RICE UNIVERSITY

"n-p Correlations Using Time-of-Flight Techniques in the $^{12}$C(d,pn)$^{12}$C Reaction"

by

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ABSTRACT

n-p Correlations in the $^{12}\text{C}(d,pn)^{12}\text{C}$ Reaction

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The $^{12}\text{C}(d,pn)^{12}\text{C}$ reaction has been studied at laboratory energies of 9.0 and 12.0 MeV using the Rice University Tandem Van de Graaff and computer-analyzer system. Multi-parameter coincidence spectra, utilizing neutron time-of-flight techniques, were obtained, and the data were analyzed with regard to reaction modes. The reaction proceeds primarily via a final state interaction corresponding to the 3.51 MeV level in $^{13}\text{N}^*$. The contribution from a direct mechanism is small, and no evidence for spatial localization was obtained.
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I. INTRODUCTION

In attempting to reach an understanding of the nature of internuclear forces, much attention in the past few years has been given to the study of three-body, final state interactions. Rice University has conducted too an extensive research program, particularly with regard to few-nucleon systems\(^1,2\) and interest has recently been extended to more complicated systems to see whether the techniques developed may be applicable.

Pitts et al.\(^3\) studied the \(^{12}\text{C}(d,pn)^{12}\text{C}\) reaction, and from an interpretation of the proton spectrum alone established the sequential decay mode through excited states of \(^{13}\text{N}\). Current interest in this reaction has also been stimulated by the studies of Lang et al.\(^4\), who reported indications of "proximity scattering" in the reaction mechanisms.

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This reaction is also of significance in that it seems well suited for observing "spatial localization" anomalies, as predicted by Phillips et al.\textsuperscript{5) It was therefore decided to undertake a study of the neutron-proton correlations in the three-body break-up of deuterons on $^{12}\text{C}$.}

The objects of this work were therefore:

i) to refine and develop experimental techniques to permit a coincidence study of protons and neutrons resulting in a three-body final state interaction,

ii) to extend the three-body break-up studies of $^{12}\text{C}(d,pn)^{12}\text{C}$, and

iii) to investigate carefully experimental evidence for "spatial localization" and "proximity scattering" effects.

The kinematics of a three-particle final state system have been reviewed extensively\textsuperscript{1,2) The coincident spectra of the two particles detected will be constrained to lie on a locus in the $T_1-T_2$ plane. If the reaction proceeds directly with the simultaneous emission of the three particles, the distribution along this locus will be isotropic, except for phase-space modulation. If however, the reaction

proceeds via sequential decay, or if there is a final state interaction between the particles, the distribution will be peaked. A study of the yield, thus, is indicative of the reaction mechanism involved.

Furthermore, as will be shown in section IIID and IIIE, spatial localization and proximity scattering will also induce an increased yield, or peak, under suitable kinematic conditions. Because of the nuclear forces involved, if the reaction occurs as a two-step process, the intermediate composite nucleus may be considered to be produced in a fairly well defined spatial region, and in certain energy regions of the spectra, the yield will be altered. This is one of the direct consequences of the concept of spatial localization.

Another alternative, in a reaction proceeding via sequential decay, is proximity scattering, which may be regarded as a second order scattering effect. After the decay of the metastable composite nucleus, under certain kinematic conditions, two of the final state products may interact further. The probability of such rescattering occurring is directly related to the lifetime of the composite nucleus, and it therefore affords a direct measurement of lifetimes of the order of $10^{-20}$ s.
From an experimental aspect, the immediate problems encountered were background, and the poor response of the neutron counter to low energy neutrons. The counter had therefore to be reconstructed, and a means of desensitising its response to unwanted background found. In sections IID and E, this has been fully outlined. Particular emphasis has been placed on a complete description of the experimental apparatus and procedure, which we believe, are now well suited for the present investigations.
II. EXPERIMENTAL APPARATUS AND PROCEDURE

A. Incident Beams

Although only incident dueteron beams were required for this experiment, extensive use of proton beams for chamber alignment was made. Both beams were provided by the Rice University Tandem Van de Graaff accelerator. By deflection through $90^\circ$ by means of an accurately calibrated analyzing magnet, the energy of these beams was determined to within a few keV. The beam entering the chamber was defined by means of a pair of insulated tantalum collimation disks, situated 60 and 30 cms prior to the target holder. The slit apertures were 1.5 mm, and each was followed by an anti-scattering disk. The current on these slits was monitored, and under optimum operating conditions, less than $1/2\%$ of the beam registered at the analyzing magnet was not transmitted through the chamber. In order to minimize gamma and neutron background, the beam was transported a further 15 meters beyond the chamber, and deposited in a beam dump housing which was heavily shielded with concrete. In addition, the beam pipes were lined with lead. The beam current was monitored in a conventional manner, but as no absolute measurements were required, its accuracy was not critical.
B. Reaction Chambers

For all the three-body investigations, as well as for the absolute neutron detector efficiency, and pulse shape discrimination studies, the chamber used was that designed by Joseph and Niiler of which fig. 1 is a simplified diagram. The chamber lid was rotatable, and had provisions for holding solid-state detectors. Detectors could also be positioned on the chamber floor at fixed angles. The chamber itself was constructed of aluminum, and to reduce the background further, a neutron exit port was provided. Here, the walls were only 1/8" thick, and the vertical angular definition of this window was 9°. Independent horizontal and vertical chamber motion was possible to facilitate alignment and there were also entrance-, and exit-viewing quartz crystals. The entire assembly was rigidly attached to the concrete foundation.

In measuring the relative neutron detector efficiencies by elastically scattering neutrons from protons, the incident neutron beam was obtained by means of the d(d,n)\(^3\)He reaction. For an increased yield, a gaseous target was used and the chamber was that constructed by Bonner\(^6\). [c.f. Fig. 2] The length of the gas cell was 3 cm, and the

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Figure 1. A simplified diagram of the chamber used in these experiments.
entrance foil was .00008" nickel, the seal being effected by pressure contact with an "0" ring. The energy of the neutron beam is uniquely determined by the incident deuteron energy, the Q-value for the \( d(d,n)\)\(^3\)He reaction 
\[
(3.26844 \pm 0.00042 \text{ MeV})
\]
and the angle of emission. For a 3.0 MeV deuteron, the energy loss in transversing a 0.00008" nickel foil is 195 keV. A correction was also made for the attenuation in passing through the target gas. The gas pressure was maintained at 19.2 p.s.i. and referring to the tabulation of Marion for the specific energy loss of a deuteron beam in a gaseous deuterium target, this correction was calculated to be 79 keV at the target center. Thus, the mean deuteron beam energy at the center of the gas target was 2.726 MeV, and the 0° neutron energy was therefore 5.99 MeV. From the measurements of Bradley and Fowler, the relevant cross-section for the production of neutrons is \((54.7 \pm 2) \text{ mb/sterad.}\) in the laboratory.

C. Targets

Self-supporting carbon foils were used to study the \(^{12}\text{C}(d,pn)^{12}\text{C}\) reaction. These were supplied by the Yissum Research Development Company, and were 100 µg/cm² thick.

7) Nuclear Data Tables, Part III (1960).
Figure 2. The "Bonner" gas-target chamber:
Being insulated, the target chamber served also as a Faraday cup.
For the absolute detector-efficiency measurements, solid deuterated polyethylene targets, nominally 100 µg/cm² thick, were used: The hydrogen composition of the polyethylene was 98.3% ²H, and the foils were prepared by depositing the polyethylene dissolved in carbon tetrachloride onto a warm water surface.

As has already been described, deuterium gas was used as the target source for neutrons in the relative efficiency measurements. For elastically scattering the neutrons, a cylindrical organic scintillator, type Pilot B, 1" in diameter, and 1" in height, was used. This is manufactured by Pilot Chemicals, Inc., and its scintillator characteristics are as follows:

   i) pulse height: 68% of anthracene
   ii) fast decay time: 2.1 nanosecs.
   iii) specific gravity: 1.02
   iv) 100% hydrocarbon, the atomic ratio of H:C being 1:1.10

This was optically coupled to an Amperex 56 AVP photomultiplier, the details of which have previously been described by Bonner⁶).

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D. Detectors

1.) The solid-state detectors used were standard silicon surface barrier detectors selected for good timing characteristics: These were supplied by Ortec, and were 1000 micron thick (i.e., 11 MeV thick to protons). Those used for the three-body studies (serial numbers 1849 and 1851) operated at a bias of 350 v had a resistivity of 10,000 ohm-cm and an active area of 50 mm$^2$. Their response in providing timing signals from $^3$He particles was questionable, and thus a third detector (3-43-DP) was used in the absolute efficiency measurements. This was a 200 mm$^2$ detector, with an operating bias of 450 v, and a resistivity of 9,500 ohm-cm. The detectors were encased in holders provided with telescope arrangements of circular apertures in tantalum disks. These defined the solid angles subtended by the detector at the center of the chamber, and eliminated the detection of particles scattered from points other than the target spot. For all the spectra, the solid-state detectors were at a distance of 5.50 cms from the target, and the solid angles subtended were $3.83 \times 10^{-4}$ steradians.

