, TRF was given its own component in the G-vector so that it could be used to tag the time-of-flight of the incident neutron responsible for each event. When the time-walk correcting version of KIOWA was used for the chopped beam data, TRF was corrected as well as T12. Since TRF involves a constant amplitude signal derived from the RF signal of the accelerator and the anode pulse from S1, TRF was only corrected for time-walk due to S1. TRF, typically, had a timing resolution of 1 ns, FWHM. This translates into an energy resolution of 26 MeV, FWHM, for a neutron with a kinetic energy of 400 MeV.

In a chopped data version of KIOWA the TRF time-walk correction parameters were used to calculate the incident neutron momentum for each valid event accepted from the TRF channel number residing in the G-vectors for those events. These neutron momenta then tag every neutron responsible for every proton momentum analyzed by the spectrometer. Although the neutron momenta as determined by TRF are not of a high resolution quality, the recoil protons associated with each neutron have high resolution momenta as determined by TEWA. We use the neutron momenta to distinguish the (n,p) elastic scattering events from the pion production events. The 139.6 MeV rest mass of the π^+ and the 135.0 MeV rest mass of the π^0 make high resolution on the neutron momentum unnecessary. The elastic events are well separated from the pion associated

inelastic events.

3. Proton Recoil Histogram Construction

The special chopped beam version of KIOWA builds five histograms of momentum for the proton recoils. Each one corresponds to a different range for the incident neutron momentum as calculated from TRF. If the neutron momentum is P_n , then the five neutron momentum bins are given in Table 4.

TABLE 4

CHOPPED BEAM INCIDENT NEUTRON MOMENTUM RANGES

<u>Bin Number</u>	<u>Momentum Range</u>
Bin #1	$750 \leq P_n < 900 \text{ MeV/c}$
Bin #2	$900 \leq P_n < 1050 \text{ MeV/c}$
Bin #3	$1050 \leq P_n < 1300 \text{ MeV/c}$
Bin #4	$1200 \leq P_n < 1350 \text{ MeV/c}$
Bin #5	$1350 \leq P_n < 1500 \text{ MeV/c}$

Many runs with several 18D36 magnet settings, with full and empty hydrogen radiator, were used with aluminum as the neutron production target. Aluminum was used because it had the largest yield of neutrons over all momenta from 380 to 1450 MeV/c of the available targets: hydrogen, deuterium, beryllium, carbon, and aluminum. The chopped beam $Al(p,n)$ measurements were performed with the full energy of the proton beam, 800 MeV. A combination program was used to collect all the data from several KIOWA jobs and average it to provide the final five proton recoil histograms corresponding to

the five incident neutron momentum bins. These histograms are shown in Figures 23 through 27. The dots and error bars are the data histogrammed in 50 MeV/c bins. The horizontal scale is for the neutron momenta. These are actually the neutron momenta as calculated from the proton momenta measured by the spectrometer. The continuous curve is our graphical interpretation of the data in each histogram. The quality of the data is not good due to the poor statistics. But note that the data are plotted on a logarithmic scale which emphasizes the lower yields. Much effort was put into producing these five histograms, but the low data rate made it impossible to obtain data with very good statistics. The (n,p) elastic scattering peak in each histogram corresponds to the neutron momentum range accepted in each histogram, respectively. Below each elastic peak is a broad region of proton recoils associated with pion production.

The five histograms were used to subtract the inelastic protons from the proton recoil spectra. Since these subtractions were relatively small in the $p(p,n)$ and $d(p,n)$ spectra, the inaccuracies present due to the poor statistics in the $Al(p,n)$ chopped beam measurements are important only at the lowest momenta. The subtractions are accomplished by first selecting the histogram which contains elastic events in the region corresponding to the largest momenta observed in the spectrum to be corrected for inelasticity. Let us denote this spectrum as spectrum T, where T stands for the neutron production target. Let spectra 1

Figure 23

Figure 24

Figure 25

Figure 26

Figure 27

through 5 correspond to the histograms for neutron bins 1 through 5 (i.e. Figures 23-27), respectively. Suppose spectrum T contains protons up to 1450 MeV/c. One takes spectrum 5 and forms the ratio of the yield of all protons in T with momenta above 1350 MeV/c to the elastic yield in spectrum 5 for $1350 \leq p_n < 1500$ MeV/c. The resulting factor is then used to boost the remainder of spectrum 5 to put it on an equal footing with spectrum T. One then subtracts the contents of spectrum 5 below the elastic peak bin by bin from spectrum T. Since the binning in spectra 1 through 5 is in 50 MeV/c bites, and spectrum T is usually given in 10 MeV/c bites one actually uses a boosting factor of 1/5 of the ratio of spectrum T elastics to spectrum 5 elastics. After removing all inelastics due to spectrum 5 incident neutrons, one moves on to spectrum 4. The spectrum 5 subtraction insures that the remaining protons in spectrum T with momenta between 1200 and 1350 MeV/c will be elastic. Therefore, one can form the boost factor for spectrum 4 and perform the subtraction of all boosted inelastic protons in spectrum 4 from spectrum T protons bin by bin. One continues this process sequentially to subtract spectrum 3, spectrum 2, and finally, spectrum 1. This sequential method insures complete inelastic subtraction provided the spectra 1 through 5 are correct. In the data presented here, the continuous curve was used to represent the events in spectra 1 through 5. The subtraction procedure described above was used for all of the spectra.

E. NEUTRON SPECTRUM CONSTRUCTION

The momentum spectra for elastic proton recoils from the (n,p) scattering in the liquid hydrogen resulting from the in-elastic subtraction can be used to determine the incident neutron spectrum provided one knows the value of the cross-section for (n,p) elastic charge exchange scattering for polar proton angles from 0 to 0.038 (the θ acceptance range employed) and also for all momenta between 380 and 1450 MeV/c. We chose to parameterize the cross section by calculating the quantity $\Delta\sigma_{np}(p)$, which is the portion of the total elastic (n,p) cross section sampled by the acceptance function of the spectrometer. The geometric efficiency is given by:

$$\epsilon(\theta) = 1 \text{ for } \theta \leq 0.018$$

$$\epsilon(\theta) = (2/\pi)\arcsin(0.018/\theta) \text{ for } 0.018 \leq \theta \leq 0.038$$

Therefore:

$$\Delta\sigma_{np}(p) = 2\pi \int_0^{0.038} \epsilon(\theta)\sigma(\theta,p)\sin\theta d\theta$$

where $\sigma(\theta,p)$ is the differential (n,p) elastic scattering cross section in the laboratory for a recoil proton with momentum, p , and polar angle, θ . This is the quantity which must be determined. We attempted to do this by collecting what we believe to be the world's supply of (n,p) elastic charge exchange data. The data were parameterized in the form $d\sigma/du$ in mb/(GeV/c)² versus u , the square of the four-momentum transfer between the incident neutron and the outgoing proton. For a constant value of the incoming

neutron beam momentum u is a function of the center of mass polar scattering angle only. Therefore, if one has $d\sigma/du$ as a function of u , one can transform it to $d\sigma/d\Omega^*$, the center of mass cross section as a function of θ^* , the center of mass scattering angle. The n-p laboratory cross section as a function of the laboratory proton angle and the value of $\Delta\sigma_{np}$ can be calculated. This was done for each experiment we considered thus obtaining a value for $\Delta\sigma_{np}$ for each incident neutron momentum, one for each experiment. $d\sigma/du$ was formed by least square fitting each set of experimental data to the form $\alpha_1 \exp(\beta_1 u) + \alpha_2 \exp(\beta_2 u)$, the standard two exponential fit employed by several experimenters to describe the shape of the (n,p) elastic charge exchange scattering distributions.

Figure 28 shows the results of the calculations of $\Delta\sigma_{np}$ as a function of incident neutron momentum for all of the fits to the experiments listed^{4,17-28}. The error bars in Figure 28 are purely statistical as propagated through the various transformations from the statistics on the original experiments. Notice the large amount of scatter in these data. The Bizard and Shepard data are recent but only appear to agree between 950 and 1150 MeV/c. The Shepard data appear to drop too low at the lower momenta, <900 MeV/c, as compared to absolute measurements such as the one by Kazarinov at 200 MeV (about 640 MeV/c). Further, the Scanlon measurements around 100 MeV were absolute measurements as are our own measurements at 645 and 800 MeV (the dark triangles).

Figure 28

Our measurements are reported in the Ph.D. thesis of Michael Evans from Texas A&M University²⁹. They consisted of angular distributions for proton scattering angles from 0° to 60° in the laboratory. A great deal of diligent analysis including corrections for granularity in the wire chambers, dead wires in the chambers, loss of events due to multiple cluster effects, and solid angle effects were undertaken to construct the angular distributions. The normalization of these data was based upon simultaneous measurement of the deuterons resulting from the $p(n,d)\pi^0$ reaction and the elastically scattered protons. The deuterons exist only in the laboratory angle range from 0° to about 15° . Therefore, the larger angles were normalized with respect to the left and right neutron monitors. The cross section for the $p(n,d)\pi^0$ reaction was assumed to be exactly one-half of the cross section for the $p(p,d)\pi^+$ reaction at each angle under the assumption of isospin invariance. The known $p(n,d)\pi^0$ cross section acts as a calibration on the left and right neutron monitor rate to determine the magnitude of the neutron flux incident upon the hydrogen radiator target. The left and right monitors tracked very well with the neutron flux as calculated from the deuteron yields for the laboratory deuteron angles from 0° to 15° . The details of the analysis allow one to determine the correct yields of protons in each angular bin and thereby generate the elastic scattering cross section at each angle. The $p(p,d)\pi^+$ cross section has been determined to an absolute accuracy of $\pm 5\%$. Therefore, with all errors considered

we believe our distributions to be normalized to an accuracy of $\pm 7\%$.

Notice the much higher values for $\Delta\sigma_{np}$ that we get as opposed to Bizard and Shepard. We cannot accept their data due to these deviations from our own data. Our conclusion is that the entire body of data is in such a bad state that we present a simple straight line representation passing through our values, the Kazarinov value at 200 MeV, the Scanlon values, and as it happens, the data of Measday, Palmieri, and Howard, all normalized by phase shift fits, as well as the region where Shepard and Bizard agree around 1000 MeV/c. This line has the equation:

$$\Delta\sigma_{np}(p) = (-1.873 \times 10^{-5} p + 0.149) \text{ mb}$$

where p is the momentum in MeV/c. We estimate the statistical error corridor to be $\pm 4.4\%$ based on the approximate size of the statistical error bars on our data, Kazarinov at 200 MeV, and the Scanlon data.

With a value for $\Delta\sigma_{np}$ at each momentum, one can generate a neutron spectrum. The number of neutrons incident upon the liquid hydrogen radiator target in each neutron momentum bin is given by

$$I_n(p_n):$$

$$I_n(p_n) = I_p (d^2\sigma/d\Omega_n dp_n) n_T \Delta\Omega_c \Delta p_n$$

where I_p is the number of protons passing through the neutron production target.

$d^2\sigma/d\Omega_n dp_n$ = the double differential laboratory cross section for (p,n) reactions in the target

n_T = number of nuclei per cm^2 in the production target T

$\Delta\Omega_c$ = solid angle subtended by the neutron collimator

Δp_n = bin size of the neutron momentum bin

The yield of protons in each proton momentum bin is given by $Y_p(p_p)$:

$$Y_p(p_p) = I_n(p_n) n_{LH_2} \Delta\sigma_{np}(p_n)$$

where n_{LH_2} is the number of nuclei per cm^2 in the hydrogen radiator target. The assumption present in the above equation is that $p_p = p_n$. This is almost true, but we take care of this exactly by constructing neutron momentum histograms from the elastic proton recoil histograms by using the (n,p) kinematics as mentioned before. This converts the $Y_p(p_p)$ into a corresponding $Y_n(p_n)$ where p_n is identical to the p_n contained in $I_n(p_n)$. The equation for the laboratory cross section for (p,n) reactions is then:

$$d^2\sigma/d\Omega_n dp_n = Y_n(p_n) / [n_{LH_2} \Delta\sigma_{np}(p_n) I_p n_p \Delta\Omega_c \Delta p_n]$$

The number of nuclei per cm^2 in the targets are easily determined from the measured cryogenic densities and target lengths.

$\Delta\sigma_{np}(p_n)$ is given by the equation for its straight line representation. Δp_n is set by the methods used in KIOWA, typically, 10 MeV/c.

I_p is given by a product of three factors. The first is the average number of protons per current integrator count for the runs contributing to a given spectrum. The second is the average value of the current integrator yield divided by the sum of the left and right ungated neutron monitor yields for the runs involved with the spectrum. The third factor is the sum of the left and right gated neutron monitor yields. Remember that the yields $Y_n(p_n)$ are normalized to the left plus right gated neutron monitor

yields. Therefore:

$$\frac{Y_n(p_n)}{L_g + R_g} = \frac{\text{true } Y_n(p_n)}{L_u + R_u}$$

since,

$$\text{live time fraction} = \frac{L_g + R_g}{L_u + R_u}$$

The lone remaining element in the cross section equation is $\Delta\Omega_c$, the solid angle subtended by the collimator. This is given to zeroth order by the area of the collimator hole divided by the square of the distance from the center of the neutron production target to the end of the collimator near the neutron detection apparatus. This value is:

$$\pi(2.54 \text{ cm})^2/4(757 \text{ cm})^2 = 8.84 \times 10^{-6} \text{ steradian}$$

where 2.54 cm is the diameter of the collimator and 757 cm is the target to collimator end distance. A correction to this solid angle has been made based on the fact that some of the high energy neutrons can pass through some of the steel undeflected and still reach the liquid hydrogen radiator target. If λ is the mean free path for a high energy neutron moving through iron, then the probability that the neutron is undeflected along a distance of x in the iron is $e^{-x/\lambda}$.

$$\lambda = 1/n\sigma$$

where

$$n = 8.4 \times 10^{22} \text{ iron nuclei per cm}^3$$

and

$$\sigma = 1100 \text{ mb } (1.1 \times 10^{-24} \text{ cm}^2)$$

This total cross section is for a neutron scattering to an angle ≥ 0.01 radian in iron with a momentum of 1400 MeV/c. λ is equal to 10.8 cm. If L is the distance from the neutron target to the end of the collimator (757 cm) and L_1 is the length of the collimator (366 cm), then the differential solid angle which has a probability, $e^{-x/\lambda}$, for a particle to get through a distance x undeflected is:

$$d\Omega = dx \, 2A/(L-x)^3$$

where A is the area of the collimator hole. The effective solid angle is then given by:

$$\Delta\Omega = A/L^2 + \int_0^{L_1} dx \, e^{-x/\lambda} \, 2A/(L-x)^3$$

This gives a result of:

$$1.03(A/L^2) = 9.108 \times 10^{-6} \text{ sr} = \Delta\Omega_c$$

If one uses this solid angle to estimate the diameter of the neutron beam at the position of the center of the hydrogen radiator target one obtains a diameter of 3.73 cm where:

$$\pi(3.73 \text{ cm})^2/4(1095 \text{ cm})^2 = 9.108 \times 10^{-6} \text{ sr}$$

The distance from the neutron production target center to the hydrogen radiator target center is 1095 cm.

Figure 29 shows a horizontal projection of proton events as constructed by extending the hit positions in W1X and W2X back to the symmetry plane half-way through the hydrogen radiator target. The proton yields in each 1 mm bin are plotted on a logarithmic scale. Notice the peak height of about 1500 counts

Figure 29

with a nearly trapezoidal falloff. The full width at half-maximum of this distribution is 3.10 cm. The full width at one-tenth maximum is 4.06 cm. Distributions like Figure 29 were compared to what one would expect for a neutron beam with constant flux across a circular disk with the 3.73 cm diameter corresponding to the calculation of the collimator solid angle. The agreement was very good. Only a fraction of a percent of the events had X-projection values outside of the model diameter of 3.73 cm. The solid angle is subject to other corrections for small-angle scattering of neutrons in the collimator and for the finite size of the proton beam spot at the neutron production target. Our estimate for the systematic error in the value of the collimator solid angle is $\pm 2\%$.

The data in the following chapters are presented in a way that shows the stages of analysis. The spectra labelled "All Proton Recoils" contain all protons detected, both from (n,p) elastic scattering and pion production scattering in the hydrogen radiator target. These spectra are presented with a constant value of $\Delta\sigma_{np}$, the value corresponding to that at the nominal beam energy corresponding to the particular spectrum. The spectra labelled "Elastic Protons Only" have been corrected by the inelastic subtraction method. These are also presented with the same constant value for $\Delta\sigma_{np}$ as are the "All Proton Recoil" spectra. This was done so that one could compare the subtraction percentage bin by bin. If in the future there are better inelastic spectra,

then one can correct the subtracted spectrum. The spectra labelled "Neutron Spectra" are indeed that. They have been constructed by using our straight line representation of $\Delta\sigma_{np}$ with the elastic proton spectra. One can compare the "Neutron Spectra" with the "Elastic Protons Only" spectra bin by bin to see the effect of the $\Delta\sigma_{np}$ momentum variation. Again, if in the future there exists a better parameterization of $\Delta\sigma_{np}$, one can correct the "Neutron Spectra".

