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Pion Absorption in Nuclei: The $(\pi^{\pm}, p)$ Reactions

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ABSTRACT

Pion absorption in nuclei has been studied using $(\pi^\pm, p)$ reactions in the region of the delta resonance. Reported here is the first experiment to measure the excitation of discrete final states following the (π^-, p) reaction. The Energetic Pion Channel and Spectrometer (EPICS) at the Los Alamos National Laboratory and the High Resolution Pion Channel and Spectrometer (π ML-SUSI) at the Swiss Institute for Nuclear Physics were used for this high resolution study of $(\pi^\pm, p)$ reactions. An average energy resolution of 500 KeV and 700 KeV was achieved at EPICS and π ML-SUSI respectively. At EPICS these reactions were measured at $T_\pi = 120$ MeV and $\theta_{lab} = 25^\circ$ on ^{24}Mg , ^{27}Al , ^{40}Ca and ^{58}Ni ; $^{12}\text{C}(\pi^-, p)$ was measured at $T_\pi = 145$ MeV. At π ML-SUSI these reactions were measured at $T_\pi = 90$ MeV and at $\theta_{lab} = 20^\circ$ on ^{23}Na and ^{24}Mg . The measurement includes both the differential cross sections and continuum up to an excitation energy of 40 MeV.

In ^{23}Na , ^{24}Mg , and ^{27}Al there are peaks in the low excitation region. The $^{24}\text{Mg}(\pi^-, p)^{23}\text{Ne}$ spectrum at $T_\pi = 120$ MeV has a peak in the bound state region at 8.4 ± 0.3 MeV with a cross section of 2.4 ± 0.6 $\mu\text{b/sr}$. This state has not been seen before and could be a $13/2^+$ state. A peak is also revealed with cross section of 15.9 ± 2.6 $\mu\text{b/sr}$ at 9.60 ± 1.0 MeV with $T_\pi = 90$ MeV. The $^{24}\text{Mg}(\pi^+, p)^{23}\text{Mg}$ spectrum at $T_\pi = 120$ MeV has two peaks of high spin states $5/2^+$ (0.47 ± 0.12 MeV) and $9/2^+$ (2.71 ± 0.18 MeV) with cross sections 8.1 ± 1.7 $\mu\text{b/sr}$ and 17.6 ± 2.6 $\mu\text{b/sr}$ respectively. At $T_\pi = 90$ MeV this reaction shows indications of two peaks at 0.85 ± 0.5 and

2.8 ± 0.5 MeV with 20.40 ± 4.10 $\mu\text{b/sr}$ and 71.48 ± 13.6 $\mu\text{b/sr}$ respectively. The $^{23}\text{Na}(\pi^-, p)^{22}\text{F}$ has a peak at 5.7 ± 0.5 MeV with cross section 4.4 ± 1.2 $\mu\text{b/sr}$. The $^{27}\text{Al}(\pi^+, p)^{26}\text{Al}$ spectrum reveals a relatively high cross section of 22.6 ± 2.0 $\mu\text{b/sr}$ for the excitation of the 5^+ ground state. ^{12}C , ^{27}Al , ^{40}Ca , and $^{58}\text{Ni}(\pi^-, p)$ yield peaks with $d\sigma/d\Omega \leq 1 \mu\text{b/sr}$ compared to 7-22 $\mu\text{b/sr}$ for peaks from (π^+, p) reactions.

The shape of the continuum in an excitation energy range of 10 to 40 MeV was found to be independent of pion charge and target mass. The magnitude of proton yield from all the targets at $T_\pi = 120$ MeV is more than twenty four times larger for π^+ than for π^- . Also the cross sections for both reactions on ^{24}Mg is slightly enhanced compared to other nuclei. At $T_\pi = 90$ MeV the ratio of the proton yield for π^+ to π^- absorption drops down to fourteen. This high ratio and its energy dependence supports the idea of a two nucleon pion absorption model. Pion absorption in the context of both the reaction mechanism and nuclear structure is discussed.

I. INTRODUCTION

Pion induced reactions are fundamental to an understanding of nuclear interactions. Pions interact with the nucleus causing a variety of reactions: elastic, inelastic, absorption, and single and double charge exchange. In all reactions the structure of the nucleus and the reaction mechanism are both of importance. Pion absorption in nuclei is a topic of considerable experimental and theoretical interest for several reasons. Pion absorption dominates the pion-nucleus reaction cross section at low energies and remains as a sizeable component at energies throughout the resonance region. Pion absorption provides high energy and momentum transfer to the nucleus, which may allow the exploration of the short-range high-momentum part of the inter-nucleonic wave function. The understanding of the pion-nucleus interaction has improved from a semi-classical level towards an ultimate goal of understanding it in terms of the underlying quark dynamics. However, many aspects of pion-nucleus interactions including pion absorption still remain a puzzle with no complete microscopic description of these processes. For example, the number of nucleons involved in pion absorption is still unsettled.

Both pion production and absorption have been studied throughout the last two decades. Recent results from the Indiana University Cyclotron Facility (IUCF) have demonstrated that the (p, π^-) reaction is strikingly selective in the population of discrete excited states in

the residual nucleus (Vig-82,83). The (p,π^-) reaction excites selectively only one or a few low lying states. The angular distributions of these states are strongly forward peaked with cross sections at forward angles comparable to those of the (p,π^+) reaction. This reaction is characterised by high momentum transfer to the nucleus and the necessity of at least a two nucleon mechanism. These few states have been described (Bro-83,Vig-83) to be two particle one hole states which are favored by a two nucleon pion production mechanism.

There have been only a few (π^-,p) experiments involving pionic atoms, activation techniques or measurement of the continuum (Jac-77a, 77b; Nav-79; Kal-80, 81a, 81b, 83; McK-80, 81), due to the relatively low cross sections and the high momentum of the outgoing proton. Yet this reaction could have a selectivity as striking as the (p,π^-) reaction. The residual nuclei are neutron rich and in a region inaccessible to high momentum transfer reactions with more conventional probes. The (π,N) reactions allow one to probe single hole states in an analogous manner to $(p,2p)$ or $(e,e'p)$ reactions. However this process has the advantage of having only one particle in the final state.

In principle there are various simple reaction mechanisms that can take place in the (π^-,p) reaction. One is direct two nucleon absorption with rearrangement of energy so that a high energy proton is detected ($\pi^- pp \rightarrow pn$). Also π^- can charge exchange to a π^0 which is then

absorbed on a pn pair ($\pi^- pp \rightarrow \pi^0 pn \rightarrow pn$), or pion absorption on a nucleon can excite a delta which subsequently interacts with another nucleon ($\pi NN \rightarrow \Delta N \rightarrow NN$). There is also the possibility of a sensitivity to Δ 's existing in the nucleus. If a Δ is formed in the nucleus as a component of the NN interactions which bind the nucleus, then the absorption mechanism $\pi^- + \Delta^{++} \rightarrow p$ is possible. Inside a nucleus pions can be absorbed on both T=0 and T=1 nucleon pairs. So by studying both the (π^+, p) and (π^-, p) reactions in a nucleus one can study absorption on T=0 and T=1 nucleon pairs, because π^+ predominantly gets absorbed on a pn (T=0) pair, whereas direct π^- absorption resulting in an outgoing proton is only possible on a pp (T=1) pair.

Nuclear structure should play an important role in the cross sections to specific states for this reaction. The (p, π^-) experiments demonstrate that the reaction has a strong selectivity to stretched 2p-1h configurations. Possibly the (π^-, p) reaction will show a similar sensitivity to stretched 1p-2h configurations. This expectation is supported by shell model calculations of Brown and Wildenthal (Bro-83,84,Wil-83).

The work presented in this dissertation investigates the selectivity of the (π^-, p) reaction, by determining the systematics of this reaction over a range of nuclei (A=12 to A=58) and at 120 and 90 MeV incident pion energy. This is the first experiment to measure the exclusive (π^-, p) reaction in this energy region. The pion production measurements by $(p, \pi^\pm)$ reaction at different laboratories

are measurements either at or near threshold energy or at very high energies. Both $(\pi^{\pm}, p)$ reactions were measured on the same targets at the same energy to study the absorption on $T = 0$ and $T = 1$ nucleons pairs. Since the $(\pi^{\pm}, p)$ reactions are high momentum transfer reactions, the outgoing protons have high energy and momentum. The energetic Pion Channel and Spectrometer (EPICS) at the Clinton P. Anderson Meson Physics Facility (LAMPF) of the Los Alamos National Laboratory and the High Resolution Pion Channel π M1 and SUSI spectrometer at the Swiss Institute for Nuclear Research (SIN) are the only two facilities in the world where high resolution $(\pi^{\pm}, p)$ reactions can be measured in a timely manner. At EPICS these reactions were measured at $T_{\pi} = 120$ MeV and at a laboratory angle of 25° on ^{24}Mg , ^{27}Al , ^{40}Ca , and ^{58}Ni ; $^{12}\text{C}(\pi^{-}, p)$ was measured at $T_{\pi} = 145$ MeV. An energy resolution of 400 to 600 keV FWHM was achieved for this reaction. At π M1-SUSI these reactions were measured at $T_{\pi} = 90$ MeV and at a laboratory angle of 20° on ^{23}Na , and ^{24}Mg . An energy resolution of 500 to 800 keV FWHM was achieved at SIN for this reaction.

In ^{23}Na , ^{24}Mg , and ^{27}Al there are peaks in the low excitation energy region. The $^{24}\text{Mg}(\pi^{+}, p)^{23}\text{Mg}$ spectrum at $T_{\pi} = 120$ MeV has two peaks presumably of high spin states $5/2^{+}$ (0.47 ± 0.1 MeV) and $9/2^{+}$ (2.71 ± 0.2 MeV) with cross sections 8.1 ± 1.7 $\mu\text{b/sr}$ and 17.6 ± 2.6 $\mu\text{b/sr}$ respectively. At $T_{\pi} = 90$ MeV this reaction reveals two peaks at 0.85 ± 0.5 MeV with a cross of 20.4 ± 4.1 $\mu\text{b/sr}$ and at 2.8 ± 0.5 MeV

with a cross section of $71.5 \pm 13.6 \text{ } \mu\text{b/sr}$. The $^{24}\text{Mg}(\pi^-, p)^{23}\text{Ne}$ spectrum at $T_\pi = 120 \text{ MeV}$ has a peak at $8.4 \pm 0.3 \text{ MeV}$ with cross section $2.4 \pm 0.6 \text{ } \mu\text{b/sr}$ which has not been seen before in ^{23}Ne and is a $13/2^+$ state. The measurement at 90 MeV also reveals a peak at $9.6 \pm 1.0 \text{ MeV}$ with cross section $15.9 \pm 2.60 \text{ } \mu\text{b/sr}$. The $^{27}\text{Al}(\pi^+, p)^{26}\text{Al}$ spectrum shows a high cross section $(22.6 \pm 2.0) \text{ } \mu\text{b/sr}$ exciting the 5^+ ground state. The $^{23}\text{Na}(\pi^-, p)^{22}\text{F}$ reaction study revealed a peak at $5.7 \pm 0.5 \text{ MeV}$ with cross section $4.4 \pm 1.2 \text{ } \mu\text{b/sr}$. In ^{24}Mg and ^{23}Na there are peaks in the (π^-, p) spectrum that are comparable in strength with those seen in (π^+, p) . Other nuclei studied do not have sufficient statistics in any bound states and cross sections of those states are $\leq 1 \text{ } \mu\text{b/sr}$ for (π^-, p) compared with $7 - 22 \text{ } \mu\text{b/sr}$ for peaks from (π^+, p) reactions.

The shape of the proton spectra above an excitation energy of 10 MeV is approximately independent of the target mass and of the incident pion charge. Ratios of cross sections for $(\pi^+, p)/(\pi^-, p)$ and ratios of the same reaction on different nuclei are flat over the range of excitation energies observed here. The magnitude of proton yield from all the targets at $T_\pi = 120 \text{ MeV}$ is more than twenty four times larger for π^+ than for π^- . At $T_\pi = 120 \text{ MeV}$ both (π^+, p) and (π^-, p) continuum cross sections are found to have little mass dependence, with the cross sections for both reactions on ^{24}Mg slightly enhanced compared to the other nuclei. At $T_\pi = 90 \text{ MeV}$ the ratios of cross sections for $(\pi^+, p)/(\pi^-, p)$ drops down to fourteen time larger for π^+

than for π^- showing the same trend as the ratio ${}^3\text{He}(\pi^+, pp)/{}^3\text{He}(\pi^-, pn)$ for absorption on T=0 and T=1 nucleon pairs.

The ratios of $(\pi^+, p)/(\pi^-, p)$ are higher than most previously published values, for heavy nuclei $A \geq 4$ (Kal-80,81a,81b,83; Jac-77A,77B; McK-80,81;) which averaged over a large range of proton energy. Those ratios thus include protons from secondary processes. The present high ratio is consistent with absorption on two nucleons if the possibility of charge exchange and delta formation is taken into account before absorption.

This dissertation consists of six chapters. The first chapter presents an introduction to this work. The next three chapters discuss the experimental techniques. Chapter II contains a detailed description of the experimental methods used in this investigation. General features of the two different laboratories, EPICS (LAMPF) and π M1-SUSI (SIN) utilized for the experiments are described and compared. The next three sections describe the optics of the EPICS system, and its detectors and electronics. The following two sections describe π M1 and SUSI, and detectors and associated electronics. Relative beam monitors and targets used at both laboratories are described in the subsequent two sections. Chapter III contains a description of the two different data acquisition and analysis systems of LAMPF and SIN. Also in this chapter a description of handling the data from CAMAC based electronics to tape storage and event processing with

different tests is given. Chapter IV contains the data analysis in which cross sections are obtained from the event histograms. Also discussed are normalization of data, correction for the acceptance of the spectrometer and calculation of cross sections. The statistical significance of possible peaks in the spectra is also discussed. Chapter V contains the analysis and calculations for this experiment. Using a simplified model of negative pion production and absorption, a calculation of the relative cross section is presented. Also optical potential calculations using the computer code CHOPER are presented. These are distorted wave calculations which employ a pion- and proton-nucleus potential to generate distorted waves for the incoming pion and the outgoing proton. Discussion of current experimental work in the context of previous works in pion absorption and production is presented. Finally conclusions are found in Chapter VI.

II. EXPERIMENTAL METHODS

The study of ($\pi^\pm, p$) reactions has been limited by the small differential cross sections (usually less than $10 \mu\text{b/sr}$) and the necessity of analysing protons of momentum 600–750 MeV/c with a resolution sufficient to separate final states. Thus the study requires a high intensity of pions and a good spectrometer with better than 1 MeV resolution for 176 – 263 MeV protons. The data presented in this dissertation result from experiments performed with two spectrometers, the Energetic Pion Channel and Spectrometer (EPICS) of the Clinton P. Anderson Meson Physics Facility in Los Alamos, New Mexico (LAMPF) and the High Resolution Pion Channel, πM1 and SUSI Spectrometer of the Swiss Institute for Nuclear Research (SIN) in Villigen, Switzerland.

The positive and negative pions were produced by high energy proton reactions in a solid target. At LAMPF a proton current of up to 1000 μA average is accelerated to 800 MeV in a linear accelerator and passes through various carbon targets. The EPICS channel sits at 35° to the proton beam and delivers $2 \times 10^8 \pi^+/\text{s}$ and $10^7 \pi^-/\text{s}$ at 120 MeV on the target. The EPICS spectrometer can detect particles of momentum up to 750 MeV/c corresponding to 263 MeV protons, with a resolution of $\sim 400\text{--}600 \text{ keV}$. At SIN a proton current of 150 μA average is accelerated in a ring cyclotron up to an energy of 592 MeV which produces $5 \times 10^6 \pi^+/\text{s}$ and $10^5 \pi^-/\text{s}$ (at 90 MeV), at the end of the πM1 channel using beryllium as a production target. The SUSI spectrometer can

detect particles of momentum up to 665 MeV/c corresponding to 212 MeV protons with a resolution of 500-800 KeV. This chapter describes both EPICS and π M1-SUSI systems, detectors and associated electronics. Parameters for the two systems are compared in TABLE 2.1.

EPICS Channel and Spectrometer

The EPICS (Thi-70) channel is at a 35° angle from the main proton beam line Area-'A'. A schematic view of the EPICS channel is shown in Fig. 1. The momentum selection is done by four dipole bending magnets (BM01 - BM04) which bend and disperse the particles in a vertical plane. The channel has three multipole focusing correction magnets (FM01 - FM03) consisting of quadrupole, sextupole (top) and sextupole (bottom) to optimize the resolution. The focusing is point to point in the vertical plane and point to parallel in the horizontal plane as shown in Fig. 1.

The channel has four collimating jaws (FJ01 - FJ04). The vertical jaw FJ01 which is located just after the production target, controls the vertical divergence of the beam and the intensity of the pions delivered to the experimental target. The collimating jaw FJ02 is located after the E x B velocity separator box which is not operational. The jaw FJ03 removes the slit scattering products from previous jaws. Jaw FJ04, located at a common focus of X and Y, defines the channel acceptance.

The pion beam at the target consists of a

Table - 2.1
Comparison of present performance of EPICS and
M1-SUSI system

	π - channel		Spectrometer	
	EPICS	SUSI	EPICS	SUSI
Energy Resolution (KeV)	--	--	500	700
Solid Angle (msr)	3.4	5.5	10.0	16.0
Momentum acceptance	$\pm 1\%$	$\pm 1.4\%$	$\pm 7.0\%$	$\pm 18\%$
Momentum Range (MeV/c)	<400	150-450	<750	100-500
Total path length	15	20.6	12.5	8.
Angular Divergence (mrad)	10	Horizontal 35 Vertical 75	60 200	150 120
Dispersion Plane	Vertical	Horizontal	Vertical	Vertical
Spot size at the target (cm)	8x20	1x2	--	--
Angular Range (Deg)	--	--	0-115	0-140

Fig. 1.

broad range of incident energies distributed on the target, with the pion momentum correlated to the vertical target position. The momentum spread of the beam across the target is $\Delta P/P = 2\%$. The dispersed target beam can handle a very large pion flux compared to an achromatic beam of the same solid angle, since no detectors in the beam are needed but requires rather large targets. The channel solid angle is 3.4 msr and produces a dispersed beam spot of 20 cm $\times$ 8 cm at the target position.

The target is centrally located in a one meter radius evacuated scattering chamber, vacuum coupled to the pion beam line. Targets are fixed to a system designed to hold three target frames at the same time which operates like a ladder, allowing them to be employed without opening the vacuum system. The spectrometer in Fig. 2 and channel are not dispersion matched, so the momentum of the incident particle needs to be measured. The reaction product passes through a set of three quadrupoles QM01-QM03 shown in Fig. 3, which focuses the particles in point to point in the vertical plane, with a magnitude of -1, and parallel to point in the horizontal plane on a set of multiwire proportional chambers placed at its focal plane. This set of eight planes of the front wire chambers F1-F4 measures two X and two Y positions and the quantities X_f , $\theta_f = (dX_f/dz)$, Y_f , $\phi_f = (dY_f/dz)$, where f represents the quantity measured in a plane in front of the spectrometer. The Z coordinate is in the direction of the particle trajectory. The X coordinate is in the direction of the vertical direction, i.e. in the

Fig. 2.

direction of the spectrometer bend. The X coordinate is used for projection back to the target and hence provides a measure of the incident pion beam momentum to an accuracy better than the momentum spread of the beam. This ability to project back to the target also allows the use of horizontal strip targets.

The reaction products are momentum analyzed by two 1.3 meter radius bending dipole magnets BM05 - BM06, which vertically bend the scattered particle by 120° to a series of detectors located at the focal plane of the spectrometer. The momentum of the scattered particle is determined with respect to a central ray through the spectrometer.

$$\delta_{sp} = \frac{P_p - P_{sp}}{P_{sp}} \times 100 \%$$

P_{sp} is the central momentum of the spectrometer and is determined by the magnetic field strength of the dipoles. The useful momentum acceptance at the focal plane of the spectrometer is $-6.0 \leq \delta \leq +6.0\%$.

The spectrometer works in a VHV mode, i.e. the beam is dispersed vertically (X- direction) at the target, undergoes a horizontal (Y- direction) scattering and is bent vertically (perpendicular to the plane of the floor) during magnetic analysis. General features of the EPICS system have been summarized in Table 2.1.

During this experiment both of the bending magnets were running at the highest attainable magnetic field and were able to momentum analyze 740 MeV/c protons at the focal plane.

