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MUON CAPTURE NEUTRONS, ASYMMETRY AND SPECTRUM

by

Ronald M. Sundelin

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Contract AT(30-1)-882

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A thesis based upon the work reported here, has been submitted to the Department of Physics, Carnegie Institute of Technology May 24, 1967, in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

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I. ABSTRACT

The asymmetry in the angular distribution of neutrons emitted following the capture of negative muons in silicon, sulfur, and calcium has been measured. The measurement was made by stopping polarized muons in a magnetic field, in which the muons precessed, and recording the number of neutrons detected in a fixed counter as a function of the time after a muon stop. The events were simultaneously sorted according to the pulse height observed in this counter. Neutrons were distinguished from gamma rays by pulse shape discrimination.

The asymmetries for the three elements, normalized to complete muon polarization, varied from near zero for small pulse heights to $+0.32 \pm 0.05$, $+0.30 \pm 0.08$, and $+0.20 \pm 0.08$ for pulse heights greater than that produced by a 15.6 MeV proton, for silicon, sulfur, and calcium, respectively. These numbers disagree both in magnitude and in sign with the results of other recent measurements.

The neutron energy spectra were obtained from the neutron pulse height spectra by an unfolding process. In the energy range studied, 7.7 to 52.5 MeV, the neutron energy spectra decreased exponentially with increasing energy. The spectral integrals between these energy limits were 0.23 ± 0.04 , 0.21 ± 0.04 , and 0.18 ± 0.03 neutrons per capture, and the exponential decay constants were 7.6, 7.3, and 7.2 MeV, for silicon, sulfur, and calcium, respectively.

II. INTRODUCTION

A. Muon Capture - General

According to the idea of a universal Fermi interaction, all fermions are coupled by the same fundamental weak interaction.^{1,2} The weak coupling of protons and neutrons with electrons and electron neutrinos is manifested by beta decay and by K-capture. The weak coupling of electrons and electron neutrinos with muons and muon neutrinos is manifested by muon decay. The weak coupling of muons and muon neutrinos with protons and neutrons is manifested by muon capture by nuclei and by muon neutrino scattering by nuclei. The present work deals with muon capture by nuclei.

The most general matrix element describing the weak interaction of muons with nuclei, in the absence of derivative coupling, is written

$$M = \sum_i (\bar{\psi}_F \sum_j (\tau^+ O_i)_j \psi_I) \cdot (\bar{\psi}_\mu O_i (g_i + \Gamma_5 g_i') \psi_{\nu_\mu}) + \text{hermitian conjugate},$$

where ψ_I is the initial nuclear wave function, ψ_F is the final nuclear wave function, τ^+ is the charge raising operator, O_i is the operator corresponding to the i^{th} form of interaction, j is a summation index over nucleons, ψ_μ is the muon wave function, $\Gamma_5 = -i\gamma_5$ is the relativistic pseudoscalar Dirac matrix, ψ_{ν_μ} is the wave function of the muon neutrino, and g_i and g_i' are the coupling constants corresponding to the i^{th} form of the interaction. The operators O_i can exhibit scalar, pseudoscalar, vector, axial vector, and tensor behavior. The number of coupling constants is double this number, since g_i and g_i' are not

necessarily the same. Violation of time reversal invariance would again double the number by introducing complex coupling constants, creating a total of 20 coupling constants.

Most of these coupling constants have been eliminated in studies of beta decay and muon decay. These studies have not shown the existence of time reversal invariance violation or of derivative coupling. In addition, the absence of scalar and tensor coupling has been shown by these studies.

If g_1 and g_1' are both non-zero, parity is violated. This possibility was first suggested to explain the τ - θ puzzle by Lee and Yang.³ That a parity violation exists was confirmed by observing an asymmetry in the angular distribution of the beta decay electrons from polarized Co^{60} ⁴ and in the angular distribution of the decay positrons from muons.⁵

The pseudoscalar coupling is not important in beta decay because the contribution of the pseudoscalar coupling to the matrix element is proportional to the nucleon recoil velocity, which is small because the momentum transfer is small.

Both beta decay and muon decay are adequately described by two coupling constants. The vector coupling constant is approximately the same for beta decay and muon decay because of weak vector current conservation⁶ and because the Cabibbo angle is small.⁷ In the case of

muon decay, the axial vector coupling constant is equal in magnitude and opposite in sign to the vector coupling constant. This was determined from the asymmetry of positrons from μ^+ decay.⁸ There is no conserved weak axial vector current, and the axial vector coupling constant for beta decay has a magnitude $(18 \pm 2.5)\%$ larger than the vector coupling constant.^{9,10} That the beta decay coupling constants are opposite in sign was established by the measurement of the angular distributions of the protons and electrons from the decay of polarized neutrons.¹¹

The coupling constants expected for muon capture by nuclei are close to those for beta decay.¹² $g_V(\mu) = 0.97 g_V(\beta)$ and $g_A(\mu) = 0.999 g_A(\beta)$.

Two approximations which are made in computing beta decay matrix elements are not valid for muon capture. The first approximation is that the neutrino wavelength is long compared to the nuclear size, and the second is that the recoil velocity of the nucleon is negligible. The significant nucleon recoil velocity in the case of muon capture causes weak magnetism and the pseudoscalar interaction to be important. In muon capture, the fundamental coupling constants are replaced by effective coupling constants as follows, where μ_p is the proton anomalous magnetic moment, μ_n is the neutron anomalous magnetic moment, v is the neutrino momentum, and M is the nucleon mass.

$$G_V = g_V(\mu) (1 + v/(2M))$$

$$G_A = g_A(\mu) - g_V(\mu) (1 + \mu_p - \mu_n) (v/(2M))$$

$$G_P = (g_P(\mu) - g_A(\mu) - g_V(\mu) (1 + \mu_p - \mu_n)) (v/(2M))$$

Weak magnetism is the result of the weak interaction between the leptons and the pion cloud of the nucleons.¹³ The induced pseudoscalar interaction is the result of the transfer of a virtual pion propagator between the nucleon vertex and the lepton vertex. The value of the induced pseudoscalar coupling constant $g_P(\mu)$ is expected to be 7 times the axial vector coupling constant.¹⁴⁻¹⁶

Each different muon capture experiment can be used to determine a particular combination of the coupling constants. The interpretation of these experiments is, however, generally complicated by the fact that the nuclear wave functions are not accurately known.

A number of experiments has been performed in which the total capture rate of muons by complex nuclei has been measured.¹⁷⁻²¹ These rates are compared to the rates predicted assuming universality and using an approximate nuclear model.²²⁻²⁴ The measured rates are in good agreement with the predicted rates.

Capture rates from two different hyperfine levels of the same muonic atom provide information on the spin dependence of the weak interaction between muons and nucleons.²⁵ Such a measurement can readily be performed in atoms in which one hyperfine level converts to another.²⁶

Such measurements have been made, and are in agreement with the V-A theory.²⁷

The radiative muon capture rate provides a measurement of the weak interaction coupling constants, and is particularly sensitive to the induced pseudoscalar coupling constant.²⁸ The energy spectrum of gamma rays from radiative muon capture in Ca has been measured and the total rate has been found to be two standard deviations above the theoretically predicted rate.²⁹ This implies that $g_p(\mu) = (13.3 \pm 2.7) g_A(\mu)$. The rate of radiative muon capture has also been measured in Cu with similar results.³⁰

The photon-neutrino angular correlation in radiative muon capture would provide a determination of another combination of the coupling constants,²² but this has not been measured because of the difficulty of the experiment.

The predicted muon capture rate in hydrogen is essentially free from theoretical uncertainties, now that the problem of the muon molecular ion existing in the initial state appears to have been solved,³¹⁻³³ and is in good agreement with experiment.³⁴⁻³⁶ (However, a recent treatment of this problem casts doubt on earlier calculations.³⁷)

The capture of muons in He^3 with the production of the bound ground state of H^3 provides accurate information on the weak interaction constants coupling muons and nucleons. The effect of uncertainties in

the nuclear wave function can largely be cancelled through use of the ft value for beta decay of H^3 into He^3 , since the ground states of these two isotopes form an isotopic doublet. The remaining uncertainties due to the difference in the momentum transfer in muon capture and in beta decay and due to the finite nuclear size is small because the nuclear form factors are well known from electron scattering.^{38,39} The predicted capture rate⁴⁰⁻⁴⁵ is in good agreement with the measured rate.⁴⁶⁻⁴⁸

The capture of muons in C^{12} with the production of the ground state of B^{12} also provides accurate information on the weak interaction constants coupling muons and nucleons. The ft value for beta decay of B^{12} into C^{12} again eliminates much of the uncertainty due to the nuclear wave function. The measured rate⁴⁹ is in good agreement with the theory.

The partial capture rates of negative muons in O^{16} to the ground state and to the first and third excited states of N^{16} have been measured.^{50,51} The results are in agreement with theoretical predictions.

Other types of experiments which would provide information concerning the weak interaction constants coupling muons and nucleons are the measurement of the angular distribution of photons from radiative muon capture with respect to the muon polarization direction, the measurement of the polarization of the photons emitted in radiative muon capture, and the measurement of the polarization of the recoil nuclei or neutrons emitted following muon capture. All of these experiments are so difficult that none of them has been successfully attempted.

The measurement of the asymmetry in the angular distribution of the neutrons emitted following muon capture is discussed in the next section.

In general, the muon capture experiments which have been performed are in good agreement with the predictions of the universal Fermi interaction.

B. Neutron Asymmetry

The angular distribution of neutrons emitted following muon capture in nuclei is expected to exhibit an asymmetry with respect to the direction of polarization of the muons. This asymmetry provides information concerning the weak interaction coupling constants, and is particularly sensitive to the induced pseudoscalar coupling constant. The angular distribution of the neutrons is of the form $1 + A \cos \theta$, where A is the asymmetry and θ is the angle between the muon spin direction and the direction of emission of the neutron. The asymmetry can be written as the product of three factors: $A = P_\mu \alpha \beta$. P_μ is the polarization of the muons in their atomic ground state. α is the fundamental asymmetry, and can be computed using the matrix element which has been discussed. β is a factor describing the reduction of asymmetry due to the interaction of the escaping neutron with the residual nucleus. P_μ is the largest value that $|A|$ can exhibit, since the magnitude of $\alpha \beta$ cannot exceed unity. The values of α and β depend both on the nucleus used and on the neutron energy.

The value of α has been computed for spin-0 nuclei using the closure approximation, in which the sum over energetically accessible final states is replaced by the sum over all final states.²² Terms proportional to the recoil momentum of the neutrons are included in the calculation, but terms proportional to the initial momentum of the capturing proton are omitted. The value of β is taken to be near unity.

Using these approximations, α is given by

$$\alpha = (G_V^2 - G_A^2 + G_P^2 - 2 G_A G_P) / (G_V^2 + 3 G_A^2 + G_P^2 - 2 G_A G_P).$$

Taking the average value of the neutrino momentum to be $0.75 m_\mu$, the average over the energies of all directly emitted neutrons yields

$\alpha = -0.39$. It is noted that α would be zero if G_V were equal to $-G_A$ and if G_P were zero. This is why α is particularly sensitive to the value of the induced pseudoscalar coupling constant.

A similar calculation has been performed in which terms proportional to the initial proton momentum have been included.⁵² This calculation leads to an expression for the asymmetry of the same form as has just been described, except that G_V becomes

$$G_V = g_V(\mu) (1 + k_F/M + v/(2M)) \text{ and } G_P \text{ becomes}$$

$$G_P = (g_P(\mu) - g_A(\mu) - g_V(\mu) (1 + \mu_p - \mu_n)) (v/(2M)) - g_A (k_F/M).$$

The terms proportional to the Fermi momentum k_F are quite important, since k_F is of the order of 270 MeV/c, whereas the neutrino momentum is of the order of 100 MeV/c. The asymmetry of the highest energy neutrons is found to be approximately -0.11 , depending on the value chosen for the effective nucleon mass. This asymmetry decreases in an approximately linear manner as the neutron energy decreases.

A number of experiments to measure the asymmetry of neutrons emitted following negative muon capture have been performed using various neutron energy thresholds.⁵³⁻⁶⁵ The majority of these experiments have yielded negative asymmetries.

Experiments in which the asymmetry of the highest energy neutrons has been measured⁶³⁻⁶⁵ have yielded values of $\alpha\beta$ near -1, in disagreement with the theoretical predictions.

The significant disagreement between theory and experiment indicated the need for additional work on both. It was decided that the experiment should be performed again to check for the possibility of a systematic error in the previous experiments. In addition, two different methods were used in repeating the experiment.

One method used was similar to the methods previously used. A beam of polarized negative muons was stopped in a target of silicon, sulfur, or calcium. The spins of the stopped muons were precessed by a vertical magnetic field. If the muon was captured by a target nucleus, an emitted neutron could be detected in a fixed neutron detector placed near the target. The time between the stopping of a muon and the detection of a neutron was measured by a digital timing system, whereas all previous experiments to measure the asymmetry of the highest energy neutrons (thresholds 18 MeV or higher) used an oscilloscope to measure this time. Pulse shape discrimination was used to reject gamma rays which would otherwise have been identified as neutrons; this method was

also used in one of the experiments mentioned,⁶³ whereas sandwich counters were used in the other two.^{64,65} The use of a digital timing system minimizes problems associated with nonlinearity of the timing system. In addition, severe dead time requirements were imposed in the present experiment to minimize distortions of the timing spectrum due to the occurrence of ambiguous events. The events were sorted, not only by time, but also by the pulse height caused by the detected neutron. Since a neutron can cause a pulse with amplitude anywhere from zero to that of a proton of equal energy, the pulse height spectrum provides only an indirect measurement of the neutron energy.

The second method used was intended to provide a direct measurement of the energy of each neutron. Since the predicted value of $\alpha\beta$ depends on the neutron energy, a direct measurement of the energy of each neutron is of considerable interest. As discussed in Appendix IV, this method was unsuccessful for reasons of rate and background. Again, a beam of polarized negative muons was stopped in a target in a magnetic field. The time between the stopping of a muon and the detection of a nuclear deexcitation gamma ray was measured by the digital timing system. Another counter, one meter from the target, was used to detect neutrons, and the energy of the neutron was determined from the time between the detection of a nuclear deexcitation gamma ray and the detection of the neutron. This time of flight was measured by a time to pulse height converter. Neutrons in the gamma ray detection counter were rejected by pulse shape discrimination.

The experimental apparatus used for both of these methods is discussed in Chapter III. The first method and its results are discussed in Chapter IV.

C. Neutron Energy Spectrum

The energy spectrum of neutrons emitted following negative muon capture in nuclei is of interest because it provides information on the capture mechanism, and because the theoretical asymmetry is energy dependent. The emitted neutrons can be classified as evaporation neutrons, giant resonance neutrons, and direct neutrons. Evaporation neutrons⁶⁶ result when the energy deposited in the nucleus as the result of muon capture is statistically shared by the nucleons, and a neutron can "boil off" when its energy exceeds its binding energy. Most evaporation neutrons have energies below 5 MeV, and were therefore unobservable in the present experiment, in which only high energy neutrons were recorded. Giant resonance neutrons are emitted following giant resonance capture of a muon.^{1,23,67} Such a capture occurs to a high energy unbound excited state, which promptly decays by nucleon emission. Direct emission⁶⁸⁻⁷⁰ occurs when a single proton is involved in the capture and when the resultant neutron escapes directly from the nucleus without the formation of any intermediate nuclear state.

The observed neutron energy spectrum can provide information concerning the relative importance of these three neutron emission mechanisms. This is especially important for the evaluation of the

neutron asymmetry, since evaporation neutrons and giant resonance neutrons involve the formation of an intermediate nuclear state which de-excites by strong interactions. Neutrons emitted by these two mechanisms are necessarily isotropic, and only the neutrons emitted directly can exhibit an asymmetry. In addition, the neutron energy spectrum provides a check of the weak interaction physics and the nuclear physics used in predicting the spectrum.

