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Quasi-Free Scattering of Protons from ^3He at Intermediate Energies.

By

Angela Bracco

A thesis submitted to the University of Manitoba in partial fulfillment
of the requirements for the degree of Doctor of Philosophy.

THE UNIVERSITY OF MANITOBA

FACULTY OF GRADUATE STUDIES

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QUASI-FREE SCATTERING OF PROTONS FROM ^3He AT INTERMEDIATE ENERGIES

by

Angela Bracco

A thesis submitted to the Faculty of Graduate Studies of
the University of Manitoba in partial fulfillment of the requirements
of the degree of

DOCTOR OF PHILOSOPHY

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ABSTRACT

Quasi-free scattering of protons from ^3He at intermediate energies has been studied. Two sets of experiments have been carried out at the TRIUMF cyclotron laboratory. A liquid ^3He target of areal density of $\sim 104 \text{ mg/cm}^2$ was used. To detect the scattered and ejected particles either a magnetic spectrometer and a NaI counter telescope or two NaI counter telescopes were employed.

The first set of experiments concerned the study of two-nucleon wavefunctions in ^3He . The $^3\text{He}(p,2p)np$ reaction was studied in a quasi-free scattering arrangement characterized by $\vec{P}(\text{recoil})=0$ and various excitation or total energies $E(\text{recoil})$ of the unobserved p-n pair. Data were obtained at 250 and 400 MeV at symmetric and asymmetric angle pairs. The ^3He spectral function deduced in the framework of the plane wave impulse approximation (PWIA) is compared to the predictions of Faddeev and variational calculations. Comparisons are also made with p-n relative motion momentum distributions calculated as the overlap integral between plane waves for the p-n pair and Irving, Irving-Gunn and Khanna wave functions for ^3He .

The second set of experiments concerned the study of the proton-deuteron relative motion momentum distribution in ^3He in the framework of PWIA. Since the PWIA predicts the same relative motion momentum distributions extracted from the $^3\text{He}(p,2p)d$ and $^3\text{He}(p,pd)p$ reactions, a comparison of the results of the two reactions is made. The $^3\text{He}(p,2p)d$ reaction was measured at 300 MeV at the angle pair $70^\circ\text{--}33^\circ$ and at 450 MeV at the angle pairs $70^\circ\text{--}30^\circ$ and $46^\circ\text{--}46^\circ$ for recoil momenta.

larger than 350 MeV/c. For the $^3\text{He}(p,pd)p$ reaction, energy sharing loci have been measured at 450 MeV for the angle pairs 25° - 68° and 50° - 68° yielding a recoil momentum range from 0 to 480 MeV/c. The present proton-deuteron relative motion momentum distributions are compared to the existing $^3\text{He}(p,pd)p$ and $^3\text{He}(e,e'p)d$ results and to the momentum distribution calculated as the overlap integral between a Hulthén deuteron wave function and an Irving-Gunn ^3He wave function. Comparisons are also made with existing spectral functions calculated using either variational techniques or Faddeev equations.

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Felix qui potuit rerum cognoscere causas.

Virgil.

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CHAPTER I

INTRODUCTION

Studies of intermediate energy knock-out reactions provide information relevant to both nuclear structure and reaction mechanisms. As far as nuclear structure is concerned, one can learn not only about the binding energy and the momentum distribution of nucleons in nuclei, but one can also in principle learn about other nuclear constituents such as the Δ and N^* . Furthermore, it is possible to obtain information on medium-energy nucleon-nucleus reaction mechanisms which can be helpful in unravelling other processes. However, the ability to obtain nuclear structure information is plagued by many difficulties such as uncertainties in the form of the off-energy-shell effective t matrix, multistep processes, final state interactions, and three-body effects. Many experiments have been carried out with the objective of disentangling these different competing effects. Comparisons of results between measurements where energy, geometry, state reached and target have been varied, have shown the conditions under which some of these effects are enhanced. Different probes with different interaction natures have also been used. The most commonly used probes for quasi-free scattering studies are protons and electrons. Although electrons are better suited probes, since the electromagnetic interaction is well known and sufficiently weak so that the first Born approximation is essentially valid (negligible distortion effects on the electron waves), the $(p,2p)$ reaction has been more extensively studied than the $(e,e'p)$ reaction

primarily because it has much larger cross sections (four orders of magnitude larger).

In the first order picture of the quasi-free scattering process the incident particle (proton or electron) is suffering a violent interaction with only one nucleon in the target nucleus and knocks it out. The residual or recoil nucleus is considered a spectator whose final state momentum is therefore the same as in the initial state (where it is the opposite of the Fermi momentum of the struck nucleon). The standard knock-out reaction experiments involve measurements of angles and energies of the scattered and ejected particles. The experiment is in this case kinematically completely determined and in this first order picture the recoil momentum distribution is related to the nuclear wavefunction of the struck nucleon. The relationship is complicated by the fact that the presence of the recoil nucleus affects both the incident and final state particle. In fact, the recoil nucleus is not in general transparent and the ejected and scattered particles can be absorbed and refracted. The amount of absorption is related to the mean free path of nucleons in nuclear matter. For instance at around 100 MeV, the mean free path of a proton through nuclear matter is of the order of 2 fm. [Re-76] Since even light nuclei have radii of 2 fm or more, one must conclude that this very naive picture does not hold. However, early experiments indicated that this very strong absorption and refraction did not qualitatively change the result from what one would expect from this simple model.

The simplest theoretical model which describes the knock-out reaction mechanism is the plane wave impulse approximation (PWIA). In this framework the incident and outgoing particles are described by

plane waves and all the interactions of the particles in the initial and final state as well as multiple scattering are neglected. A more realistic description of these reactions is given by the distorted wave impulse approximation (DWIA) which takes into account the interaction of the incident particle with the target nucleus and the interaction of the two outgoing particles with the recoil system. Many calculations both in PWIA and DWIA have been made for several nuclei and various incident energies. In addition, the ratio of the DWIA calculations to PWIA calculations [Ro-76] was studied as a function of energy and mass number at recoil momentum equal to zero. For a given A this ratio shows a rapid increase at lower energy and then becomes constant at higher energies. At incident energies of approximately 150 MeV this ratio is flat for light and medium weight nuclei and increases (becoming closer to 1) for small values of A . One would then expect light nuclei such as d , ^3He , ^3H and ^4He to be suitable targets to obtain nuclear wavefunction information since most of the distortion and multiple scattering effects are minimized. A great deal of experimental and theoretical work has been done to understand the physics of the three-nucleon system. At present, many details of the three-body nuclei are not yet understood and the comparison between experimental data and theoretical predictions is an important tool to evidence the limitations of the classic non-relativistic picture of the nucleus. In the classical model of nuclear matter the nucleus is viewed as a collection of non-composite nucleons. Nucleons interact non-relativistically through an instantaneous charge-independent two body potential. In the case of the three body nuclei one uses this potential in the Faddeev equations. These can be solved with satisfactory accuracy providing the three-nucleon wavefunction.

The question which arises is how well this classic non-relativistic model which neglects mesonic and internal nucleonic quark degrees of freedom, can quantitatively describe nuclear properties. Another difficult task is to find the dominant correction for this picture.

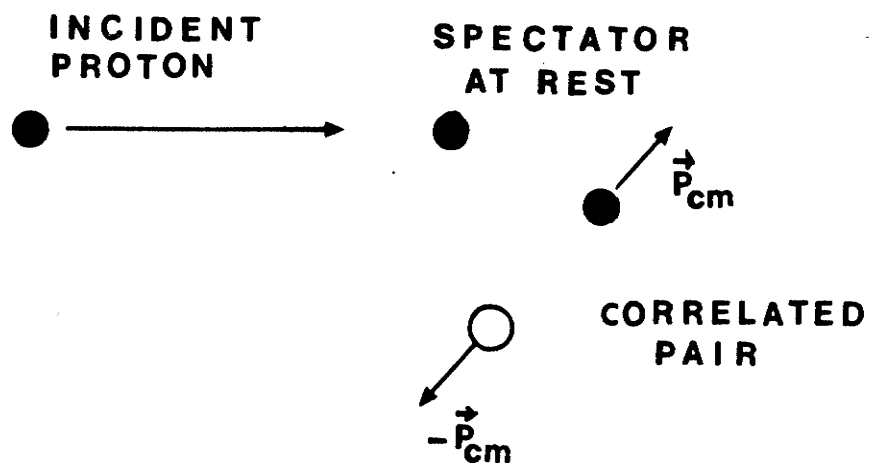
In the case of the three-nucleon system several difficulties have been encountered in describing quantitatively the bound state properties. The predicted binding energy ([Ha-81], [La-80], [Re-68]) is too small and the theoretical ^3He electromagnetic form factors are in disagreement with the experimental data. The calculated charge form factor ([Ha-81], [Me-83]) is from the secondary maximum on lower than the experimental one by a factor of 2-3. The theoretical PWIA cross section [Me-83] is satisfactory for coincidence experiments [Ja-82] but is in grave disagreement with the inclusive cross sections [Mc-76]. With the assumption of charge independent hadronic forces, the ^3He - ^3H binding energy difference is solely due to direct and indirect electromagnetic phenomena. For a three-nucleon bound state wavefunction [Be-83] based on the Paris potential, this energy difference is underestimated indicating charge symmetry breaking in the hadronic nucleon-nucleon interaction. Corrections arising from the implicit inclusion of mesonic and internal nucleonic quark degrees of freedom have been investigated [Sa-81]. In this framework, besides the purely nucleonic configuration of classic nuclear structure, pionic and isobar degrees of freedom contribute to nuclear matter. Many theoretical efforts are at present centred on the problem of determining the nuclear structure effects due to the Δ isobar. Their size is not well determined and a systematic study of the dependence of these isobar effects on the parameters of the transition potential has not yet been completed. Some preliminary results for the

three-nucleon ground state are presented in [Sa-81] indicating an improvement of the binding energy value, ^3He charge form factor, and ^3He - ^3H binding energy difference. Although the improvement of the ^3He charge form factor indicates some change in the momentum distribution of nucleons in nuclei, this change is small. Therefore, the presence of the Δ isobar cannot in a simple way improve the predictions for quasi-elastic scattering.

The present study of the $^3\text{He}(p,2p)np$, $^3\text{He}(p,2p)d$ and $^3\text{He}(p,pd)p$ knock-out reactions at intermediate energies has the objective of adding more information for the solution of this intricate problem.

The $^3\text{He}(p,2p)np$ reaction has been studied in order to investigate two-nucleon correlations in ^3He . The two-nucleon component of the ^3He wavefunction can be directly extracted in plane wave impulse approximation. In a $(p,2p)$ experiment there is sufficient kinematic information to determine separately the vector momentum $P(\text{recoil})$ and total energy $E(\text{recoil})$ of the recoiling n - p pair (assuming that the incoming particle has interacted with only one nucleon). If the kinematics is chosen so that $P(\text{recoil}) = 0$, then $E(\text{recoil})$ can be used to calculate the relative momentum of the two nucleons in their own centre-of-mass system. In figure 1 the kinematics of the $^3\text{He}(p,2p)np$ reaction is shown. The requirement $P(\text{recoil}) = 0$ serves two functions: first, a small relative momentum between the spectator and the correlated pair means, in the quantum mechanical sense, that the two have a large spatial separation and are likely to be 'decoupled'; second, only in the limit $P(\text{recoil}) = 0$ can the relative momentum of the correlated pair be determined uniquely with the available kinematic information. In chapter

BEFORE COLLISION



AFTER COLLISION

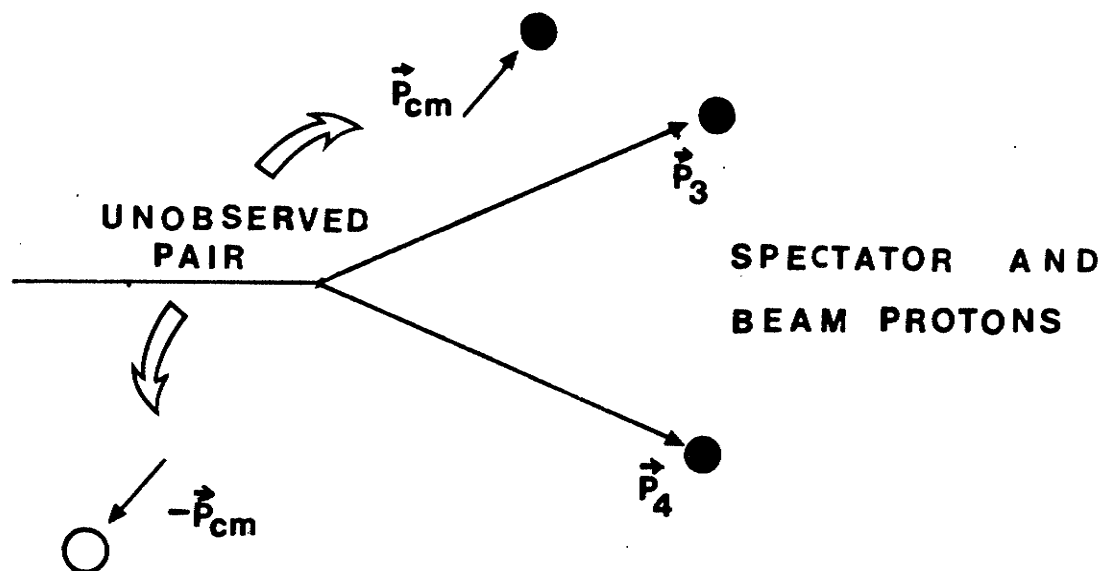


Fig. 1

5 the measurements of this reaction are described and the results are discussed and compared with the theoretical predictions.

The ${}^3\text{He}(p,2p)d$ and ${}^3\text{He}(p,pd)p$ reactions have been studied in an orthogonal way to the ${}^3\text{He}(p,2p)np$ reaction, i.e. E (recoil) was held fixed and the cross section was measured as a function of $P(\text{recoil})$. $P(\text{recoil})$ is equal to minus the relative momentum of the ejected particle before the interaction. In the framework of the PWIA the relative motion momentum distributions extracted from ${}^3\text{He}(p,2p)d$, ${}^3\text{He}(p,pd)p$, ${}^3\text{He}(e,e'p)d$ and ${}^3\text{He}(e,e'd)p$ are identical. In order to test the validity of the PWIA assumptions, the experimental relative motion momentum distributions from both ${}^3\text{He}(p,2p)d$ and ${}^3\text{He}(p,pd)p$ have been measured. The comparison of these two reactions is then an important tool in understanding the reaction model and the three-body nuclear wave function. Furthermore, the PWIA allows a direct comparison of the experimental momentum distribution with the spectral function. Although distortion effects cannot be completely neglected in the energy range under consideration, it is still interesting to see what one can learn from this simple picture. The kinematic conditions chosen for the present measurements resulted in previously unexplored high recoil momenta. A detailed description of the experimental technique and of the results of the ${}^3\text{He}(p,2p)d$ and ${}^3\text{He}(p,pd)p$ measurements is given in chapter 6.

CHAPTER II

EXPERIMENTAL APPARATUS

2.0 Overview

In the present chapter the main features of the experimental apparatus used in a study of knockout reactions from ^3He are described. The experiments were performed at beamline 4B at the TRIUMF cyclotron laboratory using a liquid ^3He target. The proton beam line used is described in brief in section 1 while the liquid ^3He target is described in section 2. The $^3\text{He}(p,2p)np$ reaction at 250 MeV was measured at the target location T1 of the beam line 4B. This set of measurements will be referred to as the T1 measurements in this chapter. The $^3\text{He}(p,2p)np$ reaction at 400 MeV, and the $^3\text{He}(p,2p)d$ and $^3\text{He}(p,pd)p$ reactions at 300 and 450 MeV were measured at the target location T2 of the same beam line. The latter set of measurements is referred to as the T2 measurements. For the T1 measurements, the detection system consisted of two identical counter telescopes which are described in section 3. For the T2 measurements, the detection system consisted of one or two counter telescopes (similar to the ones used for the T1 measurements) in coincidence with a magnetic spectrometer which is described in section 4. The electronics for the T1 measurements is presented in section 5. The electronics for the T2 measurements is presented in two sections: section 6 describes the magnetic spectrometer electronics and section 7 describes the counter telescope electronics. Section 8 contains a description of the pulser electronics used to measure data acquisition dead time. In

section 9 the polarimeter employed to determine the integrated total incident beam is described and in section 10 there is a description of the data acquisition system.

2.1 Proton beam line

The TRIUMF proton beam line used is shown schematically in figure 2. The main steps needed to tune the beam line are as follows. Firstly, the currents of the combination magnet, the bending magnets 4VB1 and 4VB2 and the vertical steering magnet 4VSM1 are adjusted to centre the beam on the X-Y beam profile monitors 4VM2 and 4VM3. Following this the currents of the doublet of quadrupole magnets 4BQ4 and 4BQ5 are adjusted to produce a vertical and horizontal waist at the target location 4BT1. To make sure the beam travels straight through the centre of the polarimeter and the T1 target, the beam is centred on the profile monitors 4BM4 (upstream of the polarimeter) and 4BM6 (downstream of the T1 target) by using the horizontal and vertical steering magnets 4BSM2 and 4BSM3 respectively. In the case of the T1 measurements the beam spot on a fluorescent screen at this target position is viewed with a closed-circuit TV monitor. Subsequently, the currents of the triplet of quadrupole magnets 4BQ6, 4BQ7 and 4BQ8 are adjusted to produce another vertical and horizontal waist at the target location 4BT2. The beam is centred on the beam profile monitors 4BM7 and 4BM8 (one upstream and another downstream of the T2 target) by adjusting the horizontal and

Fig. 2

vertical steering magnets 4BSM4 and 4BSM5 respectively. For the T2 measurements the beam spot on a fluorescent screen at the target centre is viewed again by a closed circuit TV. The tune was periodically checked throughout the experiments by reducing the current and inserting the beam profile monitors and the fluorescent screen.

2.2 Liquid ^3He target

A schematic representation of the cryostat is shown in figure 3. This cryostat consists of four principal components. They are: the liquid nitrogen jacket (at a temperature of 77^0K), the liquid helium reservoir (at 4.2^0K), the pumped liquid ^4He bath (at 1.6^0K), and the target cell (at 1.6^0K). These components are nested one within the other so that the outer vessel provides thermal isolation for the colder inner one. There are two independent vacuum systems: one which operates on the volume about the liquid nitrogen jacket and the helium reservoir and a second one which pumps on the space surrounding the pumped helium bath and the ^3He target cell.

The liquid helium reservoir holds 15 l of liquid helium and acts as a reservoir for the pumped liquid helium bath which has a volume of 1 l. A copper thermal radiation shield at the bottom of the reservoir protects the lower bath and the target cell against thermal radiation. The flow of liquid helium from the reservoir into the pumped helium bath is regulated by a needle valve. The pumped liquid helium bath hangs from a central tube through which it is pumped. The temperature of the pumped

Fig. 3 Schematic diagram of the liquid ^3He cryostat. Showing A - copper radiation shield, B - ^3He gas outlet, C - liquid ^4He reservoir, D - needle valve, E - ^3He condensing coils, F - target cell, G - tail section, H - dummy target cell, I - scintillating screen, J - liquid nitrogen radiation shield, K - liquid helium radiation shield, L - pumped liquid helium bath, M - ^3He gas inlet, N - liquid nitrogen jacket.

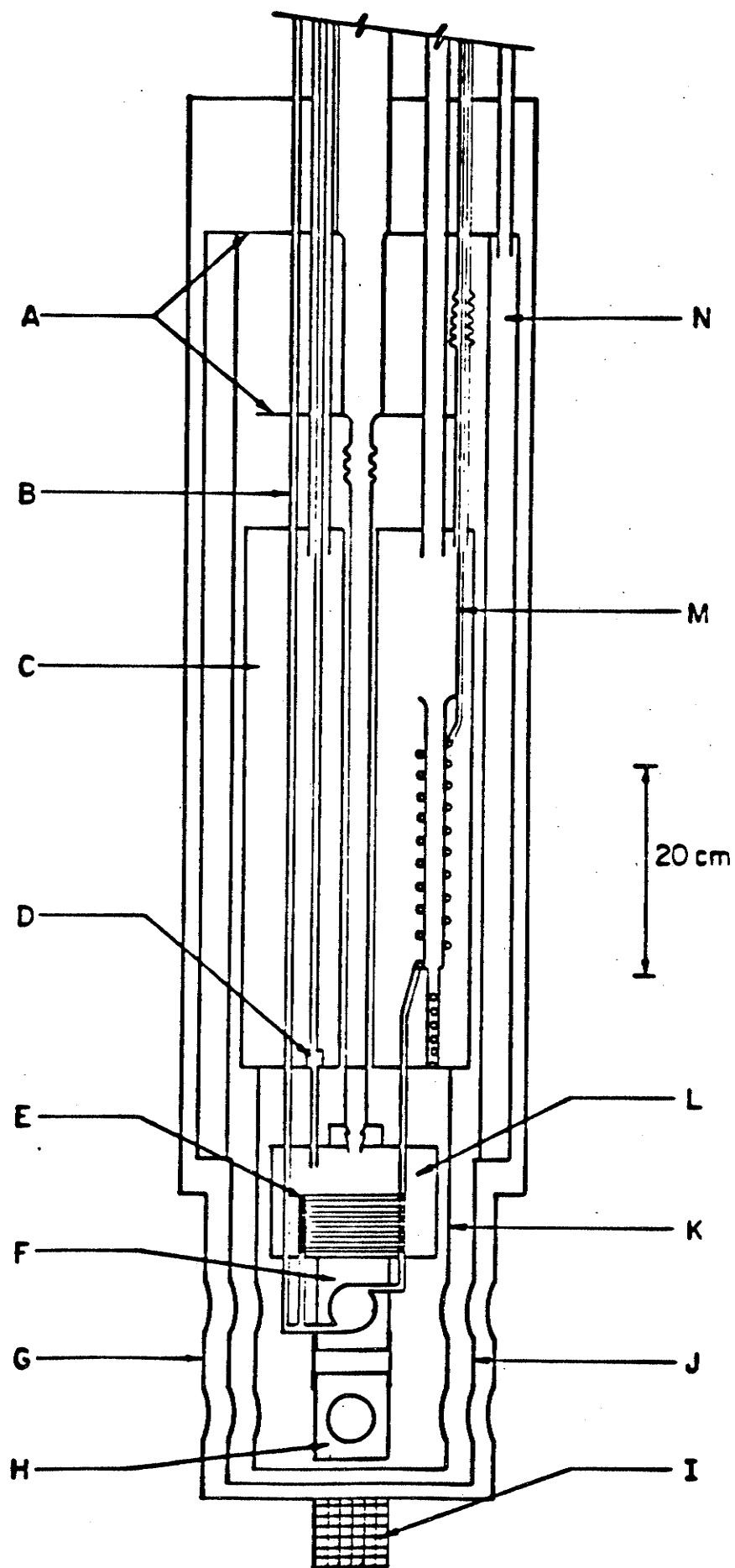


Fig. 3

liquid helium bath is maintained at approximately 1.6 K. At this temperature the density of liquid helium-3 varies only slowly. The helium-3 gas is liquefied while it flows through a copper condensing coil of 2 mm inner diameter submerged in the pumped bath. The ^3He target cell is suspended below the pumped bath using a copper bracket. The target cell has entrance and exit apertures of 4.4 cm in diameter covered with 0.025 mm thick Ni windows which are soldered onto the body of the target cell. Target cells with two thicknesses were used: a thickness of 1.63 cm for the T1 measurements and a thickness of 1.25 cm for the T2 measurements. Two stainless steel tubes connect the inside of the target cell with the condensing coil inside the pumped liquid helium bath. The target is gravity-filled. Another similar target cell is attached to the cryostat beneath the ^3He target cell and is used as a dummy target to perform background measurements. Hanging from the bottom of the cryostat enclosure is a CH_2 target and a fluorescent screen which are used for calibrations and beam tuning, respectively.

Gauges and regulators necessary to operate the target are located in the immediate vicinity and monitoring signals are also sent to the counting room. The vapour pressure of the pumped liquid helium bath is deduced from measurements taken with a thermocouple. A solid state pressure transducer monitors the pressure of the ^3He gas and controls the needle valve thus regulating the cell temperature. A multi-turn resistive potentiometer connected to the needle valve shaft provides digital read-out of the needle valve position. Two germanium resistors attached to the target cell permit a measurement of the cell temperature. An independent measurement of the cell temperature follows from the ^3He vapour pressure. The level of the liquid helium remaining in the main reservoir is

determined by passing a known current through a superconducting wire inserted in the reservoir. The voltage drop increases if an increasing portion of this resistor is above the level of the liquid and therefore gives a measurement of the helium level. The ^3He system is closed and the ^3He can be conserved in a contamination-free state for long periods of time. During the operation of the target, the ^3He gas is pumped through a liquid nitrogen cold trap to remove impurities.

The cryostat is equipped with a pneumatic lifting mechanism and with a rotation mechanism. A more complete description of the cryostat and of the target operation can be found in reference [Ha-81b].

2.3 Tl counter telescopes.

Figure 4 shows in schematic form the counter telescopes used for the $^3\text{He}(p,2p)np$ measurements at 250 MeV at the target location T1. Each telescope consisted of two plastic scintillator detectors PL1 and PL2, two multiwire proportional chambers (MWPC's) and a NaI(Tl) detector (12.5 cm in diameter by 15.2 cm thick). Each telescope was mounted on a movable boom pivoting about the scattering centre. A detailed description of the counter telescopes is presented in chapter 3 where results of the efficiency measurements are presented.

Fig. 4 Schematic diagram of the counter telescopes used at the target location T1.

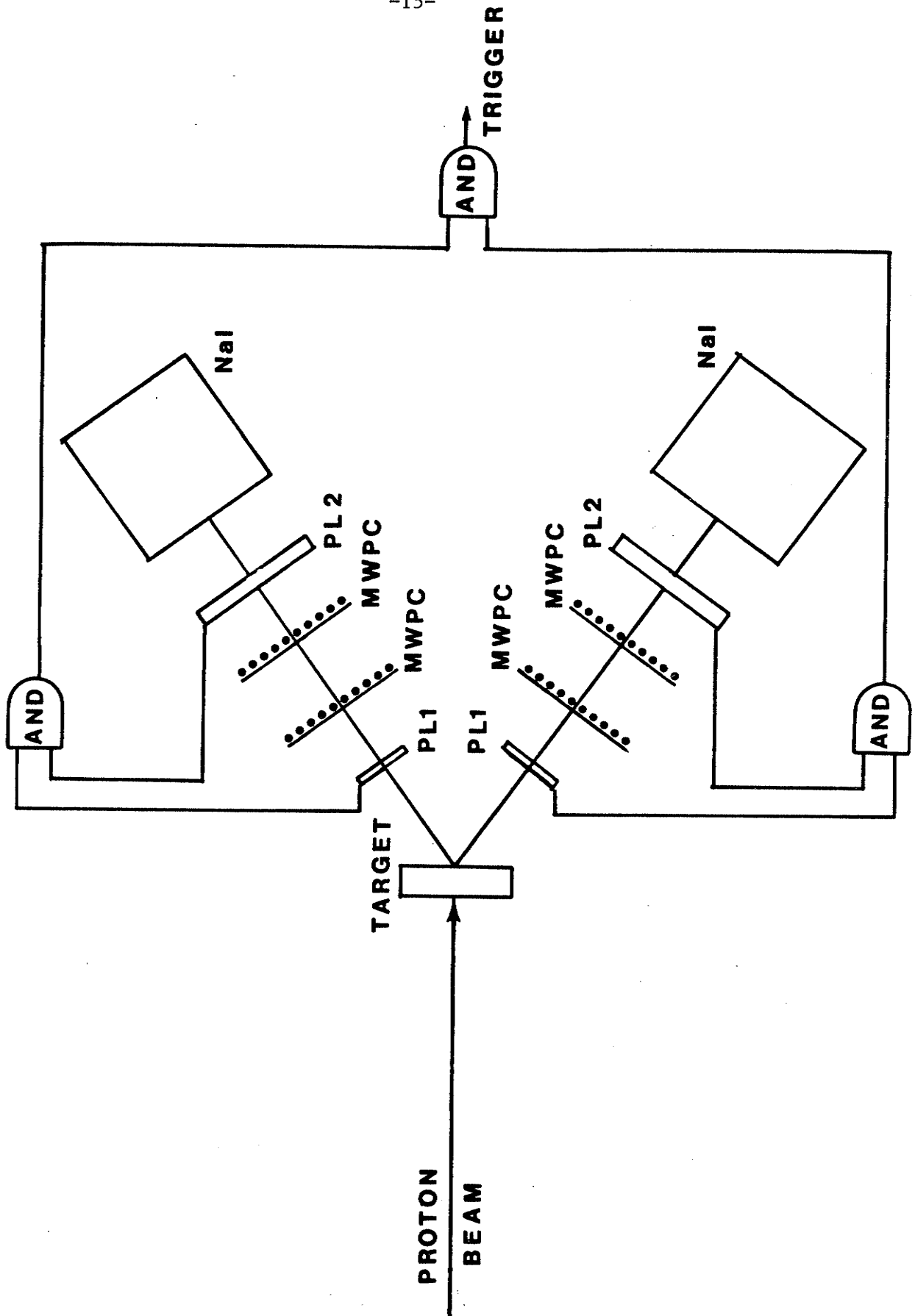


Fig. 4

2.4 The magnetic spectrometer

Figure 5 is a side view of the medium resolution magnetic spectrometer. It includes the optical elements, a quadrupole magnet followed by a dipole magnet, and the detector system consisting of MWPC's, and plastic scintillator detectors. The quadrupole magnet is usually set to give point-to-point focusing in the non-bend plane. The position of its front face can be varied between 1 and 2 m from the target centre. The dipole has a nominal 60° vertical bend angle, is strongly focusing in the bend plane, and produces an image of the target on the focal plane. This is achieved by properly selecting the ratio of the quadrupole and dipole magnetic fields. Two sets of X-Y MWPC's are positioned about the focal plane. The angle between the focal plane and the first MWPC at the exit of the dipole magnet is 66° (see figure 5). The two sets of MWPC's are labelled bottom and top, respectively. They are placed 1 m apart and determine the particle coordinates X_b , Y_b , X_t and Y_t . The coordinate system used with the spectrometer is indicated in the insert of figure 5. Two plastic scintillator detectors (2.5 cm thick) placed side by side follow the MWPC's. A thin plastic scintillator (0.08 cm thick) and X-Y MWPC are located next to the target before the quadrupole magnet at distances of 60 and 80 cm, respectively, from the target centre. The MWPC determines the coordinates X_0 and Y_0 and thus the direction of the particle before momentum analysis. Time-of-flight is measured between the thin plastic scintillator following the target and the plastic scintillators at the top of the spectrometer. The flight path is 11 m. Time-of-flight together with the particle momentum allows particle identification. The focal plane acceptance is flat to

Fig. 5 Schematic diagram of the magnetic spectrometer. a - target position, b - ΔE scintillator detector, c - X_0 - Y_0 MWPC, d - quadrupole magnet, e - dipole magnet, f,g- X_b - Y_b and X_t - Y_t MWPC's, h - E scintillator detector.