Detectors of EPICS

A schematic view of the EPICS detection system is shown in Fig. 3. The system consists of three quadrupoles QM01 - QM03 just after the scattering chamber. The three quadrupoles focus the scattered particles in the X-Y-X planes respectively onto a 1.5 mm thick plastic scintillation detector S1 and four delay line read out drift chambers (DLRDC) F1 - F4 (Mor- 82) consisting of two planes each, placed near the focal plane. After being momentum analysed by bending magnets BM05 - BM06 of the spectrometer, scattered particles are detected by a second set of four DLRDC R1 - R4, plastic scintillation detector S2, a Cêrenkov counter, another plastic detector S3 and a muon rejection system consisting of several layers of scintillators with graphite layers in between them. For this experiment both the Cêrenkov counter and muon rejection system were not used.

The first of the three scintillators, S1 is a very thin (1.5 mm) detector at the entrance of the spectrometer with one phototube and provides a signal for time of flight through the spectrometer. S2 and S3 with phototubes at both ends are behind the exit focal plane just after the last rear chamber. The flight path between S1 and

Fig. 3.

S2 is 9 meters and between S2 and S3 is 1.5 meter. The time of flight for 120 MeV pions and for 230 MeV protons through the spectrometer are 35.6 ns and 50.0 ns respectively, and that between S2 and S3 is 5.93 ns and 8.30 ns. The time of flight and pulse height for a particle through the spectrometer were recorded, which provided information for particle identification.

The wire chambers were designed and build at LAMPF. A complete description of the construction and operation of these chambers is given in by Morris et al. and Atencio et al. (Ref:- Mor-82, Ate-81). The front chambers have an active area of $30 \times 30 \text{ cm}^2$. Four pairs of chamber planes, two orthogonal sets of four planes each, are used for each trajectory measurement. The wire spacing in the chambers is 8 mm. Alternate field defining cathode wires are bussed together providing the two cathode outputs per plane, and the anode wires are coupled directly onto a fast delay line which provides two anode outputs per plane. These chambers normally operate with a gas mixture of 65% argon, 35% isobutane, 0.10% freon and 0.50% isopropyl alcohol. This mixture is used to obtain a wide voltage plateau at a pressure of 650 mm of mercury (the average atmospheric pressure in Los Alamos). The time for each end of the delay line is measured with respect to a prompt time associated with the event using a time to digital converter (TDC). The time difference between the signal at the two ends of the delay line is used to determine the anode wire position, as it is nearly a linear function of the anode wire position.

The time sum varies with the negative ion drift time and is thus used to determine the drift distance to the appropriate anode wire. To find the exact trajectory of the particle it is necessary to determine whether the particle was to the left or right of the anode wire. This left and right ambiguity is resolved by having two sets each of X and Y planes (Ate - 81). One plane is off-set one half an anode wire spacing to decide whether to add or subtract the drift distance from the anode wire position. Thus eight anode planes, four measuring vertical coordinates and four horizontal coordinates, are needed to completely specify a particle trajectory before the dipoles. The typical position resolution, averaged over the entire anode plane, is $250\text{ }\mu\text{m}$ (FWHM). This gives $180\text{ }\mu\text{m}$ resolution for an individual plane and $125\text{ }\mu\text{m}$ (FWHM) resolution for the average position for two planes. The quantities calculated from these measurements of the reaction products include X_{front} , X - coordinate at the target, as shown in Fig. 3. , Y_{front} Y - coordinate at the target, $\theta_{\text{front}} = dX_{\text{f}}/dz$ and $\phi_{\text{front}} = dY_{\text{f}}/dz$ at the target. There are eight similar but larger wire chambers planes at the focal plane of the spectrometer. The position information from these chambers are used to calculate the quantities X_{rear} , Y_{rear} , $\theta_{\text{rear}} = dX_{\text{rear}}/dz$ and $\phi_{\text{rear}} = dY_{\text{rear}}/dz$.

EPICS System Fast Electronics

The amplified and discriminated wire chamber signals and signals from the scintillators are carried

through 50 Ω coaxial cables into the counting house, where these signals are amplified, discriminated, shaped and delayed as necessary. The signals are then interfaced to the computer through analog to digital converters (ADC), time to digital converters (TDC) and scalers in CAMAC (Zac-72) crates. A Digital Equipment Corporation (DEC) VAX 11/750 computer interfaced through a microprogrammable branch driver (MBD) (Tho-73,SHL-74) to the CAMAC crate was used for collecting data during this experiment. A block diagram of the electronics is shown in Fig. 4.

As shown in Fig. 4, the signal from the two phototubes at each end of the scintillators S2 and S3 have followed a similar electronic circuit. The phototube signals S2P and S2N of scintillator S2 have two outputs each. One output directly feeds into an ADC after proper delay to be in coincidence with the ADC gate pulse. The other output goes to a discriminator. One output from the discriminator goes to a scaler, the second output is sent to a TDC stop and the third to a mean timer, where the modified signal from both phototubes are joined. If the two input signals trigger within a certain time interval, then a NIM output pulse is generated by the mean timer. So no matter where a charged particle hits the scintillator, an output pulse is generated at a constant time after the scintillation, indicating S2 has detected a particle. The output of the mean timer is again shaped and three outputs of this discriminator are inputs to a scaler and two logical .AND.

devices. The output of the two phototubes, S3P and S3N from scintillator S3 follow similar circuits as S2P and S2N, and are input to the same logical .AND. device. One logical .AND. forms a coincidence between S2 and S3 pulses and gives an output pulse (S2.S3) when both S2 and S3 triggered at the same time. Another logical .AND. is used to count the accidental coincidence between S2 and S3. Such an accidental may be caused by electronic noise or two particles passing through the detector during the allowed coincidence time.

The signals from either end of a wire chamber delay line are discriminated and then sent to a TDC. The TDC measures the time between the arrival of the two electrical pulses, one which starts the counting while the other stops it. The discriminator pulse from the wire chamber delay line stops the TDC. The TDC start is given by the coincidence signal of the two plastic scintillators (S2.S3). Another output from each discriminator is input to a logical .AND. device, with one logical .AND. for each wire chamber. There are four inputs to this logical .AND. from the four planes of the wire chamber F1. One output of this logical .AND. is input into a scaler. Another output is input to a logical .AND. where it forms a coincidence with S2.S3. The output of this coincidence for the F1 wire chamber F1.(S2.S3) is fed into a scaler, which counts the number of times the first wire chamber F1 fired in coincidence with S2 and S3. All the front and rear wire chambers follow similar electrical circuits as described below.

The event trigger is formed with the front

wire chambers, S2 and S3. A third output from the logical .AND. of the first front wire chamber F1 delay line forms a logical .OR. with the second front wire chamber F2 ($F1+F2$) and similarly ($F3+F4$). The two outputs of the two logical .OR.'s are scaled and discriminated. The outputs of the two discriminators are fed into a logical .AND. to form a coincidence ($F1+F2$).($F3+F4$) between them, which is scaled and in coincidence with S2.S3 forms an event trigger (EVENT). So a particle which gives valid signals in coincidence in S2 and S3 and two of the front chambers forms a good event trigger (i.e. $\text{Event} = S2.S3.\text{Front}, \text{Front} = (F1 \text{ or } F2).(F3 \text{ or } F4)$). Each event read consisted of approximately 40 integer data words of information into the computer. The raw data words are also written on magnetic tape for offline analysis.

To prevent the possibility of too rapid or continuous triggering of events, a Busy system is employed. The Busy system is the logical 'or' of the computer busy, a "run" gate, a "beam on" gate and a fast block. The computer provides a TTL signal when it is busy processing an event. The "beam on" gate or beam gate insures that the data acquisition system is operative only during the fraction of time when the beam is on the target. It is a NIM signal which is set up to bracket each pulse of the primary proton beam. The "run" gate is on when the system is ready to take data and is turned on by the software at the start of the run. The fast block is a 400 μsec long inhibit generated

immediately upon receipt of a good event trigger preventing the acceptance of further triggers during the time required for the LAMPF trigger module (LA-82) to begin the CAMAC readout and give the computer time to generate its busy signal. The ANTI-BUSY in coincidence with EVENT forms the final event trigger for the computer, which is triggered only when the event requirement is satisfied, computer is not busy, beam is on and run is in progress. Both the $\text{EVENT} \cdot \overline{\text{BUSY}}$ and EVENT were scaled to calculate the number of events in the data sample compared to the total number of event triggers received. Besides reading ADC's and TDC's when the event trigger is present, the computer reads scalars counting different detectors and monitors at a fixed interval of time (usually every 15 seconds).

CAMAC is a system for transmission of data and control between instrumentation modules and a computer. It defines the precise format of both module and crate, together with certain signal and power supply conventions. The CAMAC trigger module, which is connected to the software interface provided for the experiment by the MBD, allows separate triggering of up to 32 priority-ordered events as specified by the user's analyzer. Each event trigger corresponds to a particular event as defined by the user's electronics. The MBD is a dedicated microprocessor intended to serve as an interface between a CAMAC branch and a computer. When an event is signaled at an enabled input of the CAMAC trigger module, a signal "Look At Me" (LAM) is generated indicating that the module wants attention. This,

in turn, causes the MBD to execute its data acquisition code. The highest priority event number is signaled by the trigger module. This priority is read by the MBD and the specified CAMAC and MBD operations are performed for that trigger. The MBD's internal buffer stores data from several events and when it is filled, the buffer is dumped into a buffer in the VAX 11/750 which can be written on tape and distributed for processing. The event processing program may be used to do on-line analysis. The tapes are analysed off-line with several D.E.C. VAX computers at LAMPF and with the VAX 11/730 at the University of South Carolina, Columbia.

Fig. 5.

High Resolution Pion channel $\pi M1$ and SUSI Spectrometer

The main experimental hall of SIN is shown in Fig. 5. The accelerator consists of two separate cyclotron accelerators. A sector-focused injector cyclotron produces 72 MeV protons which are then injected into a ring cyclotron where they are accelerated to 592 MeV. The proton beam produces secondary beam at two production targets M (thin) and E (thick). The High Resolution Pion Channel (ALB-79) $\pi M1$ is at an angle of 22.5° from the proton beam line passing through the production target M.

The schematic layout of the pion channel is shown in Fig. 6. The channel has two symmetrical parts about the intermediate focal plane. The pion beam is dispersed in the horizontal plane at the intermediate focus of the channel. The first part consists of three quadrupoles Q_1 - Q_3 after the production target, crossed field electrostatic separator with compensating magnets D_s , a bending magnet D_1 and another pair of quadrupoles Q_4 - Q_5 . The incident pion momentum is determined by a hodoscope system, consisting of 16 scintillators placed at the intermediate focus. The second section of the channel recombines the dispersed beam into an achromatic focus at the scattering target by quadrupoles Q_6 - Q_7 bending magnet D_2 and quadrupoles Q_8 - Q_9 . Two intermediate waists are placed in the center of the two dipole magnets in order to keep the gap size small. In the dispersive plane (x) from the production target M, through the intermediate focus I_M to the scattering target T_M the

- C = Multi-Wire Proportional Chamber
 S = Scintillator
 T = Scattering Target
 D = Dipole Magnet
 Q = Quadrupole Magnet
 Sep = Electrostatic Separator
 SL = Adjustable Slit

0 5 m

Fig. 6.

focusing is point to point . In the axial (y) plane the focusing is point to point between M and T_M .

There is an electrostatic separator, Sep in between the two compensating magnets D_S , used to remove protons from the π^+ beam. The compensating magnets D_S on both sides of the separator bend the pions back to the center of the beam line. Whereas protons with different trajectories are stopped by the slits SL1. Higher order aberrations in the focusing at the intermediate focus and the target are corrected by two sets of coils that are attached near the entrance and exit of the bending magnets.

A cross-sectional view of the SUSI spectrometer (ALB-79) is shown in Fig. 7. The pion channel produces a beam spot of 1 cm $\times$ 2 cm on the target centrally located in a scattering chamber. The target holder employed was a simple arrangement which allowed one target in the beam at a desired angle. The scattering chamber was not vacuum coupled either to the pion channel or to the spectrometer. Pions and the reaction products (π and p) travel through air and thin mylar windows before and after the target respectively. Reaction products pass through a quadrupole Q_{10} which focuses the particle on a multiwire proportional chamber C_5 . A set of two orthogonal planes measure X and Y coordinates of the particle.

The reaction products are momentum and charge analysed in the vertical plane by two bending magnets A1 and A2 and intersect a series of detectors located near the focal plane of the spectrometer. A schematic view of the

Fig. 7.

spectrometer optics in the dispersive plane is shown in Fig. 8. In the radial plane there is a point to point imaging between C_5 and focal plane F. The trajectory of particles with the same momentum are parallel between the two dipoles and at the focal plane the dispersed trajectories are parallel. The optical source for the two bending magnets is not the target, but the chamber C_5 . This mode was chosen for good resolution. The dimension of the beam spot on the target is large and by having C_5 as the optical source the first order contribution to the resolution is given by the spatial resolution of chamber C_5 (1mm) and not by the dimension of the beam spot. In the axial plane the imaging is point to point between T_5 and F. The focal plane is 2m long inclined by about 35° with respect to the central ray and slightly curved, providing a $\pm 18\%$ momentum acceptance. The momentum dispersion is 5.5 cm/% along the focal plane.

As at EPICS during this run the bending magnets were at their highest attainable magnetic field and were able to momentum analyse up to 675 MeV/c protons at its focal plane.

Detectors and Electronics of π M1 and SUSI

A schematic view of the π M1 and SUSI detection system is shown in Fig. 9. The system consists of a hodoscope system HS at the intermediate focal point of the π M1 channel to detect the momentum of the incident pion. The intensity of the pion beam was determined by a 1/2 mm thick scintillator S2 placed 1/2 m upstream of the scattering

Fig. 8.

target at the end of the channel. The reaction product is detected after the quadrupole Q_{10} by a multiwire proportional chamber C_5 . The particle is then momentum analysed by bending magnets A1 and A2 and is detected by two wire chambers C_6 and C_7 located near the focal plane of the spectrometer. The particle identification is done by using a plastic scintillator S3 placed at the entrance of the spectrometer after C_5 and another scintillator S4 placed after C_7 at the focal plane. Both of the scintillators have phototubes at each end.

The wire chamber C_5 was constructed at Neuchâtel using a CERN design (CHA-70). The $10\text{ }\mu\text{m}$ anode wires are separated by 1 mm, and the cathode is a $10\text{ }\mu\text{m}$ thick aluminum foil. The total thickness of one chamber consisting of X and Y planes is 27 mg/cm^2 . The chambers C_6 and C_7 constructed at SIN with 2 mm wire spacing cover the entire 2 meter long focal plane to take full advantage of the large momentum bite (> 2 times larger than EPICS). The chambers operate with the magic gas mixture of argon, isobutane and freon (1%). A delay line read out is used to read each anode wire of the X-Y chamber C_5 . Each anode wire is connected through a tap to a delay line. For each chamber plane, both ends of the delay line are connected to a low noise current amplifier and a constant fraction discriminator. Both planes of the wire chamber are read simultaneously through a CAMAC TDC. The start and stop are given by the event trigger and the delay line channels respectively. The time difference and sum for each delay

Fig. 9.

line provides the position information of the particle. The chambers C_6 and C_7 are read by a commercial digital read out system (FILAS), which decodes the signal into digits.

The raw wire chamber and scintillator signals are carried through coaxial cable into the electronic shack, where these signals are amplified, discriminated, shaped and delayed as necessary. These signals are then interfaced to the computer through ADC's, TDC's, and scalers in CAMAC crates. The CAMAC is interfaced with a Interface JCC-11 to a PDP 11/45 computer which is used for data acquisition. A block diagram of the electronics of the SUSI system is given in Fig. 10.

As shown in Fig. 10, the downstream scintillator S2 has one phototube. The signal from S2 is fed into an ADC, and two discriminators ($S2_B$ and S2). These two discriminators pulse height analyse and eliminate electrons, muons and protons in the signal. The output of the step down discriminator is input to a scaler, to a TDC and to a logical .AND., where it forms a coincidence ($S2_B.S2$) with an output from the step up discriminator. Another output from the step up discriminator is an input to a scaler. The output of the logical .AND. is input to a scaler and to a coincidence unit. There it forms a coincidence with the 50 MHz signal from the accelerator (P) to form the incident BEAM (P.S2) trigger. As shown in Fig. 10, the upstream scintillator S3 and S4 have phototubes at both ends. The phototube signals S3P and S3N of scintillator S3 have two outputs each. One output is directly input to an ADC after

Fig. 10.

proper delay to be in coincidence with the ADC gate pulse. The other output goes to a discriminator. One output from this discriminator goes to a scaler, the second output from this discriminator is sent to a TDC stop and the third output goes to a mean timer, where the modified signals from both the phototubes of S3 are joined to give an output pulse indicating S3 has detected a particle. Outputs from S4P and S4N are amplified and are input to an ADC, and to a discriminator. The discriminator outputs go to a TDC and to a logical .AND. where the two ends of S4 form a coincidence. An output of this coincidence forms a coincidence with the S3 signal to form a signal SPECT signifying a particle through the spectrometer. The EVENT trigger is formed by a coincidence between BEAM and SPECT. For a good event the incident particle must have a valid signal in S2 in coincidence with the accelerator pulse P and the scattered particle must have a valid pulse in S3 and S4 in coincidence with the beam (i.e. $EVENT = (P.S2.S3.S4)$ $S2 = (S2_P.S2_N)$; $S3 = (S3_P.S3_N)$; $S4 = (S4_P.S4_N)$)

The rest of the fast electronics circuitry is designed to produce a hardware trigger, read and clear the wire chambers in the TDC's. The event trigger strobes the fast coincidence register, which starts the delay line chamber readout and digital encoder and may interrupt the computer. When the encoder has coded all the addresses in the CAMAC an interrupt may be generated. The encoder generates a CLEAR to reset the CAMAC if it gets too many clusters in one plane. To stop a continuous triggering of

events in the CAMAC, a fast and slow block logic similar to EPICS was set up to veto the trigger while other parts of the system are busy decoding or the computer is busy.

MONITORS

The primary proton current in line A at LAMPF is monitored by two counters 1ACMO2 and BOT. 1ACMO2 is a toroidal coil around the proton beam allowing integration of the current induced by the primary beam, while BOT is an ionization chamber located near the A-1 production target measuring the secondary emission from the production target. The relative beam flux through the EPICS channel is monitored with an ion chambers IC1 which is located in the evacuated scattering chamber at 0° and about 0.75 meter downstream from the target. So that these monitors will only count the total intensity of the pion beam on the scattering target, a one inch thick graphite absorber is placed just in front of them to stop incident protons which are thus not counted. The current from the ion chamber is an input to a charge integrator which for a fixed amount of charge (usually 10^{-10} Coulomb) gives an output signal to a scaler. The ratio of BOT/IC1 was monitored for each run during the experiment and checked for consistency.

As described earlier, the absolute beam flux was monitored at $\pi M1$ -SUSI of SIN with the BEAM signal from a 1/2 mm thick scintillation detector placed 1/2 m upstream from the scattering target at the end of the beam line, in coincidence with a 50 MHz signal from the accelerator. The

electronic diagram for this monitor is shown in Fig. 11. The pulse height from the scintillator S2 was discriminated to cut electrons, muons and protons.

Fig. 11.

TARGETS

This experiment is motivated from the results of (p, π^-) reactions measured at the Indiana University Cyclotron Facility (IUCF). Their results show a selectivity for excitation of states of high spin in residual nuclei for targets which are neutron rich isotopes. In the reverse reaction (π^-, p) , proton rich nuclei would be desirable, but since none exist beyond ^3He , we chose nuclei using another criteria. The requirement of high angular momentum mismatch in the reaction and excitation of high spin states motivates the selection of nuclei with low energy high spin states. ^{24}Mg was selected as it is near the middle of the s-d shell and $^{24}\text{Mg}(\pi^-, p)^{23}\text{Ne}$, in the ground state of ^{23}Ne yields a $5/2^+$ spin state. By spin flip and coupling in the same shell up to $13/2^+$ ($5/2^+ + 5/2^+ + 5/2^+ \rightarrow 4^+ + 5/2^+$) is possible and is predicted by a shell model calculation to lie at 7.4 MeV. also ^{23}Mg , the residual nucleus of $^{24}\text{Mg}(\pi^+, p)$, has known low energy high spin states, such as $5/2^+$ (0.45 MeV), $9/2^+$ (2.70 MeV) etc. Since the good projection of the vertical target position for each event at EPICS allows the use of strip targets of two different nuclei, another target could be used at the same time. The Q value of the reaction must be nearly the same, which requires an isotope in the same mass region as ^{24}Mg . ^{27}Al was the choice as it has a $5/2^+$ ground state, the 3^+ ground state of the residual nucleus ^{26}Na following (π^-, p) and the 5^+ ground state of ^{26}Al following (π^+, p) , which can also provide better angular momentum matching. The best results from (p, π^-) were for the neutron

rich nucleus ^{48}Ca . Isotopes ^{58}Ni and ^{40}Ca were chosen in the same mass region.