The error bars on the "All Proton Recoil" spectra are purely statistical. The error bars on the "Elastic Protons Only" spectra are also statistical with the poor subtraction statistics for the inelastic events responsible for the larger relative errors. The error bars on the "Neutron Spectra" include the $\pm 4.4\%$ statistical error corridor assigned to $\Delta\sigma_{np}$ as well as the statistics from the "Elastic Protons Only" spectra. The systematic errors in the cross section yields in the experiment are presented in Table 5. The quantities in Table 5 appear in the cross section expressions as factors or inverse factors. Therefore, the net relative systematic error is given by the square root of the sum of the squares of the relative errors. The net systematic error is $\pm 12.6\%$. Note that this error is dominated by the error in current integration of the proton beam. This 10% error is estimated on the basis of the erratic behavior of the toroid current monitor with respect to the left and right neutron monitors and the hydrogen monitor telescope. Notice that within a set of data

TABLE 5
SYSTEMATIC ERRORS IN THE CROSS SECTIONS

<u>Quantity</u>	<u>Systematic Error in Percent</u>
Current Integration	$\pm 10\%$
Neutron Production Target Density	$\pm 0.5\%$
Neutron Production Target Length	$\pm 0.9\%$
Radiator Target Density	$\pm 1.4\%$
Radiator Target Length	$\pm 1.0\%$
Average Ratio of $(L+R)_u / CI$	$\pm 1.0\%$
Collimator Solid Angle	$\pm 2.0\%$
n-p Scattering Normalization (of our data only)	$\pm 7\%$

defining a particular spectrum, the $(L+R)_u / CI$ ratio is constant to within about 1%. However, over weeks and months, the equivalent ratios had variations making the 10% error appear appropriate. If the calibration of the current integrator by nuclear chemical techniques had held constant, we would have assigned a value of $\pm 5\%$ to the absolute current integration uncertainty. This is the error quoted by the nuclear chemists. The largest portion of this error is the uncertainty in the nuclear cross sections they use. A $\pm 5\%$ current integrator error would have given a total systematic error of $\pm 9.1\%$.

The errors in the determination of the neutron momenta

result from the fundamental geometric uncertainties in determining the particle trajectories due to the 2 mm spacing of the signal wires and from the multiple Coulomb scattering of the particles as they travel from the hydrogen radiator target to the final scintillator, S2.

The average geometric uncertainty can be calculated from the model response function for an MWPC signal wire. The model function is constant from a value of 1 mm on one side of the wire to a value of 1 mm on the other side of the wire. The model function is zero for deviations greater than 1 mm from the wire. As shown previously, the root mean square deviation of a track from the wire is given by $s\sqrt{12}$, where s is the wire spacing. Therefore, if $s=2$ mm, the root mean square deviation is $1/\sqrt{3}$ mm. In order to estimate the error in the bend angle due to the wire spacing, let x_1, x_2, x_3 , and x_4 be the X-coordinates in mm of the hit positions in W1X, W2X, W3X, and W4X, respectively. Let ψ_{in} be the horizontal angle of the incoming track:

$$\psi_{in} = (x_2 - x_1)/1000$$

Let ψ_{out} be the horizontal angle of the outgoing track:

$$\psi_{out} = (x_4 - x_3)/1000$$

Then, let $\Delta x_1 = \Delta x_2 = \Delta x_3 = \Delta x_4 = 1/\sqrt{3}$ mm, the root mean square deviation of a track from a wire. Then,

$$\Delta\psi_{in} = \sqrt{\Delta x_1^2 + x_2^2}/1000 = \sqrt{2/3} /1000 = \Delta\psi_{out}$$

The horizontal bend angle, α , is given by:

$$\alpha = \psi_{\text{in}} + \psi_{\text{out}}$$

Therefore,

$$\Delta\alpha = \sqrt{\Delta\psi_{\text{in}}^2 + \Delta\psi_{\text{out}}^2} = 2/\sqrt{3} / 1000 = 2/\sqrt{3} \text{ mrad} = 1.155 \text{ mrad}$$

For a nominal bend angle, α , of 22° :

$$\Delta\alpha/\alpha = 3 \times 10^{-3}$$

The momentum of a singly charged particle in the spectrometer is given, to first order, by the horizontal bend angle, α , and the value of $\int |B_y| dl$ along the orbit of the particle by the equation:

$$p = k \int |B_y| dl / \alpha, \text{ where } k \text{ is a constant}$$

Therefore, the uncertainty in momentum due to the wire spacing only is given by:

$$\Delta p/p = \Delta\alpha/\alpha = 3 \times 10^{-3}$$

The uncertainty in momentum due to the wire spacing and the magnetic field uncertainty is given by:

$$\Delta p/p = \sqrt{(\Delta\alpha/\alpha)^2 + (\Delta B/B)^2}$$

where $\Delta B/B$ is the average relative error in the determination of the vertical field components of the spectrometer magnet. The individual field maps when compared to the flip coil $\int |B_y| dz$ measurements show consistency to within about $\pm 0.1\%$. However, the use of magnetic fields scaled up by factors of as much as 1.014 to compensate for the effects of the air pad magnet stand indicate a value of $\pm 0.7\%$ for $\Delta B/B$. Therefore, the relative

error in momentum as a result of wire spacing and magnetic field uncertainty is $\pm 7.6 \times 10^{-3}$.

The multiple scattering contribution to the momentum uncertainty was calculated with the aid of the Rossi-Greiser formula¹⁵ for the projected mean square angle of Coulomb scattering of a singly charged particle passing through a medium:

$$\langle \theta^2 \rangle = (15 \text{ MeV}/p\beta)^2 \cdot (t/L_{\text{rad}})$$

where p is the projectile momentum, β is the ratio of the velocity of the projectile to the speed of light, L_{rad} is the radiation length of the medium, and t is the thickness of the medium penetrated by the projectile. The individual values of $\langle \theta^2 \rangle$ were calculated for the various materials in the spectrometer, such as the liquid hydrogen in the radiator target, the wire chamber materials, and the helium between the wire chambers. Assuming that the multiple scattering distributions are Gaussian, as is the usual convention, the values of $\langle \theta^2 \rangle$ for the various materials are summed along with the square of the uncertainty in the bend angle due to the wire spacing to obtain a value for the total squared uncertainty in the bend angle. This value is then combined with the magnetic field uncertainty to obtain the total uncertainty in momentum due to wire spacing, magnetic field uncertainty, and multiple scattering in the spectrometer. Table 6 gives a summary of the results at representative kinetic energies for the protons in the spectrometer, using the formula:

$$\Delta E = (p^2/E) (\Delta p/p)$$

where E is the total energy.

TABLE 6

PROTON ENERGY UNCERTAINTIES IN THE SPECTROMETER

DUE TO WIRE SPACING, MAGNETIC FIELD, AND MULTIPLE COULOMB SCATTERING

<u>Kinetic Energy</u>	<u>ΔE Due to Wire Spacing</u>	<u>ΔE Due to Wires and Magnetic Field</u>	<u>ΔE Due to Wires, Field, and Multiple Scattering (Resolution)</u>
800 MeV	3.7 MeV	9.4 MeV	10.3 MeV
650	3.1	7.8	8.9
200	1.1	2.8	5.1
100	0.6	1.4	4.5

The uncertainty in the absolute values of momentum include variations in the proton beam momentum, variations in the energy loss in the neutron production target, variations in the energy loss in the radiator target, and the resolution of the spectrometer. The proton beam FWHM is calculated from the typical value of $\Delta p/p = 0.003$, FWHM. The FWHM of the energy loss distribution in a target is calculated by assuming that the interaction in the target is equally likely to occur anywhere along the path of the incident particle. For a target with a total energy loss of ΔE , and a mean point of interaction half-way through the target, the root mean square variance of the energy loss distribution is given by:

$$\langle E_{\text{rms}}^2 \rangle = \int_{-\Delta E/2}^{\Delta E/2} (1/\Delta E) E^2 dx = (\Delta E)^2/12$$

This is again a calculation of the mean square deviation from the center of a constant distribution function of finite extent. The FWHM of the energy loss distribution is given by 2.35 times the variance of the distribution. Table 7 shows the various FWHM values of the energy uncertainties, for the two beam energies.

TABLE 7

PROTON ENERGY UNCERTAINTIES DUE TO RESOLUTION, TARGET
ENERGY LOSS VARIATION, AND PROTON BEAM ENERGY SPREAD

Beam Energy	800 MeV	650 MeV
Resolution	10.3 MeV	8.9 MeV
Liquid Deuterium Target Energy Loss Variation	2.9 MeV	3.1 MeV
Liquid Hydrogen Radiator Energy Loss Variation	3.0 MeV	3.2 MeV
Proton Beam Spread	3.7 MeV	3.1 MeV
Total $\Delta E =$ Quadratic Sum of the Four	11.7 MeV	10.4 MeV

For completeness, consider Table 8 which presents the total energy uncertainties including all four quantities in Table 7 for the two incident energies and the four typical proton kinetic energies in the spectrometer.

TABLE 8

TOTAL PROTON ENERGY UNCERTAINTIES FWHM

<u>Typical Kinetic Energies of Recoil Protons</u>	<u>Beam Kinetic Energy = 800 MeV</u>	<u>Beam Kinetic Energy = 650 MeV</u>
800 MeV	11.7 MeV	---
650	10.6	10.4 MeV
200	9.2	9.0
100	11.7	11.6

C H A P T E R I V NEUTRON SPECTRA FROM THE $p(p,n)$ REACTION

The results of the measurements of the zero-degree neutron spectra from proton-proton collisions at the two LAMPF energies of 647 and 800 MeV are presented here. The experimental parameters are shown in Table 9 for the two spectral distributions.

TABLE 9

$p(p,n)$ MEASUREMENT PARAMETERS

<u>Parameter</u>	<u>Value at 647 MeV</u>	<u>Value at 800 MeV</u>
Neutron production target density (LH_2)	$4.58 \times 10^{23} \text{ nuclei/cm}^2$	$4.50 \times 10^{23} \text{ nuclei/cm}^2$
Radiator target density (LH_2)	$5.59 \times 10^{23} \text{ nuclei/cm}^2$	$5.59 \times 10^{23} \text{ nuclei/cm}^2$
$\Delta\sigma_{np}$ at "nominal" beam momentum	0.1250 mb	0.1218 mb
"Nominal" beam momentum	1280 MeV/c	1450 MeV/c
Average $(L+R)_u/CI$	26.7	80.9
Current Integrator calibration (# of protons/CI)	4.43×10^{11}	5.16×10^{11}
Collimator solid angle ($\Delta\Omega_c$)	$9.108 \times 10^{-6} \text{ sr}$	$9.108 \times 10^{-6} \text{ sr}$

The current integrator calibration for the 800 MeV $p(p,n)$ data is unusually large compared to the other spectra. The value was based on a single calibration run using beryllium as the

neutron production target. The left plus right ungated neutron monitor yield divided by the current integrator yield for this beryllium run was abnormally high. Since we believe the neutron monitors to be steady, we have corrected the current integrator calibration accordingly for the 800 MeV p(p,n) data.

The plots of the p(p,n) data are shown in Figures 30 through 35. In all cases the data are identified as to the nominal kinetic energy of the LAMPF proton beam. We have measured the proton beam energies as will be discussed in the next chapter. Suffice it to say that the average kinetic energies of the proton beam at the mean point of interaction in the neutron production target (half-way between the two windows) are 650.5 ± 10.4 MeV and 804.2 ± 11.7 MeV.

We used our values of the incident kinetic energies to calculate the appropriate kinematic variables used to determine the center of mass neutron momenta, the Jacobian transformation function, and the invariant mass, m_x , for the reaction p(p,n)x, where the neutron is observed at 0° to the incident proton beam.

The pertinent parameters in the kinematics are:

$$P_1 = \text{incident proton momentum in MeV/c}$$

$$T_1 = \text{incident proton kinetic energy in MeV}$$

$$m_p = \text{proton rest mass} = 938.26 \text{ MeV}$$

$$E_1 = \text{incident proton total energy} = T_1 + m_p$$

$$E = \text{total energy in the laboratory} = E_1 + m_p$$

$$E^* = \text{total energy in the center of mass} = \sqrt{4m_p^2 + 2T_1 m_p}$$

$$\beta = p_1/E$$

$$\gamma = 1/\sqrt{1-\beta^2}$$

$$p_3 = \text{laboratory neutron momentum at } 0^\circ$$

$$T_3 = \text{laboratory neutron kinetic energy}$$

$$m_n = \text{neutron rest mass} = 939.55 \text{ MeV}$$

$$E_3 = \text{laboratory neutron total energy} = T_3 + m_n$$

The invariant mass of the unobserved system of particles, m_x , is obtained from:

$$m_x^2 = E_x^2 - p_x^2$$

where

$$E_x = E - E_3 \quad \text{and} \quad p_x = p_1 - p_3$$

The center of mass neutron momentum, p_3^* , is obtained from:

$$p_3^{*2} = [(E^{*2} - m_x^2 - m_n^2)^2 - 4m_n^2 m_x^2]/4 \cdot \\ [(E^{*2} - m_x^2 - m_n^2) + m_n^2 + m_x^2]$$

The Jacobian transformation function, $J(p_3)$, which is multiplied by the laboratory cross sections to calculate the center of mass cross sections, is given by:

$$J(p_3) = [\gamma^2(E_3 - \beta p_3)^2 - m_n^2]E_3 / [p_3^2 \gamma(E_3 - \beta p_3)]$$

Figures 30 and 31 show the 647 MeV laboratory cross sections in mb/sr-MeV/c plotted on a linear scale for the categories: all proton recoils and neutron spectrum, respectively. The experimental points are plotted in bins of 10 MeV/c with a representative error bar on every fourth point. The mean momentum value for every eighth momentum bin is printed on the lower abscissa. The upper abscissa indicates the appropriate kinetic energy scale for the

Figure 30

Figure 31

neutrons. The 647 MeV $p(p,n)$ data required very little inelastic subtraction. At 705 MeV/c the inelastic background was only 0.4% of the elastic yield. At 425 MeV/c the inelastic background was 8.1% of the elastic yield. The 647 MeV spectra show a dominant broad peak with a small subsidiary bump at low momenta.

Figures 32 and 33 show the laboratory cross sections for the 800 MeV $p(p,n)$ spectra. The inelastic subtraction is much more drastic than at 647 MeV, especially at low momenta. At 945 MeV/c, the inelastic background was 0.3% of the elastic yield. At 705 MeV/c the inelastic background was 14% of the elastic yield. At 425 MeV/c the inelastic background was 150% of the elastic yield. The 800 MeV $p(p,n)$ spectra show a very prominent peak at about 1025 MeV/c, a broad shoulder in the momentum range from about 685 to 885 MeV/c and a small tail at yet lower momenta.

Figures 34 and 35 show the 647 and 800 MeV data, respectively, plotted in the center of mass representation. The center of mass cross section values are plotted on a logarithmic scale in units of mb/sr-MeV/c. The lower abscissa shows the linear scale of neutron center of mass momenta. The upper abscissa shows the corresponding values for the neutron laboratory momenta. All data points and error bars are shown for the neutron spectra. The dashed curve drawn for a range of negative center of mass neutron momenta is the reflection of the data existing at positive momenta through the symmetry axis corresponding to $p_n^* = 0$. Since the initial state in these reactions consists of two identical particles,

Figure 32

Figure 33

Figure 34

Figure 35

two protons, the center of mass cross sections should be symmetric about $p_n^* = 0$. The 647 MeV data begin to deviate from this symmetry criterion at a laboratory neutron momentum of 400 MeV/c. The 800 MeV data begin to show low yields at about 485 MeV/c. The 647 MeV data are subject to a very small inelastic subtraction. Therefore, these data show the low momentum limits on the efficiency of our spectrometer. At momenta of 400 MeV/c, or proton kinetic energies in the spectrometer of about 80 MeV, the multiple scattering begins to seriously hamper the protons from staying on their nominal trajectories. Several protons could be scattered outside of the acceptance region of the spectrometer at such low momenta. The 800 MeV data show low cross section values as high as 485 MeV/c because of the inaccuracies of the inelastic subtractions for low momenta. The large error bars at low momenta in the 800 MeV data are the result of the inaccuracies in the inelastic subtraction for these momenta. The fact that the data are very symmetric at both energies in Figures 34 and 35, except at the low momenta, shows that the inelastic subtractions and the choice of the variation of $\Delta\sigma_{np}$ with momentum appear to be correct, or somehow compensating, which seems farfetched.

