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*Neutron Induced Pion Production:
on C, Al, Cu, and W at Neutron Energies
of 200–600 MeV*

Melynda Louise Brooks

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by

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ABSTRACT

Inclusive double differential neutron induced π^+ and π^- production cross sections were measured for four separate targets: C, Al, Cu and W. The neutron energy range was 200-600 MeV and the pion angular range was 25° - 125° . The charge, scattering angle and energy of the pions were measured using a magnetic spectrometer. The measurements are compared with intranuclear cascade (INC) calculations and a previous experiment that measured the sum of the π^+ and π^- cross sections. Our data agree with the measured data, but the INC calculations give only moderate agreement with the double differential cross sections as well as with angular distributions and total cross sections as a function of neutron energy. The ratio of $\pi^-:\pi^+$ was found to increase rapidly with decreasing neutron energy and the pion production was found to increase approximately as $A^{2/3}$ for the different targets.

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Chapter 1

Introduction

1.1 Motivations

The motivation for measuring neutron-induced pion production cross sections from various nuclei was to provide the LCD (Large Čerenkov Detector)[1] neutrino-electron scattering proposal with cross sections to calculate the background events from neutrons producing pions in water in a large Čerenkov detector. In the LCD proposal neutrinos produced at a proton beam stop travel through several meters of iron before entering a large water Čerenkov detector where the neutrinos scatter off electrons and the electrons produce Čerenkov light which is detected by an array of phototubes lining the detector (see figure 1.1). If the iron shielding is not thick enough then neutrons which are also produced at the beam stop will pass through the iron into the Čerenkov detector and produce pions which may or may not also produce Čerenkov light. Whether the pions produce light and whether they can be distinguished from the electrons depends upon the charge, energy, and scattering angle of the pion. For this reason, it is necessary to know the energy and angular distribution of pions of both charges produced over a wide neutron energy range

Figure 1.1: Proposed design of the Large Čerenkov Detector.

(from threshold production to the maximum neutron energy that escapes the iron shielding) if the background rate is to be calculated.

When the literature was searched for measurements of neutron-induced pion production it was found that there was little data. This means that not only were there few measured values for the cross sections, but the theorists that have provided calculations to produce cross sections have had very little experimental data to verify their results. So not only would a comprehensive measurement of pion production by neutrons produce data that is needed for calculating background events wherever neutrons are produced, but it would also provide the theorists with data to compare to their calculations and might indicate where the calculations need modification.

It is important to verify that the theoretical calculations for pion production in nuclei such as the intranuclear cascade (INC) calculations are correct because these are used in transport calculations to determine experimental backgrounds.

These background calculations are then used either to determine shielding and cuts needed to get rid of background events or are used to correct measured events for the background. In either case, incorrect calculations of the background could result in incorrect experimental results. The INC codes are also used to try to understand pion production in heavy ion collisions. Obviously, if the simpler interaction of nucleon- nucleus pion production is not correctly calculated, then the nucleus-nucleus production calculations will also be incorrect.

By studying the angular and energy distributions of pions produced in nucleon-nucleus interactions, it is possible that the pion production process itself will be better understood. The Fermi motion of the nucleons, the cross sections for nucleon and pion interactions with the nucleus including absorption and charge exchange, the contribution(s) of resonant states to the cross section and the interaction of these resonant states with the nucleus must all be properly taken into account if pion production is to be accurately predicted by theoretical models. If the models do not correctly predict pion production then it is possible that the discrepancies will point to what modifications must be made to the pion production mechanisms and thus provide a better understanding of pion production.

In order to try to fill the gap in neutron induced pion cross section measurements, we set a goal to measure double differential cross sections for π^- and π^+ produced at 25° - 125° by neutrons of energy 200 to 600 MeV on various targets (covering low Z to high Z).

1.2 Neutron Induced Pion Production

Although the experimental data available for proton induced pion production has grown to cover various proton energies, targets and pion angular ranges for pions of

both charges, the data available for neutron induced pion production is still limited (see table 1.1). The most comprehensive neutron data produced recently were taken

Table 1.1: Neutron induced pion production measurements to date. Included is the energy(ies) of the bombarding neutrons, the targets, the pion angles covered and which pions were detected.

Author	T_n (MeV)	target	θ_π	π measured
Oganesyan	600	Be C Al Cu Pb	16° - 123°	π^- and π^+
Büchle	300-580	C Cu Bi	54° - 164°	$\text{sum}(\pi^- + \pi^+)$
Kleinschmidt	470-590	p	0° - 20°	π^+
Dzhelepov	600	p	16° - 123°	π^- and π^+

by Büchle, et al.[2] at the Swiss Institute for Nuclear Physics (SIN) (currently the Paul Scherrer Institute) where the production of π^+ plus π^- (not separated) by 300 - 580 MeV neutrons on C, Cu and Bi over the angular range of 54° - 164° was measured. Since the charge of the pions was not determined, however, this data can not be used directly to calculate the pion background for an experiment such as LCD.

Oganesyan[3] also measured neutron induced pion cross sections for pions of both charge from neutrons at an energy of 600 MeV on Be, C, Al, Cu and Pb at angles 16° to 123° . These data, however, disagree with Büchle's data by about a factor of two.

Kleinschmidt, et al.[4] measured the cross section for $n+p \rightarrow \pi^+ + n + n$ for incident neutron energies of 470 MeV to 590 MeV and laboratory angles up to 20° . Dzhelepov[5] also measured the cross sections for pion production from n,p interactions at a neutron energy of 600 MeV and scattering angles 16° - 123° .

Chapter 2

Theory

2.1 Background

Within a few years of the discovery of the pion (1947) theorists began working on calculations that would produce pion production cross sections for nucleon-nucleon interactions. Of all the calculations that have been done since then I will list a few highlights. In 1951 Watson and Brueckner [6] used partial wave analysis to calculate the different spin state contributions to the nucleon-nucleon pion production reactions. They incorporated into their calculations the experimental results that indicated the pion was a pseudoscalar (i.e. has spin zero and negative intrinsic parity) and that pion production was dominated by particular spin states of the pion and nucleons. These results are still used today with spin conservation rules to determine what spin states should be included in pion production calculations. By 1956 Lindenbaum and Sternheimer[7] began work on their pion production model. To determine the spin state contributions of pion production they not only used the fact that the pion is a pseudoscalar, but they also assumed pion production takes place through formation of the $(\frac{3}{2}, \frac{3}{2})$ isobar (referred to as the $(\frac{3}{2}, \frac{3}{2})$ isobar or

resonance) which further limits the number of available spin states. Mandelstam[8] also incorporated the resonant pion-nucleon interaction into a phenomenological theory similar to Watson and Brueckner's and extended the theory to cover nucleon bombarding energies up to approximately 650 MeV. In the late 1960's and early 1970's pion production models such as the Sternheimer-Lindenbaum model were incorporated into intranuclear cascade calculations which could produce pion production cross sections for complex nuclei[9],[10]. This meant that interactions of the nucleons and the pions with the nuclei such as charge exchange and absorption had to be taken into account. Beder and Bendix[12] calculated the nucleon-nuclei cross sections by multiplying the free nucleon production (corrected for the Fermi motion of the nucleons) times the absorption expected for the incoming nucleon and outgoing pion. Sparrow, et al.[13] also calculated nucleon-nuclei cross sections by using a semiclassical model which took into account absorption as well as charge exchange of the incoming nucleon and outgoing pion.

During the 1980's much of the work has involved solving the coupled integral equations derived from the various Feynman diagrams which contribute to pion production[14],[15],[16]. Some of the typical Feynman diagrams that contribute to these calculations are shown in figure 2.1 [15]. The diagrams include a) the impulse approximation where the pion is emitted by a nucleon without any intermediate resonance state being formed, b) isobar currents where one of the nucleons forms an isobar state before decaying into a nucleon and a pion, c) pair currents and d) $(\rho\pi)$ -exchange currents where a ρ meson is exchanged between the nucleons and a pion is emitted.

There are several general statements that can be made about pion production from nucleon-nucleon and nucleon-nucleus interactions that are independent of any pion production model. Application of conservation of isospin, angular momentum,

Figure 2.1: Feynman diagrams for nucleon-nucleon pion production showing a) nucleon only impulse approximation, b) isobar currents, c) pair current and d) $(\rho\pi)$ -exchange current.

parity and the Pauli principle greatly reduces the number of angular momentum spin states accessible in pion production. The results of the application of these conservation laws are used both to determine what states should be included in cross section calculations as well as to relate measured cross sections to unknown cross sections by using Clebsch-Gordon coefficients. The ability to deduce one cross section from another is necessary for many nucleon-nucleus pion production calculations where nucleon-nucleon and pion-nucleon interaction cross sections are used as input to the calculation. These cross sections are needed because in nucleon-nucleus pion production calculations the interactions of the incoming nucleon, the intermediate nucleon state if there is one, and the outgoing pion with the nucleus all affect the production cross sections. Not only is the magnitude of the cross section for a particular pion charge state changed by these interactions, but the angular and energy distribution are also changed.

In addition to conservation rules determining which spin states dominate pion production, experimental results also indicate what states are dominant. Pion energy spectra measured for nucleon-nucleon pion production show that a large portion of the kinetic energy available goes to the pion, leaving the two nucleons with relatively small kinetic energy[6]. This implies a very large momentum transfer which in turn suggests that the reaction would take place at small impact parameters (distance of closest approach between the nucleons). If the range of the interaction of the nucleons is small and the outgoing energies are small this implies that low angular momentum states (S and P states) would dominate and specifically the S-state of the two nucleons would be dominant. The attractive force between the two nucleons is also much stronger for S-states than for P-states further indicating that the nucleons would tend to be in an S-state. The assumption of the S-state being dominant is supported by the experimentally observed energy spectrum of

π^+ 's from proton induced pion production which peaks at high energy indicating that little energy is left to the two nucleons. Because of these facts, most calculations assume only the nucleon S-state contributes to pion production except when the S-state is not accessible and then only the nucleon P-state is used.

The contribution of angular momentum states of the meson relative to the two nucleons is also restricted by conservation rules and assumptions derived from experimental results. Specifically it is assumed that only s and p states of the meson will contribute to the cross-section and it will be shown later that the meson p-state is in fact the dominant state.

Listed in table 2.1 are all the allowed transitions for Sp and Ss states as well as a few Pp and Ps transitions determined by applying the Pauli principle and conservation of angular momentum, isospin and parity[17]. (In this notation the first (capital) letter represents the angular momentum of the nucleons in the final state and the second (lowercase) letter represents the angular momentum of the pion relative to the two nucleons.) These transitions are listed by the isotopic spin of the initial and final states of the nucleons, e.g. σ_{10} represents initial isotopic spin of 1 and final isotopic spin of 0. The order of the spin states is determined by the intensity of the associated partial wave with Sp giving the highest contribution, then Ss, Pp and Ps. The relation of these transitions to the various pion production reactions is listed in table 2.2 where the coefficients of the σ 's were determined from Clebsch-Gordon coefficients.

If the allowed transitions in table 2.1 and associated cross sections are combined with experimental observations it can be shown that the meson p-state is the dominant spin state in pion production as mentioned above. Experimentally, the $(pp, \pi^0 pp)$ cross section is observed to be very small which indicates that σ_{11} would have to be very small if the meson s-state were dominant. But if this statement

Table 2.1: Analysis of pion production in terms of the angular momentum of the final two-nucleon system (S or P) and the pion (s or p). The last subscript on the final-state symbols gives the overall angular momentum.

isotopic reac- tion	Class	Initial State	Final State
σ_{10}	Sp	1S_0	3S_1p_0
		none	3S_1p_1
		1D_2	3S_1p_2
	Ss	3P_1	3S_1s_1
σ_{01}	Sp	3S_1	1S_0p_1
		or 3D_1	
	Ss	none	1S_0s_0
σ_{11}	Sp	none	1S_0p_1
	Ss	3P_0	1S_0s_0
	Pp	$^3P_{0,1}$	3P_0p_1
		$^3P_{0,1,2}$ or 3F_2	$^3P_1p_{0,1,2}$
		$^3P_{1,2}$ or $^3F_{2,3}$	$^3P_2p_{1,2,3}$
	Ps	1S_0	3P_0s_0
		none	3P_1s_1
		1D_2	3P_2s_2

were true then $\sigma(np, \pi^+ nn)$ and $\sigma(np, \pi^- pp)$ would also have to be small (since the Ss contribution comes from σ_{11}) which is in contradiction with experiment. If the meson is predominantly emitted in the p-state the only restriction from tables 2.1 and 2.2 would be that $\sigma(np, \pi^0 np)$ be equal to $\sigma(np, \pi^+ nn)$ plus $1/2 \sigma(pp, \pi^+ np)$ and this is consistent with experiment. These combined statements imply that the pion is emitted predominantly in the p-state.

The resonant meson-nucleon interaction that occurs for the state which has isotopic spin of $3/2$ and angular momentum (J) of $3/2$ (referred to as the $(\frac{3}{2}, \frac{3}{2})$ resonance or isobar) also influences the spin states formed in pion production. This resonance was first seen in pion-nucleus scattering experiments which showed a resonance peak at a pion bombarding energy of 195 MeV (see figure 2.2[18]). This

Figure 2.2: The π^+p total cross-section as a function of kinetic energy of the incident pion.

Table 2.2: Pion production cross sections in terms of the three isospin state cross sections. D = deuteron, N = nucleons

$\sigma(p + p \rightarrow \pi^+ + N)$	$= \sigma_{10} + \sigma_{11}$
$\sigma(p + p \rightarrow \pi^+ + D)$	$= \sigma_{10}(D)$
$\sigma(p + p \rightarrow \pi^0 + N)$	$= \sigma_{11}$
$\sigma(n + p \rightarrow \pi^\pm + N)$	$= \frac{1}{2}(\sigma_{11} + \sigma_{01})$
$\sigma(n + p \rightarrow \pi^0 + N)$	$= \frac{1}{2}(\sigma_{10} + \sigma_{01})$
$\sigma(n + p \rightarrow \pi^0 + D)$	$= \frac{1}{2}(\sigma_{10}(D))$
$\sigma(n + n \rightarrow \pi^- + N)$	$= \sigma_{10} + \sigma_{11}$
$\sigma(n + n \rightarrow \pi^- + D)$	$= \sigma_{10}(D)$

corresponds to the formation of a particle of mass 1232 MeV and the width of the peak gives a mass width of approximately 120 MeV. Over most of the energy range of interest to us in this experiment (threshold energies to 600 MeV) this resonance so strongly dominates the scattering cross section and, correspondingly, pion production (see section on Intranuclear Cascade Model) that many of the pion production models assume that it is the only channel through which pions are formed. This assumption is reasonable except near threshold where the pion and proton would both likely be in an s-state and the $(\frac{3}{2}, \frac{3}{2})$ state is no longer accessible. Note in table 2.1 that the only transitions that allow formation of the $(\frac{3}{2}, \frac{3}{2})$ isobar are the 1D_2 state for σ_{10} Sp transition and some of the Pp and Ps transitions for σ_{11} .

If production takes place mostly through formation of the $(\frac{3}{2}, \frac{3}{2})$ isobar and the Sp final spin state is the dominant final state, then σ_{10} will be much larger than σ_{01} or σ_{11} . The σ_{01} cross section, in fact, includes no production through the $(\frac{3}{2}, \frac{3}{2})$ channel since the isotopic spin 3/2 cannot combine with the isotopic spin 1/2 of the other nucleon to give a total isotopic spin of zero. These statements indicate that for neutrons incident on a nucleus where both neutrons and protons are present, the π^- production would be much larger than the π^+ production since only $\sigma(nn, \pi^- np)$ contains σ_{10} in its cross section.

The ratio of π^- to π^+ mesons produced in nucleon-nucleus collisions can be determined from Clebsch-Gordon coefficients if interactions with the nucleons before and after production are neglected. If it is assumed that pion production takes place only through the formation of an isobar, i.e. $NN \rightarrow N\Delta \rightarrow NN\pi$, then the various pion production cross sections are related to the cross section for isobar production ($NN \rightarrow N\Delta$) as follows:

$$d\sigma(pp \rightarrow \pi^+ np) = \frac{5}{6} d\sigma_{iso}$$

$$d\sigma(pp \rightarrow \pi^0 pp) = \frac{1}{6} d\sigma_{iso}$$

$$d\sigma(pp \rightarrow \pi^- NN) = 0$$

$$d\sigma(pn \rightarrow \pi^+ nn) = \frac{1}{12} d\sigma_{iso}$$

$$d\sigma(pn \rightarrow \pi^0 np) = \frac{1}{3} d\sigma_{iso}$$

$$d\sigma(pn \rightarrow \pi^- pp) = \frac{1}{12} d\sigma_{iso}$$

$$d\sigma(nn \rightarrow \pi^- np) = \frac{5}{6} d\sigma_{iso},$$

where $d\sigma_{iso}$ is the cross section for isobar formation.

These relationships give, for an $N=Z$ nucleus with neutron incident, a ratio of π^- to π^+ produced as

$$\frac{n_-}{n_+} = \frac{(\frac{5}{6})(N) + (\frac{1}{12})(Z)}{(\frac{1}{12})(Z)} = \frac{10N + Z}{Z} = 11. \quad (2.1)$$

Experimentally, however, the ratio is on the order of 5:1 and increases with increasing Z . The increase with Z is apparent from equation 2.1, e.g. for ^{208}Pb with $Z=82$ and $N=126$, the calculated ratio would be 16.4:1. Part of the explanation for the ratio being smaller than 11:1 or 16.4:1 comes from pion charge exchange. Since the π^- and π^0 production cross sections are about the same and the π^+ cross section is much less, the π^0 's charge exchanging into π^+ 's and π^- 's will increase

π^+ production by a larger fraction than it will increase π^- production. Charge exchange of the incoming neutron would also cause the ratio of $\pi^-:\pi^+$ to decrease since protons are more likely to produce a π^+ than a π^- . As the neutron and pion energies decrease, less of the nucleus is traversed and the nucleon and pion charge exchange interactions will also decrease. Therefore, it would be expected that the π^- to π^+ ratio would be closer to the free nucleon ratio for lower incident neutron energies.

Although the neutron induced and proton induced pion production cross sections in nuclei should be similar (e.g. conservation rules indicate that the cross section for proton induced π^+ from protons should be equivalent to neutron induced π^- production from neutrons) it is not expected that they should be the same even for $N=Z$ nuclei and these differences will likely change for different neutron and proton bombarding energies. The Coulomb interactions of the proton and the small mass difference between the neutron and the proton would both contribute to differences in the cross sections. Also the net force that the nucleus exerts on π^- 's will be opposite to the net force exerted on π^+ 's. For π^+ 's produced in the nuclei the protons will tend to increase the energy and for π^- 's the energy will tend to be reduced. This causes the (p,π^+) pion energy spectra and the (n,π^-) to no longer be the same.

For larger nuclei where N is greater than Z , the (n,π^-) cross section would be larger than the (p,π^+) cross section since the dominant π^- production from neutrons is from neutrons interacting with other neutrons in the nucleus and for π^+ production from protons the dominant contribution comes from pp interactions since these allow delta production through an Sp interaction.

2.2 Intranuclear Cascade Model

The intranuclear cascade model of Bertini[19] will be described here since it is used later in this dissertation to compare to our experimental results. In intranuclear cascade calculations the incident particle is tracked through the nucleus as it interacts with the nucleons via elastic and inelastic scattering, absorption, charge exchange, and particle production and any produced particles are tracked through and allowed to interact with the nucleons as well. The differential cross sections for particle production are calculated by counting the number of particles that exit the nucleus in particular energy and angular bins. The probabilities of the incident and produced particles interacting with other particles in the nucleus are determined 1) from measured cross sections of free nucleon-particle interactions, 2) are deduced from measured ones by application of isotopic spin laws or in a few cases, 3) are calculated using other models. Statistical sampling techniques are used to determine what interactions a particular particle undergoes as it travels through the nucleus. The angular distributions of the particles involved in an interaction are determined either from experimental results or an assumption such as isotropic distribution is made. The energy of a particle is calculated as it travels through the nucleus from relativistic kinematic equations.

For pion production, the Sternheimer-Lindenbaum isobar model [20] is used to determine pion energy and angular spectra for production from nucleon-nucleon interactions. In this model all production is assumed to take place through formation of the $(\frac{3}{2}, \frac{3}{2})$ isobar. A nucleon enters the nucleus and "collides" with another nucleon. As a result of this collision there is a transfer of kinetic energy to the internal structure of one (or both) of the nucleons and it is raised to the $(\frac{3}{2}, \frac{3}{2})$ isobar state. The isobar survives long enough for it to separate from the other nucleon and it then decays into a nucleon and a pion. The probability that an isobar will be formed in

a nucleon-nucleon interaction is derived from the π^+p total scattering cross section. Over the resonance region of the π^+p scattering cross section it is assumed that the probability of transferring an excitation energy in the range between E^* and $E^* + dE^*$ to a nucleon and forming an isobar state of mass m^* is proportional to $\sigma(\pi^+ + p)dE^*$ [21]. It is further assumed that the probability of forming the isobar state with excitation energy E^* is the same for a nucleon-nucleon interaction with E^* excitation energy available as it is for a pion-nucleon interaction. The probability of a particular isobar mass state being formed in a nucleon-nucleon interaction is then taken to be proportional to the product of the probability of isobar formation and the final two body phase space factor for a system of a nucleon and another particle with mass m^* for a given total energy E . The relation to the $\sigma(\pi^+ + p)$ cross section is given by:

$$\sigma(\pi^+ + p)dE^* = \text{const.} |M_{\text{isobar}}|^2 dQ \propto P(\text{isobar formation}) \quad (2.2)$$

where dQ represents the number of final states available in the energy range dE^* and $|M_{\text{isobar}}|$ is the matrix element associated with isobar production. The angular distribution of the isobars produced is assumed to be isotropic or a combination of isotropic and forward and backward distributions. The pion distribution is then assumed to be isotropic in the rest frame of the decaying isobar. Both single and double pion (or isobar) production is included in the model with the ratio of the two being determined by a fit to experimental results.

Conservation of isospin is assumed throughout the nucleon-nucleon interaction and the probability of formation of particular isospin states is determined by the appropriate Clebsch-Gordon coefficients. This in turn determines how many pions of each charge will be produced.

Although the lifetime of the isobar is long enough (0.73×10^{-23} s) for it to interact with nucleons before it decays, these interactions are ignored in the Bertini model

and the isobar is assumed to decay at the same place where it is formed. Other models[10] have, however, taken this interaction into account. These interactions include isobar capture where the result is two nucleons and no pions and isobar-nucleon exchange scattering where the final isobar may have different charge and/or mass from the initial isobar. If the isobar capture cross section is substantial this would mean that pion production would tend to be calculated too high if isobar interactions are neglected.

For the Bertini model the nucleus is represented by three concentric spheres each having a uniform neutron and proton density. The proton density in each region is chosen to be proportional to the average charge density of the nucleus in that region as determined by electron scattering data. The neutron density is taken as the product of the proton density times the ratio of neutrons to protons in the nucleus. Refraction and reflection of nucleons at the nuclear surfaces and at boundaries between regions of different potential energy are neglected.

The Fermi energy distribution of the nucleons in the nucleus was assumed to be the same as the zero-temperature distribution. That is, the nucleons have kinetic energies ranging from zero to the zero temperature Fermi energies calculated from the density of neutrons and protons in each region of the nucleus from:

$$\epsilon_F = \frac{h^2}{2M} * \left(\frac{3\rho}{\pi}\right)^{2/3} \quad (2.3)$$

The addition of Fermi energy to the interaction makes it possible to have pion production in a nucleus below the free nucleon production threshold. For free nucleon-nucleon interactions the threshold energy for π production is approximately 300 MeV (see figure 2.3 [11]). The addition of Fermi motion to the energy available in nucleon-nucleon interactions can reduce this threshold by 100 MeV or more. Note that the threshold for double pion production from free nucleons is above the

Figure 2.3: Cross sections for (a) single and (b) double pion production from free nucleon-nucleon interactions.

energies that we are looking at and even with the addition of Fermi motion for the nucleon-nucleus interactions the cross section is smaller by an order of magnitude or more than single pion production.

Single particle negative potentials were used to represent the nuclear forces between nucleons. The potential well depth for the protons was 7 MeV (which is the binding energy of the most loosely bound nucleon) greater than the zero-temperature Fermi energy of the protons in each region and the well depth for the neutrons was calculated in an analogous manner.

Chapter 3

Experimental Apparatus and Data Acquisition

3.1 Beam Description

This experiment took place at the Weapons Neutron Research (WNR) facility at the Clinton P. Anderson Meson Physics Facility (LAMPF) in Los Alamos, New Mexico. The 800 MeV proton beam from the linear accelerator is sent to target 4, a tungsten target from which a continuous energy neutron beam is produced. The beam line for this experiment was located at 30° relative to the production target where neutrons up to about 600 MeV were produced. All charged particles were removed from the beam by permanent magnets which were located at the upstream end of the beam line. A diagram of the facility can be seen in figure 3.1. We also had a one inch thick polyethelene absorber in the beam line before the permanent magnet to remove low energy neutrons from the beam which would only be a source of background for us.

Figure 3.1: The WNR facility.

Figure 3.2: The beam structure available at WNR.

The general beam structure available at WNR is indicated in figure 3.2. Macropulses of up to $500 \mu\text{s}$ in width were delivered to the target at a repetition rate of 20-60 Hz. Within the macropulses were micropulses of width 0.25 ns that had a variable spacing of greater than $1 \mu\text{s}$. The spacing between micropulses with a beam line path of 40 meters was chosen to make it possible to measure all neutron energies by time of flight with good resolution and without any wraparound of low energy neutrons. Dead time was reduced during data acquisition by reading out most electronics only between macropulses.

Circular collimators of 5.1, 6.35, and 7.62 cm diameter were located at 12.1, 18.1 and 34.3 meters from the production target, respectively. This gave a beam size of approximately 10 cm diameter at the experimental targets.