The results of the measurements at EPICS showed that reactions on s-d shell nuclei were interesting, so for the SIN measurement ^{23}Na ($3/2^+$) was chosen as a target. The nuclei resulting from (π, p) on ^{23}Na are ^{22}Na and ^{22}F which have high spin ground states 3^+ and 4^+ respectively that are well resolved from their first excited states (0.66 and 0.58 MeV). It was hoped that the high angular momentum transfer to these states would be sufficiently matched to the large value of "qr" in the absorption reaction to yield enhanced cross sections well resolved from the continuum. Table 2.2 shows the separation energy for a proton and different light nuclei leaving the residual nucleus in a bound state.

The targets chosen for the (π^+, p) reaction studies were CD_2 (for both ^{12}C and ^2H), ^{24}Mg , ^{27}Al , ^{40}Ca and ^{58}Ni with densities 194, 196, 408, 500 and 292 mg/cm^2 respectively for the EPICS experiment. They were ^{12}C , NaOH (for ^{23}Na), ^{24}Mg with densities 200, 800, and 290 mg/cm^2 for the SIN experiment. All targets naturally consist of, or are enriched, so that the isotopes of interest are $\geq 99\%$ for that element. To have approximately the same average energy loss by the pion and the proton in the target, each target was rotated to an angle of 50° resulting in about a 55% increase in the effective target thickness.

TABLE 2.2

The separation energy for proton and different bound nuclei following $(\pi^{\pm}, p)$ reaction.

Energy Required For Breakup Of (MeV)				
	p	${}^2\text{H}$	${}^3\text{He}$	${}^4\text{He}$
${}^{12}\text{C}(\pi^-, p)$	20.9	17.9	26.3	8.4
${}^{23}\text{Na}(\pi^-, p)$	12.6	14.1	27.9	12.7
${}^{23}\text{Na}(\pi^+, p)$	6.7	11.3	18.6	8.5
${}^{24}\text{Mg}(\pi^-, p)$	15.3	18.2	23.9	10.9
${}^{24}\text{Mg}(\pi^+, p)$	7.6	16.4	27.2	9.6
${}^{27}\text{Al}(\pi^-, p)$	12.0	14.1	25.2	7.3
${}^{27}\text{Al}(\pi^+, p)$	6.3	11.4	17.6	9.5
${}^{40}\text{Ca}(\pi^-, p)$	10.7	14.2	17.5	6.8
${}^{40}\text{Ca}(\pi^+, p)$	5.8	15.6	12.0	6.7
${}^{58}\text{Ni}(\pi^-, p)$	10.6	15.6	18.2	7.3
${}^{58}\text{Ni}(\pi^+, p)$	7.3	15.2	14.8	7.6

III. SOFTWARE DATA ACQUISITION AND ANALYSIS

EPICS Events

A computer software package known as "Q" (Kel-75, Har-81), which was developed at LAMPF for data acquisition and analysis, was used to read CAMAC signals through an MBD to a VAX 11/750 and for event by event processing. A schematic flow chart (Fig. 12) of the Q data acquisition and analysis system shows the major flow between subsystems. "Q" has a histogram plotting library (HPL) (LA-82A, 82B). This system allows the user programs to create, increment, save, recall, clear and delete histogram subsystems.

The LAMPF "Q" system has an important feature in that it can work in both the data acquisition and analysis mode. All the subroutines used for online analyses of the event can be used for offline analyses. The only major difference between the online and offline analysis is that the experimental data is read from tape instead of CAMAC during offline analyses and the interrupt service routine to handle the MBD interrupts online is replaced with a routine to read input from the tape. Also the offline analysis is done in the must process mode of "Q" where each event is analysed and tested with software requirements.

The online acquisition program works in "may process" mode (i.e. process an event through the analyzer if the computer time is available) but all the events are written to magnetic tape. When the computer is not busy acquiring events, analyses and histogramming of some of the

Fig. 12.

events are performed. A valid hardware event triggers the computer to activate the system to read the CAMAC signals. A valid event includes information on the pulse height and timing signals from the scintillators and wire chambers as well as 16 bit pattern units. The online acquisition program consists of two parts. The first is a MACRO file which defines the CAMAC units (ADC's, TDC's, scalers etc) and assigns their various output to data words. The second is the analyzer which is the same for both online and offline analysis. The analyzer utilizing these raw data words from CAMAC in the case of online analysis or from the tape during off line analysis calculates the different variables of the incident and scattered particles. The main subroutine PROC6 performs logical tests on the raw data and on intermediate variables, calculates the chamber position information, and other variables to trace the trajectory of the particle, and utilizes two body relativistic kinematics (Appendix - 1) to determine the missing mass associated with each event, as discussed below.

The excitation energy of the residual nucleus is the final result of data acquisition and analysis. This is accomplished by the two subroutines PROC6 and CALKIN. PROC6 calculates the incident and outgoing particle information, such as incident and outgoing momentum and scattering angle.

The incident momentum of the particle is defined as

$$P_{in} = (\delta_c + 1) P_c$$

with,

$$\delta_c = \frac{X_{tgt}}{D_c} = \frac{-X_f}{D_c} = \frac{P_\pi - P_c}{P_c}$$

where D_c is the dispersion of the channel, δ_c is the percent difference between the incident particle momentum P_π and the central momentum of the beam channel P_c . P_c is determined by the magnetic field of the channel bending magnet.

Similarly, the outgoing momentum of the particle P_{out} is calculated by δ_{sp} and the central momentum of the spectrometer P_{sp} determined from the input value of the magnetic field and kinematic information about the reaction. δ_{sp} is calculated as a function of X_{front} , Y_{front} , θ_{front} , ϕ_{front} and X_{rear} and optimized as described above. The momentum of the outgoing particle is related to the X position at the focal plane of the spectrometer. To first order X_{rear} is given by

$$X_{rear} \approx M_{sp} \cdot X_{front} + D_{sp} \cdot \delta_{sp}$$

M_{sp} is the magnification of the spectrometer in the X direction, which is -1 , D_{sp} is the dispersion of the spectrometer (cm / % difference of the P_{out} from the central momentum P_{sp}).

So

$$\delta_{sp} \approx \frac{X_{front} + X_{rear}}{r_{sp}},$$

The outgoing momentum at the focal plane is given by

$$P_{out} = (\delta_{sp} + 1) P_{sp}$$

The scattering angle is

$$\theta_s = \theta_{spec} + \phi_{tgt}$$

where θ_{spec} is the input central spectrometer angle and ϕ_{tgt} is the calculated angle at the target as described below. From these calculated quantities, subroutine CALKIN calculates the excitation energy of the residual nucleus. This excitation energy calculation is described in Appendix - 1.

Higher order corrections to the measured data words are required due to the aberrations in the magnetic fields and misalignments of the system. The coordinates of the particle at the target X_{tgt} , Y_{tgt} , θ_{tgt} , and ϕ_{tgt} are calculated as a polynomial up to fourth order using the quantities X_{front} , Y_{front} , θ_{front} , ϕ_{front} and X_{rear} , as described by Boudrie et al. (BOU- 79). The coefficients of these polynomials are calculated from data that is obtained with horizontal and vertical rod targets and by optimizing the resolution. This optimization includes removing any linear or quadratic dependence of the resolution on any supposedly independent parameters. By using this prescription of polynomial expansion, a new data word can be calculated from other raw or calculated data words to check any correlation between data words. The polynomial expansion for δ_{sp} is optimized by keeping the spectrometer field fixed and varying the channel fields to sweep the elastic peak

from a heavy target across the spectrometer focal plane. The RAY file contains the values for the important variables in the determination of δ_{sp} for each events. By a linear least squares fit (COFEPX), δ_{sp} is optimally determined as a function of these variables across the focal plane. This procedure, called a delta scan, removes any nonlinearities in the relationship of channel number and missing mass and also optimizes the resolution of the EPICS system. The coefficients of all these polynomials are kept in a file POL.DAT. This file is read when the analyzer is initialized, but it can be changed during acquisition or analysis without recompiling or relinking of the analyzer.

Each raw and calculated data word can be tested by microtests and macrotests (AND, OR of the tests) defined in a test file (AMA-79), which has been given the name EXP809.TST (shown in Appendix-2). Microtests of the data words include the bit tests (i.e. whether a particular bit is set in the data word), direct or indirect gate tests (i.e. whether the value of the data word is in between the specified minimum and maximum limits) and BOX tests (i.e. whether the event has a specified correlation between two data words) can be performed. Macrotests are tests of microtests or other macro tests including complicated logical combinations (AND, OR(inclusive, exclusive) and NOT). This test file can also be modified at any time during the experiment without recompiling or relinking the various parts of the analyzer.

The first test was made to identify the detected

particles. The TDC and ADC of the three scintillators S1, S2 and S3 was used to set up two, two dimensional particle identification histograms PID1 shown in Fig. 13 and PID2 shown in Fig. 14. PID1 was set up with the geometric mean of the pulse height in the two scintillators S2 and S3 and the time of flight between them. As shown in Fig. 13 protons were very well separated from other particles. As well as protons, the PID1 (Fig. 13) 2D- histogram shows deuterons in the upper part of the histogram with large pulse heights and large time of flight. These deuterons are the reaction product of $(\pi, d)X$ reactions at very high excitation energy. BOX3 was set up to eliminate other particles from the protons. This box was not taken into consideration as a major background rejection, as the histogram event has a Landau tail in the pulse height values. PID2 consists of the S1 time of flight and time of flight between S2 and S3. As shown in Fig. 14 protons were very well separated from other particles (i.e. deuteron, rescattered protons) quite well. BOX1 was set to eliminate any event not falling into this box from further analysis. Separate histograms were created using only BOX1 and with both BOX1 and BOX3 as a test to investigate the accuracy of the two. It was found that 99% of the events which were in BOX1 also fall in BOX3 so only BOX1 was used as background rejection and BOX3 was used only for the testing the accuracy of this rejection.

Besides the PID test, an event has to pass a

Fig. 13.

Fig. 14.

set of other tests: chamber drift time tests, chamber drift difference tests and trajectory tests. The drift time tests are gates on the drift times for each of the sixteen chamber planes. This test rejects an event which does not produce signals in one or more of the planes. The drift difference tests are used to reject the particles for which the drift time correction has not been made correctly. In the case of the (π, p) reaction this test only removed those events in which two particles passed through the chambers at the same time. Normally this test also removes the particles that have decayed between two planes.

The trajectory tests are gates on the calculated particle position vector at the scattering target. The quantities that define the position vector are x_{tgt} (Fig. 15), y_{tgt} (Fig. 16), θ_{tgt} (Fig. 17), and ϕ_{tgt} (Fig. 18). x_{tgt} is the X coordinate at the target in the vertical direction, y_{tgt} is the Y coordinate at the target with the Z coordinate being the direction of the beam. θ_{tgt} and ϕ_{tgt} are the two spherical coordinate angles in vertical and horizontal directions respectively at the target. All four quantities have a fairly sharp edge in their allowed values and any events falling outside these edges are discarded. Two other calculated data words, θ_{check} (Fig. 19) and ϕ_{check} (Fig. 20), which are the difference between the angle measured at the front of the spectrometer and at the rear of the spectrometer were also gated to reject events which have poor trajectories due to scattering from magnet walls or particle decay. Events are rejected if these angle

Fig. 15.

Fig. 16.

Fig. 17.

Fig. 18.

measurements do not agree to within ± 10 mr.

The beam size of the EPICS channel is 20 cm X 8 cm at the target. The good beam projection of the vertical target position X_{tgt} for each event allowed us to use strip targets of two isotopes at the same time in the beam to utilize the full beam spot. The strip targets of ^{24}Mg and ^{27}Al were in one target frame and ^{58}Ni and ^{40}Ca in another. The projection of the vertical target position is shown in Fig. 21. Two gates were set to distinguish whether the events were coming from the top target strip or the bottom strip. An event falling into the gate set on a particular strip is kinematically treated as an event from that nucleus by replaying each run twice, one time each for one nucleus.

A set of histograms of various data words are created. These histograms can be gated by a specific test defined in the test file. One and two dimensional histograms are defined and plotted by different routines in the HPL library. The two dimensional histograms are useful for observing correlations between data words and also setting values for a box gate for particle identification.

Fig. 19.

Fig. 20.

Fig. 21.

SUSI events

The SUSI data acquisition and analysis system in principle is quite similar but simpler than the EPICS system. In this section only the major differences between the two systems are discussed. The data acquisition at π M1-SUSI is done with a PDP 11/45 computer using the operating system SINFUL (SIN-IR, Egg-85) based on Digital Equipment Corporation's RSX11A operating system. The online data acquisition was done by a previously written analyzer SUAN (SUSI - Analysis) in "may process" mode and all of the events were written to tape.

The CERN developed histogramming package HBOOK (Bru-84) was used for histogramming purposes. HBOOK has a step histogramming process which helps booking, filling and editing of histograms. Space for a histogram is allocated by booking with a special identifier (ID) defined for a particular raw or calculated data word. A histogram that has been booked can be filled with a count corresponding to the dataword of the histogram identifier. All booked histograms can be displayed, and/or edited.

A valid hardware event triggered the data acquisition system to read the CAMAC. The pulse height and time information from the scintillators and wire chambers are measured. The analyzer with these raw data words calculates the trajectory of the particle from the target to the rear detectors. The subroutine GECK (Good event check) performs (Appendix-3) the analysis event by event. GECK consists of various statements which can be used to request

the decoding, testing and determination of centroid information from chamber information. It also performs a logical test on the event. This subroutine also calculates the efficiency of the detecting system. An event failing any test is eliminated from further event analysis. An event passing these tests is further tested by indirect gates (i.e angle test, time of flight etc). Events passing certain tests or combinations of test are histogrammed. The subroutines ELOSS and PLOSS are used to calculate the energy loss and momentum loss for a specified reaction by using the information from the hodoscope, magnetic fields and scattered particle position.

Unlike the EPICS offline analysis, where the same programs were used for online and offline analysis, offline analysis of SUSI events were performed with an entirely different programme because of the following complications with online SUAN. The online program SUAN works with the operating system SINFUL, which operates on a PDP 11/45 under the operating system RSX11P. Both systems are descendents of RSX11A which in turn is a descendent of DOS (Disk operating system). SINFUL runs in a single user environment, thus the entire computer must be used for off line analysis. It can access only 28K of memory and most of SINFUL and its tasks are written in assembler language making it time consuming and difficult to perform even minor changes. One cannot define more than 24 histograms and doing an arithmetic calculation upon the statistics acquired by

the GECK table of tests is difficult.

The offline analysis system ANN (Ant-84) was developed to overcome these general problems. ANN runs on a VAX or on a PDP11/40. It's written in FORTRAN 77E and makes use of DEC control language (DCL). Both DCL and FORTRAN are powerful and highly flexible languages, which makes modification of the code considerably easier than assembler language. The structure of ANN is similar to SUAN. ANN has three main programmes GTTRAN, ANN and DISP. GTTRAN translates the coding of a GECK (Good event check) table into FORTRAN coding. ANN reads and analyses the DOS format tapes. DISP is used to display and manipulate the histograms stored by ANN on disk.

ANN and SUAN analyze the data event by event, so it is required to identify and access a particular word of information from the SET of event information extracted from a tape BLOCK. The event information in SUAN is stored in an array EVBUF (64 words) and in an extension EB2 (46 words). This information is accessed either by byte number or word number. In ANN, a BLOCK of event information is stored in Integer*2 array EVBUF and scaler information in array SCLRBUF. The correspondence of the event structure for SUAN and ANN is not one to one, but there is an offset of two words between them. For example in SUAN the S4(+) TDC information is the 15th word of an event, while that for ANN is the 17th word. The ANN and SUAN event structure is shown in Appendix 4. The event by event analysis program ANN can read DOS system written tape on DEC VAX computers. The

information from an event is calculated by the subroutine PARAM. Software tests for good event are applied on the data word by GECK. A gate test is applied by setting lower and higher limits on certain raw or calculated parameters by the main subroutine ANAL, using user direct or indirect input for the limits of the gate. Unlike SUAN these limits can be read in at the beginning of the replay of a run without compiling or relinking the analysis system. The subroutine ANN books and fills the histograms using HBOOK.

GECK performs a test that ensures that a good event gives a proper signal within specified limits in the wire chambers C5, C6 and C7. Any event failing to have a valid signal in any one of these three wire chambers is rejected from further analysis. It also performs calculations for efficiency of different detectors, live time and sums the scalers.

The subroutines PARAM and ANAL of ANN read the EVENT BUFFER and writes them to corresponding variables in EVBUF and in GOODEV. PARAM does most of the kinematic calculations. It calculates P_{in} , P_{out} , θ_{in} , and θ_{out} from the hodoscope, wire chamber and magnetic field information. This information is used to calculate the excitation energy of the residual nucleus. The momentum loss expression

$$P_{loss} = P_{channel} - P_{spectrometer}$$

should be zero in the case of the beam running directly through the spectrometer, with a peak width determined by

the combined resolution of channel and spectrometer. By using a least square fit, the measured width of the peak is minimized by varying the coefficient of the expression for a single region of the focal plane illuminated by the direct beam

$$\frac{dp}{p} (\text{Spect}) = \alpha X_5 + \beta X_5^2 + \gamma X_5^3 + \delta X_6 + \epsilon Y_5^2 + \phi (X_6 - X_7)$$

where X_5 , Y_5 represent the X and Y coordinates of chamber 5, and X_6 and X_7 are the X coordinates of chambers 6 and 7 respectively. To include the full beam intensity and to obtain a single expression for the full focal plane, parameterisation is further done in terms of X_6 , X_6^2 and higher order terms of X_5^2 , Y_5^2 . The optimizations used for this analysis were obtained during previous experiments using the same experimental apparatus.

The momentum of the incident pion is calculated by using the hodoscope value and the magnetic field of the first channel magnet. The momentum of the outgoing particle is determined by dp/p (Spect) and the magnetic field of the first spectrometer magnet.

ANAL performs indirect test on these raw and calculated data words, and histograms them. During offline analysis of (π, p) events many different cuts were tried on these data words. Two dimensional histograms were setup between excitation energy of the residual nucleus (EEXC_2BHOD) vs S34TOF (Time of flight from S3 to S4), Fig.

19-NOV-86 17:16:03

mgpipneg.his

ID= 30 /EEXC_28HOD_VS_534TOF

Fig. 22.

19-NOV-86 17:22:19

mgpipeq.his
ID= 40 /EEXC_2BH00_V5_54_TIME

Fig. 23.

19-NOV-86 17:08:27

mgplpneg.his
ID= 50 /EEXC_28HOD_VS_ANGLE

Fig. 24.

mgpipneg.his 19-NOV-86 17:01:35
ID= 70/EEXC_28HOD_54TIM_ANGLE

33

35 ID= 14/EEXC_28HOD

Fig. 25.

22, EEXC_2BHOD vs S4TIME (Average of S4(+) and S4(-) TDC), Fig. 23, and EEXC_2BHOD and ANGLE (Angle of the trajecting particle from front and rear chambers), Fig. 24. For the final analysis only two cuts were made on the S4TIME and ANGLE data words. An excitation energy histogram was set up with these two cuts. Another excitation energy histogram was also set up with S34TOF and ANGLE cut to check the efficiency of the first cuts. It was found the any combination of the two times from plastic scintillation detectors with ANGLE has a similar effect in reducing the background. A typical missing mass spectrum with and without software cut is shown in Fig. 25, the bottom fig is with no cut whereas the top one includes the S4TIME and ANGLE cut. As shown the background in the lower and negative energy region is reduced to a great extent without losing counts in the region of interest. All runs from the same target were replayed and added together channel by channel.

IV. DATA REDUCTION

Cross Section

This chapter describes the method of calculating the double differential cross section $d^2\sigma/d\Omega dE$ from the counts in the excitation energy histogram. The differential cross section in the center of mass is given by the expression

$$\frac{d\sigma}{d\Omega} = \frac{\text{YIELD} * \text{JAC} * \text{NORM} * \text{CORFAC}}{N_{\text{INC}} * \Delta\Omega * N_{\text{tgt}}} \quad (4.1)$$

where YIELD is the number of counts in a particular channel (or peak) of the missing mass histogram, JAC is the jacobian of the transformation from laboratory to center of mass system, CORFAC is an efficiency correction for the detecting system, N_{tgt} is the number of target nucleons per unit area, N_{INC} is the number of incident particles, which is determined by a beam monitor and $\Delta\Omega$ is the solid angle of the spectrometer. N_{INC} and $\Delta\Omega$ are relative quantities, related to the incident pion flux and the solid angle of the detection system and are normalized using NORM which is found by an indirect method discussed later.