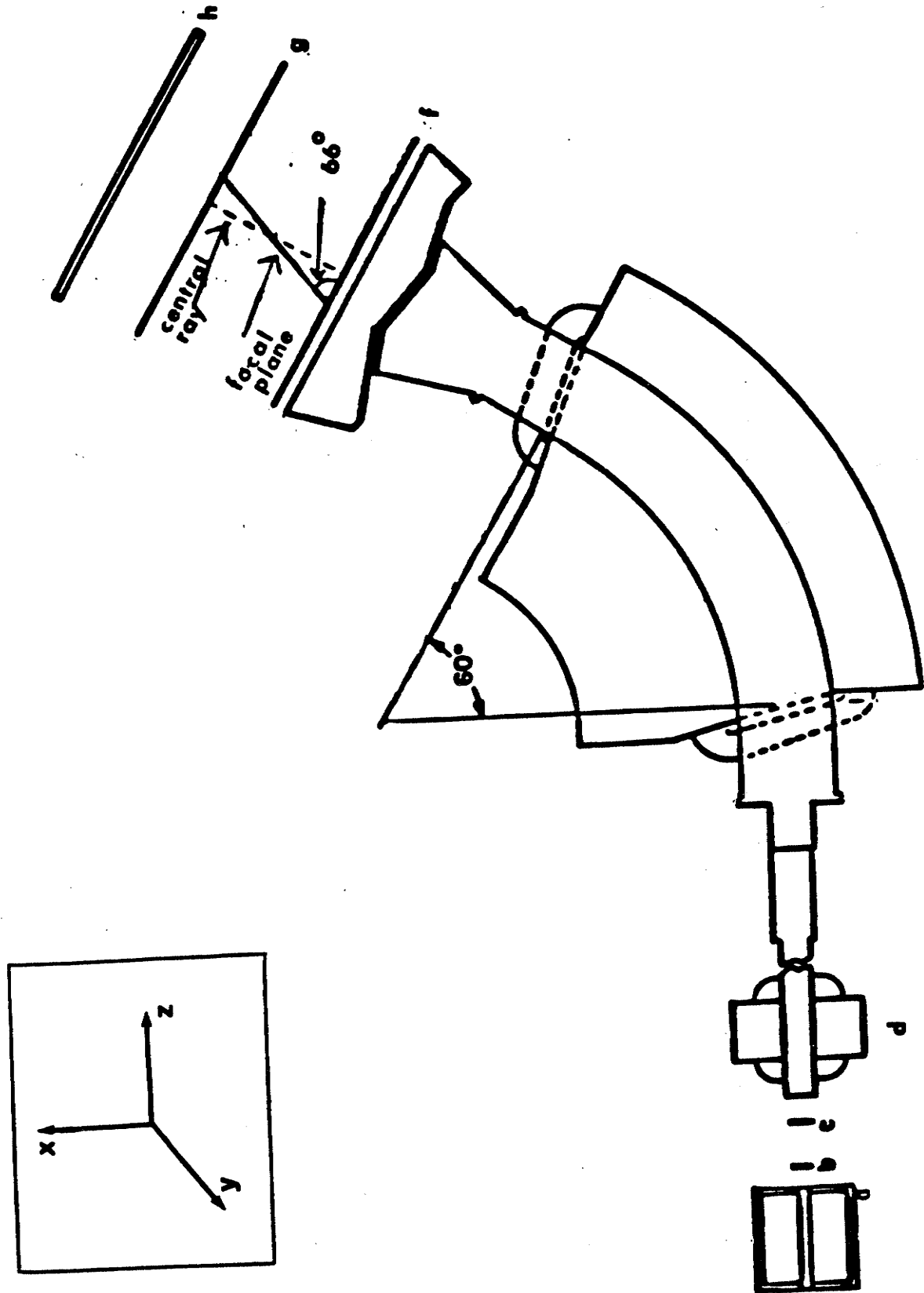


Fig. 5

within a few per cent over the range -10% to $+12\%$ of the central ray momentum only when the solid angle defining cuts are sufficiently restrictive (for the present experiments the solid angle was 1.2 msr).

The energy resolution (which is a combination of spectrometer resolution, proton beam energy spread, and broadening due to the target and other absorbing material) is typically 0.25% .

The current setting of the quadrupole and dipole magnets depends on the particle momentum and the configuration of the quadrupole magnet. The magnetic field of the dipole is measured with an NMR probe inserted between the pole faces of the magnet. The entire magnetic spectrometer assembly is mounted on a large support boom which can be remotely rotated around the 4BT2 target centre. The spectrometer angle can be set with an accuracy of $\pm 0.02^\circ$.

2.5 Electronics for the T1 measurements

A fourfold coincidence between the signals of the plastic scintillator detectors of the two counter telescopes (see figure 4) supplies a signal to hold the information of the MWPC's. A latch level is set to disable any further coincidence signals while the current event is being processed. This is the latch at the OR gate called EVENT FAST in figure 6. This part of the fast logic including the MWPC latches, was located near the detectors in the experimental area. The rest of the electronics, including the CAMAC electronics, was located in the counting room (figures 7 and 8). An event is accepted whenever the signal

Fig. 6 Block diagram of the T1 electronics located in the experimental area.

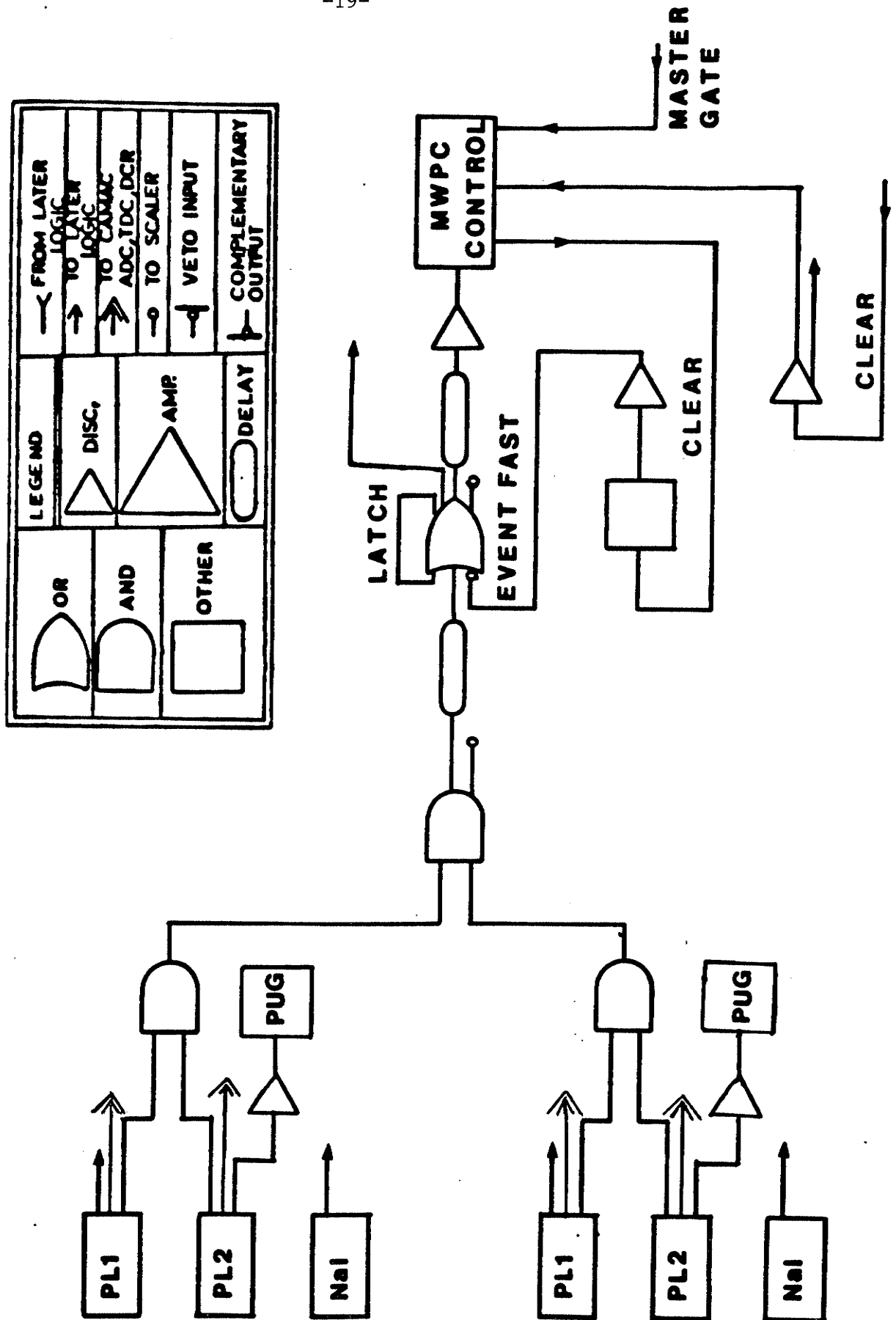


Fig. 6

Fig. 7 Block diagram of the first portion of the Tl electronics
located in the counting room.

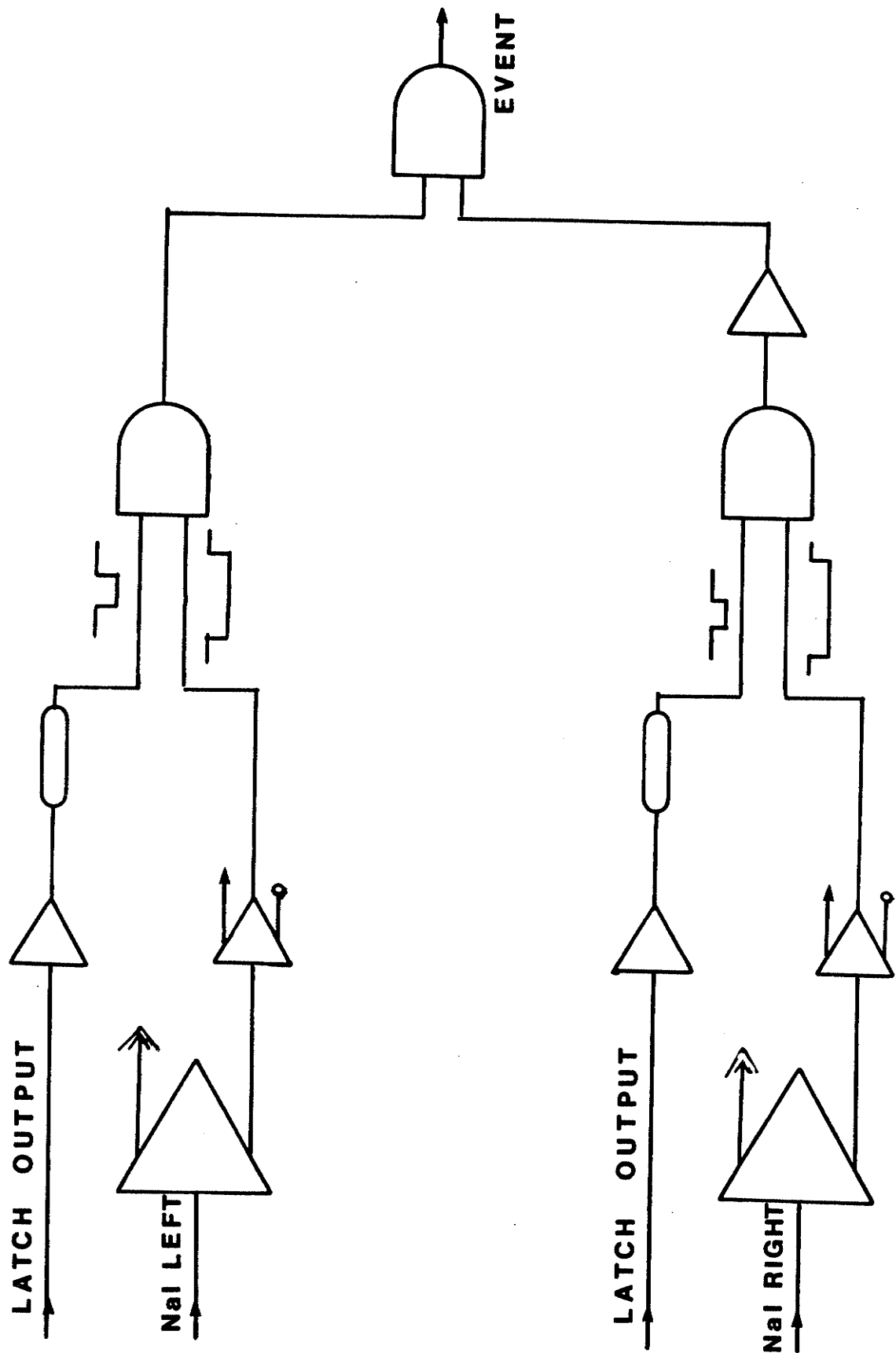


Fig. 7

of the fourfold coincidence is in time with each of the signals of the NaI(Tl) detectors (figure 7 shows the relative timing) and the computer is not busy. The final trigger is labelled MASTERGATE and is shown in figure 8. Whenever a MASTERGATE signal is generated, a latch level is set to disable the coincidence unit and a gate signal is sent to the multi-input analogue to digital converters (ADC's) (one for the plastic scintillator signals and one for the NaI(Tl) detector signals). The start signals for the left and right time to digital converters (TDC's) (indicated as LEFT and RIGHT RETIME in figure 8) are formed by requiring a coincidence between the MASTERGATE and the second plastic scintillator of each of the counter telescopes (PL2 and PR2, respectively). The relative timing between the two plastic scintillators of each arm is recorded together with the relative timing between left and right counter telescopes and the timing of each arm with respect to the cyclotron RF. The MWPC's were then read into the computer via a CAMAC input register together with the contents of the ADC's, TDC's and a digital coincidence register (DCR). The DCR bit configuration allows recognition of pileup events in the NaI(Tl) detectors and to distinguish between a beam-induced event and a pulser generated event. The pileup gate unit is indicated in figure 6 with PUG. The resolution of the pileup gate was set at 300 ns on the signals from the second plastic scintillator detectors. At the end of the read cycle, a clear signal (EVENT DONE in figure 8) resets all CAMAC modules and the latches. An internal reset, 1 μ s after the fourfold coincidence signal of the scintillator detectors, is generated by the MWPC controller in case the trigger requirement is not satisfied. To measure the dead time of the electronics and the data acquisition computer, events were simulated by a pulse generator using light

Fig. 8 Block diagram of the second portion of the T1 electronics
located in the counting room.

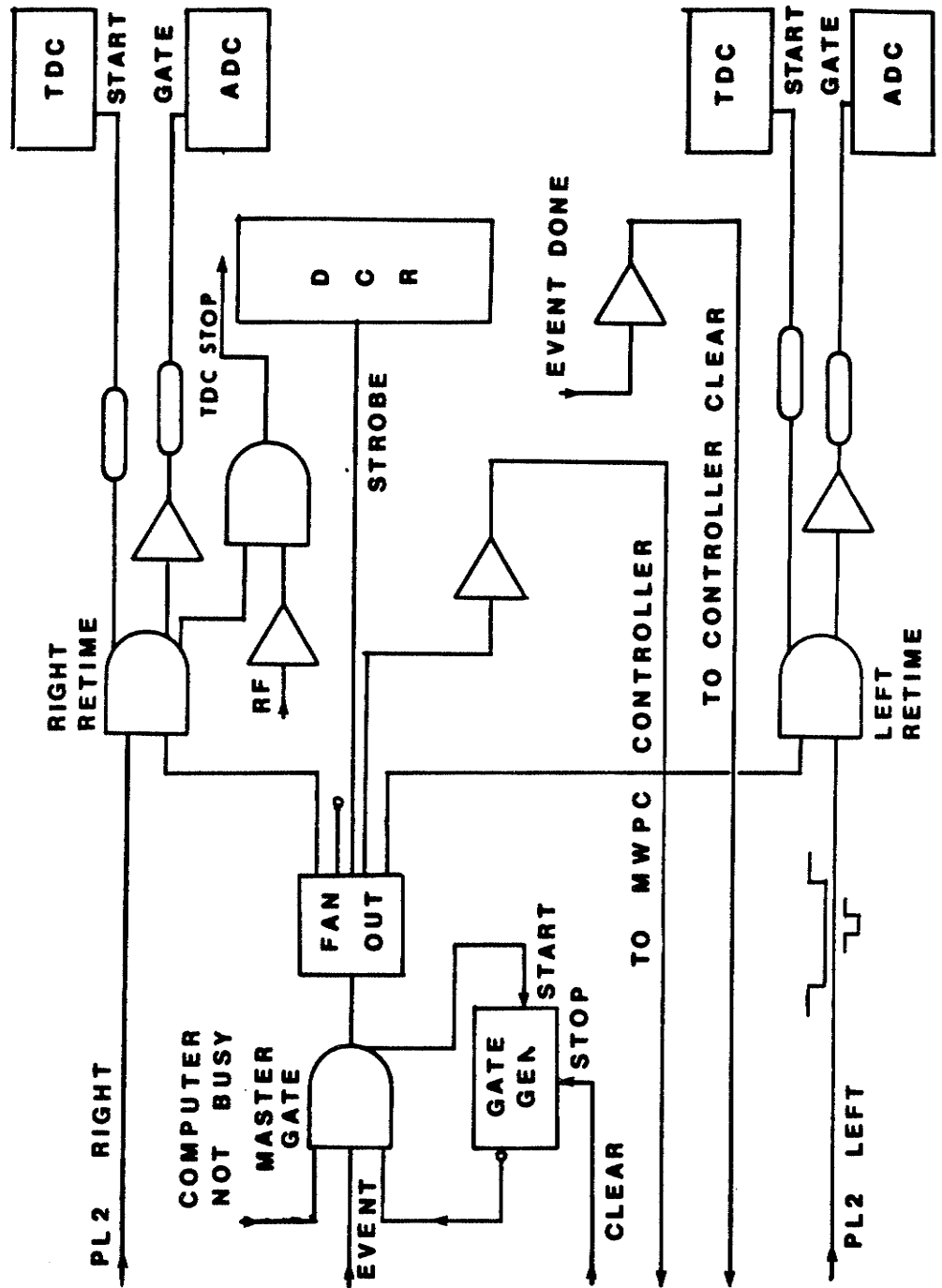


Fig. 8

emitting diodes (LED's) mounted on each of the detectors. Such pulser events were recorded with a frequency of about one in 20 beam events. At the beginning and at the end of each run (corresponding to approximately 100,000 events) the CAMAC scalers were recorded on magnetic tape. Singles as well as various coincidences were recorded together with the polarimeter and pulse generator numbers of counts.

2.6 Magnetic spectrometer electronics

The presence of a particle passing through the spectrometer is indicated by a coincidence between a signal from the thin plastic scintillator with a signal from either plastic scintillator downstream of the spectrometer. The electronics of the thin plastic scintillator detector (referred to as ΔE detector) is presented in figure 9 while the electronics of the two plastic scintillator detectors at the top of the spectrometer (referred to as L and R plastic scintillators) is shown in figure 10.

The output of the coincidence gate called MASTERGATE (shown in figure 11 and described later) generates the gating signals for the ADC's, the strobe signals for the DCR and the MWPC controller, and the start signals for the TDC's. The information stored in these modules is only recorded on magnetic tape if a second particle is detected in the counter telescopes. If this is not the case, a reset is generated and the spectrometer electronics is ready to accept another event. This is

Fig. 9 ΔE scintillator detector electronics.

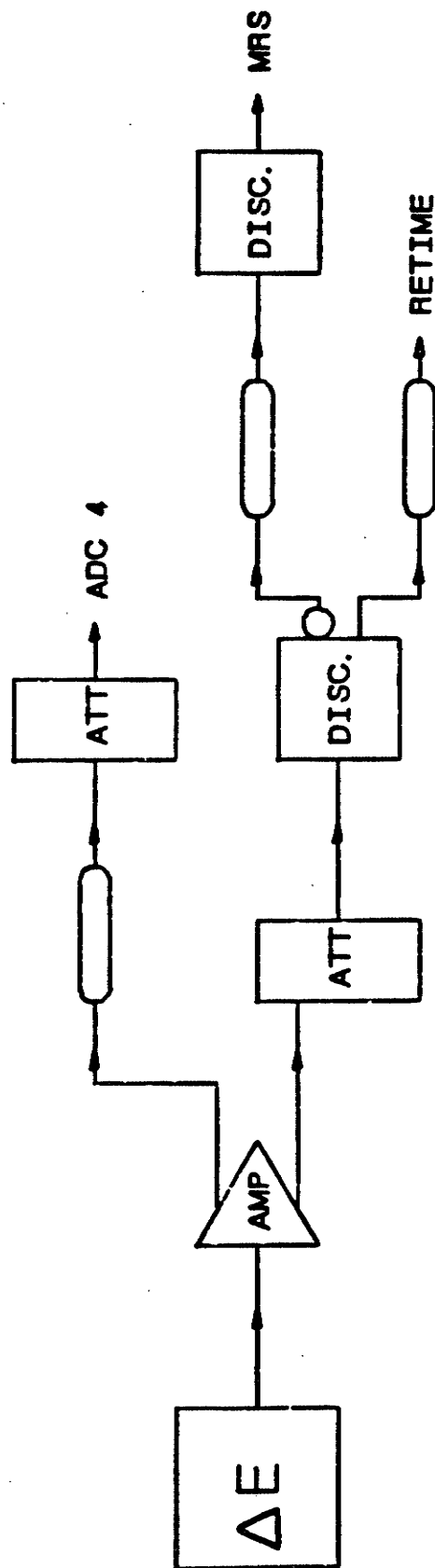


Fig. 9

the FAST CLEAR signal of figure 11. The pulse heights of the plastic scintillator detector signals were analysed using 10 bit ADC's. The plastic scintillator detector signals are labelled ΔE , and BL (left-bottom), TL (left-top), BR (right-bottom) and TR (right-top). The signals BL, TL, BR, TR are also summed and recorded in a further ADC channel (see figure 10). The signals BL and TL as well as BR and TR are processed by a meantimer. In this way, the recorded time is independent of the particle position in either the left or the right plastic scintillator panels. The OR signal labelled "tL+tR" in coincidence with the MASTERGATE output, generates a start signal for the TDC's of the spectrometer electronics. Stop signals to the TDC's are supplied by the outputs of the discriminators on the various scintillator signals and by the cyclotron RF signal. Time-of-flight between the ΔE scintillator and either the left or right scintillator panels at the top of the spectrometer is used for particle identification. The time difference between the signals from either end of the left and right scintillator panels locates the particle along the scintillator. A DCR unit records which plastic scintillator panel supplied the start for the TDC's. It also labels the pulser events as in the TL measurements. The MASTERGATE (see figure 11) is a fivefold coincidence unit. A latch level is set to disable the coincidence while the event is being processed. The inputs to the MASTERGATE are the plastic scintillator signal ΔE , the OR signal of the meantimer outputs (labelled "tL+tR"), and a signal from the MWPC controller indicating the presence of an event in at least one of the planes of the MWPC's. It also includes the summed output on the four scintillator panel signals BL, TL, BR and TR. The last signal is branched into two parts. One corresponds to signals which pass a lower

Fig. 10 E scintillator detector electronics.

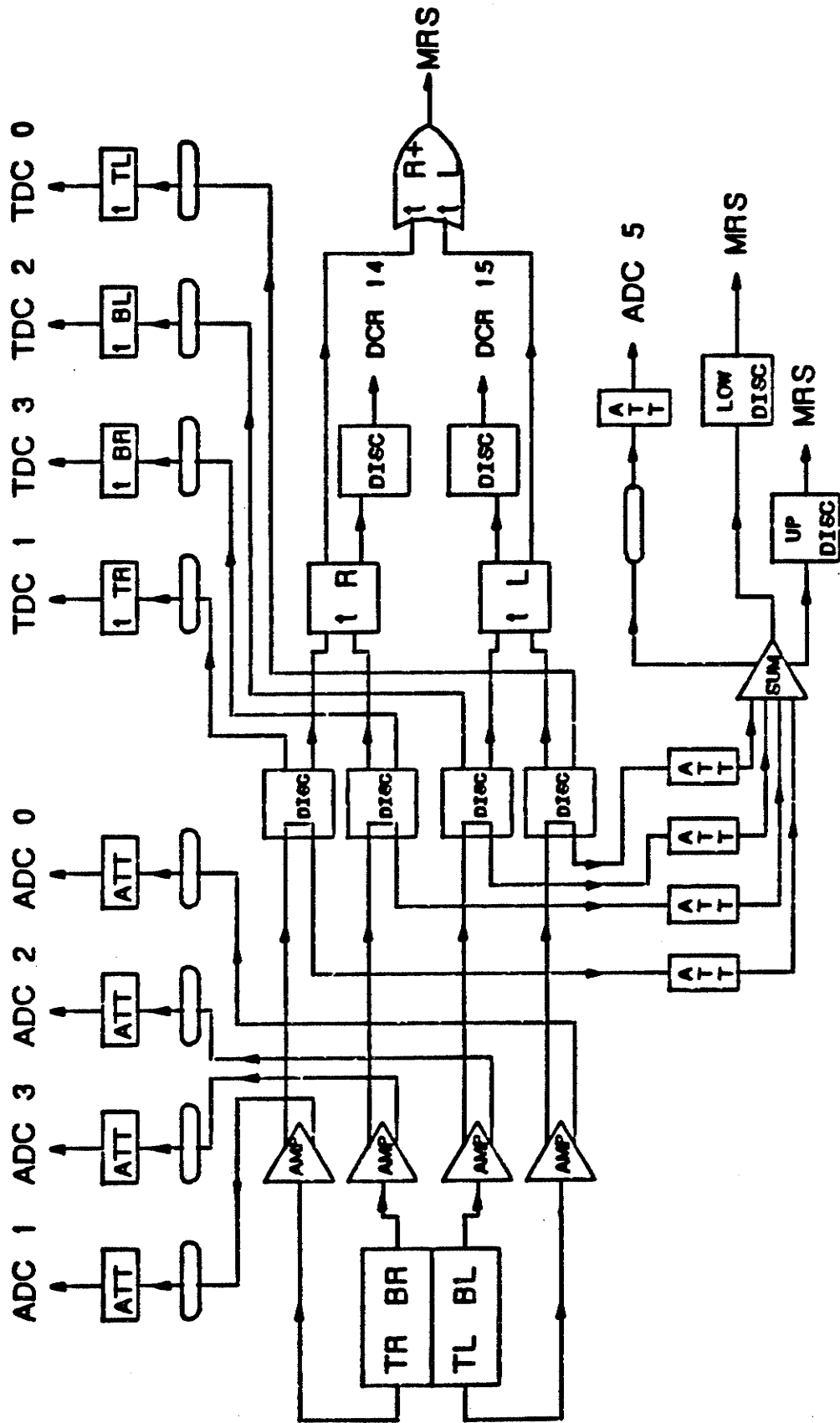


Fig. 10

Fig. 11 Magnetic spectrometer master gate and event logic electronics.

level discriminator while the other one inhibits signals surpassing an upper level discriminator. The threshold of these discriminators is set remotely via the computer. The last requirement permits the selection of particles in a desired energy range.