The pulse height spectrum measured in the present experiment can be used to determine the neutron energy spectrum. Known neutron scattering cross sections are used to unfold the neutron energy spectrum from the pulse height spectrum. This unfolding process, and associated checks, are described in Chapter V.

III. EXPERIMENT

A. Physical Apparatus

1. Beam.

The arrangement of the physical apparatus is shown in Figure 1. The negative beam from the Carnegie Tech synchrocyclotron passed through the muon channel. The muon channel has a nine turn center conductor, which was operated at 18,450 ampere-turns. The magnetic field produced by this current accelerated the negative beam particles toward the center conductor and caused them to follow helical paths. These helical paths prevented the loss of some of the muons which entered the channel at angles to its axis, and also increased the retention of the muons resulting from decay of pions in flight in the channel. The muon channel was found to increase the muon intensity by a factor of 2.7.

Due to the divergence of the beam, it was desirable to have the experimental target as close as possible to the end of the muon channel. Since an intense neutral beam was emergent from the muon channel, it was also desirable to have as much shielding as possible between the end of the muon channel and the experimental target. In order to meet both of these conditions, the Berkeley magnet, which was used as a bending magnet, was used at right angles to its usual orientation. Holes were cut in the yoke of the magnet for the beam to pass through. In this way, the yoke of the magnet

was used as shielding without increasing the distance of the target from the end of the muon channel. This arrangement also had the advantages that the Berkeley magnet fringing field present at the counters was reduced and that the homogeneity of the field through which the beam passed was improved. The bending angle was 30° . The space inside the Berkeley magnet, except for the beam path, was filled with lead.

Upon emerging from the Berkeley magnet, the beam passed through the first telescope counter and through a one foot thick lead wall. It then entered the region between the poles of a C-magnet. The experimental target was located at the center of the C-magnet.

2. Counters.

Counter 5 comprises a $7\frac{1}{2}$ " diameter by 5" thick volume of NE 213 liquid scintillant viewed by a 58AVP photomultiplier. The front of the scintillant was 6-1/16" from the center of the target.

Counters 7 and 8 were used only in the muon-gamma-neutron time of flight experiment, and are discussed in Appendix IV.

Paraffin shielding was placed as shown to reduce the flux of cyclotron-produced neutrons passing through the cyclotron shield wall and entering counters 5 and 7. The paraffin nearest counters 5 and 7 was borated to capture neutrons thermalized by the remainder of the paraffin. The one foot thick lead wall was used to stop gamma rays

produced by the thermal neutron captures and to stop any other gamma rays present.

The region inside the C-magnet pole pieces is shown in more detail in Figure 2. The C-magnet was fitted with circular pole pieces 25-1/8" in diameter. Each of these pole pieces was covered with a 1" thick sheet of lead, leaving a 7" gap between the poles.

The incident muon beam, which had momentum 170 MeV/c, passed through telescope counters 1 and 2, both of which have 4" x 4" x 1/4" plastic scintillants. Counter 1 has a 6810A photomultiplier, and counter 2 has a 56AVP photomultiplier. The beam was then moderated by copper and carbon absorbers, and passed through telescope counters 3 and 4. Counter 3 has a 3-3/4" x 4" x 1/16" plastic scintillant viewed by a 56AVP. The scintillant is backed by a 3/16" acrylic sheet, which improves the light collection uniformity. Counter 4 has a 4" x 4" x 1/16" scintillant viewed by a 6810A photomultiplier. After passing through counter 4, muons stopped in the target. Counter 9, located directly behind the target, served as an anticoincidence counter for the beam telescope, and as both an anticoincidence and a coincidence counter for counter 5. Counter 9 has a 12" x 6-7/8" x 1/8" plastic scintillant viewed by a 6810A photomultiplier. Counter 6, which has an 11" x 6-7/8" x 1/8" plastic scintillator viewed by a 6810A photomultiplier, also serves as both an anticoincidence and a coincidence counter for counter 5.

3. Shielding.

The shielding used in the vicinity of the target was primarily lead. Lead was chosen because muons in lead have a shorter lifetime than in any other readily available material. The short lifetime facilitates the analytical removal of background caused by the shielding. In places where a muon stopping in the wrapping of a counter could be identified as a muon stopping in the target, the counter wrapping was made of 0.3 or 1.0 mil tantalum. Tantalum was used because of its strength and because muons have essentially the same lifetimes in lead and in tantalum, which similarity permits the use of a single lifetime value in the high-Z background analysis.

4. Targets.

The target materials used were chemically pure silicon, sulfur and calcium. Each target used had an effective thickness of four grams per square centimeter in the direction of the beam. The targets were not made thicker than this because the scattering of neutrons by the target becomes a significant problem at greater thicknesses. A target half-thickness of 2.0 grams per square centimeter yields a neutron scattering probability less than 10 per cent for all three targets. In addition, the scattering in the neutron energy range of interest is primarily forward elastic scattering. Thus many of the neutrons which are scattered do not have their energies or directions appreciably changed. Thicker targets would also have caused problems by scattering decay electrons. That electron scattering is not a serious problem at this

target thickness was both computed and experimentally confirmed, as is discussed later. The target thickness selected is a compromise between particle scattering and muon stopping rate.

The targets were prepared as follows. The silicon target consisted of silicon powder contained in a tantalum foil and lead box. The sulfur target was a cast block supported by a lead frame. The calcium target was a cast block contained in a tantalum foil and lead box. To prevent oxidation of the calcium, the box contained an argon atmosphere which was maintained at a pressure 0.2 mm Hg above atmospheric pressure. These targets all have spin zero. Spin zero was chosen to minimize the depolarization of the muons when they are captured into atomic orbits and to avoid theoretical complications associated with hyperfine structure.

5. Muon Precession.

Muons stopping in the target were identified by coincident pulses in counters 1, 2, 3, and 4, and by the absence of pulses in counters 6, 8, and 9. The muons which stopped in the target were forward polarized in the direction of motion of the beam. The muons which stopped in the target were caused to precess about a vertical axis by the field of the C-magnet. Such precession continued for each muon until the muon decayed or was captured by the target material.

The current for the C-magnet was supplied by a transistorized, regulated current supply having a stability better than one part in a

thousand. The uniformity of the magnetic field over the target volume was measured and found to be better than 1 per cent.

6. Event Identification.

When a muon decayed into an electron, a neutrino, and an antineutrino, counter 5 was used to detect the electron. A decay electron was identified by coincident pulses in counters 5, 6, and 9.

In the neutron pulse height experiment, the reaction sought was the capture of a muon by a target nucleus, followed by the emission of a neutron. Counter 5 was used to detect the neutrons emitted. This counter is equipped with a pulse shape discriminator which distinguishes between the shapes of the light pulses produced by electrons and those produced by protons and heavier charged particles. The construction, operation, and testing of counter 5 are described in detail in Appendix I. A neutron was identified by the presence of pulses from counter 5 and from the pulse shape discriminator and by the absence of pulses from counters 6 and 9. The pulse height observed in counter 5 due to the interaction of the neutron with one or more nuclei in the counter 5 scintillant provided an indirect measurement of the energy of the neutron. The use of the pulse shape discriminator to reject gamma rays was essential because the number of gamma rays exceeded the number of neutrons at low pulse heights.

The unnormalized probability that a neutron would be detected in the interval dt at time t after a muon stopped in the target

was equal to the probability that the muon existed at time t , which probability was $\exp(-\lambda t)$, where λ is the muon disappearance rate in the target material, times the probability that the muon would be captured in the interval dt , which probability was proportional to dt , times the relative probability that an emitted neutron would be emitted in the direction of counter 5, which probability was $(1 + A \cos(\omega t + \phi))$, where A is the asymmetry factor describing the angular correlation between the direction of the muon spin and the direction of neutron emission, ω is the angular precession frequency of the muons, and ϕ is a phase angle which takes account of the angle between the muon spin and the direction from the target to counter 5 at time zero. The shape of the timing spectrum observed was therefore of the form $C \exp(-\lambda t) (1 + A \cos(\omega t + \phi))$, where C is an amplitude coefficient. In addition to this term, several background terms were present. These terms are discussed in Chapter IV.

The timing spectrum observed for the decay electrons was of the same form as the timing spectrum for the neutrons.

B. Electronics

A simplified block diagram of the electronics is shown in Figure 3. Pulses from the counters, after being limited and delayed, and in some cases clipped, attenuated, split, amplified, or clamped, entered the fast logic. The fast logic consisted primarily of Chronetics 100 MHz modules, and was used to identify muon stops, electrons, and neutrons or gammas in counter 5. The slow logic consisted entirely of

circuits designed and built at this laboratory for this experiment, and was used to impose suitable requirements on the time relationships of muon stops and electrons, neutrons, or gamma rays.

After emerging from the slow logic, pulses were processed by the two dimensional analyzer. One dimension consisted of the time between the detection of a muon stop and the detection of an electron or neutron. The measurement of this time was performed by a 100 MHz digital timing system. The second dimension consisted of the pulse height observed in counter 5. The measurement of the second dimension was performed by an eight channel pulse height analyzer. One of the eight channels, however, was assigned to the registration of decay electrons. Each event, after being processed by the digital timing system and the eight channel analyser, was stored in a SCIPP 1600 channel analyzer.

Appropriate pulses from counter 5 were sent to the PSD monitor, which consisted of circuits for monitoring the performance of the pulse shape discriminator. These circuits are described in greater detail in Appendix I.

Pulse widths and timing which are hereinafter described applied to the sulfur and calcium targets. There were some differences in the case of silicon, which was studied using a 50 MHz digital timing frequency.

1. Logic.

The fast and slow logic are shown in greater detail in Figure 4. Appropriately shaped pulses from the counters were sent to the bank of fifteen discriminators shown at the left side of the drawing. The numbers 101, 102, and 105 on circuits refer to Chronetics discriminators, coincidence circuits, and time to pulse height converters, respectively. The numbers 1 through 9 on the discriminators refer to the counter numbers from which their input pulses originated. The suffix T on some of these numbers indicates low discriminator thresholds, and the outputs of such discriminators were used as timing signals. The suffix G refers to gamma rays, and the suffix E to electrons. The suffix H refers to a high threshold.

The Carnegie Tech synchrocyclotron is equipped with a stochastic cee stretcher, which distributes the beam uniformly over an entire cycle, with the exception of a small amount of prompt beam each cycle. Discriminators 3T, 4, 4H, and 9 were turned off during the prompt beam by the beam gate I.

A coincidence between counters 1, 2, and 3 was formed in the coincidence circuit II. In coincidence circuit III, this coincidence was placed in coincidence with counter 4 and in anticoincidence with counters 6, 8, and 9. Pulses from 6, 8, and 9 were fanned-in by the tunnel rectifier fan-in XIX, before being applied to circuit III. The tunnel rectifier fan-in is a nonregenerative device, and a pulse into one of its inputs does not cause any dead time for the other inputs.

A major problem in this experiment was the elimination of background from counter 4, the last telescope counter. Muons stopping in the last telescope counter are normally indistinguishable from muons stopping in the target. This would have constituted a source of background neutrons and electrons from muons bound in the carbon in the counter 4 scintillant. It was not feasible to move counter 4 away from the target and to shield counter 5 from counter 4 because the angular spread in the muon beam after passing through the absorber was too great, and an excessive loss of beam would have occurred. A technique involving the pulse heights in both counters 3 and 4 was devised as a solution to this problem. This technique involves the rejection of pulses above certain amplitudes. The thresholds of discriminators 3H and 4H were adjusted to correspond to these amplitudes. This technique, and a preliminary experiment for testing it, are described in Appendix II.

The pulses from the 3H and 4H discriminators were fanned-in by the tunnel rectifier fan-in XI, and were applied in anticoincidence in coincidence circuit IV. The pulse from 3T was delayed so that it was the last pulse to reach the coincidence circuit IV. Since this pulse was the last to arrive, it determined the timing of the output of this circuit.

There was a considerable shift in the time of the output of a discriminator with a change in the input pulse height if the pulse height was only slightly above the discriminator threshold. This

shift was considerably reduced if the discriminator threshold was well below the actual pulse height. The threshold of discriminator 3T was set a factor of two below the threshold of discriminator 3. If a pulse from counter 3 had insufficient amplitude, discriminator 3 would not trigger, and no coincidence would be formed in coincidence circuit IV. If a pulse from counter 3 had an amplitude sufficient to trigger discriminator 3, its amplitude would be at least a factor of two greater than the threshold of discriminator 3T. The maximum error in the time of the 3T discriminator output, and therefore in the time of the coincidence circuit IV output, was reduced by more than a factor of two by this technique. The same technique was also applied to counter 5.

An output from the coincidence circuit IV was identified as a muon stop in the target. This pulse was reshaped by the univibrator V, delayed 3.0 microseconds by a length of 1500 ohm cable, and sent into the gate VI. If a pulse from the univibrator XIV and no pulse from the pulse pair detector VIII were present at the gate VI at the time of arrival of the pulse from the univibrator V, this last pulse, after being reshaped, was sent to the digital timing system as a start pulse.

The requirement was imposed that no two 1, 2, 3 coincidences occur so close in time to each other that there could be confusion as to which of them was associated with any event that might be observed. To effect this requirement, the 1, 2, 3 output of coincidence circuit

II was sent to the no-dead-time univibrator VII. The no-dead-time univibrator put out a pulse which continued for 15 microseconds after the most recent input pulse. For example, an input pulse at $t = 0$ would produce an output that extended from $t = 0$ to $t = 15$ microseconds; an input pulse at $t = 0$ and another at $t = 10$ microseconds would produce an output that extended from $t = 0$ to $t = 25$ microseconds. The output of the no-dead-time univibrator VII, after suitable delay, and the output of the coincidence circuit II were applied to the pulse pair detector VIII. The pulse pair detector VIII looked for a coincidence between its two inputs. The input from the no-dead-time univibrator was delayed sufficiently that a single 1, 2, 3 event would not produce a self-coincidence in the pulse pair detector. If, however, a second 1, 2, 3 occurred before the end of the no-dead-time univibrator pulse, a coincidence would be formed in the pulse pair detector VIII. The pulse pair detector would then produce an output which continued for the duration of the input from the no-dead-time univibrator, whose output itself was extended by the occurrence of a second 1, 2, 3 pulse. The output of the pulse pair detector VIII was applied in anticoincidence to the gate VI. Since a muon stop pulse was delayed 3.0 microseconds before reaching the gate VI, the anticoincidence pulse from the pulse pair detector had the effect of blocking a muon stop pulse if another 1, 2, 3 coincidence occurred anywhere from 15 microseconds before to 3 microseconds after the muon stop pulse. For a muon stop pulse to pass through the gate VI, the presence of a pulse from the univibrator XIV was also required. This pulse would be present at the proper

time if a suitable event associated with counter 5 had occurred between 1 microsecond before and 3 microseconds after the muon stop pulse. The operation of the dead time circuits, and their effect on the spectral shapes, are discussed in greater detail in Appendix III.

The 1, 2, 3, 4, $\bar{6}$, $\bar{8}$, $\bar{9}$ pulse from the coincidence circuit III was reshaped by the discriminator IX and applied to the coincidence circuit X in anticoincidence with the pulse from discriminator 1. The output of coincidence circuit X represented a charged particle which passed through counter 1 but did not stop in the target. The pulse from discriminator 5G, which had a slightly lower threshold than 5E and which, therefore, triggered each time 5E triggered, was reshaped by the discriminator XII and sent to the coincidence circuit XIII, which circuit formed a coincidence between the outputs of discriminator XII and the coincidence circuit X. The output of coincidence circuit XIII represented a coincidence between a pulse in counter 5 and a charged particle passing through counter 1 but not stopping in the target. Such coincidences were due primarily to neutrons and gammas from pions which stopped in the absorber. The rejection of events which were associated with such coincidences was found to reduce the random neutron background by a factor of 2.6.