The number of target nucleons per unit area N_{tgt} is

$$N_{\text{tgt}} = \frac{\rho_{\text{tgt}} * N_A}{M_{\text{tgt}} * \cos\theta_{\text{tgt}}} \quad (4.2)$$

where ρ_{tgt} is the areal density of the target, N_A is

Avogadro's number, M_{tgt} is the molecular weight of the target (gm/mole) and θ_{tgt} is the target angle with respect to the plane perpendicular to the incident beam.

The correction factor (CORFAC) is

$$\text{CORFAC} = \frac{1}{\text{CLT} * \text{CE} * \text{DE} * \text{LPE}} \quad (4.3)$$

where CLT is the computer live time, CE is the chamber efficiency, DE is the drift efficiency, and LPE is the fraction of the events analysed by software (100 % offline). The computer live time (CLT) is calculated from the scaler ratio $\text{EVENT.BUSY}/\text{EVENT}$. This ratio gives the fraction of the total number of events during which the computer was not busy.

The chamber efficiency (CE) and drift efficiency (DE) are calculated by using the information from the event test file (Appendix - 2) for EPICS chambers. The chamber efficiency at EPICS is calculated as follows

$$\text{CHAMBERS EFFI} = \text{FRONT CHAMBERS EFFI} * \text{REAR CHAMBERS EFFI}$$

Where,

$$\text{FRONT CHAMBERS EFFI} = \frac{\text{All Chambers ok}}{\text{Rear Chambers ok}} = \frac{\text{TEST 46}}{\text{TEST 45}} \quad (4.4)$$

$$\text{REAR CHAMBERS EFFI} = \frac{\text{All Chambers ok}}{\text{Front Chambers ok}} = \frac{\text{TEST 46}}{\text{TEST 44}} \quad (4.5)$$

The chamber efficiency for π M1-SUSI chambers is calculated for a particular plane by using the following relation

$$\text{Chambers Efficiency} = \frac{\text{Spec Event}}{\text{Spec Event} + \text{Good event in that Chamber}}$$

Where Spec Event = P.S2.S3.S4, as discussed in chapter II. The total chamber efficiency was given by the product of all the chamber efficiencies.

The drift efficiency (DE) corrects for events that have provided good chamber pulses from all planes but have not given good drift difference information.

The drift efficiency is calculated as follows

$$\begin{aligned} \text{DRIFT EFFI} &= \frac{\text{Drift Difference all ok} * \text{All chamber ok}}{\text{All chamber ok}} \\ &= \frac{\text{TEST 92}}{\text{TEST 46}} \quad (4.6) \end{aligned}$$

Loop per Event (LPE) is 1.0 for off line analysis because it corrects for the analysed number of events to measured number of events.

Absolute Normalization

The absolute normalization of the data to account for the spectrometer solid angle and pion constituent of the incident beam was accomplished by measuring the ${}^2\text{H}(\pi^+, p)\text{P}$ yield and comparing it to known π^+d

→ pp cross sections. The $\pi^+d \rightarrow pp$ reaction was measured at 220 MeV π^+ energy and $\theta_{\text{scat}} = 30^\circ$ at EPICS and 173 MeV π^+ and $\theta_{\text{scat}} = 20^\circ$ and 40° at SIN, which yield protons with approximately the same energy as the protons from the (π, p) reactions from the different targets. The $\pi^+d \rightarrow pp$ cross section was deduced by the parameterization of the free absorption cross section (Rit - 83, 84). By the Niskanen convention (Nis - 80), the differential cross section can be expressed as

$$\frac{d\sigma}{d\Omega} = \frac{1}{2\pi} \frac{\Sigma \alpha_n P_n(\cos \theta_{\text{cm}})}{n} \quad (4.7)$$

where α_n is a constant and θ_{cm} is the center of mass angle of the proton. α_0 represents the total absorption cross section. α_0 was taken from Eq-3 of Ref. Rit-83 in which the parameterization of recent total cross section data for $\pi^+d \rightarrow pp$ was presented. α_0 is expressed as

$$\alpha_0 = \sigma = a + \frac{b}{\sqrt{T_\pi}} + \frac{c \times 10^4}{(E - E_R) + d} \quad (4.8)$$

where $E = ((m_\pi + m_d)^2 + 2T_\pi m_d)^{1/2}$ is the invariant energy, T_π is the laboratory pion kinetic energy and remaining parameters (a , b , c , d and E_R) are (-1.2 mb, 3.5 mb MeV^{1/2}, 7.4 mb MeV², 5600 MeV² and 2136 MeV) respectively. The coefficient α_2 was parameterized by omitting the second term

of the equation (4.8) and substituting $a = -1.7$ mb, $c = 8.1$ mb MeV² and $E_R = 2131$ MeV. The predicted $\pi^+d \rightarrow pp$ cross sections are in excellent agreement with the measured results as shown in Table 4.1 .

The predicted values of $\pi^+d \rightarrow pp$ cross sections at 220 MeV and the experimental values at 170 MeV (Mat - 83) were used to find the normalization constant NORM. The relative beam monitor IC1 was used as a monitor for incident beam flux. $\Delta\Omega$ for the full size target was arbitrarily chosen to be one, as in the case for CD₂ for the $\pi^+d \rightarrow pp$ measurements. By knowing all the quantities in the equation 4.1 except NORM, it was calculated, thus giving an absolute normalization for incident beam current and solid angle. The $\pi^+d \rightarrow pp$ reaction was measured at 220 MeV pion energy which has the same energy proton in the spectrometer as produced by (π,p) on other nuclei. The (π,p) reaction on the other nuclei were measured either at 120 MeV or 145 MeV at EPICS. The response of ion chamber IC1 has been shown to be different for different energy and the sign of the pion. The calibration of the response of IC1 for π^+ beam from $70 \leq T_\pi \leq 300$ MeV was reported by Seestrom - Morris (See - 81) and this calibration was used to correct the absolute normalization factor for the response of IC1 for different pion energy and charge. At SIN the beam was directly counted so no such correction was necessary.

At EPICS strip targets were used for the (π,p) measurements, so the relative number of pions incident

Table - 4.1

Parameterization of $\pi^+d \rightarrow pp$ cross section

$T_{\pi} \text{ MeV}$	α_0		α_2	
	Expt	Pred	Expt	Pred
170	10.2(1)	10.3	9.0(1)	9.0
208	6.7(3)	6.6	5.4(1)	5.4
220	--	5.8	--	5.2
285	2.7(1)	2.4	2.0(1)	1.8

Using equation (4.7)

$$\begin{aligned}
 \frac{d\sigma}{d\Omega_{\text{cm}}} &= \frac{1}{2\pi} \sum \alpha_{2n} P_{2n}(\cos\theta_{\text{cm}}) \\
 &= \frac{1}{2\pi} \left(\alpha_0 + \alpha_2 \left(\frac{3}{2} \cos^2\theta_{\text{cm}} - 1 \right) \right)
 \end{aligned}$$

For $T_{\pi} = 220 \text{ MeV}$, $\theta_{\text{p lab}} = 30^\circ$, $\frac{d\sigma}{d\Omega_{\text{cm}}} = 1.27 \text{ mb/sr (Fit)}$

For $T_{\pi} = 173 \text{ MeV}$, $\theta_{\text{p lab}} = 20^\circ$, $\frac{d\sigma}{d\Omega_{\text{cm}}} = \begin{matrix} 2.67 \text{ mb/sr (Fit)} \\ 2.55 \text{ mb/sr (Expt)} \end{matrix}$

For $T_{\pi} = 173 \text{ MeV}$, $\theta_{\text{p lab}} = 30^\circ$, $\frac{d\sigma}{d\Omega_{\text{cm}}} = \begin{matrix} 1.81 \text{ mb/sr (Fit)} \\ 1.75 \text{ mb/sr (Expt)} \end{matrix}$

on each strip target had to be determined, as we monitored the sum of the beam. By considering CD_2 to be one and using the same software XTGT cut on it as determined by the XTGT cuts for two strips, the relative amount of pion flux on the two strips can be determined. The relative pion intensity for ^{24}Mg , ^{27}Al , ^{40}Ca , ^{58}Ni and ^{12}C was 0.37, 0.58, 0.41, 0.53 and 1.0 respectively. For SIN a single target was in the beam so this correction was taken to be one for all isotopes and hence its measurement was included in the normalization factor.

Acceptance

The solid angle of the spectrometer varies as a function of δ_{sp} where

$$\delta_{sp} = \left(\frac{P_p - P_{sp}}{P_{sp}} \right) \times 100 \% , \quad \Delta Q = D(\delta_{sp}) \Delta Q(\delta = 0) \quad (4.9)$$

where P_p = momentum of the particle in the center of the acceptance, or the central ray, P_{sp} = momentum of the detected particle. Here $\Delta Q(\delta = 0) = 1$. for a full size target. Therefore δ_{sp} , the "delta scan" is measured to determine the acceptance of the spectrometer as a function of δ_{sp} . The delta scan of the spectrometer is done by measuring the yield of a reaction across the focal plane by varying the spectrometer field to vary δ_{sp} . For the delta scan of this experiment, a measurement from a previous experiment performed several months earlier (Bla - 84) was

used. The tapes of the delta scan from that experiment were replayed using the XTGT gates from this experiment. Fig. 26 shows the relative acceptance for the different targets used in the experiment at EPICS and of SUSI spectrometer. The delta scan determines only the relative spectrometer solid angle for different values of δ_{sp} .

Energy Calibration

The relative energy calibration is accurate across the acceptance of the spectrometer since the change in momentum is linear with the field, but the absolute energy calibration or zero energy in missing mass is not as well determined due to saturation effects in the spectrometer magnets. The determination of the zero energy channel in the spectra is accomplished by measuring the energy offset for a known state in the excitation energy histogram for a particular reaction. The proton peak of the $\pi^+d \rightarrow pp$ reaction was used for the absolute energy calibration of the spectra, since by definition this reaction should yield a proton peak at 0.0 MeV.

At EPICS, this reaction yielded a calculated peak at 0.9 MeV instead of 0.0 MeV. Another known ground state, that for $^{27}\text{Al}(\pi^+,p)$ was calculated at 1.0 MeV, so a shift of -0.95 MeV has been made to all the spectra for the EPICS run. After this shift, the first two peaks in $^{24}\text{Mg}(\pi^+,p)^{23}\text{Mg}$ are at energies of known high spin states in ^{23}Mg .

Fig. 26.

At SIN, the channel calibration was obtained at low spectrometer field by requiring that the elastic peak for all target be at 0.0 MeV. The SUSI calibration at the high spectrometer field was then obtained by requiring that the $\pi^+d \rightarrow pp$ peak be at 0.0 MeV.

Spectra and Data

The cross section per event for different (π,p) reactions can be calculated by using the equation

$$\frac{d\sigma}{d\Omega} = \frac{\text{NORM} * \text{JAC} * \text{CORFAC}}{N_{\text{inc}} * \Delta\Omega * N_{\text{tgt}}} \quad (4.10)$$

The cross section per event for different (π,p) reactions are listed in TABLE 4.2 . The cross section per one event including efficiency etc., along with the acceptance of the spectrometer, energy calibration and excitation energy spectrum was used to calculate the double differential cross section $d^2\sigma/d\Omega dE$ ($\mu\text{b}/\text{sr}/\text{MeV}$) for all of the nuclei. The double differential cross sections for (π,p) reactions for all the nuclei studied are shown in Fig. 27 - 39.

In order to suppress the appearance of single channel peaks due to low statistics, these spectra have been smoothed by using the prescription that takes nearest channels into account and preserves the total area (Bev - 69). Differential cross sections for selected peaks are listed in TABLE 4.3 and TABLE 4.4. In ^{23}Na , ^{24}Mg and ^{27}Al there are peaks in the low excitation energy region. The

Table - 4.2
The Cross section per event for different
(π ,p) reactions

Reactions	$T_{\pi\text{lab}}$ MeV	θ_p c.m. Deg	Cross Section nb/sr/event
$^{24}\text{Mg}(\pi^-, p)^{23}\text{Ne}$	120.0	25.40	65.60
	90.0	20.30	1282.0
$^{24}\text{Mg}(\pi^+, p)^{23}\text{Mg}$	120.0	25.40	288.86
	90.0	20.30	5446.0
$^{23}\text{Na}(\pi^-, p)^{22}\text{F}$	90.0	20.30	416.6
$^{23}\text{Na}(\pi^+, p)^{22}\text{Na}$	90.0	20.30	4063.
$^{27}\text{Al}(\pi^-, p)^{26}\text{Na}$	120.0	25.40	17.36
$^{27}\text{Al}(\pi^+, p)^{26}\text{Al}$	120.0	25.40	78.50
$^{40}\text{Ca}(\pi^-, p)^{39}\text{Ar}$	120.0	25.20	32.46
$^{40}\text{Ca}(\pi^+, p)^{39}\text{Ca}$	120.0	25.20	182.23
$^{58}\text{Ni}(\pi^-, p)^{57}\text{Fe}$	120.0	25.20	62.67
$^{58}\text{Ni}(\pi^+, p)^{57}\text{Ni}$	120.0	25.20	356.42
$^{12}\text{C}(\pi^-, p)^{11}\text{B}$	145.0	25.90	35.40

$^{24}\text{Mg}(\pi^+, p)^{23}\text{Mg}$ spectrum Fig. 27, at $T_\pi = 120$ MeV has two peaks of high spin states $5/2^+$ (0.47 ± 0.1 MeV) and $9/2^+$ (2.71 ± 0.2 MeV) with cross section 8.1 ± 1.7 $\mu\text{b/sr}$ and 17.6 ± 2.6 $\mu\text{b/sr}$ respectively. At $T_\pi = 90$ MeV this reaction shows indications of two peaks at 0.85 ± 0.5 and 2.8 ± 0.5 MeV with cross section of 20.4 ± 4.1 $\mu\text{b/sr}$ and 71.5 ± 13.6 $\mu\text{b/sr}$ respectively. The $^{24}\text{Mg}(\pi^-, p)^{23}\text{Ne}$ spectrum at $T_\pi = 120$ MeV, Fig. 28 has a peak at 8.4 ± 0.3 MeV with cross section 2.4 ± 0.6 $\mu\text{b/sr}$ and may be a $13/2^+$ state. The measurements at 90 MeV, Fig. 29 also reveals a peak with cross section 15.9 ± 2.6 $\mu\text{b/sr}$ at 9.6 ± 1.0 MeV. The $^{27}\text{Al}(\pi^+, p)^{26}\text{Al}$ spectrum in Fig. 31 shows the large cross section for the 5^+ ground state, 22.6 ± 2.0 $\mu\text{b/sr}$. The $^{23}\text{Na}(\pi^-, p)^{22}\text{F}$ reaction study revealed a peak at 5.7 ± 0.50 MeV with a cross section of 4.40 ± 1.2 $\mu\text{b/sr}$, (Fig 32). Thus in ^{24}Mg and ^{23}Na there are peaks in the (π^-, p) spectrum that are comparable in strength with those seen in (π^+, p) . ^{12}C , ^{27}Al , ^{40}Ca and ^{58}Ni (π^-, p) yield peaks with cross sections ≤ 1 $\mu\text{b/sr}$ compared with 7-22 $\mu\text{b/Sr}$ for peaks from (π^-, p) reactions.

The shape of the proton spectra above an excitation energy of 10 MeV is approximately independent of the target mass and of the incident pion charge. Ratios of cross sections for $(\pi^+, p)/(\pi^-, p)$ and ratios of the same reaction on different nuclei are flat over the range of excitation energy. The ratios averaged over excitation energies from 10-40 MeV are presented in Table 4.5. ^{40}Ca has arbitrarily been chosen as the standard for nuclei ratios.

Table 4.3

Differential cross sections for ($\pi^{\pm}, p$)
 reactions determined at EPICS for $T_{\pi} = 120$ MeV.

Reaction	Excitation Energy (MeV)	No. of Events	$\frac{d\sigma}{d\Omega}$ c.m. $\mu\text{b/sr}$
$^{24}\text{Mg}(\pi^{-}, p)$	8.40 ± 0.30	36 ± 10	2.4 ± 0.6
	11.80 ± 0.40	20 ± 9	1.3 ± 0.6
$^{24}\text{Mg}(\pi^{+}, p)$	0.47 ± 0.12	28 ± 6	8.1 ± 1.7
	2.71 ± 0.18	61 ± 9	17.6 ± 2.6
$^{27}\text{Al}(\pi^{-}, p)$	2.7 ± 0.20	13 ± 5	0.22 ± 0.08
	8.3 ± 0.20	26 ± 11	0.45 ± 0.02
$^{27}\text{Al}(\pi^{+}, p)$	0.0 ± 0.02	288 ± 21	$22. \pm 2.$
$^{40}\text{Ca}(\pi^{-}, p)$	5.9 ± 0.2	5 ± 2	0.2 ± 0.06
$^{40}\text{Ca}(\pi^{+}, p)$	6.3 ± 0.2	36 ± 13	6.6 ± 2.3
$^{58}\text{Ni}(\pi^{-}, p)$	4.7 ± 0.2	9 ± 5	0.6 ± 0.3
	6.6 ± 0.3	14 ± 5	0.9 ± 0.3
$^{58}\text{Ni}(\pi^{+}, p)$	8.8 ± 0.2	49 ± 10	$17.5 \pm 3.$
$^{12}\text{C}(\pi^{-}, p)$	1.8 ± 0.3	14 ± 6	0.5 ± 0.2

Table 4.4

Differential cross sections for $(\pi^{\pm}, p)$
 reactions determined at π M1-SUSI for $T_{\pi} = 90$ MeV.

Reaction	Excitation Energy (MeV)	No. of Events	$\frac{d\sigma}{d\Omega}$ c.m. $\mu\text{b/sr}$
$^{24}\text{Mg}(\pi^{-}, p)$	9.60 ± 1.00	21 ± 5	15.9 ± 2.6
$^{24}\text{Mg}(\pi^{+}, p)$	0.85 ± 0.5	6 ± 3	20.4 ± 4.1
	2.80 ± 0.5	13 ± 4	71.5 ± 13.6
$^{23}\text{Na}(\pi^{-}, p)$	5.70 ± 0.5	8 ± 3	4.4 ± 1.2

Fig. 27.

Fig. 28.

Fig. 29.

Fig. 30.

Fig. 31.

Fig. 32.

Fig. 33.

Fig. 34.

Fig. 35.

Fig. 36.

Fig. 37.

Fig. 38.

Fig. 39.

As seen in the Table 4.5, the magnitude of proton yield from all targets is more than 24 times larger for π^+ than for π^- at $T_\pi = 120$ MeV. At $T_\pi = 90$ MeV the ratios of cross sections $(\pi^+, p)/(\pi^-, p)$ drops down to fourteen times larger for π^+ than for π^- . Both (π^+, p) and (π^-, p) continuum cross sections are found to have little mass dependence, with the cross sections for both reactions on ^{24}Mg slightly enhanced compared to the other nuclei at $T_\pi = 120$ MeV.

TABLE 4.5

Ratios of (π, p) cross sections averaged over an
excitation energy interval from 10 to 40 MeV.

Statistical errors are given in parenthesis.

	π^+/π^-	$\pi^+/\pi^{+40}\text{Ca}$	$\pi^-/\pi^{-40}\text{Ca}$
$T_\pi = 120 \text{ MeV}$			
^{24}Mg	26.7 (2.4) ^a	2.45(0.20) ^a	2.43(0.22) ^a
^{27}Al	22.1 (1.6)	1.25 (0.09)	1.41 (0.11)
^{40}Ca	25.8 (1.9)	-----	-----
^{58}Ni	20.4 (1.6)	1.18 (0.09)	1.55 (0.12)
^{12}C	-----	-----	1.35 (0.11)
$T_\pi = 90 \text{ MeV}$			
^{24}Mg	13.3 (1.5)		
$^{23}\text{Na(OH)}$	30.9 (3.4)		

Statistical Analysis of the peaks

The (π, p) spectra for all the nuclei have a smoothly rising continuum. To establish the statistical significance of possible peaks in the spectra, an analysis is made in the following manner. The experimental resolution is assumed to be equal to the width of the ground state peak in the $^{27}\text{Al}(\pi^+, p)^{26}\text{Al}$ spectrum, i.e. 500 KeV. In most cases the energy and probable width of the peak are known but the actual existence of the peak, with a finite number of counts, is to be determined at some level of confidence. The shape of the continuum was determined by a polynomial fit (Bev - 69) to the spectrum. The probable candidates for the peaks were removed from the spectrum before fitting with a 3rd order polynomial. Fits for $^{24}\text{Mg}(\pi^-, p)^{23}\text{Ne}$, $^{24}\text{Mg}(\pi^+, p)^{23}\text{Mg}$, $^{27}\text{Al}(\pi^+, p)^{26}\text{Al}$, $^{12}\text{C}(\pi^-, p)^{11}\text{Be}$, and $^{58}\text{Ni}(\pi^+, p)^{57}\text{Ni}$ are shown in Fig. 40a - 44a. The fitted spectrum was subtracted from each experimental spectrum with the results shown in Fig. 40b - 44b.