2.7 Counter telescope electronics for the T2 measurements.

Each counter telescope used for the T2 measurements consisted of a delayline MWPC, a plastic scintillator veto detector, a plastic scintillator detector and a NaI(Tl) detector. Figure 12 shows one of the two identical counter telescopes. It indicates how the trigger signal is formed (labelled RHS trigger in the figure because the counter telescopes were positioned at the right hand side of the incident beam) and the signals sent to the ADC's, the TDC's stops and the DCR. The trigger for the right-hand-side electronics is an OR between the signals generated from an anticoincidence between the plastic scintillator detector and the veto detector of each counter telescope. A coincidence between the signal of this OR gate and the output signal of the front plastic scintillator ΔE of the magnetic spectrometer supplies a gate for the ADC's, a strobe for the DCR's, as well as the start for the TDC's (whenever the computer is not busy). A dead time unit (called latch in figure 13) is immediately enabled after forming the coincidence signal, preventing another event from being processed. The pulse heights of the plastic scintillator and NaI(Tl) signals of each counter telescope are analysed using two ADC channels. One TDC unit records the signals from the delaylines of the

Fig. 12 Electronics of the counter telescopes used at T2 (part 1).

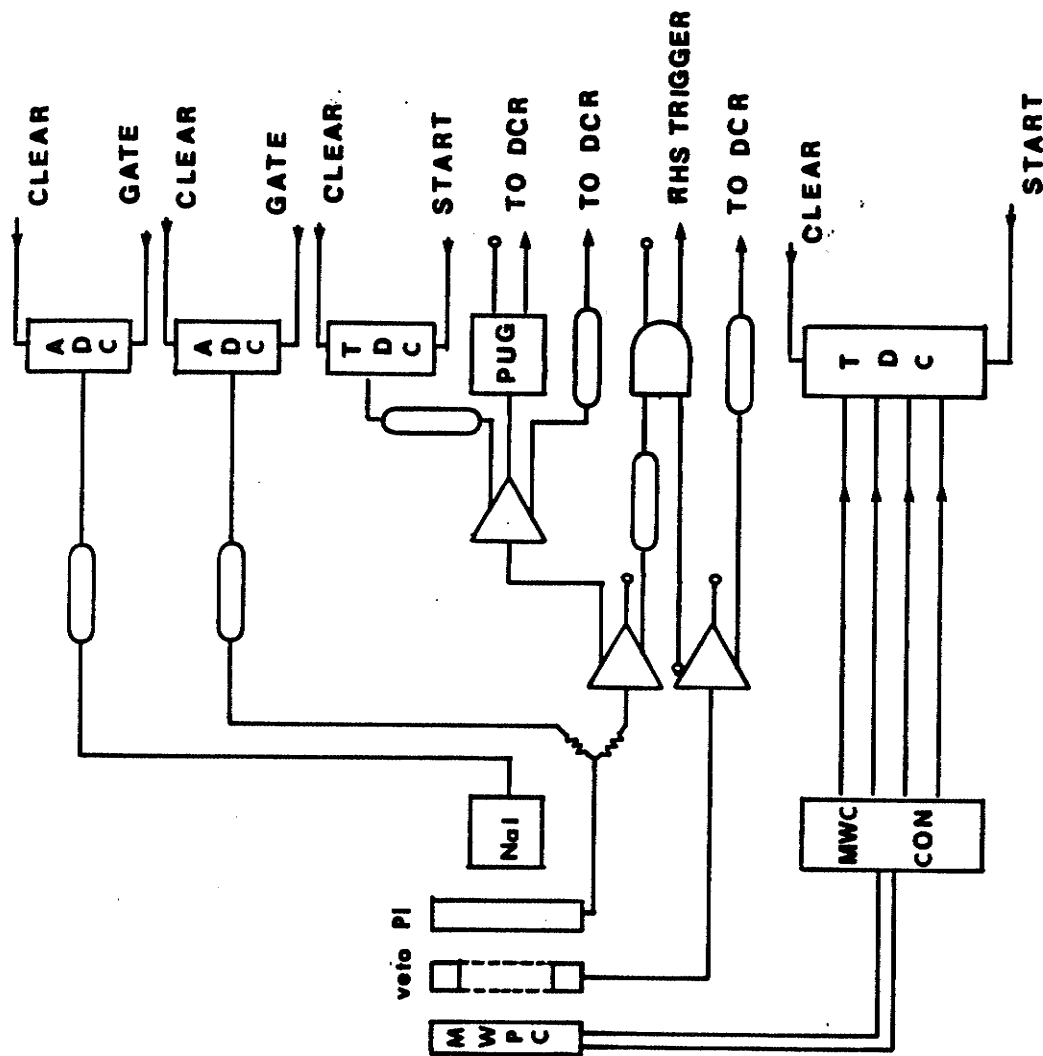


Fig. 12

Fig. 13 Electronics of the counter telescopes used at T2 (part 2).

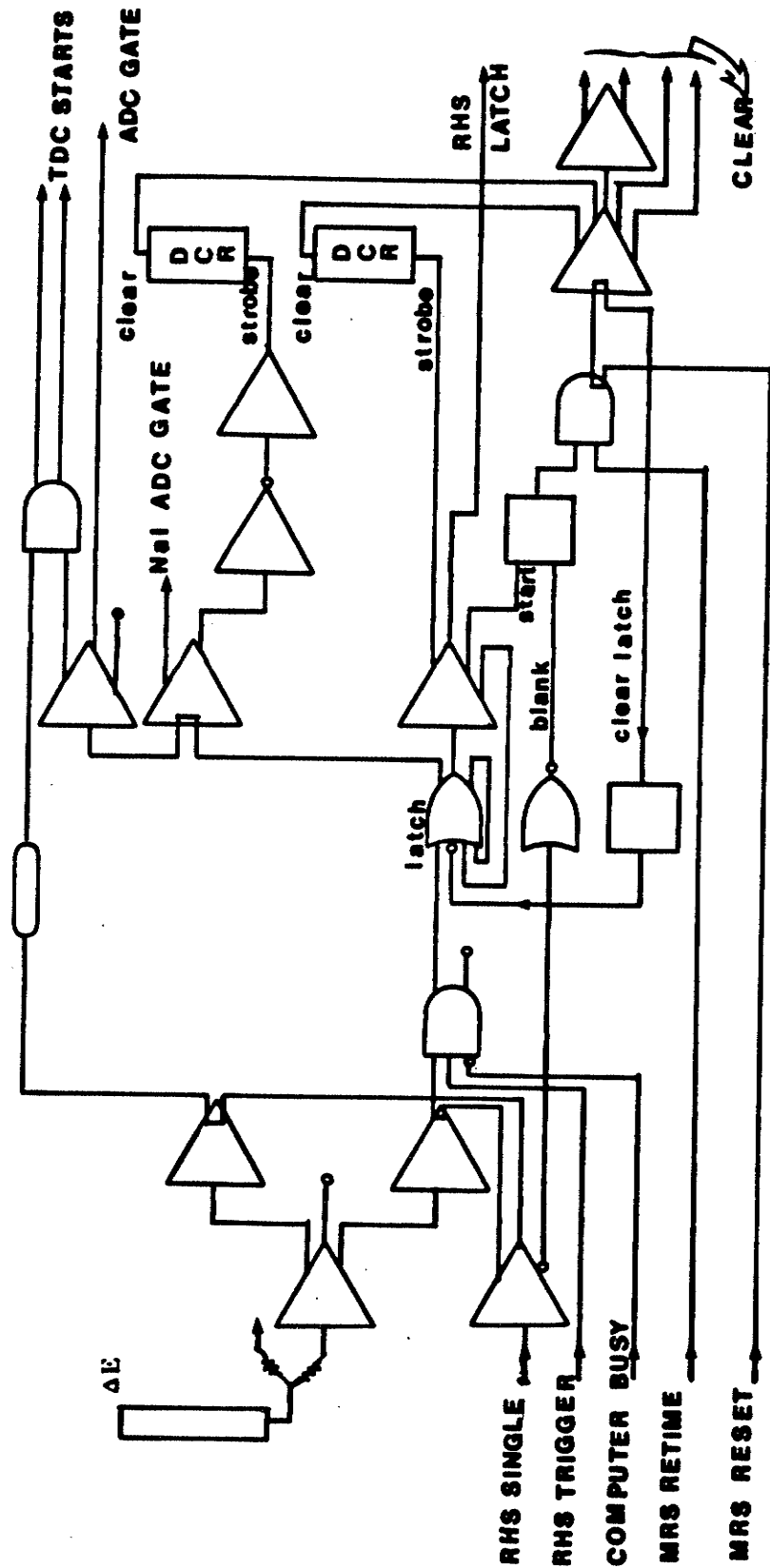


Fig. 13

MWPC's (four channels for each counter telescope). A second TDC measures the time between a signal in the ΔE plastic scintillator of the magnetic spectrometer and the signals of the plastic scintillator of each of the counter telescopes and also the RF signals. As in the Tl measurements, a pulser is used to measure the dead time of the electronics and data acquisition system. The RHS electronics can also be triggered without requiring a particle in the magnetic spectrometer through the line called RHS SINGLE (indicated in figure 13). This is used for test purposes only. If the coincidence requirement between the detector signals on both sides was not satisfied a FAST CLEAR signal cleared all the CAMAC units and latches. The same takes place after recording the events on magnetic tape. In the latter case, the clear signal originates in the computer and follows an output register located in the magnetic spectrometer CAMAC crate.

2.8 Pulser electronics.

Measurements of absolute differential cross sections require precise knowledge of the electronics and data acquisition dead time. This quantity is measured by simulating events with LED's driven by a pulse generator. An LED is mounted on each of the plastic scintillator light guides and the NaI(Tl) detectors. The electronics used to trigger the LED's is shown in figure 14. Pulses from a pulser module were shaped to generate light signals to match as best as possible the time distribution of each type of scintillator material. Pulser signals are

Fig. 14 Block diagram of the pulser electronics.

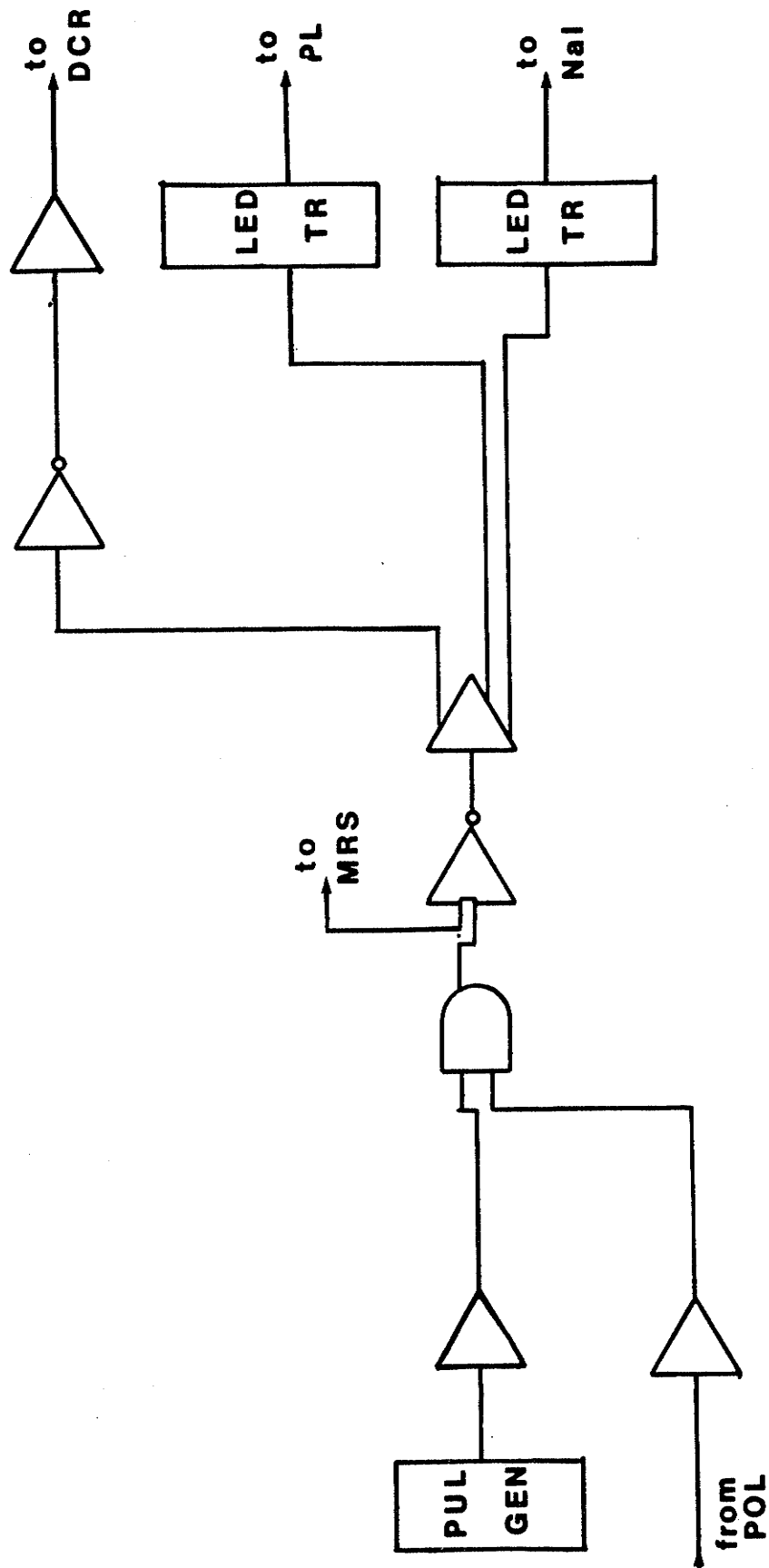


Fig. 14

also fed into one latch of the MWPC's. The signals from the pulser are set in random coincidence with the sum of the left and right detectors of the polarimeter. The pulser rates were consequently proportional to the incident beam current. The ratio of the recorded pulser events to the generated pulser events yielded the electronics and computer dead time. The software could identify pulser events by examining the appropriate bit in the DCR word.

2.9 The polarimeter

The integrated beam current is determined by using a polarimeter located upstream of the T1 target position. The polarimeter measures elastic proton-proton scattering at left-right symmetric angles. The scattered protons are observed in two forward telescopes set at 17° with respect to the incident beam. The target is a CH₂ foil located in a scattering chamber together with the two plastic scintillators which detect the recoil protons (L3 and R3 in figure 15). The scattering angle of 17° was chosen because at this angle the p-p differential cross section is relatively flat and the analysing power has a maximum in the energy range of 200 to 500 MeV. Each forward angle telescope consists of two plastic scintillators (L1, L2 and R1, R2 for the left and right telescopes, respectively). The forward angle telescopes subtend a solid angle independent of the lateral beam position on target. This was achieved by rotating the scintillators, L1 and R1 so

Fig. 15 Block diagram of the proton polarimeter electronics.

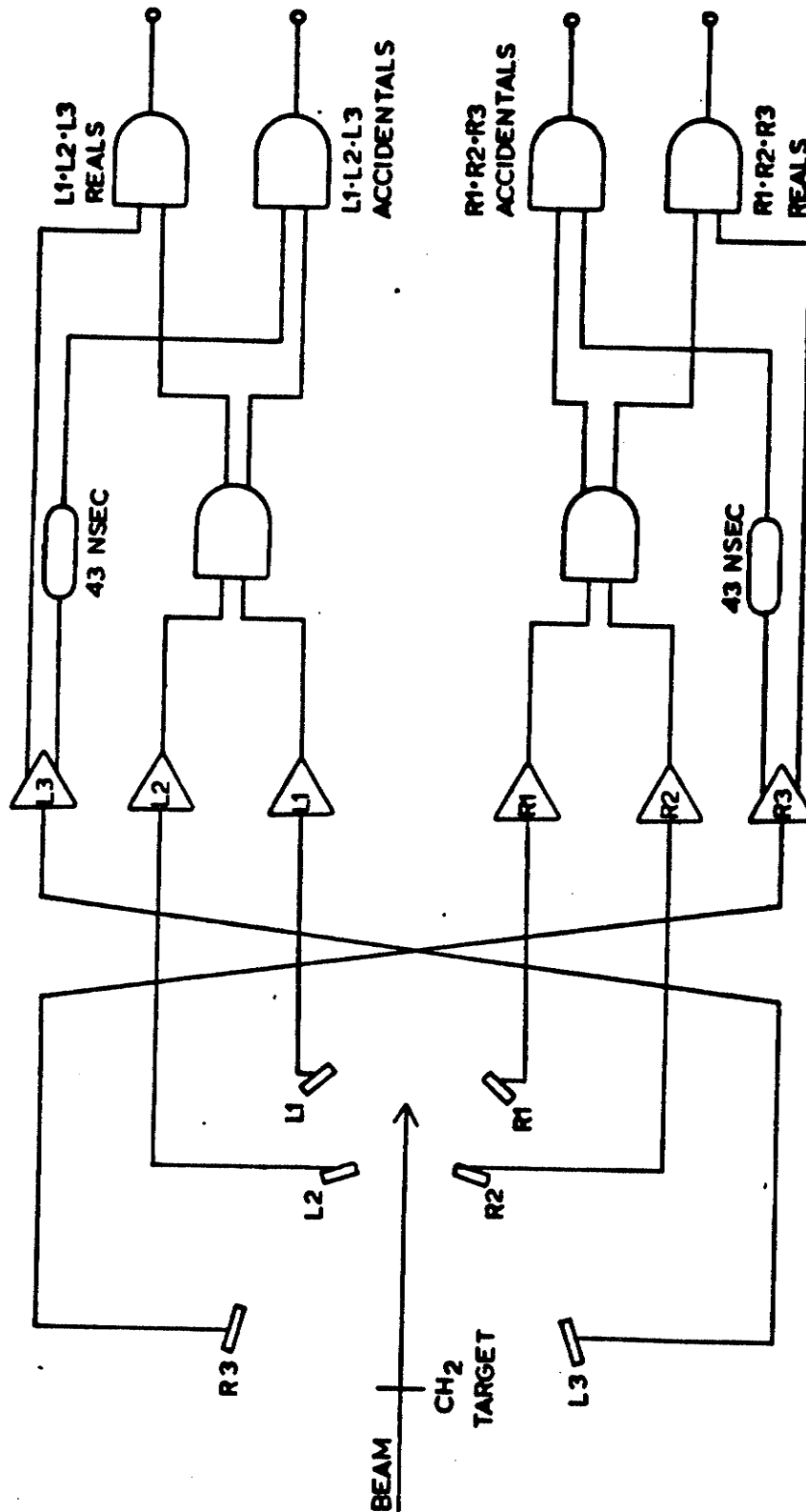


Fig. 15

that they point to a position downstream from the polarimeter target. Figure 15 shows the electronics with the polarimeter. It includes two triple coincidences $L1*L2*L3$ and $R1*R2*R3$. Accidental coincidences are obtained by delaying $R3$ and $L3$ by 43 ns and forming another set of triple coincidences.

Typical accidental coincidences were less than 1% of the real coincidences and only occasionally were accidental coincidences up to 2%. A remote controlled polarimeter target wheel was used to change periodically to a carbon foil, so that contributions from $C(p,2p)$ could be measured under identical beam conditions and appropriate corrections be made.

2.10 Data acquisition system

The data acquisition system used consisted of a HONEYWELL H316 minicomputer interfaced to three CAMAC crates. The general structure and operation of the data acquisition program HONDA are described in several TRIUMF internal reports (the most recent is [Hu-81]). This program is capable of reading various parameters generated by the electronics system via CAMAC interface, of writing the information event-by-event onto magnetic tape, and of selecting and storing portions of the data in the computer memory. The logic operations which can be performed on these stored data produce and display spectra under a series of constraints or cuts. Such spectra were essential for checking electronics and data acquisition.

CHAPTER III

DATA ANALYSIS

3.0 Overview

The procedure followed for the reduction of the $^3\text{He}(p,2p)np$ and $^3\text{He}(p,pd)p$ data is presented and discussed here. An outline of the $^3\text{He}(p,2p)d$ data reduction, performed at California State University at Los Angeles, is also given. A more complete description of that part of the analysis is given in reference [Kr-83]. Section 3.1 describes how the experimental yields of the reaction studied were extracted. Section 3.2 describes how correction factors, differential cross sections, and uncertainties were obtained.

3.1 Data reduction

The $^3\text{He}(p,2p)np$ and $^3\text{He}(p,pd)p$ data were analysed using the computer code KIOWA, a versatile data reduction program which was adapted to meet the needs of the present experiments. The analysis utilized the AMDHAL 470/V7 computer at the University of Manitoba and the VAX/780 computer at TRIUMF.

KIOWA is a data summarizing computer program which sorts and plots data stored on magnetic tape or disk file. The version used was modified to read the unprocessed data tapes written by the HONDA

acquisition program and to rewrite the data in a form compatible with KIOWA and the two computers used. In addition to the subroutines handling the standard event cuts, new subroutines were written to produce the computations needed for the data reduction of the present experiment. These subroutines deal primarily with the energy corrections for absorbers, energy calibrations, and missing energy or missing mass calculations.

First the NaI(Tl) counter telescope energy calibration and efficiency data were analysed. These measurements consisted of a set of proton-proton scattering data from a CH₂ target. The proton energies deposited in the NaI(Tl) detectors are known from kinematics corrected for energy loss in the absorbers. The description of the analysis of the energy calibration and efficiency measurement data is given in chapter 4 where the results are also presented and discussed.

Histograms and scatterplots of experimental and calculated parameters were constructed in the first instance without any stringent requirements. This preliminary examination of the data allowed the selection of the cuts necessary for the calculation of the yields of the reactions studied. The scatterplot, which was examined in all the measurements involving the magnetic spectrometer, is the time-of-flight through the spectrometer (labelled TΔE) versus the energy deposited in the plastic scintillator at the exit of the spectrometer (labelled E). This spectrum was used to determine the cuts on E and TΔE which identify either protons (for the (p,2p) measurements) or deuterons (for the (p,pd)p measurements). A TΔE versus E two dimensional spectrum for the ³He(p,pd)p measurements is given in figure 16.

Fig. 16 Two dimensional histogram of the time-of-flight through the magnetic spectrometer TAE versus energy in the plastic scintillator E. The arrows indicate the cuts set in further analysis to isolate the events of interest from accidental events (separated by 43 ns).

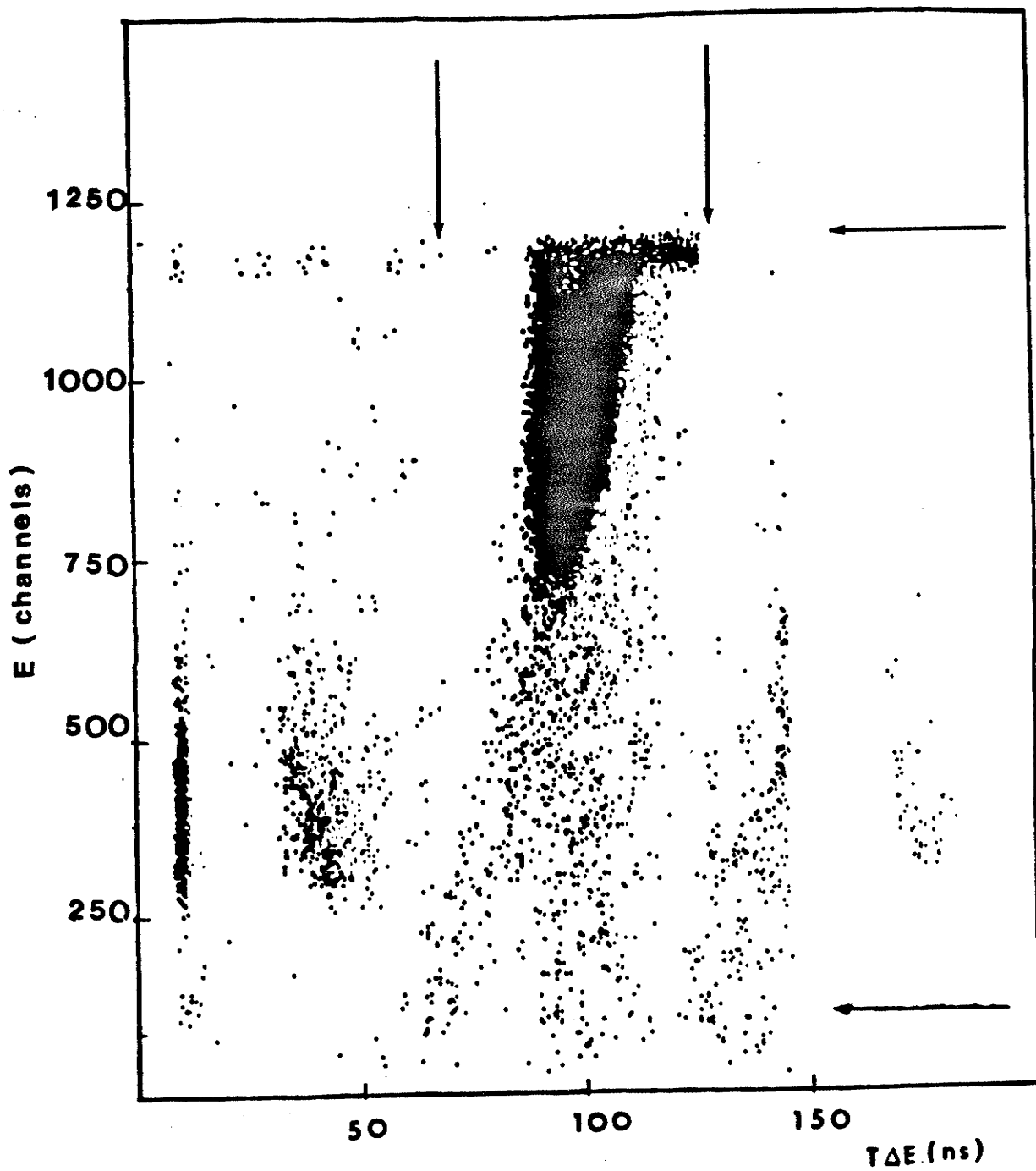


Fig. 16

In a subsequent examination of the data, events were rejected from further analysis for any of the following reasons:

- 1) Any one of the MWPC planes had a missing wire-coordinate or hits corresponding to nonadjacent wires firing in a single plane with a gap greater than one wire. In other words, events with more than one wire struck (with a gap of at most one wire) in a single MWPC plane were accepted. This choice resulted to be a good compromise to optimize both spatial resolution and efficiency.
- 2) Pile-up occurred in the NaI(Tl) detector. A pile-up event is an event which occurred within 300 ns from the previous one.
- 3) A particle entered the NaI(Tl) detectors at a distance larger than the radius defining the flat efficiency region. The cut corresponding to this radius defined the solid angle acceptance for the NaI(Tl) counter telescope and the radius depends on the energy of the detected protons. A 4.5 cm radius was chosen for the $^3\text{He}(p,2p)np$ data and a 3 cm radius for the $^3\text{He}(p,pd)p$ data. These values were taken from the efficiency measurements as a function of radial distance presented in chapter 4.
- 4) A particle entered the magnetic spectrometer outside the solid angle corresponding to the flat efficiency region in the focal plane. The value for the solid angle used is 1.2 msr.

The solid angle defining cuts on the X_0 and Y_0 planes of the MWPC at the entrance of the spectrometer were determined by examining the scatterplots of X_0 versus Y_0 and of the focal plane coordinate X_F versus X_0 . The focal plane coordinate X_F is calculated as a linear combination of the X_b and X_t coordinates (from the two MWPC's positioned about the focal plane as previously described). The values of

Fig. 17 Two dimensional representation of counts in the $X_0 - Y_0$ plane. X_0 , Y_0 are the coordinates of the MWPC at the entrance of the magnetic spectrometer. The arrows indicate the cuts set in the further analysis.