Neutrons and gamma rays were identified in the coincidence circuit XV by the coincidence 5G, 5T, $\bar{6}$, $\bar{8}$, $\bar{9}$. Electrons were identified in the coincidence circuit XVI by the coincidence 5E, $\bar{6}$, $\bar{9}$.

The counter 5 gamma pulse from coincidence circuit XV was sent to the coincidence circuit XXIII. In the neutron pulse height experiment, only the pulse from the coincidence circuit XV was required as an input to the coincidence circuit XXIII.

Electron event pulses from the coincidence circuit XVI and neutron event pulses from the coincidence circuit XXIII were combined by the tunnel rectifier fan-in XXV, and were then sent to the coincidence circuit XXVI. Pulses from the coincidence circuit XIII were applied in anticoincidence to the coincidence circuit XXVI, thereby rejecting events which were associated with the passage of a charged particle through counter 1. The output from discriminator 5T was delayed so that it was the last pulse to arrive at the coincidence circuit XXVI. The output of the coincidence circuit XXVI thus had the timing of discriminator 5T. This output was sent to the amplifier XXVII. One output of this amplifier triggered the univibrator XIV, the output of which was required for the generation of a digital timing start pulse. The other output of the amplifier XXVII drove a 1500 ohm cable of length 3.25 microseconds. This delayed pulse entered the gate XXIV.

The pulse from discriminator 5T was also sent to the no-dead-time univibrator XX and to the pulse pair detector XXII. One output of the no-dead-time univibrator XX, whose output extended 20 microseconds after its most recent input, was used to gate off both the gamma coincidence circuit XV and the electron coincidence circuit

XVI. This gating protected the following slow circuitry against excessive rates and reduced the rate of generation of digital timing start pulses which would otherwise be rejected only by the absence of a digital timing stop pulse. The timing of the gating was such that the coincidence circuits were turned off as soon as a pulse associated with the same event as the 5T pulse had passed through them. The second output of the no-dead-time univibrator XX was sent to the pulse pair detector XXII. This pulse pair detector detected pairs of pulses from the discriminator 5T in exactly the same way as the pulse pair detector VIII detected 1, 2, 3 pulse pairs. The output of the pulse pair detector XXII was applied in anticoincidence to the gate XXIV. The operation of this anticoincidence was such as to reject any event if another 5T pulse occurred between 20 microseconds before and 3.25 microseconds after the event under consideration. This operation was partially redundant, since those events which were preceded by 0 to 20 microseconds by a 5T pulse were rejected by the gating off of the coincidence circuits XV and XVI. Pulses from the amplifier XXVII which were accepted by the gate XXIV were restandardized and sent to the digital timing system as stop pulses.

An output from the electron event coincidence circuit XVI was reshaped by the univibrator XXVIII and sent to the eight channel pulse height analyzer.

The slow logic which has been described above was direct coupled wherever direct coupling was useful. The dead time coverage was such that the accepted event rate went completely to zero as the average input event spacing became small compared to the minimum acceptable pair spacing.

2. Two Dimensional Analyzer.

The two dimensional analyzer is shown in Figure 5. A start input pulse from the slow logic produced a 670 microsecond pulse in the dead time circuit and gate generator. A second start input pulse during this interval was ignored. The leading edge of the 670 microsecond pulse turned on a bistable circuit which, while in the on state, generated an output pulse. The bistable was turned off when a stop input pulse was received from the slow logic or when the cable delayed start pulse was received, whichever occurred first. The gate pulse thus generated was sent to one of the coincidence inputs of a Chronetics 102 coincidence circuit, in which the input had been modified to accept pulses several microseconds wide. A continuous sine wave from a crystal controlled oscillator was sent to another coincidence input of the same coincidence circuit. The frequency used was 100 MHz for the calcium and sulfur targets, and 50 MHz for the silicon target. The output of the coincidence circuit was a pulse train having the frequency of the oscillator and the width of the input gate pulse. One output was sent to a last pulse detector, which detected a pulse train and supplied an output pulse a fixed time after the last pulse in the train. This output

pulse was reshaped and lengthened to 6 microseconds by a univibrator. A second output from the coincidence circuit was sent to a discriminator, the output of which was sent to a Chronetics 100 MHz scaler. The count in this scaler represented the time between the stopping of a muon and its disappearance. The scaler was reset by a delayed pulse, originating from the last pulse detector, each time an event was processed.

The signal from one of the dynodes in counter 5 was integrated and allowed to decay with a 2 microsecond decay constant. This signal was amplified in the base of counter 5 and sent to the two dimensional analyzer. The polarity of this signal was inverted in the two dimensional analyzer. In the neutron pulse height experiment, a string of amplifiers in the two dimensional analyzer was connected to the inverted linear signal from counter 5.

A set of eight pulse height discriminators received inputs from various points within the string of amplifiers. The thresholds of these discriminators were set to correspond to particular electron energies in the neutron pulse height experiment. The outputs of these pulse height discriminators were connected in ascending order of threshold to eight inputs of the eight channel pulse height analyzer. These eight thresholds defined seven channels in the pulse height analyzer. Channels two through eight were assigned to the pulse height analysis. Channel one was assigned to decay electrons, and was selected by an electron pulse from the slow logic.

The pulse shape discriminator circuit was an integral part of counter 5. This discriminator produced a pulse when the particle detected was a neutron, and did not when it was a gamma. The pulse from the pulse shape discriminator was sent to a pair of univibrators, the first of which delayed the signal 2 microseconds, and the second of which produced an output pulse of width 4.5 microseconds. In the neutron pulse height experiment, the delayed PSD pulse was applied directly to the coincidence input of the eight channel pulse height analyzer. This particular coincidence input applied only to channels two through eight. A neutron caused a coincidence pulse to be applied to the pulse height analyzer, and a gamma ray did not.

The 6 microsecond pulse produced following the last pulse of a pulse train was applied to a second coincidence input of the eight channel pulse height analyzer. This pulse was required by all eight channels of the analyzer.

When the eight channel pulse height analyzer received a pulse from either the electron input or the lowest level pulse height discriminator, the pulse height analyzer waited a preset time and then examined all inputs. If an electron input pulse and a 6 microsecond coincidence pulse were present at the time of the examination, an electron output pulse was produced by the analyzer. If one or more pulse height discriminator pulses were present, and both coincidence pulses were present, an output corresponding to the

highest level discriminator pulse present was produced. If all eight pulse height discriminators were triggered, this corresponded to a pulse height above the highest channel, and no output pulse was produced. If both an electron pulse and one or more pulse height discriminator pulses were present, the electron pulse was given preference.

The output pulse from the eight channel pulse height analyzer was sent to one of eight univibrators for shaping, and from there it was sent to the interface logic module. The interface logic encoded this pulse into binary form so that it corresponded to one of eight groups of 200 channels each in the Victoreen SCIPP 1600 channel analyzer. The count in the 100 MHz scaler was used to select the corresponding channel within the proper group of 200 channels in the 1600 channel analyzer. The receipt by the interface logic of a pulse from the eight channel pulse height analyzer also caused the generation of "prepare" and "ready transfer" pulses as required by the 1600 channel analyzer. The 6 microsecond pulse resulting from the end of a pulse train was used to reset the 100 MHz scaler after the analysis of each event had been completed.

Most of the circuits in the two dimensional analyzer, with the exception of the commercial circuits, were built in this laboratory for this experiment.

See Appendix IV for a discussion of the muon-gamma-neutron time of flight experiment and of the instrumentation for this experiment.

3. Randoms Tests.

Randoms tests were performed on the timing system, including all the logic preceding it, at the beginning and end of the run, and once a week during the run. Two physically separated counters with radioactive sources near them were used as random inputs. The fast logic requirements were changed so that one counter represented muon stops and the other represented decay electrons. Randoms tests were performed at various average rates, but most were performed at input rates such that the average input pulse spacing was approximately equal to the minimum pulse spacing accepted by the dead time circuits. Tests at this high rate provided stringent tests of the operation of the slow logic as well as of the digital timing system. The randoms tests were conducted at both 100 MHz and 50 MHz.

Each of the randoms tests was analyzed separately, and the sum of all randoms tests at each digital timing frequency was analyzed. The analysis was performed on the entire randoms spectrum and was also performed on groups of 30 channels, where the starting channel of the group of 30 channels analyzed was changed in 10 channel steps so that the entire spectrum was covered. The randoms tests were analyzed by performing a least squares fit to the equation $I = U + Vt$, where I is the number of counts per channel, U is the flat component of the distribution, V is the slope of the distribution,

and t is the time. V is expected to be slightly different from zero because of a logical coupling between the dead time pulse generated by the dead time circuit and gate generator in the digital timing system and the pulse in the stop channel of the dead time circuitry in the slow logic. The value of V/U was expected to be of the order of -0.0013 per microsecond at the high input rates used in the randoms tests, but was completely negligible at the much lower rates incurred in an actual asymmetry run. The values of V/U found in the least squares analysis were in good agreement with the expected values.

When the number of degrees of freedom in a least squares analysis is sufficiently large, the probability distribution for the value of chi squared which is actually observed, assuming that the chosen equation fits the data, exhibits a gaussian shape which is centered about the number of degrees of freedom, and which has a standard deviation equal to the square root of two times the number of degrees of freedom. The number of standard deviations by which the actual chi squared value exceeds the expected chi squared value provides a good measure of the agreement between the actual distribution and the assumed distribution. The analysis of the sum of all 100 MHz randoms tests yielded a value of chi squared which was 0.27 standard deviations below the expected value, and the analysis of the sum of all 50 MHz randoms tests yielded a value of chi squared which was 0.21 standard deviations above the expected value of chi squared. There were 52 million events in the sum of the 100 MHz randoms tests, and

18 million events in the sum of the 50 MHz randoms tests. The analyses in which the randoms tests were examined 30 channels at a time also exhibited good chi squared values, with the exception of zero time. A small bump was observed around zero time, which bump was attributed to cosmic ray showers which were detected in both counters.

The results of the randoms tests analysis show that the digital timing system and the associated dead time circuitry were operating properly, and that there was no appreciable nonlinearity in the timing system.

C. Positive Beam Run

Electrons from muon decay can produce bremsstrahlung gamma rays in the target and in nearby shielding. These gamma rays can cause photonuclear reactions in the carbon in the liquid scintillant in counter 5, with the emission of neutrons or protons. These neutrons and protons are indistinguishable from neutrons and recoil protons due to muon capture in the target. Since the decay electrons have a negative asymmetry, and since the bremsstrahlung gamma rays exhibit some fraction of this asymmetry, any bremsstrahlung gamma rays identified as capture neutrons contribute a false negative component to the asymmetry. In order to determine the magnitude of this effect, a run was made using a positive beam. Positive pions and muons were stopped in the target, and the number of decay electrons and the number of events identified as neutrons as a function of pulse height was measured. The positive pions which were

stopped in the target rapidly decayed into muons. Since no positive muons are captured, all events identified as neutrons were associated with muon decay. The calcium target was used for this run because, having the highest Z of the three targets, it provided the highest production of bremsstrahlung quanta per decay electron. The ratio of the number of neutron-identified events to the number of decay electrons in the positive beam run was compared to this ratio for the negative beam runs. In the positive beam run, only the lowest energy neutron bin showed a statistically significant number of neutron-identified events. The case of silicon will be considered because silicon had the lowest ratios for the negative beam runs, and therefore represents the worst case. In silicon, approximately 1.7% of the neutron-identified events in the lowest energy neutron bin are due to decay electron bremsstrahlung. This percentage is negligible compared to other sources of error.

D. Experimental Procedure

Prior to the experiment, all counters and electronics were thoroughly tested. The input and output parameters of all modules were checked. In addition, the waveforms were checked at all internal points of the circuits built in this laboratory. The assembled electronics were checked using electronically simulated events. In this test, the waveforms in all cables connecting modules were examined, and the proper processing of each event was verified. As has been mentioned, randoms tests were performed to establish the proper operation of the digital timing system and the associated logic.

During the experiment, the applied counter voltages, pulse shape discriminator, and waveforms at critical points were checked at least once every 24 hours. Randoms tests were performed and more detailed checks of the electronics were made once a week.

At the end of the experiment, randoms tests were performed, the performance of all counters and electronic modules was checked, the waveforms in all cables connecting modules were examined, and the outputs of all high and low voltage power supplies were checked.

The descriptions which follow apply to the neutron pulse height experiment only.

Approximately 700 million muons were stopped in each of the three targets. The muon stopping rate averaged 2,000 per second.

The C-magnet was operated at a field of 415 gauss for the calcium and sulfur targets, and at a field of 207 gauss for the silicon target. The fields were measured with a Hall effect gaussmeter. These fields produced approximately two precessions per bound muon lifetime. This precession rate provided adequate analytical independence between the asymmetry and the lifetime and background terms, but was low enough that there was an adequate number of digital timing channels per precession.

For the calcium and sulfur targets, the digital timing system covered a 2 microsecond interval, and for the silicon target, it

covered a 4 microsecond interval. The zero time was displaced so that 0.27 microseconds of negative time were observed for all three targets.

In addition to the primary runs and the calibration runs, three runs were made in which gamma rays, rather than neutrons, were examined using a calcium target. In the lowest energy bin, the number of gamma rays observed per muon stop was 1.44 times the number of neutrons observed per muon stop. Above the first bin, however, the gamma ray spectrum decreased much more rapidly than did the neutron spectrum, and only the lowest pulse height bin for gamma rays had good statistical significance. The lowest gamma ray pulse height bin exhibited an asymmetry of -0.049 ± 0.052 times the maximum allowable asymmetry. The higher energy gamma ray bins are also consistent with zero asymmetry.

One run was made using a carbon target. The electronics were arranged so that the decay electrons were distributed into the pulse height bins, and the bin normally used for decay electrons was unused. This data showed a negative asymmetry which was generally increasing in magnitude as the pulse height increased. The results are shown in Table I. The values of chi squared obtained for this analysis, and also for the analysis of the sum of the data in the seven pulse height bins, are excellent.

IV. NEUTRON ASYMMETRY

This chapter discusses the analysis and results of the neutron pulse height experiment, in which the neutron asymmetry is measured as a function of the pulse height due to recoils from a muon capture neutron.

A. Data Analysis

The data for each of the elements silicon, sulfur, and calcium consisted of eight bins of two-hundred channels each. The first of the eight bins was assigned to decay electrons, and the remaining seven were assigned to capture neutrons according to the pulse height due to the recoils of protons and other charged particles. Each bin consisted of a timing spectrum in which the time between a muon's stop and its decay or capture was measured by a digital timing system.

The asymmetry exhibited by a decay electron spectrum provided a measurement of the residual polarization of the muon in the atomic ground state of the atom in which the muon became bound. This polarization was less than unity because the initial polarization of the part of the beam used was less than unity and because the muon loses a substantial fraction of its initial polarization in the process of being captured into an atomic orbit. Since the magnitude of the asymmetry in the angular distribution of decays from completely polarized muons is known to be $1/3$,⁸ the observed asymmetry provided a direct measurement of the residual polarization of the muons.

In addition to the decay electrons from the target element, the decay electron timing spectra also exhibited flat random background and decay electron background from lead and carbon. The lead background was due to muons stopping in the lead shielding in the vicinity of the target, and the carbon background was due to muons stopping in the telescope anticoincidence counter, counter 9, during the dead time of this counter's discriminator.