3.2 Beam Monitoring

It was necessary to know the absolute flux of neutrons delivered to our experiment to get absolute cross sections for the pion production. To assure ourselves that we were measuring the flux accurately three separate beam monitors were in place during data acquisition: a fission chamber which was the primary monitor, a sampling scintillator which was located upstream of the spectrometer and a monitor provided by the WNR facility which was located at 90° to the production target. The latter

Figure 3.3: Schematic of the fission chamber.

two monitors were used to monitor the stability of the fission chamber during data taking.

A schematic of the fission chamber is shown in figure 3.3. The fission foil was a tantalum foil, 11 mils thick and 15.25 cm in diameter, coated with 0.34 mg/cm^2 of uranium that was 91.1 % ^{235}U . A second foil of tantalum without any uranium was contained in the chamber to measure the amount of events caused by the tantalum alone. We found the tantalum to give no contribution to the fission chamber signal that was used for monitoring the beam. The chamber was filled with the same gas that was used for the multiwire drift chambers which was approximately 65% Ar, 35% isobutane and 0.5% isopropyl alcohol. The gas was ionized by fission fragments that were produced when the neutron beam interacted with the ^{235}U as well as by alpha particles which were produced by the natural decay of ^{235}U to ^{231}Th . The resulting electrons were collected by a collector plate biased at 300 V.

Figure 3.4: Analog spectrum from the fission foil showing alpha and fission events.

The alpha particle events were separated from the fission events by recording the pulse height from the fission foil which was typically larger for the more energetic fission fragments than for the alpha particles. A typical spectrum from the fission foil can be seen in figure 3.4.

The fission chamber was calibrated by measuring elastically scattered protons from a CH_2 target at 60° and using Keeler's[22] n-p elastic cross section measurements to get the neutron flux as a function of neutron energy. To separate the n-p elastic events from the n-carbon events the measured spectrum of (n,p) scattered protons from a carbon target was subtracted from the CH_2 data. The fission events and the neutron flux were then used to get the number of fission events per neutron as a function of neutron energy.

The sampling scintillator was a 15 x 20 cm lucite paddle with 0.1 cm diameter pieces of scintillator imbedded in the lucite in a 1.0 x 1.0 cm grid and was placed

directly in the beam line. The signal from this scintillator was sent to a scaler to monitor the neutron flux. The WNR monitor was a highly collimated scintillator telescope which was also recorded with the scaler events. Both of these monitors indicated that the fission chamber was working consistently throughout data taking.

3.3 Spectrometer

The layout of the spectrometer is shown in figure 3.5. Three separate targets were set up in the spectrometer during data taking to allow simultaneous measurement of pion differential cross sections from 25° - 125° . Pions were accepted by the spectrometer for scattering angles $(25^\circ, 45^\circ)$ from target one, $(45^\circ, 75^\circ)$ from target two, $(65^\circ, 90^\circ)$ from target three when the magnet polarity was set so that the bend angle through the magnet was negative and $(105^\circ, 125^\circ)$ when the magnet was set to the opposite polarity. Five separate target types were measured: CH_2 , C, Al, Cu and W. The targets varied in thickness from 0.3 g/cm^2 to 1.2 g/cm^2 . The magnet was used to separate different particle types and to measure particle momenta. It was set at $\pm 5 \text{ kG}$ to measure π^- and π^+ cross sections and was set at $+7 \text{ kG}$ to measure the n-p elastic scattering cross section.

Six multiwire delay line drift chambers were used to track particles through the magnet to allow measurement of the momentum of the particles as well as the scattering angle and path length through the spectrometer. Chambers 1, 2, 5 and 6 tracked particles from target #1 and chambers 3, 4, 5 and 6 tracked particles from both targets #2 and #3. These chambers are described in more detail in the following section.

Scintillators were located next to each pair of drift chambers and their purposes were four-fold. The flight times S1 to S3 and S2 to S3 were used along with the

Figure 3.5: Layout of the spectrometer used for this experiment.

measured particle momentum to give particle identification. The neutron time of flight from the production target to the experimental targets was used to get the neutron energy. This time of flight was obtained by measuring the time from the neutron production target to S1 or S2 and subtracting the time the produced particle traveled from experimental target to scintillator. The three scintillators were also needed to give start times for the time signals from the delay lines on the drift chambers. Energy loss information from the scintillators was also available for particle identification and this was used along with the time of flight vs. momentum spectra to separate π^+ particles from protons.

The close proximity of targets two and three to chamber three made it necessary to place a 0.01" thick sheet of aluminum on the front of chamber three to reduce the count rate from low energy particles which were overwhelming the detector electronics without the absorber.

3.3.1 Multi-Wire Drift Chambers

The multi-wire delay line drift chambers used in this experiment were designed by Group MP-10 at Los Alamos[23]. The design of a typical wire plane can be seen in figure 3.6. Three pairs of chambers of dimensions 30.5 x 30.5 cm, 71.1 x 22.9 cm and 88.9 x 30.5 cm were used for this experiment. These dimensions correspond to chambers 1 and 2, 3 and 4, and 5 and 6 respectively.

Each plane contained 20 μm anode wires that were spaced 0.81 cm apart with 75 μm cathode wires in between, all mounted on a 0.48 cm thick aluminum frame. All anode wires were connected to a delay line that was biased at approximately +2000 V. This delay line provided two output signals (one at each end) that were used to determine the wire position nearest to an event as well as the distance from the wire. Every other cathode wire was bussed together to give two additional

Figure 3.6: One wire plane from a multiwire drift chamber.

signals which were used to determine the side of the wire the particle was on when it passed through the detector. Wire planes were separated by ground planes of $6.3 \mu\text{m}$ thick aluminized mylar that was mounted on 0.48 cm thick aluminum frames.

One complete wire chamber contained one y wire plane, one x plane, three ground planes spaced between wire planes, one spacer plane and two frames that had 3 mil mylar windows to protect the ground planes and wire planes from punctures. The chambers were filled with a gas mixture of approximately 65% argon, 35% isobutane and 0.5% isopropyl alcohol.

When a charged particle passes through the chamber the gas is ionized and the electrons drift to the anode wires and the ions drift to the cathode wires. The electric field between the wires causes an avalanche of electrons to be produced near the anode wire which gives a large signal from the anode. This avalanche occurs on the side of the anode wire that the particle passed by and induces a large signal

on the cathode wire that is to the same side. The induced cathode signal is used to determine which side of the anode wire that the particle passed. The induced signal on the anode wire travels to each end of the delay line providing two time signals. If the start time in a TDC is set by an adjacent scintillator then the two signals produced will be

$$t_1 = (wire\#) * t_w + t_d + const. \quad (3.1)$$

$$t_2 = t_l - (wire\#) * t_w + t_d + const. \quad (3.2)$$

where t_w is the time between anode wires on the delay line, t_d is the time it took for the electrons to drift to the anode wire, t_l is the time it takes for a signal to travel the full length of the delay line and $const.$ is the travel time through cabling and electronics. It can be seen from these two equations that the difference of the two times will provide a number that is proportional to the wire number and the sum will provide a time that is proportional to the drift time. This drift time can be used to get a drift distance as described in the calibration section. Typical spectra of the time difference $t_1 - t_2$ (wire position), the time sum (drift time), and the drift position can be seen in figure 3.7. The spacing between the wires comes from the time delay induced by the delay line. The nonlinearity of the drift time occurs because the drift velocity is higher near the anode wires and can be seen clearly in the figure.

The induced signal from each set of cathode wires is also recorded for each event. These signals are sent through a difference amplifier which gives a positive pulse height when a signal appears on one set of cathode wires and a negative signal for the other set. This, combined with the wire number, tells which side of the wire the particle passed. A typical spectrum of this pulse height difference with a positive

Figure 3.7: Typical spectra of the wire position, cathode pulse height difference, drift time and drift position from a wire chamber.

offset is shown in figure 3.7 where the cut between the two sets of cathode wires is at about channel 850.

The time between anode wires on the delay line was about 1.5 ns and the drift time spectrum range was about 80 ns. The chamber resolution was approximately 100 μm . However, the long drift times combined with long delay lines (up to 225 ns of delay line) considerably restricted the count rate that the chambers could handle and still discriminate between separate events. This did cause a problem for chamber three where multiple events were not negligible for the thicker targets.

3.4 Electronics and Data Acquisition

There were four trigger events during data acquisition. Event 5 was a fission chamber event which was triggered by a coincidence between the fission chamber and the pickoff pulse at the neutron production target. Event 6 was either a coincidence between scintillators S1 and S3 or between S2 and S3 and represented a particle traveling through the spectrometer. (This coincidence was also gated by a signal from the neutron production target which eliminated neutrons below approximately 100 MeV in energy and most of the gamma flash from the trigger. The gamma flash is the burst of gamma rays that is also produced at the production target when the protons interact with the tungsten and these precede the neutrons in the beam line.) Event 6 gated the FERA (Fast Encode and Readout ADC) system which automatically stored the event data in a CAMAC Triple Port Fast Memory Unit. Event 4 occurred at the end of a macropulse and was used to trigger readout of the Triple Port Fast Memory Unit. Event 8 triggered readout of scalers every 100 macropulses. Logic diagrams for events 4-8 can be seen in figures 3.8 , 3.9 , 3.10.

Figure 3.8: Logic diagram for event 4.

Figure 3.9: Logic diagram for event 5.

Figure 3.10: Logic diagram for event 6.

Both events 5 and 6 required a RUN to be in progress, the beam to be on (which prevented event 5 alpha events from piling up) and were vetoed with a busy signal which contained the computer BUSY and allowed time for digitization and readout of the electronics. Event 8 required a RUN to be in progress and the beam to be on.

When event 5 was triggered the fission chamber pulse height and the neutron time of flight to the chamber (input from a TAC (Time-to-Amplitude Converter)) were read from a standard CAMAC ADC. The pulse height of the fission chamber was used to separate alpha events coming from the uranium decay in the chamber from the fission events induced by the neutron beam. The time of flight of the neutrons was recorded so that a cross section for neutron induced fission could be calculated for various neutron energies using the n-p elastic measurements to give the neutron flux.

Figure 3.11: Schematic of FERA electronics.

Event 4 caused the readout of the memory module which contained event 6 data. Event 6 data consisted of time signals from: 1) the five scintillators (S1, S2, S3L, S3M, and S3R), 2) the pickoff pulse at the neutron production target and 3) the ends of the delay lines on all the wire chambers, and analog signals from: 1) the five scintillators and 2) the left-right signals obtained from the cathode wires in the wire chambers.

Fast Encoding and Readout ADC's (FERA's) and Time to FERA Converters (TFC's) were used for processing time and analog signals from the wire chambers and scintillators when an event occurred in the spectrometer. After digitization this data went directly from the FERA's and TFC's to a FERA System Driver which transferred the data to a CAMAC Triple Port Fast Memory Unit where the data was stored until the end of a macropulse when readout was triggered. A diagram of the FERA interconnections can be seen in figure 3.11. The fission and scaler signals were read from CAMAC modules immediately after an event was triggered since the event rates for these were much lower, so their computer busy time did not affect live time significantly.

The FERA system was chosen for our spectrometer event triggers for two reasons. The FERA has a conversion time of only $4.8 \mu\text{sec}$ compared to $60 \mu\text{sec}$ for the LeCroy 2249A ADC that we originally planned to use in the experiment. This fast conversion time kept our electronics dead time to less than 5%. The memory module then kept our computer dead time to a minimum by making it possible to read events into the computer and process them only in between beam macropulses.

Two LAMPF modules, the trigger module and the MBD (Micro-programmable Branch Driver), served as interface between the computer and the CAMAC crates which contained the FERA electronics, the fission event electronics and the scalars. The trigger module received several inputs corresponding to the different event types 4-8. When a particular event was triggered the MBD was notified and it carried out a series of pre-programmed CAMAC commands including readout of appropriate CAMAC modules. The signals used for the trigger module were the same signals that were used for gates for the event electronics with enough delay added to allow time for the electronics to process their data. After a certain amount of buffering, the data read from the electronics were then sent to the computer where analysis took place. In our case, the data acquisition/analysis code used was a version of LAMPF's "Q" system.

The "Q" system was used to read the CAMAC data into the computer, process the data from the separate trigger module events and put any necessary cuts on the data before writing it to tape. It also included a histogramming package which allowed monitoring of all of the detector signals while data taking was in process. In order to reduce the number of tapes written during data acquisition, event 6 data were processed and a mass cut was put on the data before writing it to tape. The mass was calculated (as described later) from the time of flight of particles traveling through the scintillator and the momentum calculated from the track of

the particles through the magnet. All events that produced a measured mass of less than about 600 MeV and one out of every 10 events above 600 MeV were then written to tape. This caused approximately half of the proton events and 9/10 of deuteron events to be discarded when pion cross section data were being taken. This cut was taken out for reference runs that were run in between target changes and also for the collection of the n-p elastic data that was used to calibrate the fission chamber.

The "Q" system was also used for all analysis that took place after the data were collected.

3.5 Calibrations

In addition to the collection of data for calculating the pion cross sections and calibrating the fission chamber, several special runs were needed so that various detector spectra could be calibrated. Many of the calibrations needed were associated with measuring the time of flight of particles through the spectrometer. The zero times for S1 to S3 and S2 to S3 were obtained by placing two scintillators next to each other, illuminating with a ^{90}Sr source at the base of the scintillator material, and calling that zero time in the TFC spectrum.

Since several of the scintillators were rather large (S2 was 71 cm long) with only one photomultiplier tube for signal readout and the typical time of flight for pions through the spectrometer was only 5-10 ns it was important to correct the measured time of flight through the spectrometer for the transit time of the signal in the scintillators. The transit velocity in the scintillators was measured by placing a ^{90}Sr collimated source at either end of a scintillator and looking at the time difference between the two spectra from the TFC. The time of flight through the

spectrometer could then be corrected for the transit time in the scintillators by projecting from the chambers to the scintillators to see where the particle passed through the scintillator and calculating the transit time from the measured velocity.

Calibration runs were collected with the beam pickoff signal removed from the event 6 coincidence so that the gamma flash which preceeded the neutrons in the beam line could be used to calculate offsets in the neutron time of flight spectra. This worked for both the pickoff to S1 and S2 spectra as well as the fission time of flight spectrum since there were enough photo-fission events to produce a small peak. The gains of all TFC channels were measured using a pulser and delay line.

The drift chambers were calibrated using available software from group MP-10 at LAMPF. Two calibrations were required for each wire plane in the chambers: 1)the wire position as a function of the difference between the two ends of the delay line (t_d) and 2)the drift distance as a function of the sum of the two ends of the delay line (t_s).

The wire position is a linear function of t_d except for a small quadratic term which helps account for dispersion of the signal on the delay line. The coefficients of t_d^2 are determined by a chi-squared minimization of $\sum_{i=1}^n (x_i - k_i)^2$ where x_i is the calculated wire position and $k_i = (\text{wire number}) * (\text{wire spacing})$.

The drift time was calibrated by using a drift spectrum where the chamber was evenly illuminated (over drift space). The distribution of particles over drift time is

$$\frac{dN}{dt} = \frac{dN}{ds} \times \frac{ds}{dt} = c \times \frac{ds}{dt} \quad (3.3)$$

where s is a spatial coordinate and dN/ds is a constant since even illumination was assumed. Integration of both sides gives

$$s(t) = \frac{1}{c} \int_0^t \frac{dN}{dt} dt. \quad (3.4)$$

A table of $s(t)$ vs. t is obtained by integrating the histogram from even illumi-

Figure 3.12: Drift distance for a large angle event passing through a wire chamber.

nation in steps of t . The normalization can be determined from the maximum drift distance being set equal to the integral of the whole histogram.

The drift distances in our chambers had to be modified slightly from the above calculation because many particles passed through the drift chambers at angles far from normal to the wire planes. This meant that the shortest drift distance to a wire was no longer in the plane of the wires, so conversely the drift time did not always represent the distance of the particle from the wire when it was in the plane of the wires (see figure 3.12). This meant the measured t_d had to be corrected for the angle that the particle passed through the chamber in order to get the true distance s . This was done by calibrating the chambers with particles that were approximately normal to the chambers, calculating the distance that corresponded to the measured t_d and then dividing by the sine of the incoming angle to get s . The calibration was accomplished by using only the y (vertical) planes for calibration (the angle through the y planes was typically $\pm 5^\circ$ to the normal).

The precise geometry of the spectrometer was needed as input to both the data analysis code and the Monte Carlo code that was used for determining acceptances of the spectrometer. The positions of the drift chambers relative to the magnet and beam axis were surveyed and put into the analysis code and then several software checks were done to confirm that the geometry was correct. Most of these checks

were done while the magnet was off. The bend angle $\{(\text{angle through chambers 5 and 6}) - (\text{angle through front chambers})\}$ of particles traveling through the spectrometer was measured while the magnet was off which indicated whether the chambers were aligned properly in the software as well as giving us an indication of the resolution of the chambers by measuring the width of the bend angle spectrum. The measurement of the bend angle indicated an angular resolution of approximately 0.5° in the bend angle for particles from all targets. The alignment of the chambers relative to each other was also checked by projecting each particle's trajectory from one pair of chambers to another pair and comparing this position with the measured position of the particle. All projections indicated that the software alignment was within the measurement precision of the survey (± 0.5 mm).

The path length of the neutrons from their production target to the experimental targets was needed to calculate the energy of the neutrons from their time of flight. This path was measured[24] by putting a four inch thick carbon target in the beam line approximately seven meters from the production target and measuring the time of flight of neutrons from the production target to a specific spot in the detector house where a scintillator was located. The spectrum that resulted is shown in figure 3.13. The three neutron absorption edges at 4937.07, 5365.21 and 6297.07 keV and the gamma flash were then used to fit the two unknowns—the path length to the scintillator and the offset in the time spectrum. This measurement gave a flight path of 37.24 m to the inside of our detector shed.

Figure 3.13: Neutron time of flight spectrum from neutrons passing through a six inch block of carbon.

Chapter 4

Data Analysis

4.1 Monte Carlo

A Monte Carlo program was written for particles traveling through the spectrometer to supply data needed for the analysis of the pion cross section data and the n-p elastic scattering data. The data needed for the analyses were acceptances of the spectrometer for pions and protons of different energy and angular bins, the effect that the decay of pions to muons had on the measured pion spectrum, and data used to get equations to calculate the momentum and the flight path of the particles from the chamber positions. The Monte Carlo was also used to look at the effect of putting various cuts on the data during analysis.

There were several measured quantities that were used as input to the Monte Carlo code. A map of the magnetic field of our magnet was provided by Group MP-8 of Los Alamos on a 2" x 2" x 1" grid, extending 52" in the x direction, 7.5" in y and 120" in z. (Here z is the beam direction and y is the direction of the B-field as shown in figure 3.5.) These data were taken for one magnet setting that gave a magnetic field value of 5.000 kG half way between pole tips. The surveyed positions

Figure 4.1: Beam profile in x and y obtained from chamber projections.

and extents of the wire chambers and scintillators relative to the magnet were also needed for input to the code. The tracks of particles passing through the forward chambers were projected to the three separate targets to give a beam profile which was needed for calculating accurate acceptances of the spectrometer. An example of this spectrum in x and y is shown in figure 4.1. The dispersion from the forward targets was small enough that the same beam profile could be used for all three targets.

As the particles were stepped through the spectrometer, the tracks of the particles were obtained by using a fourth-order Runge-Kutta integrator to solve the double differential equations

$$X'' = (Q/MASS/GAMMA) * (v_y * B_z - v_z * B_y) \quad (4.1)$$

$$Y'' = (Q/MASS/GAMMA) * (v_z * B_x - v_x * B_z) \quad (4.2)$$

$$Z'' = (Q, MASS/GAMMA) * (v_x * B_y - v_y * B_x) \quad (4.3)$$

where Q is the charge of the particle, MASS is the mass of the particle, GAMMA is the relativistic γ , v is the velocity of the particle and B is the magnetic field which it is passing through.

The energy loss as well as the multiple scattering of the particles in the air and the spectrometer detectors and targets were included in the code. The decay of the pion to a muon was also included in the code and all muons as well as pions were tracked through the spectrometer. The resolution of the wire chambers which was measured to be approximately 100 μm was included in the Monte Carlo when the acceptances of the spectrometer were calculated.

Since the length of the flight path through the spectrometer typically allowed 20% - 30% of the pions to decay to muons before they reached S3 the separation of pions from muons was looked at using the Monte Carlo. The original intent for the pion analysis was to separate the muons from the pions as well as was possible and then correct the pion cross section measured for the known amount of pions that had decayed to muons. The first idea was to separate these two particles by measuring the bend of the particle relative to the x-z plane. However, the fringe fields of the magnet contained fairly large components in the x-z plane which caused at least as much as and usually more bend than a typical muon decay would. It was also not possible to separate any significant number of muons by comparing the measured momentum and track through the spectrometer with the track that the Monte Carlo would predict. Any added bend from a pion decaying to a muon just looked like a pion with larger or smaller momentum than the original pion. The particle identification spectrum did not have sufficient resolution to allow for separation of the two particles. Since we could not find any way to efficiently separate the pions from the muons, all muons were accepted into the analysis and

Figure 4.2: A typical pion momentum spectrum before and after correction for pion decay.

the Monte Carlo was used to correct the pion spectrum for the changes the pion decay caused. This was done by counting the number of pions in a particular angular bin that started out in one momentum bin at the beginning of the Monte Carlo and ended out in another momentum bin when the momentum was calculated using the same chamber quantities that were used in the data analysis. By doing this for all momentum bins that were used in the data analysis, a set of linear equations was formed relating the measured momentum spectrum to the spectrum of pions that originated at the targets. A matrix inversion was then done to get a production spectrum from a measured pion spectrum. Typically these corrections to the spectra were less than 10% for all momentum bins since as many pions were likely to be lost from a bin as were gained from adjacent pion momentum bins. An example of this correction can be seen in figure 4.2. Since the magnitude of the

momentum corrections was found to be approximately the same as the errors in the corrections, the momenta spectra were left uncorrected.

Since the magnetic field that each particle passed through was different it was necessary to get a fit for the momentum calculation that depended on where the particle passed through the magnet. A separate momentum fit was done for particles from the three separate targets since the paths through the magnet were very different for the different targets. This made it possible to make more accurate momentum calculations over the entire angular range of the cross section measurements. To get a given fit the Monte Carlo code was run for particles originating from one of the targets with energy and angular ranges corresponding to the ranges that were to be covered by the cross section measurements. For each particle the starting momentum, the positions at each of the chambers that it passed through, and various quantities calculated using the chamber positions (including the bend angle, etc.) were recorded in a data file. A minimization code was then run that fit the momentum to the variables chosen from the data file. It was possible to get a momentum fit for each target that used four variables calculated from the chamber positions with an rms error of 1%-5%.

This momentum fit was run separately for pions and protons and was run for a magnet setting of +5 kG and -5 kG for the pions. The two magnet settings were run because particles with a scattering angle less than 90° coming from targets 2 and 3 were accepted by the spectrometer if their bend angle was less than zero. This corresponds to a negative magnet setting for π^- and a positive setting for π^+ . Particles with a scattering angle larger than 90° , coming largely from target 3, were accepted by the spectrometer if their bend angle was greater than zero. This meant that there were actually four separate momentum fits: one for targets 1 and 2 and two for target 3.

The cut that was used for particle identification was a cut on the mass of the particle that was calculated from the momentum, the time of flight through the spectrometer, and the path length of the particle through the spectrometer. To get the path length of the particle a fit similar to the momentum fit was done for the three separate targets and two separate magnet settings that gave the path length as a function of the particle track through the spectrometer. This fit also gave an rms error of less than 5%.

The acceptance calculations of the spectrometer were fairly straightforward. For each momentum and angular bin particles were originated from the target and the number of particles that hit all four chambers and both scintillators along its track were counted. The mass of the particle was calculated in the same way that it was in the data analysis code and if it did not pass the mass cut that was used in the analysis it was not counted. The angular bin was increased by a few degrees beyond the analysis bin, and only the particles that fell within the analysis bin were counted. This was done to include particles that scattered into or out of the bin. The acceptance was calculated to be the number of particles that passed through all the spectrometer detectors and passed the analysis tests divided by the number of particles that originated at the target in the momentum and angular bin being measured.

4.2 Particle Identification

As was mentioned previously, most of the pions were separated from the protons by calculating the mass of the particle from the time of flight and path length through the spectrometer and the calculated momentum. A typical spectrum of the corrected time of flight (time of flight divided by the path length) vs. momentum

Figure 4.3: (a) Time of flight corrected for path length through the spectrometer vs. momentum and (b) the mass of the particle calculated from (a).

and the resulting mass spectrum are shown in figure 4.3. The cut used on the mass spectrum for pions was (0,300) MeV. A cut was also placed on the time of flight vs. momentum spectrum across the lower left hand corner to remove the small amount of electrons that were accepted by the spectrometer. An additional cut was used to separate the π^- particles from the π^+ as well as the protons by putting a cut on the bend angle of the particle through the spectrometer. A typical bend angle spectrum for a π^- run and the mass spectrum with a bend angle cut can be seen in figure 4.4. This made the π^- cut from the protons especially clean.

Energy loss vs. momentum spectra from the scintillators were also used to separate the π^+ from the protons. These extra cuts were necessary because the bend angle did not separate particles of the same sign and the proton to π^+ ratio was larger by a factor of five to ten than the proton to π^- ratio which meant

Figure 4.4: A spectrum of the bend angle of particles passing through the spectrometer and the π^- mass spectrum after the bend cut has been applied.