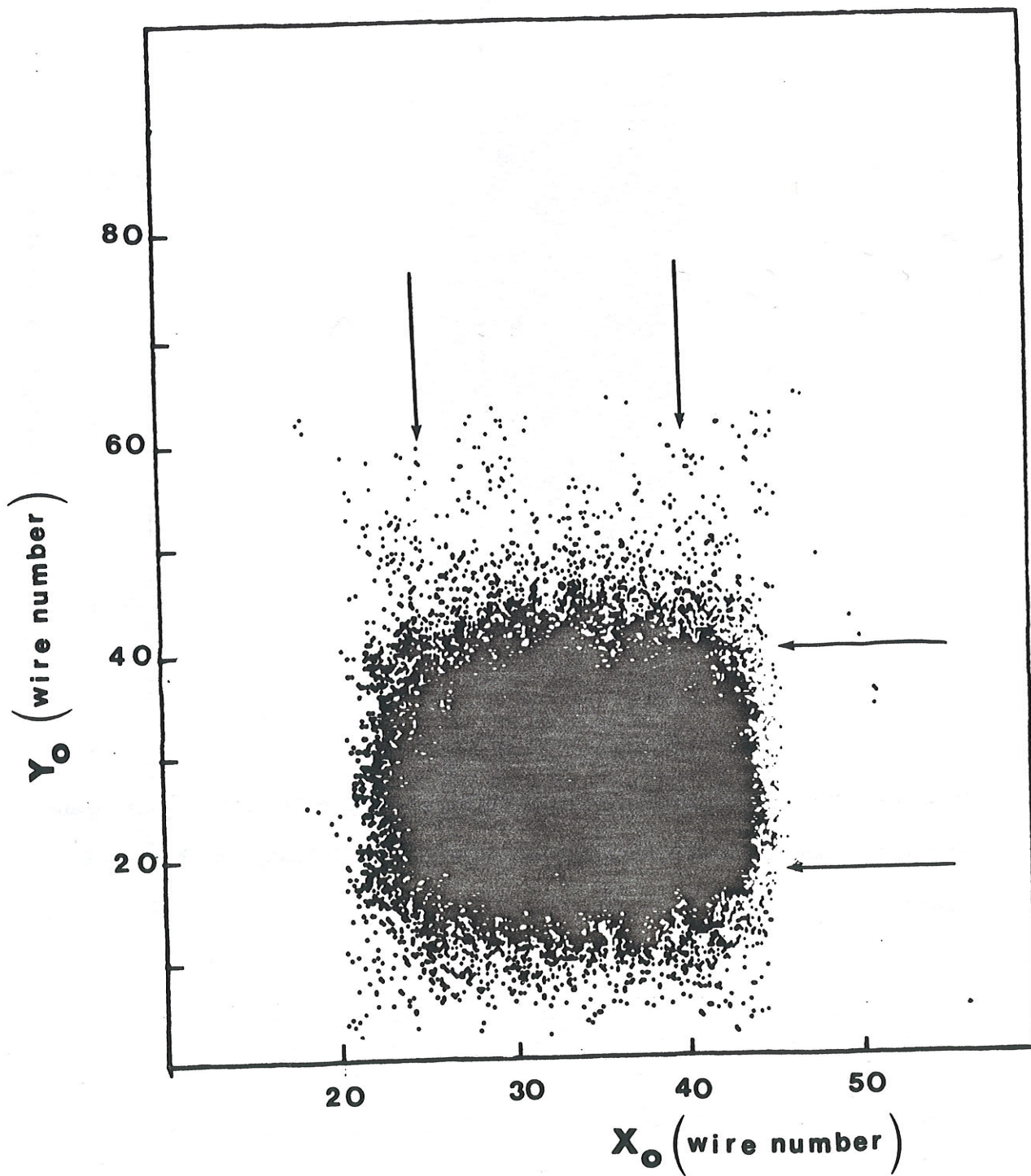


Fig. 17

Fig. 18 Two dimensional representation of counts in the $X_0 - XF$ plane
The arrows indicate the region with constant efficiency of the focal
plane.

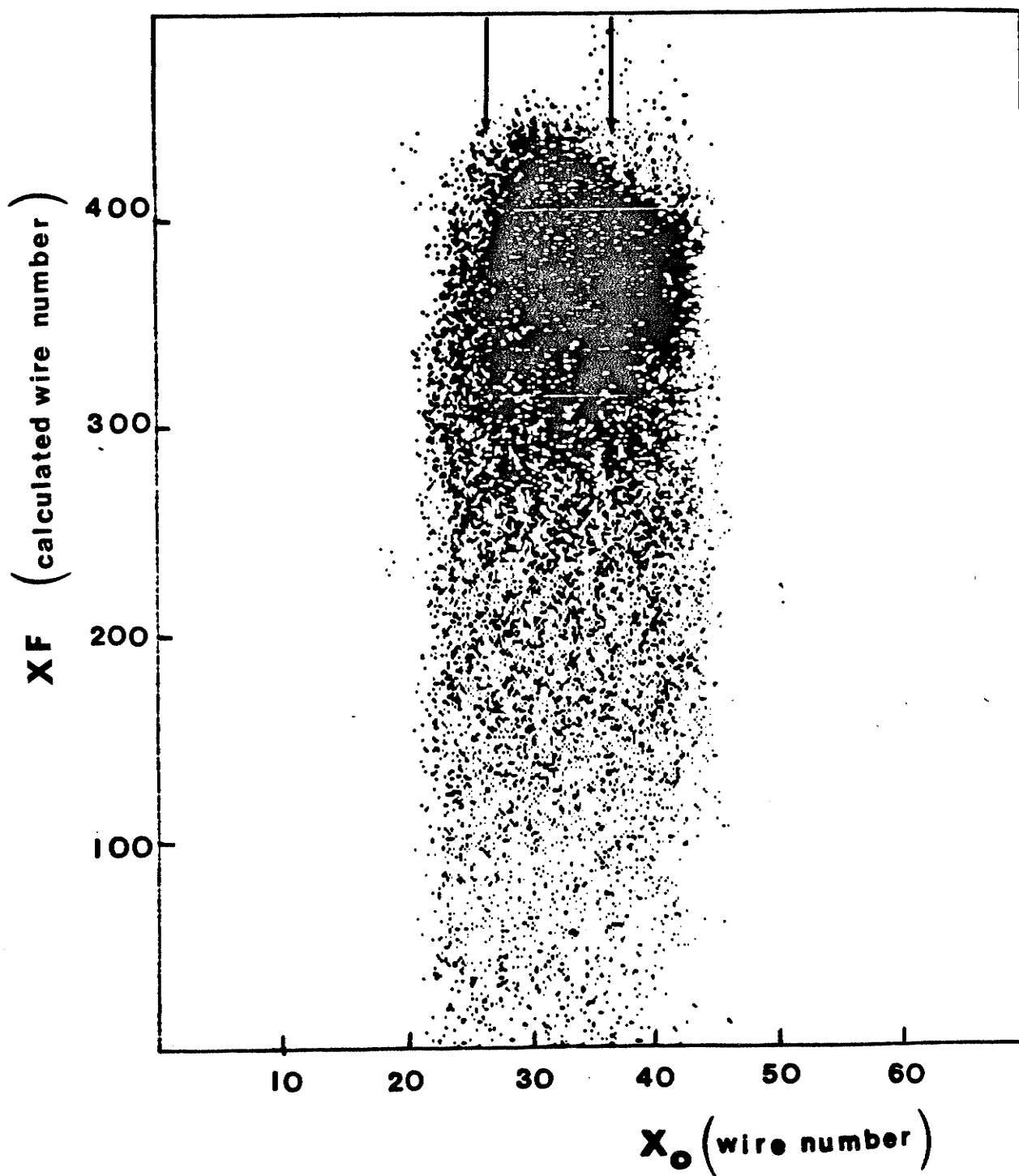


Fig. 18

the constants are given in [St-81]. Figure 17 shows a typical scatterplot of X_0 versus Y_0 and figure 18 shows a typical scatterplot of X_0 versus XF . From the latter figure one can see that the efficiency is flat only for a narrow region of the X_0 plane.

For the remaining 'good events', the kinetic energy, time-of-flight and spatial position of the detected particles were computed and histograms produced. In the case of the $^3\text{He}(p,2p)np$ data at 250 MeV, the kinetic energies of the scattered and ejected particles were deduced from the pulse heights in the two NaI(Tl) detectors and the associated calibration constants. Corrections were applied for energy losses in absorbers preceding the NaI(Tl) detectors. For $^3\text{He}(p,2p)np$ at 400 MeV, $^3\text{He}(p,2p)d$ and $^3\text{He}(p,pd)p$ at 300 and 450 MeV the energy of one of the detected particles was deduced from its pulse height in the NaI(Tl) detector while the momentum of the other particle was deduced from the focal plane coordinate XF of the magnetic spectrometer and the magnetic field strength (as presented in [St-81]). Figure 19 shows the two-dimensional histogram T_3 versus T_4 for some of the 450 MeV $^3\text{He}(p,pd)p$ data which satisfy the requirements described above. T_3 is the energy of the protons measured with the counter telescope and T_4 is the energy of the deuteron as calculated from its momentum measured with the magnetic spectrometer. This two-dimensional spectrum has a higher density of counts in the region of the three-body final state energy-sharing locus. It also shows counts due to reaction losses in the detectors, accidental events and background originating in the nickel foils containing the $L^3\text{He}$. All the $(p,2p)$ and (p,pd) spectra show these features. In addition the $(p,2p)$ spectra contain events below the three-body locus which correspond to the four-body final state continuum.

Fig. 19 Two dimensional histogram T_3 versus T_4 for some of the $^3\text{He}(p,pd)p$ data. This histogram was obtained without any restrictions on the missing energy E_{miss} . The data satisfy the conditions described in the text.

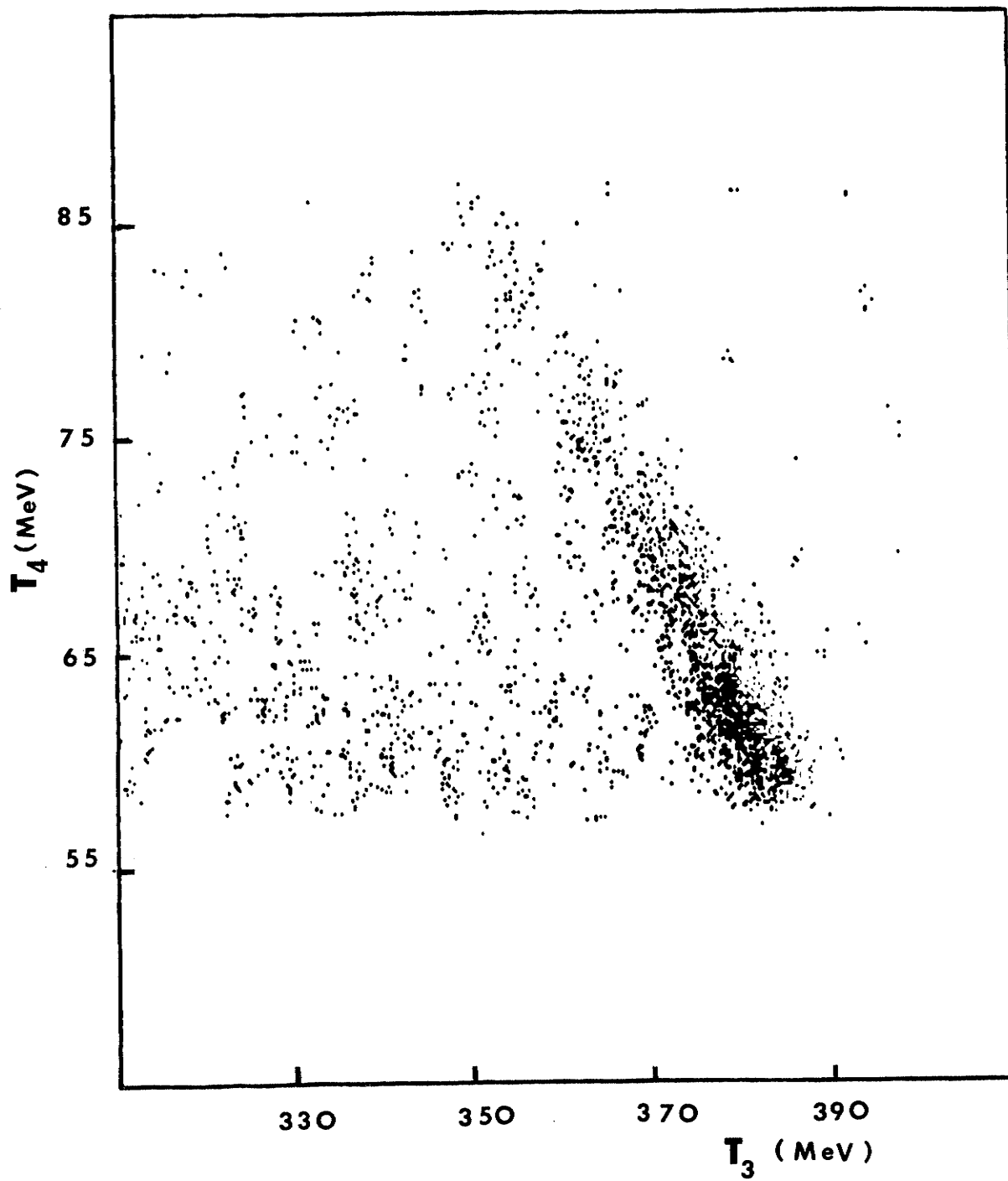


Fig. 19

The yields due to accidental coincidences between particles originating in two consecutive beam bursts were subtracted from the total yield as a correction for random coincidences between particles from the same beam burst. Correction factors for MWPC inefficiencies, pile-up rejection, and electronics and computer dead time were also calculated. The method used to calculate these corrections, their errors, and typical values are given in the next section. Additional constraints were imposed depending on whether the ${}^3\text{He}(p,2p)np$ or the ${}^3\text{He}(p,pd)p$ data were analysed.

In the case of the ${}^3\text{He}(p,2p)np$ analysis cuts in both the single particle time-of-flight spectra were needed to make a subtraction of the background events due to the ${}^3\text{He}(p,2p)d$ reaction. With the aid of figure 20 it is possible to explain the mechanism through which the more copious ${}^3\text{He}(p,2p)d$ reaction events produce background events. The kinetic energies of the scattered and ejected particles are indicated with T_3 and T_4 respectively. Let T_3^0 and T_4^0 be the kinetic energies of the scattered and ejected protons from the ${}^3\text{He}(p,2p)np$ reaction corresponding to $P(\text{recoil}) = 0$ ($P(\text{recoil})$ is the momentum of the centre of mass of the n - p pair). Let T_4' be the kinetic energy of the ejected proton from the ${}^3\text{He}(p,2p)d$ reaction when the scattered proton has kinetic energy T_3^0 and let T_3' be the kinetic energy of the scattered proton from the ${}^3\text{He}(p,2p)d$ reaction when the ejected proton has energy T_4^0 . As can be seen in figure 20 the kinematic locus of the ${}^3\text{He}(p,2p)d$ reaction is well separated from the continuum region around the point (T_3^0, T_4^0) and this was true for all the angle pairs measured. In the case of figure 20, the kinematic locus at the angle pair 30° - 30° at 250 MeV has $T_3^0 = T_4^0 = 90$ MeV while $T_3' = T_4' = 150$ MeV. Events in a rectangular

Fig. 20 Kinematic locus for the $^3\text{He}(p,2p)d$ reaction at 250 MeV and asymmetric coplanar geometry $\theta_3 = \theta_4 = 30^\circ$. The point in the box indicates the energy of the scattered and ejected protons corresponding to the centre of mass of the n-p pair being at rest.

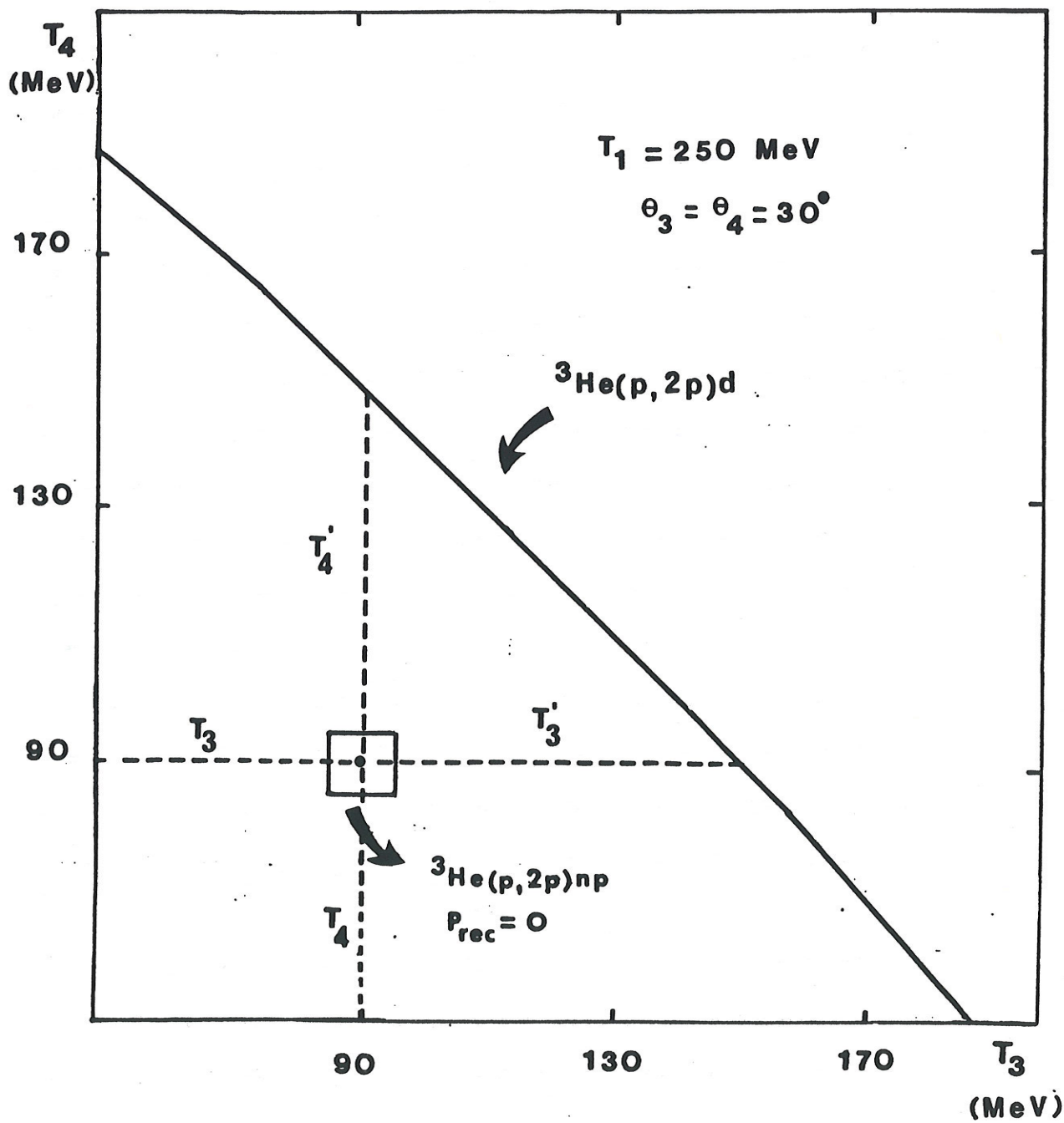


Fig. 20

energy bite centered around the point (T_3^0, T_4^0) were counted to calculate the ${}^3\text{He}(p, 2p)np$ cross sections. The ${}^3\text{He}(p, 2p)d$ events with energies (T_3^0, T_4') and (T_3', T_4^0) and also those with $T_3 > T_3^0$ and $T_4 > T_4^0$ from other points of the locus can appear in the region of interest when either one of the two protons or both protons suffer an inelastic reaction in the NaI(Tl) detectors. Background of this nature was separated from the actual yield by setting cuts in the two dimensional spectrum of the time-of-flight of the scattered particle versus the time-of-flight of the ejected particle. The ${}^3\text{He}(p, 2p)d$ events which undergo a nuclear reaction in the NaI(Tl) detector have different time-of-flight values than the ${}^3\text{He}(p, 2p)np$ events. The width of the cuts on each single arm time-of-flight was determined from time-of-flight calibration measurements using protons with a small energy spread (approximately 5 MeV) coming from proton-proton scattering. The value chosen was 1.2 nsec.

The two MWPC's which were mounted on each boom for the measurements of the ${}^3\text{He}(p, 2p)np$ reaction at 250 MeV were used for vertex reconstruction at the target. Events which did not originate at the target were rejected by setting a circular cut equal to the inner diameter of the target cell (4.4 cm).

In the case of the ${}^3\text{He}(p, pd)p$ reaction the additional constraint was instead a window around the missing energy E_{miss} . The missing energy is equal to the difference of the mass of the reaction participants before and after the reaction:

$$E_{\text{miss}} = m_1 + m_2 - m_3 - m_4 - m_5$$

$$E_{\text{miss}} = -5.4 \text{ MeV}$$

Fig. 21 Histogram of the missing energy E_{miss} for some of the ${}^3\text{He}(p, \text{pd})p$ data.

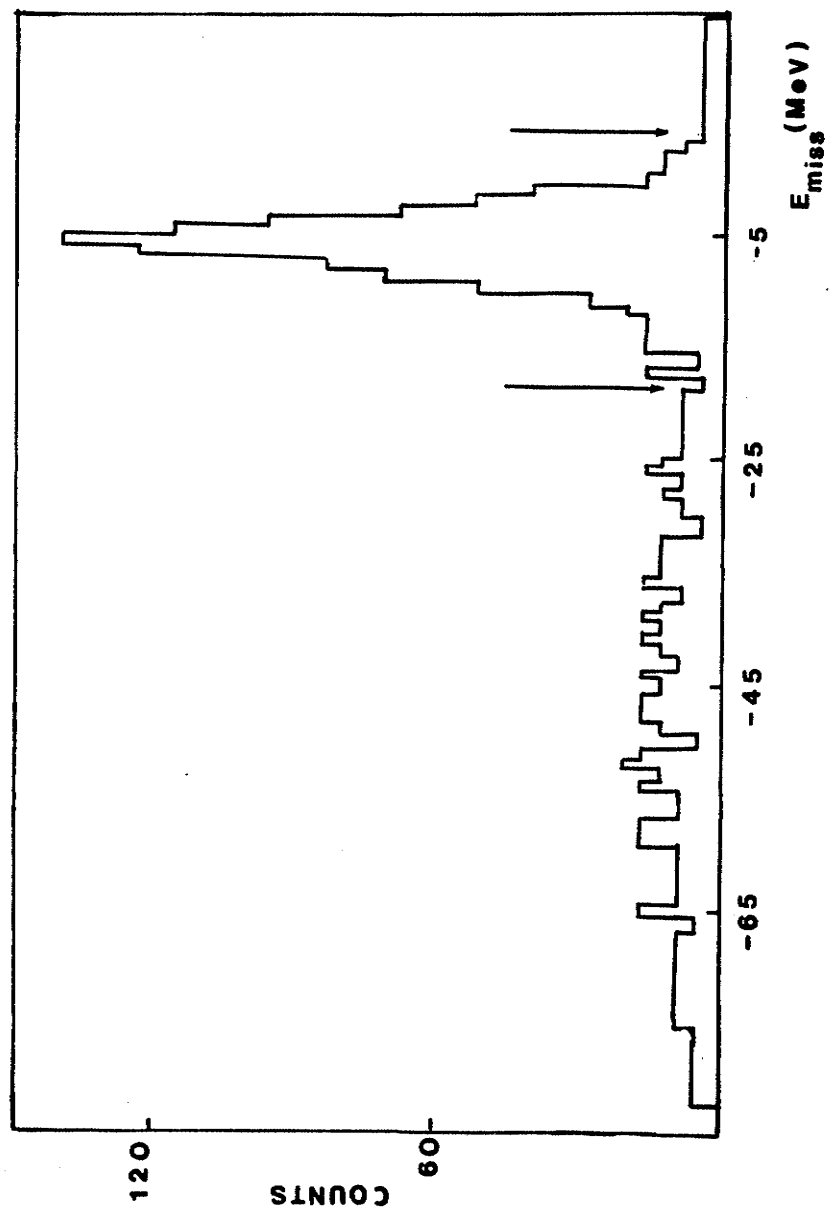


Fig. 21

The quantity E_{miss} (from total energy conservation) can also be expressed in terms of the kinetic energies of the reaction participants,

$$E_{\text{miss}} = T_3 + T_4 + T_5 - T_1 - T_2$$

where the T_i ($i=1,2,3,4,5$) are the laboratory kinetic energies of the incident, target, scattered, ejected and recoil particles. The incident proton beam energy T_1 is known while T_3 , T_4 , θ_3 , θ_4 , ϕ_3 , ϕ_4 , and the corresponding momenta P_3 and P_4 are measured quantities in the experiment. The value of T_5 follows from linear momentum conservation. Adopting the convention that the z axis is along the beam direction, the y axis is perpendicular to the reaction plane (along $k_i \times k_f$ for the scattered proton), then

$$P_{5x} = -P_3 \sin \theta_3 \cos \phi_3 - P_4 \sin \theta_4 \cos \phi_4$$

$$P_{5y} = -P_3 \sin \theta_3 \sin \phi_3 - P_4 \sin \theta_4 \sin \phi_4$$

$$P_{5z} = P_1 - P_3 \cos \theta_3 - P_4 \cos \theta_4.$$

From P_{5x} , P_{5y} , P_{5z} , it is then straightforward to derive the value of T_5 for each event.

The width of the peak of the E_{miss} spectrum depends on the combined energy resolution of the two detector systems. The resolution worsened with increasing thickness of the Cu absorber in front of the NaI(Tl) detectors. In the case of the $^3\text{He}(p, \text{pd})p$ data a 20 MeV bite was needed to include the entire E_{miss} peak. With this cut it was possible to separate the $^3\text{He}(p, \text{pd})p$ reaction from the background. In figure 21 a missing energy spectrum is shown. The two dimensional spectrum T_3 versus T_4 obtained with the restrictions already discussed and with a cut of 20 MeV around the missing energy peak is shown in figure 22. Figure 22 should be compared with figure 19 which contains the same scatterplot without the cut on the missing energy.

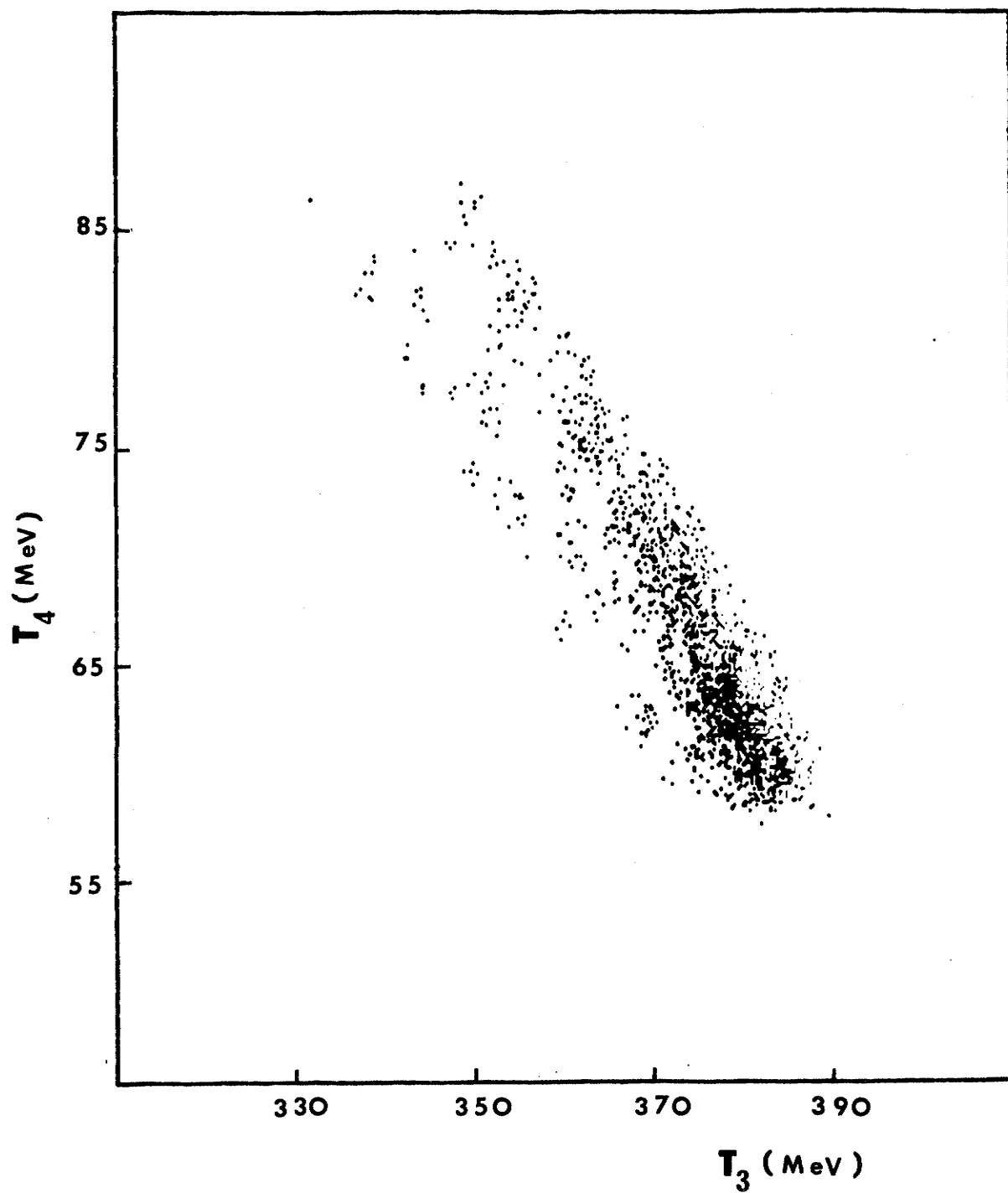


Fig. 22

A cut in the E_{miss} value was also used in the analysis of the $^3\text{He}(p,2p)d$ data. In the latter case, the energies and the angles of all three products in the final state were measured. Since thinner Cu absorbers were used, the E_{miss} cuts varied from 10 to 15 MeV. All the constraints (cuts and windows) used to extract the yields were monitored in the analysis of each magnetic tape by constructing all the spectra of the parameters on which windows were placed. By comparing these spectra for all runs an indication of the electronics and beam stability was obtained. When a small change in the gain of the NaI(Tl) detectors was found to have occurred a correction factor for the calibration constants was calculated from the relative position of the pulser peak from run to run. Only a few of the runs presented this problem.