A Monte Carlo code (Avi-85, Mil-86) was used to determine the number of counts in a peak with a certain confidence limit. The code runs on the VAX 11/730 that was used for data reduction, and it takes approximately one to five hours of CPU time to synthesize the experimental spectrum and do the calculations for estimating the number of counts in a peak centered at a known energy. The program (Mil - 86) uses the Monte Carlo method to generate a spectrum for the background and the peak in the following way. A large number of artificial background spectra are

$^{24}\text{Mg}(\pi^-, p)$ 120. MeV
 $\theta = 25^\circ$

Fig. 40.

$^{24}\text{Mg}(\pi^+, p)$ 120. MeV
 $\theta = 25^\circ$

Fig. 41.

$^{27}\text{Al}(\pi^+, p)$ 120. MeV
 $\theta = 25^\circ$

Fig. 42.

$^{58}\text{Ni}(\pi^+, p)$ 120. MeV
 $\theta = 25^\circ$

Fig. 43.

$^{12}\text{C}(\pi^-, p)$ 120. MeV
 $\theta = 25^\circ$

Fig. 44.

synthesized using random variables chosen to reproduce a Poisson fluctuation about the mean value of the background. Then some number of counts are hypothesized under a peak centered at a given data channel. These events are distributed in the neighboring channels according to the resolution of the experiment using a Monte Carlo random variable technique. This is done for a number of synthesized background spectra. At this point there are a large number of artificially generated spectra with a background of statistical fluctuations about a known mean and with a known number of counts under the peak. The total number of counts for these channels are found for each synthesized spectrum. From these sums we estimate the probability that, if the peak had Y counts, under a peak of known shape, superimposed on a purely statistical background of known mean, we would have observed more counts than were observed in the equivalent data bin in the experiment. This process is repeated for a number of values of y , being incremented by small steps until the probability of the observation of more counts than was actually seen in the corresponding experimental spectra shown in Fig. 40b - 44b is some desired value, say 0.68. This value of hypothesized Y is the upper limit contained in the peak of the experimental data with probability of 0.68, which is expressed as the 68% confidence limit. To determine the minimum number of counts in the peak the program calculates $P = 1 - P_y$, where P_y is the upper limit probability.

Quantitatively the program considers a 21

channel interval centered where the peak to be synthesized has its center, and the peak is actually contained in the 7 channels around the central channel. The program divides this 21 channel interval into three regions A, B and C with 7 channels each and B corresponds to the energy range of the peak under consideration. The numbers N_A , N_B and N_C represent the total number of events in these three intervals and $N_O = N_B - [(N_A + N_C)/2]$ the net number of real events. The numbers N_A , N_B can be expressed as the sums of mean background M and the unknown statistical fluctuations S_A and S_C . So N_O can be expressed as

$$\begin{aligned}
 N_O &= N_B - \frac{N_A + N_C}{2} \\
 &= Y + M + S_B - \frac{M + S_A + M + S_C}{2} \\
 &= Y + \frac{2S_B - S_A - S_C}{2} \quad (4.11)
 \end{aligned}$$

where Y is the number of real events in bin B and S_B is the statistical fluctuation in this bin. The quantity N_O is known from the computer simulated experiment and is calculated by slowly increasing Y until the N_O (computed) is greater than N_O (experimental) with a certain desired confidence limit. It is then interpreted that $Y(\text{exp}) < Y(\text{cal})$ with that level of confidence limit.

Table - 4.6 shows the number of counts in the selected peaks of the spectrum and the corresponding experimental counts found by the histogram fitting routine. Both of the methods agree reasonably well, and always remain within statistical error. The error quoted for statistical predictions is due to upper and lower limits for the confidence limit and the statistical error, whereas the histogram fitting error includes the statistics of the number of events and the fitted background.

This analysis was not performed for the 90 MeV measurements because of very low statistics.

Table - 4.6

Number of counts in the selected peak of the spectrum with 68% confidence limit and the number of counts by least square fitting routine.

Reactions	Peak Energy	No. Of Events	
	MeV	68% Confidence Limit	Histogram Fitting
$^{24}\text{Mg}(\pi^-, p)^{23}\text{Ne}$	8.40 ± 0.3	35 ± 7	36 ± 10
	11.80 ± 0.4	20 ± 5	20 ± 9
$^{24}\text{Mg}(\pi^+, p)^{23}\text{Mg}$	0.47 ± 0.12	22 ± 6	28 ± 6
	2.7 ± 0.2	58 ± 8	61 ± 9
$^{27}\text{Al}(\pi^+, p)^{26}\text{Al}$	0.0 ± 0.02	260 ± 17	288 ± 21
$^{58}\text{Ni}(\pi^+, p)^{57}\text{Ni}$	8.8 ± 0.2	52 ± 8	49 ± 10
$^{12}\text{C}(\pi^-, p)^{11}\text{Be}$	1.8 ± 0.3	13 ± 5	14 ± 6

V. ANALYSIS AND CALCULATIONS

Pion absorption and production reactions have been important in studying both nuclear structure and reaction mechanisms. The pion absorption reaction (π, p) in a nucleus is a high energy and a high momentum transfer reaction similar to the pion production reaction (p, π). The (p, π) reaction has been extensively studied both by experimental and theoretical work. Pion absorption is one of the least understood parts of the pion - nucleus reaction even though it is a sizable component of the total pion - nucleus cross section. In this chapter the theoretical aspect of pion absorption is discussed. The chapter is divided into three sections. In the first two sections aspects of nuclear structure and of possible reaction mechanisms are discussed. A study of the nuclear structure has been accomplished using calculations performed with the shell model code OXBASH (Bro-83) to generate the nuclear structure amplitude. A distorted wave impulse approximation calculation, using pion and proton optical potential has been performed for the (π^+, p) reaction. In the last section of this chapter a brief review of previous work in pion production and absorption in nuclei is presented, and the results of the present experiment are discussed.

SHELL MODEL STUDY OF THE (π^-, p) REACTION

Recent studies of the (p, π^-) reaction at the Indiana University Cyclotron Facility (Vig-82,83; Jac-82; Thr-83) have observed the excitation of low lying high spin

states (Fig. 45) in the residual nucleus. These states have been described to be two particle-one hole states which are favored by the two nucleon pion production mechanism. Brown et al. (Bro-83) have calculated the relative cross sections for the (p, π^-) reactions for nuclei in the region $40 < A < 50$, using the nuclear structure amplitudes for this reaction calculated with the shell model wave functions generated by the shell model code OXBASH and using a zero range plane wave approximation for the (p, π^-) reaction. A brief description of the calculation is given below.

The relative cross sections for the (π^-, p) reaction were calculated using the same algorithm as used by Brown et al. to calculate the (p, π^-) reaction relative cross sections. The relative strength of the (p, π^-) cross section is equal, within a multiplicative factor, to the (π^-, p) cross section, given by the detailed balance equation

$$\sigma_{\pi A \rightarrow pB} = \frac{2(2J_B + 1) P_{PB}^2}{(2J_A + 1) P_{\pi A}^2} \sigma_{pB \rightarrow \pi A}$$

where P_i is the center of mass relative momentum of particle i , J is the nuclear angular momentum quantum number, and the cross sections are those at the same center of mass energy.

The shell model program OXBASH (Bro-84) consists of seven main computer codes: BASIS, PREDICT, PROJ, MATRIX, LANCZOS, MVEC and TRAMP, and some subsidiary code: SHELL, OPER, WCM, CHANGE, SCHEME, TRANS and TBTDOP. A calculation is started by running SHELL which generates a

Fig. 45.

command file for the sequence in which the different programs are to be run and with all relevant information needed for a complete calculation. The Fig. 46 shows the sequence in which the programs should be run and the extensions of the input and generated disk files by each executable code. Here a brief discription of the programs is presented while a detailed discription of some of them is given in reference Bro - 84.

The codes use an m - scheme Slater determinant basis, which is generated for a particular number of particles and particular total J_z and T_z by the program BASIS. One can put restrictions on both individual J orbits and major shell. For this calculation restrictions were put on the number of particles in individual J -orbits. The calculation is carried out one partition (occupancy of each J - orbit) at a time. Both J - orbit and major shell restrictions are only considered when working out partitions. Those partitions that do not comply with the restrictions are discarded. BASIS finishes by reordering the basis vectors according to their partition and by writing them to the disk, partition by partition, starting with the partition having the larger m - scheme dimension in decreasing arithmetic order. Basis patterns are also written for each partition in decreasing arithmetic order. Subroutine FIND uses this arithmetic ordering to find whether a basis vector belongs to the basis set.

The program 'PROJ' then constructs basis states with good spin $J \geq J_z$ and isospin $T \geq T_z$. This is done by

a projection technique. The program PROJ is actually two separate codes POSTPROJ and PRIORPROJ. POSTPROJ projects from a given $J_z T_z$ state and then orthonormalises the wave function to the space generated by all previous good J, T -states. PRIORPROJ projects from a linear combination of J_z, T_z states so as to finish the projection with already orthogonal states.

The program 'MATRIX' reads the output files of 'PROJ' and constructs the Hamiltonian matrix for the case under consideration. For the calculation of $^{24}\text{Mg}(\pi^-, p)^{23}\text{Ne}$ Wildenthal's SD shell Hamiltonian (Wil-82) is used, while for $^{48}\text{Ca}(p, \pi^-)^{49}\text{Ti}$ the Kutchera et al. (Kut-82) $f_{7/2}$ shell Hamiltonian is used. A file containing the single particle energies and two body m - scheme matrix elements is required as an input to MATRIX, which is generated by running 'OPER' which reads an input data file with the two body J, T - scheme matrix element, constructed by the program HCM.

After MATRIX the program LANCZOS is run. The LANCZOS algorithm efficiently finds the lowest few eigenvalues and eigenvectors of very large matrices. The eigenvectors calculated by LANCZOS are input to the program 'MVEC' which rewrites them in terms of the m - scheme basis. This output file is needed by TRAMP for all further calculations, i.e. to calculate parentage amplitudes and one or two body transition densities.

The relative cross section of the (p, π^-) reaction is calculated considering that this reaction takes place in two steps. For the $^{48}\text{Ca}(p, \pi^-)^{49}\text{Ti}$, calculation wave

functions are generated for the ground state of ^{48}Ca and several low lying states of ^{49}Sc and ^{48}Ti . Then by using TRAMP, one body transition densities are calculated between ^{48}Ca and ^{49}Sc and one particle parentage amplitudes are calculated between different states of ^{49}Sc and ^{49}Ti . The $^{23}\text{Ne}(p,\pi^-)^{24}\text{Mg}$ calculation is done in a slightly different manner, as we are interested in the relative cross section of $^{24}\text{Mg}(\pi^-,p)^{23}\text{Ne}$. So instead of starting from the ground state of ^{23}Ne , wave functions are generated for the different excited states of ^{23}Ne and ^{24}Na , and only the ground state wave function is calculated for ^{24}Mg . Then by using TRAMP, one-body transition densities are calculated between ^{23}Ne and ^{24}Na and one particle parentage amplitudes are calculated between different states of ^{24}Na to the ground state of ^{24}Mg . The calculation of relative cross sections using these amplitudes is described below.

The diagrams for the (p,π^-) reaction are shown in Fig. 47, where the incoming proton is denoted by a solid line with momentum p and the outgoing pion is denoted by a dotted line with momentum k . The box corresponds to the s- and/or p- wave pion-nucleon scattering amplitudes. The difference between the two processes (a) and (b) is mainly the energy and momentum carried by the exchanged meson. In both (a) and (b) the exchanged meson carries high momentum but in (a) the energy transfer is essentially zero while in the process (b) it is approximately the incident proton energy, which is shown below. In Fig. 47 the incoming proton

Fig. 47.

is denoted by a solid line with momentum $\vec{p}$ and is transferred into a bound orbit in the nucleus j_3 . In this process it interacts with a bound nucleon of average momentum $\vec{p}'$ inside the nucleus by meson exchange. A pion with momentum $\vec{k}$ is emitted either by the incident proton Fig. 47(a) or by the bound nucleon Fig. 47(b). Both the incident proton and the nucleon participating in the meson exchange are bound to the nucleus in the final state. Let us consider that the kinetic energy of the incident proton, outgoing pion and recoiling nucleus is T_p , T_π and T_R respectively. Q value of the reaction is δQ , which is equal to $M_{A+1} + m_\pi - M_A - m_p$. Where M_{A+1} , m_π , M_A , and m_p are the masses of the final nucleus, initial nucleus, pion and proton. ΔE_{jh} is the binding energy of the nucleon. During this reaction the final nucleus might be left in an excited state E_x . Let us consider that $\vec{q}$ and ω_q are the momentum and energy of the exchanged meson. The two nucleons shares the energy and momentum transfer. The energy and momentum must be conserved at each vertex in these diagrams.

For this reaction

For the energy conservation

$$T_p + m_p + M_A = M_{A+1} + m_\pi + T_\pi + T_R + E_x$$

Which gives

$$\begin{aligned} T_\pi &= T_p - T_R - (M_{A+1} + m_\pi - (M_A + m_p)) \\ &= T_p - T_R - \Delta Q \quad (5.1) \end{aligned}$$

For momentum conservation

$$\vec{p} + \vec{p}_A = \vec{p}_{A+1} + \vec{k}$$

so,

$$\vec{k} = \vec{p} + \vec{p}_A - \vec{p}_{A+1}$$

where $\vec{p}_A$ and $\vec{p}_{A+1}$ are the momentum of the initial and final nucleus. But in the laboratory system $\vec{p}_A = 0$.

so,

$$\vec{k} = \vec{p} - \vec{p}_{A+1} \quad (5.3)$$

Now for the diagram (a) Fig. 47

Momentum of the incident proton in the final state = $\vec{p} - \vec{k} - \vec{q}$

Momentum of the other nucleon in the final state = $\vec{p}' + \vec{q}$

Since these two final nucleons share the momentum transfer we have

$$\vec{p} - \vec{k} - \vec{q} = \vec{p}' + \vec{q}$$

which means

$$\vec{q} = 1/2(\vec{p} - \vec{p}' - \vec{k})$$

substituting (5.3)

$$\begin{aligned} \vec{q} &= 1/2(\vec{p} - \vec{p}' - \vec{p} + \vec{p}_{A+1}) \\ &= 1/2(\vec{p}_{A+1} - \vec{p}') \end{aligned}$$

The energy of the incident proton in the final state

$$= T_p - \omega_q - T_\pi - m_\pi$$

The energy of the other nucleon in final state = $\Delta E_{jh} + \omega_q$

So the energy sharing of the two nucleons means

$$T_p - \omega_q - T_\pi - m_\pi = \Delta E_{jh} + \omega_q$$

so,

$$\omega_q = 1/2(T_p - T_\pi - m_\pi - \Delta E_{jh})$$

substituting (5.2)

$$\begin{aligned}\omega_q &= 1/2(T_p - T_p + T_R + E_x + \Delta Q - m_\pi - \Delta E_{jh}) \\ &= 1/2(T_R + E_x + \Delta Q - m_\pi - \Delta E_{jh})\end{aligned}$$

For the case in which pion is emitted by the bound nucleon
Fig. 47 (b)

Momentum of the incident proton in the final state = $\vec{P} - \vec{q}$

Momentum of the other nucleon in the final state = $\vec{P}' + \vec{q} - \vec{k}$

Since these two final nucleons share the momentum transfer
we have

$$\vec{P} - \vec{q} = \vec{P}' + \vec{q} - \vec{k}$$

which means

$$\vec{q} = 1/2(\vec{P} - \vec{P}' + \vec{k})$$

substituting (5.3)

$$\begin{aligned}\vec{q} &= 1/2(\vec{P} - \vec{P}' + \vec{P} - \vec{P}_{A+1}) \\ &= \vec{P} - 1/2(\vec{P}_{A+1} + \vec{P}')\end{aligned}$$

The energy of the incident proton in the final state

$$= T_p - \omega_q$$

The energy of the other nucleon in final state

$$= \Delta E_{jh} + \omega_q - T_\pi - m_\pi$$

So the energy sharing of the two nucleons means

$$T_p - \omega_q = \Delta E_{jh} + \omega_q - T_\pi - m_\pi$$

so,

$$\omega_q = 1/2(T_p + T_\pi + m_\pi - \Delta E_{jh})$$

substituting (5.2)

$$\begin{aligned}\omega_q &= 1/2(T_p + T_p - T_R - E_x - \Delta Q + m_\pi - \Delta E_{jh}) \\ &= T_p - 1/2(T_R + E_x + \Delta Q - m_\pi + \Delta E_{jh})\end{aligned}$$

So,

For Process (a)

For Process (b)

Momentum transfer

$$\vec{q} = 1/2(\vec{P}_{A+1} - \vec{P}')$$

$$\vec{q} = \vec{P} - 1/2(\vec{P}_{A+1} + \vec{P}')$$

Energy transfer

$$\omega_q = 1/2(T_R + E_x + \Delta Q - m_\pi - \Delta E_{jh})$$

$$\omega_q = T_p - 1/2(T_R + E_x + \Delta Q - m_\pi + \Delta E_{jh})$$

So in both the process (a) and (b) the momentum transfer are comparable to each other. Where as the energy transfer is small in process (a) but approximately equal to the incident kinetic energy of the proton in process (b). For the present case $T_p = 237$ MeV, the momentum of the incoming proton is $|P| = 707$ MeV/c. If the outgoing pion carries off all of the energy brought in by the proton, the pion momentum is $|k| = 205$ MeV/c. Hence the momentum transfer to the nucleus for pion outgoing at 20° is equal to 502 MeV/c. If this reaction takes place at the nuclear surface ($R_0 = 1.2A^{1/3}$ fm) the angular momentum transfer is $\Delta l = R_0 * \text{Momentum transfer} = 9$ for ^{24}Mg . Hence, this reaction should excite high-spin states.

The general nuclear structure amplitudes for this reaction can be expressed in terms of matrix elements of creation and annihilation operators. To separate the spatial and spin degrees of freedom it is useful to express these amplitudes in LS coupling as described by Brown et al. (Bro-83)

$$A(i, f, L_{PH}, S_{PH}, L, S, J, n_p, n_h, n_3, l_p, l_h, l_3, r) =$$

$$\sum_{j_{ph}, j_p, j_h, j_3} \begin{bmatrix} l_p & l_h & L_{ph} \\ 1/2 & 1/2 & 1/2 \\ j_p & j_h & j_{ph} \end{bmatrix} \begin{bmatrix} L_{ph} & l_3 & L \\ S_{ph} & 1/2 & S \\ j_{ph} & 1/2 & J \end{bmatrix} \times$$

$$\langle f | [[a^+(\pi\alpha_p) \circ \tilde{a}(\nu\alpha_h)]^{j_{ph}} \circ a^+(\pi\alpha_3)]^J | i \rangle F(r) \quad (5.4)$$

where $F(r) = R(\alpha_p, r)R(\alpha_h, r)R(\alpha_3, r)$, $i(f)$ stands for the quantum numbers of the initial (final) states, and α stands for the set of quantum numbers (n, l, j) of the shell model orbits. Square brackets denote the normalized 9-j coefficient.