Figure 4.5: The mass spectrum for targets 2 and 3 for π^+ data showing the proton background before dE/dx cuts are implemented. Note: Most of the upper end of the proton mass peak has been removed by the data cut that was applied during data taking.

that the tail of the proton mass peak produced a significant number of background events in the pion mass peak. A typical mass spectrum from data that has the same cuts that were used for the π^- data can be seen in figure 4.5. As can be seen the proton background is too large for the data to be useful. If cuts on the dE/dx vs. momentum spectra such as the one shown in figure 4.6 are placed on the data the amount of proton background in the mass peak is reduced as can be seen in figure 4.7. There does appear to still be proton background, however, especially in the data from target 2 which is estimated to be between 10% and 20% contamination. The dE/dx cuts do also cut out some of the pion events. This is due largely to pileup in the FERA modules which occurs because the gate for the analog signals was approximately 500 ns long, making the possibility of more

Figure 4.6: dE/dx vs. momentum spectrum for S2 showing the cut used to separate π^+ particles from protons. Note: this is π^- data and most protons have been removed by a bend angle cut.

Figure 4.7: The mass spectrum for π^+ data after dE/dx cuts are implemented.

than one event occurring during a gate much more likely than in the time of flight gate which was only 30 ns long. The loss of pion events to these dE/dx cuts was calculated by measuring the π^- cross sections with and without the dE/dx cuts on the data. It was found that for all pion momentum and angular bins the loss to these cuts was typically 10%. A correction was made to the data for this loss, but no correction was made for the proton background. For this reason, the π^+ cross sections are likely to be high. For target 2 the contamination is significant for the small angular bins (45° to 65°) but for the larger angle bins from targets 2 and 3 the proton contamination appears to be very small if the π^- spectra are compared to the π^+ spectra with dE/dx cuts.

For target 1 it was also necessary to put a cut on the target projection because the sampling scintillator produced protons that could pass through chambers 1 and 2 and be accepted as an event. In order to reduce the number of protons as much as

Figure 4.8: Projection from chambers one and two to target one for π^- and π^+ data. The π^+ projection shows background events coming from protons originating at the sampling scintillator.

possible it was necessary to cut out approximately 5% of the tail of particles coming from the target. The number of pions that were lost by this cut was calculated by looking at the same spectrum from the π^- data which did not have any proton contamination. The target projection spectra from π^- and π^+ data can be seen in figure 4.8.

The particles originating from targets 2 and 3 also had to be separated. This was done by projecting the track of the particle through chambers 3 and 4 back to the beam center and putting a cut between the two targets. A typical spectrum can be seen in figure 4.9.

Figure 4.9: Projection from chambers three and four to the beam center. Events from targets two and three can be seen with the cut that was used to separate them.

4.3 Histogram Binning

The pion cross section data were binned by three separate variables. The incoming neutron kinetic energy was separated into 25 MeV bins from 200 MeV up to 600 MeV. This covered neutron energies all the way to below the free nucleon pion production threshold at 287 MeV. The scattering angle of the pion was binned into 10° bins, the lowest bin being (25°,35°) from target 1 and the highest being (115°,125°) from target 3. The angular range was covered continuously between these two bins. The pion energy was binned into 25 MeV/c wide momentum bins with the low energy bin being (75,100) MeV/c as long as the acceptance of the spectrometer allowed it and the upper energy bin being determined either by the acceptance of the spectrometer or counting statistics.

4.4 Pion Cross Section Calculation

The double differential pion cross section was calculated from

$$\frac{d^2\sigma}{d\Omega * dT} = \frac{N}{\Delta T * N_o * n * \epsilon * lt * \Delta\Omega * acc} \quad (4.4)$$

where N is the number of pions counted in the angular and momentum bin of interest, N_o is the number of neutrons that hit the target, n is the number of atoms/cm² in the target, ϵ is the measured efficiency of the four chambers that the pions passed through, lt is the live time for the spectrometer events, acc is the acceptance of the spectrometer for the momentum and angular bin, and ΔT and $\Delta\Omega$ are the energy and solid angle covered for the measurement.

The efficiency was measured separately for each run since it varied with event rate and the event rate changed with each target as well as with changes in the beam delivery. The efficiency was also measured separately for each chamber. The

efficiency calculation for chambers 3 and 4 required a particle to pass through all four chambers 3, 4, 5, and 6 and scintillators 2 and 3 and also required the particle to pass through the center of the chamber adjacent to it. This last requirement removed any bias from poor acceptance from the calculation. A similar cut was put on the calculation of the efficiency for chambers 5 and 6. For them the particle was required to pass through S3M, the center scintillator behind chamber 6. The efficiency was then calculated as (for chamber 3)

$$\varepsilon_3 = \frac{C'3 * C'4 * C'5 * C'6 * (\text{center of } C'4) * S2 * S3}{C'4 * C'5 * C'6 * (\text{center of } C'4) * S2 * S3} \quad (4.5)$$

The chamber signals used in the efficiency measurements were the same ones used in the data analysis cuts: a signal on both ends of the delay line and a good measured drift time. The additional cut on the drift time was necessary because multiple events in the chamber would cause a signal to appear on each end of the delay line, but they would not combine to give a sensible drift time. Since it was impossible to separate these events, they had to be discarded. This also introduced some ambiguity into the efficiency calculation since we could not count the number of multiple events that were multiple pion events which should be counted twice (or more). However, the event rate in the chambers was largely from proton events, so the multiple events most of the time would not have been from two or more pions. For the n-p elastic events, the correction would have also been very small because the chambers were all operating at 95% efficiency or better for these runs.

The live time for each run was recorded in the scaler events. For both event 5 and event 6 the live time was taken as the ratio of the event trigger with the computer and electronics BUSY signal in to the same trigger without the BUSY signal.

The acceptances were calculated, as mentioned above, by the Monte Carlo for

each angular and momentum bin. The solid angle $\Delta\Omega$ that was used was the same solid angle that was used in the Monte Carlo acceptance calculations. The target densities were measured by measuring the dimensions of the targets and weighing them with a scale and targets two and three were corrected for the angle they were at relative to the beam direction. The CH_2 , C, Al, and Cu targets were all 35.6° relative to the beam and the W targets were at an angle of 29.1° . Target one was always perpendicular to the beam. The neutron flux was measured by the fission chamber as was mentioned previously.

4.5 Fission Chamber Calibration

To calibrate the fission chamber the n-p elastic scattering cross section had to be measured. To do this, the protons had to be separated from the other produced particles and then the elastic scattering events had to be separated from the non-elastic events. The protons were separated in the same way that the pions were—with a mass cut on the proton peak. The elastic events were separated by comparing the measured proton momentum of each event to the proton momentum that an elastic event would produce for the given incoming neutron energy and outgoing proton angle. When these two numbers were subtracted, the elastic peak could clearly be seen above the inelastic events as can be seen in figure 4.10. The same spectrum was produced from data from a carbon target and the two sets of spectra were subtracted after appropriate normalization to give the n-p elastic events. Figure 4.10 shows the spectra from CH_2 and carbon for a particular neutron energy bin along with the difference spectrum which shows just the n-p elastic events.

The neutron flux was calculated from the same equation that was used for pion cross section calculation 4.4, only solving for N_0 and putting in $\frac{d^2\sigma}{d\Omega dT}$ from

Figure 4.10: (a) The difference between the measured momentum and the momentum of an elastically scattered proton for data from a CH_2 target. (b) The same difference spectrum obtained from a carbon target. (c) The CH_2 spectrum after carbon subtraction.

Keeler's[22] data. The neutron energy was binned, as was mentioned above, into 25 MeV bins from 200 to 600 MeV. The angular bin used was $(55^\circ, 65^\circ)$ from target 2. A couple of calculations were also done using data from target 1 in the angular bin $(25^\circ, 35^\circ)$. These calculations agreed with the flux calculations from target 2 to within a few percent. This gave some assurance that the acceptances calculated from the Monte Carlo were consistent from target to target.

Chapter 5

Results

5.1 Determination of the Neutron Spectrum

The neutron flux was calculated from the equation

$$N_o = \frac{N}{\Delta T * n * \epsilon * lt * d\Omega * acc * \frac{d^2\sigma}{d\Omega \cdot dT}} \quad (5.1)$$

where N is the number of n-p elastic events measured in a particular neutron energy bin, dT is the proton energy bin width, n is the number of hydrogen atoms/cm² in the polyethelene target, ϵ is the chamber efficiency, lt is the live time during data acquisition, $d\Omega$ is the solid angle that the n-p elastic events were measured in, acc is the acceptance of the spectrometer for the neutron energy bin and angular bin of interest, and $\frac{d^2\sigma}{d\Omega \cdot dT}$ is the double differential cross section for n-p elastic scattering obtained by Keeler[22]. All of these quantities are either measured or known with the exception of the neutron flux, N_o .

The statistical uncertainty in the neutron flux measurement that came from measuring the number of n-p elastic events was better than 2% for all neutron energy bins but there was also an error that comes from integrating the number

of events in the elastic peak in the momentum difference spectrum. As can be seen in figure 4.10 there are some background events in the difference spectrum. This background can come from protons that are involved in pion production from hydrogen (inelastic n-p events) as well as from the subtraction of carbon events. The error in the integrated spectrum caused by this background is estimated to be less than 5% and is largest for the high neutron energy bins since there are less events in these spectra and more pion production would take place at the higher energies.

The uncertainty in Keeler's[22] data is on the order of 5% which is supported by the fact that his data agree very well with the phase shift analysis data of Arndt[25]. The uncertainty in the target thickness is estimated to be less than 3%. The thickness and weight were measured very accurately but since target two was at a large angle relative to the beam an error in the measurement of the angle of 1° would translate to a 2.5% error in the thickness. The calculation of the acceptance of the spectrometer depended on the accuracy of the survey of the chambers and scintillators relative to the magnet. Since the survey precision of the chambers was good to 0.5 mm or better and the scintillator positions were known to approximately 1 cm, these errors are estimated to be about 7%. The chamber efficiency was better than 95% for all chambers so the error in the calculation is estimated to be very small.

The neutron flux was calculated for neutrons in 25 MeV wide energy bins from (200,225) MeV to (575,600) MeV. The flux per steradian per MeV per micropulse at WNR calculated for the 30° line is shown in figure 5.1. The error bars on these points are approximately 10% errors which represent the total statistical uncertainty. During data collection for the n-p elastic cross section 97,000 fission events were recorded. This was used to get the number of neutrons/fission event from the

Figure 5.1: The spectrum of neutrons delivered to the WNR 30° beam line per steradian per micropulse per MeV.

Figure 5.2: The ratio of fission events to sampling scintillator events which was used to monitor the stability of the fission chamber during data acquisition. The dotted lines represent one standard deviation which was 2.5% for this data.

flux calculation and thus calibrate the fission chamber.

The stability of the fission chamber was monitored during data taking by comparing the fission events to the sampling scintillator events. A typical spectrum of the ratio of fission events to scintillator events is shown in figure 5.2 where the ratio is shown for the copper target data. Also shown in the figure is the standard deviation of the data which was 2.5%. This indicates that the fission chamber was very stable during data taking since the 2.5% includes the standard deviation of the sampling scintillator data as well as the fission chamber.

5.2 Pion Cross Sections

Data were collected to measure the π^- and π^+ production cross sections from CH₂, C, Al, Cu, and W targets. Since the CH₂ target was primarily used for the n-p cross section measurement which has a much larger cross section than n-p pion production we were unable to calculate pion cross sections for production from hydrogen with any statistical precision. The data collected with C, Al, and Cu targets were sufficient to calculate π^- cross sections from neutrons of energy 200 MeV (or 225 depending on statistics) up to 600 MeV and π^+ cross sections from 250 (to 300) MeV up to 600 MeV. The W target was the last target in place during data acquisition and there was only enough time to collect data with the magnet set at one polarity (-5kG). This gave us data from W for π^- production at angles (25°, 85°) and π^+ production at angles (105°, 125°).

5.2.1 Error Calculations

There are several statistical errors that enter into the calculation of the double differential cross section:

$$\frac{d^2\sigma}{d\Omega * dT} = \frac{N}{\Delta T * N_o * n * \epsilon * lt * \Delta\Omega * acc}. \quad (5.2)$$

The statistical error in the neutron flux which comes from counting the number of fission events was negligible. Therefore, the neutron flux calculation introduces just a systematic error into the cross section calculations while the number of pions measured, the target thickness, the calculated efficiencies, live time and acceptance all introduce statistical and systematic errors.

The error in the Monte Carlo acceptance calculations comes from several sources. Any error in the input geometry of the spectrometer including scintillator, wire

chamber, target, and magnet map positions will cause errors in the acceptance calculations. The magnitude of the magnetic field which was measured with a Gauss meter also has an uncertainty associated with it which would affect the calculations.

The wire chamber positions were surveyed to within 0.5 mm and the extents were known very accurately since there were a discrete number of wires associated with each chamber. Because of the accurate knowledge of the wire chamber positions there was an insignificant acceptance error caused by chamber position error.

The scintillator positions were not known as accurately because it was not possible to determine the extents as accurately as the chambers. The error in the scintillator positions did not typically cause a large error in the acceptances, however, since the scintillators very nearly covered the wire chamber acceptances. The error from the scintillator position uncertainty was calculated by assuming that the largest error that could be expected in the scintillator positions was a 2 cm error in the position of the end of the scintillator. When this geometry change was put into the Monte Carlo calculation it was found that the fractional change in the acceptances from the different targets varied from 0.95 to 1.05.

The largest uncertainty in target position was for target one since it was repositioned for each target run. The largest error that could be expected in the surveyed position was a 2 cm change in the z position. When this change was put in the Monte Carlo the fractional changes in the acceptances for the angular bin $(25^\circ, 35^\circ)$ varied from 0.96 to 1.02. For the angular bin $(35^\circ, 45^\circ)$, however, the fraction varied from 1.09 to 1.19. This large change occurred because a 2 cm change in the target position caused a significant number of pions to no longer pass through chambers 1 and 2, but for the angular bin $(25^\circ, 35^\circ)$ most pions still passed through the chambers.

Targets two and three were accurately surveyed in the z position, but it was

possible for the angle of the target to be in error. This angle was known to within approximately 1° , however, and a change of this size in the angle caused no significant change in the acceptance calculations.

The magnitude of the magnetic field could have been in error if there was an error in the calibration of the Gauss meter or if the position of the magnetic field measurements were not properly aligned with the magnetic field map. A 5% change in the magnetic field was put into the Monte Carlo to estimate the acceptance errors caused by this uncertainty in the magnetic field. The fractional changes in the acceptances varied from 0.94 to 1.07.

Combining the scintillator and target position errors with the magnetic field uncertainty for target one gives an acceptance error of 9% for the bin $(25^\circ, 35^\circ)$ and approximately a 15% error for the bin $(35^\circ, 45^\circ)$. For targets two and three the acceptance errors are approximately 7% except for the angular bin $(45^\circ, 55^\circ)$. Since it also suffered from poor acceptance (above pion energy 150 MeV) it was more strongly affected by geometry and magnetic field changes. For this reason it has an acceptance error of approximately 10 % at the higher pion energies.

The error in the neutron flux which is a systematic error was listed in the fission chamber calibration section and it was approximately 10%.

The uncertainty in the thickness of target one was less than 1% since it was accurately measured and weighed and an error in the angle relative to the beam would have caused a negligible change in the thickness since it was 90° to the beam. Targets two and three had a 2.5% uncertainty in the thickness since the angle was known to approximately 1° and they were 35.6° relative to the beam.

The measurements of the live time and chamber efficiency had negligible counting statistics errors. The efficiency calculation, however, could be in error if the acceptance of the events used was not 100% or if there were multiple pion events

that were thrown out. These errors are assumed to be very small, though, since a reasonable amount of care was taken to remove any events that had poor acceptance and most multiple events would involve protons since they dominated the count rate in the chambers.

The error in the pion mass cut for π^- is estimated to be better than 5% since virtually all protons are removed by the bend angle cut and the tail of pions above 300 MeV is small. There is a larger error in the mass cut for the π^+ data. The efficiency in counting pions should be the same but there is a significant contribution of protons in the pion mass peak that will cause the pion cross section calculations to be somewhat high. For targets two and three the proton contamination is estimated to be between 5% and 10% (by comparing π^- mass spectra to π^+ spectra). For target one the proton contamination appears to be between 10% and 15%. Also, the additional cut on the dE/dx spectra added another uncertainty of approximately 5% into the determination of pion events since the dE/dx cuts did remove some pions and a correction had to be made for this.

The errors in the calculation of double differential cross sections for π^- combine to give an overall statistical error of 9% for targets two and three and 10% for target one, a systematic error of approximately 10%, and errors from counting statistics which were typically between 3% and 10%. There are two exceptions: the angular bin ($35^\circ, 45^\circ$) has a statistical error of approximately 15% because of poor spectrometer acceptance, and the angular bin ($45^\circ, 55^\circ$) has a statistical error of approximately 12% above pion energies of 150 MeV for the same reason.

The statistical errors for π^+ production are the same except for the error associated with extracting the pions from the proton data. This causes the statistical error to be approximately 10%-15% for targets two and three and approximately 15% for target one. In addition, the errors from counting statistics are typically

5-15% for the π^+ data which is somewhat higher than the π^- data.

5.2.2 Double Differential Cross Section for π^- Production

Shown in figures 5.3 and 5.4 are the double differential cross sections ($d^2\sigma/d\Omega dT$) for π^- production from C. On each graph are shown the family of curves for pion production cross sections from neutrons in the energy bins (200,225) to (325,350) MeV, (375,400), (450,475) and (550,575) MeV for a particular angular bin. With the exception of the angular bin ($45^\circ, 55^\circ$) which had poor spectrometer acceptance for high energy pions, the full energy spectrum of pions for all angular bins was measured with the high energy cutoff being determined by counting statistics. The statistical precision of each data point was typically 5%-15% with the highest pion and lowest neutron energy bins having the worst precisions. The error bars shown include only the errors associated with counting statistics. The double differential cross sections for Al, Cu and W are very similar in shape and therefore are not reproduced here. The tabulated cross sections for all targets can be found in Appendix A.

Comparison to Experimental Data and INC Calculations

Cross sections for some energy and angular bins from carbon and copper can be compared to the cross section data taken by Büchle[2]. To compare our data with Büchle's data which give cross sections for the sum of π^- and π^+ production, the Büchle data was reduced by a factor of 0.833. The factor of 0.833 was chosen because the ratio of π^- to π^+ production that we measured was between 4.0 and 7.0 over the neutron energy range that we compare to Büchle. This means that between 80% and 88% of the Büchle data came from π^- production. If 83.3% is taken for the average, the comparison should be good to about 4%. Since we measured essentially

Figure 5.3: Measured π^- production cross sections for neutrons on carbon at neutron energies (200,225) MeV to (550,575) MeV and angles 25° to 65° .

Figure 5.4: Measured π^- production cross sections for neutrons on carbon at neutron energies (200,225) MeV to (550,575) MeV and angles 65° to 125° .

identical energy distributions for π^- and π^+ production, reducing the Büchle double differential cross section by 0.833 to give π^- cross sections should be valid over the entire pion energy range. The sum of our π^- and π^+ cross section data was not chosen for comparison because the error in our π^+ cross section measurements is much larger than in the π^- measurements. Figure 5.5 shows our data for copper and carbon at production angles 70° and 120° plotted against the Büchle data for neutron energies 542, 425, and 317 MeV. The Los Alamos data used to compare was from neutron energy bins (525,550), the average of (400,425) and (425, 450), and (300,325) MeV. The data agree with each other both in the energy distribution and the magnitude with the exception of the carbon data at 542 MeV and angular bin ($65^\circ, 75^\circ$) where the Büchle data are larger than our data by about a factor of 1.6. The energy distributions of our cross sections also agree with Oganessian's data[3] but are lower in magnitude by about a factor of two or more (see figure 5.6).

Cross sections from the intranuclear cascade (INC) code LAHET [26] which includes Bertini's INC calculations (described in the Theory section) have been compared to our cross sections for pion production. Figure 5.7 shows a typical comparison of the double differential cross section calculated by LAHET and our data. This particular figure shows the data taken for a copper target at angles 30° to 120° for neutrons of energy (550,575) MeV. The agreement shown here is similar to the agreement that is seen for all targets. LAHET produces double differential cross sections which are very similar in shape to our data but which disagree in magnitude by as much as a factor of three. The comparisons of our other targets to LAHET's calculations can be found in Appendix B.

Figure 5.5: Cross sections for carbon and copper targets at 70° and 120° compared to the data from Büchle[2]. The Büchle data were collected for neutron energies 317, 425 and 542 MeV. The Los Alamos data were collected at 312.5, 425.0, and 537.5 MeV.

Figure 5.6: Our data at 587.5 MeV compared with the data of Oganessian at 600 MeV for angles 30° and 60° .

Integrated Cross Sections

The differential cross section ($d\sigma/d\Omega$) has been calculated from the double differential cross section by calculating the sum $\sum_{i=2}^N (\frac{d^2\sigma}{d\Omega dT_i} * (\Delta T_i))$. The sum begins at the second to the lowest pion energy bin, (32.2,47.9) MeV, and ends at the last calculated data point which is determined either by statistical precision or the acceptance of the spectrometer. (The lowest data point was not used because the statistical precision was typically very poor because of poor spectrometer acceptance and at times it was not even possible to measure the cross section below 32.2 MeV.) The resulting angular distributions for the four separate targets and the same neutron energies that were used in figures 5.3 and 5.4 are shown in figure 5.8. The integrated cross section for the angular bin ($45^\circ, 55^\circ$) is low for many of the neutron energy bins because the acceptance of the spectrometer only allowed pions up to about 140 MeV to be detected in this angular bin. The angular bin ($25^\circ, 35^\circ$) may

Figure 5.7: Comparison of LAHET's double differential π^- production cross sections to our data for neutrons of energy (550,575) MeV on a copper target.

Figure 5.8: The differential cross sections ($d\sigma/d\Omega$) for π^- production obtained from integrating ($d^2\sigma/d\Omega dT$) from $T_\pi=32.2$ MeV. Cross sections are shown for C, Al, Cu and W targets for neutron energies from 200 to 600 MeV.

also be low for some of the highest neutron energy bins because the spectrum goes to very high pion energies and our integration only goes to about 300 MeV. This error, however, should be small since pion production calculations indicate that the spectrum tails off shortly after our pion energy cutoff. The cross section for the angular bin ($35^\circ, 45^\circ$) has an additional 10% error because the acceptance of the spectrometer for this particular bin was very dependent upon the position of target #1. Since target #1 was repositioned for each target run, there was a higher probability that it would not be in the same place for each run (and, more important, not in the same place as the surveyed position that was put into the Monte Carlo for acceptance calculations) than there was for targets two and three.

LAHET's energy integrated cross sections (integrated from 32 MeV pion energy as our data were) are compared to our data for copper and carbon targets in figures 5.9 and 5.10 where the integrated cross section ($d\sigma/d\Omega$) is shown for neutron energies (250,275) MeV up to (550,575) MeV. The LAHET angular distributions are systematically flatter than our measured distributions and the magnitude of the cross sections increases more rapidly with neutron energy than ours. The calculations for carbon, however, are closer in shape to the measured data than the copper data. If LAHET is used to calculate the angular distribution for n-p pion production, however, there is excellent agreement between the calculation and experimental data. The data of Dzhelepov[5] which give pion production for 600 MeV neutrons on hydrogen are compared in figure 5.11 to the calculated angular distribution of LAHET and it can be seen that there is no difference between the two distributions. This indicates that the problem in LAHET's calculation of angular distributions for complex nuclei is contained in the interactions of the nucleons or pions in the nucleus rather than in the pion production itself (at least at neutron energies near 600 MeV).

Figure 5.9: Comparison of LAHET's π^- differential cross sections to our data for neutrons of energy (250,275) MeV to (550,575) on a carbon target.

Figure 5.10: Same as figure 5.9 for neutrons on a copper target.

Figure 5.11: The angular distribution for pion production from neutrons on hydrogen from Dzhelepov's data and LAHET calculations.

Figure 5.12: The angular distribution of $d\sigma/d\Omega$ for neutron energies 287.5, 437.5, and 562.5 MeV on a copper target shown with the fit that was used to integrate over $d\Omega$ to get total cross sections.

The total π^- cross section for pions of energy greater than 32 MeV was calculated by fitting the differential cross section ($d\sigma/d\Omega$) with a second order polynomial in $\cos(\theta)$ for angles $(0^\circ, 80^\circ)$ and a first order polynomial in $\cos(\theta)$ for angles $(80^\circ, 180^\circ)$ and integrating over $d\Omega$. A typical example of the fit to the data can be seen in figure 5.12 where the fit to data from copper is shown for neutron energies (275,300), (425,450) and (550,575) MeV. The agreement of the $\cos(\theta)$ polynomial fit with the data was similar for the C and Al targets. In tables 5.1, 5.2, and 5.3 can be found the coefficients to the fits $d\sigma/d\Omega = a + b \cdot \cos(\theta) + c \cdot \cos^2(\theta)$ (for $\theta = 0^\circ, 80^\circ$) and $d\sigma/d\Omega = A + B \cdot \cos(\theta)$ (for $\theta = 80^\circ, 180^\circ$) for the C, Al, and Cu targets at all neutron energies. The results of the total cross section calculations for C, Al, and Cu are shown in figure 5.13 with the results from the LAHET calculations.

Table 5.1: Fit parameters for calculating the total cross section for π^- production from carbon.