3.2 Experimental results and uncertainties

The sixfold differential cross sections for the $^3\text{He}(p,2p)np$ reaction and the fivefold differential cross sections for the $^3\text{He}(p,2p)d$ reactions were obtained as follows:

$$d^6\sigma/(d\Omega_3 d\Omega_4 dT_3 dT_4) = (Y_a * MWPC * PU * DT * NaIEFF) / (\Omega_3 * \Omega_4 * \Delta T_3 * \Delta T_4 * T * Q)$$

$$d^5\sigma/(d\Omega_3 d\Omega_4 dT_1) = (Y_b * MWPC * PU * DT * NaIEFF) / (\Omega_3 * \Omega_4 * \Delta T_1 * T * Q)$$

Y_a is the number of proton pairs, obtained after accidental and background subtraction, corresponding to energy bites ΔT_3 and ΔT_4 centred around T_3 and T_4 for which the centre of mass momentum of the recoiling n-p pair equals zero. The energy bites ΔT_3 and ΔT_4 were taken to be 9 MeV. Ω_3 and Ω_4 are the solid angle elements for the scattered and ejected protons, respectively. The sum of accidental ${}^3\text{He}(p,2p)np$ events and background events due to reactions occurring in the nickel windows of the $L^3\text{He}$ target cell is indicated with Y_a' . The statistical error is then given by:

$$\Delta Y_a = (Y_a + 2*Y_a')^{1/2}$$

The quantity Y_b is the number of particle pairs with one of the two detected particles having an energy T_i within an energy bite ΔT_i and within solid angle elements Ω_3 and Ω_4 respectively. Similarly, the statistical error is given by :

$$\Delta Y_b = (Y_b + 2*Y_b')^{1/2}$$

MWPC represents the correction factor for the multiwire proportional chamber inefficiencies. Labelling the efficiency for each wire plane by ϵ_i ,

$$\text{MWPC} = (\prod_{i=1,n} \epsilon_i)^{-1}$$

where n is the total number of wire planes. In general, if I_i particles are incident on the i th wire plane and if R_i of them satisfy the imposed requirements,

$$\epsilon_i = R_i / I_i$$

The statistical uncertainty is calculated from the mean square deviation of the distribution of the number of particles passing through the wire plane. Since the probability for each particle to pass through the plane is ϵ_i and ranges from 0.7 to 0.95, the distribution of the number

of particles which have passed the plane is a binomial distribution. The mean value of this distribution is $I_1 \cdot \epsilon_1$ and the mean square deviation is $I_1 \cdot \epsilon_1 \cdot (1 - \epsilon_1)$. Using the last expression, the square of the fractional uncertainty (statistical only) is given by:

$$(\Delta \epsilon_1 / \epsilon_1)^2 = 1/R_1 - 1/I_1$$

The fractional uncertainty, $\Delta \text{MWPC} / \text{MWPC}$ is then the root mean square of the sum of the squares of the fractional uncertainty for each ϵ_1 . Typical values of this inefficiency correction factor MWPC, ranged between 1.25 and 1.30 with uncertainties of 0.5%. Occasionally with high beam intensities this value was as large as 1.60 with a statistical uncertainty of $\pm 0.8\%$. The MWPC efficiencies were determined from the subgroup of events for which no pile-up occurred. Pile-up events have the pile-up bit set and are accounted for through the pile-up correction factor. By determining the MWPC correction factor after pile-up events have been rejected, double counting of events which resulted in both multiple hits as well as pile-up is prevented.

The quantity PU is the pile up correction factor. In the case of the present experiment it ranges from 1.1 to 1.2 with a statistical accuracy of 0.3% to 0.4%.

The quantity DT is the electronics and computer dead time correction factor. Typical values range from 1.03 to 1.3. The statistical errors ranged from 0.5% to 1.0%.

The quantity NaIEFF is the NaI(Tl) detector efficiency for protons of the appropriate energy. These efficiencies were measured as well as calculated and are presented in chapter 4.

The quantity Q is the integrated incident proton beam current ; it is determined from the sum of L' and R' as follows:

$$Q=C*(L'+R')$$

$$L'=L-L_{acc}$$

$$R'=R-R_{acc}$$

L (R) and L_{acc} (R_{acc}) are the left (right) polarimeter number of counts and polarimeter accidental number of counts, and C is a calibration constant which depends on the incident beam energy. The quantity C has been determined in previous experiments. The uncertainty in the calibration constant, which is $\sim 3\%$ results in an absolute uncertainty in the normalisation of the data. However, polarimeter targets with the same nominal target thickness and isotopic composition were found to give different values of the integrated beam current when calibrated against a Faraday cup (these differences ranged from 3% to 10%). The statistical uncertainty arising from the polarimeter number of counts is relative to each measurement and is typically less than 1%.

The quantity T is the number of ^3He nuclei per unit area, given by:

$$T=\rho t/\cos\phi,$$

with ρ the density of the liquid, t the thickness of the target cell and ϕ the rotation angle of the target relative to the incident beam. The density ρ was deduced from an average of temperature measurements taken approximately every two to three hours. Typically the temperature could be determined within ± 0.03 $^{\circ}\text{K}$ which resulted in an uncertainty of the density of 2% to 3%. The uncertainty in the rotation angle and in the thickness measurements are $\sim 1\%$. The total uncertainty in the determination of the number T depends on all these uncertainties and is approximately 3% to 4%.

The solid angle elements Ω_3 and Ω_4 are determined by

setting software cuts on the MWPC data. The uncertainty in the solid angle determination was calculated not to be larger than 1%.

The fractional uncertainties in the differential cross sections were calculated as the square root of the sum of the squares of the fractional uncertainties in Y, MWPC, DT, PU, NaIEFF, and the statistical error in the polarimeter counts and are given in the data tables. The absolute uncertainties such as the ones in the solid angle and target thickness determination and incident beam current integration gave an overall normalisation uncertainty of about 10%.

The momentum distributions were extracted from the measured differential cross sections using the procedure described in the appendix.

CHAPTER IV

THE EFFICIENCY OF COUNTER TELESCOPES FOR INTERMEDIATE ENERGY PROTONS.⁺

4.0 Introduction

In two previous papers ([Ca-77],[Go-78]), the absolute efficiency of counter telescopes for detecting intermediate energy protons was reported and discussed. These counter telescopes consisted of a multiwire proportional chamber (MWPC), with both x and y planes, one (or more) thin plastic scintillators, a sodium iodide [NaI(Tl)] detector, and, if needed, an appropriate amount of copper used as energy degrader mounted in front of the latter detector. The thickness of the NaI crystal used in these measurements was 7.6 cm which could stop protons with energies up to 150 MeV.

In this chapter we present and compare recent results of efficiency measurements for telescopes with 15.2 cm thick NaI crystals (which can stop protons up to 230 MeV) for protons in the energy range from 50 MeV to 350 MeV. The radial dependence of the efficiency for each selected energy was also measured. This enabled an investigation of the combined effects of reaction losses and out-scattering which are the cause of telescope inefficiencies.

⁺ to be published in Nuclear Instruments and Methods.

4.1 Experimental method and data analysis

The efficiency measurements consisted of detecting proton-proton coincidences from a thin CH_2 target in either two identical detector telescopes or a detector telescope and a magnetic spectrometer set at complementary angles for p-p scattering. In the first case, using 250 MeV incident protons, the two counter telescopes were mounted on booms with platforms rotatable about a scattering chamber. Each telescope consisted of a 0.3 cm thick plastic scintillator, a 12.7 cm by 12.7 cm MWPC with 0.2 cm wire spacing at a distance of 90 cm from the scattering centre, a second 25.4 cm by 12.7 cm MWPC with the same wire spacing at a distance of 123 cm to allow vertex reconstruction, followed immediately by a second 0.3 cm thick plastic scintillator and a cylindrical NaI(Tl) crystal (12.7 cm in diameter and 15.2 cm thick) mounted on a 12.7 cm diameter photomultiplier tube. Both NaI energy signals were digitized and recorded on magnetic tape when the trigger signal, obtained from a four-fold coincidence of the four plastic scintillators, was present. Since later analysis of the data used the elastically scattered protons detected in one telescope to define the incident flux in the other, it was possible to extract simultaneously two efficiency measurements for each angle setting. In the second case, using 450 MeV incident protons, the detector telescope consisted of a 20.3 cm by 20.3 cm delay-line MWPC at a distance of 198 cm from the scattering center, followed immediately by a 0.08 cm thin plastic scintillator, an annular veto counter (with an aperture 10.2 cm in diameter), some copper energy degrader (if needed) and a 12.7 cm diameter by 15.2 cm thick NaI detector. The magnetic spectrometer detection

system consisted of a 0.08 cm thick plastic scintillator plus a 12.5 cm by 12.5 cm MWPC (with 0.2 cm wire spacing) at a distance of 80 cm to define the solid angle, mounted before a quadrupole magnet-dipole magnet combination. This was followed by a set of 25.6 cm by 102.4 cm MWPC's (with 0.2 cm wire spacing) mounted about the focal plane of the magnetic spectrometer and a 2.5 cm thick plastic scintillator. The time-of-flight distance through the spectrometer is 11.0 m. Events were recorded for a coincidence between the thin plastic scintillator in front of the NaI detector and at the entrance of the spectrometer with no signal present from the veto counter. The amount of copper was chosen so that the residual energy deposited in the NaI detector was between 200 MeV and 230 MeV. The maximum thickness of copper absorber used was 6.67 cm.

Incident proton beam intensities were of the order of a few nA. The beam position and direction were measured using wire profile monitors. The cross section of the beam at the target was about 0.5 cm in diameter. The CH₂ target thickness was 235 mg/cm² in the case of the 250 MeV measurements and 79 mg/cm² in the case of the 450 MeV measurements. The angles at which the counter telescopes were set were known to an accuracy of $\pm 0.1^\circ$. By choosing different complementary pairs of angles the energy range from 50 MeV to 350 MeV was covered.

Each event had to satisfy a number of constraints. The counts in the two arms had to originate within the same beam burst. Corrections for accidental coincidences were made in the usual fashion by delaying one side by one rf period (43 nsec). Events for which the NaI signal showed 'pile up' within 300 nsec were rejected. Only those protons entering in one of the detection systems which had the

associated proton (in the complementary arm) producing a full energy signal and being within a narrow solid angle ($\pm 0.8^\circ$ at 250 MeV and $\pm 0.7^\circ$ at 400 MeV) were used for the efficiency determinations.

The efficiency ϵ of a counter telescope is defined as $\epsilon = I/I_0$, where I_0 is the total number of protons incident on a counter telescope under the described constraints and I is the number of tagged protons which resulted in a full-energy signal in the NaI detector. This ratio was calculated as a function of distance from the centre of the NaI detector, using the MWPC information to reconstruct where the incident proton entered the NaI telescope detector. The incident proton energy in the NaI detector was calculated from kinematics taking into account energy losses in the material preceding the copper absorber and the NaI detector. Due to the finite size of the solid angle, the incident energy spread was about 3 MeV for the 250 MeV data and 4 MeV for the 400 MeV data. Corrections for the contributions of (p,2p) events from carbon were less than one half of a percent [Ty-66] while the corrections for reaction losses in the CH_2 target and in the plastic scintillator before the NaI detector, the MWPC ('s), and air ([Me-69], [So-77], [Me-69]) varied from a small fraction of a percent to about 1.5 percent. Due to energy straggling, the finite resolution of the NaI detector, and kinematic broadening, the width of the window needed to include all of the full energy peak varied from 7 to 15 MeV below the peak centroid. Since this varying window included different amounts of reaction products underneath the full energy peak, the efficiencies were corrected so that, as far as reaction products are concerned, the effective lower edge of the window was 7 MeV below the peak centroid. These corrections ranged between 0.3% and 2.4%. The same

Fig. 23 The efficiency of the counter telescopes as a function of radius for four different energies. The solid lines represent fits to the data points using the expression given in the text.

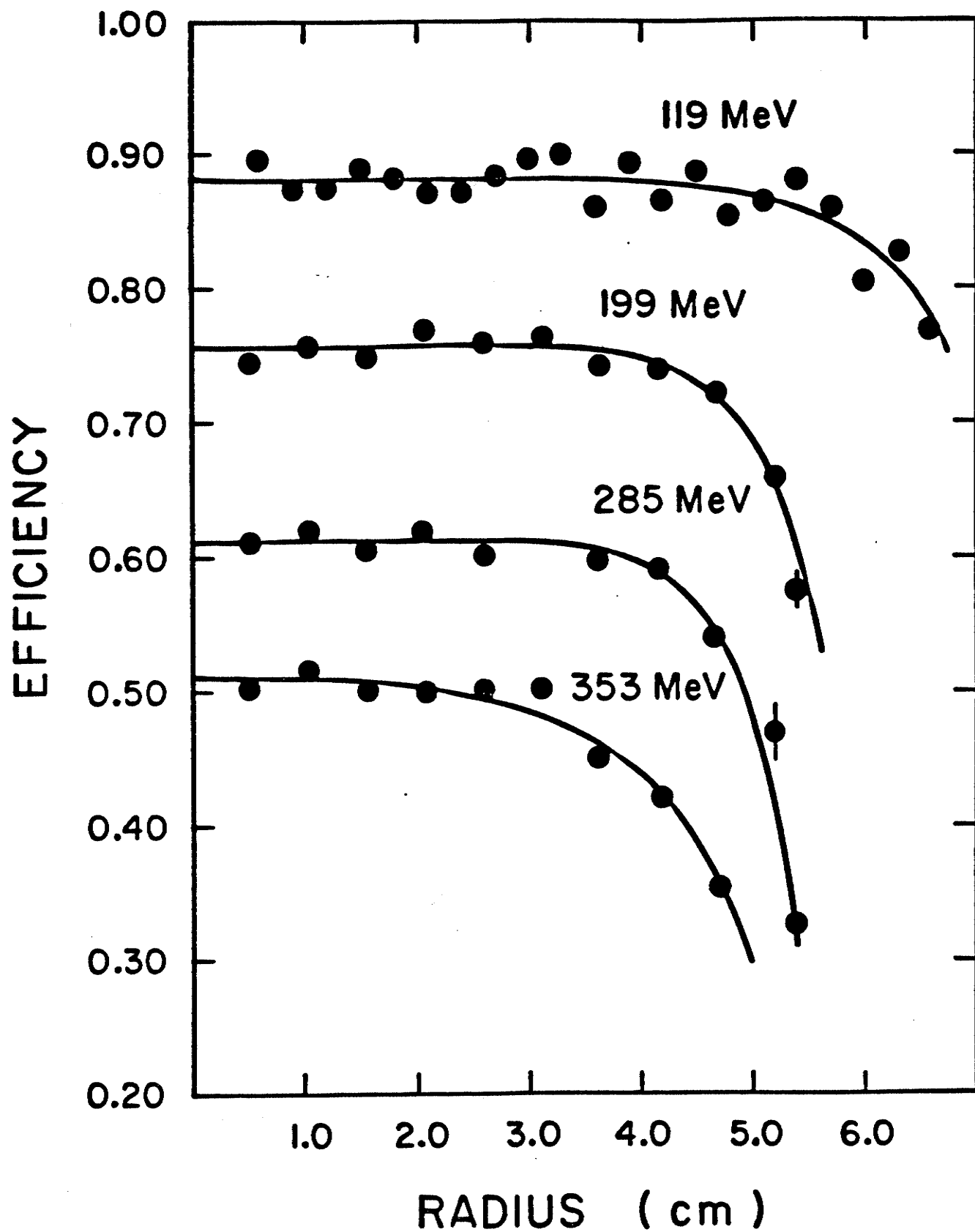


Fig. 23

value for the lower edge of the window was chosen by Goulding and Rogers [Go-78] in their reaction loss calculations.

4.2 Results and discussion

In fig. 23 the efficiency of the counter telescopes is plotted as a function of the radial position at some of the different proton energies. All the curves have a flat portion, whose value depends on the amount of nuclear reaction losses in the Cu absorber and NaI detector and whose width depends on the amount of out-scattering. The decrease in efficiency due to edge effects occurs at smaller radii as the proton energy and the thickness of the copper absorber increase indicating that the out-scattering becomes more important closer to the centre of the telescope with increasing energy.

The efficiency profile has been fitted with the function

$$\varepsilon(R) = \varepsilon_0 \left[1 - \left(\frac{R_0}{4\pi\alpha R} \right)^{1/2} \frac{\exp\{-\alpha(R-R_0)^2\}}{|R-R_0|} \right]$$

where

$$\alpha = \frac{3}{\langle \theta^2 \rangle t^2} .$$

This function was derived from a simple mathematical model based on multiple Coulomb scattering [Ca-77]. Here ε_0 is the efficiency of the central plateau region, t is the range of the particle in the telescope, $\langle \theta^2 \rangle^{1/2}$ is the effective rms scattering angle and R_0 is the effective detector radius. The smooth curves were obtained by letting ε_0 , R_0 and $\langle \theta^2 \rangle^{1/2}$ vary to minimize χ^2 . The efficiencies in the

Fig. 24 The efficiency of the central region of the counter telescopes as function of incident proton energy. The solid line is a prediction of the efficiency calculated using total reaction cross section data.

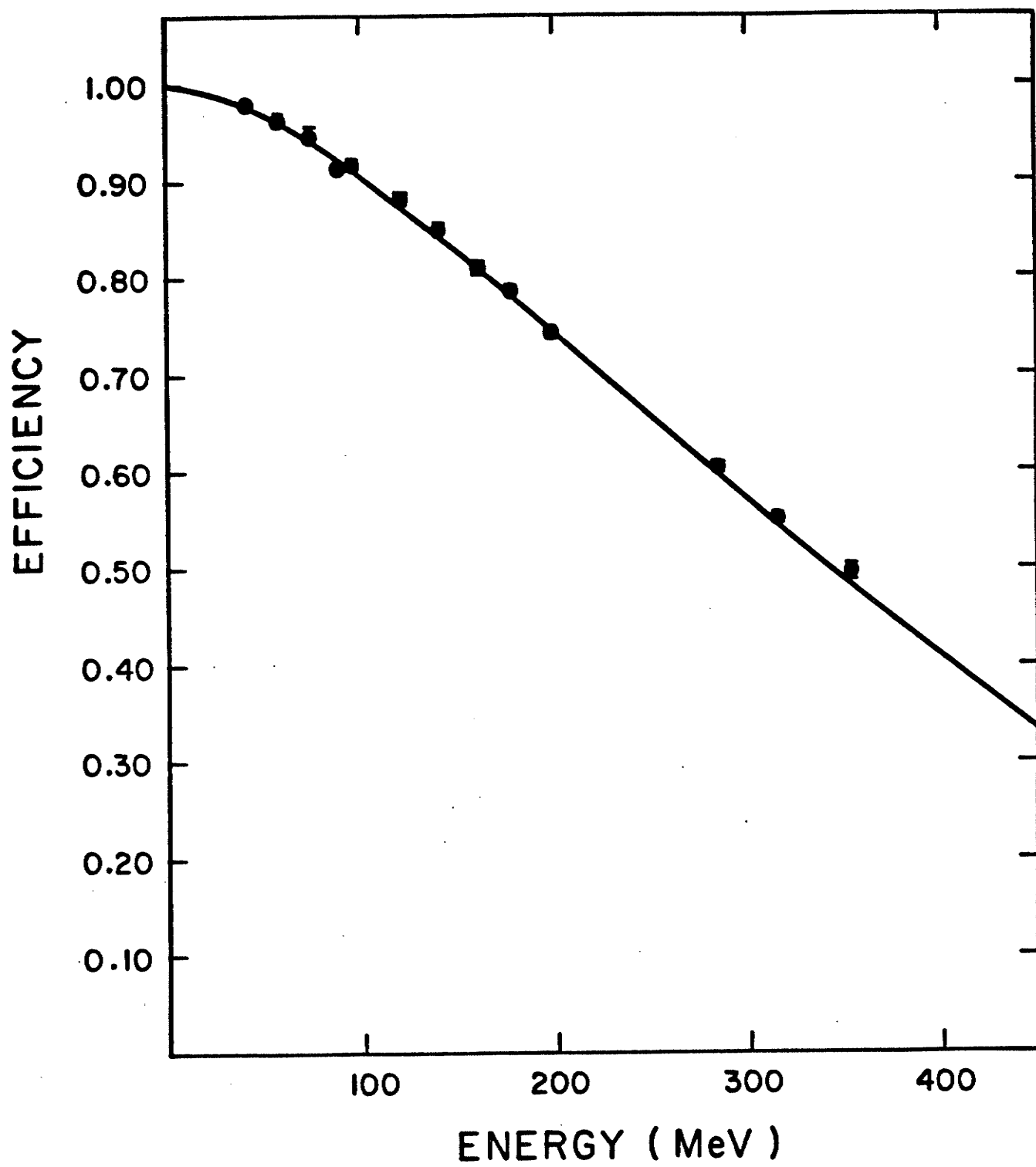


Fig. 24

central region of the detector telescopes are presented in Table 1 and shown in figure 24 as a function of incident proton energy. The uncertainties quoted in the table are the statistical errors. The variation of the tail to peak ratios due to the uncertainty in the value of the lower edge of the energy window, is also presented in the table in percent per MeV. The line in figure 24 represents the result of a calculation of the efficiency as a function of energy for the combined copper absorber and NaI detector system, using measured reaction cross sections for protons in NaI and Cu ([Go-78],[Re-72]). Values for the parameters $\langle\theta^2\rangle^{1/2}$ and R_0/R_{NaI} where R_{NaI} is the radius of the NaI crystal are shown in figure 25. The discontinuous behaviour of the $\langle\theta^2\rangle^{1/2}$ and R_0 parameters as a function of energy, in particular at low energies, can be understood as follows. The values of these parameters are determined only from the fall-off of the efficiency profile at large radii. At low energies the fall-off is very small and there are not enough experimental points to obtain accurately the values of $\langle\theta^2\rangle^{1/2}$ and R_0 from the fit. Moreover, the parameters $\langle\theta^2\rangle^{1/2}$ and R_0 are strongly correlated, as one can see from the two graphs in figure 25. The parameter ε_0 is uncorrelated to $\langle\theta^2\rangle^{1/2}$ and R_0 and its value is independent on how well $\langle\theta^2\rangle^{1/2}$ and R_0 are determined.

The measured tail-to-peak ratios in the region where geometrical edge effects can be neglected are in good agreement with the predictions of Goulding and Rogers [Go-78] calculated for the energy range up to 240 MeV. It is to be noted that tail-to-peak ratios calculated by Goulding and Rogers are in better agreement with the results of the present experiment and also with those of the previous

Fig. 25 The effective rms scattering angle and the ratio of the effective detector radius to the nominal detector radius as function of incident proton energy.

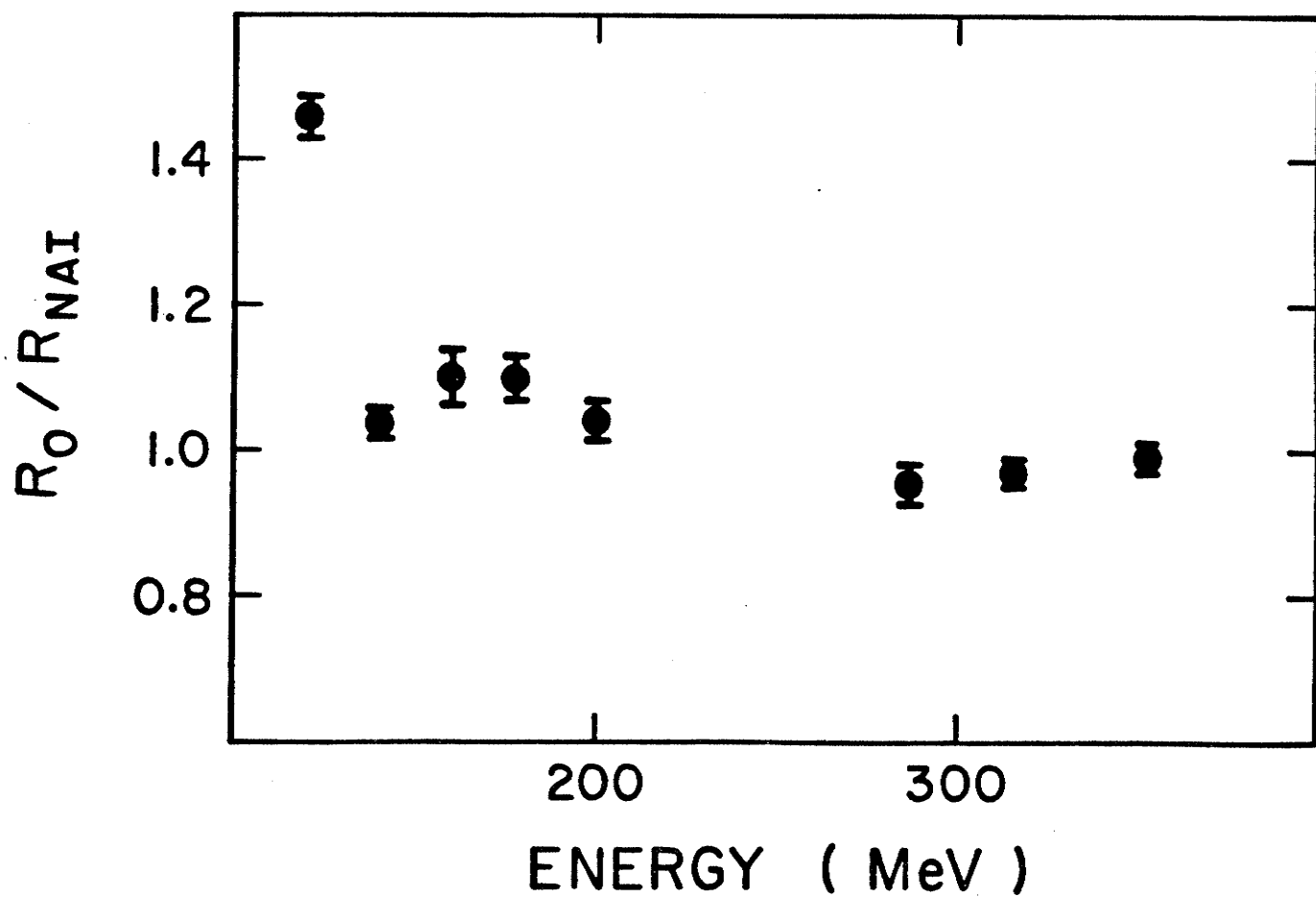
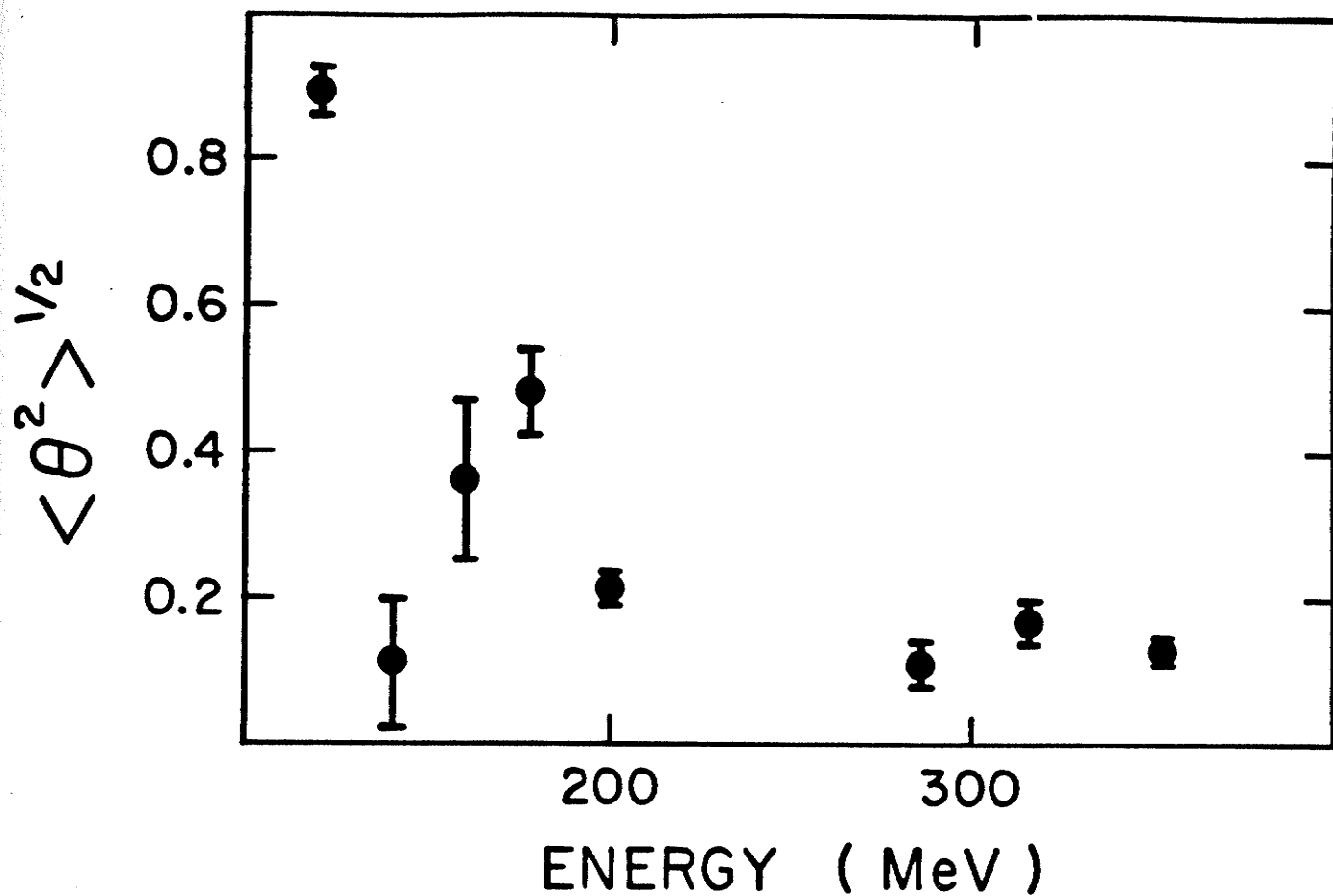


Fig. 25

experiment than those calculated by Cameron et al. [Ca-77]. This may be a consequence of including newer total reaction cross section data. The calculated efficiencies for the copper NaI combinations of the present experiment are in excellent agreement with the data. The counter telescopes have been used in various (p,2p) and (p,pd) experiments.