Both pion production and pion absorption processes are high momentum transfer reactions, and most of the momentum is taken by the interaction line in Fig. 47, which implies that the interaction is of short range and the zero range approximation should be adequate. A plane wave calculation for the incoming proton and outgoing pion then leads to the following equation for the cross section.

$$\begin{aligned} \frac{d\sigma}{d\Omega} &= \sigma_0 (2J_f + 1) \sum \{ \sum \epsilon(S_{ph}) [(2l_p + 1)(2l_h + 1)(2l_s + 1)/(2L + 1)]^{1/2} \\ &\quad (1_p 0 1_h 0 | L_{ph} 0) \times (L_{ph} 0 1_3 0 | L 0) \\ &\quad \left[A(i, f, L_{ph}, S_{ph}, L, S, J, n_i, l_i, r) j_L(qr) r^2 dr \right]^2 \quad (5.5) \end{aligned}$$

This equation was used to calculate the

relative cross section (Bro-84) for $^{48}\text{Ca}(p,\pi^-)^{49}\text{Ti}$ and $^{24}\text{Mg}(\pi^-,p)^{23}\text{Ne}$. Although this code can calculate only (p,π^-) reaction, the (π^-,p) reaction can be calculated by calculating transitions from final states of the residual nucleus to the initial state of the target nucleus, as discussed earlier. The ^{48}Ca calculation was done to reproduce the results of Brown et al. (Bro-83). As shown in Fig. 48, and 49 the calculation is very well reproduced. The relative cross section $d^2\sigma/d\Omega dE$ for $^{24}\text{Mg}(\pi^-,p)^{23}\text{Ne}$ is shown in Fig 50. Above 8.0 Mev in the excitation energy there are no strong states in the theoretical spectrum. In the $^{24}\text{Mg}(\pi^-,p)$ experimental spectra Fig. 28, at $T_\pi = 120$ MeV, there is a peak at 8.4 MeV with $2.4 \mu\text{b/sr}$ cross section. By energy levels predicted by the shell model it could be a doublet with spin $11/2^+$ and $13/2^+$. This calculation shows two peaks at 5.92 and 7.23 MeV in $^{24}\text{Mg}(\pi^-,p)$ spectrum. There are indications of peak at these energies also in the experimental spectrum. But the theory does not predict any high cross section excitation about 8 MeV or above, where as experimental spectrum does. Figs. 51 and 52 show the angular distributions of $^{48}\text{Ca}(p,\pi^-)$ and $^{23}\text{Ne}(p,\pi^-)$ reactions respectively. This simple model works quite well for (p,π^-) reactions but when applied to (π^-,p) it seems to fail drastically. One implication is that the reaction mechanism of the (π^-,p) reaction is more complicated than that for the (p,π^-) reaction. In the case of the (p,π^-) reaction the production of a pion is possible through a reaction $pn \rightarrow \pi^-$

Fig. 49.

Fig. 50.

pp, where the two nucleons in the entrance channel are not correlated. However for the (π^-, p) reaction the two absorbing nucleons must be paired in order to have a short range correlation. Also this calculation does not explicitly contain the delta mechanism. Thus it worked for the (p, π^-) reaction results of IUCE because the measurements were at threshold and were not dominated by delta formation. But this measurement is near the resonance energy where the delta is dominant.

Fig. 51.

Fig. 52.

Optical Model Calculation

The pion nucleus interaction has been studied extensively using different theoretical approaches. The most widely applied analysis is that of employing an optical model calculation. The essential physics of a particle passing through a nucleus (i.e. elastic scattering and inelastic scattering including true absorption) are similar to light passing through an optical medium. One can learn a great deal about medium energy pion-nucleus interactions from the optical analogy. Several pion-nucleus interaction optical potentials have been developed and applied with success to describe pion elastic, inelastic and charge exchange cross sections (Kis-55; Str-79,80; Car-83; Sic-86) for low to resonance energy pions. Similar success has also been achieved for the observables in proton - nucleus scattering.

The theory of meson absorption in nuclei is not as well developed or understood as that of elastic scattering. A number of models have emerged over the years, each of which is of some use in interpreting certain aspects of the subject. Models like the quasideuteron pion absorption model (Roo-81), and the delta-hole model (Hir-77A, 77B, 79; Kil - 78, Ose-79A, 79B) have been used with considerable success in describing pion absorption in nuclei. These calculations have been limited to certain reaction channels or to very light nuclei. In this section a distorted wave impulse approximation calculation of the (π^+, p) reaction to a discrete final state in the residual

nucleus is presented.

The simplest diagram of the (π^+, p) reaction is shown in Fig. 53, which essentially shows the reaction to be a neutron pickup reaction in the one nucleon pion absorption model. The cross section of the (π^+, p) reaction, assuming this to be a neutron pickup process, can be calculated by using the distorted wave Born approximation (DWBA). The cross section for single-nucleon emission following pion absorption is given in a first order time dependent perturbation theory by (Let-66; Jon-70; Ros-73; Mil-74A, 74B)

$$\sigma(\theta, \phi) = \frac{M}{(2\pi)^2} E_\pi \frac{k}{q} \sum_f |\langle f | H' | i \rangle|^2$$

where M is the mass of the nucleon, q and k are the momenta of the pion and the nucleon respectively, $E_\pi = \sqrt{(\mu^2 + q^2)}$ and i and f represents the initial state of the incident pion and the final state of the outgoing proton respectively. The transition operator H' is the Galilean invariant form of the non-relativistic reduction of the pseudoscalar interaction, which has the following form,

$$H' = \frac{f}{\mu} \sum_{i=1}^A \left[\left(1 - \frac{\mu}{2M} \right) \vec{\sigma}_i \cdot \vec{\nabla}_\pi \vec{\tau}_i \cdot \vec{\phi}_\pi - \frac{\mu}{M} \vec{\tau}_i \cdot \vec{\phi}_\pi \vec{\sigma}_i \cdot \vec{\nabla} \right]$$

where f is the pion-nucleon coupling constant ($f^2/4\pi = 0.083$), μ and M are the pion and nucleon masses respectively, $\vec{\sigma}$ and $\vec{\tau}$ are nucleon spin and isospin Pauli matrices. In this

Fig. 53.

expression for the transition Hamiltonian, the gradient $\vec{\nabla}_\pi$ acts only on the pion field $\vec{\phi}_\pi$ and $\vec{\nabla}$ acts only on the nuclear wave function. The sum extends over all nucleons.

The matrix element of the pion field $\vec{\tau} \cdot \vec{\phi}_\pi$ between an initial state $|q\rangle$, where one charged pion of momentum q is present and a final state of no pions $|0\rangle$ can be expressed as

$$\langle 0 | \vec{\tau} \cdot \vec{\phi}_\pi | q \rangle = \frac{-1}{\sqrt{2E_\pi}} \phi_\pi(q, r) \tau_+$$

where $\phi_\pi(q, r)$ in the plane wave approximation is just an incident plane wave $\exp(iq \cdot r)$. The operator τ_+ is non-zero only between nucleon states with initial neutron state ($T_z = -1/2$) and final proton state ($T_z = 1/2$). The sum on the matrix element thus extends only over the initial neutron states of the nucleus with appropriate final proton states. The distorted form of $\phi_\pi(q, r)$ can be obtained by solving the Klein - Gordon equation for pion-nucleus scattering with an appropriate optical potential. Similarly in the plane wave approximation the wave function of the proton can be expressed as $\exp(ik \cdot r)$, and the distortion of the proton wavefunction can be obtained phenomenologically.

The calculation of the (π^+, p) reaction was performed with the computer code CHOPER (Smi-79), which is a modified version of the zero range, coupled channel code CHUCK (Smi-79).

The pion optical potential used has the form (Dig-77)

$$U_{\pi}(r) = U_k(r) + U_A(r) + U_p(r) + U_{\xi}(r) + V_{\text{Coul}}(r)$$

where $U_k(r) = -b_0 k^2 \rho(r) + \nabla \cdot b_1 \rho(r) \nabla$

$$U_A(r) = -4\pi B_0 \rho^2(r)$$

$$U_p(r) = \frac{k^2}{4\pi} (b_0^2 + 2c_0^2) \left\langle \frac{1}{r} \right\rangle \rho(r)$$

$$U_{\xi}(r) = -\frac{\xi}{3} \nabla \cdot b_1^2 \rho^2(r) \nabla$$

and

$$V_{\text{Coul}}(r) = \frac{zZe^2}{2R_c} \left(3 - \frac{r^2}{R_c^2} \right) \quad r < R_c$$

$$= \frac{zZe^2}{r} \quad r \geq R_c$$

The first term is the standard Kisslinger potential. The second term $U_A(r)$ is due to s-wave pion absorption. The real part of this term accounts for the $\pi NN \rightarrow \pi NN$ process, whereas the imaginary part describes the pion absorption on nucleon pairs. The third term, $U_p(r)$ is a Pauli-blocking correction to the multiple scattering series. The term $U_{\xi}(r)$ is due to the Lorentz - Lorenz effect. All these potential terms have been discussed extensively in the literature and have proven to be quite important in describing the elastic, inelastic and charge exchange cross sections (Car-83; Str-79,80; Sic-86).

The strength of the pion optical potential parameters were calculated by this code and are listed in Table 5.1. The matter density, assumed to have the same shape for protons and neutrons, was taken to be of the two

parameter Fermi form

$$\rho(r) = \rho_0 / (1 + \exp((r-c)/a))$$

as was the charge distribution. The mass and charge density parameters were taken from a compilation of electromagnetic measurements (Dej -74). The parameters used for ^{27}Al were, $c = 3.07$ fm, $a = 0.52$ fm and $\langle r^2 \rangle^{1/2} = 3.06$ fm.

The proton optical potential used in this analysis has the form

$$U_p(r) = V_R f_O(r) + iW f_w(r) - \frac{1}{r} (V_{so} \frac{d}{dr} f_{vso}(r) + iW_{so} \frac{d}{dr} f_{wso}(r)) L.S + V_{Coul}(r)$$

with Woods - Saxon form factor $f_i(r; r_x, a_x)$. The strength of these potential parameters were determined by using the results of the systematic energy and mass dependence analysis of these potential parameters by P. Schwandt et al. (Sch - 82). They obtained the systematics by least square fits to the optical potential parameters obtained from the fits to proton elastic scattering data. The functional dependence of the optical potential parameter on proton energy T_p and target mass A is given by the following relations.

TABLE 5.1
Pion Optical Potential for $^{27}\text{Al}(\pi^+, p)^{26}\text{Al}$ Reaction.

$$T_{\pi} = 120 \text{ MeV}$$

$$b_0 = -0.6026 + i0.3373$$

$$b_1 = 6.4679 + i4.6575$$

$$c_0 = -2.6244 + i0.003$$

$$B_0 = -0.1392 + i0.1392$$

$$\epsilon = 0.2764$$

$$V = 105.5(1 - 0.1625 \ln T_p) + 16.5(N - Z)/A$$

$$r_o = 1.125 + 1.0 \times 10^{-3} T_p, T_p \leq 130 \text{ MeV}$$

$$r_o = 1.255, T_p > 130 \text{ MeV}$$

$$a_o = 0.675 + 3.1 \times 10^{-4} T_p$$

$$W = 6.6 + 2.73 \times 10^{-2} (T_p - 80) + 3.87 \times 10^{-6} (T_p - 80)^3$$

$$r_w = 1.65 - 2.4 \times 10^{-3} T_p$$

$$a_w = 0.32 + 2.5 \times 10^{-3} T_p$$

$$V_{so} = 19.0(1 - 0.166 \ln T_p) - 3.75(N - Z)/A$$

$$r_{vso} = 0.920 + 0.0305 A^{1/3}$$

$$a_{vso} = 0.768 - 0.0012 T_p, T_p \leq 140 \text{ MeV}$$

$$a_{vso} = 0.60, T_p > 140 \text{ MeV}$$

$$W_{so} = 7.5(1 - 0.248 \ln T_p)$$

$$r_{wso} = 0.877 + 0.0360 A^{1/3}$$

$$a_{wso} = 0.62$$

Optical potential parameters were calculated using these relations and are listed in Table 5.2. The potential used in the code CHOPER and that used by P. Schwandt et al. (IUCF potential) is slightly different in the treatment of the spin-orbit potential term. The IUCF potential uses the pion Compton wavelength factor $(h/m_\pi c)^2 = 2.00 \text{ fm}$, whereas the code CHOPER does not. Also this code uses an $L \cdot \vec{\sigma}$ term whereas the IUCF potential uses a $L \cdot \vec{\sigma}$ term. Thus the V_{so} and W_{so} strengths used here are four times the strength given by the IUCF potential calculation.

The result of the calculation of the $^{27}\text{Al}(\pi^+, p)^{26}\text{Al}_{gs}$ cross section is shown in Fig. 54. The cross section has been normalized (multiplied by 28) to the

TABLE 5.2

Proton Optical Potential for $^{27}\text{Al}(\pi^+, p)^{26}\text{Al}$ Reaction.

$$T_{\pi} = 120 \text{ MeV}$$

$$V = -12.353 \text{ MeV}$$

$$r_0 = 1.255 \text{ fm}$$

$$a_0 = 0.748 \text{ fm}$$

$$W = -25.925 \text{ MeV}$$

$$r_w = 1.08 \text{ fm}$$

$$a_w = 0.913 \text{ fm}$$

$$V_{so} = -6.44 \text{ MeV}$$

$$r_{vso} = 1.011 \text{ fm}$$

$$a_{vso} = 0.60 \text{ fm}$$

$$W_{so} = 10.68 \text{ MeV}$$

$$r_{wso} = 0.985 \text{ fm}$$

$$a_{wso} = 0.620 \text{ fm}$$

The value calculated for V_{so} and W_{so} is 1/4 of this value by using the formula described in the text.

experimentally measured cross section at $T_\pi = 120$ MeV and $\theta_p = 25^\circ$. The factor of 28 implies that in this one nucleon pion absorption model, the calculated interaction strength is approximately five times smaller than the total interaction strength, so it gives only four percent of the total cross section. This is a one nucleon model code for pion absorption and one expects the one nucleon part of the pion absorption to be very small compared to the two nucleon process, with initial and final state interactions, such as charge exchange of the pion before absorption, rescattering of the pion, charge exchange of a neutron after absorption or the knockout of a proton by a neutron. Similar calculations have also been performed to reproduce the results of Smith's (Smi-79) calculation for $^{12}\text{C}(\pi^+, p)$ at 90 MeV.

Using this one nucleon model the (π^-, p) reaction is not reasonable because the (π^-, p) reaction is not possible by simple neutron or proton stripping. The only possible one step process would be the absorption on a virtual Δ^{++} in the nucleus. The simplest two step process would have the pion single charge exchange and then pick up a proton. Extensions of this model have not been attempted here.

Fig. 54.

Pion Absorption in Nuclei

Pion absorption in nuclei is one of the most interesting but least understood aspects of the pion - nucleus interaction. There have been several experimental and theoretical investigations over the past decade of this reaction. Recent reviews (Sch-80, 81, 86; But-80; Mon-81; Ing-82; Red-85) discuss most of these experimental and theoretical investigations. Even with this wealth of data there is disagreement on the reaction mechanism, such as the question of the number of nucleons involved in the absorption (McK-80; Gir-84; Sch-84).

Pion absorption can be separated into in-flight pion absorption and stopped pion absorption, and absorption on light nuclei ($A < 4$) and heavier nuclei ($A \geq 4$). The complexity of the reaction increases with the energy of the pion and the mass of the nuclear target. In stopped pion absorption a π^- with very low kinetic energy is captured into an atomic orbit forming a pionic atom. The atom then deexcites by emitting X - rays and Auger electrons until the π^- reaches a sufficiently small radius (because of its large rest mass) to interact with the nuclear medium. The pion then disappears inside the nucleus and its rest mass energy appears as energetic reaction fragments. The total energy available in the stopped pion-nucleus system is about 160 MeV lower than the mass of the delta, so the dominance of this resonance is likely to be less important than for in-flight pion absorption. The stopped pions are captured from an atomic orbit and thus have a well defined

angular momentum, which in-flight pions do not. Also for stopped pions, absorption is the most probable channel, whereas for in-flight pion scattering, there are many open channels. Since the work presented in this study is for pion energies $T_\pi = 120$ and 90 MeV, in-flight absorption on different nuclei, will be emphasized here.

The experimental results show (Ash - 81) that the pion absorption cross section is quite comparable in magnitude (Fig. 55), to that of any other processes (i.e. elastic, inelastic, charge exchange etc). It is not possible to absorb a pion on a free nucleon because it will violate energy and momentum conservation. However, it is possible to have absorption on one nucleon inside the nucleus, with the residual nucleus acting as a spectator for energy and momentum conservation. This implies a very high energy and momentum transfer to one nucleon, the probability of which is small because its very unlikely to have a nucleon inside the nucleus with sufficient Fermi momentum to conserve energy and momentum alone. This suggests that one nucleon pion absorption is not a dominant process in pion absorption and at least two nucleons are involved in the pion absorption process. The absorption of a fast pion in the nucleus can be graphically represented as in Fig. 56, where the process has been divided into three parts and absorption is assumed to take place on two nucleons. The absorption process can be described by quasifree scattering of the incident pion with one nucleon (Initial state

Fig. 55.

Fig. 56.

interaction (ISI)), followed by its being absorbed by two nucleons (Absorption) and one of those nucleons interacting with other nucleons (Final state interaction (FSI)) while going out of the nucleus. The Δ -or N^* -resonance dominates the pion absorption according to the energy of the pion. Inside a nucleus the pion can be absorbed on any one of the two nucleon pairs according to the following reactions.

Thus a π^+ can be absorbed on both pn and nn pairs and have a proton in the exit channel, whereas a π^- can be absorbed on only pp pairs and have a proton in the exit channel. The π^+ absorption cross section is enhanced over that of π^- absorption by an order of magnitude. This enhancement can be simply explained from the isospin coupling of a pion with two nucleons assuming delta dominance. Since the pion has isospin 1 and the two nucleons can have isospin $T = 0, 1$ the total isospin of pion plus nucleons ($I = t_\pi + T_N + T_N$) can be $I = 0, 1, 2$ with isospin $I = 1$ occurring twice, once each with $T = 0$ and $T = 1$. Since the pion absorption leaves two nucleons, $I = 2$ will not occur. A compilation of allowed quantum numbers in pion absorption on a nucleon pair is given in Table 2.4. Before Appendix 2. The first part of the table shows the quantum numbers allowed for absorption on a $T = 0$ nucleon pair, with total isospin of pion plus nucleons

TABLE 5.3
Allowed quantum numbers in π absorption
on a nucleon pair.*

Absorbing pair		ΔN System		Final
$J^\pi; T$	$L_{(\pi-2N)}$	J^π	$L_{\Delta N}$	L_{NN}
I = 1 CHANNEL				
$J^\pi = 1^+, T = 0$	0	1^-	1	1
	1	0^+	2	0
		2^+	0, 2	2
	2	1^-	1	1
		2^-	1	1
$J^\pi = 0^+, T = 1$	0	0^-	1	1
	2	2^-	1	1
I = 0 CHANNEL				
$J^\pi = 0^+, T = 1$	1	1^+	NO Δ	0, 2

* $L_{(\pi-2N)}$, $L_{\Delta N}$ and L_{NN} are the relative orbital angular moments in the $\pi - 2$ nucleon, delta-nucleon, and final nucleon-nucleon systems; J^π is the total angular momentum and parity. Only $L \leq 2$ are listed. (Ash - 86)

to be $I = 1$. The relative orbital angular momentum of the intermediate delta-nucleon state could be either s, p or d. The second part of the table shows the quantum numbers allowed for absorption on a $T = 1$ nucleon pair. It shows that this channel cannot lead to a state where a delta and a nucleon are in relative s-state but must be in a relative p-state. Hence the π^+ absorption on a pn pair ($T = 0$) can be s-wave whereas π^- absorption on a pp pair ($T = 1$) is only p-wave. Lee and Ohta (Lee-82) have calculated the suppression of absorption on a $T = 1$ nucleon pair due to having only angular momentum $L = 1$ between the delta and nucleon to be about two orders of magnitude less than that for the s-wave delta-nucleon configuration allowed for $T = 0$ pairs.

The pion absorption process is assumed to proceed through the pion and nucleon forming an isobar and then this isobar interacting with another nucleon. The isobar can have isospin $\tau = 1/2$ or $3/2$. If we denote the amplitudes for transitions through an intermediate state having isospin τ by $g_{\tau I}$, then we can write the cross sections for s-wave absorption on deuteron 3S_1 and on two protons in an 1S_0 state as

$$\left(\frac{d\sigma}{d\Omega}\right)_{\pi^+d \rightarrow pp} = \langle 1011 | 11 \rangle^2 f_{01}^2$$

$$\left(\frac{d\sigma}{d\Omega}\right)_{\pi^-(pp) \rightarrow pp} = \frac{1}{2} \left(\langle 11 \ 11 | 10 \rangle^2 f_{11}^2 + \langle 11 \ 11 | 00 \rangle^2 f_{10}^2 \right)$$

where

$$f_{01} = (\sqrt{3}g_{3/2,1} + g_{1/2,1})/\sqrt{3}$$

$$f_{11} = (-g_{3/2,1} + \sqrt{3}g_{1/2,1})/\sqrt{3}$$

$$f_{10} = g_{1/2,0}$$

The amplitude f_{00} is not possible because the pion cannot couple to zero nuclear isospin to give a total zero isospin. The Δ dominance assumed for all transitions implies that there is no absorption for the $I = 0$ channel because there is no delta possible in this channel (Table 5.3). It also implies that $g_{1/2,I}$ is negligible with respect to $g_{3/2,I}$ the absorption of a pion by an $I = 0$ nucleon pair is four times as likely as nucleon with isospin unity.