2.) The neutron detector was an organic scintillator, type NE 218, supplied by Nuclear Enterprises LTD., and encapsulated in a thin-walled aluminum cell 5" in diameter and 3" deep. Its scintillation characteristics are:
i) pulse height: 50% of anthracene  
ii) fast decay time: 2.4 nanosecs.  
iii) specific gravity: 0.879  
iv) 100% hydrocarbons, the atomic ratio of H:C being 1:1.379

The scintillator was optically coupled directly to a double Amperex 56 AVP photomultiplier assembly. The housing and dynode voltage supply were redesigned in order to improve the counter performance. To minimize the background enhancement, aluminum was used exclusively in the construction, and bulk was eliminated without sacrificing structural stability. Each photo-tube was independently spring-mounted, and access to the dynode circuitry was possible externally without breaking the light seal. The entire detector was enclosed in an aluminum cylinder, 6-1/4 inches in diameter, its walls being .037" thick. Netic and conetic magnetic shielding was placed on this inside rim, which extended 3" beyond the photo-cathode.

In fig. 3, the phototube circuitry is reproduced. The circuit was designed for maximum stability, fast timing, and optimization of the dynode signals. Among its features are a set of zener diodes between the cathode, the focusing dynode, and the acceleration plates. Small resistors were introduced in series with the last 5 dynodes to negate
Figure 3. Circuit diagram of the photomultiplier dynode voltage chain.
ZENER TYPE IN 3044.

ALL CAPS: 2 NF.
inductance effects. There are one anode and two dynode outputs for each tube, permitting both timing and pulse height analysis of the scintillations. To insure the matched response of the two tubes, a high-voltage divider was incorporated in the design, thus, from a single supply, the photomultiplier could be operated at potentials varying by as much as 200 v. Provision was also made for a compressed air inlet so that the circuit was adequately cooled.

To minimize the detection of neutrons and gamma-rays impinging on the detector from directions other than that directly from the target, the detector shield constructed by Bonner et al. was used. This is shown schematically in fig. 4. A pulse shape discrimination circuit was also used, and this is described fully in the following section.

E. Pulse Shape Discrimination

In fast neutron spectroscopy, the technique of "pulse shape discrimination" has significantly enhanced the quality of the attainable spectra. The radiation incident on a well-shielded neutron detector consists of neutrons, γ-, and cosmic-rays, the latter being primarily lightly ionizing μ-mesons. Furthermore, in the shielding itself, many of the neutrons may be converted into γ-rays by inelastic scattering, and capture processes, further obscuring the neutron
Figure 4. The neutron detector shield used to minimize the detection of neutrons and gamma rays incident on the detector from directions other than that directly from the target.
spectra. Following a report in 1956 by Wright\textsuperscript{8}) that the
scintillations produced by α-particles and electrons in
anthracene crystals exhibited different decays, numerous
methods of utilizing this characteristic of organic\textsuperscript{9-11}),
and inorganic scintillators\textsuperscript{12}) have been proposed, thus
reducing considerably the undesirable effects of this
γ-radiation without lowering substantially the neutron de-
tection efficiency.

Owen\textsuperscript{10}) showed that both the fast and slow components
in the light pulses emitted by the scintillator were, in
fact, independent of the incident radiation. The differences
occur in the intensity of the long lived components relative
to the intensity of the initial fast spike, i.e.

\[
R_\alpha < R_p < R
\]

where

\[
R = \frac{\int_0^\tau I(t)dt}{\int_\tau^\infty I(t)dt} \quad \tau \approx 10\text{ ns}
\]

\textsuperscript{9}) Brooks, F. D., Prog. in Nucl. Phys. \textbf{5} (1956) 252.
\textsuperscript{11}) Batchelor, R., Gilboy, W. B., Purnell, A. D., and Towle,
The technique suggested by Brooks\textsuperscript{9)} compared the total light output during the scintillation with that during the initial spike. A recent modification of this system is reported to resolve neutrons and γ-rays effectively at a pulse height corresponding to about 50 keV electron energy\textsuperscript{13}). Deadtime limitations, as well as the necessity for using two outputs of the photomultiplier give rise to difficulties, and the system is also highly susceptible to gain shifts.

In a later popular method, first proposed by Owen\textsuperscript{14)}, the photomultiplier was operated such that the potential difference between its anode and last dynode was small. Thus, during the initial intense fast spike of the light pulse, space charge saturation was temporarily possible. By a suitable adjustment of the circuit parameters, the last dynode yields a positive signal for neutron induced scintillations, but not for γ-rays. The primary disadvantages of this system were that the anode signal was no longer available for other applications, the circuit was suitable only for neutrons above 500 keV, and its dynamic range was of the order of 10:1.

\textsuperscript{13)} Brooks, F. D. and Rabinowunz, B., S.U.N.I. Annual Report (1965)

\textsuperscript{14)} Owen, R. B., Nucleonics \textbf{17} (1959) 72.
Many advances towards overcoming these disadvantages have been reported in the literature, prominent amongst which are Rethmeier's circuit\(^{15}\), which used only passive elements, and also provided an anode timing signal, and Batchelor et al.\(^{11}\), who extended the effective range of the Owen circuit.

In developing a pulse-shape discrimination circuit for use in this laboratory, we attempted to meet the following specifications:

i). a highly efficient \(\gamma\)-suppression ratio, although desirable, was not to be achieved at the expense of the counter neutron detection efficiency

ii). the effective range of the neutrons detected should be from 100 keV to \(\sim 10\) MeV, i.e. a dynamic range of 100:1.

iii). the system should be adaptable to high counting rates (\(\sim 10^4\) c.p.s.)

iv). the \(\gamma\) bias level should be low (\(\sim 250\) keV)

v). the pulse shape discrimination should not interfere with the anode's timing characteristics


vi). the system's susceptibility to gain and temperature drifts should be minimal and

vii). once the circuit parameters had been determined, the system should be functional with a minimum of adjustments.

Bearing in mind the above criteria, the method of zero-crossover detection suggested by Alexander and Goulding\textsuperscript{16}) seemed particularly promising. In this technique, the charge at a photomultiplier dynode is integrated, and then twice differentiated, thus producing a base line crossover. The timing of this zero-crossover with reference to the start of the pulse is dependent on the scintillation decay components, but is amplitude-invariant for pulses of constant shape. This principle had been the basis of a system developed by Rupaal\textsuperscript{17}), who reported his results quantitatively as follows.

When \((90.0 \pm 0.5)\%\) of the 2.9 MeV neutrons were detected by the system, \((95.8 \pm 0.2)\%\) of the \(\gamma\)-rays from a \(^{60}\)Co source above 400 keV, and \((98.3 \pm 0.5)\%\) of the \(\gamma\)-rays from a Ra-Th source were rejected by the P.S.D. [Note that all percentages quoted are relative to count rates when the P.S.D. was not applied.]


\textsuperscript{17}) Rupaal, A. S., Nucl. Instr. and Meth. 49 (1967) 145.
Since this method showed the greatest promise of satisfying our requirements, it was decided to develop our technique using it as a basis.

i. Principle. In this technique, a dynode current pulse (Fig. 5a) is integrated with a time constant longer than the scintillation time-constants of interest (Fig. 5b). For a typical organic liquid scintillator, the pulse may be represented by:

$$I(t) = I_f e^{-t/\tau_f} + I_s e^{-t/\tau_s}$$

where

\[ \tau_f = 2.5 \text{ ns.} \]
\[ \tau_s = 150 \text{ ns.} \]

This pulse is then shaped by means of a shorted delay-line, resulting in an almost rectangular pulse, 1 μs wide (Fig. 5c). The resultant pulse is then split into two channels, each containing an R-C differentiating network. The time constants of these networks are carefully chosen such that for one channel (the "start" channel), all scintillator pulses cross through zero during the fast spike of the pulses' trailing edge. (Fig. 5d) However, in the "stop"
Figures 5 and 6. Wave forms and a block diagram of the pulse shape discrimination system.
channel, a larger time-constant is used so that gamma-
induced scintillations still cross over during the fast
spike, while pulses having a greater proportion of slow de-
cay components (e.g. neutron induced) cross over at a later
time. (Fig. 5e) By using zero-crossover discriminators,
the time difference between the base-line crossover of the
output pulses in the two channels may be measured in a time-
to-amplitude converter.

Since this time interval is measured from the trailing
edge of the rectangular pulse, it is extremely sensitive to
the relative amounts of the fast and slow components in the
dynode pulse. For a current pulse of the form given in
equation i), the time difference measured by the T.A.C. is
proportional to: (c.f. Appendix A).

\[
\frac{\tau}{T_s} \ln \left[ \frac{Q_s}{Q} \left( 1 - e^{-\frac{\tau_d}{T_s}} \right) \left( 1 - \frac{\tau_{rc}}{T_s} \right) \right]
\]

where

- \( Q_s \) = slow component of scintillation pulse charge
- \( Q \) = total scintillation pulse charge
- \( \tau_s \) = time constant of the slow component
- \( \tau_d = 2 \times \text{delay line length} \)
- \( \tau_{rc} \) = time constant of the RC differentiating
  network

For a \( \gamma \)-ray scintillation, the T.A.C. pulse is small,
whilst for those initiated by incident neutrons, it is
relatively large, and a means of identifying the nature of
the incident radiation is thus provided.