Table 1

Counter telescope efficiencies as function of incident proton energy.

Energy (MeV)	Efficiency (measured) %	$\frac{\Delta(\text{tail/peak})}{\Delta E}$ (%/MeV)	Efficiency (calculated) %
57	96.4 ± 0.2	0.16	95.8
74	95.0 ± 0.3	0.14	94.0
91	91.5 ± 0.2	0.14	91.8
95	91.8 ± 0.4	0.19	91.3
119	88.0 ± 0.6	0.15	87.8
125	87.2 ± 0.3	0.30	86.7
140	85.0 ± 0.6	0.13	84.2
161	81.2 ± 0.6	0.17	80.7
177	78.5 ± 0.6	0.18	78.0
199	74.5 ± 0.2	0.26	74.1
285	60.6 ± 0.3	0.25	59.1
316	55.3 ± 0.3	0.20	54.0
353	49.6 ± 0.3	0.30	48.1

The thickness of copper absorber used at 285 MeV was 5.08 cm, at 316 MeV 5.08 cm and at 353 MeV 6.67 cm.

CHAPTER V

STUDY OF TWO-NUCLEON WAVE FUNCTION IN ${}^3\text{He}$.⁺

Studies of quasi-free scattering from ${}^3\text{He}$ allow nucleon-nucleon correlations to be determined directly assuming the plane wave impulse approximation (PWIA) to be valid. For ${}^3\text{He}$ the experimental momentum distribution as a function of the variables $\vec{P}$ and E can be compared directly with the spectral function obtained using the Faddeev equations and a realistic nucleon-nucleon interaction. Here $\vec{P}(\text{recoil})$ is the vector momentum and $E(\text{recoil})$ is the total energy of the unobserved pair of particles in ${}^3\text{He}(e,e'p)$ or ${}^3\text{He}(p,2p)$. The ${}^3\text{He}$ spectral function has been calculated by Dieperink et al. [Di-76] from the ${}^3\text{He}$ ground state wave function obtained by Brandenburg, Kim and Tubis [Br-75] for the Reid soft-core interaction acting in 1S_0 and 3S_1 - 3D_1 states only, and by Meier et al. [Me-83] for the Paris potential. Furthermore the ${}^3\text{He}$ spectral function has been calculated by Ciofi degli Atti, Pace and Salmé [Ci-81] using the variational wave function of Nunberg, Prosperi and Pace [Nu-77] with a corrected asymptotic behavior of the harmonic oscillator basis expansion wave function. Previous ${}^3\text{He}(p,2p)$ experiments have all been concerned with sections through the spectral function surface for constant $E(\text{recoil})$. Both bound p-n pairs [${}^3\text{He}(p,2p)d$] and unbound p-n pairs with low energy for their relative motion [${}^3\text{He}(p,2p)d^*$] have been considered [Sl-71]. The present

⁺ published in Physical Review Letters, 50, 1741-1744(1983).

experiment is unique in that it defines a section through the spectral function surface for constant $P(\vec{P}=0)$. Such measurements have never been made previously.

The experiment was performed using proton beams of 250 and 400 MeV from the TRIUMF accelerator incident on a liquid ^3He ($L^3\text{He}$) target. Beam intensities ranged between 0.5 nA and 5 nA. Normalization of the differential cross sections followed from the sum of left and right counts from the incident beam polarimeter (containing a $\sim 5 \text{ mgcm}^{-2}$ thick CH_2 target) located upstream from the $L^3\text{He}$ target and from an ionization chamber downstream from the $L^3\text{He}$ target. Both polarimeter and ionization chamber had previously been calibrated against a Faraday cup collecting the beam charge. The target thickness followed from measurements of the temperature of the target cell through germanium resistors embedded in the body of the cell and from its physical dimensions [Ha-81b]. The thickness so determined was $132 \pm 4 \text{ mgcm}^{-2}$. The target cell could be raised or lowered remotely. This permitted the $L^3\text{He}$ target cell to be replaced with a dummy cell in order to allow appropriate background subtractions.

Two different detection arrangements were used. At 250 MeV the scattered and ejected protons from the $^3\text{He}(p,2p)pn$ reaction were detected in coincidence by a pair of counter telescopes placed (each to an accuracy of 0.1°) symmetrically with regard to the incident beam direction. Each counter telescope consisted of two 0.31 cm thick plastic scintillators, two sets of multiwire proportional chambers each with vertical and horizontal coordinates, and a 15.2 cm thick by 12.7 cm diameter NaI(Tl) detector (stopping protons up to ~ 210 MeV). The first plastic scintillator served to reduce the number of unwanted

coincidence events by restricting the field of view of the counter telescopes. The wire chambers were located at distances of 0.90 m and 1.20 m, respectively, from the target centre. The second plastic scintillator provided the trigger signal corresponding to coincident events, while the two plastic scintillators of each counter telescope gave time-of-flight (t.o.f.) information. At 400 MeV the left-hand side proton was detected by the MRS magnetic spectrometer, while the right-hand side proton was detected by either one or two counter telescopes at the appropriate angles. The two counter telescopes consisted each of a 0.08 cm thick plastic scintillator providing the trigger signal and t.o.f. information, an annular plastic scintillator (with an aperture 5.1 cm in radius) defining the solid angle, an appropriate amount of copper absorber, and a 15.4 cm thick by 12.7 cm diameter NaI(Tl) detector. The QD spectrometer was preceded by a 0.08 cm thick plastic scintillator for t.o.f. information and a set of multiwire proportional chambers giving vertical and horizontal coordinates at a distance of 0.8 m from the target centre. The spectrometer detection system consisted of two large 2.5 cm thick plastic scintillators and two sets of multiwire proportional chambers around the focal plane. The t.o.f. distance through the spectrometer was 11.0 m.

At 250 MeV data were taken at four coplanar symmetric pairs of laboratory angles (40° - 40° , 38° - 38° , 35° - 35° , and 30° - 30°) while at 400 MeV data were taken at four coplanar symmetric pairs of angles (40° - 40° , 37° - 37° , 34° - 34° , and 30° - 30°) and two coplanar asymmetric pairs of angles (34° - 42° , and 30° - 38°) all containing $\vec{P}(\text{recoil}) = 0$. The range of relative momenta of the recoiling n-p system extended to 600 MeV/c. Energy calibrations for the counter telescopes were

obtained by observing proton-proton scattering from a CH_2 target at a series of angles covering the range of energies of interest.

The analysis of the 250 MeV data was as previously reported [va-82] except that the use of a double set of wire chambers in the present experiment allowed for track reconstruction and vertex definition. In addition, the t.o.f. information for both observed protons in the form of a two-dimensional array enabled the events of interest to be distinguished from the background of $^3\text{He}(p,2p)d$ with both protons undergoing nuclear reactions in the stopping detectors. At 400 MeV momentum analysis and t.o.f. information gave a signal for the spectrometer side unencumbered by such background events. For the other proton, being detected in a counter telescope, the energy region of interest needed to be corrected for background events from $^3\text{He}(p,2p)d$ (with the second proton undergoing a nuclear reaction in the stopping detector) using t.o.f. information. The data were further corrected for computer deadtime, multiwire chamber inefficiencies and losses due to nuclear reactions in the NaI scintillators. The latter corrections were based upon earlier measurements of counter telescope efficiencies. The energy resolutions of the counter telescopes were in the range 7-9 MeV (FWHM), while the time resolutions varied between 1.2 and 1.6 nsec (FWHM). The sixfold differential cross sections were obtained from a bite 9 MeV by 9 MeV centered around $\vec{P}=0$. The data are presented in Table II.

In the PWIA the six-fold differential cross section can be written as

$$\begin{aligned} d^6\sigma/(d\Omega_3 dT_3 d\Omega_4 dT_4) &= F(d\sigma/d\Omega)_{1/2}^{p-p} N |\phi(p_5, p_6)|^2 \\ &= F'(d\sigma/d\Omega)_{1/2}^{p-p} S(\vec{P}, E), \end{aligned}$$

with the following index convention $p + {}^3\text{He} \rightarrow p+p + p+n \equiv 1+2 \rightarrow 3+4+5+6$

Here F and F' are kinematic factors and are defined as follows:

$$\begin{aligned} F &= \frac{p_3 p_4}{4} \frac{\pi}{M_{56}} \frac{[\{M_{56}^2 - (m_5 - m_6)^2\} \{M_{56}^2 - (m_5 + m_6)^2\}]^{1/2}}{2M_{56}} \frac{(E_3' + E_4')^2}{p_1} \times \\ &\quad \frac{16E_5 E_6}{m_4} \frac{1}{(hc)^6} \end{aligned}$$

with $|\phi(\vec{p}_5, \vec{p}_6)|^2$ expressed in fm^6 , and

$$F' = \frac{p_3 p_4}{4} \frac{(E_3' + E_4')^2}{p_1} \frac{4}{m_4} \frac{1}{(hc)^3},$$

with $S(\vec{P}, E)$ expressed in $\text{fm}^3 \text{MeV}^{-1}$, and where the primed quantities E_3'

and E_4' refer to the centre-of-mass (c.m.) system of particles 3 and 4

and $M_{56} = E$ since $\vec{P} = 0$. The quantity $(d\sigma/d\Omega)_{1/2}^{p-p}$ is a half-off-energy-

shell p-p differential cross section, N is a spectroscopic factor de-

termined using spin algebra, $|\phi(\vec{p}_5, \vec{p}_6)|^2$ is the square of the momentum

distribution of a p-n pair with momenta $\vec{p}_5$ and $\vec{p}_6$, respectively, and

$S(\vec{P}, E)$ is the spectral function. For the present experiment with $\vec{P} = 0$

the p-n pair has $\vec{p}_5 = -\vec{p}_6$. Also with $\vec{P} = 0$ the off-energy-shell depen-

dence of $(d\sigma/d\Omega)_{1/2}^{p-p}$ is reduced (the struck proton is at rest before the

collision). The half-off-energy-shell p-p scattering amplitude was

Fig. 26 Differential cross sections $d^6\sigma/(d\Omega_3 dT_3 d\Omega_4 dT_4)$ divided by the factor $F(d\sigma/d\Omega)_{1/2}^{p-p} N$ as function of the relative momentum of the unobserved p-n pair. The 250 MeV results are presented as open circles, while the 400 MeV results are presented as filled circles. The 155 MeV datum of Frascaria et al. is presented as a filled square. The solid, dashed and dot-dash curves correspond to p-n relative motion momentum distributions as indicated.

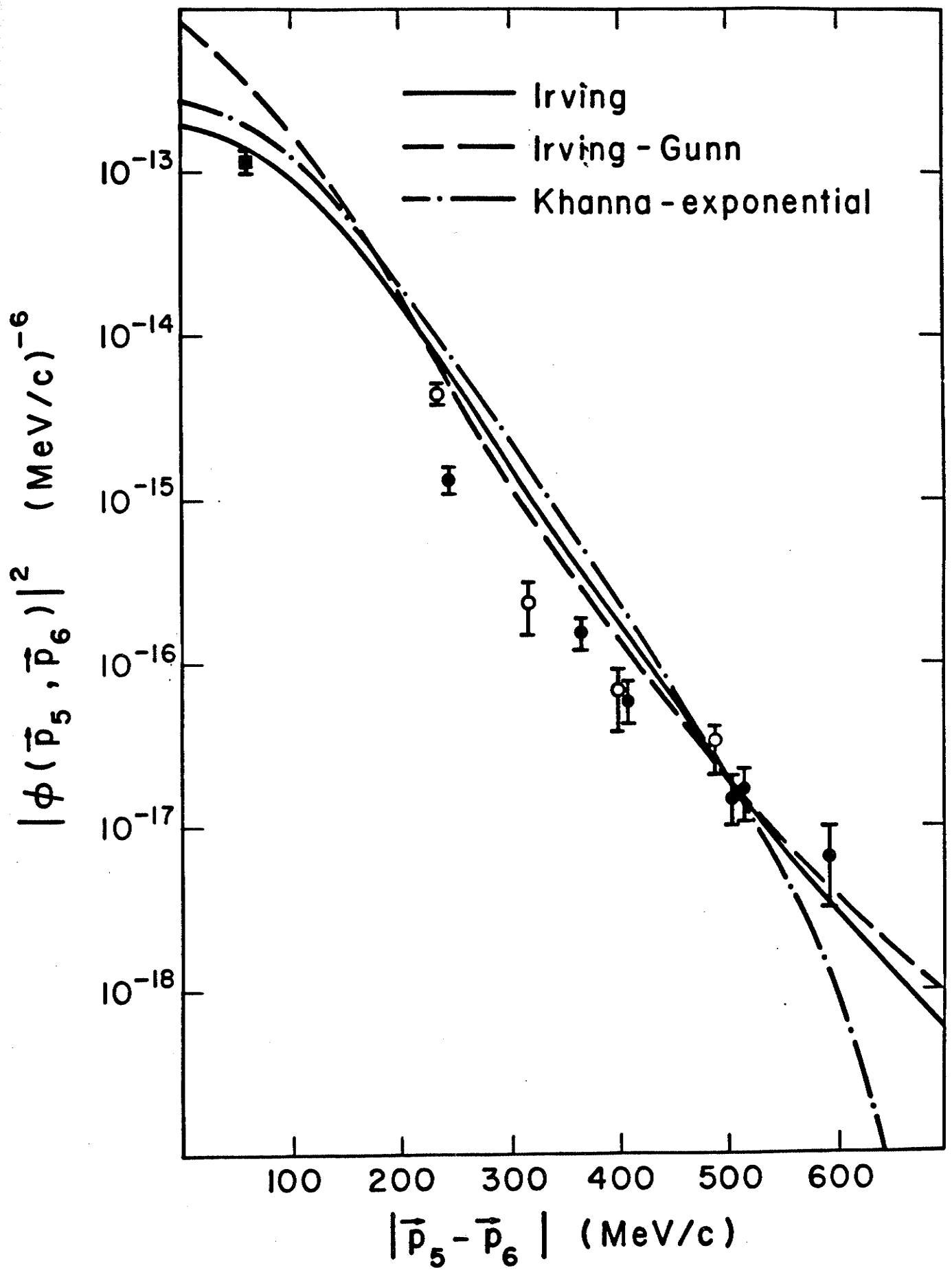


Fig. 26

calculated using the expansion for the t-matrix [Mo-69]:

$$t_{\ell}(\vec{q}_i, \vec{q}_f, T_f) = f_{\ell}(\vec{q}_i, \vec{q}_f) t_{\ell}(\vec{q}_f, \vec{q}_f, T_f) ,$$

with $\vec{q}_i$ the c.m. momentum of the interacting p-p system in the initial state and with $\vec{q}_f$ and T_f , the c.m. momentum and energy, respectively, of the interacting p-p pair in the final state. The quantity $t_{\ell}(\vec{q}_f, \vec{q}_f, T_f)$ is the on-energy-shell t-matrix while $f(\vec{q}_f, \vec{q}_f)$ is the half-off-energy-shell extension function. The calculations were done using the Reid soft-core interaction [Re-68]. For the kinematics of the present experiment the difference between the half-off-energy-shell p-p differential cross section and the quite often used final state on-energy-shell approximation was never more than 30% and in general was less than 10%.

The data represented as $[d^6\sigma/(d\Omega_3 dT_3 d\Omega_4 dT_4)]/[F(d\sigma/d\Omega)_{1/2}^{pp} N]$ are plotted in figure 26 as a function of $|\vec{p}_5 - \vec{p}_6|$, twice the momentum for the relative motion in the c.m. system of the unobserved p-n pair. The error bars shown reflect counting statistics only. The data are subject to an over-all normalization uncertainty of $\pm 10\%$. It should be noted that all the data, but the one at 235.6 MeV/c, which were taken under various kinematic conditions, present a smooth distribution pointing to the validity of the PWIA to first order.

The data are compared with p-n relative motion momentum distributions calculated as the overlap between plane waves for the

neutron and proton and Irving, Irving-Gunn and Khanna wave functions for ^3He ([Gu-51], [Kh-71]). It was assumed that the $T=0$ component of the p-n relative motion wave function mainly contributes to the $^3\text{He}(p,2p)d$ reaction and therefore N was set equal to $1/2$. This assumption is strictly valid only for small p-n relative energies. There appears to exist reasonably good agreement in magnitude and shape with the theoretical distributions for the Irving and Irving-Gunn wave functions. However, the use of plane waves should fail for small p-n relative momenta. The agreement with the theoretical distribution for the more realistic Khanna exponential wave function (with $\beta=307.5$ MeV) is somewhat poorer.

The data represented as $[d^6\sigma/(d\Omega_3 dT_3 d\Omega_4 dT_4)]/[F'(d\sigma/d\Omega)_{1/2}^{p-p}]$ are compared with various theoretical predictions for the ^3He spectral function $S(\vec{P}=0, E)$ in figure 27. It is apparent that the shape of the data agrees fairly well with the spectral functions of Ref. [Me-83] and [Ci-81], which are the dashed-dotted and continuous line in figure 27 and calculated using Faddeev techniques for the Paris two-nucleon potential and using variational techniques with an harmonic oscillator basis, respectively. In these calculations both $T=0$ and $T=1$ contributions have been added. The experiment shows clearly an excess of p-n relative momenta greater than ~ 200 MeV/c amounting to a factor 4 of approximately. Discrepancies have also been observed [Ja-82] (although in a different part of phase space) in a comparison between $^3\text{He}(e,e'p)d$ results and the spectral functions of Ref. [Di-76] and [Ci-81]. In this case both theoretical predictions overestimate the experimental result. However, reasonably good agreement was obtained in comparing $^3\text{He}(e,e'p)pn$ results with the same spectral functions

Fig. 27 Differential cross sections $d^6\sigma/(d\Omega_3 dT_3 d\Omega_4 dT_4)$ divided by the factor $F'(d\sigma/d\Omega)_{1/2}^{P-P}$ as function of the relative momentum of the unobserved p-n pair and the missing energy E_m . The quantity $E_m = E - m_2 + m_4 = E_x - Q$ with E_x the excitation energy of the p-n pair and Q the reaction Q value. The calculated spectral functions are as indicated.

$$|\vec{p}_5 - \vec{p}_6| \text{ (MeV/c)}$$

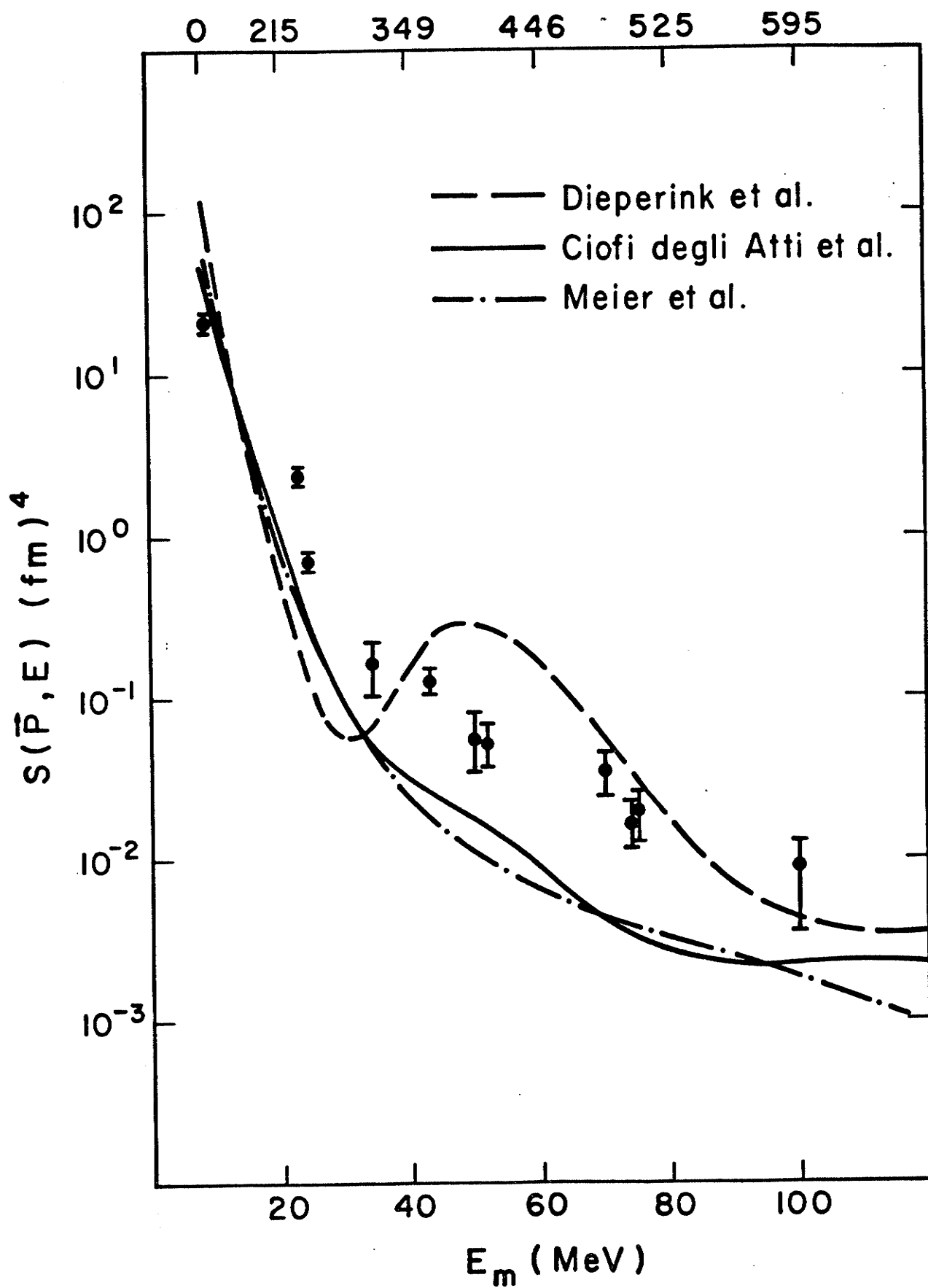


Fig. 27

integrated over missing energies up to 20 MeV [Ja-82]. As a first step in investigating these discrepancies one should further examine the various distortions such as those due to multiple scattering and final state interaction effects. Note that the p-n excitation energies considered here are still far from a real N- Δ pair. Only after the above effects have been studied in more detail can further conclusions be drawn about the spectral functions and the p-n relative motion wave function.

Table II

Kinematics, the measured six-fold differential cross sections and quantities used in deriving $|\phi(\vec{p}_5, \vec{p}_6)|^2$ and $S(\vec{P}, E)$.

T_1 (MeV)	θ_3 (deg.)	θ_4 (deg.)	$ \vec{p}_5 - \vec{p}_6 $ (MeV/c)	E (MeV)	$d^6\sigma / (d\Omega_3 dT_3 d\Omega_4 dT_4)$ $\mu b / (sr^2 MeV^2)$	$(d\sigma/d\Omega)^{p-p^*}$ (mb/sr)	$(d\sigma/d\Omega)^{p-p}_{1/2}$ (mb/sr)
250	40	40	235.6	1892.5	7.29 ± 0.67	3.75	3.60
400	40	40	249.5	1894.3	3.43 ± 0.46	3.82	3.55
250	38	38	316.7	1904.4	0.532 ± 0.181	3.73	3.88
400	34	42	365.6	1913.1	0.516 ± 0.063	3.85	3.39
250	35	35	399.0	1919.7	0.159 ± 0.067	3.83	3.76
400	37	37	409.8	1922.0	0.210 ± 0.062	3.85	3.55
250	30	30	487.0	1939.9	0.070 ± 0.021	4.67	3.12
400	30	38	504.3	1944.4	0.057 ± 0.018	3.82	3.39
400	34	34	507.7	1945.2	0.074 ± 0.025	3.76	3.75
400	30	30	597.3	1970.5	0.029 ± 0.014	3.75	3.69

* $(d\sigma/d\Omega)^{p-p}$ is the on-energy-shell p-p differential cross section obtained from experimental phase shift [Ar-80] using the final state energy approximation.

CHAPTER VI

COMPARISON OF THE $^3\text{He}(p,2p)d$ AND $^3\text{He}(p,pd)p$ REACTIONS.[†]

A direct way to investigate the reaction mechanism for the $(p,2p)$ and (p,pd) reactions is to compare $^3\text{He}(p,2p)d$ with $^3\text{He}(p,pd)p$. In the framework of the Plane Wave Impulse Approximation (PWIA) the proton-deuteron relative motion momentum distributions extracted from $^3\text{He}(p,2p)d$ and $^3\text{He}(p,pd)p$ should be the same. In the PWIA the incident proton interacts only with the ejected proton [or deuteron in the case of (p,pd)] while the recoil system acts as a spectator. Quantitatively, the PWIA differential cross section for these reactions can be written:

$$\frac{d^5\sigma}{d\Omega_3 d\Omega_4 dT_3} = F \left(\frac{d\sigma}{d\Omega} \right)_{1/2}^{p-1} N |\phi(q)|^2$$

where N is a spectroscopic factor determined from spin algebra (for $^3\text{He}(p,2p)d$, $N = 3/2$), F is a kinematic factor, $(d\sigma/d\Omega)_{1/2}^{p-1}$ is properly the half-off-energy-shell p - p or p - d differential cross section, $\phi(q)$ is the Fourier transform of the overlap integral between the ^3He and deuteron wave functions, and q is the recoil momentum of the unobserved particle. The quantity $|\phi(q)|^2$ describes the proton-deuteron relative motion momentum distribution in the target nucleus. It has to be noted that $|\phi(q)|^2$ can be unambiguously extracted in the framework of the PWIA only when the energy of the scattered and ejected particles is much larger than the energy of the recoil system. The product $N|\phi(q)|^2$ is the

[†]to be published in Physics Letters B.

spectral function $S(q,E)$ where E is the separation energy for two-body breakup of ^3He . Spectral functions have been calculated for different nucleon-nucleon potentials using the Faddeev equations or variational techniques.