T(n) (MeV)	a	b	c	A	B	σ_{tot} (mb)
225	.047	-.218	.357	.0131	.0094	.389
250	.100	-.458	.728	.0313	.0097	.841
275	.167	-.717	1.149	.0569	.0120	1.46
300	.281	-1.211	1.851	.0948	.0300	2.23
325	.399	-1.628	2.497	.148	.0601	3.72
350	.535	-2.195	3.303	.193	.0678	4.19
375	.701	-2.765	4.088	.236	.0373	5.36
400	.7343	-3.089	4.820	.342	.1240	6.59
425	1.089	-3.968	5.840	.476	.0936	8.96
450	1.072	-3.756	5.605	.493	.0755	9.21
475	1.308	-4.704	6.712	.572	.1090	10.33
500	1.436	-4.900	6.913	.677	.0515	11.76
525	1.421	-4.560	6.443	.710	.0756	11.91

For the Cu target the ISABEL[29] as well as the Bertini[9] model were used to calculate total cross sections. As can be seen the ISABEL calculation appears to give results that are closer to the experimental data at high neutron energies, but at about 500 MeV the results of the two calculations are approximately the same. For both the carbon and copper targets the LAHET cross sections become larger than our data above 450 MeV and appear to increase more rapidly than ours. Note, however, that the errors in the normalizations of the last two points of our data are on the order of 10% or more so, although our cross section curves appear to be turning over at 550 MeV it is likely that our last point is just a statistical outlier and the cross section continues to rise as the INC calculations indicate. Below free nucleon-nucleon pion production threshold energies LAHET underpredicts the pion production cross sections. This could be an indication that the Fermi motion of the nucleons in the nucleus is not properly accounted for or it could just be a result of the fact that Bertini's model only allows pion production through formation of a delta and at low neutron energies the delta state is not accessible.

Figure 5.13: Total cross sections for pion production above 32 MeV for C, Al and Cu. The LAHET calculations are presented for comparison to the C and Cu data. For Cu both the ISABEL and Bertini model calculations are presented.

Table 5.2: Fit parameters for calculating the total cross section for π^- production from aluminum.

T(n) (MeV)	a	b	c	A	B	σ_{tot} (mb)
225	.111	-.522	.796	.0315	.0105	.844
250	.183	-.768	1.23	.0654	.0337	1.55
275	.294	-1.20	1.95	.106	.0535	2.54
300	.496	-2.04	3.12	.183	.0766	3.97
325	.778	-3.22	4.72	.269	.145	5.60
350	.941	-3.88	5.73	.343	.109	7.19
375	1.13	-4.41	6.72	.458	.101	9.50
400	1.50	-5.88	8.54	.593	.152	11.6
425	1.72	-6.34	9.55	.766	.186	14.6
450	1.87	-6.75	9.83	.834	.214	15.1
475	2.03	-7.30	10.69	.897	.174	16.7
500	2.26	-7.66	11.14	1.07	.153	19.0
525	2.37	-7.92	11.32	1.13	.109	19.8

5.2.3 Double Differential Cross Section for π^+ Production

Figures 5.14 and 5.15 show the measured double differential cross sections for π^+ production from Cu with the errors from counting statistics. The angular bins $(35^\circ, 45^\circ)$ and $(45^\circ, 55^\circ)$ have not been included in the π^+ data because the acceptance of the spectrometer for these bins is lower than for the other angular bins which caused the statistical precision of the data we collected to be poor. The π^+ cross sections for the different targets were only measured down to $T_n=250, 275$ or 300 MeV depending on the target and angular bins because the statistical precision was too poor to measure the cross sections at the lowest neutron energy bins. The C, Al and W data for π^+ production were similar to the Cu data, but had various statistical precisions. (The π^+ double differential cross sections typically had statistical precisions of 15%-20%; some of the high neutron and low pion energy bins had precisions closer to 10% and some of the lowest bins had precisions of only 30% or 40%.) For all the data we found that the shape of the π^+ spectra are very similar

Table 5.3: Fit parameters for calculating the total cross section for π^- production from copper.

T(n) (MeV)	a	b	c	A	B	σ_{tot} (mb)
225	.112	-.434	.878	.0566	.00795	.235
250	.254	-.940	1.73	.114	.0738	.424
275	.413	-1.32	2.54	.210	.0999	.741
300	.642	-2.34	4.18	.305	.0391	1.12
325	.990	-3.44	5.94	.465	.192	1.57
350	1.38	-4.91	8.03	.630	.269	2.03
375	1.27	-3.40	7.01	.783	.269	2.51
400	1.93	-6.23	10.87	1.01	.266	3.23
425	2.47	-7.60	13.41	1.34	.201	4.27
450	2.44	-6.48	12.27	1.49	.440	4.48
475	2.88	-8.16	14.31	1.67	.415	4.92
500	3.39	-9.61	16.38	1.94	.363	5.68
525	2.94	-6.87	13.46	1.99	.105	5.85

to the π^- spectra but are smaller in magnitude by a factor of 5 to 10 depending on the neutron energy and the nucleus that is involved.

Comparison to INC Calculations

In figures 5.16 and 5.17 are shown the comparisons of our π^+ cross section data for carbon and copper at 562.5 MeV for the angles 30°, 60°, 80°, and 120° to the calculations of LAHET. As can be seen, the agreement is similar to what was seen for π^- : the energy distributions are similar but the agreement in the magnitude of the cross sections changes for different angular bins.

Integrated Cross Sections

The differential cross sections ($d\sigma/d\Omega$) were calculated using the same sum that was used for the π^- data and these are shown in figure 5.18 for C, Al and Cu. Since the W data cover only two angular bins these data are not shown in the figure. Figure 5.19 shows the angular distributions for C and Cu at 362.5 and 562.5 MeV

Figure 5.14: Measured π^+ production cross sections for neutrons on copper at neutron energies (250,275) MeV (when possible) to (575,600) MeV and angles 25° to 85°.

Figure 5.15: Measured π^+ production cross sections for neutrons on copper at angles 105° to 125° and neutron energies (300,325) MeV to (575,600) MeV.

Figure 5.16: The π^+ double differential cross sections at angles 30° , 60° , 80° , and 120° for 562.5 MeV neutrons on carbon compared to LAHET calculations.

Figure 5.17: Same as figure 5.16 for copper.

Figure 5.18: The differential cross sections ($d\sigma/d\Omega$) for π^+ production obtained from integrating ($d^2\sigma/d\Omega dT$) from $T_\pi=32.2$ MeV. Cross sections are shown for C, Al, and Cu targets for neutron energies from 300 to 600 MeV.

compared to LAHET's calculations. Again, similar to the π^- data, the shape of the distribution is better for carbon than for Cu where LAHET predicts a much flatter distribution than our measured data.

Figure 5.20 shows the total cross section for π^+ produced above 32 MeV from carbon and copper targets along with LAHET's predictions. The LAHET cross sections seem to increase more rapidly with neutron energy than the measured cross sections, as was seen for the π^- cross sections.

5.2.4 Ratio of π^- to π^+ Production

The differential cross sections for π^- and π^+ production have been used to calculate the ratio $\pi^-:\pi^+$ produced from the different nuclei. These ratios for angles 55° to 115° for the C, Al and Cu targets can be seen in figure 5.21 for neutron energies 300 to 600 MeV. In this figure the error bars associated with these calculations are only given for the carbon target at $(55^\circ, 65^\circ)$ to keep the graphs more clear. These error bars are typically 15-20%. The ratio was not calculated from our forward angles because the pion separation from the protons was especially poor for these angles and so the error bars on the π^+ cross sections are large. As can be seen from the figure, the ratios we calculate for the different angular bins are reasonably consistent with each other except for some of the ratios calculated for C and Al at 110° . This discrepancy could come from either of the following: 1) possibly a statistical error since the statistics for π^+ are not that good at 110° , and so it was difficult to get cross sections for the entire pion energy range at the large angles, or 2) proton contamination in the π^+ mass peak since the contamination was smaller at the large angles.

These $\pi^-:\pi^+$ ratios can be compared to the ratios measured by Büchle[2] and Oganessian[3] and calculated by LAHET. Büchle measured the ratio of π^- to π^+

Figure 5.19: The angular distributions of $d\sigma/d\Omega$ for π^+ produced from C and Cu at 362.5 and 562.5 MeV compared to the LAHET calculations.

Figure 5.20: Total cross sections for π^+ produced above 32 MeV from carbon and copper compared to the cross sections calculated by LAHET.

Figure 5.21: The ratio π^-/π^+ produced at 55° to 115° from C, Al, and Cu targets. The ratios are calculated from the differential cross sections $d\sigma/d\Omega$ for different neutron energies.

produced by 541 and 466 MeV neutrons at angles 165° to 179° for a carbon target. He then took an average ratio from the different neutron energies and π angles and found an average ratio of 4.7. We also measure a ratio of 4.7 for pions produced from a carbon target by 500 MeV neutrons if the average ratio is taken from the angular bins falling between 55° and 85° . Oganessian measured a higher pion ratio than we did. At angles 16° to 123° and 600 MeV neutron energy he measured the pion ratio and found a ratio of 6.0. LAHET calculates a ratio of 4.22 for Cu and 4.04 for carbon at 562.5 MeV which is close to the value that we measure. The LAHET calculations also predict an increase in the ratio with decreasing neutron energy as is seen in our figures, but not as dramatic an increase. At 262.5 MeV neutron energy LAHET predicts a ratio of 5.52 for Cu and 4.94 for C compared to our data which produce a ratio at 262.5 MeV which is between 7:1 and 8:1. The change in the ratio with neutron energy presumably is caused by the fact that there are fewer π^+ 's produced by charge exchange at low neutron energies which causes the ratio to increase.

A reasonably good fit to the pion ratio over neutron energy can be obtained if the ratio is fit as a function of $1/(\text{neutron energy})$. Figure 5.22 shows the results of fitting the carbon $\pi^-:\pi^+$ ratio to $\text{ratio} = -.1466 + 2.14e3/T_n$.

5.2.5 Cross Section Dependence on Atomic Number

Most pion production measurements have supported the theory that pion production takes place on the surface of the nucleus [2], [3], [30], [31] (or, in the case of (p, π^-) production on the periphery). The support has been developed as follows. If production takes place on the surface then the cross sections for different nuclei should be proportional to the surface area of the nucleus involved in production which is related to the atomic number, A, as follows:

Figure 5.22: The ratio of $\pi^-:\pi^+$ produced from carbon as a function of neutron energy. Shown are our data as well as the fit to the data which gives ratio= $-.1466 + 2.14e3/T_n$.

Figure 5.23: σ_{tot} from Cochran and Crawford for proton induced π^- production, neutron induced π^- differential cross sections from Büchle and neutron induced π^- total cross sections from Oganessian divided by $A^{2/3}$.

$$(\text{surface area}) \propto (r^2) \propto (A^{1/3})^2 = A^{2/3}. \quad (5.3)$$

Therefore, for surface production, the cross sections for different nuclei divided by $A^{2/3}$ would be a constant. Shown in figure 5.23 are various measured cross sections for π^- production divided by $A^{2/3}$ for different nuclei. As can be seen, most of the cross sections do fall on a straight line although the neutron induced cross sections all have a slight negative slope. Note, however, that π^- 's produced from proton induced production will have a large contribution of the spectrum coming from charge exchange interactions as opposed to neutron induced production, so the atomic number dependence will probably not be quite the same for the two.

If only the nuclear surface participates in pion production the implication is that

either the nucleons are unable to penetrate the nuclear surface and produce pions and/or pions produced in the interior of the nucleus tend to be absorbed before they escape the nucleus. If just the surface contributes to pion production then an $A^{\frac{2}{3}}$ dependence is expected. If more than the surface contributes the exponent would be larger than $\frac{2}{3}$ and if the surface contribution is reduced by absorption and/or charge exchange then the exponent would be less than $\frac{2}{3}$. A dependence of $Z^{1/3}$ was seen for proton induced π^+ production[30], [31] which was attributed to production taking place only on the periphery of the nucleus.

For pion absorption it would be expected that pions produced near the pion resonance (195 MeV) (seen in figure 2.2) would tend to be absorbed by the nucleus, but lower energy pions which have a much longer mean free path would be more likely to escape the nucleus. On the other hand, as the nuclear radius increases and the path length through the nucleus increases, fewer pions of all energies would escape from the center of the nucleus so pion production would be more likely to take place on the surface of the nucleus.

When our differential cross sections ($d\sigma/d\Omega$) are divided by $A^{\frac{2}{3}}$ we also get a reasonably flat distributions as can be seen in figure 5.24 where the cross sections ($d\sigma/d\Omega$) divided by $A^{\frac{2}{3}}$ are shown for production angles 30° to 120° for π^- and 120° for π^+ . At the forward angles (30° and 40°) the cross section appears to increase less rapidly than $A^{\frac{2}{3}}$. This might be explained by the fact that more pions are produced near the pion resonance at the forward angles, so more of the pion energy spectrum is likely to be absorbed by the nucleus. However, at low neutron energies where pions are not produced near the pion resonance, the same A dependence is seen at the forward angles. (The ratio of the aluminum cross section divided by $A^{\frac{2}{3}}$ to the tungsten cross section divided by $A^{\frac{2}{3}}$ at 30° is 1.30, 1.27, 1.32, and 1.33 for neutron energies 262.5, 362.5, 462.5, and 562.5, i.e. the $A^{\frac{2}{3}}$ distribution is not

Figure 5.24: Differential cross sections ($d\sigma/d\Omega$) for C, Al, Cu and W divided by $A^{2/3}$ for angles 30°, 40°, 60°, 80° and 120° and 450 MeV neutron energy.

Figure 5.25: Oganessian's cross sections at 30°, 60°, 90°, and 120° divided by $A^{2/3}$.

flat even at the lowest neutron energies.) This implies that the change in the cross section dependence with angle is not caused by the pion resonance. It is more likely that the change with angle comes from the fact that pions that are involved in scattering interactions, etc. within the nucleus are more likely to be produced at the large angles than at the forward angles. Therefore, at the large angles the pion production contributions are likely to come from a larger fraction of the nucleus than at forward angles.

A similar change in the A dependence with production angle was seen by Oganessian[3] as can be seen in figure 5.25 where the data for angles 30° to 120° can be seen for neutrons at 600 MeV. At 120° both Oganessian's and our data are very close to an $A^{2/3}$ distribution.

LAHET calculations predict a reasonably flat distribution for the total cross section divided by $A^{2/3}$. As can be seen in figure 5.26 the distribution actually tends

Figure 5.26: Total cross sections predicted by LAHET divided by $A^{2/3}$ for neutrons of energy 250, 350 and 550 MeV.

to increase with increasing atomic number as opposed to the slight decrease that we measured for our data. In figure 5.26 the total cross sections divided by $A^{2/3}$ for 250, 350 and 550 MeV neutrons are shown.

The neutron induced pion production experiments have also found a change in the atomic number dependence of the cross section with pion energy[2], [3]. If a significant fraction of pions produced near the resonance energy of 195 MeV are absorbed by the nuclei, but the low energy pions pass through the nuclei, then the cross section for pion production should increase less rapidly with atomic number at high pion energies than at low pion energies. To see if this is true for our data, we have fit the cross section $d\sigma/d\Omega$ to the equation

$$d\sigma/d\Omega = A^{\alpha(E)} \quad (5.4)$$

where A is the atomic number, and we calculated α for different pion energies. If

Figure 5.27: The exponent α from a fit of $d\sigma/d\Omega = A^\alpha$ versus pion energy for pions produced at 30°, 70°, and 120° by 450 MeV neutrons on carbon.

the high energy pions are absorbed more than low energy pions, then α should decrease with increasing pion energy. Figure 5.27 shows the results of the α fit for pions produced by 450 MeV neutrons on carbon. As can be seen, the absorption does seem to increase with increasing pion energy, but it is less dramatic at the forward angles than at the backward angle.

5.2.6 Search for Resonance at 350 MeV

There has been some evidence[27], [28], [2] of a resonance structure in proton induced and neutron induced pion production on copper at 90° and 350 MeV bombarding energy. A 10 MeV wide "resonance" was seen by Julien, et al. between the energies of 338 and 362 MeV proton energy. At low pion energies (around 40 MeV) the pion double differential cross section at 90° was found to be larger at 350

MeV bombarding energy than at 362 MeV. The explanation for this discrepancy was that there is a 3F_3 dibaryon resonance at 2220 MeV that was enhancing the cross section at 350 MeV. The anomaly at 350 MeV was first seen by Krasnov[27], was confirmed by Julien[28] and the data taken at SIN[2] for neutrons on copper also saw a small anomaly, though their data at 350 MeV was only 1.5 standard deviations out of line from the rest of their data.

Our data have been analyzed at 340, 350, and 360 MeV in 10 MeV wide neutron energy bins for neutrons on copper in the pion angular bin ($75^\circ, 85^\circ$). Our data show no evidence of any resonance structure as seen in figure 5.28 where the data of Julien[28] are also shown. However, our neutron beam is not a monoenergetic source and the statistical precision in our data points when the neutrons are binned in 10 MeV bins is only 7%-15%. Since the resonant structure observed has been within a couple standard deviations of measured values, it is possible that it is obscured by the precision of our measurements.

Figure 5.28: Double differential cross sections for neutrons of energy 340, 350, and 360 MeV on copper producing pions (a) at 80° from our data and (b) at 90° from Julien's[28] data. No evidence of any resonant behavior at 350 MeV is seen in our data.

Chapter 6

Conclusions

Cross sections for π^- production have been measured for 200-600 MeV neutrons on C, Al, Cu, and W at a wide range of angles. The statistical and systematic errors on the data points are both typically 10%. Cross sections for π^+ production have been measured for 300-600 MeV neutrons on C, Al, Cu and some from W over the same angular range, though the data below 55° are highly contaminated with protons and so have large error bars associated with them. The statistical errors on the π^+ data are typically 15-20% with an additional error caused by proton contamination which would cause the data to be 5-15% high.

It was found that the energy and angular distributions of both the π^- and π^+ data are very similar for the different nuclei and the two charge states, and the variation with neutron energy appears to be governed by the kinematics of the interaction. The Fermi motion of the nucleons causes the energy distributions to be extended to higher energies than would be available in free nucleon-nucleon interactions, and also reduces the production threshold relative to the free nucleon-nucleon pion production threshold by at least 100 MeV.

The intranuclear cascade calculations of LAHET show only moderate agreement

with our data. The energy distributions predicted by LAHET are very similar to our data but the angular distributions are systematically flatter than our data which causes the magnitude of the double differential cross sections to be different from our data by as much as a factor of three for different angular bins. The error in the LAHET angular distribution calculations does not appear to come from the nucleon-nucleon pion production part of the calculation since LAHET does a very good job of calculating the angular distribution for pions produced in n-p interactions.

The total cross sections for pion production calculated by LAHET agree reasonably well with our data, although they do appear to increase more rapidly with neutron energy than our data does and pion production is typically underpredicted at the low neutron energies. Some discrepancy at low neutron energies was expected, however, since the Bertini model only allows pion production through formation of a delta state and at low neutron energies production through delta formation would not be the dominant channel since the delta state is not accessible when the two interacting nucleons and the pion are both in an s state relative to each other.

The ratio of π^- production to π^+ production depends rather strongly on the energy of the bombarding neutron. The ratio at the high neutron energies is much smaller than the ratio predicted by Clebsch-Gordon coefficients if delta formation and no interactions within the nucleus are assumed. At the lower neutron energies the ratio approaches the predicted value. The likely explanation for the change in the ratio is that interactions such as charge exchange within the nucleus are changing the ratio. It is also possible that some contribution may come from the fact that as the neutron energy changes the contributions of different spin states changes and this could cause the ratio to change. The calculations of LAHET do not show nearly as much of an increase in the ratio with decreasing energy as the measurements do. If the ratio change is caused by charge exchange of the pions

and nucleons within the nucleus then this implies that the LAHET code may not be properly accounting for the charge exchange interactions within the nucleus.

The atomic number dependence of the cross section indicates that the pions measured come mostly from production on the surface of the nucleus. There is some change in the atomic number dependence with scattering angle indicating that the scattering that takes place after the pion is produced is significant. There is also some variation in the A dependence with pion energy which indicates that the pion resonance at $T_{\pi}=195$ MeV causes pions to be preferentially absorbed at high pion energies (near the resonance).

Although there have been several pion production measurements which have found evidence that a dibaryon resonance may exist near 350 MeV neutron energy, we were unable to produce any data which supports this.

Appendix A

Pion Double Differential Cross Sections

Listed in tables A.1- A.18 are the double differential cross sections ($d^2\sigma/d\Omega dT$) measured for π^- and π^+ production from carbon, aluminum, copper and tungsten. The cross sections are listed for neutron energy bins (200,225) MeV to (575,600) MeV and angular bins covering 25° to 125° . The pion energies listed are the average kinetic energy of the momentum bin acceptance (e.g. the lowest pion momentum bin was (75,100) MeV/c which gives a midpoint kinetic energy of 25.6 MeV). The errors listed are only the errors produced by counting statistics and these are given as fractional errors. The other systematic and statistical errors have been listed in the Results section.

At the bottom of the neutron energy bin columns are the differential cross section ($d\sigma/d\Omega$) that were calculated (as described in the Results section) by performing the sum $\sum_{i=2}^N (\frac{d^2\sigma}{d\Omega \cdot dT_i} * (\Delta T_i))$ which is summed from 32 MeV to the highest pion energy bin available.

Table A.1: Double differential cross sections for π^- 's produced at 25° to 55° from neutrons on carbon.

T(π)	T(n)					Carbon, π^-					
	(200,225)		(225,250)		(250,275)	(275,300)		(300,325)			
$\theta=$	(25°, 35°)		$\frac{d^2\sigma}{d\Omega dT}$ (microbarns/MeV/Sr), %error								
25.6	2.46	.068	3.02	.061	3.86	.057	4.83	.054	5.67	.052	
40.1	2.04	.068	2.83	.057	4.07	.05	5.4	.046	6.64	.044	
56.7	1.06	.089	2.15	.061	3.97	.048	5.29	.044	6.63	.041	
75	.414	.139	1.59	.07	3.31	.051	4.96	.044	6.68	.04	
94.5			.55	.117	1.86	.067	3.38	.052	5.5	.043	
115			.111	.258	.738	.105	2.06	.067	3.44	.054	
136.3					.219	.2	.958	.101	2.34	.068	
158.1							.402	.167	1.52	.091	
180.4							.209	.25	.494	.171	
203.1									.387	.21	
226.6											
249.3											
272.7											
$\theta=$	(35°, 45°)										
25.6	2.5	.098	2.71	.093	3.36	.088	3.83	.087	4.97	.081	
40.1	1.57	.107	2.19	.089	3.3	.077	4.55	.069	5.57	.066	
56.7	.782	.144	1.95	.09	3.27	.073	4.06	.07	5.34	.064	
75	.433	.177	1.13	.108	2.2	.082	3.72	.066	4.86	.061	
94.5			.281	.2	1.19	.103	2.26	.079	3.81	.064	
115					.394	.174	1.14	.108	2.55	.076	
136.3							.619	.144	1.62	.094	
158.1							.339	.189	.727	.136	
180.4									.192	.258	
203.1											
226.6											
249.3											
272.7											
$\theta=$	(45°, 55°)										
25.6	.559	.072	.92	.055	1.3	.049	1.74	.045	2.23	.042	
40.1	.513	.075	.986	.053	1.59	.044	2.24	.039	2.89	.036	
56.7	.281	.11	.693	.069	1.18	.056	1.67	.049	2.5	.043	
75	.095	.218	.409	.104	.792	.079	1.44	.062	2.02	.055	
94.5			.163	.196	.536	.114	.9	.093	1.44	.077	
115					.318	.177	.676	.128	.986	.112	
136.3							.271	.25	.697	.164	
158.1											

$T(\pi)$	$T(n)$		$T(n)$		$T(n)$		$T(n)$		$\text{Carbon, } \pi^-$	
	(325,350)		(350,375)		(375,400)		(400,425)		(425,450)	
$\theta = (25^\circ, 35^\circ)$										
25.6	6.24	.053	6.63	.053	7.4	.053	8.6	.051	9.46	.052
40.1	7.63	.044	8.48	.042	9.51	.042	10.5	.042	11.6	.043
56.7	8.7	.038	9.44	.038	9.85	.039	10.7	.039	12.6	.038
75.	8.09	.039	9.22	.037	10.8	.034	11.5	.037	13.6	.036
94.5	7.41	.04	8.8	.038	9.63	.038	10.8	.037	12.9	.037
115.	5.55	.046	7.54	.04	8.56	.04	10.3	.038	11.4	.039
136.3	3.86	.057	5.42	.049	7.23	.045	9.0	.042	10.9	.041
158.1	2.45	.076	4.21	.06	5.92	.053	8.09	.047	8.99	.048
180.4	1.43	.108	2.44	.085	3.61	.073	6.17	.058	7.59	.057
203.1	.637	.174	1.8	.106	2.52	.094	3.9	.079	5.7	.07
226.6			.783	.171	1.43	.134	2.29	.11	3.55	.095
249.3			.388	.26	.861	.183	1.24	.158	2.41	.122
272.7										
$\theta = (35^\circ, 45^\circ)$										
25.6	6.33	.076	6.01	.08	7.06	.078	7.66	.078	9.48	.075
40.1	5.48	.071	5.91	.07	7.98	.064	7.81	.067	9.86	.064
56.7	7.06	.06	8.02	.057	9.09	.057	9.77	.057	13.1	.053
75.	6.43	.057	8.44	.051	8.96	.052	10.3	.05	11.3	.052
94.5	5.52	.057	6.71	.053	7.49	.053	9.17	.049	10.7	.049
115.	4.43	.062	5.23	.058	7.11	.053	8.5	.05	10	.05
136.3	2.59	.08	3.74	.068	5.31	.06	7.13	.054	8.98	.052
158.1	1.41	.105	2.46	.081	4.06	.067	4.65	.065	6.05	.061
180.4	.763	.139	.983	.125	1.67	.101	2.98	.079	4.12	.072
203.1	.305	.174	.702	.151	1.08	.128	1.55	.111	2.77	.089
226.6					.369	.213	.543	.183	.797	.162
249.3							.387	.213	.633	.18
272.7										
$\theta = (45^\circ, 55^\circ)$										
25.6	2.8	.04	3.16	.039	3.67	.038	4.37	.036	5.35	.035
40.1	3.43	.036	4.02	.034	5.22	.031	6.18	.03	7.55	.029
56.7	3.23	.04	3.57	.039	4.52	.037	5.85	.033	6.68	.034
75.	2.74	.05	3.2	.048	4.08	.045	4.96	.042	6.54	.039
94.5	2.42	.064	2.9	.06	3.6	.057	4.4	.053	5.07	.053
115.	1.5	.097	2.15	.083	2.52	.081	3.67	.07	4.47	.068
136.3	1.15	.137	1.59	.12	2.11	.109	2.58	.103	3.15	.1
158.1	.969	.192	1.28	.171	1.46	.169	1.85	.156	2.98	.132

T(π)	T(n)			Carbon, π^-						
	(450,475)	(475,500)	(500,525)	(525,550)	(550,575)					
$\theta = (25^\circ, 35^\circ)$										
25.6	9.8	.05	8.69	.054	10.7	.053	8.81	.058	8.48	.062
40.1	10.4	.044	11.9	.042	11.7	.045	11.5	.046	11.1	.05
56.7	11.3	.04	11.9	.039	12.7	.04	11.8	.043	11.9	.045
75.	12.7	.037	13.6	.036	13.9	.037	13.2	.04	11.8	.044
94.5	12	.037	13.4	.036	12.7	.038	12	.041	11.4	.044
115.	11.5	.038	11.6	.038	12.5	.039	11.9	.041	10.8	.045
136.3	10.4	.041	11.5	.039	11.7	.041	10.9	.044	10.4	.047
158.1	9.25	.046	10.5	.044	11.2	.045	12	.045	9.64	.053
180.4	7.95	.054	9.5	.05	10.5	.05	8.94	.056	9.59	.057
203.1	5.45	.07	7.65	.06	7.49	.064	7.64	.065	7.86	.068
226.6	4.86	.079	5.42	.076	5.68	.079	6.09	.078	6.65	.079
249.3	2.64	.114	4.03	.094	4.72	.091	5.21	.089	5.25	.094
272.7	1.71	.151	2.37	.13	3.67	.11	3.6	.115	3.72	.119
$\theta = (35^\circ, 45^\circ)$										
25.6	8.74	.077	8.81	.078	8.97	.081	9.87	.081	7.6	.095
40.1	9.83	.063	10.1	.063	9.53	.068	9.77	.069	9.91	.072
56.7	11.3	.056	12.7	.053	12.3	.057	11.9	.06	10.1	.068
75.	12	.049	12.1	.05	11.4	.054	11.6	.055	11.6	.058
94.5	9.96	.05	10.9	.048	11.5	.05	11.3	.052	9.16	.06
115.	10.7	.047	10.2	.049	11.3	.049	10	.054	9.67	.057
136.3	8.94	.051	9.49	.05	10.1	.051	9.33	.055	9.19	.058
158.1	6.05	.06	7.36	.055	8.73	.053	6.58	.063	6.26	.068
180.4	5.3	.062	5.66	.061	6.2	.061	5.98	.064	5.07	.074
203.1	3.32	.08	3.83	.076	4.47	.074	4.8	.073	5.04	.075
226.6	1.9	.103	2.53	.091	2.9	.089	3.27	.087	3.34	.09
249.3	1.24	.127	1.61	.113	1.98	.108	2.27	.104	2.21	.11
272.7	.624	.177	.684	.171	1.12	.108	1.28	.136	1.15	.151
$\theta = (45^\circ, 55^\circ)$										
25.6	5.54	.034	5.79	.033	6.11	.034	5.87	.036	6.38	.036
40.1	7.48	.029	7.81	.028	8.79	.028	8.77	.029	8.53	.031
56.7	6.45	.033	7.05	.033	7.27	.034	7.84	.033	7.21	.037
75.	6.44	.039	6.87	.038	7.24	.039	6.76	.042	7.03	.043
94.5	6.04	.048	5.58	.05	6.6	.049	6.93	.049	6.67	.053
115.	4.66	.065	4.4	.065	5.03	.067	5.62	.065	6.33	.065
136.3	3.64	.091	4.44	.084	4.82	.085	5.63	.081	5.41	.086
158.1	3.09	.127	3.6	.12	3.95	.12	5.22	.108	4.56	.121

Table A.2: Double differential cross sections for π^- 's produced at 55° to 85° from neutrons on carbon.