The form of the equation used in fitting the timing spectra of the decay electrons was

$$I(t) = C \exp(-R_1 t) (1 + A \cos(\omega t + \phi)) + L \exp(-R_2 t) + D \exp(-R_3 t) + W,$$

where I is the number of events per unit time, t is time, C is the amplitude of real events, R_1 is the disappearance rate of muons in the target, A is the asymmetry in the angular distribution of the decay electrons, ω is the angular precession frequency of the muons, ϕ is the phase of the asymmetry and is determined by the direction of the muon beam polarization and the geometry of the apparatus, L is the amplitude of lead events, R_2 is the disappearance rate of muons in lead, D is the amplitude of carbon events, R_3 is the disappearance rate of muons in carbon, and W is the amplitude of the random background. The decay electrons from lead and carbon are also expected to exhibit asymmetries, but the number of lead and carbon events was sufficiently small that their asymmetries were not statistically significant, and were therefore omitted from the equation fitted.

The coefficients of the equation were fitted to the data by a least squares calculation, using an IBM 7040 computer. The coefficients R_2 and R_3 were taken from the literature²¹ because their values were not well determined in this experiment due to the small number of lead and carbon background events. The values used were $R_2^{-1} = 74.6 \pm 0.6$ nanoseconds and $R_3^{-1} = 2034 \pm 4$ nanoseconds. The coefficients R_1 and ω were obtained by successive approximations. The phase was found by writing ϕ as $\phi_0 + \phi'$, where ϕ_0 is a trial value, and a linear expansion in ϕ' is performed. An iteration was performed in which ϕ_0 was replaced each time by its previous value plus ϕ' . The iteration was repeated until ϕ' became sufficiently small. The coefficients C , A , L , W , and ϕ' were solved for directly using a matrix inversion technique. The term $L \exp(-R_2 t)$ was then subtracted from the data, and the coefficients C , A , D , W , and ϕ' were solved for directly using the matrix inversion technique. The lifetimes of lead and carbon are sufficiently different that the omission of the carbon term in solving for the lead amplitude was found to be valid. This procedure considerably simplified the analysis.

The values of C , A , L/C , D/C , W/C , R_1 , C/R_1 , ω , and ϕ found for the decay electrons from each of the three target elements are presented in Table II. The number of degrees of freedom in the analysis was large, so that the probability distribution for the value of chi squared expected was approximately gaussian, and the number of standard deviations by which the observed value of chi

squared exceeded the expectation value was a good measure of the quality with which the equation fit the data. This number of standard deviations is also given in the table.

All background to real amplitude ratios were computed at zero time. The error on the disappearance rate R_1 was considerably larger than it would have been if the lead and carbon background terms were omitted from the analysis. The ratio C/R_1 is approximately equal to the number of real events observed. The observed values of ω were in good agreement with those expected based on the measured magnetic fields. The silicon data was accumulated using a 20 nanosecond channel width, and the sulfur and calcium data were accumulated using 10 nanosecond channel widths. The time region used in the analysis included 100 through 3580 nanoseconds after zero time in the case of silicon, and 50 through 1660 nanoseconds after zero time in the cases of sulfur and calcium.

The errors quoted are statistical. It is noted that the number of standard deviations by which the observed value of chi squared exceeds the expectation value increases as the percentage of isotopic contamination of the principal isotope in the target increases. However, no measurements of the lifetimes of muons in the contaminating isotopes were available, and the isotopic lifetime shift could not be identified as the cause of the poor fits in the cases of silicon and sulfur, which have 7.8% and 5.0% isotopic contamination, respectively.⁷²

Calcium, which has a 3.0% isotopic contamination,⁷² exhibits good agreement between the equation and the data.

The timing spectra of the neutrons were fitted by an equation similar to that used for the decay electrons. In the case of the neutrons, however, the random background was modulated with a sine wave having the frequency of the synchrocyclotron at the time the protons struck the internal target. This modulation was not visible in the electron timing spectra because most of the electron background arose from decays of muons stopping in the absorber. The lifetime of the muons in the absorber is sufficiently long compared to the period of the cyclotron radio frequency that the modulation was washed out. The capture rate in carbon was sufficiently low and the random background was sufficiently high that the neutron background from carbon was statistically not significant. The carbon term was therefore deleted from the analysis.

The form of the equation used in fitting the timing spectra of the muon capture neutrons was

$$I(t) = C \exp(-R_1 t) (1 + A \cos(\omega t + \phi)) + L \exp(-R_2 t) + W (1 + A_1 \cos(\omega_1 t + \phi_1)),$$

where the symbols have the same meanings as in the equation used in fitting the decay electron spectra. A_1 is the fractional radio frequency modulation amplitude, ω_1 is the angular radio frequency, and ϕ_1 is the phase of the radio frequency. The value of R_2 used for the decay electron spectra was used in fitting the neutron spectra. The values

of R_1 and ω found for the electron spectra were used in this equation. At first, the value of ϕ was fitted for the neutron spectra in the same manner as it had been fitted for the electron spectra. After it had been established that the values of ϕ found for the neutron spectra were within statistical errors of the values of ϕ found for the electron spectra, the values of ϕ found for the electron spectra were used in the equation for the neutron spectra. This eliminated one of the variables to be fitted and reduced the statistical errors on the neutron asymmetries because the errors on the values of ϕ for the electron spectra were much smaller than the errors obtained by fitting ϕ for the neutron spectra.

The values of C , A , L , W , and A_1 were found by the inverse matrix technique. The values of ω_1 and ϕ_1 were found by computing chi squared for a trial value of each of these two variables and for trial values slightly on each side of the initial trial values. Since the two parameters were varied independently, nine values of chi squared were computed. A quadratic dependence of chi squared on these variables was assumed, and the values of ω_1 and ϕ_1 which corresponded to the minimum of this quadratic function were determined. The trial values of ω_1 and ϕ_1 were changed to the new values thus found, unless either or both of the new values differed from the original value by more than the amount of the variation used in the calculation. If the change exceeded the variation, the value was changed instead by the amount of the variation. The calculation was

then repeated with the new trial values of ω_1 and ϕ_1 . The size of the variation was reduced to two-thirds of its previous value, unless the change in one or both of the trial values equaled the previous variation, in which case the size of the variation was not reduced. This process was repeated until the size of the variation used became sufficiently small. The statistical errors in ω_1 and ϕ_1 were determined from the curvature of the quadratic function. The high frequency of the cyclotron, compared to other characteristic frequencies in the timing spectrum, made the errors in ω_1 and ϕ_1 essentially independent of the errors on other parameters in the equation.

The average value found for $\omega_1/(2\pi)$, the radio frequency of the cyclotron, was 20.45 MHz for the three targets. All radio frequency phases were near zero degrees, as expected. There was some variation in the phase due to the finite distance between the target and the detector, with the resulting non-zero flight time of the neutrons, and due to the time shift with pulse height of the discriminators. The values found for C , A , L/C , W/C , C/R_1 , A_1 , and the number of standard deviations by which the observed value of chi squared exceeded the expectation value of chi squared are presented in Table III. The energies of recoil protons corresponding to the lower and upper pulse height limits of each bin are given in columns II and III, respectively, of the table. The number of standard deviations by which the observed value of chi squared exceeded the

expectation value of chi squared is given in column X of the table. It is noted from column X that the fit of the equation to the data is, in general, excellent.

Two typical timing spectra are shown in Figure 6. The decay electron spectrum and the neutron spectrum corresponding to 15.62 to 19.54 MeV protons are shown for the silicon target. Arrows indicate the fitted positions of the electron asymmetry peaks. Groups of five channels have been summed to increase the number of counts per channel. The negative background region is not shown. The gradual curvature of the neutron spectrum is due to random background.

The sinusoidal component of the timing spectrum becomes more readily visible when this component is extracted from the spectrum. This extraction is performed by subtracting the fitted background from the data, by dividing this difference by $C \exp(-R_1 t)$, and by subtracting 1. Such an extracted sinusoidal component actually represents the product of the asymmetry and the projection of a unit vector, in the direction of the muon polarization, on a line from the target to counter 5. The extracted sinusoidal component for the silicon decay electron data, together with the fitted function $A \cos(\omega t + \phi)$, is shown in Figure 7.

The extracted sinusoidal component for the same silicon decay electron data, but with the use of an appropriately weighted five channel averaging of the data, is shown in Figure 8. The

corresponding extracted sinusoidal component for silicon neutrons with pulse heights between 15.62 and 19.54 proton equivalent MeV is shown in the same figure.

B. Asymmetry Corrections

The measured electron asymmetry determines the residual polarization of the muons in the atomic ground state. The residual polarization is the maximum asymmetry that it is physically possible for the neutrons to exhibit, and the ratio of the measured neutron asymmetry to the residual polarization is the quantity of interest. Since the electron and neutron asymmetries were measured simultaneously, this ratio was not subject to any effect due to variations in the beam polarization.

One effect which did enter this ratio was a partial washing out of the measured asymmetries due to the finite size of the target and counter 5. Since the electrons were detected at the surface of counter 5 nearest the target, and since the neutrons were detected throughout counter 5, the effective distance between the target and counter 5 is smaller for electrons than for neutrons. As a result of this difference, the electron asymmetry was washed out more than was the neutron asymmetry. A Monte Carlo calculation was performed to determine the ratios of measured asymmetries to actual asymmetries for electrons and for neutrons. It was found to be necessary to multiply the ratio of the measured electron asymmetries to the

measured neutron asymmetries by 1.021 ± 0.021 in order to compensate for the difference in angular smearing. This multiplication has been performed.

Calculations performed in planning the experiment indicated that an effective target half-thickness of 2.0 grams per square centimeter would cause decay electron scattering with a sufficiently small mean scattering angle that the measured asymmetry would not be significantly reduced. In addition to these calculations, a set of measurements was made to establish that the measured asymmetry was not appreciably affected by electron scattering and electron energy loss. Since the target half-thickness was a greater source of scattering than the rest of the material between the target and the scintillator of counter 5, thinner targets were used to measure the electron asymmetry. In addition to the normal targets with effective thicknesses of 4.0 grams per square centimeter, targets with effective thicknesses of 2.0 and 1.0 grams per square centimeter were used for sulfur and calcium. No effect of the thickness on the asymmetry was observed. The results of the electron asymmetry measurements for the different target thicknesses are presented in Table IV. Although no thin silicon targets were used, silicon, which has a lower Z than sulfur and calcium, would necessarily have even less electron scattering than the targets used.

C. Neutron Asymmetry Results

The measured neutron asymmetries have been divided by the polarization of the muons in the atomic ground state, which polarization was determined from the measured decay electron asymmetries. The correction for angular smearing due to the finite sizes of the target and the detector have been included. The numbers computed in this way are the fractions of the maximum allowable asymmetries exhibited by the neutrons. These fractions are presented in Table V. The numbers of standard deviations by which these asymmetries differ from zero are also given in the table. The observed asymmetries are very close to zero for low energy neutrons, and all three targets exhibit an asymmetry which, in general, becomes increasingly positive as the neutron energy increases. The fractions of the maximum allowable asymmetries are shown as a function of median bin energy for the three targets in Figures 9, 10, and 11.

Since the observed asymmetries have the opposite sign from the theoretically predicted asymmetries, the possibility of a systematic error which would cause a false positive asymmetry has been explored as follows.

No particles emitted from the target, with the exception of neutrinos, are expected to exhibit a positive asymmetry. Nuclear gamma rays are isotropic, and decay electrons and their associated bremsstrahlung gamma rays exhibit negative asymmetries.

The possibility that the random background contains a sinusoidal modulation with a frequency near the precession frequency is eliminated by the fact that the silicon data was accumulated using a precession frequency that was a factor of two lower than the precession frequency used for sulfur and calcium. A background modulation frequency which appeared as an asymmetry in one case would have simply caused a poor value of chi squared in the other case.

The possibility that the asymmetry was induced by the digital timing system is eliminated by the good values of chi squared obtained in the randoms tests and by the fact that the asymmetry approached zero for low neutron energies.

Three mechanisms were found by which an amount proportional to the amplitude in the electron digital timing spectrum was subtracted from the random neutron background. This had the effect of inducing an apparent positive asymmetry in the neutron spectra. The first such mechanism occurred when a decay electron passed through counters 9, 6, and 5 within too short a time of the occurrence of a random background neutron event. If the two events occurred within approximately ± 50 nanoseconds of each other, the pulse pair detector in the stop circuitry did not register a pair because of the dead time of the counter 5 discriminator, and the events were not rejected. Since electrons were given priority over neutrons by the logic, the event was recorded as an electron event. This had the effect of

removing a random neutron event having the timing of an electron event from the neutron timing spectrum. A timing spectrum having the same shape as the electron timing spectrum was therefore subtracted from the neutron timing spectrum. Given that a random neutron event had occurred, the probability that it was recorded instead as an electron event was equal to the probability that a decay electron was emitted within ± 50 nanoseconds of the neutron event times the probability that the decay electron entered counter 5. Near zero time, this probability was equal to the muon decay rate times the width of the pulse pair acceptance interval times the solid angle factor of counter 5. This was $0.45 \cdot 10^6 \text{ sec}^{-1} \cdot 10^{-7} \text{ sec} \cdot 0.071 = 0.0032$. In the worst case, the highest energy sulfur bin, the background to real ratio at zero time was 2.80. In this bin, a timing spectrum having the shape of the electron timing spectrum and an amplitude $0.0032 \cdot 2.80 = 0.0089$ times the real neutron timing spectrum amplitude was subtracted from the neutron timing spectrum. Since the decay electrons exhibit an asymmetry $-1/3$ times the polarization, a positive asymmetry 0.0030 times the polarization was induced in the neutron timing spectrum by this mechanism. This induced asymmetry is negligible compared to the statistical errors on the measured asymmetries.

The second mechanism by which a false positive asymmetry was induced occurred when a decay electron passed through counters 9 and 6 within a sufficiently short time of a random neutron event in

counter 5 that a 5E, 6, 9 coincidence was produced. Given that a random neutron event had occurred, the probability that the event would be recorded as an electron by this mechanism, rather than as a background neutron, was equal to the probability that a decay electron would be emitted within the coincidence interval times the solid angle factor of counter 6. Near zero time, this probability was equal to the decay rate times the width of the coincidence times the solid angle factor of counter 6. This was approximately $0.45 \cdot 10^6 \text{ sec}^{-1} \cdot 36 \cdot 10^{-9} \text{ sec} \cdot 0.2 = 0.0032$. This is the same as the probability for the first mechanism, and is negligible.

The third mechanism by which a false positive asymmetry was induced occurred when a decay electron passed through counter 9 within a sufficiently short time of a random neutron event in counter 5 that the pulse in counter 9 caused an anticoincidence in 5G, 5T, $\bar{6}$, $\bar{8}$, $\bar{9}$. Given that a random neutron event had occurred, the probability that the event would be rejected by this mechanism was equal to the probability that a decay electron would be emitted within the anticoincidence interval times the solid angle factor of counter 9. Near zero time, this probability was equal to the decay rate times the width of the anticoincidence times the solid angle factor of counter 9. This was approximately $0.45 \cdot 10^6 \text{ sec}^{-1} \cdot 16 \cdot 10^{-9} \text{ sec} \cdot 0.5 = 0.0036$. This is nearly the same as the probability for the first mechanism, and is negligible.