Table 10 presents the mean values of each momentum bin, the laboratory cross sections for all proton recoils with the constant value of 0.125 mb for $\Delta\sigma_{np}$, the cross sections for the elastic protons with the same constant $\Delta\sigma_{np}$, and the neutron spectrum of the cross sections for the 647 MeV data.

Table 11 presents the data for the 800 MeV $p(p,n)$ spectra in a similar format. The value of $\Delta\sigma_{np}$ for the all proton recoil and elastic proton spectra is 0.1218 mb.

Table 12 presents the mean values of each laboratory neutron bin, the corresponding center of mass momenta, the values of the Jacobian function, the values of the invariant mass of the unobserved particle system, and the values of the center of mass cross sections for the 647 MeV $p(p,n)$ data.

Table 13 presents the center of mass data for the 800 MeV $p(p,n)$ spectra in a similar format.

TABLE 10

p(p,n) SPECTRA AT 647 MeV IN THE LABORATORY

<u>Mean Value of Neutron Momentum (MeV/c)</u>	<u>Laboratory Cross Sections for All Proton Recoils ($\mu\text{b/sr-MeV/c}$)</u>	<u>Laboratory Cross Sections for Elastic Protons Only ($\mu\text{b/sr-MeV/c}$)</u>	<u>Neutron Spectrum of the Laboratory Cross Sections ($\mu\text{b/sr-MeV/c}$)</u>
1095	0.4 ± 0.2	0.4 ± 0.2	0.4 ± 0.2
1085	1.6 ± 0.4	1.6 ± 0.4	1.6 ± 0.4
1075	2.3 ± 0.5	2.3 ± 0.5	2.2 ± 0.4
1065	2.8 ± 0.5	2.8 ± 0.5	2.7 ± 0.5
1055	5.0 ± 0.7	5.0 ± 0.7	4.9 ± 0.7
1045	8.8 ± 1.0	8.8 ± 1.0	8.5 ± 1.0
1035	7.2 ± 0.9	7.2 ± 0.9	6.9 ± 0.9
1025	12.5 ± 1.0	12.5 ± 1.0	12.0 ± 1.1
1015	15.1 ± 1.1	15.1 ± 1.1	14.5 ± 1.3
1005	14.7 ± 1.1	14.7 ± 1.1	14.1 ± 1.2
995	21.2 ± 1.4	21.2 ± 1.4	20.4 ± 1.6
985	24.8 ± 1.5	24.8 ± 1.5	23.7 ± 1.7
975	23.1 ± 1.4	23.1 ± 1.4	22.1 ± 1.6
965	28.7 ± 1.6	28.7 ± 1.6	27.4 ± 1.9
955	33.5 ± 1.7	33.5 ± 1.7	32.0 ± 2.2
945	32.0 ± 1.7	32.0 ± 1.7	30.5 ± 2.2
935	32.6 ± 1.7	32.6 ± 1.7	31.0 ± 2.2
925	37.0 ± 1.9	37.0 ± 1.9	35.1 ± 2.3
915	43.3 ± 1.7	43.3 ± 1.7	41.0 ± 2.4
905	52.3 ± 1.9	52.3 ± 1.9	49.5 ± 2.9

895	52.9 ± 1.9	52.9 ± 1.9	50.0 ± 2.9
885	56.8 ± 2.0	56.8 ± 2.0	53.6 ± 2.9
875	62.3 ± 2.2	62.3 ± 2.2	58.7 ± 3.3
865	62.7 ± 2.2	62.7 ± 2.2	59.1 ± 3.3
855	66.7 ± 2.2	66.7 ± 2.2	62.7 ± 3.5
845	71.9 ± 2.3	71.9 ± 2.3	67.5 ± 3.7
835	74.9 ± 2.3	74.9 ± 2.3	70.2 ± 3.8
825	72.8 ± 2.3	72.8 ± 2.3	68.2 ± 3.7
815	72.2 ± 2.3	72.2 ± 2.3	67.5 ± 3.7
805	71.6 ± 2.2	71.6 ± 2.2	66.9 ± 3.6
795	77.6 ± 2.3	77.6 ± 2.3	72.3 ± 3.9
785	76.1 ± 2.3	76.1 ± 2.3	70.8 ± 3.8
775	74.2 ± 3.0	74.1 ± 3.0	68.9 ± 4.2
765	80.6 ± 3.1	80.5 ± 3.1	74.8 ± 4.4
755	73.3 ± 2.9	73.1 ± 2.9	67.8 ± 4.0
745	81.3 ± 2.9	81.1 ± 2.9	75.1 ± 4.3
735	76.3 ± 2.8	76.1 ± 2.8	70.4 ± 4.0
725	80.6 ± 2.8	80.4 ± 2.8	74.2 ± 4.2
715	78.8 ± 2.7	78.6 ± 2.7	72.4 ± 4.1
705	77.6 ± 2.7	77.3 ± 2.7	71.2 ± 4.0
695	84.1 ± 2.8	83.8 ± 2.8	77.1 ± 4.2
685	74.9 ± 2.6	74.6 ± 2.6	68.5 ± 3.8
675	68.1 ± 2.5	67.7 ± 2.5	62.1 ± 3.5
665	65.8 ± 2.0	65.4 ± 2.0	59.9 ± 3.2
655	62.9 ± 2.0	62.5 ± 2.0	57.2 ± 3.1

645	52.5 ± 1.8	52.0 ± 1.8	47.5 ± 2.7
635	53.1 ± 1.8	52.6 ± 1.8	48.0 ± 2.7
625	52.4 ± 1.8	51.9 ± 1.8	47.3 ± 2.7
615	45.4 ± 1.7	44.9 ± 2.2	40.8 ± 2.7
605	40.4 ± 1.6	39.8 ± 2.1	36.1 ± 2.5
595	40.6 ± 1.6	40.0 ± 2.1	36.2 ± 2.5
585	38.4 ± 1.6	37.6 ± 2.1	34.1 ± 2.4
575	36.7 ± 1.6	35.9 ± 2.1	32.5 ± 2.3
565	35.3 ± 1.5	34.4 ± 2.2	31.1 ± 2.4
555	35.4 ± 1.8	34.4 ± 2.7	31.1 ± 2.8
545	37.0 ± 1.7	35.8 ± 2.9	32.3 ± 2.9
535	33.9 ± 1.6	32.6 ± 3.1	29.3 ± 3.1
525	33.0 ± 1.6	31.6 ± 3.3	28.4 ± 3.2
515	33.9 ± 1.6	32.4 ± 2.9	29.1 ± 2.9
505	35.0 ± 1.6	33.2 ± 2.6	29.8 ± 2.7
495	32.0 ± 1.6	30.2 ± 2.2	27.0 ± 2.3
485	35.7 ± 1.8	33.7 ± 2.2	30.1 ± 2.4
475	32.1 ± 1.7	29.9 ± 2.2	26.7 ± 2.3
465	32.3 ± 1.5	30.0 ± 2.0	26.7 ± 2.2
455	35.6 ± 1.6	33.2 ± 2.1	29.5 ± 2.2
445	33.9 ± 1.6	31.4 ± 2.1	27.9 ± 2.2
435	35.4 ± 1.6	32.8 ± 2.1	29.1 ± 2.2
425	35.8 ± 1.6	33.1 ± 2.1	29.4 ± 2.2
415	35.3 ± 2.1	32.6 ± 2.6	28.9 ± 2.6
405	33.0 ± 2.0	30.2 ± 2.6	26.7 ± 2.6

395	31.6 ± 1.8	28.7 ± 2.5	25.4 ± 2.5
385	26.3 ± 1.6	23.5 ± 2.4	20.7 ± 2.3

TABLE 11

p(p,n) SPECTRA AT 800 MeV IN THE LABORATORY

<u>Mean Value of Neutron Momentum (MeV/c)</u>	<u>Laboratory Cross Sections for All Proton Recoils ($\mu\text{b/sr-MeV/c}$)</u>	<u>Laboratory Cross Sections for Elastic Protons Only ($\mu\text{b/sr-MeV/c}$)</u>	<u>Neutron Spectrum of the Laboratory Cross Sections ($\mu\text{b/sr-MeV/c}$)</u>
1285	0.6 ± 0.6	0.6 ± 0.6	0.6 ± 0.6
1275	1.4 ± 0.6	1.4 ± 0.6	1.3 ± 0.6
1265	2.2 ± 0.7	2.2 ± 0.7	2.2 ± 0.7
1255	2.9 ± 1.0	2.9 ± 1.0	2.8 ± 1.0
1245	6.2 ± 1.2	6.2 ± 1.2	6.0 ± 1.2
1235	10.1 ± 1.5	10.1 ± 1.5	9.8 ± 1.5
1225	9.6 ± 1.5	9.6 ± 1.5	9.3 ± 1.5
1215	11.3 ± 1.6	11.3 ± 1.6	10.9 ± 1.6
1205	19.5 ± 1.7	19.5 ± 1.7	18.8 ± 1.8
1195	20.0 ± 1.7	20.0 ± 1.7	19.2 ± 1.8
1185	24.5 ± 1.9	24.5 ± 1.9	23.5 ± 2.1
1175	26.0 ± 2.1	26.0 ± 2.1	24.9 ± 2.3
1165	36.4 ± 2.3	36.4 ± 2.3	34.8 ± 2.7
1155	37.0 ± 2.4	37.0 ± 2.4	35.4 ± 2.7
1145	42.6 ± 2.5	42.6 ± 2.5	40.7 ± 2.9
1135	48.1 ± 2.7	48.1 ± 2.7	45.9 ± 3.2
1125	61.4 ± 3.1	61.4 ± 3.1	58.5 ± 3.9
1115	61.2 ± 3.1	61.2 ± 3.1	58.2 ± 3.9
1105	72.7 ± 3.4	72.7 ± 3.4	69.0 ± 4.4
1095	81.6 ± 3.5	81.6 ± 3.5	77.3 ± 4.8

1085	80.4 ± 2.8	80.4 ± 2.8	76.1 ± 4.3
1075	92.8 ± 3.1	92.7 ± 3.1	87.6 ± 4.8
1065	99.4 ± 3.3	99.3 ± 3.3	93.8 ± 5.2
1055	110.2 ± 3.4	110.1 ± 3.4	103.8 ± 5.6
1045	120.7 ± 3.6	120.7 ± 3.6	113.6 ± 6.0
1035	125.3 ± 3.7	125.2 ± 3.7	117.7 ± 6.2
1025	117.0 ± 3.6	116.9 ± 3.6	109.7 ± 5.8
1015	122.1 ± 3.7	122.0 ± 3.7	114.5 ± 6.1
1005	121.1 ± 3.7	121.0 ± 3.7	113.2 ± 6.0
995	118.7 ± 3.5	118.6 ± 3.5	110.8 ± 5.8
985	109.0 ± 3.5	108.9 ± 3.5	101.6 ± 5.5
975	109.2 ± 3.4	109.1 ± 3.4	101.6 ± 5.5
965	95.8 ± 3.3	95.7 ± 3.3	89.0 ± 4.9
955	91.6 ± 3.1	91.4 ± 3.1	84.9 ± 4.8
945	76.2 ± 2.9	76.0 ± 2.9	70.5 ± 4.1
935	76.6 ± 3.3	76.4 ± 3.3	70.7 ± 4.4
925	71.8 ± 2.8	71.6 ± 2.8	66.2 ± 3.9
915	70.8 ± 2.7	70.4 ± 2.7	65.0 ± 3.7
905	63.5 ± 3.5	62.9 ± 3.5	58.0 ± 4.1
895	61.6 ± 3.3	60.8 ± 3.3	56.0 ± 3.9
885	53.1 ± 3.1	52.2 ± 3.2	48.0 ± 3.7
875	46.0 ± 3.0	45.0 ± 3.1	41.3 ± 3.4
865	47.4 ± 2.7	46.3 ± 2.8	42.4 ± 3.2
855	48.1 ± 2.7	47.0 ± 2.7	43.0 ± 3.1
845	44.4 ± 2.6	43.2 ± 2.6	39.5 ± 2.9

835	40.1 ± 2.5	38.8 ± 2.5	35.5 ± 2.7
825	39.9 ± 2.4	38.6 ± 2.4	35.2 ± 2.7
815	42.3 ± 2.6	40.9 ± 2.6	37.2 ± 2.8
805	37.3 ± 2.4	35.8 ± 2.5	32.6 ± 2.7
795	35.1 ± 2.4	33.5 ± 2.5	30.5 ± 2.7
785	38.9 ± 2.6	37.3 ± 2.7	33.8 ± 2.8
775	33.9 ± 2.4	32.2 ± 2.6	29.2 ± 2.7
765	29.4 ± 2.7	27.5 ± 2.8	24.9 ± 2.7
755	30.8 ± 2.4	28.7 ± 2.6	25.9 ± 2.6
745	29.9 ± 2.6	27.6 ± 2.7	24.9 ± 2.7
735	23.1 ± 2.4	20.6 ± 2.7	18.6 ± 2.6
725	27.1 ± 2.7	24.4 ± 2.9	22.0 ± 2.8
715	24.1 ± 2.6	21.3 ± 2.8	19.1 ± 2.7
705	23.6 ± 2.6	20.7 ± 2.8	18.5 ± 2.7
695	16.2 ± 2.3	13.1 ± 2.6	11.7 ± 2.4
685	23.3 ± 2.7	20.1 ± 2.9	17.9 ± 2.7
675	19.0 ± 2.6	15.5 ± 2.8	13.8 ± 2.6
665	18.1 ± 1.8	14.4 ± 2.3	12.8 ± 2.1
655	19.5 ± 1.7	15.6 ± 2.2	13.9 ± 2.0
645	19.1 ± 2.4	15.0 ± 2.7	13.3 ± 2.5
635	19.6 ± 2.6	15.4 ± 2.9	13.6 ± 2.7
625	19.9 ± 2.3	15.6 ± 2.7	13.8 ± 2.5
615	14.5 ± 2.0	10.0 ± 2.7	8.9 ± 2.5
605	15.5 ± 2.4	10.8 ± 3.2	9.5 ± 2.8
595	22.3 ± 2.2	17.4 ± 3.1	15.3 ± 2.8

585	14.3 ± 2.0	9.2 ± 3.1	8.1 ± 2.7
575	16.1 ± 1.8	10.7 ± 3.1	9.5 ± 2.7
565	14.9 ± 2.1	9.2 ± 3.4	8.1 ± 3.0
555	17.5 ± 1.9	11.6 ± 3.4	10.2 ± 3.0
545	22.5 ± 1.9	16.1 ± 3.7	14.2 ± 3.3
535	15.5 ± 1.8	8.8 ± 3.7	7.7 ± 3.3
525	17.2 ± 1.8	10.3 ± 4.0	9.0 ± 3.6
515	19.7 ± 1.8	12.2 ± 3.9	10.6 ± 3.5
505	20.7 ± 1.7	12.3 ± 3.8	10.8 ± 3.4
495	21.6 ± 1.7	13.1 ± 3.7	11.3 ± 3.3
485	21.5 ± 2.0	11.9 ± 3.9	10.4 ± 3.5
475	20.5 ± 2.2	10.3 ± 4.0	8.9 ± 3.5
465	17.6 ± 1.9	7.0 ± 3.9	6.1 ± 3.4
455	19.5 ± 1.7	8.7 ± 3.7	7.5 ± 3.3
445	19.6 ± 1.9	8.5 ± 3.9	7.3 ± 3.4
435	18.0 ± 1.8	6.7 ± 3.9	5.8 ± 3.4
425	18.7 ± 1.8	7.4 ± 3.9	6.4 ± 3.4
415	17.8 ± 2.3	6.6 ± 4.2	5.7 ± 3.7
405	16.1 ± 2.4	4.9 ± 4.3	4.2 ± 3.7
395	13.9 ± 2.1	3.0 ± 4.2	2.7 ± 3.8
385	18.1 ± 2.0	7.4 ± 4.2	6.4 ± 3.7