It should be noted that cosmic-ray induced pulses
will have characteristics similar to those for \( \gamma \)-rays, as
will noise pulses, and the system should therefore discrimi-
nate against these pulses as well.

ii) Circuitry. Commercially available modules were
used extensively since, in general, they exhibit excellent
stability and reliability. In Fig. 6, a block diagram of
the electronics associated with the pulse shape discrimina-
tion is given.

Particular attention was given to obtaining a "clean"
dynode pulse, and this included the insertion of small
resistors ( 51 ) in series with the last five dynodes,
thus offsetting self-inductance effects. From the 11th
dynode, the current pulse is fed into a F.E.T. preamplifier
(c.f. Fig. 7) which serves not only as an integrator
\( (\tau_{\text{int.}} = 10 \ \mu s) \), but also matches the high input impedance
to a 100 ohm load. The integrated pulse is amplified in a
linear amplifier (Ortec Model 410) which is operated in a
single delay-line clipped mode, and the resultant pulse is
split into two channels for RC differentiation. The decay
constant in the "start" channel is 5.5 \( \mu s \), and its cross-
over point was determined in a fast zero-crossing dis-
Figure 7. Circuit diagram of the F.E.T. preamplifier.
criminator (E.G. & G. model T140). This output served as the start signal for the time-to-amplitude converter (E.G. & G. Model TH200A). In the "stop" channel, the time constant is 1.1 μs, and here, the zero-crossing discriminator output is delayed for 350 ns. Before being used as the T.A.C. stop signal, the pulse is shaped in a fast trigger (E.G. & G. Model TR104S). The T.A.C. positive output from its 300 nanosecond range passes through a variable discriminator, and serves as a gate signal. The linear gate with a variable discriminator [BESTE Model 7463/2] was expressly designed for this purpose by James Buchanan (c.f. Fig. 8). Featuring an integrated circuit differential discriminator, it accepts bipolar 8v. analog inputs signals, and may be operated in an open, gated, or closed mode. It is designed for positive 6v. maximum gate pulses, and two potentiometers vary the gate threshold and width (this width is adjustable from 2 to 14 μs). By means of a front panel switch, either a coincidence or anti-coincidence gate requirement can be selected. For pulse shape discrimination against gammas, the module is used in a gated, anti-coincidence mode.

Many variations of the circuit parameters were considered experimentally, and the values presented here are those which appeared to optimize the effect. It should be noted that saturation in the delay-line clipped linear
Figure 8. Circuit diagram of the linear gate and differential discriminator gate input designed for the P.S.D. system.
amplifier had a pronounced effect on the system's behavior.

iii) Experimental Performance. In order to test the effectiveness of the system in discriminating against $\gamma$-rays, an experimental circuit as shown in fig. 9, was used.

An integrated dynode signal for pulse height analysis was obtained by splitting the F.E.T. preamplifier output. This pulse was fed into an Ortec model 410 linear amplifier, in which it was suitably shaped. The resultant bipolar pulse was then delayed 4 $\mu$s., and sent as an input signal into the Rice University computer-analyzer system. The linear amplifier positive unipolar output was delayed 2.5 $\mu$s., and then introduced into a slow coincidence module (Cosmic Radiation Laboratories, model 801).

The pulse shape discrimination circuit was as described previously. The negative output from the pulse shape discrimination T.A.C. (P.S.D.T.A.C.) served as an input into the linear gate, but it was first delayed .5 $\mu$s. in order to meet timing requirements. This linear gate output was then amplified by an Ortec model 410. The resultant unipolar signal was then delayed 2 $\mu$s., and served as a second input into the computer-analyzer, while the bipolar signal was fed directly into a Cosmic coincidence module.
Figure 9. A block diagram of the electronics used for evaluating the effectiveness of the P.S.D. system.
In order to minimize the photomultiplier tube noise level, a fast coincidence requirement was demanded of the two delay-line clipped anode signals. Each such signal was sent through a zero-crossover discriminator (E.G. & G. model T140), and the principal tube's signal was then delayed 12 ns. before being introduced into a fast coincidence unit (E.G. & G. model C102A). The zero-crossover discriminator output resulting from the second photomultiplier was sent into a fast trigger (E.G. & G. model TR104). This produced an essentially rectangular negative pulse, whose width was chosen to be .5 μs., and served as the second input into the fast coincidence unit. By this technique, a good proportion of the random noise pulses was eliminated. The coincidence output signal was stretched to a width of .5 μs. using an E.G. & G. model TR104 fast trigger, and after amplification (Ortec model 410), was delayed a further 2.5 μs., and sent into a third Cosmic coincidence module.

In fig. 10, the response of the system to a plutonium-beryllium neutron source is shown. In this 2-dimensional display, the T.A.C. output is along the x-axis, while the y-axis corresponds to the integrated dynode pulse height. On this contour plot, the distinction between neutrons and gamma-rays is evident. Other significant features are the
Figure 10. A contour plot of the P.S.D. system's response to a plutonium-beryllium source. In this 2-dimensional display, the T.A.C. output is along the x-axis, while the y-axis corresponds to the integrated dynode pulse height.
dynamic range capabilities afforded by this technique, and the poorer time resolution of neutron induced events. The maximum neutron energy associated with a Pu-Be source is 10.6 MeV, and thus, the system is effective from the detector's threshold to beyond 10 MeV neutrons. For large dynode pulses, saturation effects in the delay-line clipped amplifier distort the response, which could be overcome by the use of a limiter. However, the interference caused by this effect was minimal in the energy range of current interest. The broadening of the neutron time peak is thought to be due primarily to the increased dispersion in the crossover point associated with the pulse's small slope. It can be shown that the time resolution is inversely proportional to this slope\(^{19}\). Moreover, statistical fluctuations in organic scintillators are always greater for heavily ionizing particles than for electrons. The non-symmetrical nature of the peak was at first considered to be a pile-up phenomenon. Indeed, at higher count rates, there was a shift in the $\gamma$ time peak towards that of the neutrons (c.f. fig. 11) but it would appear as if there are other such contributing factors. Similar observations have been reported by Hollandsworth, and Bucher\(^{19}\).

Figure 11. The shift in the pulse shape discrimination T.A.C. output with high count rates (20,000 c.p.s.)
The pulse height spectrum for a $^{60}$Co source with and without P.S.D., is shown in fig. 12. These spectra were gated by the P.S.D. and anode signals (thus reducing tube noise interference), and the effect of the system's bias level is evident. This was measured to correspond to an incident gamma energy of 160 KeV. Thus, this technique identified $\gamma$-rays above 160 KeV positively. Below this level, they were not vetoed by the system. In fig. 13 similar spectra for a $^{60}$Co plus plutonium-beryllium neutron source are displayed.

In evaluating the response of the system to neutrons, neutron detection efficiency measurements, described in section II-G, were repeated with the linear gate open and gated. The ratio of these two efficiencies thus gave the system's neutron acceptance figure of merit.

Quantitatively, these results may be summarized as follows. When $(97.8 \pm .2)\%$ of the 2.75 MeV neutrons from the $d(d,n)^{3}He$ reaction were accepted by the system, $(96.8 \pm .2)\%$ of the $\gamma$-rays above 160 KeV from a $^{60}$Co source were rejected. All these percentages are relative to count rates without the pulse-shape discrimination.

Many of the circuits previously reported have shown a strong count rate dependence. This aspect of the system was also investigated, but in the range 700 c.p.s. to
**Figures 12 and 13.** The response of the detector, with and without P.S.D. to a $^{60}$Co, and $^{60}$Co + neutron source respectively.
31,000 c.p.s., the gamma rejection ratio decreased only from 96.8% to 96.2% (c.f. fig. 14). The system's count rate capabilities appear even higher, but neither the linear amplifiers, nor the computer-analyzer system have this capability.

The response of the circuit to different integration and differentiation time constants does not seem to correlate completely with the accepted values of the scintillation pulse decay components. The behavior is far more consistent with the presence of a component with a decay time of approximately 1 μs. It would thus be interesting to investigate more fully the nature of the scintillator's light pulses. This might lead not only to further improvements in this technique, but should also increase one's understanding of the system.

In summary a system of pulse shape discrimination has been developed which meets adequately the requirements of this laboratory. In particular, it incorporates the following major advances over previous techniques:

i) It has effectively a neutron bias of 100 KeV, responding positively to γ-rays above 160 KeV.

ii) Its dynamic range is greater than 100:1.

and iii) It is capable of operating at count rates exceeding 30,000 c.p.s.
Figure 14. The gamma-rejection efficiency of the system as a function of count-rate.
This circuit is now a standardized component of our neutron time-of-flight system, and it has considerably improved the quality of our spectra.