If there were only one anticoincidence counter in front of the neutron detector, the dead time of the discriminator to which this counter was connected would cause some electrons to register as uncharged particles. If these uncharged particles were identified as neutrons, a false negative asymmetry would be induced. Due to photomultiplier saturation, pulse shape discriminators tend to identify electrons as neutrons for sufficiently large pulse heights. The number of electrons accepted as neutrons may not be insignificant, even when the percentage dead time of the discriminator is small, because the ratio of neutron events to electron events is very small at large neutron energies. For example, in the present experiment, the ratio in silicon of the number of neutron events in the 15.62 to 19.54 MeV neutron bin to the number of electrons is 0.004. For the highest energy bin in silicon, the ratio is 0.0002. This problem was avoided in the present experiment by using two independent anticoincidence counters between the target and the neutron detector. The dead times of the discriminators for these two anticoincidence counters were found to be due primarily to low energy background which registered in one or the other of the counters, but not both. The nonregenerative tunnel rectifier fan-in used with these discriminators kept their dead times independent, and the fraction of the time that both were dead due to independent counts in each was $3 \cdot 10^{-7}$. This fraction is nearly a factor of 1000 smaller than the smallest neutron to electron ratio, thus indicating that the number of electrons identified as uncharged particles was negligible in the present experiment.

Misidentification of gamma rays as neutrons can induce a false negative asymmetry due to the asymmetry of the bremsstrahlung from muon decay electrons. This effect was negligible in the present experiment, as is discussed in Chapter III, Section C and in Appendix I, Section 5.

The possibility of an analysis error has been ruled out by checking the analysis programs using artificial analytic data. The statistical errors quoted by the analysis programs were verified by appropriately modulating the artificial analytic data with several different groups of random numbers and by checking that the spread in the coefficients found by the analysis programs for the different sets of randomized data was consistent with the statistical errors quoted.

In summary, no mechanisms capable of causing significant false positive asymmetries have been found.

D. Discussion of Asymmetry Results

The asymmetry of neutrons due to the capture of negative muons in various nuclei has been measured by a number of other authors.⁵³⁻⁶⁵ All of these measurements were made using techniques similar to the technique used in this experiment. One difference which existed among the techniques used was the method used to distinguish gamma rays from neutrons. The experiment by Coffin et al.⁵³ did not distinguish gamma rays from neutrons.⁵⁴ Experiments by Baker and Rubbia⁵⁴ and by Evseev et al.^{57,59-61,64,65} used sandwich counters and the fact that

recoil protons have shorter ranges than Compton electrons to distinguish neutrons from gamma rays. All the other experiments used pulse shape discrimination to distinguish neutrons from gamma rays.

A second difference which existed among the techniques used was the method of measuring the time spectra. One method used was that of a timing gate. The incident muons were precessed until the polarization vector pointed toward the neutron detector. The gate was then opened, and capture neutrons which registered in the neutron detector during the gate were recorded. The direction of the precession field was then reversed, and the incident muons were precessed until the polarization vector pointed away from the neutron detector. The gate was then opened, and capture neutrons which registered in the neutron detector during the gate were recorded. The neutron asymmetry was determined from the ratio of the counts with the muon polarization vector pointing toward and away from the neutron detector. This method was used by Coffin et al.,⁵³ by Baker and Rubbia,⁵⁴ and by Evseev et al.⁵⁷ Reversal of the magnetic field has the disadvantage that effects of the field reversal on the gain of the neutron detector photomultiplier must be carefully taken into account.

The other three methods of measuring the timing spectrum are similar to each other. These methods measure and record the time between each muon stop and an ensuing neutron by the use of a time to pulse height converter and a pulse height analyzer, by the

use of an oscilloscope and film, or by the use of a digital timing system. The last of these methods has the advantage that its associated nonlinearity is negligibly small, although the nonlinearity of the other two methods can be measured and taken into account in the analysis of the data.

The results of previous neutron asymmetry experiments are presented in Figure 12. The targets used and the methods of measuring the asymmetries used by each group are given in the legend of this figure. The asymmetries are plotted as a function of the neutron energy threshold, rather than as a function of the median bin energy, because many of the bins are integral rather than differential. Only the lowest two digital calcium values and the lowest two digital carbon values from the data of Anderson⁶³ are presented in differential form; all other points are integral. With the exceptions of the Anderson digital data, the calcium scope value of Evseev et al.⁵⁹ at 7.0 MeV, which point was obtained in a separate experiment, and the two values of Astbury et al.,^{55,58} which points were obtained in separate experiments, the data represented by a point of one symbol is included in the data of all lower energy points having the same symbol.

If it is assumed that the fraction of maximum asymmetry is not a sensitive function of the spin-zero nucleus used, all of the data can be compared. The results of the present experiment are consistent with the results of Baker and Rubbia,⁵⁴ with the digital

calcium results of Anderson,⁶³ and with the digital and scope carbon results of Anderson.⁶³ The results of the present experiment are inconsistent with the results of Astbury et al.,^{55,58} with the results of Telegdi,⁵⁶ with the results of Evseev et al.,^{57,59-61,64,65} and with the scope calcium results of Anderson.⁶³

The results of the present experiment disagree both in magnitude and sign with the statistically most significant results of previous experiments. The asymmetry of high energy neutrons was found to be +0.3 in the present experiment, whereas the asymmetry of these neutrons was found to be -1.0 in previous experiments.

In conclusion, no reason is known for the wide divergence of neutron asymmetry results. As has been discussed in Section C of this chapter, there are systematic effects which could conceivably cause a false negative asymmetry, but no effects were found which could cause an appreciable false positive asymmetry. It is planned that the present experiment be repeated with cleaner background conditions and with an even greater number of checks for possible systematic errors.

V. NEUTRON SPECTRUM

The neutron pulse height experiment, discussed in the preceding chapter, yielded two-dimensional spectra containing both time and pulse height information about each event. Analysis of the timing spectra yielded the number of real events in each pulse height interval. The number of real events as a function of pulse height interval yields a pulse height spectrum. This chapter discusses the unfolding of the neutron energy spectrum from this pulse height spectrum.

A. Pion Capture Neutron Time of Flight

The pulse height response of counter 5 to monoenergetic neutrons was determined by accumulating pulse height spectra at various incident neutron energies. The neutron energies were determined by a narrow time window imposed on the time of flight of a neutron. The time of flight of the neutron was equal to the time between the stopping of a negative pion in the target and the detection of a neutron in counter 5. The accumulation of these pulse height spectra is described in more detail in Appendix I.

The pulse height spectrum which would result from a certain neutron energy spectrum may be described by the set of linear equations $p_i = m_{ij} n_j$, where p_i is the number of pulses observed in the i^{th} pulse height interval, n_j is the number of neutrons emitted in the j^{th} energy interval, and m_{ij} is a coefficient determined by

the target and detector geometry and by the properties of the detector scintillant. These linear equations can be represented in matrix form as $P = M N$. Since P is determined by the experiment, and if M is known, N , the energy spectrum of the neutrons emitted from the target, is given by $N = M^{-1} P$.

M cannot be determined directly from the pion capture neutron measurements for a number of reasons. The principal reason is that the number of neutrons emitted in each energy interval from the target is not known. In addition, the difference in the geometries of the detector with respect to the target in the pion capture neutron measurement and in the muon capture neutron pulse height experiment is expected to cause a small change in the shape of the pulse height spectra and to cause a large change in the solid angle. The finite width of the neutron time of flight window and the finite resolution of the timing system in the pion capture neutron measurement also cause difficulties in determining M . As a result, it was necessary to perform two sets of Monte Carlo calculations to determine M .

B. Pion capture Neutron Monte Carlo Calculations

The first set of Monte Carlo calculations performed simulated the pion capture neutron time of flight measurement. The purpose of these calculations was to establish that the methods of calculation adequately simulated the experimental data.

A parallel beam of neutrons was assumed to be incident upon counter 5 along the counter's axis of symmetry. The distance from the target to counter 5 was sufficient that a parallel beam was a good approximation. The energy distribution of these neutrons was taken to be that obtained by folding the two nanosecond full width at half maximum resolution of the timing system into the two nanosecond time of flight window. An energy for each incident neutron was selected at random from this distribution. The neutron was tracked as it passed through the counter. Another random number was used, together with the mean free path of a neutron of the selected energy in the scintillant, to determine a distance which the neutron traveled. If the neutron had passed completely through the scintillant by traveling this distance, the absence of a pulse was recorded. If the distance traveled placed the neutron scattering at a point within the scintillant, the type of scattering which occurred was selected on the basis of another random number and of total cross sections.⁷³ The types of scattering which were considered were $n + p \rightarrow n + p$, $n + C \rightarrow n + C$, $n + C \rightarrow n + C_{4.433}^*$, $n + C \rightarrow n + 3 \text{ He}$, and $n + C \rightarrow p + B$. Although only the first of these reactions produces appreciable scintillation light for neutron energies below 16 MeV, the other reactions, which cause a reduction of the neutron energy, are important because the large thickness of the scintillant causes neutron scattering from carbon followed by neutron scattering from hydrogen to occur frequently. The $n + C \rightarrow p + B$ reaction contributes

appreciable scintillation light for neutron energies above 16 MeV. The center of mass polar scattering angle was selected, using another random number, on the basis of differential scattering data.⁷⁴ The deviation from S-wave scattering becomes significant for neutron energies above 13 MeV for elastic scattering from hydrogen and above 1 MeV for elastic scattering from carbon. The azimuthal scattering angle was selected at random using another random number. Relativistic calculations were performed to determine the laboratory direction and energy of the neutron after the collision. The energy of the recoil particle was also determined. It was assumed that inelastic scattering was isotropic in the center of mass system because differential scattering data for the inelastic processes was not sufficiently complete. In addition, it was assumed that the three alpha particles from the reaction $n + C \rightarrow n + 3 \text{ He}$ have negligible velocity relative to each other. The relative amount of light produced by the recoil particle was computed from curves based on Birks' equation.⁷⁵ The curve for protons has been discussed in Appendix I. Curves were also computed for completely ionized C, He, and B using the value of the constant k_B found for protons. At the center of the highest energy neutron bin, an estimated 4% of the maximum energy recoil protons escape through the surfaces of the scintillant. This effect has been neglected to avoid the substantial increase in computation time that would accompany the tracking of the charged recoil particles. This percentage decreases rapidly as the energy decreases. After the first scattering, a check is made to see

if the scattered neutron has a sufficient residual energy to merit further tracking. If it does, a random number is used to determine the distance at which its next scattering will occur. The coordinates of the new scattering location are computed, and a check is made to see if these coordinates lie within the scintillant. If they do, the type of scattering and recoil direction are again selected. The light produced in the new scatter is added to the light produced in the first scatter. The neutron is followed in this way until it escapes from the scintillant or has a negligible residual energy. If an $n + C \rightarrow p + B$ reaction occurs, the tracking of the neutron is terminated, and the recoil energies and associated light production of both the proton and boron nuclei are computed.

When the tracking of a neutron and the computation of the total light produced have been completed, additional random numbers are used to simulate the photostatistics of the counter, based on the measured 165 photoelectrons per electron equivalent MeV. The event is then analyzed, with and without photostatistics, by simulated pulse height analyzers. The number of hydrogen scatters and the total number of scatters is also recorded for each event.

These calculations were performed using an IBM 7040 computer at each of the energies used in the pion capture neutron time of flight experiment. Between 15,000 and 45,000 incident neutrons were used at each energy, the number depending on the

energy. Larger numbers of neutrons were used at higher energies because of the lower cross sections. Approximately seven neutrons per second were processed, depending on the energy.

The pulse height spectra obtained experimentally were compared to the calculated pulse height spectra to substantiate the computations. At low neutron energies, the agreement was quite good. At neutron energies above 17.5 MeV, the $n + C \rightarrow p + B$ total cross section had not been measured, and it was necessary to work backwards and determine this cross section from the comparison of the experimental and calculated curves. This was possible because the highest energy proton from the $n + C \rightarrow p + B$ reaction has several MeV less than the highest energy proton from the $n + p \rightarrow n + p$ reaction, for incident neutrons of the same energy. The higher energy edge of the spectrum could therefore be used as a vertical amplitude normalization in determining the $n + C \rightarrow p + B$ cross section. It was possible to obtain good agreement between the experimental and calculated shapes by suitable selection of this cross section.

Smooth curves were fitted to the Monte Carlo spectra. With suitable vertical normalization, these curves were drawn on top of the experimental points. Two typical curves of this type are shown in Figure 13. The negative slope near channel 80 in the 32.36 MeV neutron spectrum is due primarily to $n + C \rightarrow p + B$ reactions. The statistical accuracy of the Monte Carlo calculations was similar to or slightly better than the statistical accuracy of the experimental data.

C. Muon Capture Neutron Monte Carlo Calculations

After establishing the validity of the assumptions made in the Monte Carlo calculations by comparing the results of these calculations to measured pion capture neutron pulse height spectra, it was necessary to perform similar calculations to take account of the actual geometry used in the neutron pulse height experiment. These calculations differed from the pion capture neutron calculations in that exactly monoenergetic neutrons were used, the actual distribution of muons in the target was used, and the actual geometry of the counter with respect to the target was taken into account.

In order to determine the distribution of muons in the target, a Monte Carlo calculation was performed. A uniform parallel beam of muons was assumed to be incident on the first telescope counter. The measured energy distribution of the incident muon beam was used. The scattering in each counter was determined using random numbers and the electromagnetic scattering distribution.⁷⁶ The muon was tracked between counters, and the change of direction and energy in each counter was computed. The copper absorber, carbon absorber, and target were each divided into ten scattering layers of equal thicknesses for computational purposes. The final disposition of each muon, in terms of which counter coincidence and anticoincidence requirements it satisfied, was recorded. The vertical and transverse coordinates of each muon that stopped in the target after passing through counters 1, 2, 3, and 4 were recorded. A total of 40,000 incident muons were tracked.

Using the results of this Monte Carlo calculation, muon positions in the target were selected at random according to the stopping distribution found. A neutron of a specified energy was assumed to emerge in a random direction from the selected location of the muon. If the direction of this neutron passed through counter 5, a decision was made as to whether or not the neutron scattered in the counter. If it scattered, it was then tracked until its energy became negligible, it escaped from the counter, or it engaged in an $n + C \rightarrow p + B$ reaction. The remainder of this calculation was identical to the pion capture neutron Monte Carlo calculation. Pulse height spectra were computed with and without photostatistics. 400,000 events were generated at each of 13 energies.

Two typical Monte Carlo pulse height spectra, with photostatistics, are shown in Figure 14. The bump near the center of the lower spectrum is due to $n + C \rightarrow p + B$ reactions.

The total number of neutrons which entered counter 5, whether or not they interacted, was recorded. The effective solid angle of counter 5 for decay electrons was determined from the ratio of this number to the total number of neutrons emitted. The effective fraction of unit sphere subtended was found to be 0.0710 ± 0.0001 .

D. Neutron Energy Spectrum Calculation

The number of real events in each pulse height bin has already been determined from the analysis of the neutron asymmetry.

The analysis of the digital timing spectra permitted the unambiguous subtraction of lead and random background. The number of observed events in each pulse height bin can be divided by the width of the bin in MeV to obtain the number of events per MeV. These neutron pulse height spectra are presented, with statistical errors shown, in Figures 15, 16, and 17. These spectra represent the vector P discussed in section A of this chapter.

There was some ambiguity in the calculation of the neutron energy spectra from the neutron pulse height spectra because of the finite size of the energy bins. Within each bin, the energy which should be considered representative of the entire bin had to be specified. This problem was minimized as follows.

Since the neutron pulse height spectra exhibited approximately exponential shapes, with slight positive curvatures on semilog graphs, each pulse height bin was represented by a point whose ordinate was the average number of events per MeV in the bin and whose abscissa was the average of the upper and lower proton energy limits of the bin. The points representing adjacent bins were connected by an exponential whose amplitude and characteristic constant were determined by the coordinates of the pair of points. The region below the lowest point and above the highest point was fitted by the same exponential used between the lowest pair of points and the highest pair of points, respectively. The fitted exponentials were then integrated over each bin, and the integrals

were compared to the number of events actually observed in each bin. The average of the two characteristic constants associated with each bin was computed, and, using this average, the first order displacement of the energy coordinate of each point required to remove the discrepancy between the integral over each bin and the actual count in each bin was computed. All energy coordinates were changed by the computed amounts, and new exponential fits were made to the displaced points. The integral of each bin was again computed and compared to the actual count in each bin, and the energy coordinate of each point was again shifted. This process was continued until all the energy shifts became negligibly small.