TABLE 12

CENTER OF MASS DATA FOR $p(p,n)x$ AT 647 MeV

<u>Neutron Laboratory Momentum (MeV/c)</u>	<u>Neutron Center of Mass Momentum (MeV/c)</u>	<u>Invariant Mass, m_x (MeV)</u>	<u>Jacobian Transfor- mation Function</u>	<u>Neutron Spectrum of the Center of Mass Cross Sections ($\mu\text{b}/\text{sr-MeV/c}$)</u>
1095	421.2	1067.9	.2074	0.09 $\pm$.04
1085	414.0	1073.8	.2036	0.32 $\pm$.09
1075	406.9	1079.6	.1998	0.44 $\pm$.09
1065	399.7	1085.3	.1960	0.54 $\pm$.10
1055	392.5	1090.9	.1921	0.93 $\pm$.13
1045	385.3	1096.4	.1882	1.59 $\pm$.18
1035	378.0	1101.8	.1842	1.28 $\pm$.16
1025	370.8	1107.1	.1802	2.16 $\pm$.20
1015	363.5	1112.3	.1761	2.55 $\pm$.23
1005	356.2	1117.4	.1721	2.43 $\pm$.19
995	348.9	1122.4	.1679	3.43 $\pm$.29
985	341.6	1127.3	.1638	3.88 $\pm$.28
975	334.2	1132.1	.1596	3.53 $\pm$.26
965	326.8	1136.8	.1554	4.26 $\pm$.30
955	319.4	1141.4	.1511	4.83 $\pm$.33
945	312.0	1145.9	.1468	4.48 $\pm$.32
935	304.6	1150.3	.1425	4.42 $\pm$.31
925	297.1	1154.6	.1381	4.85 $\pm$.32
915	289.6	1158.8	.1337	5.48 $\pm$.32
905	282.1	1162.9	.1293	6.40 $\pm$.37

895	274.6	1166.9	.1248	6.42	± .36
885	267.0	1170.8	.1204	6.45	± .35
875	259.5	1174.6	.1159	6.80	± .38
865	251.9	1178.3	.1114	6.58	± .37
855	244.2	1181.9	.1068	6.70	± .37
845	236.6	1185.4	.1023	6.90	± .38
835	228.9	1188.8	.09773	6.86	± .37
825	221.2	1192.0	.09317	6.35	± .34
815	213.5	1195.2	.08860	5.98	± .33
805	205.7	1198.3	.08404	5.62	± .30
795	197.9	1201.3	.07949	5.75	± .31
785	190.1	1204.1	.07495	5.31	± .28
775	182.2	1206.9	.07043	4.85	± .30
765	174.4	1209.5	.06593	4.93	± .29
755	166.5	1212.1	.06147	4.17	± .25
745	158.5	1214.5	.05705	4.28	± .25
735	150.6	1216.8	.05268	3.71	± .21
725	142.6	1219.0	.04837	3.59	± .20
715	134.6	1221.1	.04412	3.19	± .18
705	126.5	1223.1	.03996	2.85	± .16
695	118.4	1224.9	.03590	2.77	± .15
685	110.3	1226.7	.03194	2.19	± .12
675	102.1	1228.3	.02810	1.75	± .10
665	93.9	1229.8	.02441	1.46	± .08
655	85.7	1231.2	.02087	1.19	± .06

645	77.5	1232.4	.01752	.83	± .05
635	69.2	1233.6	.01437	.69	± .04
625	60.8	1234.6	.01144	.54	± .07
615	52.5	1235.5	.00878	.36	± .02
605	44.1	.236.3	.00640	.23	± .02
595	35.6	1236.9	.00433	.16	± .01
585	27.1	1237.4	.00263	.090	± .006
575	18.6	1237.7	.00132	.043	± .003
565	9.9	1238.0	.00046	.0143	± .0011
555	-1.5	1238.1	.000098	.0030	± .0003
545	-6.7	1238.0	.00029	.0094	± .0008
535	-15.6	1237.8	.00109	.032	± .003
525	-24.4	1237.5	.00258	.073	± .008
515	-33.1	1237.0	.00484	.141	± .014
505	-41.9	1236.4	.00795	.24	± .02
495	-50.8	1235.7	.01202	.33	± .03
485	-59.7	1234.7	.01714	.52	± .04
475	-68.6	1233.7	.02346	.63	± .05
465	-77.6	1232.4	.03111	.83	± .07
455	-86.6	1231.0	.04024	1.19	± .09
445	-95.7	1229.5	.05104	1.42	± .11
435	-104.8	1227.8	.06371	1.85	± .14
425	-113.9	1225.9	.07848	2.31	± .17
415	-123.1	1223.9	.09562	2.76	± .25
405	-132.4	1221.6	.1154	3.08	± .30

395	-141.7	1219.2	.1382	3.51	+ .35
385	-151.0	1216.7	.1644	3.40	+ .38

TABLE 13

CENTER OF MASS DATA FOR $p(p,n)x$ AT 800 MeV

<u>Neutron Laboratory Momentum (MeV/c)</u>	<u>Neutron Center of Mass Momentum (MeV/c)</u>	<u>Invariant Mass, m_x (MeV)</u>	<u>Jacobian Transfor- mation Function</u>	<u>Neutron Spectrum of the Center of Mass Cross Sections ($\mu\text{b}/\text{sr-MeV}/c$)</u>
1285	493.8	1073.4	.2214	0.13 $\pm$.13
1275	487.1	1079.8	.2184	0.28 $\pm$.13
1265	480.4	1086.1	.2154	0.47 $\pm$.15
1255	473.7	1092.4	.2123	0.59 $\pm$.21
1245	467.0	1098.5	.2091	1.25 $\pm$.28
1235	460.2	1104.6	.2060	2.02 $\pm$.31
1225	453.5	1110.6	.2028	1.89 $\pm$.30
1215	446.7	1116.5	.1996	2.18 $\pm$.32
1205	439.9	1122.3	.1963	3.69 $\pm$.35
1195	433.1	1128.0	.1930	3.71 $\pm$.35
1185	426.3	1133.6	.1897	4.46 $\pm$.40
1175	419.5	1139.1	.1864	4.64 $\pm$.43
1165	412.6	1144.6	.1830	6.37 $\pm$.49
1155	405.8	1149.9	.1796	6.36 $\pm$.48
1145	398.9	1155.2	.1761	7.17 $\pm$.51
1135	392.0	1160.4	.1726	7.92 $\pm$.55
1125	385.1	1165.5	.1691	9.89 $\pm$.66
1115	378.1	1170.5	.1656	9.64 $\pm$.65
1105	371.2	1175.4	.1620	11.2 $\pm$.7
1095	364.2	1180.3	.1584	12.2 $\pm$.8

1085	357.2	1185.0	.1548	11.8	±	.7
1075	350.2	1189.7	.1511	13.2	±	.7
1065	343.2	1194.3	.1474	13.8	±	.8
1055	336.1	1198.8	.1437	14.9	±	.8
1045	329.0	1203.2	.1400	15.9	±	.8
1035	321.9	1207.5	.1362	16.0	±	.8
1025	314.8	1211.7	.1324	14.5	±	.8
1015	307.7	1215.9	.1286	14.7	±	.8
1005	300.5	1220.0	.1247	14.1	±	.7
995	293.4	1223.9	.1209	13.4	±	.7
985	286.1	1227.8	.1170	11.9	±	.6
975	278.9	1231.6	.1131	11.5	±	.6
965	271.7	1235.3	.1092	9.71	±	.53
955	264.4	1238.9	.1052	8.93	±	.51
945	257.1	1242.5	.1013	7.14	±	.42
935	249.8	1245.9	.09731	6.88	±	.43
925	242.4	1249.2	.09334	6.18	±	.36
915	235.1	1252.5	.08937	5.31	±	.33
905	227.7	1255.7	.08540	4.95	±	.35
895	220.2	1258.7	.08143	4.56	±	.32
885	212.8	1261.7	.07746	3.72	±	.29
875	205.3	1264.6	.07351	3.04	±	.25
865	197.8	1267.4	.06956	2.95	±	.22
855	190.3	1270.1	.06564	2.82	±	.20
845	182.7	1272.7	.06173	2.44	±	.18

835	175.1	1275.2	.05786	2.05	± .16
825	167.5	1277.6	.05402	1.90	± .15
815	159.9	1279.9	.05021	1.87	± .14
805	152.2	1282.1	.04646	1.51	± .13
795	144.5	1284.2	.04276	1.30	± .12
785	136.7	1286.2	.03913	1.32	± .11
775	129.0	1288.1	.03557	1.04	± .10
765	121.1	1289.9	.03209	.80	± .09
755	113.3	1291.6	.02870	.74	± .08
745	105.4	1293.1	.02542	.63	± .07
735	97.5	1294.6	.02225	.41	± .06
725	89.6	1296.0	.01922	.42	± .05
715	81.6	1297.2	.01633	.31	± .04
705	73.6	1298.4	.01360	.25	± .04
695	65.6	1299.4	.01106	.13	± .03
685	57.5	1300.3	.00871	.16	± .02
675	49.4	1301.1	.00659	.09	± .02
665	41.2	1301.8	.00471	.06	± .01
655	33.0	1302.3	.00311	.04	± .01
645	24.8	1302.8	.00180	.024	± .005
635	16.4	1303.1	.00082	.011	± .002
625	8.0	1303.3	.00021	.0029	± .0005
615	-2.2	1303.3	.00000069	.000006±	.000002
605	-8.2	1303.3	.00023	.0022	± .0006
595	-16.7	1303.1	.00095	.015	± .003

585	-25.3	1302.7	.00221	.018	±	.006
575	-33.8	1302.3	.00407	.039	±	.011
565	-42.4	1301.7	.00657	.053	±	.020
555	-51.0	1300.9	.00980	.10	±	.03
545	-59.6	1300.1	.01383	.20	±	.05
535	-68.3	1299.0	.01874	.14	±	.06
525	-77.1	1297.9	.02462	.22	±	.09
515	-85.9	1296.6	.03158	.34	±	.11
505	-94.7	1295.1	.03973	.43	±	.14
495	-103.6	1293.5	.04920	.56	±	.16
485	-112.5	1291.7	.06013	.63	±	.21
475	-121.5	1289.8	.07269	.65	±	.25
465	-130.5	1287.7	.08706	.53	±	.30
455	-139.6	1285.5	.1034	.63	±	.34
445	-148.7	1283.0	.1221	.89	±	.41
435	-157.9	1280.5	.1432	.83	±	.49
425	-167.1	1277.7	.1671	1.07	±	.57
415	-176.4	1274.8	.1941	1.11	±	.72
405	-185.7	1271.7	.2247	.94	±	.83
395	-195.1	1268.4	.2592	.70	±	.98
385	-204.5	1264.9	.2981	1.91	±	1.10

CHAPTER V

NEUTRON SPECTRA FROM THE $d(p,n)$ REACTION

The results of the measurements of the zero-degree neutron spectra from proton-deuteron collisions at the two LAMPF energies of 647 and 800 MeV are presented here. Table 14 shows the experimental parameters for the two spectral distributions.

TABLE 14
 $d(p,n)$ MEASUREMENT PARAMETERS

<u>Parameter</u>	<u>Value at 647 MeV</u>	<u>Value at 800 MeV</u>
Neutron production target density (LD_2)	5.35×10^{23} nuclei/cm ²	5.29×10^{23} nuclei/cm ²
Radiator target density (LH_2)	5.59×10^{23} nuclei/cm ²	5.59×10^{23} nuclei/cm ²
$\Delta\sigma_{np}$ at "nominal" beam momentum	0.1250 mb	0.1218 mb
"Nominal" beam momentum	1280 MeV/c	1450 MeV/c
Average $(L+R)_u / CI$	137.3	210.1
Current integrator calibration (# of protons/CI)	4.43×10^{11}	4.20×10^{11}
Collimator solid angle ($\Delta\Omega_c$)	9.108×10^{-6} sr	9.108×10^{-6} sr

The distributions feature a very strong narrow peak near the energy of the incident proton beam and a broad region at lower momenta associated with pion production in the p-d collisions. Figure 36

shows the neutron spectrum from 1200 to 1300 MeV/c with a nominal proton bombarding energy of 647 MeV. This spectrum has been binned in steps of 2 MeV/c. The line represents a least squares Gaussian fit to the spectrum through the fifteen points connected by the line. The fit has four free parameters, A, B, C, and D. The functional form is:

$$(A/B\sqrt{2\pi})\exp[-(p-C)^2/2B^2] + D$$

where p is the neutron momentum in MeV/c. The function is a Gaussian plus the constant D . The important parameters are C , the centroid of momentum, and B , the variance of the Gaussian distribution. C has the value 1278.93 ± 0.06 MeV/c. B has the value 7.37 ± 0.13 MeV/c. The errors on B and C are those generated by the fitting program from the statistical errors in the yields only. The mean momenta in the 2 MeV/c bins are considered to be exact during the fit. The variance parameter, B , transforms into a full width at one-half maximum of 17.35 MeV/c. This implies an energy width of 13.98 MeV FWHM. Notice that a very shallow valley exists at momenta just below the peak. The ratio of the peak channel to a representative channel in the valley is 71 ± 14 . The area of the peak (cross section in mb/sr) divided by an area in the valley with the same total momentum width as used to calculate the peak cross section gives a ratio of 30 ± 2 . This high ratio shows why the $d(p,n)$ reaction was chosen to provide a nearly monochromatic neutron beam. We have demonstrated experimentally

Figure 36

that with the TRF neutron time-of-flight technique one can unambiguously separate peak neutrons from any lower momentum neutrons even without beam chopping when the proton beam bursts have their nominal 5 ns separation. The d(p,n) neutron beam would then have a relative width ($\Delta E/E$) of $13.98/647 = 0.0216$. The integrated yield for this peak over the momentum range from 1200 to 1330 MeV/c is equal to 28.5 ± 2.0 mb/sr. 89.4% of this cross section is within 25 MeV/c to either side of the centroid of the peak.

The position of the centroid (1278.93 MeV/c) was used to make an estimate of the energy of the proton beam which passed through the deuterium to create this neutron spectrum. Assuming the kinetic energy of the proton beam to be equal to the kinetic energy of the centroid of the neutron peak plus the energy loss for a 650 MeV proton through one-half of the length of the liquid deuterium in the neutron production target plus the 2.2 MeV binding energy of the deuteron, we estimate the proton beam energy to be 652.5 ± 10.4 MeV. The nominal energy was 647 MeV. This is well within the 10.4 MeV energy uncertainty of our experiment at 647 MeV. The 647 MeV p(p,n) measurements were made during the same cycle as the measurement of this d(p,n) peak. Therefore, the value of 650.5 MeV, just 2.0 MeV below the proton beam energy was used as the energy at interaction between the two protons, where 2 MeV corresponds to the energy loss of a 650 MeV proton in half of the neutron production target when it is filled with liquid hydrogen.

Figures 37 and 38 show the proton recoil and neutron spectra, respectively, in the format already described, for the 647 MeV d(p,n) reaction for neutron momenta below 1100 MeV/c. These spectra are very reminiscent of the 647 MeV p(p,n) spectra shown in the previous chapter. There is, however, a greater relative inelastic subtraction in the d(p,n) spectra than in the p(p,n) spectra. At 705 MeV/c the inelastic background in the d(p,n) spectra is 11% of the elastic yield. At 425 MeV/c the inelastic background is 16% of the elastic yield. The greater inelasticity for deuterium results from the large number of high momentum neutrons in the d(p,n) spectrum. There are no neutrons above 1100 MeV/c in the p(p,n) spectra.

Figure 39 shows the neutron spectrum for large neutron momenta from the d(p,n) reaction at a nominal proton bombarding energy of 800 MeV. Again, the line represents a Gaussian fit of the type already described to the sixteen points connected by the line. The centroid parameter, C, has the value 1465.98 ± 0.14 MeV/c. The variance parameter, B, has the value 9.27 ± 0.33 MeV/c. The variance transforms into a full width at one-half maximum of 21.83 MeV/c. This transforms to an energy width of 18.38 MeV, FWHM. The relative energy width is $18.38/800 = 0.0230$. The ratio of the peak channel yield to a channel in the valley is 64 ± 8 . The ratio of the area of the peak to an equivalent momentum bite in the valley is 28.5 ± 1.6 . Again, the d(p,n) reaction at this energy provides an excellent source of monoenergetic neutrons.

Figure 37

Figure 38

Figure 39

The integrated yield for this peak is 29.7 ± 1.4 mb/sr, only slightly higher than the peak cross section at 647 MeV. 90.0% of the 800 MeV peak yield is within 25 MeV/c to either side of the centroid of the peak. Using the position of the centroid (1465.98 MeV/c), the energy loss in one-half of the liquid deuterium target, and the deuteron binding energy, we estimate the proton beam energy to be 806.0 ± 11.7 MeV. This value is consistent with the nominal energy of 800 MeV to within the 11.7 MeV energy uncertainty at 800 MeV. The 800 MeV p(p,n) spectra were assigned a value of 804.2 MeV for the kinetic energy of the incident proton based on the 806.0 MeV value for the beam energy and the 1.8 MeV energy loss for an 800 MeV proton through one-half of the neutron production target when it is full of liquid hydrogen.