F. Electronic Circuitry

In fig. 15, a block diagram of the electronics used in the 3-body investigations, as well as the absolute-efficiency determination is given.

As mentioned in the previous section, the photomultiplier tube noise was minimized by requiring a fast coincidence between the two delay-line clipped anode signals. Each such signal was sent through a zero-crossover discriminator (E.G. & G. model T140), and the primary tube's signal was then delayed 12 ns before being introduced into a fast coincidence unit (E.G. & G. model 102a). The zero-crossover discriminator's output resulting from the second photomultiplier was also sent into a fast trigger (E.G. & G. model TR104). This produced an essentially rectangular negative pulse whose width was chosen to be 15 ns., and served as the second input into the fast coincidence unit. The coincidence output signal, which results from the input signals' overlap, served as the "start" for the time-of-flight time-to-amplitude converter (E.G. & G. model TH200/A).

The solid-state detector signal was fed into a charge-sensitive, low-noise preamplifier (Tennelec model 100A).
Figure 15. A block diagram of the electronics used in 3-body data accumulation, and in the detector efficiency measurements.
From this, a timing signal was extracted by means of a time pick-off unit (Ortec model 210), which then led to discriminator. As it was preferable to use the neutron counter for the T.A.C. start pulse, it was necessary to delay a fast signal for some hundreds of nanoseconds. Thus the "clipped" output from the discriminator for the charged particles was inverted and fed into a second discriminator. Since these respond only to negative signals, by varying the width of the "clipped" pulse, these signals could be delayed for as much as 1 μs. This "trigger" output served as the stop signal for the T.A.C. The time-of-flight signal was then delayed 1.5 μs., and passed into the linear gate designed by James Buchanan (B.E.S.T.E. model 7463/2) and described in section II-E ii). This output passed into a linear amplifier (Ortec model 410), and the resultant unipolar pulse was used as an input into the computer-analyzer system, while the bipolar signal generated a gate for the analyzer by means of a Cosmic coincidence module (model 801).

The pulse shape discrimination circuit has been fully described in the preceding section. The dynode signal driving the P.S.D. circuit was also used for pulse height analysis. This was effected by means of a conventional amplifier (Ortec model 401), the resultant unipolar and bipolar signals serving, after being delayed suitably, as a
computer input, and gate signal respectively.

In order to analyze the charged particle spectra, the charge sensitive preamplifier output was fed into a linear amplifier, which provided a third computer input signal and gate. Furthermore, in measuring the absolute neutron-detection efficiency, a third output from the linear amplifier was inverted, and fed into a 400 channel analyzer (T.M.C. model 404). This enabled both coincidence and free charged particle spectra to be recorded simultaneously.

For the n-p elastic scattering, the circuitry was analagous to the above, except that the time-of-flight stop signal was now provided by the scattering scintillator. To effect this, its anode signal was fed into a fast amplifier (E.G. & G. stretcher amplifier model AN105 used in a non-stretching mode), and thereafter into a fast discriminator. After a suitable delay, this signal generated a stop pulse for the time-of-flight T.A.C. In order to observe the pulse height spectra of the scattered protons in the scintillator, an amplifier and coincidence module were used in the normal manner to provide signals for analysis, and gating conditions respectively.

In all circuits, extreme care was taken to ensure that the timing was correct, and where necessary a test pulse generator (Berkeley Nucleonics Company, model RP-1) was used
to verify that the timing was correct.

G. Calibrations and Detector Efficiencies.

The solid state detectors were calibrated by taking free spectra, and identifying the reaction products through a knowledge of the two-body kinematics. For convenience, the kinematic relationships for the various two-body reactions arising from deuterons on $^{12}\text{C}$ were graphically represented. Figures 16 and 17 show these energy dependences as a function of the (laboratory) detection angle for bombarding energies of 9.0 MeV and 12.0 MeV. In fig. 18, a typical free spectrum is reproduced. A charged-particle detector resolution of 50 KeV (f.w.h.m) was readily attainable.

Since a particle's time-of-flight is directly related to its energy by the relation

$$t = 72.3 \sqrt{\frac{A}{E}} \text{ nanoseconds/meter}$$

where $A$ is the atomic number of the particle, and $E$ is its energy in MeV, it was necessary to determine the T.A.C. calibration. This was done by inserting variable calibrated delays. The integral linearity of the module was claimed by the manufacturer to be better than 0.2% and this was verified. Figure 19 is an example of a time-of-flight spectrum obtained by this system, and the overall time-resolution (f.w.h.m.), in this case for the 2.75 MeV neutron from the
Figures 16 and 17. The energy as a function of the (laboratory) detection angle for the various 2-body reactions from $d + ^{12}C$ at incident deuteron energies of 9.0 and 12.0 MeV respectively.
Figure 18. A free charged-particle spectrum from the d + $^{12}$C reactions for an incident deuteron energy of 9.0 MeV at a detection angle of 30°.
Figure 19. A time-of-flight T.A.C. spectrum obtained from the $d(d, ^3\text{He})$ reaction requiring charged particle-neutron counter coincidences.
\[ d(d,^3\text{He})n \]

- \( E_d = 3 \text{ MeV} \)
- \( f-p = 80 \text{ cm} \)
- \( \theta_n = 103^\circ \)
- \( 1.903 \text{ ch/ns} \)
d(d, $^3$He)n reaction, over a flight path of 1.5 meters, is 3.7 ns. From equation i), for a neutron,

$$\frac{dE}{E} = \frac{2}{72.3} \times \frac{\sqrt{E \text{ (MeV)}}}{d \text{ (meters)}}$$

Thus, the overall energy resolution was 3%. The transit time of such a neutron through the scintillator alone is 3.2 ns.

Also of importance was the efficiency of the neutron detector. Since this is strongly dependent on the detector's bias, particularly at energies near the counter's threshold, care was taken to reproduce the bias settings accurately, and as a further test on the system, an absolute detector efficiency measurement, both with and without the pulse shape discrimination, was made prior to the commencement of each run.

The d(d, $^3$He)n reaction was used for this determination. By recording the free-, and $^3$He-n coincidence charged-particle spectra simultaneously, the ratio of the counts in the $^3$He peak measured the efficiency of the detector for that particular energy directly. After reviewing the kinematics for this reaction comprehensively, it was decided that an incident energy of 3.0 MeV, with the solid state counter at 30°, provided optimum conditions. The neutron
thus emerges at a (laboratory) angle of 103° with an energy of 2.75 MeV. In these measurements, care was taken to ensure that the neutron counter subtended a solid angle larger than that of the solid state detector (for all practical purposes, the solid state counter's $^3$He detection efficiency is 100%). Furthermore, dead-time and background corrections in the charged-particle free spectrum were of importance.

Unfortunately, the above technique is only suitable for a limited energy range of neutrons. It was therefore necessary to resort to a n-p scattering technique to obtain the relative efficiencies at various neutron energies as outlined by Jackson et al.\textsuperscript{20) In} fig. 20, the geometrical arrangement for these measurements is shown. The scatterer was situated at 0° to the incident neutrons at a distance of 50 cms and the neutron counter was placed at a distance of 2.0 meters from the scatterer. The (lab) angle $\theta$ relative to the incident beam was varied from 48° to 80°. A BF\textsubscript{3} proportional counter was used as a monitor of the neutron flux.

Figure 20. The experimental geometry for the relative neutron detection efficiency measurements using n-p elastic scattering.
Target

\[ \text{BF}_3 \text{ Monitor} \]

\[ \text{Scatterer} \]

\[ 50 \text{ cm} \]

\[ \theta \]

\[ 2 \text{ meters} \]

\[ \text{Detector} \]
Let:

\[
\frac{d\sigma}{d\Omega} (\theta)_{np} = \text{the differential cross-section for the elastic scattering of neutrons by protons at a lab angle } \theta \text{ relative to the beam direction,}
\]

\[
C = \text{total number of elastically scattered neutrons detected by the counter,}
\]

\[
M = \text{total number of counts recorded by the monitor,}
\]

\[
\text{Eff}_{r}(E_n) = \text{relative efficiency of the counter for detecting neutrons of energy } E_n,
\]

\[
A(E_n,\theta) = \text{a geometrical factor to account for attenuation in the scatterer of the scattered neutrons.}
\]

Thus

\[
\frac{C}{M} \propto \frac{d\sigma}{d\Omega} (\theta)_{np} A(E_n,\theta) \text{ Eff}_{r}(E_n).
\]

However, the n-p scattering is isotropic in the center-of-mass system for energies below about 15 MeV\(^{21}\)), therefore,

\[
\frac{d\sigma}{d\Omega} (\theta)_{np} \propto \cos\theta.
\]

The relative neutron efficiency thus satisfies the following relation,

\[
\text{Eff}_{r}(E_n) \propto C \frac{1}{M A(E_n,\theta)}
\]