[illegible]

T(π)			T(n)				Carbon, π^-			
	(325,350)		(350,375)		(375,400)		(400,425)		(425,450)	
$\theta =$	(55°, 65°)									
25.6	2.14	.056	2.56	.052	3.01	.051	3.13	.052	4.22	.048
40.1	3.9	.035	4.35	.045	5.65	.031	6.54	.03	8.64	.028
56.7	3.33	.036	4.21	.033	4.92	.032	5.6	.031	7.34	.029
75.	2.42	.043	2.98	.039	3.94	.036	4.79	.034	6.04	.033
94.5	1.37	.055	2.58	.045	2.57	.044	3.09	.041	4.21	.038
115.	.928	.068	1.28	.059	1.64	.055	2.27	.049	2.97	.046
136.3	.506	.092	.73	.079	.982	.072	1.22	.067	2.3	.052
158.1	.216	.143	.355	.114	.481	.103	.674	.091	1.06	.078
180.4	.109	.204	.176	.164	.312	.13	.445	.113	.629	.103
203.1			.108	.218	.189	.174	.217	.169	.28	.16
226.6					.11	.236			.244	.174
249.3										
$\theta =$	(65°, 75°)									
25.6	2.	.124	1.96	.128	2.82	.113	2.74	.119	3.53	.113
40.1	2.65	.047	3.29	.043	3.88	.042	5.03	.038	6.5	.036
56.7	3.02	.039	3.67	.036	4.59	.034	5.65	.032	7.03	.031
75.	2.4	.043	2.84	.04	3.85	.036	4.68	.034	6.34	.032
94.5	1.34	.056	1.92	.048	2.76	.042	3.11	.041	4.23	.038
115.	.794	.074	1.15	.063	1.58	.057	2.33	.049	3.23	.044
136.3	.378	.104	.579	.086	.88	.073	1.27	.064	1.7	.059
158.1	.148	.169	.358	.111	.438	.106	.737	.085	.971	.08
180.4	.122	.183	.132	.18	.247	.139	.287	.134	.629	.097
203.1			.086	.23	.121	.204	.261	.144	.303	.144
226.6							.103	.224	.185	.18
249.3										
$\theta =$	(75°, 85°)									
25.6	.92	.177	.722	.204	1.4	.154	1.48	.156	1.8	.152
40.1	2.46	.047	3.19	.042	4.37	.038	4.94	.037	6.03	.036
56.7	2.98	.038	3.55	.036	4.6	.033	6.21	.03	7.49	.029
75.	1.76	.048	2.42	.042	3.36	.037	4.2	.035	6	.031
94.5	.956	.063	1.25	.057	1.8	.05	2.37	.045	3.31	.041
115.	.394	.099	.601	.082	.97	.068	1.27	.061	1.98	.053
136.3	.183	.141	.31	.111	.514	.091	.586	.088	.882	.102
158.1	.084	.209	.111	.186	.175	.156	.364	.113	.518	.14
180.4					.131	.18	.109	.204	.269	.164
203.1									.199	.25

T(π)	T(n)					Carbon, π^-				
	(450,475)	(475,500)	(500,525)	(525,550)	(550,575)	(450,475)	(475,500)	(500,525)	(525,550)	(550,575)
$\theta = (55^\circ, 65^\circ)$										
25.6	3.76	.05	4.7	.045	4.93	.047	4.38	.051	4.93	.051
40.1	8.08	.028	8.79	.028	9.05	.029	9.66	.029	9.77	.03
56.7	7.35	.028	8.34	.027	8.98	.028	8.6	.029	8.39	.031
75.	6.26	.031	6.65	.031	7.46	.031	7.33	.032	7.36	.033
94.5	4.24	.037	4.84	.035	5.44	.035	5.35	.036	5.15	.039
115.	3.13	.044	3.6	.041	4.17	.041	4.21	.042	3.9	.045
136.3	1.97	.055	2.48	.05	2.71	.051	2.86	.051	2.78	.054
158.1	1.41	.066	1.44	.066	1.81	.062	2.01	.061	1.91	.066
180.4	.777	.09	.77	.092	1	.085	1.14	.082	1.15	.086
203.1	.363	.137	.601	.108	.606	.085	.733	.107	.837	.105
226.6	.277	.162	.286	.162	.41	.114	.337	.162	.421	.152
249.3	.154	.224	.215	.192	.319	.143	.376	.158	.239	.174
$\theta = (65^\circ, 75^\circ)$										
25.6	4.18	.101	3.57	.111	3.38	.12	2.8	.136	3.96	.12
40.1	6.22	.036	6.78	.035	7.76	.035	7.61	.036	7.29	.039
56.7	7.2	.03	8.08	.028	8.91	.029	8.81	.03	8.36	.032
75.	6.28	.031	6.76	.031	7.9	.03	8.13	.03	7.91	.032
94.5	4.65	.035	4.84	.035	5.77	.034	5.81	.035	6.03	.036
115.	3.47	.042	3.99	.04	4.3	.04	4.73	.039	4.32	.043
136.3	1.98	.053	2.28	.051	2.57	.05	2.87	.049	2.66	.053
158.1	1.24	.069	1.48	.064	1.55	.066	1.81	.063	1.52	.072
180.4	.674	.092	.655	.094	.995	.081	1.22	.075	1.07	.084
203.1	.404	.122	.467	.115	.623	.105	.752	.099	.842	.098
226.6	.268	.146	.27	.147	.405	.127	.346	.141	.39	.14
249.3			.178	.183	.251	.162	.238	.171	.216	.189
$\theta = (75^\circ, 85^\circ)$										
25.6	1.52	.162	2.35	.132	2.38	.139	3.4	.12	2.47	.147
40.1	6.04	.035	6.74	.034	7.84	.033	7.91	.034	8.28	.035
56.7	7.92	.028	8.95	.026	10	.026	10.9	.026	10.4	.028
75.	5.75	.031	6.61	.03	7.61	.029	7.87	.029	8.12	.03
94.5	3.64	.038	4.3	.036	5.11	.035	5.45	.034	5.61	.036
115.	2.15	.05	2.53	.047	2.97	.045	3.23	.045	3.33	.046
136.3	1.04	.07	1.37	.062	1.72	.058	1.8	.059	1.87	.06
158.1	.637	.089	.716	.086	.843	.083	1.02	.078	1.04	.081
180.4	.241	.144	.473	.104	.572	.101	.527	.108	.5	.116
203.1	.123	.204	.175	.174	.265	.149	.375	.129	.359	.139

Table A.3: Double differential cross sections for π^- 's produced at 105° to 125° from neutrons on carbon.

T(π)	T(n)					Carbon, π^-				
	(200,225)	(225,250)	(250,275)	(275,300)	(300,325)					
$\theta =$ (105°, 115°)										
25.6		.0924	.56	.308	.33	.228	.408	.679	.25	
40.1		.295	.174	.735	.116	1.218	.095	1.99	.079	
56.7		.297	.162	.609	.12	1.29	.087	1.71	.079	
75				.302	.162	.416	.146	.857	.107	
94.5						.157	.236	.35	.167	
115										
136.3										
158.1										
$\theta =$ (115°, 125°)										
25.6	.097	.333	.228	.213	.497	.152	.188	.14	.916	.125
40.1	.63	.115	.923	.094	1.50	.078	2.058	.07	2.94	.062
56.7	.333	.152	.444	.13	.811	.102	1.091	.092	1.86	.075
75					.181	.209	.315	.167	.682	.12
94.5									.183	.229
115										
136.3										
158.1										

T(π)	T(n)					Carbon, π^-				
	(325,350)	(350,375)	(375,400)	(400,425)	(425,450)					
$\theta =$	(105°, 115°)									
25.6	.876	.236	.969	.229	1.86	.174	1.47	.204	2.20	.18
40.1	2.90	.07	3.47	.065	4.73	.059	5.46	.057	8.46	.049
56.7	2.58	.069	3.37	.062	4.68	.055	5.474	.053	8.12	.047
75.	1.37	.091	1.75	.082	2.79	.069	3.15	.067	5.01	.057
94.5	.501	.149	.781	.122	1.47	.094	1.74	.09	2.69	.083
115.		.356	.177	.493	.158	.706	.137	1.31	.108	
136.3						.386	.186	.340	.213	
$\theta =$	(115°, 125°)									
25.6	1.41	.108	1.58	.104	2.48	.088	2.8	.086	3.63	.081
56.7	4.19	.056	4.79	.053	6.19	.049	7.69	.046	9.51	.044
75.	2.62	.067	3.46	.06	4.16	.058	5.6	.052	7.87	.047
94.5	.951	.108	1.50	.088	2.21	.077	2.83	.07	3.98	.064
115.	.414	.167	.489	.154	.802	.127	1.24	.106	2.07	.088
136.3		.262	.213	.503	.162	.584	.156	.627	.162	

T(π)	T(n)					Carbon, π^-				
	(450,475)	(475,500)	(500,525)	(525,550)	(550,575)					
$\theta = (105^\circ, 115^\circ)$										
25.6	2.63	.16	3.21	.147	3.88	.141	2.55	.18	2.63	.186
40.1	7.56	.051	8.60	.049	10.1	.047	9.63	.05	11.55	.048
56.7	9.03	.044	8.95	.045	10.6	.043	11.8	.042	12.5	.043
75.	5.42	.054	5.85	.053	8.13	.047	8.06	.049	7.85	.052
94.5	2.41	.08	3.44	.068	4.55	.063	5.07	.061	5.24	.063
115.	1.32	.106	1.79	.092	2.37	.085	1.83	.099	2.67	.063
136.3	.458	.18	.806	.137	.847	.141	.969	.136	1.19	.086
158.1		.360	.204	.333	.224	.531	.183	.819	.129	
$\theta = (115^\circ, 125^\circ)$										
25.6	4.17	.074	4.31	.074	5.59	.069	6.24	.067	5.80	.073
40.1	10.2	.042	10.8	.041	13.0	.04	14.4	.039	16.2	.039
56.7	7.95	.046	9.39	.043	10.9	.042	11.9	.041	12.3	.042
75.	4.55	.058	4.9	.057	6.87	.051	7.90	.049	8.134	.051
94.5	2.28	.082	2.73	.076	3.01	.077	4.21	.067	4.06	.071
115.	.883	.134	1.11	.121	1.61	.106	2.09	.096	1.95	.104
136.3	.465	.192	.533	.183	.731	.164	.837	.158	.948	.156
158.1	.						.480	.213	.532	.209

Table A.4: Double differential cross sections for π^- 's produced at 25° to 55° from neutrons on aluminum.

$T(\pi)$	$T(n)$					Aluminum, π^-				
	(200,225)	(225,250)	(250,275)	(275,300)	(300,325)					
$\theta = (25^\circ, 35^\circ)$										
25.6	4.33	.009	6.23	.075	7.51	.072	8.2	.073	9.94	.07
40.1	3.58	.009	5.68	.072	6.67	.07	9.57	.062	10.8	.061
56.7	2.24	.11	4.44	.076	6.61	.066	8.96	.06	12.4	.053
75	.833	.174	2.84	.092	5.94	.068	7.93	.062	11.4	.055
94.5			1.18	.141	3.4	.089	5.87	.071	8.84	.061
115			.42	.236	1.35	.139	3.7	.088	5.79	.075
136.3					.5	.236	1.8	.131	3.82	.095
158.1							.779	.213	2.2	.134
180.4									1.06	.209
203.1										
226.6										
249.3										
272.7										
$\theta = (35^\circ, 45^\circ)$										
25.6	4.11	.136	4.22	.132	6.09	.116	9.09	.101	7.45	.117
40.1	4.27	.115	5.04	.105	6.09	.101	8.44	.09	10.8	.084
56.7	2.22	.152	3.91	.113	5.4	.102	9.13	.082	10.3	.082
75		.814	.229	1.92	.147	4.26	.104	6.14	.092	.076
94.5			.854	.204	2.57	.124	4.37	.101	7.41	.081
115					.983	.196	2.53	.129	4.92	.098
136.3							1.06	.196	2.41	.137
158.1									1.02	.204
180.4										
203.1										
226.6										
249.3										
272.7										
$\theta = (45^\circ, 55^\circ)$										
25.6	1.08	.091	1.81	.07	2.54	.062	3.42	.056	3.72	.57
40.1	1.18	.09	1.78	.07	2.93	.057	4.43	.049	5.39	.047
56.7	.574	.135	1.22	.091	2.21	.078	3.23	.062	4.81	.054
75			.882	.25	2.07	.085	2.14	.089	3.61	.072
94.5					1.22	.132	1.87	.113	2.93	.095
115							1.16	.171	1.67	.151
136.3										
158.1										

T(π)			T(n)				Aluminum, π^-			
	(325,350)		(350,375)	(375,400)	(400,425)	(425,450)				
$\theta=$	(25°, 35°)									
25.6	13.2	.065	13.7	.065	14.3	.068	16.1	.066	18.2	.067
40.1	15.6	.054	15.7	.055	18.1	.054	20.8	.053	20.4	.057
56.7	14.9	.052	17	.05	19.6	.049	20.8	.049	23.4	.05
75.	14.2	.052	17	.049	18.3	.05	20.8	.048	25	.048
94.5	13.1	.054	13.5	.054	16.1	.052	18.9	.05	20.6	.051
115.	8.78	.065	11.7	.057	14	.055	14.6	.056	17.5	.055
136.3	6.88	.076	8.98	.056	11.9	.062	14.5	.059	17.6	.057
158.1	4.42	.101	6.38	.086	8.46	.079	12.6	.067	14.1	.068
180.4	2.96	.134	3.76	.121	6.02	.101	9.08	.085	12.3	.079
203.1	1.41	.209	2.56	.158	4.2	.13	5.6	.117	8.46	.103
226.6			1.39	.224	2.62	.171	3.58	.152	4.92	.14
249.3					1.91	.218	2.06	.218	4.54	.158
272.2										
$\theta=$	(35°, 45°)									
25.6	12.4	.097	10.3	.109	12.4	.105	13.7	.104	18.1	.097
40.1	9.89	.094	14.1	.081	16.5	.079	17.8	.079	21.4	.077
56.7	13.2	.077	14.4	.076	18.5	.71	21.2	.069	22.2	.072
75.	10.8	.078	13.5	.072	16.8	.068	18.2	.067	20.5	.068
94.5	10.2	.074	11.8	.071	13.6	.07	13.6	.072	18.8	.066
115.	7.58	.084	10.1	.075	10.2	.078	13	.072	16.3	.069
136.3	4.74	.105	6.6	.091	8.79	.083	10.9	.077	13.7	.074
158.1	2.01	.156	3.02	.13	5.92	.098	7.43	.091	9.82	.085
180.4	.975	.218	2.04	.154	2.81	.139	4.89	.109	6.96	.099
203.1					1.74	.18	3.15	.139	4.84	.12
226.6							1.62	.189	2.48	.164
249.3									1.66	.2
272.2										
$\theta=$	(45°, 55°)									
25.6	5.46	.05	6.08	.049	7.67	.046	8.96	.044	10.3	.044
40.1	7.5	.043	7.43	.044	9.85	.04	12.2	.037	14.6	.037
56.7	5.79	.053	6.48	.059	8.12	.048	10.6	.044	11.9	.044
75.	4.79	.067	3.44	.063	7.29	.059	8.37	.057	10.2	.055
94.5	3.88	.089	4.48	.085	5.58	.08	6.9	.075	8.84	.071
115.	2.44	.114	3.7	.111	4.47	.107	5.31	.102	6.8	.097
136.3	1.27	.229	2.59	.164	3.57	.147	4.02	.144	6.02	.127
158.1			2.09	.236	3.48	.192			4.18	.196

T(π)	T(n)					Aluminum, π^-				
	(450,475)	(475,500)	(500,525)	(525,550)	(550,575)					
$\theta = (25^\circ, 35^\circ)$										
25.6	16.9	.068	18.5	.066	21	.065	19.6	.07	18	.076
40.1	20.8	.056	23.4	.053	24.8	.055	24	.057	21	.064
56.7	21.4	.051	20.2	.054	24.2	.052	25.6	.052	25.2	.055
75.	21	.051	22.4	.05	24	.051	24.4	.052	22	.057
94.5	20.4	.051	18.7	.054	22.2	.052	20.4	.056	21.4	.062
115.	17.4	.054	18.5	.054	20.6	.053	18.7	.058	17.8	.064
136.3	16.5	.058	16.5	.059	18.2	.073	18.1	.061	17.8	.075
158.1	16.2	.062	16.7	.062	17	.065	17.2	.067	15.1	.079
180.4	12.8	.076	14.5	.072	17.8	.69	17	.073	15.8	.092
203.1	9	.097	10.1	.093	12.9	.087	14.3	.085	13.4	.108
226.6	7.08	.114	10.3	.093	7.3	.12	10.3	.104	10.6	.115
249.3	4.44	.156	6.06	.096	6.74	.136	6.2	.146	10.9	.183
272.2	3.58	.189	4.84	.136	4.64	.174	5.7	.162	4.98	
$\theta = (35^\circ, 45^\circ)$										
25.6	15.5	.103	16.1	.102	20.6	.095	19	.102	16.4	.115
40.4	17	.085	19.7	.08	16.9	.091	20.4	.085	19.1	.092
56.7	20.6	.073	22.3	.07	21.4	.077	22.2	.078	23.1	.08
75.	18.5	.07	22.9	.064	19.6	.073	20.9	.073	20.4	.078
94.5	17.3	.067	20.9	.062	19.4	.068	19.2	.07	18.6	.075
115.	16.7	.067	16.3	.069	20.8	.064	17.1	.073	16.3	.079
136.3	13.5	.073	16.3	.068	14.5	.076	14.1	.079	15	.081
158.1	9.31	.085	10.7	.081	12.5	.079	13.6	.078	13.5	.082
180.4	7.81	.091	9.59	.083	10.2	.085	9.42	.091	10.3	.092
203.1	5.43	.111	6.5	.103	7.24	.103	8.24	.1	7.83	.107
226.6	2.82	.151	5.22	.113	4.85	.123	5.84	.115	5.25	.128
249.3	1.9	.183	3.01	.113	3.28	.149	2.93	.162	3.75	.151
272.2	1.29	.224	1.87	.147	1.78	.204	2.05	.196	3.22	.164
$\theta = (45^\circ, 55^\circ)$										
25.6			11.1	.042	12.4	.042	13.1	.042	12.3	.046
40.1	15.5	.035	15.7	.035	17.9	.035	18.4	.035	17	.039
56.7	12.1	.043	13.2	.042	13.8	.043	16.1	.041	15.1	.044
75.	10.8	.053	10.1	.055	12.4	.052	12.8	.053	12.4	.057
94.5	9.5	.067	9.73	.067	10.2	.069	11.4	.067	11.5	.07
115.	7.58	.089	6.51	.098	9.26	.087	10	.086	6.27	.114
136.3	5.47	.13	5.94	.127	7.99	.115	8.24	.117	7.72	.118
158.1					4.62	.183			5.66	.177

Table A.5: Double differential cross sections for π^- 's produced at 55° to 85° from neutrons on aluminum.