Figure 40 is an example of the effects to be corrected for by bend angle randomization and energy loss correction. As stated earlier, we correct our proton spectra by randomizing the horizontal bend angle and therefore the momenta. We also apply an energy loss correction for the front end of our spectrometer to increase the momenta of the protons from the values obtained by the magnetic momentum analysis in TEWA. Figure 40 shows the raw recoil proton momentum spectrum without randomization or energy loss correction for the same set of data as shown in Figure 39. The peak channel position in Figure 40 is at a momentum of 1461 MeV/c. The corresponding point in Figure 39 is at the centroid value of 1466 MeV/c. The 5 MeV/c shift is due to an energy loss correction

Figure 40

to the momentum of about 4 MeV/c and a shift of about 1 MeV/c due to the (n,p) charge exchange kinematics. Figure 40 is a proton momentum histogram and Figure 39 is a neutron momentum histogram. The ragged spectrum in Figure 40 is made smooth in Figure 39. For momenta around 1465 MeV/c bend angle randomization of the momenta will result in shifts of ± 4.4 MeV/c on the average. Figures 39 and 40 both show the momenta binned in 2 MeV/c wide bins. Therefore, it is not too surprising to find Figure 39 much cleaner than Figure 40. Because of the triple peak nature of Figure 40, it is also understandable that Figure 39 appears to be a bit wider than Figure 40.

Figures 41 and 42 show the proton recoil and neutron spectra, respectively, for the 800 MeV d(p,n) reaction for neutron momenta below 1290 MeV/c. As in the 647 MeV spectra, these spectra are very similar to their 800 MeV p(p,n) counterparts in Figures 32 and 33. The d(p,n) spectrum in Figure 42 shows the same features as the p(p,n) spectrum in Figure 33. There is a strong peak at 1025 MeV/c, a broad shoulder in the momentum range from about 685 to 885 MeV/c, and a small tail at yet lower momenta. The 800 MeV d(p,n) spectra show considerable inelastic correction. At 945 MeV/c the inelastic background is 16% of the elastic yield. At 705 MeV/c the inelastic background is 31% of the elastic yield. At 425 MeV/c the inelastic background is 210% of the elastic yield.

Tables 15 and 16 present the data for the d(p,n) spectra at 647 and 800 MeV, respectively. The mean values of each

Figure 41

Figure 42

laboratory neutron momentum bin, the cross sections for all proton recoils assuming a constant value of $\Delta\sigma_{np}$ (0.125 mb at 647 MeV and 0.1218 mb at 800 MeV) the cross sections of the elastic proton recoils with the same constant $\Delta\sigma_{np}$, and the neutron spectrum of the laboratory cross sections are presented in these tables.

By integrating the spectra over the neutron momenta, the following results are obtained:

1. The d(p,n) spectrum at 800 MeV shows a cross section of 31.2 mb/sr for momenta greater than 1285 MeV/c.
2. The d(p,n) spectrum at 800 MeV shows a cross section of 67.1 mb/sr for momenta less than 1285 MeV/c.
3. The d(p,n) spectrum at 647 MeV shows a cross section of 30.1 mb/sr for momenta greater than 1105 MeV/c.
4. The d(p,n) spectrum at 647 MeV shows a cross section of 50.1 mb/sr for momenta less than 1105 MeV/c.
5. The p(p,n) spectrum at 800 MeV shows a cross section of 32.8 mb/sr integrated over all momenta.
6. The p(p,n) spectrum at 647 MeV shows a cross section of 29.3 mb/sr integrated over all momenta.

Since the d(p,n) and p(p,n) spectra are very similar in the regions where they have coinciding neutron momenta, one would be interested in the d(p,n) to p(p,n) cross section ratios at the two energies,

800 and 647 MeV. At 800 MeV, the appropriate ratio is obtained by dividing the value in 2. above by the value in 5. The $d(p,n)/p(p,n)$ ratio at 800 MeV is 2.05. Similarly, one divides 4. above by 6. above to obtain the $d(p,n)/p(p,n)$ ratio at 647 MeV. This value is 1.71.

TABLE 15

d(p,n) SPECTRA AT 647 MeV IN THE LABORATORY

<u>Mean Value of Neutron Momentum (MeV/c)</u>	<u>Laboratory Cross Sections for All Proton Recoils ($\mu\text{b}/\text{sr-MeV/c}$)</u>	<u>Laboratory Cross Sections for Elastic Protons Only ($\mu\text{b}/\text{sr-MeV/c}$)</u>	<u>Neutron Spectrum of the Laboratory Cross Sections ($\mu\text{b}/\text{sr-MeV/c}$)</u>
1315	1 $\pm$ 1	1 $\pm$ 1	1 $\pm$ 1
1305	2 $\pm$ 1	2 $\pm$ 1	2 $\pm$ 1
1295	16 $\pm$ 1	16 $\pm$ 1	16 $\pm$ 1
1285	52 $\pm$ 2	52 $\pm$ 2	52 $\pm$ 3
1275	249 $\pm$ 5	249 $\pm$ 5	249 $\pm$ 12
1265	911 $\pm$ 9	911 $\pm$ 9	909 $\pm$ 41
1255	982 $\pm$ 9	982 $\pm$ 9	978 $\pm$ 44
1245	337 $\pm$ 5	337 $\pm$ 5	335 $\pm$ 16
1235	103 $\pm$ 3	103 $\pm$ 3	103 $\pm$ 5
1225	64 $\pm$ 2	64 $\pm$ 2	64 $\pm$ 4
1215	50 $\pm$ 2	50 $\pm$ 2	50 $\pm$ 3
1205	37 $\pm$ 2	37 $\pm$ 2	37 $\pm$ 2
1195	27 $\pm$ 1	27 $\pm$ 1	26 $\pm$ 2
1185	30 $\pm$ 2	30 $\pm$ 2	29 $\pm$ 2
1175	25 $\pm$ 1	25 $\pm$ 1	25 $\pm$ 2
1165	28 $\pm$ 1	28 $\pm$ 1	27 $\pm$ 2
1155	24 $\pm$ 1	24 $\pm$ 1	24 $\pm$ 2
1145	19 $\pm$ 1	19 $\pm$ 1	19 $\pm$ 2
1135	21 $\pm$ 2	21 $\pm$ 2	21 $\pm$ 2
1125	19 $\pm$ 1	19 $\pm$ 1	19 $\pm$ 2

1115	19 ± 2	19 ± 2	19 ± 2
1105	18 ± 1	18 ± 1	18 ± 1
1095	18 ± 1	18 ± 1	18 ± 1
1085	18 ± 1	18 ± 1	18 ± 1
1075	17 ± 1	14 ± 3	14 ± 3
1065	17 ± 2	14 ± 3	14 ± 3
1055	23 ± 2	20 ± 3	19 ± 3
1045	26 ± 2	23 ± 3	22 ± 3
1035	32 ± 3	28 ± 3	27 ± 3
1025	43 ± 2	39 ± 3	37 ± 4
1015	46 ± 2	42 ± 3	40 ± 4
1005	48 ± 3	43 ± 4	42 ± 4
995	56 ± 3	51 ± 4	49 ± 4
985	61 ± 3	56 ± 4	53 ± 4
975	63 ± 3	57 ± 4	54 ± 4
965	73 ± 3	66 ± 4	63 ± 5
955	72 ± 3	64 ± 4	61 ± 5
945	88 ± 4	80 ± 4	76 ± 5
935	80 ± 3	72 ± 4	68 ± 5
925	90 ± 4	80 ± 5	76 ± 5
915	89 ± 4	78 ± 5	74 ± 5
905	100 ± 4	88 ± 5	83 ± 6
895	100 ± 4	88 ± 5	83 ± 6
885	100 ± 4	87 ± 5	82 ± 6
875	121 ± 4	108 ± 5	102 ± 7

865	119 ± 4	106 ± 5	100 ± 7
855	128 ± 5	115 ± 5	107 ± 7
845	118 ± 4	105 ± 5	98 ± 7
835	131 ± 5	118 ± 5	110 ± 7
825	121 ± 4	107 ± 5	101 ± 7
815	126 ± 4	113 ± 6	106 ± 7
805	114 ± 4	100 ± 5	93 ± 6
795	127 ± 4	114 ± 5	106 ± 7
785	130 ± 5	117 ± 6	109 ± 7
775	136 ± 5	123 ± 6	114 ± 8
765	127 ± 5	114 ± 6	105 ± 7
755	124 ± 4	111 ± 6	103 ± 7
745	121 ± 4	108 ± 6	100 ± 7
735	124 ± 4	111 ± 6	102 ± 7
725	120 ± 4	107 ± 6	99 ± 7
715	122 ± 4	109 ± 6	101 ± 7
705	122 ± 4	110 ± 6	101 ± 7
695	135 ± 4	123 ± 6	113 ± 8
685	128 ± 4	116 ± 6	106 ± 7
675	122 ± 4	109 ± 6	100 ± 7
665	115 ± 4	103 ± 6	94 ± 7
655	117 ± 4	105 ± 6	96 ± 7
645	100 ± 4	88 ± 6	80 ± 7
635	99 ± 4	87 ± 6	80 ± 7
625	96 ± 4	84 ± 6	77 ± 7

615	87 ± 4	76 ± 6	69 ± 7
605	83 ± 4	72 ± 7	65 ± 7
595	83 ± 4	72 ± 6	66 ± 6
585	77 ± 3	66 ± 6	60 ± 6
575	67 ± 3	56 ± 6	51 ± 6
565	75 ± 4	64 ± 6	58 ± 6
555	58 ± 5	48 ± 8	43 ± 7
545	72 ± 5	61 ± 8	55 ± 8
535	68 ± 5	58 ± 8	52 ± 7
525	63 ± 5	53 ± 8	47 ± 8
515	65 ± 5	55 ± 8	49 ± 7
505	64 ± 5	53 ± 7	47 ± 7
495	89 ± 5	79 ± 8	70 ± 7
485	71 ± 5	60 ± 8	54 ± 7
475	77 ± 6	66 ± 8	59 ± 8
465	65 ± 5	54 ± 8	48 ± 7
455	66 ± 5	55 ± 8	49 ± 7
445	74 ± 6	64 ± 8	57 ± 8
435	61 ± 5	50 ± 8	45 ± 7
425	72 ± 6	62 ± 8	55 ± 8
415	48 ± 9	38 ± 11	34 ± 9
405	84 ± 12	74 ± 13	65 ± 12
395	57 ± 9	48 ± 11	42 ± 10
385	46 ± 7	36 ± 10	32 ± 9

TABLE 16

d(p,n) SPECTRA AT 800 MeV IN THE LABORATORY

<u>Mean Value of Neutron Momentum (MeV/c)</u>	<u>Laboratory Cross Sections for All Proton Recoils ($\mu\text{b}/\text{sr-MeV/c}$)</u>	<u>Laboratory Cross Sections for Elastic Protons Only ($\mu\text{b}/\text{sr-MeV/c}$)</u>	<u>Neutron Spectrum of the Laboratory Cross Sections ($\mu\text{b}/\text{sr-MeV/c}$)</u>
1495	1 $\pm$ 1	1 $\pm$ 1	1 $\pm$ 1
1485	2 $\pm$ 1	2 $\pm$ 1	2 $\pm$ 1
1475	8 $\pm$ 2	8 $\pm$ 2	8 $\pm$ 2
1465	54 $\pm$ 5	54 $\pm$ 5	54 $\pm$ 5
1455	319 $\pm$ 12	319 $\pm$ 12	319 $\pm$ 18
1445	987 $\pm$ 20	987 $\pm$ 20	985 $\pm$ 48
1435	920 $\pm$ 19	920 $\pm$ 19	918 $\pm$ 45
1425	331 $\pm$ 11	331 $\pm$ 11	330 $\pm$ 18
1415	128 $\pm$ 7	128 $\pm$ 7	127 $\pm$ 9
1405	83 $\pm$ 6	83 $\pm$ 6	82 $\pm$ 7
1395	56 $\pm$ 5	56 $\pm$ 5	56 $\pm$ 6
1385	37 $\pm$ 4	37 $\pm$ 4	36 $\pm$ 4
1375	28 $\pm$ 3	28 $\pm$ 3	28 $\pm$ 4
1365	23 $\pm$ 4	23 $\pm$ 4	23 $\pm$ 4
1355	28 $\pm$ 3	28 $\pm$ 3	28 $\pm$ 4
1345	20 $\pm$ 3	20 $\pm$ 3	19 $\pm$ 3
1335	24 $\pm$ 3	24 $\pm$ 3	24 $\pm$ 3
1325	22 $\pm$ 3	22 $\pm$ 3	22 $\pm$ 3
1315	20 $\pm$ 2	20 $\pm$ 2	19 $\pm$ 2
1305	21 $\pm$ 3	21 $\pm$ 3	21 $\pm$ 3

1295	18 ± 2	18 ± 2	18 ± 2
1285	19 ± 2	19 ± 2	18 ± 2
1275	17 ± 2	17 ± 2	16 ± 2
1265	22 ± 3	22 ± 3	22 ± 3
1255	20 ± 3	20 ± 3	19 ± 3
1245	27 ± 3	27 ± 3	26 ± 3
1235	33 ± 3	33 ± 3	32 ± 4
1225	43 ± 4	42 ± 4	41 ± 5
1215	49 ± 4	48 ± 4	46 ± 5
1205	59 ± 4	58 ± 5	56 ± 5
1195	63 ± 5	61 ± 5	59 ± 6
1185	74 ± 5	69 ± 6	66 ± 6
1175	77 ± 5	68 ± 6	66 ± 6
1165	92 ± 5	79 ± 6	76 ± 7
1155	103 ± 6	89 ± 6	86 ± 7
1145	124 ± 6	108 ± 7	103 ± 8
1135	131 ± 6	115 ± 7	109 ± 8
1125	140 ± 6	124 ± 7	118 ± 9
1115	152 ± 7	135 ± 7	128 ± 9
1105	159 ± 7	142 ± 8	135 ± 9
1095	167 ± 7	149 ± 8	141 ± 10
1085	167 ± 7	148 ± 8	140 ± 10
1075	196 ± 7	176 ± 8	167 ± 10
1065	198 ± 7	178 ± 8	168 ± 11
1055	201 ± 9	181 ± 10	170 ± 12

1045	210 ± 9	190 ± 10	179 ± 12
1035	208 ± 9	186 ± 10	175 ± 12
1025	205 ± 9	184 ± 10	172 ± 12
1015	221 ± 9	200 ± 10	187 ± 12
1005	218 ± 9	196 ± 10	184 ± 12
995	209 ± 9	186 ± 10	174 ± 12
985	198 ± 9	175 ± 10	163 ± 12
975	196 ± 9	173 ± 10	162 ± 11
965	199 ± 9	176 ± 10	164 ± 12
955	185 ± 8	162 ± 9	150 ± 11
945	170 ± 9	147 ± 10	137 ± 11
935	166 ± 9	144 ± 10	133 ± 11
925	159 ± 8	136 ± 9	126 ± 10
915	156 ± 7	133 ± 8	123 ± 9
905	131 ± 6	109 ± 7	100 ± 8
895	123 ± 6	102 ± 8	94 ± 8
885	126 ± 6	106 ± 8	97 ± 8
875	117 ± 6	97 ± 8	89 ± 8
865	109 ± 6	90 ± 7	82 ± 8
855	113 ± 6	94 ± 7	86 ± 8
845	113 ± 6	96 ± 7	88 ± 8
835	106 ± 6	89 ± 7	81 ± 8
825	96 ± 6	81 ± 7	74 ± 7
815	101 ± 6	86 ± 7	78 ± 7
805	94 ± 5	80 ± 7	73 ± 7

795	87 ± 5	74 ± 6	67 ± 6
785	98 ± 7	85 ± 8	77 ± 8
775	80 ± 7	66 ± 7	60 ± 7
765	89 ± 7	75 ± 7	68 ± 7
755	86 ± 6	72 ± 7	65 ± 7
745	90 ± 6	76 ± 7	68 ± 7
735	75 ± 6	60 ± 7	54 ± 7
725	78 ± 6	63 ± 7	57 ± 7
715	85 ± 6	70 ± 7	63 ± 7
705	68 ± 5	52 ± 7	47 ± 6
695	79 ± 6	63 ± 7	57 ± 7
685	63 ± 5	46 ± 6	41 ± 6
675	65 ± 5	48 ± 7	43 ± 6
665	64 ± 4	47 ± 6	42 ± 5
655	69 ± 4	51 ± 6	46 ± 6
645	60 ± 4	42 ± 6	38 ± 6
635	60 ± 4	42 ± 6	38 ± 6
625	61 ± 4	43 ± 6	38 ± 6
615	64 ± 4	45 ± 7	40 ± 6
605	53 ± 4	34 ± 7	30 ± 6
595	55 ± 4	36 ± 7	31 ± 6
585	54 ± 4	34 ± 7	30 ± 7
575	57 ± 4	37 ± 7	33 ± 7
565	59 ± 5	39 ± 8	34 ± 7
555	60 ± 5	39 ± 8	34 ± 7

545	56 ± 5	34 ± 9	30 ± 8
535	50 ± 5	27 ± 9	24 ± 8
525	55 ± 5	32 ± 9	28 ± 8
515	48 ± 5	24 ± 9	21 ± 8
505	53 ± 4	27 ± 8	23 ± 7
495	48 ± 5	21 ± 9	18 ± 8
485	53 ± 5	24 ± 8	21 ± 7
475	47 ± 4	17 ± 8	14 ± 7
465	58 ± 4	27 ± 8	23 ± 7
455	47 ± 4	15 ± 8	13 ± 7
445	54 ± 4	21 ± 9	19 ± 8
435	47 ± 4	14 ± 10	12 ± 8
425	50 ± 4	16 ± 11	14 ± 9
415	52 ± 5	19 ± 11	16 ± 10
405	52 ± 5	20 ± 11	17 ± 11
395	44 ± 5	13 ± 13	11 ± 11
385	42 ± 4	12 ± 12	10 ± 10

C H A P T E R VI

INTERPRETATION AND COMPARISON OF THE SPECTRA

Each of the $d(p,n)$ spectra (shown in Figures 43 and 44) exhibits a very strong and narrow peak near the energy of the incident proton beam which is well separated from a broad bump at lower momenta. The $p(p,n)$ spectra (also shown in Figures 43 and 44) have shapes which are very similar to the lower momentum spectra of the corresponding $d(p,n)$ spectra. Therefore, it seems logical to separate the discussions of the spectra according to the regions of neutron momenta relating to the two distinct processes of quasi-elastic scattering in the $d(p,n)2p$ reaction and the single pion production contributions in the $d(p,n)$ and $p(p,n)$ spectra.