\(^{21}\) Marion, J. B. and Fowler, J. L., Fast Neutron Physics, Part I (Interscience Pub. 1960) Chapt. 2-
In order to calculate the geometrical correction factor 
\( A_n(E_n, \theta) \), for calculation purposes, let the scatterer be 
replaced by a 1" cube, with one face normal to the incident 
neutron beam, and let multiple scattering events above the 
second order be neglected. In fig. 21, the defining rela-
tions and reference axes necessary for this calculation are 
indicated. The z-axis is along the direction of the beam 
whilst the x-axis is perpendicular to the z-axis and the 
plane containing the detector and the beam. Furthermore, 
let:

\[
\begin{align*}
N_p & = \text{number of hydrogen atoms per c.c. in the scatter} \\
N_c & = \text{number of carbon atoms per c.c. in the scatter} \\
A_{pn}(E_n) & = \text{total n-p cross-section for a neutron of} \\
& \quad \text{energy of } E_n \\
A_{cn}(E_n) & = \text{total n-}^{12}\text{C cross-section for neutrons of} \\
& \quad \text{energy } E_n \\
N_0 & = \text{number of neutrons per cm}^2 \text{ initially present} \\
& \quad \text{in the incident neutron beam} \\
\theta & = \text{the distance from a point of primary scatter-} \\
& \quad \text{ing to the edge of the scatter in the direction } \theta \\
E'_n & = \text{the neutron energy after the initial} \\
& \quad \text{scattering} \\
a & = N_c A_{cn}(E_n) + N_p A_{pn}(E_n) \\
a' & = N_c A_{cn}(E') + N_p A_{pn}(E') 
\end{align*}
\]

Then, if \( N \) is the total number of neutrons per cm\(^2\) as a 
function of \( z \),
Figure 21. The scatterer geometry and defining relations as used in the calculation of the geometric factor, $A(E_n, \theta)$. [after Joseph$^{22}$]
Figure 22. The relative efficiency obtained from the n-p scattering measurements. A is the ratio of the number of counts in the n-p peak to the number of counts in the monitor long counter.

B is the result of applying the correction due to the geometrical factor \( A(E_n, \theta) \), and the variation in the laboratory differential cross-section for n-p scattering.
Figure 23. The absolute neutron detector efficiency.
X - Calculated efficiency points

Efficiency (%)

\( E_n \) (MeV)
\[ dN = -aN \, dz \]
\[ N = N_0 e^{-az} \]

Thus, the geometrical factor \( A(E_n, \theta) \) is determined by:

\[
A(E_n, \theta) = \frac{\xi}{\lambda} \int_{x=-\xi}^{x=\lambda} \int_{z=-\lambda}^{z=\lambda} e^{-az} e^{-a'z} \, dx \, dz
\]

This integration has been programmed for computer evaluation by Joseph\(^\text{22)}\) and his results are summarized in Appendix B.

In figure 22, the relative efficiency measurements are shown, whilst in fig. 23 these values normalized to the absolute detector efficiency at \( E_n = 2.75 \text{ MeV} \) are displayed. All these values are for the detector operating with pulse shape discrimination.

Neutrons are detected in an organic scintillator principally through elastic scattering by protons in the scintillator, and to calculate their detection efficiency theoretically, the number of such recoil protons must be calculated. Considering primary n-p scattering alone, this number \( N_{rp} \) is given by:

\[
N_{rp} = \int_{0}^{s} N_{p} A(E_n) \, dz
\]

where \( s \) is the length of the scintillator.

Figure 24. An integrated dynode pulse height spectrum, gated by the anode signals to reduce tube noise, of the detector's response to $^{137}\text{Cs}$. 
Thus

\[ N_{rp} = \frac{1}{a} \int_0^s \int_0^{z'} N O P P N_A(E_n) \cdot N_A(E_n') \, dz \, dz' \]

\[ = \frac{1}{a} N O P C P N_A(E_n') \cdot A_c(E_n) \cdot (1-e^{-as}) \cdot (1-e^{-a'l'}) \]

where \( l' \) is some characteristic distance presented by the scintillator to neutrons initially scattered off carbon. For these calculations a distance of 2.0 cm was chosen. This corresponds to the distance a 1 MeV neutron beam would traverse in the scintillator before being reduced to slightly less than half its intensity.

Thus, if every such recoil proton were seen by the detector system, the efficiency would be given by:

\[ \text{Eff} = \frac{(N_{rp} + N_{rpc})}{N_o} \]
However, there exists an inherent bias level in the system, below which the protons are not seen. If the relationship between the neutron energy and its associated recoil proton pulse height is linear, this bias effect may readily be accounted for: Thus, the observed detector efficiency is given theoretically by:

\[ \text{Eff}(E_n) = (1 - \frac{E_{\text{bias}}}{E_n}) \left( \frac{N_{\text{rp}} + N_{\text{rpc}}}{N_0} \right) \]

\( E_{\text{bias}} \) is the neutron energy corresponding to the detector bias level; and to a first approximation, the linearity of the energy-pulse height function is a valid assumption.

The bias level was also determined experimentally. For \( \gamma \)-rays, the Compton peak is readily identified, and the corresponding channel number is related to this in the following manner. After background corrections, half the maximum peak value is equivalent to 1.05 times the maximum Compton energy\(^{23}\). A \(^{137}\)Cs spectrum is shown in fig. 24 and the \( \gamma \)-ray bias is seen to be < 20 keV. For neutrons, difficulty is experienced in measuring this bias, as the lowest monoenergetic neutron available conveniently was 2.75 MeV,

and thus the bias level is close to the 1024 channel-
alyzer cut-off. Furthermore, the neutron-energy recoil
pulse height dependence is non-linear, and is not known to
a sufficient degree of accuracy. Such a determination is
currently being undertaken for our counter system. Figure
25 shows the response of the detector to a mono-energetic
(6.67 MeV) neutron. Theoretically, it can be shown that,
under idealized conditions, the recoil-proton spectrum
should be rectangular, with the maximum value corresponding
to a proton-recoil energy, $E_n$.

The laboratory differential cross-section for n-p
scattering at an angle $\psi$ is:

$$\frac{d\sigma_{np}}{d\psi} = \frac{1}{\pi} \sigma_t(E_n) \cos \psi$$

where $\sigma_t(E_n)$ is the neutron-proton total cross-section.

The energy of the scattered proton, in the laboratory system
is

$$E_{p} = E_n \cos^2 \psi_p$$

$$dE_p = -2E_n \cos \psi_p \sin \psi_p d\psi_p$$

$$I_o d\sigma_{np} = -I_o \sigma_t(E_n) \frac{dE_p}{E_n}$$

$$= N(E_{p}) dE_p$$
Figure 25. An integrated dynode pulse height spectrum, gated by the anode, for a 6.67 MeV neutron from the d(d,n)$^3$He reaction, $E_d = 12.0$ MeV.
where \( I_0 \) is the incident intensity.

In reality however, the observed proton recoil pulse height deviates from this rectangular shape. The non-linear response of the scintillator, statistical fluctuations, and multiple scattering are primary causes for this distortion, and because of the complexity of the problem, no attempt was made to compensate for these in the efficiency calculations.

The theoretical detector-efficiency values are consistently higher than those determined experimentally. As to whether this is due to the model used, or to a systematic error in the experimental technique is presently being investigated.
A. Introduction and Reaction Mechanisms

There are several possible 3-body reaction mechanisms involved when a deuteron is incident upon $^{12}\text{C}$. These may diagrammatically be summarized as follows:

\[ d + ^{12}\text{C} \rightarrow ^{14}\text{N}* \]

- \[ ^{12}\text{C} \rightarrow p+n+^{12}\text{C}, \ \text{simultaneous breakup} \]
- \[ p+^{13}\text{C}* \rightarrow p+n+^{12}\text{C} \]
  - sequential decay via $^{13}\text{C}*$
- \[ n+^{13}\text{N}* \rightarrow p+n+^{12}\text{C} \]
  - sequential decay via $^{13}\text{N}*$
- \[ "\text{rescattering and interference}\" \rightarrow p+n+^{12}\text{C} \]
- \[ p+^{13}\text{C}* \rightarrow p+n+^{12}\text{C} \]
  - final state interactions via $^{13}\text{C}*$
- \[ n+^{13}\text{N}* \rightarrow p+n+^{12}\text{C} \]
  - final state interactions via $^{13}\text{N}*$

The study of the coincident spectra of protons and neutrons from the 3-body breakup should yield information concerning the reaction mechanisms described above, and the
relative yields due to simultaneous and sequential decay.

If the energies, and angles of emission of these two particles are measured, the kinematics of the reaction are determined completely, and the distribution of events along the allowed kinematical locus indicates the mechanism of the interaction. These processes have been discussed in detail previously, but an outline will be included here for completeness.

Of particular interest in this study was experimental support for the concept of "spatial localization" and an investigation of "rescattering" or "proximity scattering". If the reaction proceeds via sequential decay, i.e.

\[ b + t \rightarrow 1 + (2-3)^* \rightarrow 1 + 2 + 3 \]

Phillips et al. suggested that the spectrum of particle 1 will have a peak at that energy at which the (2+3) system has a small energy. This peak corresponds therefore not to metastable states in the intermediate compound nucleus, (2-3)*, but is rather a manifestation of the localized nature of the interaction.