T(π)	T(n)				Aluminum π^-					
	(200,225)	(225,250)	(250,275)	(275,300)	(300,325)					
$\theta = (55^\circ, 65^\circ)$										
25.6	.835	.127	1.61	.09	1.92	.087	2.21	.086	3.45	.076
40.1	1.13	.091	1.77	.071	2.99	.058	4.38	.051	5.36	.048
56.7	.563	.123	1.04	.089	2.16	.065	2.95	.059	4.64	.05
75	.135	.25	.46	.134	1.09	.092	1.79	.075	2.64	.066
94.5					.375	.152	1.16	.092	1.42	.087
115					.168	.236	.53	.14	.971	.109
136.3							.153	.258	.429	.164
158.1										
180.4										
203.1										
226.6										
$\theta = (65^\circ, 75^\circ)$										
25.6	.981	.25								
40.1	.586	.141	1.29	.094	2.09	.078	2.84	.071	4.08	.062
56.7	.321	.167	1.15	.088	1.88	.072	2.99	.061	3.95	.056
75			.376	.151	1.1	.092	1.94	.074	3.06	.062
94.5					.429	.144	1.09	.096	1.47	.087
115							.447	.151	.779	.12
136.3							.191	.224	.339	.177
158.1										
180.4										
203.1										
226.6										
$\theta = (75^\circ, 85^\circ)$										
25.6	.263	.408	.596	.267	.852	.236	.845	.25	1.47	.2
40.1	.577	.134	1.01	.1	1.52	.085	2.32	.073	3.49	.063
56.7	.258	.183	.677	.111	1.49	.079	2.16	.069	3.79	.055
75			.292	.162	.879	.099	1.28	.086	1.94	.074
94.5					.229	.189	.557	.128	1.1	.096
115							.227	.2	.555	.135
136.3									.194	.224
158.1										
180.4										
203.1										

T(π)	T(n)			Aluminum π^-						
	(325,350)	(350,375)	(375,400)	(400,425)	(425,450)					
$\theta = (55^\circ, 65^\circ)$										
25.6	4.12	.071	4.66	.068	5.81	.064	6.91	.061	8.53	.059
40.1	7.61	.043	8.33	.042	10.5	.04	12.1	.038	15.7	.036
56.7	5.85	.047	7	.044	9.51	.04	10.5	.04	12.9	.039
75.	4.11	.056	4.83	.053	5.75	.051	7.83	.046	9.33	.045
94.5	2.48	.071	2.98	.066	3.88	.061	4.59	.058	6.7	.052
115.	1.57	.092	1.78	.088	2.65	.076	3.11	.073	4.28	.067
136.3	.639	.144	1.07	.114	1.67	.096	1.99	.092	2.73	.084
158.1	.406	.183	.737	.139	1.2	.115	1.27	.115	1.79	.105
180.4			.381	.189	.553	.174	.79	.149	1.18	.131
203.1					.459	.196	.514	.192	.97	.151
226.6									.446	.229
$\theta = (65^\circ, 75^\circ)$										
25.6										
40.1	5.4	.058	6.36	.054	8.11	.051	8.88	.05	10.8	.049
56.7	5.51	.05	6.09	.049	8.14	.045	9.77	.042	11.5	.042
75.	3.99	.058	5.2	.053	6.44	.049	7.78	.047	9.47	.046
94.5	2.52	.071	2.85	.068	4.16	.06	5.6	.053	6.32	.054
115.	1.09	.109	1.87	.085	2.53	.077	3.25	.071	4.43	.065
136.3	.609	.141	.867	.121	.992	.12	1.42	.104	2.37	.086
158.1	.343	.192	.479	.167	.784	.137	1.07	.123	1.26	.121
180.4					.43	.183	.402	.196	.734	.156
203.1				.306	.224			.382	.224	
226.6										
$\theta = (75^\circ, 85^\circ)$										
25.6	2.49	.164	1.48	.218	1.88	.204	2.28	.192	3.04	.18
40.1	4.97	.056	5.65	.054	6.61	.053	8.97	.047	10.2	.048
56.7	5.41	.049	6.53	.046	8.53	.042	10.7	.039	13.3	.04
75.	3.24	.061	4	.056	5.38	.051	6.56	.048	8.48	.046
94.5	1.81	.08	2.27	.073	2.98	.067	4.62	.56	6.03	.053
115.	.822	.119	1.15	.103	1.82	.086	2.15	.082	2.95	.076
136.3	.278	.2	.629	.136	.725	.134	.964	.12	1.49	.1
158.1					.327	.2	.367	.196	.818	.141
180.4									.454	.189

T(π)			T(n)				Aluminum π^-			
	(450,475)		(475,500)		(500,525)		(525,550)		(550,575)	
$\theta = (55^\circ, 65^\circ)$										
25.6	8.4	.059	8.61	.059	10.1	.057	9.35	.061	10.1	.062
40.1	15.7	.036	16.3	.035	20.2	.034	18.6	.036	20.2	.036
56.7	13	.037	15.2	.035	15.6	.037	16.1	.037	15.1	.04
75.	9.37	.044	11.6	.04	11.9	.042	11.8	.043	12.6	.044
94.5	6.39	.052	7.21	.05	7.92	.05	7.95	.051	9.08	.051
115.	4.53	.064	4.64	.064	5.65	.061	6.52	.055	6.1	.063
136.3	2.75	.082	3.49	.074	4.27	.071	4.27	.073	4.7	.072
158.1	2.35	.089	2.21	.094	2.96	.085	3.09	.086	3.1	.089
180.4	1.13	.131	1.65	.11	1.9	.108	1.82	.114	1.88	.117
203.1	.905	.152	.891	.156	1.21	.141	1.41	.135	1.34	.144
226.6			.809	.169	.849	.174	1.12	.156	.983	.174
249.3					.464		.636	.213	.728	.209
$\theta = (65^\circ, 75^\circ)$										
25.6										
40.1	11.9	.046	13.4	.044	14.2	.045	14.8	.045	14.3	.049
56.7	13.3	.038	13.9	.038	15.5	.038	16.1	.038	15.2	.041
75.	9.98	.043	11.4	.041	12.2	.042	14.7	.39	13	.044
94.5	6.53	.052	7.42	.05	9.08	.047	9.28	.048	9.2	.051
115.	4.75	.062	5.3	.59	6.53	.056	7.19	.056	7.04	.059
136.3	2.64	.08	3.21	.074	4.04	.069	3.98	.073	3.57	.08
158.1	1.45	.11	1.75	.102	2.03	.1	2.91	.087	2.33	.101
180.4	.889	.139	1.32	.115	1.1	.134	1.61	.115	1.72	.115
203.1			.791	.154	.796	.162	1.08	.144	1.18	.144
226.6					.516	.196	.361			
$\theta = (75^\circ, 85^\circ)$										
25.6	1.78	.229	2.99	.18	3.76	.169	3.99	.169	4.27	.171
40.1	11.1	.045	12	.044	13.6	.043	14.5	.043	13.5	.047
56.7	14.2	.036	14.9	.036	17.1	.035	17.6	.036	17.8	.037
75.	9.96	.041	9.78	.042	12.7	.039	12.6	.04	13.7	.041
94.5	5.81	.053	6.61	.05	7.82	.049	7.74	.05	7.87	.053
115.	3.38	.069	3.45	.69	4.53	.064	4.8	.64	5.34	.064
136.3	1.64	.097	1.92	.091	1.99	.094	2.63	.085	2.99	.083
158.1	.984	.126	1.15	.119	1.17	.124	1.37	.118	1.36	.124
180.4	.743	.144	.543	.171	.8	.149	.829	.151	.873	.154
203.4			.327	.224	.419	.209	.482	.2	.383	.236

Table A.6: Double differential cross sections for π^- 's produced at 105° to 125° from neutrons on aluminum.

T(π)	T(n)						Aluminum, π^-			
	(200,225)		(225,250)		(250,275)		(275,300)		(300,325)	
<hr/>										
$\theta=$	(105°, 115°)									
25.6	.583	.243	.4	.289	.445	.289	.991	.24	1.29	.189
40.1	.319	.177	.861	.106	1.36	.89	2.47	.07	3.57	.061
56.7	.288	.174	.627	.116	1.27	.086	1.81	.076	3.27	.06
75			.178	.29	.396	.147	.585	.128	1.39	.088
94.5					.136	.25	.284	.183	.641	.128
115									.181	.236
136.3										
158.1										
<hr/>										
$\theta=$	(115°, 125°)									
25.6	.289	.2	.54	.144	1.08	.108	1.37	.101	2.42	.08
40.1	1.11	.091	1.6	.074	2.38	.064	4.02	.052	5.36	.048
56.7	.57	.121	.717	.107	1.3	.083	2.13	.069	3.34	.058
75	.134	.243	.153	.224	.264	.18	.655	.12	1.22	.093
94.5							.132	.267	.262	.2
115										
136.3										

T(π)	T(n)					Aluminum, π^-				
	(325,350)	(350,375)	(375,400)	(400,425)	(425,450)					
$\theta = (105^\circ, 115^\circ)$										
25.6	1.84	.169	2.26	.156	3.68	.129	3.57	.136	4.75	.127
56.7	4.87	.056	6.23	.051	8.45	.046	10.2	.043	14	.04
75.	4.49	.055	5.75	.049	8.18	.044	9.48	.042	11.9	.04
94.5	2.11	.076	3.52	.06	4	.06	5.94	.051	7.03	.05
115.	1.01	.109	1.38	.096	2.39	.077	3.06	.07	4.14	.065
136.3	.207	.236	.457	.162	.735	.135	1.18	.11	1.82	.096
158.1			.156	.277	.227	.243	.462	.177	.669	.158
180.4									.214	.277
$\theta = (115^\circ, 125^\circ)$										
25.6	2.83	.079	3.82	.07	4.2	.07	5.47	.064	5.93	.066
40.1	7.22	.044	9.4	.039	11	.038	13.3	.036	16.5	.035
56.7	4.84	.052	5.89	.048	7.28	.045	9.4	.041	13.1	.038
75.	1.91	.08	2.71	.068	3.34	.065	4.56	.058	6.69	.051
94.5	.566	.146	1.08	.108	1.47	.098	1.95	.088	3.34	.072
115.	.246	.224	.245	.229	.572	.158	.71	.147	1.52	.108
136.3					.203	.277	.269	.25	.507	.196

T(π)	T(n)					Aluminum, π^-				
	(450,475)	(475,500)	(500,525)	(525,550)	(550,575)					
$\theta = (105^\circ, 115^\circ)$										
25.6	4.69	.125	4.23	.134	5.8	.12	6.15	.12	5.02	.14
40.1	13.5	.04	14.2	.039	17.2	.038	17.9	.038	17.7	.04
56.7	13.2	.038	13.3	.038	16.8	.036	18.2	.035	19.1	.036
75.	8.42	.045	9.21	.044	12.7	.043	12.2	.041	12.6	.043
94.5	4.57	.061	5.74	.055	5.62	.059	6.97	.054	7.47	.055
115.	1.61	.1	2.62	.079	2.79	.081	3.53	.074	3.73	.076
136.3	.735	.147	1.17	.119	.673	.122	1.63	.109	1.91	.106
158.1	.22	.267	.471	.186	.488	.192	.517	.192	.718	.171
180.4			.249	.25	.19	.302	.33	.236	.304	.258
$\theta = (115^\circ, 125^\circ)$										
25.6	7.14	.059	7.93	.057	9.36	.055	9.56	.056	9.09	.06
40.1	18.3	.033	19.6	.032	21.9	.032	22.9	.032	25.1	.032
56.7	11.8	.039	13.7	.037	17.2	.034	20.2	.033	21.4	.034
75.	6.64	.05	8.32	.046	9.46	.045	10.9	.043	12.6	.042
94.5	3.38	.07	4.87	.06	5.05	.062	6.08	.058	5.75	.063
115.	1.61	.103	1.69	.102	2.26	.093	2.37	.094	3.19	.085
136.3	.652	.169	1.13	.13	1.22	.132	1.22	.136	1.4	.134
158.1			.489	.209	.402	.243	.651	.196	.525	.229

Table A.7: Double differential cross sections for π^- 's produced at 25° to 55° from neutrons on copper.

	T(n)				Copper, π^-				
T(π)	(200,225)	(225,250)	(250,275)	(275,300)	(300,325)				
$\theta=$	(25°, 35°)								
25.6	5.73	9.02	.079	11.53	.074	15.2	.068	18.9	.064
40.1	6.05	8.91	.072	13.38	.062	17.8	.057	22.4	.054
56.7	3.47	7.1	.076	11.8	.062	15.9	.057	20.1	.053
75	1.63	4.33	.095	9.34	.068	13.5	.06	20.6	.051
94.5	.752	1.73	.147	5.75	.085	9.67	.07	15.5	.058
115				2.32	.134	8.2	.075	11.2	.068
136.3						3.1	.126	6.96	.089
158.1						1.18	.218	3.26	.139
180.4									
203.1									
226.6									
249.3									
272.7									
$\theta=$	(35°, 45°)								
25.6	4.07	7.9	.122	9.84	.115	12.6	.108	13.3	.11
40.1	5.22	8.11	.104	10.3	.098	9.51	.107	16	.087
56.7	3.55	6.15	.114	8.16	.104	12.7	.088	16.1	.083
75	1.18	3.59	.136	6.86	.104	9.55	.093	12.9	.084
94.5		1.19	.218	3.03	.144	5.47	.113	8.99	.083
115				1.33	.213	3.22	.113	5.67	.115
136.3						1.69	.144	3.03	.154
158.1									
180.4									
203.1									
226.6									
249.3									
272.7									
$\theta=$	(45°, 55°)								
25.6		3.18	.067	4.62	.058	6.42	.052	7.88	.05
40.1		3.93	.06	6.62	.048	8.97	.044	11.6	.041
56.7		2.96	.076	6.08	.055	8.1	.05	11.4	.045
75		1.92	.115	3.85	.08	6.58	.064	11.1	.052
94.5		.659	.267	2.41	.124	4.7	.091	6.96	.09
115						2.17	.16	4.69	.115
136.3									
158.1									
180.4									

T(π)	T(n)						Copper, π^-			
	(325,350)	(350,375)	(375,400)	(400,425)	(425,450)					
$\theta =$	(25°, 35°)									
25.6	23.4	.062	23.6	.063	29.8	.059	31.2	.06	37.6	.059
40.1	27.2	.052	28.6	.052	30.8	.053	34.1	.052	36.7	.054
56.7	23.9	.052	28.6	.049	30	.05	36	.047	40.5	.048
75.	23.	.052	29.1	.047	34.1	.046	34.7	.047	41.2	.047
94.5	22.5	.052	24.9	.05	30.8	.047	31	.049	43.1	.045
115.	17.3	.058	23.7	.051	2.8	.049	32.7	.047	38.6	.047
136.3	11.6	.074	18	.061	26	.053	27.5	.054	39.3	.048
158.1	9.13	.089	13.9	.061	18.9	.067	26.5	.058	33.1	.056
180.4	3.95	.146	6.18	.074	11.3	.093	20.1	.073	25.6	.069
203.1			3.5	.12	6.57	.131	10.4	.108	16.4	.093
226.6							3.45	.196	7.99	.139
249.3										
272.7										
$\theta =$	(35°, 45°)									
25.6	21.8	.092	16.6	.108	22.9	.098	25.1	.097	33.4	.09
40.1	18.9	.086	19.4	.087	26	.079	24.6	.084	29.8	.082
56.7	19.4	.081	23.7	.075	29.1	.071	29.5	.073	28.8	.08
75.	15.9	.081	16.8	.08	20.1	.078	22.9	.076	30	.071
94.5	12.8	.084	15.7	.077	16.4	.08	19.4	.082	26.7	.07
115.	10.5	.09	11.3	.089	16.9	.077	15.9	.083	22.9	.074
136.3	6.48	.113	8.26	.103	11.9	.09	15	.093	15.9	.087
158.1	2.56	.174	3.92	.144	7.52	.11	11.2	.108	15.1	.087
180.4			2.95	.162	5.16	.129	7.88	.149	8.71	.111
203.1					2.15	.204	4.33	.186	8.28	.116
226.6									4.05	.162
249.3										
272.2										
$\theta =$	(45°, 55°)									
25.6	10.4	.046	11.4	.045	13.8	.044	16.6	.041	20.1	.04
40.1	13.7	.04	16.8	.037	20.5	.035	22.6	.035	27.5	.034
56.7	14.4	.042	17.1	.04	19.3	.04	24.1	.037	28.8	.036
75.	14.1	.05	16.2	.047	19	.046	24.6	.042	29.2	.042
94.5	11.3	.066	13.5	.062	18.4	.056	22	.053	28.6	.05
115.	5.46	.113	9.65	.088	12.5	.081	14.8	.078	19.9	.07
136.3	4.88	.149	5.79	.14	9.84	.113	12.2	.105	19.2	.091
158.1			4.71	.2	5.23	.2	11.1	.143	11.8	.149
180.4										

T(π)	T(n)				Copper, π^-					
	(450,475)	(475,500)	(500,525)	(525,550)	(550,575)					
$\theta = (25^\circ, 35^\circ)$										
25.6	32.7	.062	31.5	.064	37.1	.116	37.6	.063	35	.069
40.1	38.1	.052	40.7	.051	45.2	.062	40.2	.056	37.1	.061
56.7	37.9	.049	36.9	.05	42.1	.051	38.1	.054	36	.058
75.	37.8	.048	43	.045	40.9	.05	39.8	.051	37.4	.055
94.5	36.7	.047	40	.046	39.5	.049	37.4	.052	33.8	.057
115.	34.7	.049	37.4	.047	41.6	.049	36.6	.052	33.1	.058
136.3	35.3	.05	36.9	.049	41.4	.048	39.3	.052	35.7	.057
158.1	33.6	.055	38.3	.052	41.1	.049	37.6	.057	34	.063
180.4	31.4	.061	30.1	.063	36.6	.053	33.8	.065	31.7	.07
203.1	18.4	.086	22.7	.079	29.1	.061	28.6	.076	28.6	.08
226.6	10.6	.118	15.4	.099	17	.073	24.9	.085	25.3	.088
249.3	8.47	.16	9.46	.137	14.1	.1	17.8	.108	15.8	.121
272.2					6.55	.119	9.32	.16	14.3	.136
$\theta = (35^\circ, 45^\circ)$										
25.6	30.1	.093	27.9	.098	30.3	.099	26.5	.109	15.1	.118
40.1	31.4	.079	30.3	.081	31.9	.084	35.5	.081	30.5	.092
56.7	26.9	.081	32.9	.074	33.8	.077	31	.083	34.3	.083
75.	29.8	.07	29.6	.071	32.2	.072	30.8	.076	26.5	.086
94.5	24.3	.072	23	.075	25.8	.074	24.8	.078	24.4	.083
115.	20.3	.077	24.6	.071	29.8	.068	25.5	.075	23.2	.083
136.3	21.1	.074	18.9	.079	22.2	.077	20.3	.083	18.4	.092
158.1	18.5	.076	15	.086	18.2	.082	19.6	.082	14.5	.1
180.4	10.9	.097	13	.09	17.7	.082	14.3	.082	14.4	.098
203.1	8	.115	9.37	.108	10.9	.106	10.9	.094	10.3	.118
226.6	4.8	.146	7.05	.122	8.56	.117	8.94	.109	8.49	.127
249.3	5.42	.139	6.62	.132	5.28	.118	6.38	.146		
272.2	3.31	.189	3.52	.152	3.88	.189				
$\theta = (45^\circ, 55^\circ)$										
25.6	19.6	.04	20.9	.039	23.9	.039	23.8	.065	24.6	.041
40.1	29.2	.032	31.3	.032	34.2	.032	35	.033	36.7	.033
56.7	29.1	.035	33.2	.034	34.8	.035	37.1	.034	35.5	.037
75.	31.3	.039	31.5	.04	38	.038	38.5	.039	37.2	.042
94.5	25.9	.052	32.9	.046	34	.048	34	.05	32.3	.054
115.	23.9	.064	24.2	.065	26.6	.065	29.8	.063	24.2	.074
136.3	18.4	.091	17.7	.094	23.9	.085	25.7	.085	22.9	.094
158.1			15.2	.128	18.6	.118	16.9	.13	25.2	.11
180.4									11.3	.213

Table A.8: Double differential cross sections for π^- 's produced at 55° to 85° from neutrons on copper.

T(π)	T(n)				Copper, π^-				
	(200,225)	(225,250)	(250,275)	(275,300)	(300,325)				
$\theta =$ (55°, 65°)									
25.6	1.1	2.5	.092	3.32	.085	4.87	.074	5.44	.074
40.1	2.57	3.55	.064	5.88	.053	8.31	.047	10.8	.043
56.7	.698	2.35	.076	4.31	.059	6.95	.049	8.89	.046
75	.149	1.01	.115	2.58	.076	3.92	.065	5.91	.056
94.5				.962	.124	2.52	.081	3.63	.071
115						1.15	.121	2.05	.096
136.3								.85	.149
158.1									
180.4									
203.1									
226.6									
$\theta =$ (65°, 75°)									
25.6		1.75	.236	3.22	.183	2.88	.204	3.86	.186
40.1		2.05	.095	3.31	.079	5.52	.064	6.86	.061
56.7		1.87	.088	3.02	.073	4.95	.06	6.81	.054
75		.61	.149	1.91	.09	3.3	.072	4.55	.065
94.5				.798	.135	1.68	.098	2.39	.087
115						.664	.16	1.4	.116
136.3								.406	.209
158.1									
180.4									
203.1									
226.6									
$\theta =$ (75°, 85°)									
25.6		.826	.289	1.53	.224	1.19	.267	2.09	.213
40.1		1.84	.094	2.95	.078	4.73	.065	5.95	.061
56.7		1.1	.11	2.76	.074	4.63	.06	6.23	.055
75		.533	.152	1.12	.111	2.23	.083	3.37	.071
94.5				.569	.152	1.11	.115	1.64	.1
115						.393	.196	.589	.169
136.3								.385	.204
158.1									
180.4									
203.1									

T(π)	T(n)					Copper, π^-				
	(325,350)	(350,375)	(375,400)	(400,425)	(425,450)					
$\theta = (55^\circ, 65^\circ)$										
25.6	7.7	.066	8.38	.065	10.7	.061	11.9	.06	14.4	.058
40.1	14.2	.041	16.2	.039	20.6	.036	24.5	.035	29.4	.034
56.7	11.6	.043	13.1	.041	16.9	.038	21.3	.036	25.9	.035
75.	9.01	.049	10.8	.045	14.1	.042	15.5	.041	21.7	.038
94.5	6.23	.058	6.86	.057	9.95	.05	11.6	.048	16	.044
115.	3.11	.083	4.64	.07	5.91	.065	8.71	.056	11.4	.053
136.3	1.54	.119	2.91	.088	3.41	.086	4.82	.075	7.48	.065
158.1	.883	.158	1.34	.131	2.21	.108	2.69	.102	5.01	.08
180.4					.69	.196	1.2	.154	2.29	.12
203.1										
226.6										
$\theta = (65^\circ, 75^\circ)$										
25.6	5.81	.162	4.96	.18	6.23	.169	9.4	.143	8.01	.167
40.1	9.54	.055	11.7	.052	14.5	.048	15.5	.049	21.3	.045
56.7	9.9	.048	11.7	.045	14.9	.042	17.2	.047	22.7	.038
75.	7.28	.055	8.41	.052	10.8	.049	14.3	.044	18	.042
94.5	4.09	.071	5.32	.064	7.13	.058	8.99	.054	12.7	.049
115.	2.52	.093	3.34	.082	4.88	.072	5.97	.068	8.12	.062
136.3	.911	.149	1.36	.125	2.33	.101	3.15	.09	4.13	.083
158.1			.639	.186	1.08	.151	1.56	.13	2.66	.107
180.4					.59	.2	.764	.183	1.18	.158
203.1								.911	.186	
226.6										
$\theta = (75^\circ, 85^\circ)$										
25.6	2.72	.2	2.74	.204	3.04	.204	3.82	.189	5.38	.171
40.1	8.13	.056	11	.049	11.8	.05	14	.048	17.3	.046
56.7	9.84	.047	11.4	.049	13.8	.042	17.3	.039	22.1	.037
75.	5.04	.062	7.54	.052	9.38	.049	11.5	.046	14.8	.044
94.5	2.99	.079	4.02	.07	5.69	.062	6.89	.059	10.2	.052
115.	1.45	.115	2.36	.092	2.87	.088	4.55	.073	5.76	.07
136.3	.553	.183	.906	.146	1.35	.126	1.87	.111	3.11	.093
158.1			.504	.196	.969	.258	1.07	.147	1.83	.121
180.4							.734	.177	.771	.186
203.1										

T(π)	T(n)					Copper, π^-				
	(450,475)	(475,500)	(500,525)	(525,550)	(550,575)	(450,475)	(475,500)	(500,525)	(525,550)	(550,575)
$\theta = (55^\circ, 65^\circ)$										
25.6	14.7	.056	15.1	.057	19	.053	17.2	.058	17.7	.06
40.1	31.5	.032	32.3	.032	35.7	.032	36.3	.033	35.4	.035
56.7	26.6	.033	28.8	.033	30.7	.033	29.7	.035	31.4	.036
75.	21.8	.037	22.7	.037	23.7	.038	27	.036	24.2	.04
94.5	15.8	.043	18.4	.041	20.5	.04	21	.041	20.2	.044
115.	13.8	.047	14	.047	15.8	.047	16.6	.047	17.1	.049
136.3	8.32	.06	9.89	.056	10.9	.056	11.8	.056	12.2	.058
158.1	5.24	.076	6.33	.071	8.76	.082	8.28	.067	8.19	.071
180.4	3.2	.1	3.99	.091	4.22	.12	4.66	.091	6.13	.083
203.1	1.89	.135	1.95	.135	2.76	.186	3.05	.117	3.55	.114
226.6			1.32	.169			1.56	.169	1.67	.171
$\theta = (65^\circ, 75^\circ)$										
25.6	9.77	.147	7.46	.171	9.03	.164	11.6	.149	10.8	.162
40.1	21.1	.044	21.8	.044	23.5	.045	24.9	.045	24.4	.047
56.7	22.8	.037	23.6	.037	28.6	.036	27.2	.038	25.9	.04
75.	19.3	.04	19.7	.04	23.6	.038	22.9	.04	22.5	.043
94.5	12	.049	15.2	.044	16.4	.045	18	.044	17.3	.471
115.	10.2	.054	9.34	.058	12.9	.052	13.1	.053	12.4	.057
136.3	5.71	.07	6.68	.066	7.56	.065	7.56	.067	7.18	.073
158.1	2.98	.099	3.83	.089	4.5	.086	4.59	.088	5.02	.088
180.4	1.97	.12	2.36	.111	2.43	.115	2.4	.12	3.41	.106
203.1	1.05	.169	1.15	.164	1.62	.146	1.72	.146	1.33	.174
226.6	.911	.189	1.07	.174						
$\theta = (75^\circ, 85^\circ)$										
25.6	4.69	.18	5.15	.174	3.99	.209	5.34	.186	4.88	.204
40.1	19.5	.043	20.8	.042	23.8	.041	22.1	.044	23.4	.045
56.7	23.8	.035	26.5	.034	28.7	.034	28.4	.036	29.2	.037
75.	17.7	.039	18.3	.039	22.3	.037	21.4	.039	22.3	.057
94.5	10.4	.05	12.5	.046	14.2	.046	15.3	.046	15.2	.048
115.	6.62	.064	7.45	.061	9.21	.058	9.92	.057	10.4	.059
136.3	3.74	.083	4.75	.075	5.94	.07	5.73	.074	6.43	.073
158.1	2.39	.104	2.73	.099	2.98	.1	3.5	.094	3.73	.096
180.4	1.19	.146	1.18	.149	1.81	.126	2.01	.124	2.56	.115
203.1	.674	.196	.695	.196	.863	.186	1.04	.174	1.32	.162

Table A.9: Double differential cross sections for π^- 's produced at 105° to 115° from neutrons on copper.