A. QUASI-ELASTIC PEAK FROM THE $d(p,n)2p$ REACTION

As can be seen in Figures 43 and 44, there exists a very sharp peak in the neutron momentum spectrum from the $d(p,n)$ reaction at both 647 and 800 MeV. Each of these peaks occurs at a neutron momentum close to the momentum of the proton beam. Since the neutron and proton have nearly the same mass and the deuteron is a loosely bound state of the neutron and proton, the dominant mechanism responsible for the peak neutrons should be quasi-elastic charge exchange scattering between the incident proton and the neutron in the deuteron. One would like to consider the proton in the deuteron to be a spectator to the charge exchange scattering

Figure 43

Figure 44

of the incident proton and the neutron. Such a mechanism to explain the $d(p,n)2p$ reaction at medium energies and for small neutron angles and large neutron momenta has been investigated in detail by Dan S. Ward and T.A. Griffy during the course of Dan Ward's Ph.D. research at the University of Texas at Austin³⁰. Ward shows in his thesis how to calculate cross sections and polarizations for neutrons generated in p-d collisions at energies from 384 to 750 MeV. His methods are based on the impulse approximation to relate the proton-deuteron scattering matrix to that of the free proton-neutron matrix. Multiple scattering of the incident proton from the two target nucleons is neglected. Furthermore, the calculations are made for regions of phase space in which the relative energies of the two interacting nucleons are high but the spectator energy is nearly zero (called the quasi-free regime by Ward) and also for regions of phase space in which both the momentum transfer and the relative momentum of the center of mass of the diproton system are small (called the slightly inelastic regime by Ward). These two regimes of validity of the impulse approximation overlap each other when one considers the spectrum of the peak energy zero-degree neutrons from the $d(p,n)2p$ reaction. Ward calculates the cross sections and polarizations in the distorted wave Born approximation (DWBA) by calculating the matrix elements of the nucleon-nucleon Hamiltonian operator between the initial and final time independent nuclear states. The initial state consists of a plane wave for the high energy incident proton

and the Hulthén wave function as given by Moravcsik³¹ for the S state of the deuteron. The final state consists of a plane wave for the high energy neutron, a plane wave for the motion of the center of mass of the diproton subsystem, and the wave function for the final state diproton subsystem. The diproton wave function is dependent only upon the position coordinate between the two protons. The diproton exists in a low relative energy state. Therefore, in the spirit of the impulse approximation, the diproton wave function is evaluated in a plane wave form for the ($L=1$) and higher partial waves and only the ($L=0$) wave is distorted. Ward uses the Hamada-Johnson potential³² to solve the Schrodinger equation for the ($L=0$) diproton state. The $L=0$ choice causes the linear and quadratic spin-orbit terms and the tensor interaction in the Hamada-Johnson potential to vanish. Only the central potential remains from which the ($L=0$) partial wave of the diproton wave function is calculated. Ward calculates both the simple plane wave Born approximation (simple BA) and the DWBA, where the ($L=0$) diproton wave is distorted by the Hamada-Johnson potential. In the spirit of the impulse approximation, he relates the proton-deuteron inelastic scattering matrix elements to the free proton-neutron scattering matrix elements to accomplish the integration over the nucleon-nucleon Hamiltonian between the initial and final nuclear states. The free proton-neutron scattering matrix elements are calculated using Arndt, MacGregor and Wright phase shifts³³⁻³⁴.

Ward calculated the double differential cross section, $d^2\sigma/d\Omega_n dE_n$, as a function of the laboratory kinetic energies of the neutrons emitted at 0° to the incident proton for the reaction $d(p,n)2p$. His calculations at 600, 690, and 750 MeV, his three highest energies, can be compared to our data at 647 and 800 MeV. Figure 45 shows a plot of Ward's calculation at 750 MeV. The solid curve is the DWBA calculation containing the final state interaction (FSI) of the diproton in the ($L=0$) partial wave. The area under this curve from 730 MeV to 747.8 MeV is 62.0 mb/sr. The dashed curve in Figure 45 is the simple plane wave Born approximation. The area under the simple BA is 25.6 mb/sr. The highest energy neutrons occur at an energy 2.2 MeV below the incident proton kinetic energy in accord with the 2.2 MeV binding energy of the deuteron. The simple BA curve has a FWHM of about 4 MeV. The DWBA curve has a FWHM of nearly 9 MeV. Therefore, the final state interaction tends to increase the cross section and widen the high energy neutron peak.

Figures 46 and 47 show how Ward's predictions compare to our measurements. In Figure 46 Ward's data is presented as an interpolation at 651 MeV between his 600 and 690 MeV calculations. Our peak is shown by the connected dots. Figure 47 shows an extrapolation to 804 MeV from Ward's 750 MeV calculation. The various widths are shown in Figures 46 and 47 as are the integrated cross sections. Our peak yields are only a bit larger than Ward's simple Born approximation. His DWBA FSI gives about

Figure 45

Figure 46

Figure 47

twice the cross section that we measured.

The relative energy positions of our data with respect to Ward's predictions are based on our choice of the proton beam energy. We measure the neutron kinetic energy, but calculate the kinetic energy of the proton at interaction by invoking a shift of only 2.2 MeV for the break-up of the deuteron. This shift is applied to the centroid of the peak that we measure. Ward's calculations show a much larger shift. The centroid of Ward's DWBA FSI peak in Figure 47 is 8.2 MeV below the incident proton kinetic energy. The centroid of Ward's simple BA peak in Figure 47 is 6.3 MeV below the incident proton kinetic energy.

The widths of our data include the resolution of the spectrometer and the widening caused by the randomization of the momentum. The data in Figures 46 and 47 are the same as that presented versus neutron momentum in Figures 36 and 39. The randomization widening is fairly large in the 804 MeV data as our comparisons of Figures 39 and 40 have already shown.

We are able to make a few simple statements relating to the energy shift of the centroid from the incident proton energy and to the width of the peak because we measured both $d(p,n)2p$ and $d(n,p)2n$ break-up spectra at 800 MeV. The $d(p,n)2p$ quasi-elastic peak was measured with liquid hydrogen in the radiator target as already discussed. From this spectrum we can obtain a centroid neutron momentum and a width. By putting liquid deuterium in the radiator target and keeping liquid deuterium in the neutron

production target as well, we can investigate the $d(n,p)2n$ quasi-elastic peak by using the $d(p,n)2p$ neutron beam as a probe. The proton momentum histograms for the $d(n,p)2n$ spectrum were constructed with the usual bend angle randomization and with energy loss correction that took into account the presence of deuterium instead of hydrogen in the radiator target. The centroid of the proton momentum distribution and the width can then be obtained and compared to the $d(p,n)2p$ neutron values. The $d(p,n)2p$ spectrum and the $d(n,p)2n$ spectrum were each fit to a Gaussian function by a least squares fitting routine as described previously. Figures 36 and 39 show examples of such fits. The $d(p,n)2p$ centroid had a value of 1466.14 ± 0.09 MeV/c. The width was 19.35 ± 0.38 MeV/c FWHM, which transforms into an energy width of 15.59 MeV, FWHM. The $d(n,p)2n$ centroid had a value of 1457.59 ± 0.11 MeV/c. The width was 21.16 ± 0.54 MeV/c FWHM, which transforms to an energy width of 17.05 MeV, FWHM. All of the errors were those generated by the fitting routine from the statistical errors on the data, with no errors assigned to the means of each 2 MeV/c wide momentum bin. The $d(n,p)2n$ centroid is down-shifted from the centroid of the $d(p,n)2p$ neutron beam by 8.55 ± 0.14 MeV/c or by 7.20 ± 0.12 MeV. Assuming this shift is about the same for either the $d(n,p)2n$ or the $d(p,n)2p$ reaction, it lies right between the 6.3 and 8.2 MeV shifts obtained from Ward's simple BA and DWBA FSI predictions, respectively.

Measday⁵ measured his proton beam energy to be 158.5 MeV.

The mean energy loss of the proton in the deuterium was 2.5 MeV. He measured the neutron peak energy to be 151.8 ± 1.0 MeV. His data give a shift of 4.2 ± 1.4 MeV.

One can also obtain information about the intrinsic widths of the $d(p,n)2p$ and $d(n,p)2n$ distributions if one estimates the spectrometer resolution, target energy loss variations, and proton beam spread. Let W_{pp} be the intrinsic FWHM for the $d(p,n)2p$ quasi-elastic peak. Let W_{nn} be the intrinsic FWHM for the $d(n,p)2n$ quasi-elastic peak. Let W_a be the observed FWHM for the $d(p,n)2p$ neutron momentum distribution. Let W_b be the observed FWHM for the $d(n,p)2n$ proton momentum distribution. Let W_{beam} be the FWHM energy spread of the proton beam. Let W_1 be the FWHM of the energy loss distribution for protons in the neutron production target (target 1). Let W_2 be the FWHM of the energy loss distribution for protons in the radiator target (target 2). Let R be the resolution. The relevant equations relating these widths are:

$$W_a^2 = W_{pp}^2 + W_{beam}^2 + W_1(LD_2)^2 + W_2(LH_2)^2 + R^2$$

$$W_b^2 = W_{pp}^2 + W_{beam}^2 + W_1(LD_2)^2 + W_2(LD_2)^2 + R^2 + W_{nn}^2$$

Putting in the FWHM energy widths one obtains:

$$W_a^2 = (15.59)^2 = W_{pp}^2 + (3.74)^2 + (2.91)^2 + (3.03)^2 + (10.3)^2$$

$$W_b^2 = (17.05)^2 = W_{pp}^2 + (3.74)^2 + (2.91)^2 + (3.62)^2 + (10.3)^2 + W_{nn}^2$$

Subtracting the two previous equations allows one to solve for W_{nn} :

$$W_{nn}^2 = (17.05)^2 - (15.59)^2 - (3.62)^2 + (3.03)^2 = 43.73$$

$$W_{nn} = 6.61 \text{ MeV, FWHM}$$

Solving then for W_{pp} yields a value of 10.26 MeV, FWHM. This value is a bit larger than Ward's 804 MeV DWBA FSI prediction of 8.7 MeV, but then our method of obtaining the widths is not too accurate since we must make an accurate estimate of the resolution, etc. Let us predict the observed FWHM of the 650 MeV d(p,n)2p peak:

$$W_a^2 = W_{pp}^2 + W_{beam}^2 + W_1(LD_2)^2 + W_2(LH_2)^2 + R^2$$

$$W_a^2 = (10.26)^2 + (3.13)^2 + (3.11)^2 + (3.24)^2 + (8.9)^2$$

$$W_a^2 = 214.4$$

$$W_a = 14.6 \text{ MeV}$$

The observed FWHM at 650 MeV was 14.0 MeV. Therefore, our estimate is a factor of $14.6/14.0 = 1.04$ too large. This shows the level of our ability to estimate the energy loss spreads, resolution, etc.

Measday's 152 MeV data⁵ show a width of 6 MeV as opposed to our 10.3 MeV FWHM for W_{pp} . His shift is 4.2 ± 1.4 MeV as opposed to our 7.2 ± 0.12 MeV. Perhaps this shows consistency since the shifts are measured between centroids and the centroid positions can be influenced by the widths. At low energies, experimenters have found narrow widths for the d(p,n)2p peaks. Perhaps the width

increases with energy as perhaps the shift does. Ward's results go as low as 384 MeV with little change in the widths and shifts.

Table 17 shows a comparison between our data (including the $d(p,n)2p$ and $d(n,p)2n$ shift and width results) and Ward's calculations between 600 and 804 MeV.

Only at 804 MeV did we carry out the $d(p,n)2p$ and $d(n,p)2n$ measurements together. Therefore, only the 804 MeV values of the shifts and widths are really meaningful for comparison between Ward and experiment.

It appears that Ward's calculations show the general features of the $d(p,n)2p$ quasi-elastic peak such as the shift of the centroid of the neutron energy distribution from the incident proton kinetic energy and the width of the neutron energy distribution. However, Ward's FSI DWBA prediction of the cross section is about two times too large. The MacGregor, Arndt, and Wright phase shifts used by Ward to calculate the 600, 690 and 750 MeV $d(p,n)2p$ cross sections were obtained from an energy dependent analysis up to an energy of 750 MeV. Probably the only experiment relating directly to Ward's predictions on n-p scattering which was fit by these phase shifts was the 630 MeV n-p elastic angular distribution made at Dubna in 1960 by Amaglobeli, *et al.*²⁸ MacGregor, *et al.*³⁴ state that this experiment should be multiplied by a factor of 1.042 to make it consistent with the phase shift solution. After correcting the Amaglobeli data at zero degrees by the 1.042 factor we find that the phase shift fit should give an n-p charge exchange cross

TABLE 17

 $d(p,n)2p$ QUASI-ELASTIC PEAK COMPARISONS

Experiment or Calculation	Nominal Incident of Proton Kinetic Energy (MeV)	Laboratory Cross Section of the Peak (mb/sr)	Shift of the Centroid from the Incident Proton Energy (MeV)	Width of the Peak W _{pp} FWHM (MeV)
Ward's Simple BA	600	22.5	≈ 6	≈ 4
Ward's DWBA	600	54.9	≈ 8	≈ 9
Interpolation for Ward of the Simple BA	651	23.6	≈ 6	3.9
Interpolation for Ward of the FSI DWBA	651	57.4	≈ 8	8.6
Our Data	651	28.5	---	10.3
Ward's Simple BA	690	24.5	≈ 6	≈ 4
Ward's DWBA	690	59.4	≈ 8	≈ 9
Ward's Simple BA	750	25.6	≈ 6	≈ 4
Ward's DWBA	750	62.0	≈ 8	≈ 9
Extrapolation of Ward of the Simple BA	804	26.6	6.3	3.9
Extrapolation of Ward of the DWBA	804	64.3	8.2	8.7
Our Data	804	29.7	7.2	10.3

section that is only 1.014 times larger than our own n-p cross section at zero degrees.

Therefore, Ward's FSI DWBA predictions still look about two times too large. His simple BA predictions are about right compared to our d(p,n)2p cross sections at zero degrees.

An interesting comparison can be made between the zero-degree d(p,n)2p laboratory cross section and the p(n,p)n charge exchange cross section in the laboratory. Table 18 shows a comparison of these data for a few measurements between 50 and 710 MeV.