Ginocchio (Gin-78) in his calculation of pion induced nuclear reactions using the isobar model calculated the ratio of protons produced by π^- and π^+ absorption assuming the process to take place on two nucleons. The absorption of π^- on two protons ($T = 1$) will produce one proton and one neutron and on a neutron proton pair ($T = 0$) will produce no protons. Whereas absorption of a π^+ on two neutrons ($T = 1$) will produce one proton and on a neutron-proton pair will produce two protons. Ginocchio calculated this ratio of proton production by π^- and π^+ absorption as

$$R_a(\text{No Rescattering}) = \frac{Z^2}{2Z + N^2}$$

where

$$Y = 6(2|f_{01}|^2 + |f_{11}|^2) / (2|f_{10}|^2 + 3|f_{11}|^2)$$

and N , Z are the number of neutrons and protons respectively. The quantity Y accounts for the extent to which absorption takes place on an n - p pair as opposed to an nn pair for π^+ and a pp pair for π^- .

In the channel with Δ ($\tau = 3/2$) dominance $Y = 10$, independent of the magnitude of absorption. Hence for $N = Z$ nuclei, $R_a = 1/11$ and for $N > Z$ it is even smaller. The introduction of the $\tau = 1/2$ channel will change Y in either direction depending on the relative magnitude of the $I = 0$ and $I = 1$ amplitudes.

In this section a discussion of some of the previous works in pion absorption is presented.

Pion absorption on the deuteron

The deuteron is the lightest nucleus on which the pion can be absorbed and it leads to states with well defined quantum numbers, which can be identified experimentally and addressed in theoretical calculations. Pion absorption on the deuteron has been studied from very low energy to above resonance energy. A compilation of the measurements of the total cross section of the $\pi^+d \rightarrow pp$ process is shown in Fig. 57 (Rit - 83A). Several approaches have been tried to describe the differential cross section for the process. The most frequently used method is the Legendre polynomial expansion method, where the differential cross section is expressed as

$$\frac{d\sigma}{d\Omega} = \frac{1}{2\pi} \sum_{m=0}^n \alpha_{2m} P_{2m}(\cos \theta)$$

Fig. 57.

This method has the advantage of being directly connected with the angular momentum expansion in the reaction, it is a complete orthogonal set, and in the fitting procedure it is more stable with nearly independent error for each coefficient.

Most theoretical models used to describe this pion absorption reaction consider that it proceeds through an intermediate state of the Δ -isobar or a model of overlapping six quark bags. Niskanen (Nis - 78) used the coupled-channel method to calculate the inverse reaction $pp \rightarrow d\pi^+$. In his calculation the Δ -resonance, as an intermediate state, has been treated on equal footing with nucleons. He includes the possibility of ρ meson exchange along with π exchange between nucleons Fig. 58A, in his transition potential. As shown in Fig. 57, (broken curve) the agreement between Niskanen's calculation of the total cross section and the experimental measurements is rather poor. The calculation shows a very narrow energy dependence with peak position at a higher energy than the experimental measurement.

The calculations of Blankleider and Afnan (Bla - 81) are in better agreement with the data. In their calculation, they decomposed the πN interaction t_1 in the P_{11} channel into the sum of two parts, a pole part and non-pole part, Fig. 58B. Also, the calculation included terms corresponding to the mechanism in which a pion is being absorbed by one nucleon while another is emitted by the second nucleon. The inclusion of these terms treats both the

Fig. 58. (a)

Fig. 58. (b)

nucleons on equal footing and the NN intermediate states satisfy the Pauli exclusion principle. Their calculation is in rather good agreement with the data (solid line) Fig. 57.

Bentz and Lee (Ben - 81) have proposed a coupled-channel model, using nucleons, mesons and isobars, in which pion production and absorption take place explicitly only through the delta resonance. A phenomenological Hamiltonian is then produced and fitted to NN phase shifts to get the relative contributions from the various partial waves. This method provides reasonable agreement with the experimental measurements and has been proposed (Oth - 85) to be applicable for treating pion absorption in nuclei.

Miller and Kisslinger (Mil - 83) have introduced the effect of quark degrees of freedom in calculating the pion absorption cross section. The total energy available in the system is enough to excite a delta inside the nucleus. Because of a large momentum transfer, the wavefunction of delta and nucleon can overlap, being in the relative s - state, with a typical separation of < 0.5 fm. This small separation implies overlapping quark bags and the two baryons can be treated as a six quark object, where quark-quark interactions lead to a transformation of $\Delta N \rightarrow NN$. Miller, et al. suggest that this component in the pion absorption should add coherently to the normal quasideuteron component and may explain some of the remaining discrepancies. This model of overlapping quark bags has also been applied to the pion absorption

measurements on ^3He and provides a reasonable explanation of the data (Mil - 86).

All these investigations of pion absorption on the deuteron focus on two basic interactions possible in pion absorption, i.e. pion rescattering from one nucleon before being absorbed by another nucleon and the formation of a delta isobar as an intermediate state. The usefulness of the knowledge obtained from this reaction for treating pion absorption in heavy nuclei will be discussed in the following sections.

Pion absorption in ^3He

The next simplest nucleus for pion absorption is ^3He , which has received a lot of attention in recent years. The deuteron provides only a $T = 0$ nucleon pair for pion absorption, whereas in ^3He both $T = 0$ and $T = 1$ nucleon pairs are available, and by selecting a proper reaction channel, one can isolate absorption on either pair. Thus a direct comparison of the two processes can be made. Also this can provide useful information for pion absorption in heavy nuclei. By measuring the $^3\text{He}(\pi^+, pp)$ and $^3\text{He}(\pi^-, pn)$ reactions, and by taking advantage of the fact that the initial nucleons are in relative s-states in ^3He , one can directly compare absorption on $T = 1$ and $T = 0$ nucleon pairs.

There have been several kinematically complete experiments (Ash - 81,84; Moi - 84; Ani - 84; Got - 82; Wey - 85; and Bac - 84A, 84B) of π^+ absorption on ^3He detecting

two outgoing nucleons in coincidence. The two nucleon pion absorption peak is seen in these experiments from the angular correlation between the outgoing nucleons. The angular distribution of π^+ and π^- absorption on ^3He is shown in Fig. 59. The shapes of the angular distributions are similar to that of $\pi^+d \rightarrow pp$ and the absolute magnitude is about 1.5 times larger for π^+ . The similar shape of the angular distributions suggests that both π^+ and π^- absorption have a similar pion absorption mechanism. The angular distribution of π^- absorption is not symmetric about 90° for measurements at 65, 85 and 120 MeV. This asymmetry is due to an interference of the s- and p- partial waves in the interaction.

Fig. 60 (from Red - 85) shows a compilation of results of the ratio of $T = 0$ to $T = 1$ absorption cross section in ^3He . The ratio is smoothly and slowly increasing with energy up to the resonance. The published ratios are $R = 15.3 \pm 1.2$ at $T_\pi = 65$ MeV (Moi -84), $R = 15.0 \pm 0.9$ (Alt-84) at $T_\pi = 85$ MeV, $R = 22.2 \pm 7.5$ at $T_\pi = 120$ MeV (Bac - 84) and $R = 25.0 \pm 7$ at $T_\pi = 165$ MeV (Bac- 84). This enhancement of π^+ absorption over π^- absorption can be understood by considering the pion absorption process to proceed through a Δ - isobar as in $\pi^+NN \rightarrow \Delta N \rightarrow NN$. The intermediate Δ and nucleon are in a relative s-state for π^+ absorption on a $T = 0$ nucleon pair, which is forbidden in the $^3\text{He}(\pi^-, pn)$ reaction.

The results from the present experiment show

Fig. 59.

Fig. 60.

a similar energy dependence for the ratio of proton yield for π^+ to π^- absorption. It is twenty times larger for π^+ at $T_\pi = 120$ MeV and drops down to fourteen at $T_\pi = 90$ MeV. This suggests that even in heavy nuclei the absorption resulting in a single energetic nucleon is dominated by two nucleon clusters and that the π^+ is absorbed on a pn pair, and while the π^- is absorbed on a pp pair predominantly.

Pion absorption in heavy nuclei

Pion absorption in heavy nuclei has been studied either by inclusive $(\pi^\pm, p)$ reactions or by $(\pi^\pm, 2N)$ coincidence reactions.

i. Inclusive measurements

The study of inclusive $(\pi^\pm, p)$ reactions is the simplest pion absorption measurement with an advantage of detecting a sizable amount of the absorption process with no coincidence constraints. The major disadvantage of this is that many reaction products may not be uniquely assigned to the absorption process. The large amount of inclusive pion absorption data has mainly been measured by two groups McKeown et al. (Mck - 80,81) and Jackson et al. (Jac - 77A, 77B). McKeown et al. measured a broad range of the angular distribution of protons ($30^\circ \leq \theta_{lab} \leq 150^\circ$) with energies greater than 50 MeV. They used pions of 100, 160 and 220 MeV on targets of ^{12}C , ^{27}Al , ^{58}Ni and ^{181}Ta . Jackson et al. measured $(\pi^\pm, p)$ reactions with 60, 100 and 200 MeV pions on ^4He , ^{12}C , ^{27}Al , ^{62}Ni and ^{181}Ta at laboratory angles of 45° , 90° and 94° . They counted the outgoing protons with energies

in between 60 and 200 MeV.

The characteristic features of the proton inclusive spectra are as follows: (a) The proton yield for energy $T_p > 40$ MeV are in the ratio of $\approx 3:1$ for π^+ versus π^- absorption independent of pion energy for light nuclei and increases to 6:1 for heavy nuclei. (b) The proton yield increases with target mass and is roughly proportional to $A^{2/3}$. (c) The proton spectra with π^+ and π^- absorption at the same T_π and proton angle is similar in shape, i.e. monotonically decreasing with increasing proton energy and contains little structure.

The first two observations of the inclusive measurements are in disagreement with our results. As mentioned earlier, the proton yield in the low excitation continuum is more than twenty times larger for π^+ than for π^- at 120 MeV and drops down to fourteen at 90 MeV. Also the proton yield in the continuum is approximately independent of target mass and pion charge. This disagreement with inclusive measurements can be interpreted as follows. In this exclusive measurement, the continuum is only the higher energy end of the outgoing protons. In this process the incident pion may suffer an initial state interaction before being absorbed inside the nucleus. But the outgoing proton, due to its high energy and the long mean-free-path for the protons of energy above 150 MeV, is the proton from a cluster on which the pion was absorbed rather than being a secondary proton. For example, in McKeown's et al. measurement of the proton yield, they consider protons with

$E_p \geq 50$ MeV for 220 MeV pions. A pion with $T_\pi = 220$ MeV can quasifree scatter off a proton knocking it out of the nucleus with considerable kinetic energy at forward angle and still have its rest mass energy and some momentum to provide another proton with considerably high kinetic energy. By measuring only those protons which have a kinetic energy requiring pion absorption, one eliminates most of the secondary processes. The independence of proton yield on target mass and pion charge in this exclusive measurement suggests that the pion is absorbed on similar nucleon clusters rather than being affected by the size and specific structure of the nucleus.

There have been several model dependent explanations of the pion absorption results of McKeown et al. and Jackson et al. McKeown et al. (McK - 80) discuss the number of nucleons participating in pion absorption by a rapidity analysis of their inclusive (π^+, p) data. The rapidity y is defined as

$$y = \tanh^{-1}(\beta_{||})$$

where $\beta_{||}$ is the projection of the proton velocity parallel to the beam direction, $\beta_{||} = v_{||}/c$ with $v_{||} = p_{||}c^2/E$ is the velocity of the proton parallel to the beam direction. The kinematics of the proton spectra following the inclusive π^+p reaction can be displayed on a rapidity plot, where the values of the constant invariant cross section $d^2\sigma/d^2\Omega dE$ are plotted in the plane defined by the

rapidity "y" (x-axis) and the coordinate $p_{\perp}$ (component of proton momentum perpendicular to the beam direction). Fig. 61 shows such a plot for protons from π^- absorption on ^{181}Ta at $E_{\pi} = 220$ MeV. The rapidity (velocity) of the frame in which the cross section is most nearly isotropic (y_0) is indicated by a dashed line and the contours corresponding to the isotropic distributions of protons in this y_0 frame with $T_p = 80$ and 122 MeV given by the solid lines. McKeown et al. extracted the value of rapidity y_0 and found it to be constant for a given target and pion charge over the observed range of proton energies. The value of y_0 was found to be a little larger for π^+ than π^- for the same beam energy and target and also it decreases with the mass of the target.

Assuming that y_0 represents the velocity of the center of mass of the pion plus the nucleons which absorb the energy and momentum of the pion, the rapidity can be written as

$$y_0 = \tanh^{-1} \beta_{c.m.} = \tanh^{-1} [p_{\pi} c / (E_{\pi} + M_{abs} c^2)]$$

where E_{π} and p_{π} are the total energy and momentum of the incident pion and M_{abs} is the average mass of the absorbing nucleon cluster. The average number of nucleons, N in the absorbing cluster for each value of y_0 can be found, because $M_{abs} = N \cdot \text{mass of a single nucleon}$. The right hand side of Fig. 61 shows the value of N averaged over pion energy as a function of A . The number N increases with target mass but

Fig. 61.

no significant variation was observed as a function of pion energy. From this analysis of rapidity McKeown et al. concluded that the average number of nucleons participating in pion absorption is 3 to 6 over the range of nuclei studied.

Considering the observations of McKeown et al. in their rapidity analysis Brown et al. (Bro - 82) and Ko et al. (Ko - 80) proposed two different models for pion absorption. Brown et al. suggested that the multinucleon pion absorption vertex proceeds through a double delta as an intermediate state (Fig. 62). In this model the pion absorption proceeds through $\pi NN \rightarrow \Delta N \rightarrow \Delta\Delta$ interaction, where the two deltas interact with two more nucleons resulting in the direct emission of four nucleons. This model can describe the small ratio of proton yield from π^+ to π^- absorption very well. Ko et al. introduces another model of multinucleon pion absorption, assuming that the incident pion is absorbed by a row of target nucleons in the direction parallel to the direction of the beam. Since the data of inclusive (π^+, p) reactions are mainly for resonance energy pions, a virtual delta can be excited by the incident pion. In this model this virtual Δ has been considered to propagate through the medium and collides with other nucleons, and during this time it may convert into a nucleon. Assuming all this propagation takes place in a straight line parallel to the beam direction Ko et al. were able to describe the proton spectra, the integrated proton cross section, the ratio of the integrated proton yields seen with

Fig. 62.

π^+ to those seen with π^- absorption and the average number of nucleons participating in the absorption process as function of target mass, found by a rapidity analysis rather well.

Recently Girija et al. (Gir - 84, 85) have reanalysed the rapidity analysis of $(\pi^\pm, p)$ inclusive data using a statistical transport model. They were able to reproduce the rapidity data by introducing an initial state interaction (ISI) of the pion followed by its absorption on a two-nucleon cluster. Both pion and delta are considered to propagate along a one dimensional trajectory with fixed impact parameter, but in either direction relative to the initial beam. They concluded that ISI of the pion such as inelastic scattering or charge exchange could account for the observed proton momentum leaving little room for pion absorption on multinucleon ($N > 2$) clusters.

ii. $(\pi^\pm, 2N)$ measurements

Coincidence measurement of $(\pi^\pm, 2N)$ reactions have been studied extensively recently (Alt - 83, 84, 86; Bur-86) and many experiments (Rit - 86) are in progress. In most of these measurements a large part of the two nucleon contribution to pion absorption has been investigated along with pion absorption on quasideuteron, but as noted earlier it is very difficult to interpret because of the initial and final state interactions. The $(\pi^\pm, 2N)$ reactions do not directly connect with the present work but have provided much insight into the pion absorption mechanism and an

estimate has been made of different interactions, so a brief report of some of the important results of these measurements is also included here.

In the $^{12}\text{C}(\pi^+, 2p)$ measurements of Altman et al., at $T_\pi = 165$ MeV Fig. 63 and 245 MeV, it was found that one step quasideuteron absorption (QDA) accounts for 25% of the total absorption cross section over a broad kinematic range. The bulk of the absorption cross section is therefore a process such as multiple pion scattering followed by absorption on two nucleons, absorption on a nucleon cluster with $n > 2$, or double delta formation (Bro - 82). This data was later reanalysed by Ritchie et al. (Rit - 84), where they suggest the quasideuteron contribution to be higher.

Altman et al. in their recent measurement (Alt - 86) have measured the $(\pi^+, 2p)$ and $(\pi^\pm, pn)$ reactions by coincidence detection of the two outgoing nucleons on C, Fe and Bi at 165 and 245 MeV and on ^{16}O and ^{18}O at 165 MeV. The quasideuteron component is found to be about 10% of the total absorption cross section for carbon which drops down to 2% for Bismuth. After considering the corrections for final state interaction of the outgoing nucleons it amounts to at most 40%. The data also indicates that quasideuteron absorption following pion scattering is not likely and the absorption on $T = 1$ nucleon pairs is about 4% of that on a quasideuteron.

Burger et al. (Bur - 86) have measured $^{58}\text{Ni}(\pi^+, 2p)$ reaction at $E_\pi = 160$ MeV. In their measurement the resultant angular correlations of two protons whose sum of

Fig. 63.

energy is greater than 160 MeV (which assures that pion has been absorbed) peaks at a separation angle corresponding to absorption on a deuteron at rest. After considering the initial and final state interactions less than 50% of the absorption cross section is predicted to arise from absorption on nucleon pairs.

Similar measurements are planned by Ritchie *et al.* (Rit - 86), where pion absorption on quasideuterons in ${}^6\text{Li}$ and ${}^{10}\text{B}$ using the $(\pi^+, 2p)$ reaction will be studied using low energy pions. The ${}^6\text{Li}$ nucleus can be well represented in a cluster model by an $l = 0$ deuteron orbiting an alpha core, whereas it is in a relative $l = 2$ state in ${}^{10}\text{B}$ orbiting a ${}^8\text{Be}$ core. This experiment will provide a good testing ground for the cluster model. In an impulse approximation (Roo - 81), the absorption of a pion on a deuteron within a cluster is directly related to the fundamental reaction $\pi^+ d \rightarrow pp$. The inclusion of distortions may alter the observed angular distribution somewhat, but the overall strength scale is the underlying deuterium absorption cross section. For a deuteron in a relative $l = 0$ state, the observed $(\pi^+, 2p)$ angular distributions should show a characteristic enhancement at the angle corresponding to quasideuteron absorption (QDA).

This feature has been seen in all $(\pi^+, 2p)$ experiments from light to heavy mass targets, (for example the angular distribution for ${}^1\text{H} \rightarrow p$ at 15 MeV, Alt - 83) Fig. - 63. The observed enhancement strongly suggests that QDA is important in those nuclei, but the overall

strength remains controversial. In some of these studies a broader gaussian shaped distribution centered at the QDA angles has been considered, which underestimates the contributions due to QDA, and has been considered to be due to multinucleon contributions to pion absorption.

These disagreements provide a strong motivation of measuring the $(\pi^+, 2p)$ reaction on simple nuclei, where QDA is supposed to clearly play an important role. The expectation is that the reaction on ${}^6\text{Li}$ should show a peak at the QDA angle whereas for ${}^{10}\text{B}$ it should show a dip at that angle because it will be an absorption on a relative $l = 2$ state deuteron. This dip in the angular distribution, for absorption on $l = 2$ deuterons can be seen in the calculation of ref Rit - 84. (Fig. - 64), although it has never been seen experimentally.

Fig. 64.

Conclusions

The first high resolution measurements of the exclusive (π^-, p) reaction have been performed on several nuclei, in an attempt to obtain data for the excitation of discrete excited states. This is the first experiment to measure the exclusive (π^-, p) reaction in this energy region. The pion production reaction has been measured either at threshold or at very high energies, leaving this energy region unexplored either by absorption or production reactions. To complement this measurement, measurement of the (π^+, p) reaction at the same energy and on the same nuclei was also performed to compare pion absorption on $T = 0$ and $T = 1$ nucleon pairs. The measurements include differential cross section at $\theta_{lab} = 25^\circ$ for $(\pi^\pm, p)$ reactions on ^{24}Mg , ^{27}Al , ^{40}Ca and ^{58}Ni at $E_\pi = 120$ MeV and (π^-, p) on ^{12}C at 145 MeV. There are also measurements on ^{24}Mg and ^{23}Na at $\theta_{lab} = 20^\circ$ and 90 MeV. ^{12}C , ^{27}Al , ^{40}Ca , $^{58}\text{Ni}(\pi^-, p)$ yield peaks with $d\sigma/d\Omega < 1 \mu\text{b/sr}$ compared to 7-22 $\mu\text{b/sr}$ for peaks from (π^+, p) reaction at 120 MeV. In $^{24}\text{Mg}(\pi^-, p)^{23}\text{Ne}$ spectra, both at 120 and 90 MeV, there are peaks in the spectrum that are comparable in strength to those seen in $^{24}\text{Mg}(\pi^+, p)^{23}\text{Mg}$ spectra. The $^{23}\text{Na}(\pi^\pm, p)$ reaction also reveals peaks, but with very low statistics.