Under certain kinematic conditions, in a sequential
decay reaction, immediately following the decay of the
intermediate "composite nucleus," two of the three outgoing
particles may approach sufficiently close to permit a further
interaction, generally elastic scattering, to occur. This
process is termed "rescattering" or "proximity scattering,"
and is represented diagrammatically in fig. 26. A measure
of the intensity of this reaction mechanism determines di-
rectly the lifetime of the unstable particle, and a study
of this process might therefore be of value in measuring
exceedingly small lifetimes.

B. Kinematics for Simultaneous Breakup

The problem to be considered is that of a bombarding
particle of momentum \( p_0 \), in the laboratory system, incident
upon a target essentially at rest in this system, and the
resultant reaction giving rise to three separated particles
in the final state, i.e. 3-body breakup. The kinematics of
the reaction for simultaneous breakup, i.e. all three final-
state particles being emitted simultaneously from the com-
posite nucleus. [c.f. fig. 26] will be determined first.

The reaction is described in the laboratory system by
fig. 27. \( p_i \) is the momentum of the \( i^{\text{th}} \) final state par-
ticle \((i = 1,2,3)\), and \( \theta_i \) is the angle between \( p_i \) and the
incident beam momentum, \( p_0 \). \( \theta_i \) measures the angle about the
Figure 26. Graphical representation of
a) simultaneous breakup,
b) sequential decay,
c) sequential decay and proximity scattering,
d) simultaneous breakup followed by a final interaction.
Figure 27. A laboratory momentum diagram for the three particles in the final state. The $\bar{z}$ axis corresponds to the incident beam axis. [after Simpson]
beam axis (z) from the plane containing the beam axis and the x axis. The kinetic energies and masses of the particles are $T_i$ and $m_i$ respectively ($j = 0, 1, 2, 3$). The energy necessary for the 3-particle breakup process is represented by $Q$. The energies involved in this experiment were sufficiently low to justify a nonrelativistic treatment.

Applying the conservation of energy

$$T_0 + Q = \sum_{i=1}^{3} T_i$$

$$\frac{P_0^2}{2m_0} + Q = \sum_{i=1}^{3} \frac{P_i^2}{2m_i}$$

From the conservation of momentum:

$$P_0 = \sum_{i=1}^{3} P_i$$

which may be written in terms of its 3 components. There are thus 4 linearly independent equations, and a solution for $p_2$ as a function of $p_1$ for a particular set of laboratory angles $\theta_1, \theta', \theta_2$ and $\theta_2$ may be readily derived\footnote{Simpson, W. D., Ph.D. Thesis, Rice University (1965), unpublished.}

$$p_2 = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A}$$
where

\[ A = \frac{1}{2} \left[ \frac{1}{m_2} + \frac{1}{m_3} \right] \]

\[ B = \frac{1}{m_3} \left[ p_1 \cos \theta_1 \cos \theta_2 + p_1 \sin \theta_1 \sin \theta_2 \cos (\theta_1 - \theta_2) - p_0 \cos \theta_2 \right] \]

\[ C = p_0 \sqrt{\frac{1}{2m_3} - \frac{1}{2m_0}} + \frac{p_1}{2} \left[ \frac{1}{m_1} + \frac{1}{m_3} \right] \]

\[ - \frac{1}{m_3} \left[ p_0 p_1 \cos \theta_1 \right] - Q \]

Thus, for a given value of \( p_1 \), there are, in general, 2 values of \( p_2 \), and the loci of possible solutions may be calculated for the experimentally observable system in the \( T_2 \) versus \( T_1 \) plane. [Note that, by convention, subscript 1 is associated with the parameter of that particle seen by detector 1, and similarly, subscript 2 refers to detector 2.] In order to completely determine the reaction, only five of the system's 9 parameters need therefore be measured, but because of the degeneracy of the solution, a further parameter is necessary to specify the kinematics completely.

For a reaction proceeding completely via simultaneous breakup, there are no further kinematic restrictions, and the distribution along the locus should be uniform.

C. Kinematics for Sequential Decay

Each point on the kinematically allowed locus obtained for a simultaneous breakup process corresponds to a par-
ticular "reaction channel" for each of the sequential decay or final state interaction modes associated with one of the three final state particles being emitted first. If, for some reason, one of these channels is favored by the reaction, it will manifest itself by an increase in the yield along the locus. Thus, if the intermediate composite nucleus is in a state, either real or virtual, this should be seen on the experimental locus provided the reaction channel is not restricted by selection rules.

The internal energy of this intermediate system may be calculated, and this gives rise to a further restraint on the kinematics. If $Q$ is the energy necessary for the 3-body breakup reaction and $E_{ij}$ is the internal energy in the intermediate system of $(i+j)$ when particle $k$ is emitted first [$i,j,k = 1,2,3$, $i \neq j \neq k \neq i$], the following 2 relations are obtained from the conservation laws.

\[ T_0 + Q = T_{jk} + E_{jk} \quad \text{(i)} \]
\[ \bar{p}_o = \bar{p}_i + \bar{p}_{jk} \quad \text{(ii)} \]

Rewriting the momentum conservation relationship in components:

\[ p_o = p_i \cos \theta_i + p_{jk} \cos \theta_{jk} \quad \text{(iii)} \]
\[ 0 = p_i \sin \theta_i \cos \phi_i + p_{jk} \sin \theta_{jk} \cos \phi_{jk} \quad \text{iv}) \]

\[ 0 = p_i \sin \theta_i \sin \phi_i + p_{k} \sin \theta_k \sin \phi_k \quad \text{v}) \]

Since the two-body reaction is restricted to a plane, \( \phi_i = \phi_{jk} + \pi \). Eliminating \( \phi_i \) and \( \phi_{jk} \) between equations iv) and v):

\[ p_i^2 \sin^2 \theta_i = p_{jk}^2 \sin^2 \theta_{jk} \]

Eliminating \( \theta_{jk} \) by using equation iii) and vi):

\[ p_{jk}^2 = p_i^2 \sin^2 \theta_i + (p_o - p_i \cos \theta_i)^2 \]

\[ = p_o^2 + p_i^2 - 2p_o p_i \cos \theta_i \]

Furthermore

\[ T_k = \frac{p_{jk}^2}{2m_{jk}} \]

(from equation i),

\[ E_{jk} = T_o + Q - T_i - \frac{1}{2m_{jk}} [p_o^2 + p_i^2 - 2p_o p_i \cos \theta_i] \quad \text{vii}) \]

Particle 1 has been chosen as a reference particle, and it is clear that while \( E_{23} \) will be a single valued function
of $T_1$, $E_{12}$ and $E_{13}$ will be double valued. These will be written as $E_{12}^+$, $(E_{12}^-)$ and $E_{13}^-$, $(E_{13}^-)$ according as $p_+^+$ or $p_-^+$ is chosen.

Explicitly:

\[
E_{23} = T_0 + Q - T_1 - \frac{1}{2m_{33}} (p_0^2 + p_1^2 - 2p_0 p_1 \cos \theta_1)
\]

\[
E_{13}^\pm = T_0 + Q - T_2^\pm - \frac{1}{2m_{13}} [p_0^2 + p_2^2 - 2p_0 p_2^\pm \cos \theta_2]
\]

\[
E_{12}^\pm = T_0 + Q - \frac{1}{2m_{12}} [C_2^\pm + D_2^\pm] - \frac{1}{2m_3} [(p_0 - C_2^\pm)^2 + D_2^2]
\]

where

\[
C_2^\pm = p_1 \cos \theta_1 + p_2^\pm \cos \theta_2
\]

\[
D_2^\pm = p_1 \sin \theta_1 - p_2^\pm \sin \theta_2
\]

The kinematical considerations for simultaneous break-up apply here also, but there will now be an intensification of the yield if the internal energy of the composite system corresponds to a state.

D. Spatial Localization

If the 3-body break-process proceeds via sequential decay, i.e.

\[
b + t \rightarrow d^* \rightarrow 1 + (2-3)^* ,
\]

\[(2-3)^* \rightarrow 2 + 3 ,\]
then the (2-3)* system may be considered to be produced as a localized decaying state due to the short range nature of the nuclear forces, and the implications of this have been discussed in detail by Phillips et al.\textsuperscript{5) }

In the case where there are no nuclear forces between the final state particles, the generalized density of states function may be written as, \( \delta_i = 0 \):

\[
\rho_i (E_{(2-3)*}) = \frac{1}{\pi} \frac{d \varphi_i}{dE_{(2-3)*}} \tag{a}
\]

"a" is the radius of localization. Since \( \frac{d \varphi_i}{dE_{(2-3)*}} \) has, in general, a maximum at a certain low energy, the spectrum of particle 1 may be expected to exhibit\textsuperscript{5) } an increased yield at this energy. This may occur even though there are only small, or no nuclear forces binding the composite system. To a first approximation, this effect should be most pronounced when the wavelength associated with the unstable nucleus' internal energy equals the radius of localization.