T(π)	T(n)								Copper, π^-	
	(200,225)		(225,250)		(250,275)		(275,300)		(300,325)	
$\theta = (105^\circ, 115^\circ)$										
25.6	.437	.408	.707	.316	1.02	.277	1.67	.229	2.92	.183
40.1	.655	.18	1.58	.114	2.83	.089	5.04	.071	7.22	.063
56.7	.537	.186	1.37	.115	1.82	.105	3.32	.819	6.37	.062
75			.263	.25	.657	.167	1.28	.126	2.47	.096
94.5							.482	.204	.959	.152
115									.369	.243
136.3										
158.1										
$\theta = (115^\circ, 125^\circ)$										
25.6	.469	.229	1.15	.144	1.15	.152	2.97	.1	4.13	.089
40.1	1.9	.101	2.7	.084	4.93	.065	4.77	.057	9.59	.052
56.7	1.02	.132	1.16	.122	2.18	.094	3.94	.074	5.45	.066
75					.671	.164	.971	.144	1.64	.117
94.5									.425	.229
115										
136.3										
158.1										
180.4										

T(π)	T(n)				Copper, π^-	
	(325,350)	(350,375)	(375,400)	(400,425)	(425,450)	
$\theta = (105^\circ, 115^\circ)$						
25.6	3.24	.186	3.05	.196	4.16	.177
40.1	9.71	.058	12.1	.053	16.1	.048
56.7	8.02	.06	10.8	.052	11.9	.053
75.	3.56	.085	5.3	.072	6.8	.06
94.5	1.92	.115	2.01	.115	3.16	.097
115.	.317	.277	.817	.177	1.3	.147
136.3			.307	.289	.426	.258
158.1					.796	.196
						1.07
						.183
						.419
						.289
$\theta = (115^\circ, 125^\circ)$						
25.6	5.42	.084	7.54	.073	8.51	.072
40.1	14	.046	17.6	.042	21.2	.04
56.7	8.16	.058	9.86	.054	14.7	.047
75.	3.2	.089	4.78	.075	6.43	.068
94.5	1.13	.151	1.59	.13	2.66	.106
115.			.549	.223	.763	.2
136.3						1.71
158.1						.139
180.4						2.14
						.134
						.666
						.25

T(π)	T(n)				Copper, π^-					
	(450,475)	(475,500)	(500,525)	(525,550)	(550,575)					
$\theta =$ (105°, 115°)										
25.6	7.3	.146	8.5	.137	10.2	.132	12.7	.122	10.4	.141
40.1	25.3	.042	29.3	.04	33.1	.04	34.6	.04	37.3	.04
56.7	24.3	.04	26.1	.04	31.9	.038	34.2	.037	35.8	.038
75.	13.6	.052	17.7	.046	16.9	.05	20.1	.047	24.2	.045
94.5	7.01	.071	8.81	.065	11	.061	12.2	.059	12.5	.062
115.	3.69	.096	3.64	.098	4.94	.089	5.56	.086	5.82	.088
136.3	1.32	.16	1.64	.146	2.38	.128	2.35	.132	2.78	.128
158.1	.434	.277	.551	.25	.958	.2	.934	.209	.897	.224
$\theta =$ (115°, 125°)										
25.6	13	.064	14.1	.062	19.2	.056	18.4	.059	21.4	.057
40.1	31.2	.036	34.4	.035	41.5	.034	43.4	.034	45.9	.035
56.7	21.9	.042	26.2	.039	29.2	.039	34.6	.037	36.6	.037
75.	11.4	.056	12.4	.055	15.8	.051	20.1	.047	19	.05
115.	6.17	.076	6.92	.073	8.8	.068	10.3	.065	11.1	.066
136.3	1.97	.185	3.42	.105	4.31	.099	5.24	.092	5.19	.097
158.1	.914	.209	1.15	.189	1.6	.169	1.79	.164	2.72	.14
180.4			.544	.289	.706	.267	.694	.277	.943	.25

Table A.10: Double differential cross sections for π^- 's produced at 25° to 55° from neutrons on tungsten.

T(π)	T(n)					Tungsten, π^-				
	(200,225)	(225,250)	(250,275)	(275,300)	(300,325)					
$\theta = (25^\circ, 35^\circ)$										
25.6	4.39	.209	19.2	.1	26.6	.089	31.1	.087	40.6	.144
40.1	5.02	.189	19.5	.09	27.1	.081	37.3	.073	41.7	.081
56.7	2.81	.267	11.4	.11	17.7	.093	27.2	.08	40.4	.072
75			7.17	.136	15.1	.099	27.3	.078	30.9	.069
94.5			2.69	.218	5.7	.158	13.3	.109	28.6	.077
115					3.79	.192	12.1	.114	17.9	.099
136.3							4.02	.204	11.2	.126
158.1									5.11	.204
180.4										
203.1										
226.6										
249.3										
272.7										
$\theta = (35^\circ, 45^\circ)$										
25.6		14	.169	20.9	.146	24.3	.143	33.1	.129	
40.1		13.5	.149	18.3	.135	31.2	.109	38	.104	
56.7		12.7	.146	18.4	.128	26.5	.113	29.1	.113	
75		6.54	.186	11.3	.149	16.5	.13	23	.116	
94.5		1.73	.186	4.93	.209	9.07	.162	15.7	.13	
115						3.88	.243	8.11	.177	
136.3								5.16	.218	
158.1										
180.4										
203.1										
226.6										
$\theta = (45^\circ, 55^\circ)$										
25.6		7.18	.089	9.25	.083	14.8	.069	16.3	.07	
40.1		6.95	.09	14.5	.066	17.2	.064	23.2	.071	
56.7		4.63	.12	11	.082	16	.072	21.9	.065	
75		3.63	.156	9.15	.104	13.9	.058	18.8	.081	
94.5		1.64	.277	4.34	.18	9.83	.089	14.2	.11	
115						4.91	.126	9.92	.158	
136.3								4.17	.302	
158.1										

T(π)			T(n)			Tungsten, π^-				
	(325,350)		(350,375)	(375,400)		(400,425)		(425,450)		
$\theta = (25^\circ, 35^\circ)$										
25.6	43.9	.083	52	.078	64.8	.074	70.3	.074	67.9	.081
40.1	50.4	.071	57.4	.068	63	.068	72.3	.066	76.2	.069
56.7	39.1	.075	48.7	.069	58	.066	59.2	.068	58.8	.074
75.	44.5	.069	46.8	.069	44.2	.074	53.5	.07	67.5	.067
94.5	37.1	.074	36.3	.076	45.3	.072	53.7	.069	61.6	.069
115.	25.8	.088	33	.08	45.6	.071	53.7	.069	55.5	.072
136.3	18.2	.108	26	.093	35.6	.084	46.9	.076	52.6	.077
158.1	13.7	.134	21.5	.109	27.6	.102	33.1	.096	46.9	.087
180.4	6.29	.213	9.88	.174	15.6	.146	28	.113	33.7	.111
203.1							13.7	.174	28.4	.13
226.6									11	.22
249.3										
272.2										
$\theta = (35^\circ, 45^\circ)$										
25.6	34.2	.136	43.8	.123	57.5	.113	59.7	.115	75.6	.11
40.1	32.2	.121	42.2	.108	47.4	.108	61.8	.098	62.7	.105
56.7	42	.101	48	.097	59.4	.092	54.3	.1	68	.096
75.	38.5	.096	35.1	.103	44	.097	48.3	.092	51.9	.1
94.5	22.9	.115	21.7	.121	34.7	.101	39	.099	36.4	.11
115.	16.9	.131	21.3	.12	30.8	.105	28.5	.113	42	.101
136.3	12.7	.149	12.1	.156	15.8	.144	20.5	.131	32.4	.113
158.1	4.24	.25	4.71	.243	11.1	.167	15.3	.147	23.9	.127
180.4					6.14	.218	8.52	.192	15	.156
203.1							4.91	.192	5.7	.258
226.6										
$\theta = (45^\circ, 55^\circ)$										
25.6	19.5	.068	23.9	.063	29.1	.06	36.3	.056	45.2	.055
40.1	29.7	.055	31.3	.054	37.5	.052	46.2	.049	62.4	.045
56.7	29.9	.059	31.8	.059	43.2	.053	44.2	.054	58.4	.051
75.	23.5	.077	30.2	.07	41.4	.063	49.5	.06	57	.06
94.5	20.7	.098	25.9	.09	31.3	.086	43.5	.076	49.8	.076
115.	13	.147	18.2	.128	23.5	.119	28.9	.111	39.8	.102
136.3	6.97	.25	14.6	.177	18.7	.164	22.9	.154	32.3	.14
158.1										

T(π)			T(n)			Tungsten, π^-				
	(450,475)		(475,500)	(500,525)		(525,550)	(550,575)			
$\theta = (25^\circ, 35^\circ)$										
25.6	66.7	.079	66.9	.081	71	.082	73.2	.084	65.6	.093
40.1	69.8	.071	70	.072	76.7	.072	82.6	.072	60.3	.088
56.7	56.3	.074	66.8	.069	75.7	.068	69.8	.073	62.3	.081
75.	57.6	.071	69	.067	69.7	.069	64.6	.074	72.1	.074
94.5	55.6	.071	53.6	.074	64.7	.071	54.5	.079	57.5	.081
115.	57.9	.069	59	.07	54.5	.076	55.4	.078	48.5	.088
136.3	59	.071	58.8	.073	63.5	.073	52.4	.083	45.9	.093
158.1	42	.09	61.1	.076	62.8	.079	67.8	.078	52.5	.093
180.4	37.2	.103	40.9	.101	48.8	.097	41.6	.109	44.3	.11
203.1	24.3	.137	36.3	.115	39.6	.115	31.9	.132	35.2	.132
226.6	10.4	.224	24.7	.149	19.8	.174	28.7	.149	35.2	.141
249.3			10.5	.243	14.4	.213	19.3	.192	18.2	.209
272.2									23.3	.258
$\theta = (35^\circ, 45^\circ)$										
25.6	54.6	.127	61.8	.121	68.8	.121	68.6	.125	62.7	.137
40.1	57.2	.107	71.3	.098	67.3	.106	85.7	.097	64.5	.117
56.7	63.7	.097	67	.096	69.1	.1	65.2	.105	67.2	.109
75.	48.1	.102	46.5	.105	47.2	.11	54.3	.105	56.6	.108
94.5	43.2	.099	49.4	.094	55.4	.094	46.4	.105	36.4	.125
115.	39.2	.102	36.7	.107	37.1	.112	47.7	.102	34.8	.125
136.3	21.9	.134	36	.106	42.8	.103	39.1	.11	35.3	.122
158.1	27.6	.115	30	.113	31.7	.115	33.1	.116	29.2	.13
180.4	15	.152	17.7	.143	21.7	.136	28	.123	21.1	.149
203.1	11.2	.18	9.99	.204	19.2	.147	16.3	.164	12.7	.196
226.6					9.15	.209	10.1	.204		
$\theta = (45^\circ, 55^\circ)$										
25.6	45.4	.052	46.7	.053	48.6	.054	49.2	.056	46.1	.06
40.1	56.5	.047	62.5	.045	70	.045	68.6	.047	66.5	.05
56.7	58.3	.05	59.8	.05	63.4	.051	64.9	.052	59.5	.057
75.	56.2	.059	60.4	.058	65.6	.058	61.5	.062	59.3	.066
94.5	54.5	.071	48.9	.076	61.7	.072	54.9	.078	59.9	.079
115.	47.1	.092	39.6	.102	57.7	.089	46.2	.102	51	.102
136.3	37.5	.127	44.3	.119	40.3	.131	42.7	.131	40.6	.141
158.1	28.1	.189	26.9	.196						

Table A.11: Double differential cross sections for π^- 's produced at 55° to 85° from neutrons on tungsten.

$T(\pi)$	$T(n)$				Tungsten, π^-			
	(200,225)	(225,250)	(250,275)	(275,300)	(300,325)			
$\theta = (55^\circ, 65^\circ)$								
25.6	4.02	.146	7.14	.115	10.2	.102	15.4	.087
40.1	8.81	.082	10.8	.078	17.1	.066	21.9	.061
56.7	4.72	.107	6.63	.095	11.7	.076	14.7	.071
75	2.2	.156	4.3	.118	7.19	.096	10.4	.084
94.5	.801	.258	1.31	.213	3.64	.135	5.81	.113
115					1.9	.189	3.17	.065
136.3							1.52	.224
158.1								
180.4								
203.1								
$\theta = (65^\circ, 75^\circ)$								
25.6	3.49	.333	4.75	.302	2.89	.408	2.67	.447
40.1	4.61	.127	8.17	.101	12.1	.087	14.4	.084
56.7	2.91	.14	6.09	.103	11	.081	13.5	.077
75	1.67	.183	4.21	.121	5.18	.115	8.83	.093
94.5			1.57	.192	2.01	.18	3.76	.139
115					1.23	.236	2.2	.186
136.3								
158.1								
180.4								
203.1								
$\theta = (75^\circ, 85^\circ)$								
25.6	1.57	.378	2.24	.333	3.6	.277	4.01	.277
40.1	4.31	.11	6.83	.092	8.99	.085	13.5	.073
56.7	2.28	.139	5.32	.096	8.54	.08	13.2	.068
75	1.25	.18	2.28	.14	4.44	.106	5.82	.098
94.5			.516	.289	2.4	.141	3.25	.128
115					1.13	.209	2.13	.16
136.3							.73	.267
158.1								
180.4								
203.1								

T(π)				T(n)		Tungsten, π^-				
	(325,350)		(350,375)	(375,400)		(400,425)		(425,450)		
$\theta = (55^\circ, 65^\circ)$										
25.6	17.1	.089	18.7	.087	26.6	.077	25.7	.081	33.1	.06
40.1	31.4	.055	35.1	.053	43.1	.05	46.4	.05	63.1	.046
56.7	24	.06	27.8	.057	36	.053	39.4	.052	50.1	.05
75.	14.7	.076	17.1	.072	24.8	.063	31.9	.058	38	.057
94.5	11.1	.087	11.8	.086	18	.074	23.3	.067	28.8	.065
115.	5.55	.125	7.81	.108	11.2	.095	13	.092	19.3	.081
136.3	3.48	.158	4.74	.139	7.99	.113	10.6	.102	12.5	.1
158.1	1.5	.243	1.85	.218	3.81	.164	5.45	.142	7.99	.127
180.4	1.49	.267	2.07	.236	3.86	.186				
203.1	.51	.378	3.03	.213						
$\theta = (65^\circ, 75^\circ)$										
25.6	1.04	.243	11.6	.236	23.6	.174	18.5	.204	21.4	.204
40.1	20.4	.076	25.1	.07	27.9	.07	33.2	.067	38.8	.066
56.7	20.3	.067	22.8	.065	26.5	.063	37.3	.055	43.3	.055
75.	13.9	.08	15.3	.078	20.8	.07	25.6	.066	33.8	.062
94.5	7.96	.102	9.72	.094	14.1	.083	17	.078	21.2	.075
115.	3.23	.164	4.29	.146	9.43	.104	9.41	.108	14.1	.095
136.3	1.55	.229	2.89	.171	3.12	.174	5.51	.136	6.98	.13
158.1					2.46	.2	2.75	.196	4.05	.174
180.4									2.61	.213
203.1										
$\theta = (75^\circ, 85^\circ)$										
25.6	6.37	.236	4.44	.029	10.7	.196	7.55	.243	12.4	.204
40.1	16.8	.07	20.8	.065	25.1	.062	30.1	.059	37.5	.057
56.7	17.5	.063	21.1	.059	29	.053	34	.051	42.7	.049
75.	9.82	.081	13.8	.07	16.8	.066	22.1	.06	28.9	.057
94.5	6.06	.101	7.43	.093	10.5	.082	13.5	.075	19.9	.067
115.	3.26	.139	3.81	.131	7.22	.101	8.34	.097	14.9	.078
136.3	2.21	.164	2.44	.16	3.27	.146	4.73	.126	5.66	.124
158.1					2.03	.186	2.34	.18	2.89	.174
180.4									2.16	.2
203.1										

T(π)	T(n)									
	(450,475)		(475,500)		(500,525)		(525,550)		Tungsten, π^- (550,575)	
$\theta = (55^\circ, 65^\circ)$										
25.6	33.5	.075	35.2	.074	36.8	.077	36.2	.08	33.6	.087
40.1	63.1	.045	66.6	.045	69.3	.046	63.3	.05	70.2	.05
56.7	50	.053	49.9	.05	59.9	.048	59.9	.049	58.2	.052
75.	41.4	.063	41.6	.054	46.2	.054	42.9	.058	41.8	.062
94.5	29.8	.073	34.2	.06	32.2	.065	32	.067	34.4	.068
115.	22.8	.091	24	.072	32.6	.065	24.7	.077	26.7	.078
136.3	14.6	.113	15.9	.089	23.8	.076	19.7	.086	19.7	.091
158.1	9.72	.141	10.8	.108	12	.108	12.3	.11	14.7	.106
180.4	6.36	.204	6.04	.147	9.06	.127	8.51	.135	6.49	.162
203.1	3.31	.277	3.13	.213	3.17	.224	4.86	.186	3.89	.218
$\theta = (65^\circ, 75^\circ)$										
25.6	21.3	.2	22.9	.196	21.6	.213	17.6	.243	9.17	.354
40.1	41.9	.062	40.8	.064	46.1	.064	43.5	.068	44.5	.07
56.7	43.8	.054	49.1	.052	51.8	.053	53.7	.054	50.4	.058
75.	36.6	.058	38.8	.057	43.2	.057	38.6	.062	36.2	.067
94.5	26.4	.068	29.4	.064	30.4	.066	30.5	.068	26	.077
115.	17.9	.082	18.4	.082	21.7	.08	19.9	.077	22.3	.085
136.3	10.3	.105	11.3	.102	10.5	.111	12.5	.086	9.11	.129
158.1	5.4	.147	8.24	.121	6.2	.147	8.28	.105	7.72	.143
180.4	2.94	.196			5.72	.151	4.82	.131	5.17	.171
203.1							4.25	.169	3.56	.213
$\theta = (75^\circ, 85^\circ)$										
25.6	8.35	.243	9.64	.229	8.47	.258	13.8	.209	7.92	.289
40.1	39.6	.054	41.2	.054	44.9	.054	47.1	.055	43	.06
56.7	46.8	.045	47.7	.046	55.9	.044	51.7	.048	52.3	.05
75.	31.9	.053	34.6	.052	41.2	.05	37.4	.054	34.8	.058
94.5	17.8	.069	23.1	.062	25.5	.062	24.5	.065	25.9	.066
115.	12.7	.083	13.8	.081	18.1	.074	16.2	.081	18.6	.079
136.3	7.9	.103	8.84	.099	9.84	.099	10.7	.097	11.1	.101
158.1	4.35	.139	4.92	.132	6.81	.119	5.39	.137	7.07	.126
180.4	3.05	.164	2.9	.171	4.17	.151	3.71	.164	4.88	.151
203.1	1.74	.224	2.32	.204	2.25	.213				

Table A.12: Double differential cross sections for π^+ 's produced at 25° to 75° from neutrons on carbon.

T(π)	T(n)				Carbon, π^+	
	(250,275)	(275,300)	(300,325)	(325,350)	(350,375)	
$\theta = (25^\circ, 35^\circ)$						
25.6	1.28	.156	1.18	.171	1.35	.169
40.1	1.30	.152	.572	.243	.823	.213
56.7	.663	.196	.826	.186	1.23	.13
75.	.285	.289	.635	.204	.618	.218
94.5			.305	.289	.451	.25
115.						.938
136.3						.574
						.236
						.667
						.224
						.526
						.258
$\theta = (55^\circ, 65^\circ)$						
25.6		.397	.2	.563	.177	.687
40.1		.433	.158	.458	.162	.788
56.7		.252	.192	.416	.158	.334
75.		.168	.236	.229	.213	.395
94.5				.139	.267	.333
115.						.186
						.336
						.189
						.142
						.289
						.186
						.258
$\theta = (65^\circ, 75^\circ)$						
25.6				.942	.316	1.19
40.1				.528	.177	.661
56.7				.397	.174	.414
75.				.188	.243	.470
94.5				.259	.213	.308
						.2

T(π)	T(n)								Carbon, π^+	
	(375,400)	(400,425)	(425,450)	(450,475)	(475,500)					
$\theta = (25^\circ, 35^\circ)$										
25.6	1.76	.171	2.78	.141	2.77	.152	2.95	.144	3.056	.144
40.1	2.10	.154	2.42	.149	3.00	.144	2.62	.151	3.57	.131
56.7	2.23	.137	1.50	.174	2.20	.151	2.82	.134	2.70	.139
75.	1.89	.144	1.94	.147	1.77	.167	3.05	.124	3.15	.124
94.5	1.39	.164	1.87	.186	1.97	.139	2.34	.139	2.59	.134
115.	1.37	.164	1.16	.213	2.08	.149	2.25	.14	2.73	.129
136.3	.974	.2	.924	.218	1.81	.164	1.63	.169	1.72	.169
158.1										
180.4									1.43	
$\theta = (55^\circ, 65^\circ)$										
25.6	.964	.156	.912	.167	1.20	.156	1.60	.132	1.02	.139
40.1	1.21	.115	1.75	.095	1.68	.109	2.37	.09	2.30	.093
56.7	.946	.121	1.21	.111	1.71	.101	1.60	.102	2.02	.092
75.	.668	.144	1.05	.12	1.41	.111	1.48	.106	1.60	.104
94.5	.586	.151	.761	.137	1.03	.127	.971	.128	1.23	.115
115.	.387	.189	.328	.213	.690	.158	.725	.151	.782	.147
136.3			.237	.25	.395	.209	.655	.158	.642	.162
158.1					.199	.302	.327	.229	.392	.213
$\theta = (65^\circ, 75^\circ)$										
25.6	1.13	.333	1.63	.289	1.73	.302	2.25	.258	2.96	.229
40.1	1.06	.144	1.42	.129	1.35	.143	1.83	.12	2.15	.113
56.7	.930	.131	1.31	.115	1.96	.101	1.40	.117	2.27	.093
75.	.829	.134	1.04	.119	1.24	.122	1.48	.109	1.85	.1
94.5	.371	.192	.725	.143	1.08	.126	1.07	.124	.981	.131
115.	.263	.229	.479	.177	.539	.18	.696	.154	.719	.154
136.3			.249	.236			.322	.302	.395	.2

T(π)	(500,525)		T(n) (525,550)		(550,575)		Carbon, π^+ (575,600)	
$\theta=$	(25°, 35°)							
25.6	3.33	.146	2.63	.169	3.47	.154	3.20	.192
40.1	3.35	.143	2.97	.156	3.29	.156	3.56	.18
56.7	3.31	.132	3.50	.132	3.58	.137	3.39	.169
75.	3.29	.128	2.69	.146	2.65	.154	2.97	.174
94.5	2.73	.137	2.51	.147	2.35	.16	2.42	.189
115.	2.44	.137	3.02	.134	2.79	.146	2.81	.20
136.3	2.14	.144	2.38	.154	2.56	.156	2.24	.218
158.1	1.78	.158	2.49	.162	1.66	.209	2.16	.20
180.4	1.97	.186	1.77	.209			2.44	.25
203.1	1.86	.192					2.25	.258
$\theta=$	(55°, 65°)							
25.6	1.32	.156	1.37	.158	1.70	.149	1.46	.192
40.1	2.23	.1	2.68	.093	2.92	.094	3.70	.1
56.7	2.27	.092	2.05	.099	1.98	.106	2.37	.116
75.	1.75	.104	1.92	.103	1.94	.107	2.46	.114
94.5	1.22	.122	1.63	.109	1.20	.134	1.38	.149
115.	1.21	.125	1.04	.139	1.24	.134	1.68	.137
136.3	.752	.158	.816	.156	.726	.174	1.10	.169
158.1	.774	.16	.631	.183	.581	.2	.831	.2
$\theta=$	(65°, 75°)							
25.6	1.90	.302	2.02	.302	1.21	.41	2.03	.378
40.1	1.82	.129	2.08	.124	1.55	.151	2.33	.147
56.7	2.34	.097	2.41	.098	2.21	.108	2.62	.119
75.	1.97	.102	2.11	.101	1.93	.11	2.30	.121
94.5	.978	.139	1.46	.117	1.56	.119	1.77	.134
115.	1.12	.13	.869	.152	1.03	.147	1.18	.164
136.3	.722	.156	.504	.192	.514	.2	.737	.2
158.1							.437	.209

Table A.13: Double differential cross sections for π^+ 's produced at 75° to 125° from neutrons on carbon.

T(π)			T(n)				Carbon, π^+			
	(300,325)		(325,350)		(350,375)		(375,400)		(400,425)	
$\theta =$	(75°, 85°)									
25.6	.225	.578	.776	.333			1.102	.302	.756	.378
40.1	.265	.229	.352	.213	.670	.158	.688	.164	.760	.164
56.7	.256	.204	.477	.16	.474	.164	.967	.12	.952	.127
75.			.264	.204	.368	.177	.499	.16	.592	.152
94.5					.208	.229	.316	.196	.378	.186
115.							.211	.25		
$\theta =$	(105°, 115°)									
25.6	.0718	.707	.167	.5	.349	.354	.387	.354	.521	.316
40.1	.275	.169	.416	.147	.379	.158	.705	.122	.805	.119
56.7	.205	.177	.326	.152	.533	.122	.646	.117	.706	.116
75.	.116	.224	.193	.186	.306	.151	.449	.131	.592	.128
94.5			.102	.25	.0739	.302	.171	.209	.249	.18
115.									.152	.267
$\theta =$	(115°, 125°)									
25.6	.317	.196	.296	.218	.471	.177	.653	.158	.653	.164
40.1	.339	.146	.405	.143	.598	.12	.750	.113	1.03	.101
56.7	.166	.196	.322	.151	.390	.14	.552	.124	.788	.108
75.	.0518	.333	.0989	.258	.159	.209	.222	.186	.297	.167
94.5	.156	.218	.192	.204						

T(π)			T(n)				Carbon, π^+			
	(425,450)		(450,475)	(475,500)	(500,525)		(525,550)			
$\theta =$	(75°,	85°)								
25.6	.877	.378	1.20	.316	1.73	.267	1.65	.289	.291	.707
40.1	1.37	.13	1.40	.126	1.63	.119	1.83	.118	1.62	.129
56.7	1.37	.114	1.24	.117	1.88	.097	2.15	.095	2.05	.101
75.	.975	.128	.824	.136	1.18	.115	1.10	.126	1.41	.115
94.5	.424	.189	.768	.137	.867	.131	.981	.13	1.16	.123
115.	.322	.218	.482	.174	.482	.177	.671	.158	.676	.162
136.3			.249	.236	.328	.209	.365	.209	.386	.209
$\theta =$	(105°,	115°)								
25.6	.908	.258	.752	.277	.895	.258	.995	.258	1.06	.258
40.1	.829	.126	1.14	.105	1.49	.093	1.61	.094	1.74	.937
56.7	1.24	.095	1.2	.094	1.46	.086	1.69	.085	1.94	.814
75.	.861	.106	.795	.108	.877	.104	1.10	.098	1.25	.095
94.5	.279	.183	.364	.156	.485	.137	.448	.151	.787	.117
115.	.155	.277	.326	.192	.315	.192	.260	.224	.528	.167
136.3									.202	.213
$\theta =$	(115°,	125°)								
25.6	.817	.158	1.03	.137	.865	.152	1.30	.131	1.66	.12
40.1	1.13	.103	1.5	.087	1.69	.084	1.99	.081	1.94	.085
56.7	1.09	.099	1.10	.096	1.32	.089	1.76	.081	2.04	.077
75.	.469	.143	.621	.121	.783	.11	.798	.115	1.12	.1
94.5	.250	.192	.301	.171	.329	.167	.477	.146	.474	.151
115.					.16	.289	.355	.204	.362	.209

T(π)	(550,575)		T(n)		Carbon, π^+
$\theta=$	(75°, 85°)				
25.6	.805	.447	1.85	.354	
40.1	1.61	.136	2.30	.136	
56.7	2.24	.101	3.20	.101	
75.	1.57	.114	1.94	.123	
94.5	1.11	.132	1.75	.126	
115.	.785	.158	1.07	.162	
136.3	.371	.224	.584	.213	
$\theta=$	(105°, 115°)				
25.6	1.40	.236	1.55	.267	
40.1	2.11	.089	2.28	.103	
56.7	1.98	.085	2.47	.091	
75.	1.37	.095	2.32	.087	
94.5	.679	.132	1.11	.124	
115.	.454	.189	.906	.16	
136.3	.193	.229	.203	.267	
$\theta=$	(115°, 125°)				
25.6	1.54	.13	2.62	.12	
40.1	3.04	.071	3.91	.075	
56.7	2.14	.08	3.52	.075	
75.	1.32	.096	1.81	.099	
94.5	.784	.123	.748	.151	
115.	.330	.229	.571	.209	

Table A.14: Double differential cross sections for π^+ 's produced at 25° to 75° from neutrons on aluminum.