This simple description of the knockout process neglects many effects such as multiple scattering, final state interactions, and isobar configurations. It accounts though for the dominant part of the reaction mechanism for small recoil momenta and is a first step of the investigation. In addition, only in the framework of the PWIA is it possible to compare directly the theoretical spectral function with the experimental momentum distributions as extracted from $^3\text{He}(p,2p)d$, $^3\text{He}(p,pd)p$, $^3\text{He}(e,e'p)d$, and $^3\text{He}(e,e'd)p$.

Previous studies of the $^3\text{He}(p,2p)d$ and $^3\text{He}(p,pd)p$ reactions have been made by sampling recoil momenta less than 130 MeV/c at incident energies of 35, 45, 65, 85, and 100 MeV ([Sl-71], [Bu-75], [Co-74]). At higher energies the two reactions have been measured at 155 MeV and 590 MeV ([Fr-71], [Ki-72]). The momentum distributions extracted from the $^3\text{He}(p,2p)d$ and $^3\text{He}(p,pd)p$ reactions at 155 MeV range between 0 and 120 MeV/c and are in good agreement with each other indicating the validity of factorization for the three-body differential cross sections. The $^3\text{He}(p,2p)d$ data obtained at 590 MeV could not be directly compared with the $^3\text{He}(p,pd)p$ data at the same incident energy because they lacked adequate resolution so that a separation between $^3\text{He}(p,2p)d$ and $^3\text{He}(p,2p)d^*$ was not possible. For the $^3\text{He}(p,pd)p$ reaction at 590 MeV recoil momenta up to 230 MeV/c were obtained.

The objectives of the present experiment were to measure $^3\text{He}(p,2p)d$ and $^3\text{He}(p,pd)p$ for large recoil momenta (up to 500 MeV/c,

which is a region of recoil momenta previously unexplored), to compare the experimental results with each other and with the recent quasi-free electron scattering results for $^3\text{He}(e,e'p)d$ [Ja-82], and finally to compare the extracted momentum distributions with various predictions for the spectral function.

The experiment was performed using proton beams from the TRIUMF accelerator incident on a liquid ^3He ($L^3\text{He}$) target [Ha-81b].

Normalization of the differential cross sections was obtained from the sum of left and right counts in the proton beam polarimeter (containing a 5 mg/cm^{-2} thick CH_2 foil) located upstream of the target location, which had previously been calibrated against a Faraday cup. The $L^3\text{He}$ target thickness was determined through measurements of the temperature of the target cell taken with germanium resistors placed at its top and bottom and from the target cell physical dimensions. The thickness so determined was $104 \pm 4\text{ mg/cm}^2$. The target cell radius was 2.2 cm.

The detection system for $^3\text{He}(p,2p)d$ consisted of a quadrupole-dipole magnetic spectrometer to measure the momentum of the ejected proton and two identical NaI(Tl) counter telescopes to measure energy and position of the other, scattered proton and recoil deuteron. The combined energy resolution of the incident beam and detection apparatus was not quite adequate to resolve the $^3\text{He}(p,2p)d$ locus from the four-body continuum when detecting only the two protons. Thus, in addition to the two protons, the recoil deuteron was detected in a triple coincidence arrangement. The range of recoil momenta was restricted to $q > 350\text{ MeV/c}$. The counter telescopes were mounted on a platform and they were positioned with an accuracy of 0.1° . Each counter telescope consisted of a 12.5 cm by 12.5 cm delayline multiwire proportional

chamber (MWPC) followed immediately by a 0.08 cm thin plastic scintillator, an annular veto counter (with an aperture 10.2 cm in diameter), some copper energy degrader (if needed), and a 12.7 cm diameter by 15.2 cm thick NaI(Tl) detector. The magnetic spectrometer detection system consisted of a 0.08 cm thick plastic scintillator plus a 12.5 cm MWPC with horizontal and vertical coordinates used to define the solid angle, a set of 25.6 cm by 102.4 cm MPWC's mounted about the focal plane and a 2.5 cm thick plastic scintillator. The time-of-flight distance through the spectrometer was 11.0 m. The $^3\text{He}(p,2p)d$ reaction was measured at 300 MeV at the angle pair $70^\circ-33^\circ$ and at 450 MeV at the angle pairs $70^\circ-30^\circ$ and $46^\circ-46^\circ$.

For the $^3\text{He}(p,pd)p$ reaction, the momentum of the ejected deuteron was measured with the magnetic spectrometer while the scattered proton was detected by either one of the two right hand side counter telescopes. The flight path through the spectrometer was sufficiently long to separate protons from deuterons. The $^3\text{He}(p,pd)p$ reaction was measured at the angle pairs $25^\circ-68^\circ$ and $50^\circ-68^\circ$ at an incident energy of 450 MeV. At the first angle pair a complete energy spectrum was obtained corresponding to recoil momenta from 0 to 450 MeV/c, while at the second angle pair only part of the energy spectrum was measured. The kinematical conditions chosen correspond to large relative energies between the three final state particles and a small momentum transfer $|\vec{p}_3 - \vec{p}_1|$ (where $\vec{p}_1$ and $\vec{p}_3$ are the momenta of the incident and scattered protons, respectively). The first requirement reduces the final state

interactions between the reaction products, the second leads to a larger p-d differential cross section which is necessary to maintain an adequate counting rate at large recoil momenta.

Energy calibrations for the counter telescopes were obtained by observing p-p scattering from a CH₂ target at a series of angles covering the range of energies of interest.

An important aspect of the data reduction was the construction of the missing energy spectra. The missing energy is defined as $E_{\text{miss}} = T_3 + T_4 + T_5 - T_1$ with the T_i denoting the kinetic energies of the particles. The only events selected were within the missing energy peak whose centroid has a value equal to the two-body breakup energy for ³He. This peak is very well separated from the rest of the events since most of the background was eliminated by the trigger requirement. The background due to accidental events was removed using standard techniques. Background events originating in the entrance and exit foils of the target cell and cryostat tail section were subtracted using the data collected with a dummy target. The data were further corrected for computer dead time, pile-up rejections, MWPC inefficiencies, inefficiencies, and losses due to nuclear reactions in the NaI(Tl) detectors. The efficiency of the counter telescopes was previously measured and reported in Ref. [Br-83] and chapter 4. The energy resolution of the counter telescopes varied between 7 and 9 MeV (FWHM). The fivefold differential cross sections were obtained from 10 MeV bites in the kinetic energy T_3 of the scattered particle for the ³He(p,2p)d reaction and from 10 MeV bites in the kinetic energy T_4 of the ejected particle for the ³He(p,pd)p reaction. The solid angles corresponded to the regions of the NaI(Tl) detectors and magnetic spectrometer with

constant efficiency. The data are presented in Tables III, IV, V and VI. The relative energies (T_{34} , T_{35} , T_{45}) of the ejected and scattered particles, of the scattered and recoil particles, and of the ejected and recoil particles are also presented.

Figure 28 shows the experimental spectral functions as extracted from the $^3\text{He}(p,2p)d$ and $^3\text{He}(p,pd)p$ data as a function of recoil momentum in the laboratory system. The error bars, in most cases within the symbols, reflect the statistical error only. The overall normalization uncertainty is $\pm 10\%$. The kinetic energies and the scattering angles for either the p-p or the p-d differential cross sections were calculated in the center of mass system of the scattered and ejected particles. The half-off-energy-shell p-p or p-d differential cross sections were approximated by on-energy-shell values. The values of the p-p differential cross sections were calculated from phase shift analyses [Ar-83], while the values of the p-d differential cross sections were obtained from spline fits of existing data ([Ch-53], [Po-61], [Ku-66], [Sc-51], [Ch-56], [Bo-71], [Bo-72] and [Wi-80]).

Although a distorted wave impulse approximation approach may be interesting, it presents many computational difficulties, in particular, in generating distorted waves. Instead, a direct comparison of the data to the PWIA calculations is made to establish the overall effect of other contributions to the reaction mechanism. Curve 1 in figure 28, which is a PWIA prediction based on an Irving-Gunn ^3He wave function and a Hulthén deuteron wave function, is inadequate only at high recoil momenta. A number of ^3He spectral functions have been calculated from different N-N potentials and using different techniques to obtain approximate solutions of the Schrödinger equations. The spectral func-

Fig. 28 Experimental proton-deuteron relative motion momentum distribution times the spectroscopic factor as function of the p-d relative momentum. The ${}^3\text{He}(p,pd)p$ 25° - 68° data are presented as filled squares, the ${}^3\text{He}(p,pd)p$ 50° - 68° data are presented as open circles, and the ${}^3\text{He}(p,2p)d$ data as solid squares. Curve 1 is a PWIA calculation with a Hulthén deuteron wave function and an Irving-Gunn ${}^3\text{He}$ wave function. Curves 2 and 3 are the spectral functions calculated by Gibson and Lehman with 4% and 7% D-state for the deuteron, respectively.

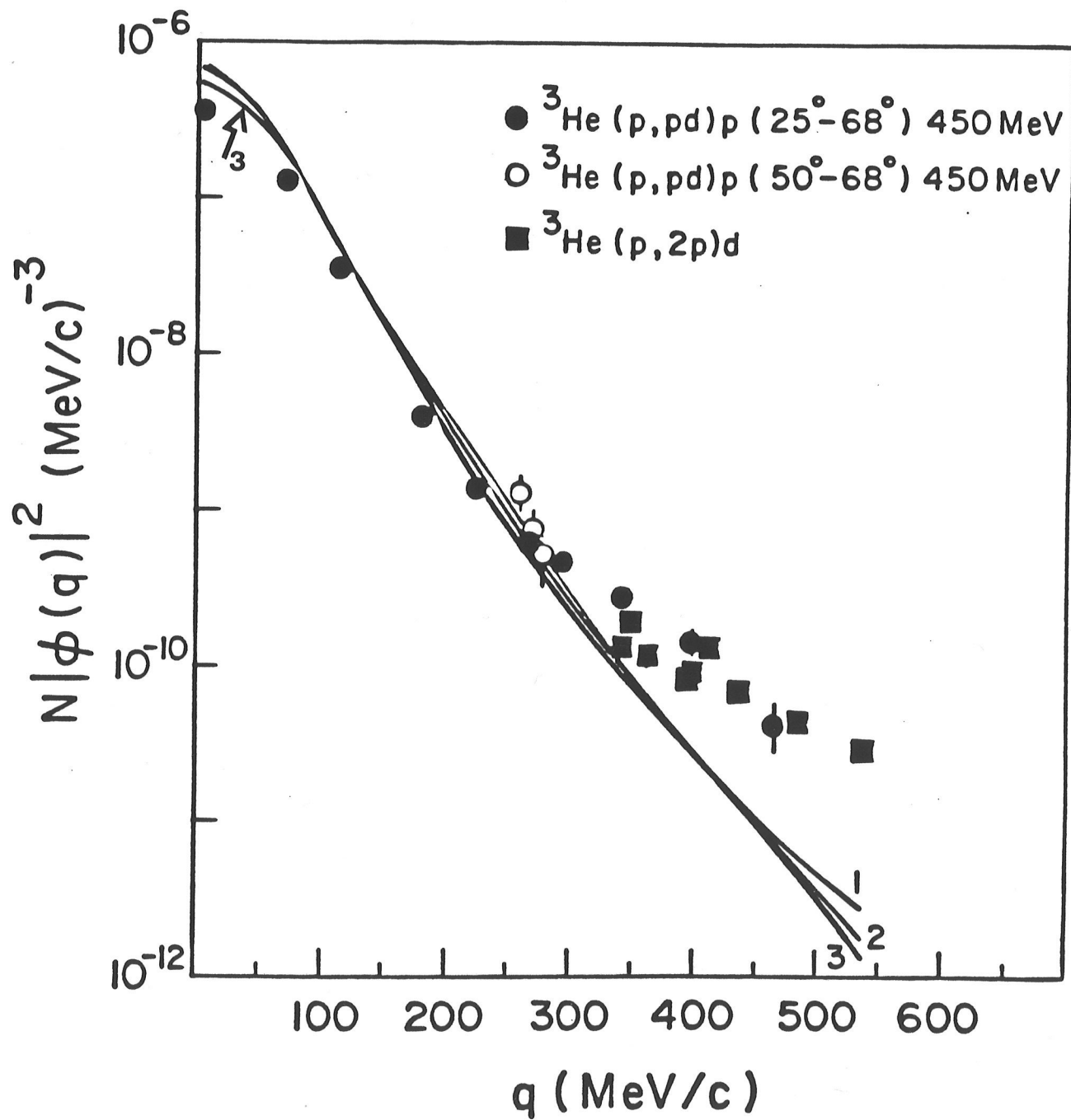


Fig. 28

tions calculated by Gibson and Lehman [Gi-82] are shown in figure 28 (curves 2 and 3). They have been obtained using separable potentials (1S_0 , 3S_1 - 3D_1) of the Yamaguchi form. The strength and range parameters were determined by fitting the low energy properties of the two-nucleon system such as scattering length, effective range, and deuteron binding energy and quadrupole moment. Curve 2 is obtained with 4% D-state for the deuteron, while curve 3 corresponds to 7% D-state. In figure 29 the momentum distribution extracted from the data of the present experiment is compared with those extracted from the $^3\text{He}(p,pd)p$ data at 590 MeV and from the $^3\text{He}(e,e'p)d$ data at 530 MeV. There is fairly good agreement of the present results with the 590 MeV $^3\text{He}(p,pd)p$ results while the agreement with the $^3\text{He}(e,e'p)d$ momentum distribution is good only for $50 \text{ MeV}/c < q < 200 \text{ MeV}/c$. In the case of the present data the discrepancy near zero recoil can be ascribed to the low relative energy between the ejected deuteron and the recoil proton which makes distortion effects particularly large. For the high recoil momentum region of the $^3\text{He}(p,pd)p$ reaction, the relative energy of the scattered and recoil protons decreases as the recoil momentum increases and therefore distortion effects cannot be entirely neglected also in this region. Curve 1 of figure 29 is the ^3He spectral function calculated by Dieperink et al. [Di-76] from a ^3He ground state wave function obtained by Brandenburg, Kim and Tubis [Br-75] for the Reid soft core (RSC) interaction acting in the 1S_0 and 3S_1 - 3D_1 states using Faddeev techniques. More recently, Meier-Hajduk et al. [Me-83] have derived the ^3He spectral function with improved numerical accuracy using both the RSC and Paris potentials. These results are indicated by curves 2 and 3 of figure 29, respectively. One can notice, that these spectral functions are not very

Fig. 29 Experimental momentum distribution times the spectroscopic factor as in figure 28 plus the 590 MeV $^3\text{He}(p, pd)p$ data shown as filled diamonds, and the 530 MeV $^3\text{He}(e, e'p)d$ data shown as asterisks. Curve 1 is the spectral function calculated by Dieperink et al., curves 2 and 3 by Meier-Hajduk et al. with the RSC and Paris potential, respectively, and curve 4 by Ciofi degli Atti et al.

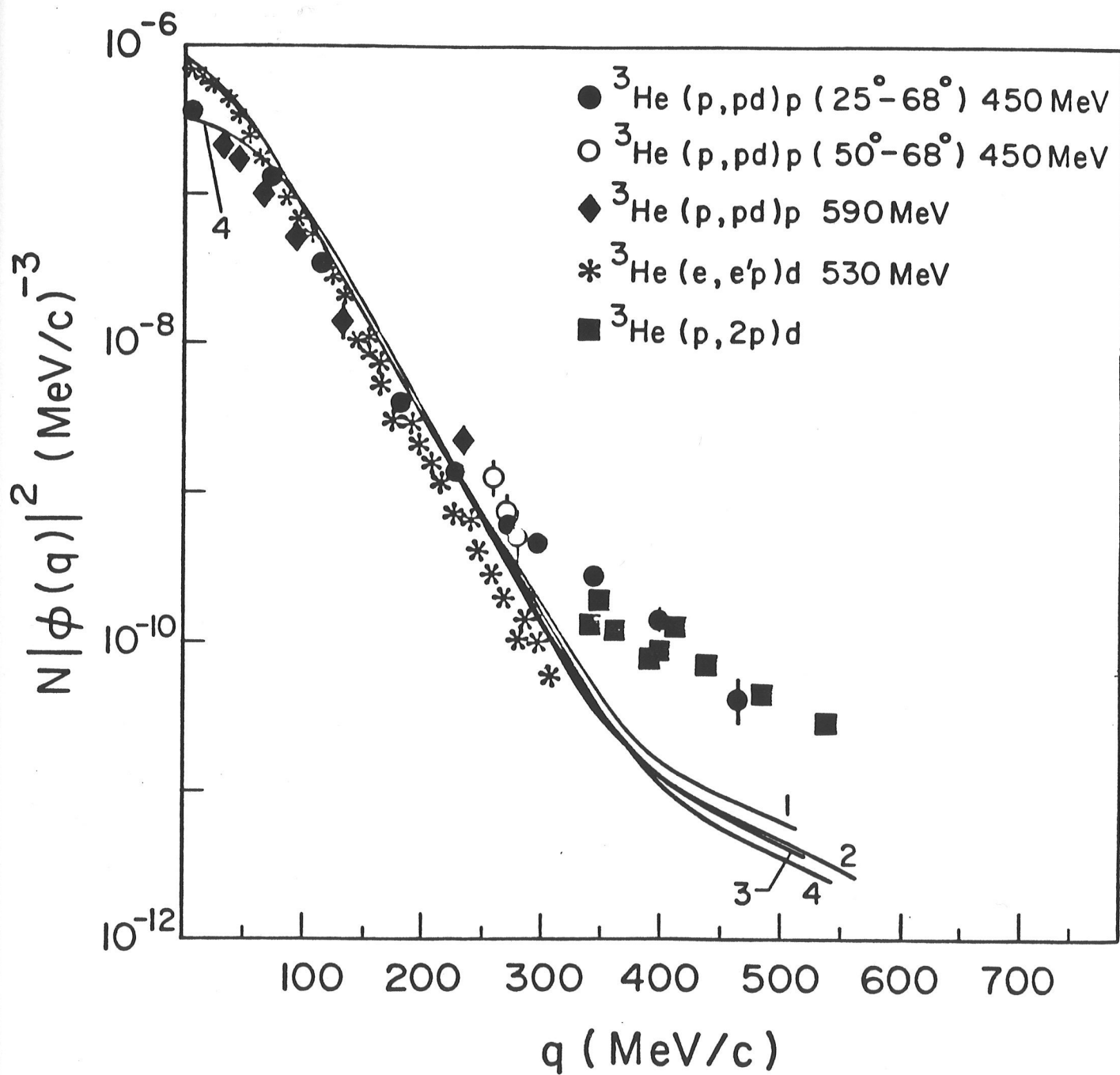


Fig. 29

sensitive to the choice of the N-N potential. The data are in disagreement with the theoretical results in the region of large recoil momenta. Curve 4 of figure 29 is the spectral function calculated by Ciofi degli Atti, Pace and Salmé [Ci-81] using the variational wave function of Nunberg, Prosperi and Pace [Nu-77] with corrected asymptotic behaviour of the harmonic oscillator basis expansion wave function. The disagreement with the experimental results is also here present.

The failure of the PWIA to account for the measured yield at large recoil momenta ($q > 250$ MeV/c) indicates the presence of other contributions neglected in this first order scheme. Although these effects are large, it is to be noted that the ratio of the cross sections for $^3\text{He}(p,2p)d$ and $^3\text{He}(p,pd)p$ agrees with that predicted by the PWIA. The same result was obtained by Cowley et al. in a comparison of $^3\text{He}(p,2p)d$ and $^3\text{He}(p,pd)p$ at 65, 85, and 100 MeV at low recoil momenta and by Frascaria et al. at 155 MeV for recoil momenta < 120 MeV/c. It should be pointed out that the agreement between $^3\text{He}(p,2p)d$ and $^3\text{He}(p,pd)p$ is destroyed for less judiciously selected $^3\text{He}(p,pd)p$ kinematic configurations [Ep-83]. To explain the large discrepancies between the experimental and calculated spectral functions at large recoil momenta, more sophisticated calculations including multiple scattering, final state interaction, and off-energy-shell effects need to be made. Only then will it be possible to assess the adequacy of the wave functions used. Examining these effects will be a challenging task.

TABLE III

${}^3\text{He}(p, \text{pd})p$ $T_1 = 450 \text{ MeV}$ $\theta_3 = 25^\circ$ $\theta_4 = 68^\circ$

P_5 (MeV/c)	T_4 (MeV)	$T_{\text{lab}}^{\text{pd}}$ (MeV)	θ_{cm}	$(d\sigma/d\Omega)^{p-d}$ ($\mu\text{b/sr}$)	Kin. fact. (MeV^2)	$d^5\sigma/(d\Omega_3 d\Omega_4 dT_4)$ ($\mu\text{b}/(\text{sr}^2 * \text{MeV})$)
4.7	50.0	441.5	40.8°	613 ± 57	$0.207 * 10^7$	460 ± 11
72.4	65.0	435.1	40.6°	624 ± 60	$0.240 * 10^7$	191 ± 5.0
116.2	75.0	427.8	40.5°	636 ± 62	$0.261 * 10^7$	58.1 ± 1.7
181.1	90.0	412.6	40.4°	661 ± 64	$0.292 * 10^7$	7.51 ± 0.36
224.9	100.0	399.4	40.4°	686 ± 82	$0.313 * 10^7$	2.91 ± 0.22
270.1	110.0	383.4	40.4°	730 ± 88	$0.337 * 10^7$	1.40 ± 0.15
293.5	115.0	374.3	40.4°	795 ± 95	$0.350 * 10^7$	1.26 ± 0.17
342.9	125.0	353.0	40.9°	902 ± 108	$0.380 * 10^7$	0.926 ± 0.139
397.9	135.0	326.6	41.5°	1050 ± 126	$0.424 * 10^7$	0.677 ± 0.119
464.8	145.0	291.1	42.6°	1178 ± 141	$0.514 * 10^7$	0.249 ± 0.080

${}^3\text{He}(p, \text{pd})p$ $T_1 = 450 \text{ MeV}$ $\theta_3 = 50^\circ$ $\theta_4 = 68^\circ$

259.8	115.0	503.2	69.4°	747 ± 48	$0.370 * 10^7$	0.342 ± 0.086
264.0	125.0	500.7	69.0°	746 ± 48	$0.407 * 10^7$	0.217 ± 0.076
278.2	135.0	493.8	68.5°	745 ± 48	$0.452 * 10^7$	0.172 ± 0.070

TABLE IV

${}^3\text{He}(p, pd)p$ $T_1 = 450 \text{ MeV}$ $\theta_3 = 25^\circ$ $\theta_4 = 68^\circ$

P_5 (MeV/c)	T_3 (MeV)	T_4 (MeV)	T_{34} (MeV)	T_{35} (MeV)	T_{45} (MeV)	$N \Phi(P_5) ^2$ (MeV/c) $^{-3}$
4.7	394.5	50.0	280.4	186.2	17.1	$(0.362 \pm 0.009) \cdot 10^{-6}$
72.4	376.7	65.0	276.4	167.1	35.2	$(0.128 \pm 0.004) \cdot 10^{-6}$
116.2	362.3	75.0	272.0	153.6	49.6	$(0.350 \pm 0.010) \cdot 10^{-7}$
181.1	337.2	90.0	262.7	132.4	74.5	$(0.389 \pm 0.019) \cdot 10^{-8}$
224.9	317.9	100.0	254.7	117.6	93.2	$(0.135 \pm 0.010) \cdot 10^{-8}$
270.1	296.4	110.0	244.9	102.5	113.7	$(0.569 \pm 0.061) \cdot 10^{-9}$
293.5	284.7	115.0	239.3	94.8	124.8	$(0.453 \pm 0.061) \cdot 10^{-9}$
342.9	258.8	125.0	226.2	79.2	148.7	$(0.270 \pm 0.041) \cdot 10^{-9}$
397.9	228.6	135.0	209.9	63.2	175.8	$(0.152 \pm 0.027) \cdot 10^{-9}$
464.8	190.7	145.0	187.8	46.9	208.4	$(0.411 \pm 0.132) \cdot 10^{-10}$

${}^3\text{He}(p, pd)p$ $T_1 = 450 \text{ MeV}$ $\theta_3 = 50^\circ$ $\theta_4 = 68^\circ$

259.8	294.2	115.0	317.5	94.8	41.3	$(0.124 \pm 0.031) \cdot 10^{-8}$
264.0	283.1	125.0	316.0	79.2	53.6	$(0.715 \pm 0.250) \cdot 10^{-9}$
278.2	269.1	135.0	311.9	63.2	69.0	$(0.511 \pm 0.208) \cdot 10^{-9}$

TABLE V

${}^3\text{He}(p, 2p)d$ $T_1 = 450 \text{ MeV}$ $\theta_3 = 46^\circ$ $\theta_4 = 46^\circ$

P_5 (MeV/c)	T_3 (MeV)	$T_{\text{lab}}^{\text{pp}}$ (MeV)	θ_{cm}	$(d\sigma/d\Omega)^{p-p}$ ($\mu\text{b/sr}$)	Kin. fact. (MeV^2)	$d^5\sigma/(d\Omega_3 d\Omega_4 dT_4)^*$ ($\mu\text{b}/(\text{sr}^2 \cdot \text{MeV})$)
340.4	325.0	457.8	92.6°	3595	$0.259 \cdot 10^7$	1.26 ± 0.14
397.5	335.0	438.7	91.9°	3666	$0.287 \cdot 10^7$	0.954 ± 0.124

${}^3\text{He}(p, 2p)d$ $T_1 = 450 \text{ MeV}$ $\theta_3 = 70^\circ$ $\theta_4 = 30^\circ$

356.3	200.0	535.1	125.7°	3808	$0.271 \cdot 10^7$	1.24 ± 0.09
393.8	210.0	524.5	125.7°	3807	$0.276 \cdot 10^7$	0.857 ± 0.070
434.7	220.0	511.1	125.7°	3788	$0.283 \cdot 10^7$	0.738 ± 0.064
480.5	230.0	493.7	125.7°	3777	$0.293 \cdot 10^7$	0.482 ± 0.050
534.5	240.0	470.4	124.5°	3781	$0.313 \cdot 10^7$	0.333 ± 0.041

${}^3\text{H}(p, 2p)d$ $T_1 = 300 \text{ MeV}$ $\theta_3 = 70^\circ$ $\theta_4 = 33^\circ$

349.6	152.0	342.4	121.9°	3805	$0.220 \cdot 10^7$	1.53 ± 0.09
407.2	162.0	323.7	121.2°	3804	$0.239 \cdot 10^7$	1.17 ± 0.08

*
From [Kr-83]

TABLE VI

${}^3\text{He}(p, 2p)d$ $T_1 = 450 \text{ MeV}$ $\theta_3 = 46^\circ$ $\theta_4 = 46^\circ$

P_5 (MeV/c)	T_3 (MeV)	T_4 (MeV)	T_{34} (MeV)	T_{35} (MeV)	T_{45} (MeV)	$N* \Phi(P_5) ^2$ (MeV/c) $^{-3}$
340.4	325.0	88.9	216.4	255.1	22.5	$(0.135 \pm 0.015)*10^{-9}$
397.5	335.0	67.9	207.8	271.1	11.4	$(0.908 \pm 0.012)*10^{-10}$

${}^3\text{He}(p, 2p)d$ $T_1 = 450 \text{ MeV}$ $\theta_3 = 70^\circ$ $\theta_4 = 30^\circ$

356.3	200.0	211.0	250.8	182.1	74.5	$(0.120 \pm 0.009)*10^{-9}$
393.8	210.0	193.6	246.1	197.3	62.0	$(0.815 \pm 0.067)*10^{-10}$
434.7	220.0	174.8	240.2	213.4	49.5	$(0.689 \pm 0.059)*10^{-10}$
480.5	230.0	154.0	232.5	230.6	36.9	$(0.436 \pm 0.045)*10^{-10}$
534.5	240.0	129.8	222.0	249.6	24.2	$(0.282 \pm 0.035)*10^{-10}$

${}^3\text{He}(p, 2p)d$ $T_1 = 300 \text{ MeV}$ $\theta_3 = 70^\circ$ $\theta_4 = 33^\circ$

349.6	152.0	110.2	164.0	144.4	29.7	$(0.182 \pm 0.010)*10^{-9}$
407.2	162.0	88.8	155.4	162.1	17.3	$(0.128 \pm 0.008)*10^{-9}$

CONCLUSION

The experimental p-n relative motion momentum distribution extracted from the $^3\text{He}(p,2p)np$ measurements is rather smooth and appears independent of geometry and incident energy. This indicates the validity of the PWIA to first order. The experimental data show a reasonably good agreement in magnitude and shape with the p-n momentum distribution calculated as the overlap between plane waves for the neutron and proton and Irving, Irving-Gunn, and Khanna wave functions for ^3He . However it is assumed that the $T=0$ component of the p-n relative motion wave function contributes mainly to the $^3\text{He}(p,2p)d$ reaction and this assumption is strictly valid only for small p-n relative energies where the use of plane waves to describe the p-n relative motion should fail. The comparison of the data with the predictions for the ^3He spectral function $S(P=0,E)$ where both $T=0$ and $T=1$ contributions have been added, shows that there is only fair agreement in terms of shape. The spectral functions had been calculated using Faddeev techniques with the Paris two-nucleon potential and variational techniques with an harmonic oscillator basis. An excess of p-n relative momenta greater than ~ 200 MeV/c is found which amounts to approximately a factor of 4.