Each of the original pulse height bins was then divided into four bins of equal width. The count associated with each of these new bins was computed by integrating the fitted exponentials over the new bins. The dimensionality of the vector P was thus increased from 7 to 28. The energy at the upper edge of each of the new bins was taken to be representative of the bin. Since the new bins were relatively narrow, the energy error which was made by using the energy at the top of the bin was small. The advantage of using the energy at the top of the bin was that the propagation of statistical errors was much smaller than if an energy at the center of each bin, for example, had been chosen.

The elements of the matrix M were computed from the muon capture neutron Monte Carlo pulse height spectra. These spectra were

normalized so that the maximum pulse height in each spectrum, without photostatistics, was unity. In computing the matrix elements M , a linear interpolation between all pairs of corresponding channels of the two Monte Carlo spectra nearest in energy to the energy value of the matrix element being computed was performed. The energy normalization of the interpolated spectrum was then adjusted, using the calibration curve for protons in NE 213, so that the pulse height at the top of the spectrum corresponded to the actual pulse height at the energy value being computed. The matrix element m_{ij} was found by integrating the Monte Carlo spectrum corresponding to the j^{th} energy over the portion of the spectrum corresponding to the i^{th} pulse height interval. The matrix element m_{ij} is equal to the expectation number of pulses that would be observed in counter 5 in the i^{th} pulse height interval due to one neutron having the j^{th} energy.

The 28 by 28 matrix M was inverted and multiplied into the vector P to obtain the vector N . The matrix inversion was considerably simplified by the fact that a neutron cannot produce a pulse larger than that of a proton of the same energy. As a result of this fact, all matrix elements below the principal diagonal were zero.

The computation of the statistical errors was complicated by the presence of statistical errors on the matrix elements m_{ij} as well as on the pulse height spectrum elements p_i . The problem of

direct computation of the statistical errors on the inverse matrix M^{-1} was prohibitive, so all errors on the neutron energy spectrum were determined by numerical methods. The standard deviations on each of the neutron pulse height spectrum elements and on each of the Monte Carlo pulse height spectrum elements were computed. After computing the vector N once, the value of each element of the neutron pulse height spectrum was varied individually by a small fraction of a standard deviation. For each element changed, the value of N was recomputed, and the change in each value n_j from its original value was determined. As the values of the different elements were varied, one at a time, the sums of the squares of the changes in the values of the elements n_j from their original values were accumulated. Each element of each Monte Carlo pulse height spectrum was also varied one at a time, and the squares of the changes in the values of n_j were accumulated in the same way as was done for the neutron pulse height spectrum elements. The square root of the sum of the squares of the changes was taken for each n_j , and these values were divided by the fraction of a standard deviation by which each of the original independent elements was varied, to obtain the standard deviation on each of the values of n_j . The above sets of calculations were performed using two different fractions of a standard deviation. The purpose of this was to establish that the fractions used were small enough that the assumption of a quadratic error dependence remained valid and large enough that computer rounding errors were negligible.

The fractions of a standard deviation used were 0.003 and 0.01.

The errors computed using both fractions were the same. The statistical errors near the low energy end of the neutron energy spectrum were found to be due approximately equally to experimental and to Monte Carlo errors. The errors near the high energy end of the spectrum were found to be due primarily to experimental errors.

After the neutron energy spectrum had been unfolded, the 28 bins were recombined into the original seven bins.

In addition to the statistical errors found, several other sources of error are of importance. The errors on the neutron scattering cross sections used were typically less than 10%, particularly on the neutron-proton cross section, which accounts for most of the light produced in the scintillant. The effect of the larger errors associated with the determination of the $n + C \rightarrow p + B$ cross section is minimized by the rapid fall of the neutron pulse height spectra, which typically fall by a factor of ten when the energy is increased by twelve MeV, and by the fact that the highest energy proton from the $n + C \rightarrow p + B$ reaction has an energy approximately 14 MeV below the energy of the neutron. The contribution to the pulse height spectrum of the $n + C \rightarrow p + B$ reaction is therefore buried under the much larger contribution from the $n + p \rightarrow n + p$ reaction involving lower energy neutrons, and the percentage errors introduced into the neutron energy spectra by the errors in the $n + C \rightarrow p + B$ cross section are therefore negligible.

The contribution of the errors in the knowledge of the neutron scattering cross sections to the error in each bin of the neutron energy spectrum is estimated to be 10%.

Another source of error in the neutron energy spectrum is the systematic error caused by the finite bin size and the technique used in obtaining the neutron energy spectrum from the neutron pulse height spectrum. Several techniques differing from the one described were used. Based upon the variations in the results obtained using these various techniques, an error of 10% on each bin of the neutron energy spectrum due to the finite bin size is quoted.

E. Neutron Energy Spectrum Normalization

The number of neutrons emitted from the target in each of seven energy intervals has been found. It is desired that these numbers be normalized to the number of muons stopping in the target.

Since many of the registered target stops were due to electrons which scattered in the absorber, and did not strike the anticoincidence counter 9, and since some of the registered stops were due to pions, the number of target stops is not a good measurement of the number of muons stopping in the target. Also, the uncertainties in the dead fractions of the dead time circuits would introduce an additional uncertainty in the number of acceptable muon stops in the target.

The observed number of decay electrons was therefore used to determine the number of acceptable muon stops in the target. The effective fraction of unit sphere subtended at the target by counter 5 was determined as described in section C of this chapter. It was necessary to make a correction to the number of decay electrons because the decay electrons lost energy by ionization and bremsstrahlung and because the pulse height threshold for electron detection in counter 5 was non-zero.

Estimates were made of the number of decay electrons which were not detected because of energy loss and threshold effects as follows. Electrons were assumed to be emitted from the center of the target and to travel along the axis of symmetry of counter 5. The materials through which they passed were divided into layers. The original energy spectrum of the electrons was determined using both the standard V-A theory for free muons and using the calculations of Huff⁷⁷ for muons bound in iron. The change in these spectra due to ionization and bremsstrahlung as the electrons passed through each layer between the center of the target and the scintillant of counter 5 was computed. The initial V-A spectrum, and the altered spectra at the point of entry into the counter 5 scintillant for electrons originally having the free spectral shape and the iron bound spectral shape, are shown in Figure 18. The electron detection threshold is indicated in the figure. The fraction of the shifted free muon decay spectrum below the 3.29 MeV threshold was 0.0676,

and the fraction of the shifted iron bound muon decay spectrum below threshold was 0.0910. The actual fraction not detected should lie between these limits. Factors not taken into account in the calculation were the loss by bremsstrahlung in the scintillant of sufficient energy that the energy lost by ionization in the scintillant was below threshold, the loss of energy due to increases in path length due to scattering and diagonal entry into counter 5, and the loss of counts due to electrons escaping through the edges and front face of counter 5 before depositing the required threshold energy. Since these factors all represent the loss of counts, the lost fraction computed for muons bound in iron, 0.0910, was used in the spectrum normalization. The factors not included in the calculations are estimated to introduce an uncertainty of 10% into the normalization. It should be noted that this error affects all neutron energy bins equally.

The normalization of the neutron spectra was performed by multiplying the number of neutrons per MeV by the fraction of unit sphere subtended at the target for electrons by counter 5 times the fraction of the shifted decay electron spectrum above threshold times the reciprocal of the number of decay electrons observed times the ratio of the decay fraction to the capture fraction. The result is the number of neutrons emitted per MeV per muon capture. It is noted that no dead time corrections had to be made, because the dead time circuits affected the electrons and neutrons in an identical manner.

The normalized neutron energy spectra are presented in Figures 19, 20, and 21. The errors shown in the figures are the total errors, both statistical and systematic, and include the normalization error. These results are also presented in Table VI. The integral spectra are also presented in this table. The integral spectra are the total number of neutrons per muon capture emitted with energy greater than the lower energy limit of the associated bin. The errors on the integral spectra have been computed assuming that all individual bin errors are completely dependent. The errors quoted on the integral spectra are thus slightly larger than the actual errors.

F. Conclusion

The neutron energy spectra for the three elements studied are strikingly similar. The number of neutrons per MeV per capture decreases slightly with increasing atomic number Z . Whereas the neutron pulse height spectra, when plotted on a semilog graph, exhibited distinct positive curvatures, the neutron energy spectra can all be fitted over the measured energy region, within the errors, by straight lines on semilog graphs. The characteristic decay constants of the observed exponentials are 7.6 MeV for silicon, 7.3 MeV for sulfur, and 7.2 MeV for calcium. These decay constants are quite similar, and show only a slight decrease with increasing Z .

The energy spectrum for calcium can be compared to the results of two other experiments in which the energy spectrum of muon capture neutrons from calcium was measured.

The energy spectrum of muon capture neutrons from calcium, among other elements, in the energy interval 2 to 16 MeV has been measured by Hagge.⁷⁸ This energy spectrum was measured by accumulating the pulse height spectrum resulting from neutron detection in a liquid scintillant. The neutron energy spectrum was divided into 1 MeV intervals, but was not normalized. This spectrum overlapped the lowest two energy bins of the present experiment, and the ratio of the average number of counts per MeV in the second bin to the average number of counts per MeV in the first can be compared to the present experiment by integrating Hagge's spectrum between the energy limits of each of the first two bins of the present experiment and dividing by the energy width of the bins. The ratio for Hagge's spectrum is 0.66. Since the spectrum was obtained by unfolding the pulse height spectrum, the errors on the spectral points are partially dependent. The standard deviation of the ratio quoted lies between 0.09 and 0.23, depending upon the degree of dependence of the errors, the lower value corresponding to complete independence, and the upper value to the worst case of complete dependence.

The value of this ratio for the present experiment is found to be 0.53. The standard deviation lies between 0.13 and 0.18, again depending on the degree of dependence introduced by the unfolding

process. Even if the smallest error is assumed for each case, the ratios for the two experiments are in agreement with each other.

The energy spectrum of muon capture neutrons from calcium and from lead in the energy interval 4 to 50 MeV has been measured by Turner.⁷⁹ This energy spectrum was determined using a hydrogen bubble chamber containing a plate of the target material. The energy of a neutron was determined from the range and direction of a recoil proton in the chamber. The neutron energy spectra were divided into 2 MeV intervals. Since Turner's energy range overlaps the energy range of the present experiment, his spectrum can be integrated over the energy ranges corresponding to the various bins in the present experiment for comparison. The ratio of the average number of counts per MeV in the second bin to the average number of counts per MeV in the first bin obtained by integrating Turner's data is 0.53 ± 0.32 , in agreement with the present experiment. The errors have been taken to be independent, since no unfolding process is involved in this case. The ratios for other bins are also in agreement with the present experiment, but are of less statistical significance.

Turner's spectra were normalized, so an absolute comparison of his calcium spectrum to that of the present experiment can be made. Integration of his spectrum from 7.73 MeV to 50 MeV yields 0.187 ± 0.047 neutrons per muon capture. Completely independent errors have again been assumed. An integration of the calcium spectrum from

the present experiment between the same limits yields 0.183 ± 0.032 neutrons per muon capture. The two experiments are in excellent agreement.

The neutron energy spectra are the sum of three contributions: the evaporation spectrum, the giant resonance spectrum, and the direct spectrum. Only the neutrons from the direct spectrum are capable of exhibiting an asymmetry, because the other two types of neutrons involve the strong decay of a compound intermediate state.

The lowest energy threshold used in the present experiment, 7.73 MeV, was sufficiently high that this experiment does not provide a good measurement of the evaporation spectrum. Turner,⁷⁹ using the results of his experiment, the results of Hagge's experiment, and the total neutron emission, obtains 0.5 MeV for the nuclear temperature of calcium in muon capture. From this temperature and the total neutron emission per muon capture,⁸⁰ it follows that the contribution of evaporation neutrons to the portion of the spectrum observed in the present experiment is negligible.

The contribution of the giant resonance spectra has been computed in the case of calcium by Überall.⁸¹ Giant dipole resonances are expected to produce peaks in the neutron energy spectrum at 5.8, 10.3, 10.8, and 11.3 MeV. The lowest of these energies would not be observed in the present experiment, but the remaining three energies should contribute to the lowest energy neutron bin.

A recent calculation of the giant resonance levels has been performed by Foldy and Klein⁸² for the case of muon capture by O^{16} and Ca^{40} . They find a residual excitation energy of about 12 MeV in K^{40} following muon capture by Ca^{40} . Since the binding energy of the highest neutron level in K^{40} is 8 MeV, their calculation indicates that the highest energy that a neutron emitted following capture to one of the principal giant resonance states can have is 4 MeV. Such a neutron would not be observed in the present experiment.

The failure of the lowest energy neutron bin to exhibit any significant increase above the amplitude obtained by extrapolating the higher energy portion of the spectrum could signify one of a number of possibilities. The energies of the giant dipole states could be lower than expected so that the neutron energies would be below the lower threshold of the lowest energy bin. The giant dipole states could be neutron decaying primarily to excited states of the K^{39} nucleus with the emission of lower energy neutrons. This, however, seems unlikely because of the shortage of neutron-gamma events observed in the muon capture neutron time of flight portion of this experiment. The widths of the giant dipole resonances could be so great compared to the bin widths in the present experiment that the associated neutron peaks are spread over several bins. The giant dipole rate could be small compared to the direct rate in the energy interval of interest. The amplitude of the direct spectrum in the lowest energy bin could be below the amplitude obtained by extrapolating the remainder of the spectrum. In

this case, the giant dipole resonance spectrum in the lowest energy bin could have an amplitude of the same order of magnitude as the direct spectrum.

If it is assumed that the neutrons observed in this experiment were primarily direct neutrons, the spectrum observed is not in good agreement with the direct spectra which have been predicted on the basis of various models. The direct spectrum computed for calcium by Lubkin⁶⁸ has its maximum at 5 MeV, and falls completely to zero at 11 MeV. The computed neutron rate is $36,000 \text{ sec}^{-1}$. This spectrum was computed using a modified Fermi gas model. The neutron energy spectrum for calcium observed in the present experiment extends at least to 50 MeV, and the portion of the spectrum above 7.73 MeV exhibits a rate of $450,000 \pm 78,000$ neutrons per second, in disagreement with Lubkin's spectrum and rate.