E. Rescattering

The theory of rescattering in 3-body break-up reactions has been comprehensively investigated using wave mechanics.

by Fox\textsuperscript{24}, while Aitchison and Kacser\textsuperscript{25} have also considered the problem. The treatment presented here follows that of Lang \textit{et al.}\textsuperscript{4}, who used a classical particle model approach.

Consider a generalized 3-body reaction proceeding via sequential decay, with $Q$ being the energy associated with the complete reaction, i.e.:

$$b + T \rightarrow 1 + (2-3)^* \rightarrow 1 + 2 + 3$$

$Q_1$ and $Q_2$ are the respective energies released by the two stages of the overall interaction.

It is assumed that the lifetime of the $(2-3)^*$ composite system is large compared with the times necessary for a particle to traverse a nucleus (10\textsuperscript{-22}s). Also, relativistic and Coulomb potential effects have not been taken into consideration.

In the center-of-mass system, the energy of particle 1 is given by:

$$\frac{1}{2} m_1 v_1^2 \text{c.m.} = \frac{m_c}{m_1 + m_c} Q'_1$$

\textsuperscript{24}Fox, R., Phys. Rev. \textbf{125} (1962) 311.


where $m_c$ is the mass of the intermediate composite system, \((2-3)\)*

\[ Q'_1 = \text{available energy in the c.m. system} \]

\[ = Q_1 + E_{\text{lab}}^l \frac{m_t}{m_b + m_t}. \]

Similarly, the composite system, denoted by the subscript c, has an associated energy given by:

\[ \frac{1}{2} m_c v_{c, \text{c.m.}}^2 = \frac{m_1}{m_1 + m_c} Q'_1. \quad \text{ii) } \]

Transforming to a coordinate system in which the unstable nucleus is at rest (the R-system), the energy of particle 1 is

\[ T_1^o = \frac{1}{2} m_1 v_1^2 \]

\[ = \frac{1}{2} m_1 \left( v_{1, \text{c.m.}}^2 + v_{c, \text{c.m.}}^2 \right)^2 \]

\[ = \frac{1}{2} m_1 \left[ \left( 2 \frac{m_c}{m_1 + m_c} \frac{Q'_1}{m_1} \right)^{1/2} + \left( 2 \frac{m_1}{m_2 + m_1 + m_c} \frac{Q'_1}{m_1} \right)^{1/2} \right] \]

\[ = \frac{m_1 Q'_1}{m_1 + m_c} \left( \frac{m_c}{m_1} \right)^{1/2} + \left( \frac{m_1}{m_2} \right)^{1/2}. \quad \text{iii) } \]

For particle 2, which is emitted in the decay of the unstable nucleus, its energy in the R-system is:

\[ T_2^o = \frac{1}{2} m_2 v_2^2 \]

\[ = \frac{m_c Q_2}{m_2 + m_3}. \quad \text{iv) } \]
If particle 2 is emitted in the direction of particle 1, and if its velocity is greater, these two particles may approach sufficiently closely to interact, and it is this which is termed rescattering. If $\tau_0$ is the time interval between the emission of particle 1, and the rescattering process, and $\tau$ is the lifetime of the unstable composite nucleus, then (in the R-system),

$$d = v_1 \tau_0 = v_2 (\tau_0 - \tau)$$

$$d = \frac{v_1 v_2}{v_2 - v_1} \tau.$$

Assuming that particle 2 is emitted isotropically with respect to particle 1, and denoting by $\sigma(T)$ the integrated scattering cross-section, the probability $W$ for such a process to occur is:

$$W = \frac{\sigma(T_{12}^o)}{4\pi d^2}$$

$$= \frac{\sigma(T_{12}^o)}{4\pi} \frac{v_2 - v_1}{v_1 v_2} \frac{2^2}{\tau^2}$$

where

$$T_{12}^o = \frac{1}{2} \frac{m_1 m_2}{m_1 + m_2} (v_2 - v_1)^2.$$
If the scattering cross-section is known from other measurements, by determining \( v_1 \) and \( v_2 \), and the relative contribution to the reaction yield by rescattering, the lifetime of the intermediate composite nucleus may be deduced from equation vi).

Furthermore, if the center-of-mass system associated with particles 1) and 2) is considered, the velocity of the center-of-mass in the R-system is:

\[
\frac{m_2}{m_1 + m_2} (v_2 - v_1) . \quad \text{viii)}
\]

Thus, after rescattering, the kinetic energies, \( T_1^1 \), and \( T_2 \) of particles 1) and 2) in the R-system lie within the following bounds:

\[
T_1^0 < T_1^1 < T_1^\max
\]

where

\[
T_1^\max = \frac{1}{2} m_1 \left[ v_1 + \frac{2m_2(v_2 - v_1)}{m_1 + m_2} \right]^2
\]

\[
= \frac{1}{2} m_1 \left[ \frac{(m_1 - m_2)v_1 + 2m_2v_2}{m_1 + m_2} \right]^2
\]

and

\[
T_2^\min < T_2^1 < T_2^0
\]
where

\[ T_{2}^{\text{min}} = \frac{1}{2} m_{2} \left( \frac{(m_{2} - m_{1}) v_{2} + 2m_{1} v_{1}}{m_{1} + m_{2}} \right)^{2} \]

There are thus tight bounds on the energies associated with particles involved in rescattering, and the maximum angle of divergence of the rescattered particles is restricted. In general, the process will be forbidden kinematically.
IV. EXPERIMENTAL DATA

The reaction \( ^{12}\text{C}(d,\text{pn})^{12}\text{C} \) was observed at deuteron bombarding energies of 9.0 and 12.0 MeV using the methods described in Chapter II. These data are presented in fig. 28 in a format similar to that given by the computer-analyzer system. The locus is shown in the time-of-flight-charged particle plane and the associated neutron-, and proton-energy scales have been included. The kinematically allowed locus has also been superimposed on the experimental data.

At 9.0 MeV with the solid-state detector at a (laboratory) angle of 30°, the neutron counter was placed at 50°, the neutron flight path being 1.40 meters (fig. 28). With the neutron counter fixed at 25°, its distance to the target being 1.58 m, the reaction was also observed with the charged particle detector at 90° (fig. 29) and 120° (fig. 30). This first set of angles corresponds to the recoil axis for sequential decay via the 3.51 level in \( ^{13}\text{N}^{*} \), whilst the latter angles correspond to the recoil axis for low-lying "levels" of excitation in \( ^{13}\text{C}^{*} \). This geometry was selected in order to enhance the probability of observing spatial localization.
Figures 28-31. n-p coincidence spectra from the $^{12}\text{C}(d,pn)^{12}\text{C}$ reaction at incident energies of 9.0 and 12.0 MeV. The solid curve in fig. 28 is the calculated kinematic locus. In the projections of the 3-body locus onto the charged-particle detector axis, background corrections have been included.
$^{12}\text{C} (d, pn)^{12}\text{C}$  
$E_d = 9.0 \text{ MeV}$  
$\theta_{85} = 50^\circ$  
$\theta_\pi = 30^\circ$

Counts

Cell Number (8 channels / cell)
$^{12}\text{C}(d, p n)^{12}\text{C} \quad E_d = 9 \text{ MeV}$

$\theta_{ss} = 90^\circ \quad \theta_n = 25^\circ \quad f_\ast p_\ast = 1.56 \text{ m}$

$^{12}\text{N}_{3,34}$

Cell Number (8 channels/cell)

Counts
$^{12}_C(\,d,\,pn\,)^{12}_C \quad E_d = 9 \text{ MeV}$

$\theta_{ss} = 120^\circ \quad \theta_n = 25^\circ \quad f_{p_n} = 1.56 \text{ m}$

Counts

Cell Number (8 channels / cell)
$^{12}$C ($d, p n$) $^{12}$C  \( E_d = 12 \) MeV

\( \theta_{ss} = 90^\circ \)  \( \theta_{\pi} = 25^\circ \)  \( f_{p\pi} = 1.50 \) m

Counts

Cell Number (8 channels/Cell)  \( E_{13} \approx 200 \) keV
Also included in these figures is a projection of the locus onto the charged-particle detector axes. In these histograms, background corrections have been included, and the levels in the composite nucleus corresponding to the final state interaction reaction modes have been indicated.

A projection of the data onto the solid-state detector axis for an incident deuteron energy of 12.0 MeV, with the charged particle detector at 90°, and the neutron counter 1.5 meters from the target and at an angle of 25° is also shown. [fig. 31].
V. RESULTS AND CONCLUSIONS

The striking feature of the data is the preference of the reaction mechanism in proceeding via a final state interaction corresponding to the 3.51 MeV level in $^{13}\text{N}^*$. For the data collected at ($\theta_{ss} = 30^\circ$, $\theta_n = 50^\circ$), the 9.51 level in $^{13}\text{C}^*$ is also extremely strong. As the ($^{12}\text{C} + p$) elastic scattering spectrum shows no strong resonance at this energy, this is indicative of a "pure" final-state interaction process. Final state interactions via the 6.87, 7.50, 7.55, 7.68, 8.33, and 8.85 MeV levels in $^{13}\text{C}^*$, and the 6.38 MeV, as well as the 6.91 and 7.40 MeV levels for an incident energy of 12.0 MeV, in $^{13}\text{N}^*$, were also observed.