The p-d relative motion momentum distributions were extracted from the $^3\text{He}(p,2p)d$ and $^3\text{He}(p,pd)p$ reactions in the framework of the PWIA and compared with existing $^3\text{He}(p,pd)p$ and $^3\text{He}(e,e'p)d$ data and ^3He spectral functions. The data of the present experiment show good agreement with the existing data and the calculated spectral

functions only for recoil momenta up to 250 MeV/c . The excess of high momentum components at large recoil momenta can be understood, at least in part, since a number of contributions are neglected in PWIA. However, the ratio of the momentum distributions obtained from $^3\text{He}(p,2p)d$ and $^3\text{He}(p,pd)p$ reactions is consistent with 1 as predicted in the PWIA. The same results have been obtained in low energy experiments. It is clear though, that more sophisticated calculations are required. Of particular significance and interest are the inclusion in the calculations of multiple scattering, final state interaction, and off-energy-shell effects.

In conclusion, to obtain a more rigorous derivation of the momentum distributions from the $^3\text{He}(p,2p)d$, $^3\text{He}(p,2p)np$, and $^3\text{He}(p,pd)p$ reactions, it is necessary to account for many interfering effects also at intermediate energies. The equivalent corrections for these effects have also been suggested for other light nuclei like d and ^4He ([Fe-76], [va-82]). One way to understand these effects is to study the knockout reactions with different probes. For example, further experimental studies, such as $^3\text{He}(e,e'd)p$ for high recoil momenta and $^3\text{He}(e,e'p)np$ for the same region of momentum space as the present $^3\text{He}(p,2p)np$ experiment are suggested as one way to continue investigation of knockout reactions and wave functions for few-nucleon systems.

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APPENDIX

I. $^3\text{He}(p,2p)d$ and $^3\text{He}(p,pd)p$ in PWIA

A derivation of the five-fold differential cross section for the $^3\text{He}(p,2p)d$ and $^3\text{He}(p,pd)p$ reactions in the framework of the PWIA is given. The kinematical variables (such as kinetic energy T , momentum p , total energy E , position r) of the incident particle, target nucleus, scattered particle, ejected particle and recoil system are labelled with the indices 1,2,3,4, and 5, respectively. The primed quantities refer to the centre of mass system (CM) while the unprimed quantities refer to the laboratory system. The spatial coordinates of the reaction participants are defined with respect to the centre of mass of the target nucleus. The coordinates which describe the system before the interaction are $\vec{r}_1, \vec{r}_2^*, \vec{r}_3^*$, and $\vec{r}_4^*$. The position of the incident proton is given by $\vec{r}_1$, while $\vec{r}_2^*, \vec{r}_3^*$, and $\vec{r}_4^*$ are the coordinates of the nucleons inside ^3He . The wave functions describing the reaction participants in the initial state are a plane wave for the incident proton (function of $\vec{r}_1$ and $\vec{k}_1$) and a ^3He wave function. It is convenient to use the Jacobi coordinates $\vec{r}$ and $\vec{\rho}$ and to express the ^3He wave function in terms of these coordinates which are given by:

$$\vec{r} = \vec{r}_3^* - \vec{r}_4^* . \quad (\text{I.1})$$

$$\vec{\rho} = \vec{r}_2^* - \frac{1}{2}(\vec{r}_3^* + \vec{r}_4^*) . \quad (\text{I.2})$$

According to this picture, the relative motion of two of the ${}^3\text{He}$ nucleons is described by the coordinate $\vec{r}$ while the relative motion of the other nucleon with respect to the CM of the remaining pair inside ${}^3\text{He}$ is described by the coordinate $\vec{\rho}$. The CM of the three nucleon system is at rest before the collision. The wave functions describing the system after the reaction has taken place are plane waves (for the motion of the centre of mass of the scattered, ejected, and recoiling particles) and a deuteron wave function which is a function of $\vec{r}$. $\vec{r}_1$ becomes $\vec{r}_3$ in the final state and the coordinate of the relative motion of the CM of the ejected and recoiling system is again $\vec{\rho}$.

Starting with the transition probability per unit time, one can write:

$$w = \frac{2\pi}{\hbar} |T_{fi}|^2 \rho(E) \quad (I.3)$$

where T_{fi} is the matrix element for the transition from initial to final state, and $\rho(E)$ is the final state density per unit energy or phase space factor. It is a function of the total energy of the system E .

One can also express w in terms of a Lorentz invariant phase space factor $R(E)$ and transition matrix element $|\bar{M}_{fi}|^2$. Before giving the expressions of $R(E)$ and $|\bar{M}_{fi}|^2$, it is convenient to make a short digression to explain how relativistically-invariant probability densities are obtained. In non-relativistic quantum mechanics the probability density of one particle is $|\phi|^2$ with ϕ being the wave function describing the particle and

$$\int |\psi|^2 d^3x = 1 .$$

This last expression is not relativistically invariant. The density observed by a moving system appears greater by a factor $\gamma=(1-v^2/c^2)^{-1/2}$ because of the Lorentz contraction of the volume element. However, the total energy has also changed by the same factor γ . If one therefore uses as probability density the expression $|(2E/2m)\psi|^2$, the density will be relativistically invariant (the factor of 2 is a convention). The expression of the transition probability is multiplied by

$$\left(\prod_{i=1}^n \frac{2E_i}{2m_i} \right) \left(\prod_{i=1}^n \frac{2m_i}{2E_i} \right) . \quad (I.4)$$

The transition probability then becomes:

$$w = \frac{2\pi}{\hbar} \left(\prod_{i=1}^n \frac{2m_i}{2E_i} \right) \cdot \left(\prod_{i=3}^5 2m_i \right) |M_{fi}|^2 \cdot \left(\prod_{i=1}^5 \frac{1}{2E_i} \right) \rho(E) . \quad (I.5)$$

Since the Lorentz invariant phase space factor is

$$R(E) = \left(\prod_{i=3}^5 \frac{1}{2E_i} \right) \rho(E) , \quad (I.6)$$

one can rewrite (I.5) as

$$w = \frac{2\pi}{\hbar} |\overline{M}_{fi}|^2 R(E) , \quad (I.7)$$

with

$$\bar{M}_{fi} = \left(\prod_{i=1}^2 \frac{2m_i}{2E_i} \right)^{1/2} \left(\prod_{i=3}^5 \frac{2m_i}{2E_i} \right)^{1/2} M_{fi} . \quad (I.8)$$

The five-fold differential cross section in terms of the transition probability is:

$$\frac{d^5\sigma}{d\Omega_3 d\Omega_4 dT_4} = L^3 \cdot \frac{E_1}{p_1 c} \cdot \frac{2\pi}{M} |\bar{M}_{fi}|^2 \cdot \frac{dR_3}{d\Omega_3 d\Omega_4 dT_4} .$$

(I.9) M_{fi} is the Lorentz invariant transition matrix given by:

$$M_{fi} = \int d\vec{r}_3 d\vec{r}_4 \bar{\chi}(3) \bar{\chi}(4) V(\vec{r}_3 - \vec{r}_4) \chi(1) \chi(2) \psi_d(\vec{r}_4) , \quad (I.10)$$

$$\psi_d(\vec{r}_4) = \int d\vec{r}_5 d\vec{r} \bar{\chi}(5) \psi_d(\vec{r}) \psi_{3He}(\vec{\rho}, \vec{r}) .$$

(I.11) $V(\vec{r}_3 - \vec{r}_4)$ is a potential describing the interaction between particles 3 and 4.

The $\chi(i)$ and $\bar{\chi}(i)$ are the plane waves defined as

$$\chi(i) = [2E_i/2m_i]^{1/2} (L)^{-3/2} \exp(i\vec{k}_i \cdot \vec{r}_i) \quad (I.12)$$

$$\bar{\chi}(i) = [2E_i/2m_i]^{1/2} (L)^{-3/2} \exp(-i\vec{k}_i \cdot \vec{r}_i) . \quad (I.13)$$

Since $\vec{\rho} = \vec{r}_4 - \vec{r}_5$ [see (I.2)] $\bar{\chi}(5)$ can be rewritten as:

$$\begin{aligned} \bar{\chi}(5) = & \left\{ \left(\frac{2m_4}{2E_{42}} \right)^{1/2} \cdot L^{3/2} \right\} \cdot \left\{ \left(\frac{2E_{42}}{2m_4} \right)^{1/2} \cdot L^{-3/2} \cdot \exp(-\vec{k}_5 \cdot \vec{r}_4) \right\} \cdot \\ & \cdot \left\{ \left(\frac{2E_5}{2m_4} \right)^{1/2} \cdot L^{-3/2} \cdot \exp(\vec{k}_5 \cdot \vec{\rho}) \right\} , \end{aligned} \quad (I.14)$$

with

$$E_{42}^2 = (-\vec{k}_5)^2 + m_4^2 \quad (I.15)$$

In addition, let $\chi^*(4)$ be:

$$\chi^*(4) = \left[\frac{2E_{42}}{2m_4} \right]^{1/2} (L)^{-3/2} \exp(-\vec{k}_5 \cdot \vec{r}_4) . \quad (I.16)$$

After defining $\rho^{1/2}(k_5)$ to be the overlap integral between the deuteron and the ^3He wave function and T_{LAB}^{p-j} to be the transition matrix element for the scattering of incident proton and ejected particle, the expression of M_{fi} is:

$$M_{fi} = T_{\text{LAB}}^{p-j} \cdot \left\{ \left[\frac{2m_4}{2E_{42}} \right]^{1/2} L^{2/3} \right\} \left\{ \left[\frac{2E_5}{2m_5} \right]^{1/2} L^{-3/2} \right\} \rho^{1/2}(k_5) \quad (I.17)$$

with

$$\rho^{1/2}(k_5) = \int d\vec{\rho} \exp(i\vec{k}_5 \cdot \vec{\rho}) \int d\vec{r} \psi_d(\vec{r}) \psi_{^3\text{He}}(\vec{\rho}, \vec{r}) , \quad (I.18)$$

$$T_{\text{LAB}}^{p-j} = \int d\vec{r}_3 d\vec{r}_4 \chi(3) \bar{\chi}(4) V(\vec{r}_3 - \vec{r}_4) \chi(1) \chi^*(4) . \quad (I.19)$$

T_{LAB}^{p-j} can be expressed in terms of the two-body differential cross section in the centre of mass of particles p and j. The differential cross section for the interaction of the incident proton with the ejected particle is:

$$\left(\frac{d\sigma}{d\vec{r}} \right)_{\text{CM}}^{p-j} = \frac{L^3}{v_{34}} w = \left(\frac{L^3}{v_{34}} \right) \frac{2\pi}{\hbar} |T_{\text{CM}}^{p-j}|^2 \frac{dR_2}{d\Omega_3} \quad (I.20)$$

with

$$\frac{1}{v_{34}'} = \frac{1}{v_3' + v_4'} = \frac{1}{p_3' c} \frac{E_3' E_4'}{E_3' + E_4'} . \quad (I.21)$$

T_{CM}^{P-J} is the transition matrix element which is Lorentz invariant and, as a consequence, it has the same value in the CM and laboratory systems:

$$|T_{CM}^{P-J}|^2 = |T_{LAB}^{P-J}|^2 . \quad (I.22)$$

The two-body differential phase space factor is obtained as follows.

The two-body phase space factor R_2 is:

$$R_2 = \left(\frac{L}{\hbar c}\right)^3 \cdot \int \frac{d^3 \vec{p}_3'}{2E_3'} \frac{d^3 \vec{p}_4'}{2E_4'} \delta^3(\vec{p}_3' + \vec{p}_4') \delta(E_3' + E_4' - E_{34CM}) . \quad (I.23)$$

Let

$$B(p_3') = E_3' + E_4' - E_{34CM} , \quad (I.24)$$

$$\frac{dB(p_3')}{dp_3'} = \frac{p_3'}{E_3'} + \frac{p_4'}{E_4'} . \quad (I.25)$$

The differential two-body phase space factor is then:

$$\frac{dR_2}{d\Omega_3} = \left(\frac{L}{\hbar c}\right)^3 \frac{p_3'}{4(E_3' + E_4')} , \quad (I.26)$$

and the expression of the two-body differential cross section can be written :

$$\left(\frac{d\sigma}{d\Omega}\right)_{CM}^{P-J} = \frac{\pi^2 L^6}{(\hbar c)^4} \cdot \frac{E_3' E_4'}{(E_3' + E_4')^2} \cdot \left[2m_3 \cdot 2m_4 \cdot \frac{2m_1}{2E_1'} \cdot \frac{2m_4}{2E_{42}'} \right] \cdot |T_{CM}^{P-J}|^2 . \quad (I.27)$$

The transition matrix for the two-body interaction of the incident proton with the ejected particle j (proton or deuteron in the present case) in the laboratory system is related to the differential cross section in the CM system in the following fashion:

$$\left| T_{LAB}^{P-j} \right|^2 = \frac{(\hbar c)^4}{\pi^2 L^6} \cdot \frac{(E_3' + E_4')^2}{E_1 E_{4,2}} \cdot \left[\frac{2E_1 \cdot 2E_{4,2}}{2m_1 \cdot 2m_2 \cdot 2m_3 \cdot 2m_4} \right] \left(\frac{d\sigma}{d\Omega} \right)_{CM}^{P-j} . \quad (I.28)$$

The previous expression has been obtained from (I.22) and (I.27) and noting that:

$$E_3' = E_1' \quad E_4' = E_{4,2} \quad m_2/E_2 = 1 . \quad (I.29)$$

The three-body invariant phase space factor needs to be calculated. One starts from:

$$R_3(\vec{P}, E) = \left(\frac{L}{\hbar c} \right)^6 \int \frac{d^3 p_3}{2E_3} \frac{d^3 p_4}{2E_4} R_1(0, \epsilon) , \quad (I.30)$$

where

$$R_1(0, \epsilon) = \delta(\epsilon^2 - m_5^2) , \quad (I.31)$$

$$\epsilon^2 = (E - E_3 - E_4)^2 - (\vec{P} - \vec{p}_3 - \vec{p}_4)^2 , \quad (I.32)$$

$$\vec{P} = \vec{p}_1 + \vec{p}_2 = \vec{p}_3 + \vec{p}_4 + \vec{p}_5 , \quad (I.33a)$$

$$E = E_1 + E_2 = E_3 + E_4 + E_5 . \quad (I.33b)$$

The argument of the δ function is a function of p_3

$$A(p_3) = \epsilon^2 - m_5^2 . \quad (I.34)$$

The property of the δ function ,

$$\delta(A(p_3)) = \frac{1}{|\partial A / \partial p_3|} \delta(\vec{p} - \vec{\bar{p}}_3), \quad (I.35)$$

where $\vec{\bar{p}}_3$ is the value of $\vec{p}_3$ for which $A(p_3)=0$, is used.

It is convenient to introduce the variables ω, v, α :

$$\omega = E - E_4 \quad (I.36)$$

$$\vec{v} = \vec{p} - \vec{p}_4 \quad (I.37)$$

$$\alpha = \arccos \frac{(\vec{p} - \vec{p}_4) \cdot \vec{p}_3}{|\vec{p} - \vec{p}_4| \cdot |\vec{p}_3|} \quad (I.38)$$

$$A(p_3) = (\omega - E_3)^2 - (\vec{v} - \vec{p}_3)^2 - m_5^2 \quad (I.39)$$

$$A(p_3) = \omega^2 + p_3^2 + m_3^2 - 2\omega\sqrt{p_3^2 + m_3^2} - |\vec{v}|^2 - p_3^2 + 2vp_3\cos\alpha - m_5^2 \quad (I.40)$$

The derivative of the function $A(p_3)$ with respect to p_3 is

then:

$$\frac{\partial A}{\partial p_3} = -\frac{2\omega}{E_3} p_3 + 2v\cos\alpha \quad (I.41)$$

Using (I.32) one gets for the phase space factor:

$$R_3(\vec{p}, E) = \left(\frac{L}{\hbar c}\right)^6 \int \frac{p_4^2 p_3^2 d\Omega_3 dp_3 d\Omega_4 dp_4}{4E_3 E_4} \frac{\delta(p_3 - \bar{p}_3)}{|-2\omega(p_3/E_3) + 2v\cos\alpha|} \quad (I.42)$$

The differential phase space is then obtained by noting that:

$$dp_4 = \frac{E_4}{p_4} dE_4 \quad (I.43)$$

After the integration is performed and the values of ω, v, α are substituted one obtains:

$$\frac{dR_3(\vec{P}, E)}{dE_4 d\Omega_3 d\Omega_4} = \left(\frac{L}{\hbar c}\right)^6 \frac{p_4 p_3^2}{4E_3} \frac{1}{|-2(E-E_4) \cdot (p_3/E_3) + (2/p_3) \cdot (\vec{p}_3 \cdot (\vec{P}-\vec{p}_4))|}, \quad (I.44)$$

which can be rearranged and expressed as

$$\frac{dR_3(\vec{P}, E)}{dE_4 d\Omega_3 d\Omega_4} = \left(\frac{L}{\hbar c}\right)^6 \frac{p_4 p_3^2}{8} \frac{1}{|E_3 p_3 + E_5 p_3 + E_3 p_4 \cos(\theta_3 + \theta_4) - p_1 E_3 \cos \theta_3|}. \quad (I.45)$$

The latter expression together with (I.8, 17, 18, 28) is inserted in (I.9) so that the expression of the five-fold differential cross section is

$$\frac{d^5 \sigma}{dE_4 d\Omega_3 d\Omega_4} = N \cdot F \left(\frac{d\sigma}{d\Omega}\right)_{34CM}^{p-j} \cdot |\phi(k_5)|^2 \quad (I.46)$$

with

$$N = 3/2, \quad (I.47)$$

$$F = \frac{(E_3^1 + E_4^1)^2}{p_1} \frac{p_4 p_3^2}{|E_3 p_3 + E_5 p_3 + E_3 p_4 \cos(\theta_3 + \theta_4) - E_3 p_1 \cos \theta_3|} \frac{E_5}{E_{42}}, \quad (I.48)$$

$$|\phi(k_5)|^2 = \frac{1}{(\hbar c)^3} \left| \int d\vec{\rho} \exp(i\vec{k}_5 \cdot \vec{\rho}) \int d\vec{r} \phi_d(r) \phi_{He}(\vec{r}) \right|^2. \quad (I.49)$$

$|\phi(k_5)|^2$ is the momentum distribution of the recoil particle.

Note that the spectroscopic factor accounts for the spin algebra not explicitly derived here.

The expression of the total energy of particles 3 and 4 in their own centre of mass system is:

$$E_{34CM} = [m_3^2 + m_4^2 + 2E_3 E_4 - 2|p_3||p_4|\cos(\theta_3 + \theta_4)]^{1/2} . \quad (I.50)$$

The previous relation was derived from considering the Lorentz invariant $(p_3 + p_4)$ in the CM and laboratory systems. The notation used is the following:

$$p_i = (E, \vec{p}_i) = (E_i, p_{ix}, p_{iy}, p_{iz}) , \quad (I.51)$$

$$E_{34CM} = (E_3' + E_4') , \quad (I.52)$$

$$(p_3 + p_4)_{CM}^2 = (p_3 + p_4)_{LAB}^2 , \quad (I.53)$$

$$E_{34CM}^2 = p_3^2 + p_4^2 + 2p_3 p_4 = m_3^2 + m_4^2 + 2E_3 E_4 - 2|p_3||p_4|\cos(\theta_3 + \theta_4) . \quad (I.54)$$

The laboratory energy for the scattering of particle 3 and 4 with particle 4 at rest is obtained from:

$$E_{34LAB} = (\bar{E}_3 + m_4) = \gamma E_{34CM} \quad (I.55)$$

with

$$\beta = \frac{\bar{p}_3}{\bar{E}_3 + m_4} , \quad (I.56)$$

$$\gamma = (\bar{E}_3 + m_4) \cdot ((\bar{E}_3 + m_4)^2 - |\bar{p}_3|^2)^{1/2} , \quad (I.57)$$

$$E_3 = \frac{E_{34CM}^2 - m_3^2 - m_4^2}{2m_4} , \quad (I.58)$$

$$T_{34LAB} = \frac{E_{34CM}^2 - m_3^2 - m_4^2}{2m_4} - m_3 . \quad (I.59)$$

The scattering angle in the centre of mass system of particles 3 and 4 is obtained starting with the Lorentz invariant:

$$(p_1 \cdot p_3)_{LAB} = (p_1 \cdot p_3)_{CM} , \quad (I.60)$$

$$\cos \theta_{34CM} = \frac{E_{1CM} E_{3CM} + |\vec{p}_1| \cdot |\vec{p}_3| \cos \theta_{13} - E_1 E_3}{|\vec{p}_{1CM}| \cdot |\vec{p}_{3CM}|} . \quad (I.61)$$

The expression of E_{1CM} is obtained from the Lorentz invariant:

$$((p_3 + p_4) \cdot p_1)_{LAB} = ((p_3 + p_4) \cdot p_1)_{CM} , \quad (I.62)$$

$$E_1(E_3 + E_4) - \vec{p}_1 \cdot \vec{p}_3 - \vec{p}_3 \cdot \vec{p}_4 = E_{34CM} E_{1CM} , \quad (I.63)$$

$$E_{1CM} = \frac{E_1 \cdot (E_3 + E_4) - p_1 \cdot (p_3 \cos \theta_3 + p_4 \cos \theta_4)}{E_{34CM}} , \quad (I.64)$$

and in a similar way the expression of E_{3CM} is:

$$E_{3CM} = \frac{m_3^2 + E_3 E_4 - |\vec{p}_3| \cdot |\vec{p}_4| \cos(\theta_3 + \theta_4)}{E_{34CM}} . \quad (I.65)$$

II. $^3\text{He}(p,2p)np$ in PWIA

The derivation of the six-fold differential cross sections for the $^3\text{He}(p,2p)np$ reaction follows the same steps as presented for the $^3\text{He}(p,2p)d$ and $^3\text{He}(p,pd)p$ reactions. However, the $^3\text{He}(p,2p)np$ matrix has four unbound particles in the final state and, in first approximation, their interactions have been neglected. The wave functions which describe the system in the final state are four plane waves of the type given in (I.12,13). The matrix element for the transition probability is:

$$M_{fi} = \left[L^{-3/2} \cdot \int d\vec{r}_3 d\vec{r}_4 \bar{\chi}(3)\bar{\chi}(4)V(\vec{r}_3 - \vec{r}_4)\chi(1) \right] \cdot L^{-6} \cdot \left\{ \frac{2E_5 \cdot 2E_6}{2m_5 \cdot 2m_6} \right\}^{1/2} \cdot \phi(k_5, k_6) \quad (\text{II.1})$$

with

$$\phi(k_5, k_6) = \int d\vec{r}_5 d\vec{r}_6 \exp(-i\vec{k}_5 \cdot \vec{r}_5) \exp(-i\vec{k}_6 \cdot \vec{r}_6) \psi_{^3\text{He}} \quad (\text{II.2})$$

In the present study the centre of mass of the n-p recoiling system is at rest and the impulse approximation implies that the recoiling system is not affected by the reaction (the CM of the n-p pair was at rest also before the reaction). Then, since the CM of the target is at rest, the momentum of the ejected particle before the interaction is also zero. The part of expression (II.1) in square brackets is the matrix element of the transition probability of the two-body interaction:

$$T_{\text{LAB}}^{P-j} = L^{-3/2} \cdot \int d\vec{r}_3 d\vec{r}_4 \bar{\chi}(3)\chi(4)V(\vec{r}_3 - \vec{r}_4)\chi(1) \quad (\text{II.3})$$

As was shown in (I.28), T_{LAB}^{P-J} can be expressed as a function of $(d\sigma/dr)_{CM}^{P-J}$. The transition matrix element for the ${}^3\text{He}(p,2p)np$ reaction is then:

$$M_{fi} = L^{-6} \cdot \left\{ \frac{2E_5 \cdot 2E_6}{2m_5 \cdot 2m_6} \right\}^{1/2} \cdot T_{LAB}^{P-J} \cdot \phi(k_5, k_6) . \quad (\text{II.4})$$

The differential four-body phase space factor needs to be calculated.

The latter one is given by:

$$R_4(P, E) = \left(\frac{L}{\hbar c} \right)^9 \cdot \int \frac{d^3 p_3}{2E_3} \frac{d^3 p_4}{2E_4} R_2(0, \epsilon) \quad (\text{II.5})$$

with

$$R_2(0, \epsilon) = \frac{\pi p_{5CM}}{\epsilon} , \quad (\text{II.6})$$

or, taking into account that

$$\epsilon = M_{56} = E'_5 + E'_6 = (m_5^2 + p_{5CM}^2)^{1/2} + (m_6^2 + p_{5CM}^2)^{1/2} \quad (\text{II.7})$$

and expressing p_5 as a function of the sum of the total energies E_5 and E_6 , then:

$$R_2(0, \epsilon) = \frac{\pi}{M_{56}} \cdot \frac{[\{M_{56}^2 - (m_5^2 + m_6^2)\}^2 - 4m_5^2 m_6^2]^{1/2}}{2M_{56}} . \quad (\text{II.8})$$

From (II.5) and

$$d^3 p_i = p_i^2 \frac{E_i}{p_i} dE_i d\Omega_i \quad (\text{II.9})$$

one can obtain the differential four-body phase space:

$$\frac{dR_4(\vec{p}, E)}{d\Omega_3 d\Omega_4 dE_3 dE_4} = (L/\hbar c)^9 \cdot \frac{p_3 p_4}{4} \cdot \frac{\pi}{M_{56}} \cdot \frac{[\{M_{56}^2 - (m_5 - m_6)^2\} \{M_{56}^2 - (m_5 + m_6)^2\}]^{1/2}}{2M_{56}}, \quad (II.10)$$

and the six-fold differential cross section is then obtained by using the expressions (II.4), (I.28) (II.2) and (I.8) with the next equation

$$\frac{d^6 \sigma}{d\Omega_3 d\Omega_4 dT_3 dT_4} = L^3 \cdot \frac{E_1}{p_1 c} \cdot \frac{2\pi}{M} |\overline{M}_{fi}|^2 \cdot \frac{dR_4}{d\Omega_3 d\Omega_4 dT_3 dT_4}, \quad (II.11)$$

so that

$$\begin{aligned} \frac{d^6 \sigma}{d\Omega_3 d\Omega_4 dT_3 dT_4} = N \cdot \frac{p_3 p_4}{4} \cdot \frac{\pi}{M_{56}} \cdot \frac{[\{M_{56}^2 - (m_5 - m_6)^2\} \{M_{56}^2 - (m_5 + m_6)^2\}]^{1/2}}{2M_{56}} \cdot \\ \frac{4(E_3' + E_4')^2}{p_1} \cdot \frac{4E_5 E_6}{m_4} \cdot \left(\frac{d\sigma}{d\Omega}\right)^{p-p} \cdot \frac{1}{(\hbar c)^6} \cdot |\phi(k_5, k_6)|^2 \end{aligned} \quad (II.12)$$

with

$$\phi(k_5, k_6) = \int d\vec{r}_5 d\vec{r}_6 \exp(-i\vec{k}_5 \cdot \vec{r}_5) \exp(-i\vec{k}_6 \cdot \vec{r}_6) \psi_{3He}. \quad (II.13)$$

The quantity N is the spectroscopic factor whose value is 1/2 for the T=1 component of the n-p relative motion wave function and 3/2 for the T=0 component. Only when the T=0 and T=1 momentum distributions are identical is the value of N equal to 2. In the comparison of the n-p results with the calculated distributions using the Khanna, Irving, and Irving-Gunn wave functions, N was taken equal to 1/2.

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