TABLE 18

d(p,n)2p LABORATORY CROSS SECTION VERSUS n-p CHARGE EXCHANGE AT 0°

Kinetic Energy of the Incident Projectile (MeV)	Experiment	n-p Charge Exchange Cross Section (σ_H in mb/sr)	d(p,n)2p Cross Section (σ_D in mb/sr)	σ_D/σ_H
50	Montgomery ¹⁷	78.8	---	0.46
50	Batty ³⁵	---	36.2	
150	Measday ³⁶	55.0	36.0	0.65
645	Our Data ²⁹	49.4	28.5	0.58
710	Larsen ⁴	33.9	16.4	0.48

All of the measurements show σ_D/σ_H near or a bit greater than one-half. The Measday measurement of σ_D is actually for d(n,p)2n but charge symmetry states that the d(p,n)2p cross section should be the same. Larsen assumed charge symmetry and our d(p,n)2p

and $d(n,p)2n$ data bear this out. Larsen's data are very low compared to the rest but his σ_D/σ_H ratio is nearly consistent with the other data. We can only conclude that Larsen had some sort of inefficiency in determining the quotient of proton yield exiting his radiator target and proton flux in the primary beam.

We conclude that our $d(p,n)2p$ and $n-p$ charge exchange data are consistent with most of the other measurements and show a σ_D/σ_H ratio of 0.58 at zero degrees.

The fact that σ_D/σ_H is not equal to one shows that there is a partial rejection of purely charge exchange quasi-elastic scattering in the $d(p,n)2p$ reaction at zero degrees. Larsen points out that the Pauli principle acts to restrict the number of quantum mechanical states which are allowed. Since the final state interaction in the diproton occurs for low relative energies between the two protons, only the ($L=0$) orbital angular momentum is important in the FSI. Antisymmetrization of the diproton therefore demands that it exist in the singlet (spin=0) state. The Pauli rejection of the triplet spin states tends to reduce the yield of high energy neutrons compared to $n-p$ charge exchange scattering.

Certainly Ward's calculations contain the proper angular momentum and isospin formalism since his simple Born approximation cross section is less than the free $n-p$ charge exchange cross section. It just appears that the DWBA FSI is too large. The simple BA agrees with our data.

The use of liquid deuterium as a source of monoenergetic

neutrons through proton bombardment at zero-degrees is vividly pointed out in Figure 48. This figure shows preliminary data on the zero-degree (p,n) neutron momentum spectra for targets of liquid deuterium, beryllium, carbon, and aluminum. Deuterium, beryllium, and aluminum all provide a strong charge exchange peak of high neutron momentum. They all have a neutron which can be thought of as being loosely bound and available for charge exchange with the incident proton. Carbon, on the other hand, may be thought of as containing three alpha particles, or at the least, six pairs of nucleons. Therefore, carbon should show much less charge exchange scattering, as it does. There is an extremely low yield of neutrons outside of the high energy peak in the case of deuterium as compared to the other three nuclei. Further discussion of the carbon, beryllium, and aluminum spectra can be found in the dissertation of Constantine Cassapakis submitted to the Graduate School of the University of New Mexico at Albuquerque³⁷.

B. SINGLE PION PRODUCTION IN THE $p(p,n)$ AND $d(p,n)$ REACTIONS

Figures 49 and 50 show the $d(p,n)$ and $p(p,n)$ spectra plotted together on a logarithmic scale. The striking feature is the similarity between the $d(p,n)$ and $p(p,n)$ spectra in the pion production region.

At our energies the dominant reaction for producing neutrons in proton-proton collisions is the $p(p,n)p\pi^+$ reaction.

The $p(p,n)$ spectra exhibit a strong peak reminiscent of the strong resonance in pion-nucleon elastic scattering known as the

Figure 48

Figure 49

Figure 50

N_{33}^* or the Δ . This resonance is present in the P_{33} partial wave, which is to say, the orbital angular momentum quantum number is one, the total angular momentum quantum number is $3/2$ and the total isotopic spin quantum number is $3/2$.

There have been previous experiments on the reaction $p+p \rightarrow n+p+\pi^+$ below 1 GeV. One type measured the pion spectrum at several angles⁶. Another type was carried out in a bubble chamber, where both of the final state charged particles were detected⁷. The bubble chamber experiments are kinematically complete but suffer from large statistical uncertainty. Nevertheless, calculations have shown that the reaction is dominated by peripheral processes in which the neutron is a spectator to the recoiling Δ^{++} . The Mandelstam model and the one-pion-exchange model are two of the important models to be considered. The Mandelstam model³⁸ is based on the following hypotheses³⁹:

1. Pion production takes place in a few angular momentum states of the nucleon-nucleon system.
2. The outgoing pion is in a resonant N_{33}^* state with one of the nucleons.
3. The production matrix elements are constant with respect to energy, apart from factors which take into account the pion-nucleon and nucleon-nucleon interactions.

4. The nucleon-nucleon interaction is felt in the final state after the production of the N_{33}^* resonance.

The Mandelstam model fits the lower energy data, below about 600 MeV, very well. However, above about 600 MeV, the Mandelstam model breaks down because more partial waves are involved and the constancy of the matrix elements with energy is overextended.

The one-pion-exchange (OPE) model with attendant use of form factors, a la Ferrari and Sellari⁴⁰, for example, has been useful at energies above about 1 GeV. The low energy limit of validity of this model seems to be due to the neglect of the final state nucleon-nucleon interaction.

Therefore, one is left with a gap in the theory between about 600 MeV and 1 GeV. Figure 51 shows a $p(p,n)x$ spectrum for the zero-degree neutron obtained by our group at LAMPF with a proton beam energy of 766 MeV. Accounting for energy loss in one-half of the liquid hydrogen neutron production target, the kinetic energy of the proton at interaction, T_p , is 764 MeV. The solid curve is a plot of the invariant mass, m_x , in the π^+p system as a function of the neutron momentum, p . The strong peak observed around a momentum of 970 MeV/c can be attributed to the N_{33}^* resonance, specifically to the Δ^{++} . The observed peak momentum and the FWHM of the spectrum correspond to an invariant mass in the π^+p system of 1215 MeV and a width of 95 MeV. The spectrum is fairly well fit by the theoretical curve shown by the dashed line in Figure 51.

Figure 51

This fit⁴¹ was generated by Gibbs, Gibson, and Stephenson of the T-5 medium energy theoretical physics group of the Los Alamos Scientific Laboratory. Their fit is based on the model of Goplen, et al.⁴² to study π^+ d absorption. The fit includes all second order graphs but only includes s- and p-wave pion-nucleon scattering amplitudes. The diagrams in which the pion does not rescatter are negligible. The dominant graph is the charge exchange graph presented in Figure 52.

Figure 52

Three adjustable parameters are used to generate the fit. They include a form factor parameter at the pion production vertex, a form factor parameter at the pion-nucleon scattering vertex, and an absorption radius at the pion production vertex. The absorption parameter defines a Gaussian shaped volume which is removed from integration over the nucleon-nucleon relative coordinate to mock up absorption effects at the pion production vertex. The dominance of the Δ^{++} resonance is felt by way of the pion-nucleon elastic scattering vertex.

Richard Slansky⁴³ of the T-8 group at LASL obtained a fit

nearly the same as that shown in Figure 51. He invoked one-pion-exchange using the dominant charge exchange graph already shown with a single parameter at the pion production vertex. He treated the pion-proton scattering vertex by using his own parameterization of the existing data on the π^+ -p elastic scattering total cross section. His calculation shows a peak slightly down-shifted in neutron momentum from the observed peak and a yield slightly lower than the Gibbs, et al. fit. Both fits show the dominance of the Δ^{++} resonance but both also show a lack of cross section in the region centered around 780 MeV/c in Figure 51. The 780 MeV/c value of neutron laboratory momentum corresponds to the kinematical region where the final state neutron and proton can have zero relative energy. In the 647 MeV p(p,n) spectra (Figures 31, 34, 43, and 49) the corresponding value of laboratory neutron momentum is 700 MeV/c. In the 800 MeV p(p,n) spectra (Figures 33, 35, 44, and 50) the value is 800 MeV/c. In all of the spectra there exists an enhancement region centered around these momentum values. These enhancements show the presence of the final state interactions between the neutron and proton. Gibbs, Gibson, and Stephenson have tried the inclusion of on-shell s-wave rescattering between the neutron and proton scaled by a parameter to reflect absorption. They obtained a preliminary fit⁴⁴ that was nearly correct in the neutron-proton final state interaction region but a little low and slightly down-shifted in the Δ^{++} peak region. Stephenson⁴⁴ points out that inclusive reactions, such as our

zero-degree neutron spectra, involve integrations over regions of phase space where the pion can resonate with both nucleons in the final state. Therefore, full three body treatment of the problem may be required. Also, treatment of the reaction as direct production of a Δ by the exchange of particles other than pions should be considered.

Nonetheless, the one pion exchange mechanism with form factors and simple n-p final state interaction gives a good representation of the 766 and 800 MeV p(p,n) spectra we obtained.

The 647 MeV p(p,n) spectrum is strikingly different from either the 766 or 800 MeV spectrum. It exhibits a very strong n-p final state interaction region centered around 700 MeV/c. It also shows a high yield up to momenta of about 860 MeV/c. The dominant charge exchange graph already shown peaks at about 800 MeV/c for an incident energy of about 650 MeV. Therefore, the broad, flat-topped peak observed in the 647 MeV p(p,n) spectrum is a combination of n-p final state interaction contributions and Δ^{++} resonant pion production contributions. By examining the 647 MeV p(p,n) center of mass plot (Figure 34) one can see that the low momentum portion (around $p_n = 415$ MeV/c) of the spectrum corresponds to the n-p final state interaction contribution (around $p_n = 700$ MeV/c) but at neutron momenta which are backward in the center of mass. Likewise, examination of the 800 MeV p(p,n) center of mass spectrum (Figure 35) shows that the low momentum neutrons (centered around $p_n = 440$ MeV/c) are the backward counterparts of the neutrons

centered around 800 MeV/c, the n-p final state interaction neutrons. Further work by the theoreticians in T-5 is proceeding with the goal of generating simultaneous fits to the 647, 766, and 800 MeV p(p,n) spectra, based on one-pion-exchange Δ^{++} production combined with n-p final state interaction.

The similarities between the d(p,n) and p(p,n) spectra suggest that similar mechanisms exist in both reactions. One might expect that the d(p,n) spectra result from p(p,n)p π^+ reactions with the neutron in the deuteron acting as a spectator and from the reactions n(p,n)n π^+ and n(p,n)p π^0 with the proton in the deuteron acting as a spectator. Let us investigate some isotopic spin arguments about nucleon-nucleon pion production to ascertain relative magnitudes possible for the various reactions.

With the assignments of one-half to the total isospin of the nucleon and one to the total isospin of the pion, one obtains the isospin states $|I, I_z\rangle$ for every nucleon and pion as follows:

$$\text{proton} = |p\rangle = |1/2, 1/2\rangle$$

$$\text{neutron} = |n\rangle = |1/2, -1/2\rangle$$

$$\pi^+ = |\pi^+\rangle = |1, 1\rangle$$

$$\pi^0 = |\pi^0\rangle = |1, 0\rangle$$

$$\pi^- = |\pi^-\rangle = |1, -1\rangle$$

The initial state of a proton and a neutron is given by:

$$|1(p), I_z(p); 1(n), I_z(n)\rangle = |1/2, 1/2; 1/2, -1/2\rangle$$

This state is given by the following combinations of $|I(NN), I_z(NN)\rangle$ isospin states for the two nucleons (NN):

$$|1/2, 1/2; 1/2, -1/2\} = \sqrt{1/2}|1, 0\} + \sqrt{1/2}|0, 0\}$$

The proton-proton initial state is given by:

$$|I(NN), I_z(NN)\} = |1, 1\}$$

The isospin state corresponding to a proton and a π^+ is formed by combining $|1/2, 1/2\}$ and $|1, 1\}$. $|p\pi^+\}$ is therefore simply $|3/2, 3/2\}$, which is the isospin state of the Δ^{++} . The isospin state of a proton and a π^0 is formed by combining $|1/2, 1/2\}$ and $|1, 0\}$. $|p\pi^0\}$ is therefore given by:

$$|p\pi^0\} = \sqrt{2/3}|3/2, 1/2\} - \sqrt{1/3}|1/2, 1/2\}$$

The isospin state of a neutron and a π^+ is formed by combining $|1/2, -1/2\}$ and $|1, 1\}$. $|n\pi^+\}$ is therefore given by:

$$|n\pi^+\} = \sqrt{1/3}|3/2, 1/2\} + \sqrt{2/3}|1/2, 1/2\}$$

The final isospin states in the $N(N, N)\pi$ reactions are formed as follows:

$$\begin{aligned} |np\pi^0\} &= \sqrt{2/3}|n\}|3/2, 1/2\} - \sqrt{1/3}|n\}|1/2, 1/2\} = \\ &(\sqrt{1/3}|1, 0\} + \sqrt{1/3}|2, 0\})_{I=3/2} \text{ for } |p\pi^0\} \\ &- (\sqrt{1/6}|1, 0\} + \sqrt{1/6}|0, 0\})_{I=1/2} \text{ for } |p\pi^0\} \end{aligned}$$

$$\begin{aligned} |nn\pi^+\} &= \sqrt{1/3}|n\}|3/2, 1/2\} + \sqrt{2/3}|n\}|1/2, 1/2\} = \\ &(\sqrt{1/6}|1, 0\} + \sqrt{1/6}|2, 0\})_{I=3/2} \text{ for } |n\pi^+\} \\ &+ (\sqrt{1/3}|1, 0\} + \sqrt{1/3}|0, 0\})_{I=1/2} \text{ for } |n\pi^+\} \end{aligned}$$

$$|np\pi^+\} = |n\}|3/2, 3/2\} = (\sqrt{3/4}|1, 1\} + \sqrt{1/4}|2, 1\})_{I=3/2} \text{ for } |p\pi^+\}$$

The initial isospin states are formed as follows:

$$\{pp\} = \{1,1\}$$

$$\{pn\} = \sqrt{1/2}\{1,0\} + \sqrt{1/2}\{0,0\}$$

If H is the Hamiltonian for the reaction, then we wish to compute the following transition matrix elements:

$$\{pp|H|np\pi^+\}, \{pn|H|np\pi^0\}, \text{ and } \{pn|H|nn\pi^+\}$$

Let us assume, as is the usual case, that the total isospin is conserved in the reactions and that the values of the matrix elements depend on the total isospin only and not on the particular projections of isospin involved. Also, let us state that the interactions proceed through the interaction of the undetected nucleon and the pion in the final state, where one neutron is detected in each reaction. This fact is borne out in the data thus far obtained by us and others as previously stated in the $p(p,n)$ discussion. The $N(N,N)N\pi$ reactions are dominated by $(N\pi)$ resonances and not by particular (NN) amplitudes. Therefore, in developing the final isospin states, the $I=3/2$ and $I=1/2$ parts of the interacting $(N\pi)$ system have been kept separated. With these assumptions there exist three independent amplitudes A_{ij} where i is the total isospin in the initial and final state, either 0 or 1, and j is twice the value of the isospin of the interacting $(N\pi)$ system, either 1 or 3. The matrix elements thus become:

$$\{pp|H|np\pi^+\} = \sqrt{3/4} A_{13}$$

$$\{pn|H|np\pi^0\} = \sqrt{1/6} A_{13} - \sqrt{1/12} A_{11} - \sqrt{1/12} A_{01}$$

$$\{pn|H|nn\pi^+\} = \sqrt{1/12} A_{13} + \sqrt{1/6} A_{11} + \sqrt{1/6} A_{01}$$

Let us compute

$$\sigma_{pp} = |\{p p | H | n p \pi^+\}|^2 = 3/4 |A_{13}|^2$$

Similarly, let us attempt to compute

$$\sigma_{pn} = |\{p n | H | n p \pi^0\}|^2 + |\{p n | H | n n \pi^+\}|^2$$

This computation involves several cross terms as well as the absolute squares of the three amplitudes. First, let us assume that the reactions proceed strictly through the formation of a Δ . This was a good assumption in the $p(p,n)p\pi^+$ case, but then only the $I = 3/2$ ($N\pi$) system can exist in this reaction. The Δ assumption forces:

$$A_{11} = A_{01} = 0$$

Therefore,

$$\sigma_{pn} = |\sqrt{1/6} A_{13}|^2 + |\sqrt{1/12} A_{13}|^2 = 1/6 |A_{13}|^2 + 1/12 |A_{13}|^2 = 1/4 |A_{13}|^2$$

Therefore,

$$\sigma_{pn} / \sigma_{pp} = 1/3$$

if only Δ production is involved. If one assumes that the $d(p,n)$ spectra are the result of Δ production in either a proton-neutron or a proton-proton collision with the extra nucleon as a spectator, then one would say that the cross section for the reaction $d(p,n)\Delta^{++}p_s$, where s denotes the spectator, was identical to the cross section for the $p(p,n)\Delta^{++}$ reaction. One would also say that the $d(p,n)\Delta^+n_s$ cross section was equal to the $n(p,n)\Delta^+$ cross section which is equal to the $n(p,n)p\pi^0$ cross section plus the

$n(p,n)n\pi^+$ cross section. One would then form the cross section ratios for $d(p,n)/p(p,n)$ as follows:

$$\begin{aligned} d(p,n)/p(p,n) &= [d(p,n)\Delta^{++}_{p_s} + d(p,n)\Delta^+_{n_s}]/p(p,n)\Delta^{++} = \\ &= [p(p,n)\Delta^{++} + n(p,n)\Delta^+]/p(p,n)\Delta^{++} = \\ &= (1 + 1/3)/1 = 1.33 \end{aligned}$$

The peak heights in mb/sr-MeV/c are 0.115 and 0.070 for the $p(p,n)$ spectra at 800 and 647 MeV, respectively. The corresponding values in the $d(p,n)$ spectra are 0.18 and 0.105, respectively. Therefore, $d(p,n)/p(p,n)$ ratios of Δ resonance peak heights are:

$$0.18/0.115 = 1.57 \text{ at } 800 \text{ MeV}$$

$$0.105/0.07 = 1.50 \text{ at } 647 \text{ MeV}$$

The ratio of the cross sections integrated over all momenta in the pion production region are 2.05 and 1.71 at 800 and 647 MeV, respectively. The larger integrated yield ratios are not surprising since the $d(p,n)$ spectra are broadened by the Fermi motion of the nucleons in the deuteron. This can be demonstrated by calculating an estimated cross section, σ_{est} , for each spectrum in mb/sr by multiplying the peak height by the FWHM of the peak. These results are shown in Table 19. From the results in Table 19 one would compute the estimated $d(p,n)/p(p,n)$ integrated ratios to be:

$$50.4/25.3 = 1.99 \text{ at } 800 \text{ MeV}$$

$$44.1/25.2 = 1.75 \text{ at } 647 \text{ MeV}$$

These ratios are very close to the measured ones. One feature which seems to be present is the relatively larger yield of neutrons at

the lower momenta in the 800 MeV d(p,n) spectrum. Nevertheless, the 1.33 prediction is small compared to the measured ratios of 1.50 and 1.57.