Shell model calculations of the direct spectra from Ca^{40} ⁶⁹ and from Si^{28} and S^{32} ⁷⁰ have been performed. For Ca^{40} , the computed neutron energy spectrum⁶⁹ has a peak around 5 MeV, and then falls in an approximately exponential manner to zero around 22 MeV. The total direct rate varies from $34,000 \text{ sec}^{-1}$ to $139,000 \text{ sec}^{-1}$, depending on the value assumed for the imaginary part of the potential describing the interaction of the direct neutron with the residual nucleus. Approximately 40% of this spectrum is above 7.73 MeV. This spectrum falls to zero with increasing neutron energy more rapidly than does the experimentally observed spectrum, and the total rate is significantly lower

than the experimentally observed rate. The computed neutron energy spectra⁷⁰ for Si^{28} and S^{32} have shapes similar to that of Ca^{40} , except when ξ , the ratio of the imaginary part of the neutron-nucleus potential to the real part, is assumed to be zero, in which case the Si^{28} spectrum exhibits sharp peaks at 1 MeV and at 7 MeV, and the S^{32} spectrum exhibits a sharp peak at 5 MeV. For $\xi = -0.10$ to -0.15 , the Si^{28} spectrum exhibits a maximum near 7.5 MeV, and the S^{32} spectrum exhibits a maximum near 5.5 MeV. Both spectra approach zero for energies above 10 MeV in an approximately exponential fashion, and exhibit characteristic decay constants of the order of those observed in the present experiment. The behavior of the spectra above 20 MeV was not presented. The computed silicon spectrum approaches zero more slowly with increasing energy than do the calcium and sulfur spectra, as has also been observed in the present experiment. The total computed direct rate for Si^{28} varied between $4,300 \text{ sec}^{-1}$ and $21,400 \text{ sec}^{-1}$, again depending on the value of ξ used. Approximately 50% of this spectrum is above 7.73 MeV. This is to be compared to the rate of $197,000 \pm 35,000 \text{ sec}^{-1}$ above 7.73 MeV observed in the present experiment. The total computed direct rate for S^{32} varied between $10,800 \text{ sec}^{-1}$ and $25,000 \text{ sec}^{-1}$. Approximately 50% of this spectrum is above 7.73 MeV. The rate found in the present experiment for S^{32} was $281,000 \pm 50,000 \text{ sec}^{-1}$ for the part of the spectrum above 7.73 MeV.

In conclusion, the experimental neutron energy spectra are in disagreement with the Fermi gas model direct neutron spectrum calculation⁶⁸ in both shape and amplitude. The experimental neutron energy spectra show qualitative agreement with the shape of the shell model direct neutron spectra^{69,70} over the energies common to the two, but the amplitudes of the experimental spectra exceed the amplitudes of the computed spectra in the common energy region by factors between 8 and 23 for $\xi = 0.0$, and between 33 and 92 for $\xi = -0.15$. There is no evidence for giant dipole resonance neutrons in the energy range studied.

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APPENDIX I

Neutron-Gamma Counter

Counter 5 was used to detect neutrons and gamma rays, and was capable of distinguishing them by the shapes of the light pulses which they produced.

1. Construction.

The principal parts of counter 5 were manufactured by Nuclear Enterprises, Ltd. The scintillant consisted of a $7\frac{1}{2}$ " diameter by 5" long volume of NE 213 liquid scintillator housed in a sealed glass cell. The glass cell was viewed along its axis of symmetry, through an acrylic light pipe 24" in length, by a 58AVP photomultiplier. The phototube was housed in an iron shell, and was further shielded inside the iron shell by Netic and Conetic shielding. High voltage distribution and pulse shape discrimination circuits were housed in the base of the counter. The purpose of the long light pipe was to isolate the phototube from the C-magnet field.

2. Principle of Operation.

NE 213 is an organic liquid scintillator having a density of 0.88 grams per cubic centimeter and a hydrogen to carbon atomic ratio of 1.213. Gamma rays are detected in this scintillant primarily by Compton scattering and pair production. Neutrons are detected by their collisions with protons and carbon nuclei. The scintillation decay time of certain scintillators has been found⁸³ to be a

sensitive function of the energy loss per unit distance of the particle giving rise to the scintillation. The scintillation as a function of time in NE 213 scintillant is well represented by the sum of two exponentials, one of which has a time constant of 2.4 nanoseconds, and the other of which has a time constant of the order of 300 nanoseconds. The ratio of the slow component to the fast component is much larger when the particle producing the light is heavily ionizing than when it is minimum ionizing. Since the electrons produced by gamma rays which Compton scatter or produce pairs are nearly minimum ionizing, and since the recoil protons and heavier particles produced by neutron scattering are heavily ionizing, there is a significant difference in the pulse shapes produced by these two types of particles.

A circuit of the type first introduced by Brooks,⁸⁴ and further improved by Daehnick and Sherr,⁸⁵ was used to determine the algebraic difference between the slow component of the scintillation and a constant times the fast component of the scintillation. When this constant was suitably chosen, the difference exhibited one sign if the particle producing the scintillation was a gamma ray, and the other sign if the particle producing the scintillation was a neutron. This difference signal was amplified, clamped, and applied to a discriminator. In the circuit used in this counter, neutron associated pulses were positive, and the discriminator

triggered only on positive pulses. A neutron was therefore identified by the presence of a pulse shape discriminator output, and a gamma ray by the absence of one.

As explained by Birks,⁷⁵ using the exciton theory of Bowen et al.,⁸⁶ heavily ionizing particles cause damage to some of the surrounding molecules. These damaged molecules absorb some of the excitons produced by the passage of a charged particle and thereby cause a reduction in the number of excitons absorbed by the undamaged fluorescent molecules, and hence in the amount of light reaching the photomultiplier. The number of excitons produced per unit length is $J dE/dx$, where J is a proportionality constant, E is energy, and x is distance. The fraction of molecules which are damaged is also proportional to the specific ionization, provided that this fraction is small compared to unity, and is given by $B dE/dx$, where B is a proportionality constant. The ratio of the cross section for capture of an exciton by a damaged molecule divided by the cross section for its capture by an undamaged molecule is designated by k . The constant k is found to be large compared to unity, and is sufficiently large that $kB dE/dx$ becomes large compared to unity while the requirement that $B dE/dx$ be small compared to unity is still met. The probability that an exciton will be captured by an undamaged molecule is given by $(1 - B dE/dx) / ((1 - B dE/dx) + k(B dE/dx))$. Since $B dE/dx \ll 1$, this expression is approximately equal to $1 / (1 + kB dE/dx)$.

The light output of the scintillant per unit distance traveled by the incident particle is proportional to $(J \, dE/dx) / (1 + k_B \, dE/dx)$.

3. Calibration and Testing.

For electrons with energies of the order of 1 MeV and higher, $k_B \, dE/dx$ is small compared to unity during most of the stopping distance of the electron. The light output for such electrons is nearly proportional to dE/dx , and a linear relationship exists between photomultiplier output pulse height and electron energy. This linearity was checked using radioactive gamma sources. Since there is no visible photopeak in this scintillant for gamma rays in the MeV range, the Compton edges of various gamma rays were used for calibration. The Compton spectra for gamma rays in this energy region have edges which are roughly rectangular, but are broadened by photostatistics. The half-fall point of the observed edge is identified with the Compton edge energy. The sources, and their Compton edge energies, used in checking linearity were Cs^{137} , 0.478 MeV; Co^{60} , 1.04 MeV (the two gamma energies are not resolved, and the average is used); Na^{24} , 1.16 and 2.52 MeV; the first excited state of C^{12} , 4.19 MeV. The first excited state of C^{12} was obtained from a PuBe source. The root-mean-square fractional deviation of the measured points from a fitted straight line was 0.083. In view of the poor resolution of plastic counters, this fit was considered satisfactory. The calibration point at 4.19 MeV is considered the most reliable because the percentage resolution

of the counter improves with increasing energy. The uncertainty in the 4.19 MeV calibration point is estimated from the shape of the spectrum at the Compton edge to be 4%.

The radial uniformity of counter 5 was measured using a highly collimated beam of gamma rays. The root-mean-square fractional deviation of the pulse height from the average pulse height was 0.012.

The number of photoelectrons per electron equivalent MeV was determined using a light pulser. The light from the light pulser was attenuated by various amounts, and the position and width of the resulting peak were determined. The intrinsic width of the peak due to fluctuations in the light pulser was extracted, and the width of the peak due to photostatistics was determined. The number of photoelectrons per unit pulse height (additional statistical effects in the first few dynodes of the photomultiplier were ignored) was thereby determined. This was translated into photoelectrons per electron equivalent MeV by using the 4.19 MeV gamma ray calibration point, and it was found that there were 165 photoelectrons per electron equivalent MeV.

4. Pulse Height Response to Heavy Particles.

Since the pulse height in counter 5 was used to determine the energy of neutrons detected in this counter, it was necessary to determine the relationship between the energy of heavy charged particles in the scintillant and the amount of light that these

particles produced. It was not practical to bombard the scintillant directly with heavy charged particles of known energy, as from a Van de Graaff accelerator, because this type of scintillator is extremely sensitive to small quantities of dissolved oxygen and other contaminants, and could not have been removed from its sealed glass cell without encountering significant contamination problems. The thickness of the scintillator's cell and the short ranges of low energy protons made it impractical to bombard the scintillant through the glass cell and to correct for the loss of energy in the cell walls. The response of the scintillator to heavy charged particles, in particular to protons, was therefore determined by bombarding the scintillant with neutrons of known energy. The energy spectrum of the recoil protons has an approximately rectangular shape, and the half-fall point of the upper edge of this spectrum is identified with the energy of a proton having the same energy as the incident neutron.

Monoenergetic neutrons were obtained by applying time of flight to neutrons produced by the capture of negative pions. Counter 5 was placed at a distance of 1.5 meters from the experimental target for this calibration. Since negative pions are captured immediately after they stop in the target, the time of stopping of a pion was used as a start signal for the neutron time of flight, and the detection of the neutron in counter 5 was used as a stop signal. A two nanosecond time window was applied to the neutron time of flight

to select only neutrons with energies in a certain band. In addition, the timing system had a time resolution of approximately two nanoseconds, full width at half maximum. This resolution had only a small dependence on pulse height in the pulse height interval of interest. The timing system also exhibited a shift in time depending on the pulse height in counter 5. This shift was measured and corrected for in determining neutron energies. The pulse height spectra associated with nine different neutron energy bands were measured. The neutron time of flight spectrum was also measured. Since the time of flight spectrum was found to be reasonably flat over the width of each time window used, the average neutron energy in each bin was taken to be equal to the neutron energy at the center of the bin. The half-fall point of each pulse height spectrum was associated with a proton energy equal to the neutron energy at the time of flight bin center. The error in this determination is estimated to be one-fourth of the bin width. The energy of an electron having a pulse height equal to that of the proton of interest was determined using the half-fall point of the Compton edge of the gamma spectrum from the first excited state of C^{12} , and the property that the pulse height is a linear function of the electron energy.

Using the theory of Birks,⁷⁵ the ratio of the pulse height of a proton to that of an electron of equal energy is given by the integral over the proton path of $-dx (dE/dx) / (E_0 (1 + kB dE/dx))$, where E_0 is the initial proton energy. The approximation that the

electron is minimum ionizing over its entire path has been used here. Since dE/dx is not an analytic function, this integral has been performed numerically. Values of dE/dx for hydrogen and carbon have been obtained from the tables of Rich and Madey.⁸⁷ A power law fit was used for interpolation between points in the tables.

The data obtained in the pion capture time of flight measurements were fitted using Birks' equation. The value of k_B was adjusted to minimize chi squared. The optimum value of k_B was found to be 0.01015 grams per MeV per square centimeter. The two lowest energy experimental points were not used in the fit because the threshold in counter 5 was not sufficiently far below the upper edge of the spectrum to permit accurate identification of the half-fall point of the spectrum. The fitted curve and the experimental points are shown in Figure 22. The brackets shown on the points indicate the energy band associated with the two nanosecond time of flight window. The straight line with unit slope represents the response of the scintillator to electrons.

An excellent fit using Birks' equation was obtained for NE 102 scintillator by Evans and Bellamy,⁸⁸ who found a value for k_B of 0.010 grams per MeV per square centimeter. Since NE 102 is solid rather than liquid, they were able to perform their calibration using protons rather than neutrons. However, there was no reason to expect the values of k_B to be identical in two

different types of scintillator, and it was necessary to determine the value of k_B for the NE 213 scintillator used in the present experiment. The response of NE 213 scintillator has also been measured by Batchelor et al.⁸⁹ and by Rothberg et al.³⁴

5. PSD Testing.

The pion capture neutron time of flight measurements also checked the operation of the pulse shape discriminator (PSD). The time spectrum of the neutrons and gamma rays was accumulated both ungated and gated by events identified as neutrons by the PSD. The absence of the gamma peak in the latter case demonstrated the proper operation of the PSD.

A more detailed study of the performance of the PSD was made using a photographic technique. An output was taken from the pulse shape circuit in counter 5 before discrimination. This pulse was amplified and sent to two stretchers. One stretcher detected the amplitude of the positive peak of the pulse, and the other detected the amplitude of the negative peak of the pulse. These stretchers stored the peak amplitudes in analog form for a preset time after the input pulse amplitude had exceeded a certain threshold. At the end of this preset time, the information was promptly erased. The outputs of the two stretchers were added and applied to the vertical input of an oscilloscope. The linear output of counter 5 was also sent to a stretcher of the type just described. The output of this stretcher was applied to the horizontal input of the same

oscilloscope. The oscilloscope beam was normally gated off. When a pulse had occurred in counter 5, and after all resulting waveforms had had time to reach their peak amplitudes, the oscilloscope beam was turned on for one microsecond. Since the stretcher outputs were constant during this one microsecond interval, each event produced a single point on the oscilloscope screen. These points were recorded photographically in time exposures. The groups of points recorded in the photographs exhibit two bands, the upper one associated with neutrons, and the lower one associated with gamma rays.

A typical photograph is shown in Figure 23. The top picture shows a normal photograph in which both the positive and negative stretcher outputs are added. The center picture was taken with the output of the negative stretcher removed from the sum. The purpose of this picture was to establish that the output of the pulse shape circuit for gamma rays did not at any time become positive. A positive part of this pulse would have triggered the pulse shape discriminator if it were of sufficient amplitude. The fact that gamma rays appear in the center picture as a horizontal line with no vertical displacement shows that the gamma ray associated pulses at no time become positive. The bottom picture shows only events identified as neutrons by the pulse shape discriminator. The stretchers were equipped with limiters so that any point which would otherwise be vertically off the oscilloscope screen is shown at the top or bottom of the screen.

The photograph shown was taken during an actual asymmetry run. The events accepted for photographing were subjected to the same dead time requirements as the events accepted for analysis. Although the neutron and gamma ray bands are clearly separated, these bands are significantly widened by the low energy background present at counter 5. The bands were significantly narrower when the photographs were taken under reduced beam conditions. The horizontal scale in the photographs was calibrated so that one large division corresponds to 5 electron equivalent MeV.

During the neutron pulse height experiment, PSD photographs were taken at least once a day to monitor the PSD performance.

As an even more quantitative check on the performance of the PSD, various pulse height bands from the linear output of counter 5 were selected. Events having linear outputs within the selected pulse height band opened a gate on a pulse height analyzer, and the amplitude of the pulse from the pulse shape circuit, after passing through a peak detecting stretcher, was analyzed by the pulse height analyzer. Pulse shape spectra were accumulated separately for both positive and negative stretchers. In addition, pulse shape spectra were accumulated for positive pulse stretcher outputs that were identified as neutrons by the pulse shape discriminator. The pulse height bands used were those corresponding to each of the seven pulse height channels used in the neutron pulse height experiment. The

normalization for the comparison of the three spectra in each pulse height interval was obtained from the 5G, 5T, $\overline{6}$, $\overline{8}$, $\overline{9}$ scaler. The measurements were made during actual asymmetry runs. The worst separation of neutrons and gamma rays was found in the lowest pulse height bin. In this bin, an estimated 0.4% of the gamma rays were identified as neutrons, and an estimated 5.0% of the neutrons were identified as gamma rays. The percentages of each type of particle that were misidentified decreased in the higher pulse height bins.

In the neutron pulse height experiment, misidentified gamma rays introduce errors into both the asymmetry and neutron spectrum measurements. The ratio of gamma rays to neutrons in each pulse height bin and the fraction of gamma rays identified as neutrons is such in each bin that the error is negligible compared to other sources of errors. Misidentified neutrons introduce errors only into the neutron spectrum measurements, because the deletion of a fraction of the neutrons does not change the shape of the asymmetry timing spectra. The percentages of misidentified neutrons are small compared to other errors in the neutron spectrum measurements.