There was no indication of an increased yield due to the presence of levels in $^{13}\text{C}^*$ of an excitation energy of 5.51 or 6.10 MeV.

The loci obtained were extremely clean, and it is thus possible to estimate the contribution of simultaneous break-up to the reaction. At both 9.0 and 12.0 MeV bombarding energies, this was less than a few percent.

Spatial localization should cause an increase in the proton yield at an internal energy in the ($^{12}\text{C} + n$) system of 200 keV. [c.f. Appendix C]. No such effect was observed,
indicating that the cross-section for this reaction mode is small relative to the other possible channels.

No data were taken at which rescattering effects were kinematically possible.

From this preliminary study of the \(^{12}\)C + d three-body breakup, it is clear that the primary mode of the reaction is via final state interaction and sequential decay modes. In order to understand the process more completely, further data are necessary, particularly at higher energies.

Regarding spatial localization, since this is similar in its mechanics to a spectator-pole effect, studies at lower bombarding energies should prove of interest. Reaction cross-sections have not been particularly adverse, and the low neutron detector threshold bias would permit such a decrease in the incident deuteron energy.

Of interest also is a verification of the proximity scattering reported by Lang et al.\(^4\), and Bohne et al.\(^{26}\) at bombarding energies of 5.4 MeV, and such an experiment is contemplated. In all such measurements, extreme caution

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must be taken to compensate for the variation in the neutron-detection efficiency, as well as to avoid deuteron breakup contributions not associated directly with a three-body final state interaction.

In developing a detector-system for this experiment, much knowledge regarding organic scintillator neutron detectors was gained. As has been previously mentioned, these phenomena do not correlate completely with the extant values of the scintillator decay components. Such knowledge may be of value in further improving the system.

Another interesting phenomenon was seen in the n-p elastic scattering data. When viewed in a multi-parameter display (in which the time-of-flight-scatterer pulse height spectrum is presented), the n-p scattering peak is strongly visible, and its dispersion is as anticipated. There are, however, tails associated with this peak corresponding to both increased and decreased scattered-proton energies, and this may well be the multiple-inscattered contribution. If this is true, a direct means of measuring such inscattering is now feasible.

As a sequel to this preliminary investigation of the $^{12}$C(d,pn)$^{12}$C reaction, it is planned

i) to investigate further the nature of scintillation decay pulses

\[ \text{56.} \]
ii) to observe this reaction at various other incident energies and geometries, particularly at 5.4 MeV with regard to proximity scattering, and between 7 and 9 MeV with regard to spatial localization

iii) to restudy the n-p scattering with emphasis on possible experimental determination of the "inscattering" contribution

Over the past few years, significant progress has been made in the study of three-body final state interactions. A system well suited to the detection of a neutron as one of these three particles is now available at Rice, and a second neutron detector, similar in performance to that outlined here, but capable of finer timing resolution, will soon be completed. There is thus a fertile, if not inexhaustible field of studies awaiting one.
APPENDIX A.

DERIVATION OF THE ZERO-CROSSOVER TIME EXPRESSION

If the dynode current pulse is integrated with a long time constant

\[ Q = I_f \tau_f + I_s \tau_s = Q_s + Q_f \]

where

\[ Q = \text{total pulse charge} \]
\[ Q_s = \text{slow component of the scintillation pulse charge} \]

It is however, more convenient, to consider the charge as an explicit function of time, i.e.:

\[ Q(t) = Q - Q_s e^{-t/\tau_s} + Q_f e^{-t/\tau_f} \]  

Since we are interested in the integrated pulse at \( t = 1 \mu\text{sec} \), the fast component in the above expression may be overlooked to a first approximation \( e^{-t/\tau_f} \approx 10^{-175} \) for \( t = 1 \mu\text{sec}; \tau_f = 2.5\text{ns}. \)

Applying the Laplace transformation:

\[ Q(s) = \frac{Q}{s} - \frac{Q_s}{s + 1/\tau_s} \]

The operation of single delay-line differentiation may be represented by:
where: \[ \tau_d = 2 \times \text{delay-line length} \]

whilst the RC-differentiation may be represented by:

\[ s + \frac{1}{\tau_{rc}} \]

where \[ \tau_{rc} = R \times C. \]

Thus, the Laplace transform of the doubly differentiated pulse is

\[ Q''(s) = \left[ Q_s - \frac{Q_s}{s + 1/\tau_s} \right] \left[ 1 - e^{-t \tau_d / s} \right] \left[ s + \frac{1}{\tau_{rc}} \right]. \]

Its inverse is:

\[ Q''(t) = \frac{Q_s}{\tau_{rc}} + Q_s \left( 1 - e^{-t \tau_d / s} \right) \left( \frac{1}{s} - \frac{1}{\tau_{rc}} \right) e^{-t / \tau_s}. \]

Equating this to zero, in order to obtain the zero-crossover point:

\[ t = \tau_s \ln \left[ \frac{Q_s}{Q} \left( 1 - e^{-t \tau_d / s} \right) \left( \frac{s - \tau_{rc}}{s} \right) \right]. \]
APPENDIX B.

CALCULATION OF THE GEOMETRIC FACTOR, $A(E_n, \theta)$

As stated in section IIG, this factor has the form

$$A(E_n, \theta) = \int \int e^{-az} e^{-a'z} \, dx \, dz$$

$$x = -\xi, \quad y = -\lambda$$

There are four cases of relevance:

i). If $0 < \theta < \eta$

$$A = \frac{\sin \theta}{a a'} [1 - e^{-2a\xi}] - \frac{\sin \theta}{a'(a - a'/\cos \theta)} [1 - e^{-(a-a'/\cos \theta)2\lambda}] \cdot$$

$$+ \frac{(2\xi - 2a\lambda \tan \theta)}{a - (a'/\cos \theta)} e^{-2a'\lambda/\cos \theta} - 2\xi e^{-2a\lambda}$$

$$+ \frac{e^{-2a'/\cos \theta}}{(a-a'/\cos \theta)^2} [1 - e^{-(a-a'/\cos \theta)2\lambda}] \cdot$$

ii). If $\eta < \theta \pi/2$

$$A = \frac{\sin \theta}{a a'} [1 - e^{-a'\xi / \sin \theta}] + \frac{e^{-2a\xi \tan \theta}}{a(a-a'/\cos \theta)} [1 - e^{(a-a'/\cos \theta)2\xi / \tan \theta}]$$

$$- \frac{2\xi e^{-2a\lambda}}{a-a'/\cos \theta} - \frac{e^{-2a\lambda \tan \theta}}{(a-a'/\cos \theta)^2} [1 - e^{(a-a'/\cos \theta)2\xi / \tan \theta}] \cdot$$
iii). If $\pi/2 < \pi < \pi - \eta$

\[
A = -\frac{\sin \theta e^{-2a\lambda}}{a a'} \left[ 1 - e^{-2a' \xi / \sin \theta} \right] + \frac{2 \xi}{(a-a'/\cos \theta)}
\]

\[
- \frac{\tan \theta}{a(a-a'/\cos \theta)} \left[ 1 - e^{-2a'/\cos \theta) \xi / \tan \theta} \right]
\]

iv.) If $(\pi - \eta) < \theta < \pi$

\[
A = \frac{\sin \theta}{a a'} \left[ 1 - e^{-2a\lambda} \right] - \frac{\sin \theta}{a'(a-a'/\cos \theta)} \left[ 1 - e^{-(a-a'/\cos \theta)2\lambda} \right]
\]

\[
+ \frac{2 \xi - (2 \xi + 2\lambda \tan \theta) e^{-(a-a'/\cos \theta)2\lambda}}{(a-a'/\cos \theta)}
\]

\[
- \frac{\tan \theta}{(a-a'/\cos \theta)^2} \left[ 1 - e^{-(a-a'/\cos \theta)2\lambda} \right]
\]
APPENDIX C.

SPATIAL LOCALIZATION CALCULATIONS

The interaction is considered to be localized in a spatial region of radius $a$. The energy of excitation of this composite nucleus may then be calculated. Considering its associated wavelength, $\lambda$,

$$\lambda = 4r$$

$r$ is of the order of $4^{-1/2}$ fermis.

$$\lambda = 4r = 1.8 \times 10^{-12} \text{ cms}$$

$$p = \frac{h}{\lambda} \frac{6.625 \times 10^{-27}}{1.8 \times 10^{-12}} \text{ erg. secs.}$$

$$= 3.68 \times 10^{-15}$$

$$E = \frac{p^2}{2m}$$

$$= \frac{13.54 \times 10^{-30}}{2 \times 1.67 \times 13 \times 10^{-24}} \text{ ergs}$$

$$= 3.12 \times 10^{-7} \frac{\text{ MeV}}{1.6 \times 10^{-6}}$$

$$\approx 200 \text{ Kev.}$$
VII. REFERENCES


7) Nuclear Data Tables, Part III (1960).


9) Brooks, F. D., Prog. in Nucl. Phys. 5 (1956) 252.


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