TABLE 19
PION PRODUCTION CROSS SECTIONS AND WIDTHS

<u>Reaction</u>	<u>Peak Cross Section (mb/sr-MeV/c)</u>	<u>FWHM (MeV/c)</u>	<u>Product σ_{est} (mb/sr)</u>	<u>Actual Integrated Cross Section (mb/sr)</u>
d(p,n) @ 800 MeV	0.18	280	50.4	67.1
p(p,n) @ 800 MeV	0.115	220	25.3	32.8
d(p,n) @ 647 MeV	0.105	420	44.1	50.1
p(p,n) @ 647 MeV	0.07	360	25.2	29.3

Therefore, let us allow the $I=1/2$ ($N\pi$) system to contribute, which is to say that A_{11} and A_{01} are not zero. Let us also assume that the reactions proceed strictly through the ($N\pi$) system interaction independent of the value of the total isospin for the ($NN\pi$) final state. Therefore, we set $A_{11} = A_{01}$. Only conservation of total isospin is retained. This statement says that the detected neutron is a spectator to the ($N\pi$) interaction, whether the ($N\pi$) object is a Δ ($I=3/2$) or an $I=1/2$ object. We therefore calculate σ_{np} to be:

$$\sigma_{np} = \left| \sqrt{1/6} A_{13} - 2/\sqrt{12} A_{11} \right|^2 + \left| \sqrt{1/12} A_{13} + 2/\sqrt{6} A_{11} \right|^2$$

$$\begin{aligned}
\sigma_{np} &= 1/6 |A_{13}|^2 + 4/12 |A_{11}|^2 - 4/\sqrt{72} \operatorname{Re} A_{13}^* A_{11} \\
&\quad + 1/12 |A_{13}|^2 + 4/6 |A_{11}|^2 + 4/\sqrt{72} \operatorname{Re} A_{13}^* A_{11} \\
&= 1/4 |A_{13}|^2 + |A_{11}|^2
\end{aligned}$$

where the cross terms cancel. We wish to show that the $d(p,n)/p(p,n)$ ratio can be given by $1 + \sigma_{pn}/\sigma_{pp}$. Since

$$\sigma_{pp} = 3/4 |A_{13}|^2$$

then

$$\sigma_{pn}/\sigma_{pp} = 1/3 + |A_{11}|^2/|A_{13}|^2$$

To obtain a value of 1.5 for $d(p,n)/p(p,n)$ we would require

$$|A_{11}|^2/|A_{13}|^2 = 0.17$$

Perhaps an $I=1/2$ resonance such as the P_{11} resonance at 1470 MeV could have a strength of 0.17 of the P_{33} , Δ , resonance at 1232 MeV. But the current values of phase shifts predict a ratio of about 0.01 near an invariant mass of 1230 MeV in the $(N\pi)$ system.

One might next say that final state interaction between the two final state nucleons is needed in nucleon-nucleon pion production. This was certainly shown by the $p(p,n)$ spectra. This would open the way for A_{11} being different from A_{01} . However, it is hard to see how the Δ resonance can be anything but dominant in a model which looks at the $(N\pi)$ system as the important one.

The qualitative similarity of shape between the $d(p,n)$ and $p(p,n)$ spectra led us to investigate the $d(p,n)$ pion production as being either from p - p or p - n interactions with a truly spectator nucleon in the deuteron. Perhaps the higher order contributions

of rescattering among the three nucleons and the pion in the final state make significant contributions. We must also not forget the possibility of exchange particles other than pions contributing.

We welcome the forthcoming calculations of pion production which must fit our $p(p,n)$ and $d(p,n)$ data if they are to be extended to include pion production in nuclei, a problem of great importance what with the advent of the meson factories around the world.

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A P P E N D I X A

PHOTOMULTIPLIER TUBE BASE AND TESTS

The twelve stage RCA 8575 photomultiplier tube base was chosen for its high gain and high rate capabilities. It was used on all of the scintillation counters in these experiments. With the help of Richard Hiebert of the electronics group E-4 of the Los Alamos Scientific Laboratory, we developed a base for use with the 8575 tube. A schematic diagram of the negative high voltage bleeder string circuit is shown in Figure 53. It features Zener diode voltage stabilization among dynodes Dy 1 through Dy 5 and from Dy 10 to ground potential. The Zener diodes maintain the final elements at fixed potential even though large currents in high rate situations can be drawn from the anode and from the linear signal pick-off on the eleventh dynode. There are ferrite beads surrounding the leads from the ninth through the twelfth dynodes. There are individual capacitors from the ninth through the twelfth dynodes attached independently to a heavy ground buss rod. The capacitors tend to stabilize the dynodes and provide the needed charge as pulses propagate along the photomultiplier. The ferrite beads together with the capacitors keep the dynode Dy 11 and anode signals very clean with almost no ringing. Back termination with a 50 Ω resistor on the anode BNC connector is used to prevent reflections. 50 Ω coaxial cables are used for the anode and dynode

RCA 8575 BLEEDER STRING

Figure 53

Dy 11 signals (even within the tube base).

The bleeder string shown in Figure 53 is a temperature compensated version of the original design which had Zener diodes from the cathode, K, to dynode Dy 3. Zener dynodes placed on the early stages insure good quantum efficiency. However, with a series of tests where we measured the gain of the photomultiplier versus the temperature of the air in the housing of the bleeder string, we found that the original design had a gain slump of about -3% per $^{\circ}\text{C}$. A calculation of the gain slump based on a voltage temperature coefficient for the Zener diodes equal to $+0.1\%$ per $^{\circ}\text{C}$ gave a value of -2.3% per $^{\circ}\text{C}$. The gain slump is due to the decrease of the voltage drop across the resistors in the bleeder string as the voltage of each Zener diode increases with temperature. We hold the high voltage fixed in the tests and calculations. The bleeder string in Figure 53 gave a calculated gain slump of -0.14% per $^{\circ}\text{C}$ and a measured slump of only -0.2% per $^{\circ}\text{C}$. The Figure 53 bleeder string was used on the left and right monitor and hydrogen monitor counters where we wished to maintain nearly constant pulse heights well above discriminator thresholds. The air temperature in Area B at LAMPF varies daily and seasonally.

A timing test with a light flasher that had a rise time no longer than 0.8 ns and a width no wider than 1.2 ns FWHM resulted in an anode pulse with a rise time of 3 ns and a width of 6 ns FWHM . The high voltage was -2400 volts and the anode pulse

height was 2 volts.

Gain stability tests in high rate situations were also performed. These showed that -2 to -6% gain slumps can result for anode currents above 100 microamperes. For typical one volt anode pulses into 50 Ω with widths of 7 ns FWHM, 100 microamperes corresponds to 7×10^5 pulses per second.

A high gain version of the bleeder string was used on the S0, S1, S2R, and S2L phototubes. It has resistors from the cathode to dynode Dy 10 but was otherwise identical to Figure 53. The resistors allowed the voltages of all but the last three stages to be raised just by adjusting the high voltage. The MWPC spectrometer scintillation counters serve mainly as trigger counters and are checked periodically to be sure that there are no discriminator cut-offs.

A magnetic shield assembly was also designed which included a cylindrical μ -metal shield of thickness 0.11 cm insulated from an outer mild steel cylinder 0.635 cm thick. The two-shield combination was tested to provide adequate shielding, interior fields ≤ 0.1 Gauss, in magnetic fields of up to 100 Gauss in any orientation with respect to the axis of the concentric shielding cylinders. This proved to be essential because some of the scintillation counters in the experimental set-up were placed in stray magnetic fields as high as 70 Gauss.

All phototubes in the system were equipped with the negative high voltage bases and magnetic shield assemblies.

A P P E N D I X B

MAGNETIC FIELD MEASUREMENTS ON THE 18D36 MAGNET

The magnetic field measurements incorporated three pieces of apparatus to measure the magnetic fields. These were a Skandatronics nuclear magnetic resonance (NMR) gaussmeter; a flip-coil $\int |B_y| dz$, set-up; and the LAMPF "rapid-mapper".

The magnet-mapping and the TEWA momentum analysis were both done in a magnet-centered coordinate system. The z-axis of the coordinate system was defined to be the geometric symmetry axis through the gap of the 18D36 magnet. The z-axis is therefore parallel to the 36-inch edges of the pole pieces of the magnet. The y-axis passes vertically from the center of the lower pole piece to the center of the upper pole piece. The x-axis is then mutually perpendicular to the y-axis and to the z-axis. The origin of the coordinate system is the geometric center of symmetry of the H-frame 18D36 dipole magnet.

The $\int |B_y| dz$ was measured with a flip-coil set-up consisting of a fibreglass rod 320.0 cm long with a groove cut along the surface of the cylinder on a line parallel to the axis of the cylinder, across a diameter at the end of the cylinder, back along the surface of the cylinder diametrically opposite the other groove, and across the second end of the rod. This groove was used to hold the coil of 25 turns of wire wound around from one end of the rod to the other.

The rod is held in an aluminum boom that can be oriented inside the gap of the magnet at any value of x and y, with the axis of the rod oriented parallel to the z-axis, symmetry axis of the magnet. The coil can be flipped (rotated about the axis of the cylindrical rod) through an angle of about 200° , the coil wires thus "cutting" through the lines of force of the magnetic field. The two leads of the coil are connected to an integrating digital volt meter which will integrate the induced EMF in the coil and present it in volt-seconds for each flip. The DVM will integrate only for 180° of the flip when the EMF has a constant polarity. As soon as the polarity changes the integration is stopped. One usually flips the coil back and forth and records the average integrated EMF of the two flips for each current and each position of the boom. The $\int |B_y| dz$ in kilogauss-cm is given by:

$$\frac{2 \cdot (10^3) (1.0006147) (\text{average integrated EMF in volt-sec})}{(\text{coil width in cm} = 1.9209 \text{ cm})}$$

where

$$1.0006147 = \frac{(\text{resistance of DVM} + \text{resistance of coil})}{(\text{resistance of DVM})}$$

The $\int |B_y| dz$ measurements shown as the circled dots in Figure 19 connected by the continuous curve are for the boom oriented along the symmetry (z) axis of the 18D36 magnet. The magnetization measurements, circled dots connected by the dashed curve in Figure 19, were made by placing the NMR probe near the center of symmetry inside the gap of the magnet (the origin of the xyz coordinate system of the magnet. The magnet measuring crew at LAMPF calibrated

the flip-coil (determining the coil width) and assigned an error of $\pm 0.05\%$. Since back and forth flips of the coil result in equal values for the integrated EMF to within about 0.01%, the flip coil results are probably accurate to better than 0.1%. In addition to the points measured in Figure 19, several others were measured for various orientations of the boom in the gap at all of the currents measured in Figure 19. Although the flip-coil is a good way to determine the bending power of a magnet, probably sufficient for magnets in a beamline transport system, it is insufficient for accurate use of a dipole magnet in a spectrometer like ours. Therefore, we took advantage of another facility of the magnet crew at LAMPF, the "rapid-mapper".

The rapid-mapper consists of a boom oriented in the magnet parallel to the symmetry axis. The boom houses a small cart which is stepped uniformly from one end of the boom to the other and back again to its starting position. The cart carries four coils of wire. Two have axes parallel to the y-axis (vertical) of the magnet. These two measure the principal (B_y) field of the magnet. There is also a coil parallel to the x-axis and one parallel to the z-axis. As the cart steps along the induced EMF in each coil is integrated, and recorded on magnetic tape. A minicomputer controls the operation of the rapid-mapper. It zeroes the integrators, signals the stepping motor to move the cart one step, and records the data from each coil on the magnetic tape. After the cart steps from one end to the other (116 steps of 2.549 cm each) and

then steps back to the starting end, the computer scans the boom in the x-direction by the specified amount of 2.54 cm. A stepping motor is located on each end of the boom. They operate simultaneously to scan the boom from x-position to neighboring x-position. One therefore maps the magnet in xz-planes ($y=\text{constant}$ planes) which are parallel to the pole faces of the magnet. The x-coordinate grid extends from -40.64 cm to +40.64 cm with uniform spacing of 2.54 cm. The z-coordinate grid extends from -147.85 cm to +147.85 cm with the uniform cart-stepping spacing of 2.549 cm. The integrator outputs for each position in the grid for each coil are normalized with the aid of an NMR gaussmeter, the same one already mentioned. One measures the central vertical field at the y-position for a given map with the NMR probe and thus establishes a coil constant for the two vertical coils equal to the ratio of the field to the integrated EMF value. The constants for the x and z coils are assigned from the vertical coil constants according to an established ratio among the various coils at the time of their installation. At that time they were each aligned in a known uniform field and their relative constants were determined. A computer program on the CDC 6600 computer is used to generate the magnetic field map for the measured xz-plane from the data on the magnetic tape. The data is smoothed by this program. Electronic drift for each back and forth scan of the cart is assumed to be linear and the data are corrected for this drift by the program. The five largest values of B_y are averaged by the program in determining the vertical

coil constants.

Examples of computer graphic output from the CDC 6600 program are shown in Figures 54 through 56. They all correspond to a map of the plane at $y=5.08$ cm, 2.54 cm beneath the upper pole face of the 18D36, for a current of 800 amperes. Plotted vertically, in each case, is the magnitude of the field component as a function of the position in the xz -plane. Figure 54 shows the B_y field component. There is a strong, nearly uniform, field corresponding to the region between the pole pieces of the magnet. There is also a fairly intense fringe field. Figure 55 shows the B_x component. The positive values of B_x are on one side of the pole pieces and the negative values on the other. Figure 56 shows the B_z component. It also shows positive values of B_z on one end of the pole pieces and negative values at the other end of the pole pieces. Both B_x and B_z are equal to zero in the region between the pole faces.

Such maps were obtained for planes with y -values of 5.08 cm, 2.54 cm, 0.0 cm, -2.54 cm, and -4.95 cm at settings of 200, 400, 600, and 800 amperes. The values of the three components of the magnetic field at each xyz grid point for a given current setting have been stored on magnetic tapes compatible with the TEWA analysis program for use in the momentum determination for each event.

A check on the validity of these field maps was made between $\int |B_y| dz$ as measured by the flip-coil and as calculated from the measurements of the rapid-mapper. The symmetry axis value for

1.0 G. MAGNET AT 500 AMPS AT θ OF 2.0 IN.

Figure 54

18036 MAGNET AT 800 AMPS AT Y OF 2.0 IN.

Figure 55

18036 MAGNET AT 800 AMPS AT Y OF 2.0 IN.

Figure 56

$\int |B_y| dz$ for the 600 ampere magnet current is 0.05% higher as measured by the rapid-mapper than by the flip-coil. This is excellent agreement for two independent methods of measurement. Taking into consideration the effects of the magnet stand which slightly modify the original magnetic field maps, the values of the magnetic field components are believed to be correct to within $\pm 0.7\%$.