The shape of the continuum in an excitation energy range of 10 to 40 MeV was found to be independent of pion charge and target mass. The magnitude of the proton yield at $E_\pi = 120$ MeV, in the low excitation continuum, is more than twenty times larger for π^+ than π^- . Also the cross

sections for both reactions on ^{24}Mg is slightly enhanced compared to other nuclei. This ratio of proton yield of π^+ to π^- absorption at $E_\pi = 90$ MeV drops down to fourteen. This energy dependence behavior has been seen for pion absorption in ^3He and can be explained by considering pion absorption on $T = 0$ and $T = 1$ nucleon pairs. One of the dominant channels for the pion absorption is $\pi NN \rightarrow \Delta N \rightarrow NN$. This enhancement of the proton yield of π^+ to π^- absorption by an order of magnitude suggests that a π^+ is predominantly absorbed on a $T = 0$ nucleon pair, whereas π^- is absorbed on $T = 1$ nucleon pairs. For a $T = 0$ pair, the delta and nucleon can be in a relative s state, and this is a forbidden channel for a $T = 1$ pair, hence the absorption on $T = 1$ is quite suppressed.

Shell model calculations, using a two nucleon model have been used to study this reaction. This simple model describes the threshold (p, π^-) excitation very well, but when applied to (π^-, p) fails to predict the relative cross sections of the excited states. This failure maybe because of differences in the reaction mechanism or more probably because the calculations donot contain any contributions from delta dynamics. Optical model analysis of the (π^+, p) reaction, using a one nucleon pion absorption or neutron pickup model, shows a very small cross section. The poor results of these two simple model calculations suggest that pion absorption in nuclei is a rather complicated reaction and effects like two nucleon absorption, charge

exchange of the pion, and initial and final state interactions are important and should be taken into consideration in developing a pion absorption theory.

To understand the pion-nucleus interaction completely one has to understand pion absorption much better than our present understanding of this process. More experimental and theoretical effort is needed.

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APPENDIX -- 1

Kinematic Calculation for Excitation Energy

Missing mass (Excitation energy) of the residual nucleus for both the EPICS and SIN analyzer was calculated using the following kinematic formulas, which was used by programme CALKIN of the EPICS analyzer and is a subroutine to PARAM of the SIN analyzer. The incident particle momentum were calculated with the information from the wire chambers and the values of the magnetic field of the pion channel and spectrometer.

The reaction is $A + B \rightarrow C + D$, where A is the incident particle, B the target nucleus, C the scattered particle and D the residual nucleus. Masses of these are looked up in the mass table and Q value of the reaction is calculated.

E_A, P_A = Energy and Momentum of the incident particle

E_B, P_B = Energy and Momentum of the target

($P_B = 0$, the target is at rest)

E_C, P_C = Energy and Momentum of the Scattered particle

E_D, P_D = Recoil Energy and Momentum of the residual nucleus

M_A, M_B, M_C and M_D are the masses of A, B, C and D respectively

θ_s = scattering Angle

θ_t = Target Angle

DEI = Energy loss in target by incident particle (Rotated)

DEO = Energy loss in target by scattered particle (Rotated)

$$E_A = \sqrt{P_A^2 + M_A^2}$$

$$E_B = M_B$$

$$E_C = \sqrt{P_C^2 + M_C^2}$$

The recoil momentum of the residual nucleus, P_D is calculated by P_A , P_C and θ_s information

$$P_D^2 = P_A^2 + P_C^2 - 2P_A P_C \cos \theta_s$$

$$E_D = \sqrt{P_D^2 + M_D^2}$$

The total energy loss by the incident and scattered particle in the target is given by

$$DET = DEI + DEO$$

so the Missing Mass or Excitation energy is equal to

$$E_A + E_B - (E_C + E_D) = DET$$

By calculating the incident particle momentum P_A , scattered particle momentum P_B , as well as the scattering angle for a particular nuclear reaction the excitation energy of the residual nucleus can be calculated.

Appendix - 2

Test File EXP809.TST

This is a test output file for $^{24}\text{Mg}(\pi^-, p)^{23}\text{Ne}$ run. The total number of event is 61112. The number on the left of each test is the number of event that has passed that test.

*** T E S T R E S U L T S *** 24-JUN-86 13:52:49

TEST COUNTERS FROM SAVED FILE

SY0:RUNMAG.HSV

; EXP809.TST 04-JUL-84 CYCLE 41

/TE:150/BL:3/IG:10/IB:10

61112 = BLOCK,1

;FIRST PID STUFF

18577 = 1,GAT,253,32,144, ;1 ;X OF PID

57075 = 2,GAT,260,466,1788, ;2 ;Y OF PID(S23 TOF)

1844 = 3,GAT,257,0,3000, ;3 ;Y2 OF PID(S1 TOF)

;MUON REJ TESTS

2256 = 4,BI,2,0, ;4 ;S4 MUON

1797 = 5,BI,2,1, ;5 ;S5

989 = 6,BI,2,2, ;6 ;S6

714 = 7,BI,2,3, ;7 ;S7

10 = 8,BI,2,4, ;8 ;S8

1080 = 9,BI,2,5. ;9 ;S9

;FAST CLEAR

249 = 10,GAT,3,2,32001, ;10 ;FAST CLEAR (1/10)

;PID

```

283 = 13,AND,1,3,          ;13      ;KLUGE BOX S1 TOF
17955 = 14,AND,1,2,        ;14      ;KLUGE BOX S2 TOF
59620 = 15,IBOX,1,         ;15      ;BOX 1 ==> PID
61112 = 16,IOR,1,-1,       ;16      ;LOOP1 COUNTER
61112 = BLOCK,2,
; CHAMBER DRIFT TIME TESTS
59988 = 17,GAT,121,-2,42,   ;17      ;1A DRFTMX
                                   ;CHAMBER LOOP 2
60187 = 18,GAT,122,-2,42,   ;18      ;2A DRFTMX
59832 = 19,GAT,123,-2,42,   ;19      ;3A DRFTMX
59799 = 20,GAT,124,-2,42,   ;20      ;4A DRFTMX
59200 = 21,GAT,125,-2,42,   ;21      ;5A DRFTMX
59294 = 22,GAT,126,-2,42,   ;22      ;6A DRFTMX
59291 = 23,GAT,129,-2,42,   ;23      ;9A DRFTMX
60067 = 24,GAT,130,-2,42,   ;24      ;10A DRFTMX
60239 = 25,GAT,181,-2,42,   ;25      ;1C DRFTMY
60222 = 26,GAT,182,-2,42,   ;26      ;2C DRFTMY
60234 = 27,GAT,183,-2,42,   ;27      ;3C DRFTMY
60158 = 28,GAT,184,-2,42,   ;28      ;4C DRFTMY
58997 = 29,GAT,185,-2,42,   ;29      ;5C DRFTMY
59126 = 30,GAT,186,-2,42,   ;30      ;6C DRFTMY
59894 = 31,GAT,189,-2,42,   ;31      ;9C DRFTMY
59964 = 32,GAT,190,-2,42,   ;32      ;10C DRFTMY
;DRIFT DIFFERENCES
52401 = 35,GAT,272,-9,16,   ;35      ;FRONT DRF DIF PLANE A
53152 = 36,GAT,273,-9,16,   ;36      ;FRONT DRF DIF PLANE C
51293 = 37,GAT,274,-9,16,   ;37      ; REAR DRF DIF PLANE A
50605 = 38,GAT,275,-9,16,   ;38      ; REAR DRF DIF PLANE C

```

37244 = 39,AND,15,35,36,37,38, ;39 ; DRIFT DIFF ALL OK

; CHAMBER EFF. TESTS

57625 = 40,AND,15,25,26,27,28, ;40 ;FRONT C CHAMBERS OK*PID

56948 = 41,AND,15,17,18,19,20, ;41 ;FRONT A CHAMBERS OK*PID

56357 = 42,AND,15,29,30,31,32, ;42 ;REAR C CHAMBERS OK*PID

57183 = 43,AND,15,21,22,23,24, ;43 ;REAR A CHAMBERS OK*PID

55635 = 44,AND,40,41, ;44 ;FRONT OK

55191 = 45,AND,42,43, ;45 ;REAR OK

51544 = 46,AND,44,45, ;46 ;ALL OK*PID ==> CHMBRS

37485 = 47,AND,35,36,37,38, ;47 ; DRIFT DIFF ALL OK-PID

58481 = 48,AND,25,26,27,28, ;48 ;FRONT C CHAMBERS OK*NOPID

57800 = 49,AND,17,18,19,20, ;49 ;FRONT A CHAMBERS OK*NOPID

57342 = 50,AND,29,30,31,32, ;50 ;REAR C CHAMBERS OK*NOPID

58110 = 51,AND,21,22,23,24, ;51 ;REAR A CHAMBERS OK*NOPID

36648 = 52,AND,47,48,49,50,51, ;52 ;ALL OK EXCEPT NO PID

;TARGET TESTS

1587 = 64,GAT,266,0,3000, ;64 ;PID(S1 TOF CORRECT)

55972 = 65,GAT,233,-999,1001, ;65 ;XTGT

;BACKGROUND REJECTION LOOP 3

57327 = 66,GAT,234,-1199,1201, ;66 ;THTTGT

39391 = 67,GAT,235,-399,401, ;67 ;YTGT

57784 = 68,GAT,236,-799,801, ;68 ;PHITGT

44991 = 69,GAT,237,-99,101, ;69 ;THTCHK

44442 = 70,GAT,238,-99,101, ;70 ;PHICLK

32508 = 71,GAT,236,-262,262, ;71 ;PHITGT 3 DEG BIN

;GATES AND BOXES (DO WITH THESE AS YOU WISH


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1987 = 75,IBOX,2,                ;75      ;BOX 2
56453 = 76,IBOX,3,                ;76      ;BOX 3
56909 = 77,IBOX,4,                ;77      ;BOX 4
0 = 78,IBOX,5,                    ;78      ;BOX 5
0 = 79,IBOX,6,                    ;79      ;BOX 6
258 = 80,IGAT,6,                  ;80      ;GATE 6 ELASTIC
47443 = 81,IGAT,2,                ;81      ;TGT 1 27AL   ROD 1
10852 = 82,IGAT,1,                ;82      ;TGT 2 24MG   ROD 2
0 = 83,IGAT,3,                    ;83      ;TGT 3 58NI   ROD 3
0 = 84,IGAT,4,                    ;84      ;TGT 4 40CA   ROD 4
0 = 85,IGAT,5,                    ;85      ;ROD 5
25247 = 88,AND,52,65,66,67,68,
                ;88      ;TARGET TESTS*GOOD CHMBRS NO PID
184 = 89,AND,1,64,
                ;89      ;PID S1 CORRECTED
25091 = 90,AND,39,46,65,66,67,68,
                ;90      ;TARGET TESTS*GOOD CHMBRS ==> (TGT)

;VARIOUS GOOD EVENT TESTS
33584 = 91,AND,39,46,69,70,
                ;91      ;THTCHK AND PHICLK*GOOD CHMBRS==>(ANG CHK)
36415 = 92,AND,39,46,
                ;92      ;DRF*CHKSUM ==> (GOOD CHMBRS)
23641 = 93,AND,90,91,
                ;93      ;TGT*ANG CHK ==> (GOOD EVENT)
23772 = 94,AND,88,69,70,
                ;94      ;THTCHK AND PHICLK*GOOD CHMBRS==>(ANG CHK)
;
; EXPERIMENT SPECIFIC GOOD EVENT TESTS
;
23327 = 100,AND,93,-6,
                ;100     ;GOOD EVENT -S5 ==>(PION EVENT)

19129 = 101,AND,100,81,77,        ;101      ;PION EVENT 27AL
4686 = 102,AND,100,82,77,        ;102      ;PION EVENT 24MG

```

```

260 = 103,AND,93,6,81,    ;103    ;PION EVENT 27AL MU
60  = 104,AND,93,6,82,    ;104    ;PION EVENT 24MG MU
0   = 105,AND,100,83,      ;105    ;PION EVENT 58NI
0   = 106,AND,100,84,      ;106    ;PION EVENT 40CA
0   = 107,AND,93,6,83,      ;107    ;PION EVENT 58NI MU
0   = 108,AND,93,6,84,      ;108    ;PION EVENT 40CA MU
32  = 109,AND,92,75,        ;109    ;GOOD+BOX2 DEUTERONS
22921 = 110,AND,100,76,      ;110    ;GOOD+BOX3
18850 = 111,AND,101,76,      ;111    ;TGT1+BOX3+GOOD (PI,P)
4613  = 112,AND,102,76,      ;112    ;TGTTOP+BOX3 GOOD (PI,P)
26    = 113,AND,92,81,75,    ;113    ;TGT1+BOX2 DEUTERON EVENT (PI,D)
7     = 114,AND,92,82,75,    ;114    ;TGTTOP+BOX2 DEUTERON EVENT (PI,D)
1388  = 115,AND,81,75,        ;115    ;DEUTERON ONLY WITH TARGET TEST
307   = 116,AND,82,75,        ;116    ; SAME
61112 = 150,IOR,1,-1,        ;150    ;LOOP 4 COUNTER

;***** GATE PARAMETERS *****
;GATE 1
;          -1055 < OR = IDAT(233) <    -237
;GATE 2
;          -231 < OR = IDAT(233) <    1118
;GATE 3
;          0 < OR = IDAT( 0) <    0
;GATE 4
;          0 < OR = IDAT( 0) <    0
;GATE 5

```

```

;          0 < OR = IDAT( 0) <          0
;GATE      6
;          3307 < OR = IDAT(266) <      3558

;***** BOX PARAMETERS *****
;BOX      1
;          133 < OR = IDATX(260) <      2685
;          -592 < OR = IDATY(257) <      995
;BOX      2
;          282 < OR = IDATX(253) <      468
;          1822 < OR = IDATY(260) <      2864
;BOX      3
;          90 < OR = IDATX(253) <      193
;          758 < OR = IDATY(260) <      2079
;BOX      4
;          136 < OR = IDATX(260) <      1773
;          -592 < OR = IDATY(257) <      -245
*****

```

Appendix - 3

GECK (GOOD EVENT CHECK) TABLE

ONLINE SUAN GECK TABLE

.TITLE C5, X6 AND X7 MUST FOR (π^+ ,p) experiment.

```

DELAY      5.
DIGIT      44.
$DJ        X6,7.,9.,-2.0,1023.
$DJ        X7,10.,10.,-2.0,1023.
$DJ        C5X,13.,7.,-1.,96.
$DJ        C5Y,16.,8.,1.,-96.
$DJ        C4X,19.,5.,-1.,96.
$DJ        C4Y,22.,6.,1.,96.
SUBR       REJC
EQUAL      C4,<A$ C4X,C4Y>
EQUAL      C5,<A$ C5X,C5Y>
EQUAL      X6E,<A$ <N$ X6>,<A$ X7,<A$ C5X,C5Y>>>
EQUAL      X7E,<A$ <N$ X7>,<A$ X6,<A$ C5X,C5Y>>>
EQUAL      C5XE,<A$ <N$ C5X>,<A$ C5Y,<A$ X6,X7>>>
EQUAL      C5YE,<A$ <N$ C5Y>,<A$ C5X,<A$ X6,X7>>>
EQUAL      SPEC,<A$ C5,<A$ X6,X7>>
EQUAL      $REJC,<N$ SPEC>
.END

```

OFFLINE ANN GECK TABLE

\$TIT OFF-LINE ($\pi^{\pm}$,p) 90 MEV - ** C5 NOT IN TRIGGER **
C

C C5,X6,X7 MUST PASS

C REQUIRES PAT1, C5, WC, NOT(PAT2) FOR \$IR

C " C5, X6 FOR \$RE

\$PU PAT1,1

\$PU PAT2,2

\$LE GPAT1=PAT1 .AND. .NOT.(PAT2)

\$DJ C5X,15,+1.,-96.,7

\$DJ C5Y,18,-1.,+96.,8

\$DJ X6,9,-2.0,1023.,9

\$DJ X7,12,-2.0,1023.,10

LOGICAL TEST ON DATA WORDS

\$LE C5=C5X .AND. C5Y

\$IR IREJ=(.NOT. C5)

\$LE C5E=(.NOT. C5) .AND. (GPAT1)

\$LE C5XE=(.NOT. C5X) .AND. (C5Y .AND. (X6 .AND. X7))

\$LE C5YE=(.NOT. C5Y) .AND. (C5X .AND. (X6 .AND. X7))

\$LE X6E=(.NOT. X6) .AND. (C5 .AND. X7)

\$LE X7E=(.NOT. X7) .AND. (C5 .AND. X6)

\$LE SPEC=(C5 .AND. (X6 .AND. X7))

\$RE REJC=(.NOT. SPEC)

SCALERS ARE READ FROM SCALER BUFFER

\$SC BEAM1,3

\$SC EMPTY,5

\$SC EMPTY,7

\$SC S2E6,9
 \$SC S2BE3,11
 \$SC TIME1,13
 \$SC S3E3,15
 \$SC S4E3,17
 \$SC SPS34,19
 \$SC WHAT3,21
 \$SC SE4,23
 \$SC S22BN,25
 \$SC BEASP,27
 \$SC BEAFR,29
 \$SC SPEC2,31
 \$SC BEAE6,33
 \$SC BEAM2,35
 \$SC STIME,37
 \$SC LAM,39
 \$SC SPEVE,41
 \$SC SAMPL,43
 \$SC EVENT,45
 \$SC TRIGG,47
 \$SC TRNLA,49
 \$SC SPACC,51

EFFICIENCY AND OTHER CALCULATION

\$AE EFF5X=SPEC/(SPEC+C5XE)
 \$AE EFF5Y=SPEC/(SPEC+C5YE)
 \$AE EFF6=SPEC/(X6E+SPEC)
 \$AE EFF7=SPEC/(X7E+SPEC)

```
$AE EFF67=EFF6*EFF7
$AE EFF5=(SPEC/(SPEC+C5XE))*(SPEC/(SPEC+C5YE))
$AE COR2=COSTG
$AE CMLT1=TIME1/STIME
$AE CMLT2=BEAM1/BEAE6
$AE TGTH=NOTGT
$AE CFAC1=1./(CMLT1*EFF67*EFF5)
$AE CFAC2=1./(CMLT2*EFF67*EFF5)
$AE CF1=COSTG*CFAC1
$AE CF2=COSTG*CFAC2
$AE NOR11=CF1/BEAM1
$AE NOR12=CF2/BEAM1
$PA PAT$=8
```


BLOCK	ANN	SUAN	SUAN	
WORD #	OFFSET	OFFSET	OFFSET	DESCRIPTION
	WORD #	BYTE #	WORD #	
9	9	10	7	S4(+) TDC INFORMATION
10	10	12	8	S4(-) TDC INFORMATION
11-13	11-13	14-18	9-11	X6 WIRE CHAMBER INFORMATION
14-16	14-16	20-24	12-14	X7 WIRE CHAMBER INFORMATION
17-19	17-19	26-30	15-17	X5 WIRE CHAMBER INFORMATION
20-22	20-22	32-36	18-20	Y5 WIRE CHAMBER INFORMATION
23-25	23-25	38-42	21-23	X4 WIRE CHAMBER INFORMATION
26-28	26-28	44-48	24-26	Y4 WIRE CHAMBER INFORMATION
29	29	50	27	S2 TDC INFORMATION
30	30	52	28	S3 TDC INFORMATION
				EMPTY
				"
				"
105	105	202	103	S2 ADC INFORMATION
106	106	204	104	S3 ADC INFORMATION
107	107	206	105	S4P ADC INFORMATION
108	108	208	106	S4N ADC INFORMATION

(B) STRUCTURE OF A DOS SCALER BLOCK

BLOCK	ANN	SUAN	SUAN	
WORD #	OFFSET	OFFSET	OFFSET	DESCRIPTION
	WORD #	BYTE #	WORD #	
1	-	-	-	BLOCK LENGTH IN WORDS (260)
2	-	-	-	TIME AND DATE (EXCEPT FOR THE SCALER BLOCK IMMEDIATELY PRECEDING THE STOP BLOCK-IN THIS CASE VALUE OF THIS WORD IS ZERO)
3	1	-	-	BLOCK TYPE CODE (=6 FOR SCALER BLOCK)
4	2	-	-	SET LENGTH = LENGTH IN WORDS OF THE SET OF INFORMATION FOLLOWING THIS WORD (ONLY ONE SET OF LENGTH 256)
5	3	-	-	LOW ORDER PART OF FIRST SCALER
6	4	-	-	HIGH ORDER PART OF FIRST SCALER
7	5	-	-	LOW ORDER PART OF SECOND SCALER
8	6	-	-	HIGH ORDER PART OF SECOND SCALER
260	256	-	-	