$T(\pi)$	$T(n)$			Aluminum, π^+						
	(225,250)	(250,275)	(275,300)	(300,325)	(325,350)					
$\theta = (25^\circ, 35^\circ)$										
25.6	2.15	.16	2.70	.151	3.99	.131	3.66	.144	6.21	.119
40.1	.987	.189	1.53	.16	2.22	.14	1.75	.167	2.62	.146
56.7	.596	.224	.729	.213	1.55	.154	1.93	.146	2.82	.129
74.			.648	.218	1.03	.183	1.41	.164	2.46	.134
94.5					.722	.213	.839	.29	1.97	.146
115.									.703	.243
$\theta = (55^\circ, 65^\circ)$										
25.6			.557	.167	.587	.171	.632	.174	1.12	.14
40.1			.508	.144	.662	.134	1.03	.108	1.64	.096
56.7			.220	.204	.459	.149	.691	.128	1.34	.107
75.			.168	.229	.325	.174	.492	.149	.778	.127
94.5					.187	.224	.261	.2	.502	.154
$\theta = (65^\circ, 75^\circ)$										
25.6			.563	.354						
40.1			.507	.162	.580	.16	.860	.139	1.24	.124
56.7			.332	.171	.478	.151	.774	.125	1.18	.108
75.			.220	.204	.327	.177	.364	.177	.717	.135
94.5					.202	.218	.214	.224	.479	.16

T(π)	T(n)						Aluminum, π^+			
	(350,375)	(375,400)	(400,425)	(425,450)	(450,475)					
$\theta = (25^\circ, 35^\circ)$										
25.6	5.39	.13	7.23	.119	6.80	.127	7.62	.129	8.37	.12
40.1	4.08	.12	3.88	.129	4.48	.125	5.99	.116	6.80	.107
56.7	3.60	.117	4.23	.114	3.38	.132	4.52	.123	4.33	.123
75.	2.84	.127	3.48	.121	2.82	.14	4.59	.118	5.06	.11
94.5	1.89	.152	2.84	.131	2.63	.141	3.73	.128	3.96	.121
115.	1.56	.167	2.02	.154	2.79	.136	4.27	.119	3.05	.137
136.3	.909	.224	1.42	.189	1.69	.18	3.11	.143	2.65	.151
158.1					1.70	.192	2.04	.189	3.55	.14
180.4							2.32	.192	1.73	.218
$\theta = (55^\circ, 65^\circ)$										
25.6	1.17	.14	1.31	.14	2.12	.114	2.34	.117	2.29	.115
40.1	1.63	.099	2.55	.083	2.14	.094	3.25	.082	3.52	.077
56.7	1.30	.103	1.67	.095	2.22	.086	2.74	.083	3.06	.077
75.	1.01	.114	1.20	.11	1.71	.096	1.90	.098	2.30	.082
94.5	.615	.143	.906	.124	1.05	.12	1.48	.108	1.96	.092
115.	.407	.18	.495	.171	.77	.143	.729	.158	1.29	.116
136.3					.457	.186	.639	.169	.888	.14
158.1							.386	.224	.498	.192
$\theta = (65^\circ, 75^\circ)$										
25.6										
40.1	1.17	.13	1.73	.113	1.83	.114	3.03	.095	2.93	.095
56.7	1.29	.106	1.57	.102	2.39	.085	2.79	.085	3.05	.08
75.	1.16	.108	1.54	.1	1.79	.096	2.38	.089	2.39	.087
94.5	.617	.144	.714	.141	1.08	.12	1.46	.11	1.45	.108
115.	.356	.192	.441	.183	.570	.167	.716	.16	.947	.136
136.3					.339	.209	.513	.183	.440	.192
158.1									.318	.236

T(π)	T(n)						Aluminum, π^+			
	(475,500)	(500,525)	(525,550)	(550,575)	(575,600)					
$\theta = (25^\circ, 35^\circ)$										
25.6	9.29	.116	7.26	.139	8.14	.135	8.14	.141	9.12	.16
40.1	5.79	.118	7.45	.109	6.49	.12	6.24	.129	7.73	.139
56.7	5.20	.114	7.29	.102	5.32	.122	6.08	.12	8.94	.119
75.	4.47	.119	5.11	.117	4.38	.13	4.99	.18	6.20	.137
94.5	4.22	.12	4.41	.123	3.96	.134	4.62	.13	4.71	.154
115.	3.33	.134	4.36	.123	5.39	.114	4.41	.132	4.97	.149
136.3	2.62	.154	2.83	.156	3.89	.137	3.89	.144	4.76	.156
158.1	2.95	.156	2.95	.164	3.65	.152	3.37	.16	3.74	.189
180.4	1.95	.29			3.49	.169	3.87	.169	3.80	.204
203.1					2.08	.236	2.81	.213		
$\theta = (55^\circ, 65^\circ)$										
25.6	2.94	.104	2.84	.111	3.24	.107	2.22	.136	2.94	.141
40.1	4.05	.073	4.66	.072	4.69	.074	4.97	.075	6.69	.079
56.7	2.89	.08	3.94	.073	3.88	.075	3.28	.086	4.55	.087
75.	2.82	.08	2.82	.084	2.76	.088	3.42	.083	3.35	.1
94.5	1.94	.094	2.06	.096	2.43	.091	1.96	.107	3.19	.1
115.	1.36	.115	2.01	.1	1.74	.11	1.87	.112	2.44	.117
136.3	.755	.154	1.18	.13	1.08	.14	1.38	.13	1.37	.156
158.1	.553	.186	.785	.164	.877	.16	.868	.169	.959	.192
180.4	.378	.224	.400	.229	.669	.183	.443	.236		
203.1					.464	.229				
$\theta = (65^\circ, 75^\circ)$										
25.6										
40.1	3.05	.094	4.08	.086	3.82	.092	3.62	.099	4.15	.11
56.7	3.38	.077	3.61	.078	4.24	.075	3.81	.082	5.11	.085
75.	2.35	.089	2.98	.084	2.56	.093	3.31	.086	4.00	.093
94.5	1.64	.104	2.15	.095	2.78	.086	2.08	.105	2.71	.11
115.	1.23	.121	1.14	.132	1.82	.108	1.86	.113	1.93	.132
136.3	.759	.149	.844	.149	1.01	.14	.789	.167	1.32	.154
158.1					.710	.174	.664	.189	1.15	.171
180.4									.629	.192

Table A.15: Double differential cross sections for π^+ 's produced at 75° to 125° from neutrons on aluminum.

T(π)			T(n)			Aluminum, π^+				
	(275,300)		(300,325)	(325,350)		(350,375)	(375,400)			
$\theta =$	(75° ,	85°)								
25.6	.338	.408	.69	.302	1.01	.267	.452	.408	.922	.302
40.1	.487	.164	.482	.174	.806	.144	1.16	.123	1.34	.12
56.7	.413	.158	.516	.149	.923	.12	1.09	.113	1.44	.103
75.	.203	.213	.370	.167	.613	.139	.802	.124	1.04	.115
94.5			.168	.243	.249	.213	.296	.2	.631	.144
115.									.396	.183
136.3										
158.1										
$\theta =$	(105° ,	115°)								
25.6					.559	.408	.488	.447	.868	.354
40.1					.608	.183	.891	.154	1.04	.151
56.7					.460	.192	.838	.146	1.21	.128
75.							.484	.18	.781	.149
94.5							.180	.289	.216	.277
115.										
$\theta =$	(115° ,	125°)								
25.6			.466	.243	.304	.302	.610	.218	.741	.209
40.1			.614	.162	.636	.16	1.04	.128	1.46	.114
56.7			.3	.218	.461	.177	.813	.137	.442	.132
75.					.246	.229	.259	.229	.285	.189
94.5										
115.										

T(π)			T(n)		Aluminum, π^+					
	(400,425)		(425,450)		(450,475)		(475,500)		(500,525)	
$\theta=$	(75°,	85°)								
25.6	.814	.333	1.46	.267	1.00	.316	2.38	.209	1.15	.316
40.1	1.68	.112	2.53	.098	1.89	.111	2.50	.098	2.81	.098
56.7	1.80	.096	2.50	.088	2.60	.084	3.35	.075	3.45	.078
75.	1.20	.111	1.95	.094	2.02	.09	2.21	.087	2.57	.085
94.5	.837	.13	1.09	.123	.848	.136	1.29	.113	1.49	.11
115.	.441	.18	.710	.152	.662	.139	.960	.13	1.34	.116
136.3					.570	.162	.573	.164	.397	.209
158.1										
$\theta=$	(105°,	115°)								
25.6	1.05	.333	1.22	.333	.777	.408	1.20	.333	1.19	.354
40.1	1.58	.12	2.41	.11	2.14	.115	2.26	.113	2.65	.11
56.7	1.42	.123	2.05	.11	2.12	.105	2.47	.1	2.75	.1
75.	1.12	.129	1.43	.123	1.47	.119	1.52	.119	1.67	.12
94.5	.413	.209	.687	.174	.557	.189	1.01	.143	1.07	.146
115.			.312	.302	.325	.289	.334	.289	.558	.236
$\theta=$	(115°,	125°)								
25.6	1.29	.164	1.12	.186	1.23	.177	1.59	.158	1.50	.171
40.1	1.45	.119	1.88	.113	2.26	.1	2.76	.092	2.84	.096
56.7	1.40	.113	1.8	.102	1.92	.103	1.94	.103	2.30	.1
75.	.619	.162	.963	.14	.991	.135	1.23	.123	1.43	.12
94.5	.379	.204	.347	.229	.437	.2	.720	.158	.581	.186
115.							.315	.289	.498	.243

T(π)	T(n)		Aluminum, π^+			
	(525,550)	(550,575)	(575,600)			
$\theta =$	(75°,	85°)				
25.6	2.06	.243	1.75	.277	2.50	.277
40.1	3.43	.091	3.13	.1	4.12	.104
56.7	3.94	.075	4.36	.075	5.07	.083
75.	2.75	.085	2.94	.086	4.50	.084
94.5	2.03	.097	2.34	.095	2.96	.101
115.	1.32	.12	1.1	.139	2.09	.12
136.3	.840	.147	.928	.147	.865	.183
158.1	.516	.192				
$\theta =$	(105°,	115°)				
25.6	2.37	.258	2.09	.289	2.99	.289
40.1	2.5	.117	2.99	.113	4.49	.11
56.7	2.71	.103	3.66	.093	4.82	.097
75.	2.12	.109	2.08	.115	3.07	.114
94.5	.968	.158	1.37	.14	1.98	.139
115.	.757	.209	.690	.229	1.40	.192
$\theta =$	(115°,	125°)				
25.6	1.31	.189	1.65	.177	2.66	.167
40.1	3.66	.087	4.11	.086	6.61	.081
56.7	2.63	.096	3.10	.093	4.69	.091
75.	1.54	.12	1.89	.113	2.15	.127
94.5	.977	.147	1.03	.151	1.44	.152
115.			.754	.213	.539	.302

Table A.16: Double differential cross sections for π^+ 's produced at 25° to 75° from neutrons on copper.

$T(\pi)$	$T(n)$				Copper, π^+			
	(250,275)	(275,300)	(300,325)	(325,350)	(350,375)			
$\theta = (25^\circ, 35^\circ)$								
25.6		6.37	.152	6.25	.162	7.94	.154	7.34 .164
40.1		2.79	.183	3.31	.177	4.63	.16	4.35 .169
56.7		2.39	.18	3.51	.156	4.23	.152	4.41 .152
75.		3.19	.192	3.62	.2	5.88	.16	6.02 .162
94.5				1.52	.224	2.19	.2	2.56 .189
115.						1.88	.213	2.33 .196
136.3								1.59 .243
158.1								
180.4								
203.1								
$\theta = (55^\circ, 65^\circ)$								
25.6	.857 .209	1.57	.162	1.38	.183	2.12	.158	1.88 .171
40.1	1.15 .149	1.65	.131	1.80	.132	2.69	.116	3.15 .11
56.7	.661 .183	.981	.158	1.12	.156	2.07	.123	2.52 .114
75.	.425 .224	.688	.186	1.03	.16	1.18	.16	1.61 .14
94.5				.576	.213	.871	.186	1.01 .177
115.						.653	.218	.651 .224
136.3								
158.1								
180.4								
$\theta = (65^\circ, 75^\circ)$								
25.6	1.51 .33	2.26	.289					
40.1	1.02 .177	1.68	.146	1.82	.147	2.46	.136	2.81 .13
56.7	.561 .204	1.12	.152	1.51	.139	1.99	.129	2.51 .118
75.	.330 .258	.735	.183	.872	.177	1.03	.174	1.99 .128
94.5				.436	.243	.618	.218	.801 .196
115.								.556 .243
136.3								

T(π)	(500,525)		T(n) (525,550)		(550,575)		Copper, π^+ (575,600)	
$\theta =$	(25°, 35°)							
25.6	12.4	.156	16.3	.14	17.3	.143	19.2	.162
40.1	11.5	.128	11.4	.132	12.4	.134	14.3	.149
56.7	9.39	.129	11.9	.118	6.78	.164	11.8	.149
75.	11.8	.143	16.1	.126	17.7	.126	14.5	.167
94.5	9.21	.123	6.51	.151	8.66	.137	8.40	.167
115.	5.86	.152	8.09	.134	5.90	.164	8.00	.169
136.3	5.96	.154	6.77	.149	4.81	.186	4.76	.224
158.1	6.87	.154	5.03	.186	3.84	.224	6.59	.204
180.4	3.06	.258	3.88	.236			6.47	.229
$\theta =$	(55°, 65°)							
25.6	5.33	.126	4.21	.146	4.94	.141	5.52	.16
40.1	8.51	.082	9.26	.081	8.87	.087	10.2	.098
56.7	6.90	.035	7.04	.087	7.13	.091	8.11	.102
75.	5.35	.095	4.80	.103	6.54	.093	8.07	.1
94.5	5.17	.096	3.71	.117	4.59	.11	5.13	.125
115.	3.42	.12	3.89	.116	3.65	.126	4.40	.137
136.3	2.46	.141	2.35	.149	2.25	.16	3.79	.147
158.1	1.98	.162	1.55	.189	2.50	.156	1.57	.236
180.4					1.25	.209	1.02	.243
$\theta =$	(65°, 75°)							
25.6								
40.1	5.95	.11	5.84	.115	6.20	.117	7.29	.129
56.7	6.26	.092	5.23	.104	7.01	.094	8.27	.104
75.	4.99	.1	4.23	.112	6.59	.094	7.02	.109
94.5	4.09	.107	3.24	.124	4.45	.111	4.09	.139
115.	2.19	.151	2.64	.141	2.04	.169	2.59	.18
136.3	.967	.218	1.46	.183	1.94	.167	2.54	.174
158.1				.946	.236	1.16	.224	

Table A.17: Double differential cross sections for π^+ 's produced at 75° to 125° from neutrons on copper.

T(π)	T(n)					Copper, π^+				
	(300,325)		(325,350)		(350,375)	(375,400)		(400,425)		
$\theta=$	(75°,	85°)								
25.6	.744	.447	1.02	.408	1.61	.333	1.99	.316	2.15	.316
40.1	1.11	.177	2.13	.14	1.50	.167	2.69	.131	2.89	.131
56.7	1.06	.16	1.57	.143	1.60	.143	2.77	.115	3.61	.104
75.	.657	.192	1.09	.16	1.35	.147	1.72	.137	2.14	.128
94.5			.376	.267	.871	.18	.936	.183	1.38	.156
115.							.711	.213	.732	.218
$\theta=$	(105°,	115°)								
25.6					1.03	.408	1.14	.408	1.02	.448
40.1	1.17	.162	1.66	.146	1.93	.139	2.39	.131	2.45	.135
56.7	.754	.186	1.25	.154	1.5	.144	1.76	.14	2.81	.115
75.	.455	.224	.653	.2	1.43	.139	1.24	.156	1.63	.141
94.5	.262	.289			.367	.267	.875	.183	.628	.224
115.									.684	.25
$\theta=$	(115°,	125°)								
25.6	.671	.267	.553	.316	1.38	.204	1.79	.189	2.20	.177
40.1	1.07	.162	2.01	.127	2.28	.122	2.79	.116	3.79	.104
56.7	.774	.18	1.49	.139	1.86	.127	2.00	.129	3.64	.1
75.	.247	.302	.568	.213	.703	.196	1.36	.149	1.62	.141
94.5									.470	.258

T(π)	T(n)						Copper, π^+			
	(425,450)		(450,475)		(475,500)		(500,525)		(525,550)	
$\theta=$	(75°,	85°)								
25.6	2.74	.302	3.79	.25	4.16	.243	2.18	.354	2.30	.354
40.1	3.88	.122	4.26	.114	4.90	.108	5.01	.113	5.51	.11
56.7	5.41	.092	5.30	.091	4.97	.095	5.59	.094	8.09	.081
75.	2.44	.129	3.41	.107	3.61	.105	4.14	.104	4.25	.105
94.5	2.10	.136	2.13	.132	2.34	.128	3.13	.117	3.13	.12
115.	1.17	.186	1.35	.169	.836	.218	1.29	.186	2.01	.152
136.3			.802	.213			.796	.229	1.199	.192
$\theta=$	(105°,	115°)								
25.6	1.90	.354	2.49	.302	2.10	.333	2.09	.354	3.86	.267
40.1	4.59	.106	3.94	.112	5.04	.101	6.05	.097	7.38	.09
56.7	4.00	.104	3.97	.102	5.09	.092	5.90	.09	6.25	.09
75.	2.62	.12	2.68	.116	2.96	.113	3.62	.107	3.89	.107
94.5	1.39	.162	1.15	.174	2.23	.127	2.27	.132	2.71	.125
115.	.843	.243	.710	.258	1.37	.189	1.03	.229	1.62	.189
136.3					.428	.267				
$\theta=$	(115°,	125°)								
25.6	1.92	.204	2.91	.162	3.71	.146	3.77	.152	2.71	.186
40.1	4.91	.098	4.64	.099	4.89	.098	6.58	.089	6.75	.09
56.7	3.34	.112	4.30	.096	4.76	.093	5.40	.092	6.54	.086
75.	2.33	.127	2.51	.12	2.82	.115	3.30	.112	3.75	.108
94.5	1.16	.177	1.32	.162	1.19	.174	1.84	.123	2.36	.134
115.			.862	.243			1.048	.236	1.048	.243

T(π)			T(n)		Copper, π^+	
	(525,550)		(550,575)	(575,600)		
$\theta =$	(75°,	85°)				
25.6	2.30	.354	2.87	.333	2.74	.408
40.1	5.51	.11	5.27	.119	6.38	.129
56.7	8.09	.081	7.00	.091	9.35	.094
75.	4.25	.105	5.43	.098	5.60	.115
94.5	3.13	.12	3.50	.12	4.87	.121
115.	2.01	.152	2.28	.151	2.60	.169
136.3	1.20	.192	.980	.224	1.55	.213
$\theta =$	(105°,	115°)				
25.6	3.86	.267	1.52	.447	3.06	.378
40.1	7.38	.09	6.81	.099	9	.103
56.7	6.25	.09	7.07	.092	8.60	.096
75.	3.89	.107	5.12	.098	6.14	.107
94.5	2.71	.125	2.76	.13	4.55	.121
115.	1.62	.189	1.71	.192	1.92	.218
$\theta =$	(115°,	125°)				
25.6	2.71	.186	3.19	.18	4.86	.174
40.1	6.75	.09	7.88	.088	13	.082
56.7	6.54	.086	6.64	.09	10.7	.085
75.	3.75	.108	4.97	.099	6.14	.085
94.5	2.36	.134	1.96	.154	3.54	.106
115.	1.05	.243	.749	.302	2.34	.137

Table A.18: Double differential cross sections for π^+ 's produced at 105° to 125° from neutrons on tungsten.

T(π)	T(n)					Tungsten, π^+				
	(325,350)	(350,375)	(375,400)	(400,425)	(425,450)	(325,350)	(350,375)	(375,400)	(400,425)	(425,450)
<hr/>										
$\theta =$	(105°, 115°)									
25.6	.572	.707	.898	.577	.998	.577	2.51	.378	1.24	.577
40.1	2.00	.204	2.87	.174	4.15	.152	5.00	.144	6.16	.14
56.7	2.40	.174	2.74	.167	2.96	.169	4.74	.139	6.24	.13
75.	1.40	.218	1.32	.229	1.78	.213	2.50	.183	4.64	.144
94.5			.960	.267	.988	.277	1.97	.204	2.86	.183
115.							.782	.316	.998	.302
<hr/>										
$\theta =$	(115°, 125°)									
25.6	1.25	.277	1.31	.277	1.68	.258	2.18	.236	2.81	.224
40.1	2.20	.186	4.46	.134	5.47	.127	6.29	.123	9.05	.11
56.7	1.61	.209	2.57	.169	3.82	.146	3.52	.158	6.92	.121
75.	1.31	.224	1.93	.189	2.21	.186	2.89	.169	4.11	.152
94.5			.616	.333	.911	.289	1.40	.243	1.9	.224

T(π)	T(n)					Tungsten, π^+				
	(450,475)	(475,500)	(500,525)	(525,550)	(550,575)					
$\theta = (105^\circ, 115^\circ)$										
25.6	1.99	.447	1.64	.5	4.56	.316	5.80	.289	3.73	.378
40.1	5.07	.151	7.50	.126	7.02	.137	8.70	.127	10.4	.122
56.7	6.87	.121	9.28	.106	8.58	.116	9.60	.113	9.60	.119
75.	4.06	.151	5.71	.129	6.56	.127	7.41	.123	9.04	.117
94.5	2.09	.209	3.66	.16	4.18	.158	4.09	.164	4.28	.169
115.	1.56	.236	1.34	.258	1.79	.236	2.21	.218	2.21	.229
$\theta = (115^\circ, 125^\circ)$										
25.6	2.81	.218	2.49	.236	4.93	.177	4.89	.183	5.95	.174
40.1	8.44	.112	9.88	.105	11.4	.103	11.8	.104	15.0	.097
56.7	7.09	.17	6.41	.125	8.81	.113	11.5	.102	11.1	.108
75.	4.56	.314	5.18	.182	7.44	.119	6.77	.128	6.62	.136
94.5	2.54	.189	2.81	.183	5.00	.144	4.30	.16	3.90	.177
115.	1.67	.236	.861	.333	1.81	.243	1.92	.243	2.37	.229

Appendix B

Pion Double Differential Cross Sections Compared to LAHET

Figures B.1- B.10 show the comparisons of our double differential cross sections to the calculations of LAHET for C, Cu, and W targets at neutron energies 262.5 MeV to 562.5 MeV and angles 30° to 120° .

Figure B.1: Double differential cross sections for neutrons of energy 262.5 MeV on carbon compared to LAHET calculations.

Figure B.2: Double differential cross sections for neutrons of energy 362.5 MeV on carbon compared to LAHET calculations.

Figure B.3: Double differential cross sections for neutrons of energy 462.5 MeV on carbon compared to LAHET calculations.

Figure B.4: Double differential cross sections for neutrons of energy 562.5 MeV on carbon compared to LAHET calculations.

Figure B.5: Double differential cross sections for neutrons of energy 262.5 MeV on copper compared to LAHET calculations.

Figure B.6: Double differential cross sections for neutrons of energy 362.5 MeV on copper compared to LAHET calculations.

Figure B.7: Double differential cross sections for neutrons of energy 462.5 MeV on copper compared to LAHET calculations.

Figure B.8: Double differential cross sections for neutrons of energy 262.5 MeV on tungsten compared to LAHET calculations.

Figure B.9: Double differential cross sections for neutrons of energy 362.5 MeV on tungsten compared to LAHET calculations.

Figure B.10: Double differential cross sections for neutrons of energy 562.5 MeV on tungsten compared to LAHET calculations.

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