APPENDIX II

Telescope Stop Rejection

Muons stopping in the last telescope counter before the target were a potential source of background from a material other than the target material. Standard solutions to this problem include the use of target counters and the shielding of the last telescope counter from the reaction detection counters. Neither of these solutions was practical in this case, since the targets could not be used as detectors, and the loss in muon stopping rate, due to the beam scattering by the absorber, would have been prohibitive if the last telescope counter had been moved far enough away from the target to permit its shielding from the reaction detection counters 5 and 7.

This problem could have been partially overcome by placing the last telescope counter in anticoincidence with the reaction detection counters. Most of the decay electrons from muon stops in the last telescope counter would be rejected by this technique, but a substantial fraction of them would not be rejected because such electrons are nearly minimum ionizing and the effective dead layer of the telescope counter is therefore large. Neutrons and gamma rays due to muon captures in the last telescope counter would usually not be rejected by this technique, since no light output by the scintillant is normally associated with their emission.

The problem was solved by a technique involving the pulse heights produced by the muon in the last and next to last telescope

counters. This technique is illustrated in Figure 24. This figure shows the energy deposited in counters 3 and 4 as a function of the energy of the muon incident upon counter 3. An upper level discriminator was used for both counters 3 and 4. Any incident muon which produced a pulse larger than this threshold in either counter was rejected.

The detailed operation of this technique is best described by dividing the possible energies of incident muons into groups, as shown in the figure. Muons with energies in group I were rejected because they stopped in counter 3, and produced no coincidence pulse in counter 4. Muons in group II were rejected because they produced excessive pulse heights in counter 3. Muons in group III were rejected because they produced excessive pulse heights in counter 4. Since these three regions overlap and completely cover the energy range of muons stopping in counters 3 and 4, those muons which were accepted by this technique passed completely through counter 4, and either stopped in the target, or passed through the target and were rejected by the anticoincidence counter behind the target.

This technique involves the rejection of some of the muons which stopped near the front of the target, in order to reject all of the muons which stopped in counter 4. It is, in principle, possible not to set an upper level on the pulse height in counter 4. However, due to photostatistics in counter 3, the number of muons stopping in the target which must be rejected in order to reject all stops in counter 4

is reduced by using an upper level discriminator on counter 4. The dashed curves indicate the maximum fluctuations in pulse heights due to photostatistics.

Uniformity of light collection in the telescope counters 3 and 4 was quite important for the use of this technique. It was found that there were two principal factors in obtaining uniform light collection efficiency. The first was the use of twisted light pipes of constant cross sectional area. The type of light pipe which is machined from a solid piece of acrylic was found to cause a significant increase in the light collection efficiency from the end of the scintillant nearest the light pipe, whereas twisted light pipes were found not to cause this effect. The second factor was the degree of polish of the scintillant. A number of attempts to improve the polish of the scintillant as received from the manufacturer were unsuccessful, and it was therefore necessary to avoid damaging the initial polish of the scintillant. Counter 3 was backed by a 3/16" acrylic sheet to reduce the number of internal reflections required and thereby to improve the light collection uniformity. The scintillant on counter 3 was shortened by 1/4" to reduce the number of muons passing through the scintillant of counter 3, the light pipe of counter 4, and the scintillant of counter 4.

The light collection uniformities of counters 3 and 4 were measured using the internal conversion electron from a Bi^{207} source. A collimated beam of electrons was directed normally to the surface of the scintillant at various positions on the scintillant. The maximum variation

in the light output of counter 3 was found to be $\pm 3.2\%$ from the median, and the maximum variation in counter 4 was found to be $\pm 7.8\%$ from the median.

A preliminary experiment was conducted to determine the effectiveness of this technique of rejecting stops in the last telescope counter. Muons were distinguished from pions and electrons by beam time of flight. A plastic counter was used as the target in order to identify target stops, and to separate them from stops in counter 4. The target counter had a scintillant thickness of $1/4"$. It was found to be possible to reject 98.8% of the muon stops in counter 4 by relinquishing 13% of the stops in the target counter. This is equivalent to giving up 0.08 grams per square centimeter of the target counter surface nearest counter 4. Another adjustment of the thresholds permitted the rejection of 99.3% of the stops in counter 4 while relinquishing the first 0.12 grams per square centimeter of the target counter.

Since the plastic-equivalent thicknesses of the targets used in the neutron asymmetry experiment were about 2.9 grams per square centimeter, this performance was extremely satisfactory. On the basis of this preliminary experiment, in the neutron asymmetry experiment the number of accepted muon stops in counter 4 was less than 0.03% of the number of accepted muon stops in the target.

APPENDIX III

Dead Time Circuits

The events which controlled the dead time circuitry of the start channel of the digital timing system were all of one type, namely 1, 2, 3 coincidences. Such coincidences were due almost entirely to real charged particles entering the apparatus through the beam telescope, and were random in time with the exception of an extremely high frequency structure, having the frequency of the cyclotron at the time the protons struck the internal target, and with the exception of the prompt beam spike. Each 1, 2, 3 event was independent, and the occurrence of one did not alter the probability of the occurrence of another. Each 1, 2, 3 had a fixed probability, which will be designated P_1 , of also registering as a 1, 2, 3T, 3, $\overline{3H}$, 4, $\overline{4H}$, $\overline{6}$, $\overline{8}$, $\overline{9}$ target stop coincidence.

The operation of the dead time circuitry is illustrated in Figure 25. An example in which a start event is rejected because of the occurrence of a previous event is shown in the second section of this figure. In 2A, 1, 2, 3, start pulses occurring at times -10 microseconds and 0 microseconds are shown. Assume that the pulse at time 0 represents a muon stopping in the target. As shown in 2B, the no-dead-time uni-vibrator (NDTUV) is turned on by the first start pulse at -10 microseconds. If no other 1, 2, 3 pulse occurred, this pulse would end 15 microseconds later, at +5 microseconds. However, the occurrence of a second 1, 2, 3 pulse at time 0 extends the NDTUV pulse in 2B to +15 microseconds. The pulse pair detector detects the coincidence between

the NDTUV in 2B and the start pulse at time 0 in 2A. The pulse pair detector then produces an output, shown in 2C, extending from the time of the coincidence to the end of the NDTUV pulse. This output is applied in anticoincidence to the start gate. The start pulses in 2A, after being delayed by a 3 microsecond delay cable, enter the start gate, and are shown in 2D. The event at time 0, after delay, is shown at +3 microseconds in 2D. This event is rejected because the anticoincidence pulse in 2C exists at this time. This form of rejection will apply to any event which has another 1, 2, 3 event preceding it by 0 to 15 microseconds.

An example in which a start event is rejected because of the occurrence of a following event is shown in the third section of this figure. In 3A, 1, 2, 3 start pulses occurring at times 0 microseconds and +2 microseconds are shown. As shown in 3B, the NDTUV is turned on at time 0 by the first 1, 2, 3 pulse, and continues to +15 microseconds. The 1, 2, 3 event at +2 microseconds extends the NDTUV pulse to +17 microseconds. The pulse pair detector detects a coincidence between the 1, 2, 3 pulse at +2 microseconds in 3A and the NDTUV pulse in 3B. The pulse pair detector output then extends from the time of the coincidence at +2 microseconds to the end of the NDTUV pulse at +17 microseconds. The delayed 1, 2, 3 start pulses are shown in 3D. The event at time zero, after delay, is at +3 microseconds in 3D. Since the anticoincidence pulse from the pulse pair detector, shown in 3C, is present at the start gate at the time of arrival of the delayed zero time pulse, shown in 3D, the

event is rejected. This form of rejection will apply to any event which has another 1, 2, 3 event following it by 0 to 3 microseconds.

If the average 1, 2, 3 rate is designated S , the target stop rate is $S P_1$. The rate of target stop acceptance is $S P_1 \exp(-R_1 \cdot 18 \text{ microseconds})$. The a priori probability of acceptance of any particular target stop is a constant.

The events in the stop channel of the digital timing system in the neutron pulse height experiment were of three types. The first type consisted of background pulses. With the exceptions of the prompt beam spike and the cyclotron radio frequency structure, the background pulses were random in time. The second type consisted of prompt events associated with target stops. Such events were due to muonic X-rays. Several muonic X-rays could be detected in counter 5, but would be registered as a single event because of the short time separation between them. As a result, zero or one prompt event could be detected. The probability distribution for the detection of the second type of event may be described by the function $g(0)$, where the 0 indicates zero time after the stop of a muon. The third type consisted of events associated with muon captures or decays. More than one such event could be associated with a particular muon stop, but would be identified as a single event due to the short time separation of the two events. An example of such a double event would be the detection of two neutrons produced by the capture of a muon. The probability distribution for the third class of events can be described by a function $f(t)$, where t is the time

between the stopping of a muon and the detection of an event. Zero or one such event may be detected for each muon.

Background events are uncorrelated with the other two classes of events. The second and third classes of events are also uncorrelated with each other.

The operation of the dead time circuitry applying to the digital timing stop channel was the same as that applying to the start channel. The dead time circuitry was controlled by the 5T discriminator pulse. The timing is such that an event is rejected if a second 5T pulse occurs between 20 microseconds before and 3.25 microseconds after the event of interest.

The time region analyzed by the digital timing system extended from 0.27 microseconds before to 1.73 microseconds after the stopping of a muon.

The control of the start gate by the stop pulse is illustrated in the first section of the figure. In the example shown, a start pulse occurs at time zero in 1A, and a stop pulse occurs at time 1 microsecond in 1B. The stop pulse generates a 4 microsecond pulse which opens the start gate, as shown in 1C. As shown in 1D, the delayed start pulse arrives at the start gate at 3 microseconds, and is transmitted because the stop coincidence pulse is present, and no pulse pair anticoincidence pulse is present. As shown in 1E, the delayed stop pulse arrives at the stop gate at 3.25 microseconds, and is transmitted because no pulse pair

anticoincidence pulse is present.

The requirement that no 5T pulse precede a stop event by 0 to 20 microseconds was imposed on the stop pulse before it was used to open the start gate. This had the effect of reducing the number of start pulses, for which there was no corresponding stop pulse, that were sent to the digital timing system. Such events would not have been incorrectly processed by the digital timing system, but would have increased the fraction of the time that the digital timing system was dead.

The times which have been stated above applied to the calcium and sulfur targets. In the case of the silicon target, the start dead time coverage extended from -15 to +5 microseconds, the stop dead time coverage extended from -20 to +5.25 microseconds, the time region analyzed by the digital timing system extended from -0.27 microseconds to +3.73 microseconds, and the width of the stop coincidence pulse applied to the start gate was 6 microseconds.

The dead time requirements imposed on muon stops were such that there was not more than one muon in the target vicinity during the digital timing analysis interval. Since the lifetime of a stopped muon does not exceed 2.2 microseconds in any material, and since only one muon stopped within 16.73 microseconds before the end of the digital timing interval, no other muon could be in the target at the same time. Any ambiguity concerning which muon produced an observed event was therefore avoided.

If an accepted muon stop is taken to have occurred at zero time, the probability distribution for events in the stop channel, before dead time requirements are imposed, is $f(t) + g(0) + h$, where h is the random background probability amplitude. The corresponding probability distribution for the detection of events in $5T$ will be designated $F(t) + G(0) + H$. These three terms are independent of each other. The restriction that not more than one event per muon stop can occur applies to the distributions $F(t)$ and $G(0)$. The stop channel dead time coverage extends sufficiently far into positive and negative times that the fraction of the distribution $F(t)$ extending past the ends of the stop channel dead time interval is negligible. The integral of $F(t) dt$ over the dead time interval is therefore essentially a constant, and will be denoted by F . The integral over the dead time interval of $G(0) dt$ is a constant, and will be denoted by G . There are also effects due to real events in the stop channel dead time interval associated with muons which stop before -15 microseconds or after $+3$ microseconds. However, these effects are negligible in the present experiment.

If a background pulse occurs during the digital timing acceptance interval, the probability that it will not be rejected by another background pulse is $\exp(-H \cdot 23.25 \text{ microseconds})$. The probability that it will not be rejected by a muon associated event is $(1 - F) \cdot (1 - G)$. If a real prompt event occurs during the digital timing acceptance interval, the probability that it will not be rejected by a background pulse is $\exp(-H \cdot 23.25 \text{ microseconds})$. The probability that it will not

be rejected by a muon associated event is $(1 - F)$. If a real delayed event occurs during the digital timing acceptance interval, the probability that it will not be rejected by a background pulse is $\exp(-H \cdot 23.25 \text{ microseconds})$. The probability that it will not be rejected by a muon associated event is $(1 - G)$.

The observed timing distribution is therefore $\exp(-H \cdot 23.25 \text{ microseconds}) \cdot ((1 - G) \cdot f(t) + (1 - F) \cdot g(0) + (1 - F) \cdot (1 - G) \cdot h)$. Each of the three components of this distribution has the same shape as it did before the dead time restrictions were imposed, and only the amplitudes of the components are altered. It may be noted that all background would be eliminated from the accepted distribution if the value of F were unity. However, the small solid angle subtended at the target by counter 5 made the background suppression a small effect.

APPENDIX IV

Muon-Gamma-Neutron Time of Flight

In the neutron time of flight experiment, the reaction sought was the capture of a muon by a target nucleus, followed by the emission of a neutron and the formation of an excited state in the daughter nucleus. In most cases, the lifetimes of the excited states of the daughter nuclei are sufficiently short compared to the neutron flight times that they can be neglected. If the excited state of the daughter nucleus decays immediately, the decay gamma ray carries information of the time of capture of the muon. Counter 5 was used to detect the decay gamma rays. Gamma rays in counter 5 were identified by the presence of a pulse from counter 5 and the absence of pulses from counters 6 and 9 and from the pulse shape discriminator. This gamma ray pulse, corrected for the flight time from the target to counter 5, represented the time of capture of the muon. The use of the pulse shape discriminator served to reject neutrons in counter 5. This was necessary because neutrons had flight times long compared to the gamma ray flight time. Counter 7 was used to detect neutrons emitted following muon capture in the target. A neutron was identified by a pulse in counter 7 and the absence of a pulse in counter 8. Counter 8 served to reject charged particles entering counter 7. The difference in time between the detection of a neutron in counter 7 and the detection of a gamma ray in counter 5 provided a direct measurement of the energy of the neutron. The angular distribution of the gamma rays is isotropic,⁷¹ so that the

angular dependence of the probability that a muon capture will produce a detected event includes only the correlation between the spin direction of the muon and the direction of emission of the neutron.

The muon-gamma-neutron time of flight experiment used all the counters used in the neutron pulse height experiment, plus counters 7 and 8. Counter 7 comprises a 10" diameter by 4" thick piece of plastic scintillant viewed by a 58AVP photomultiplier. The center of the scintillant was one meter from the center of the target. Charged particles entering counter 7 from the direction of the target were detected by counter 8, which has a 12" x 12" x 3/8" piece of plastic scintillant viewed by a 6810A photomultiplier. See Figure 1.

Muons stopping in the target served as start signals for the digital timing system. The detection of an electron or a nuclear gamma ray in counter 5 signaled the decay or capture, respectively, of a muon. The pulse from counter 5 served as a stop signal for the digital timing system, and, if the pulse was due to a gamma ray, also served as a start signal for the time to pulse height converter. A pulse in counter 7 was required if the pulse in counter 5 was due to a gamma ray. The counter 7 pulse served as a stop signal for the time to pulse height converter. The particle producing the pulse in counter 7 was required to be uncharged, so that it was either a neutron or gamma ray.

The digital timing system measured the time between a muon's stop and its decay or capture. The time to pulse height converter

measured the time between the production of a gamma ray or neutron in the target and the arrival of this particle in counter 7. Two dimensional analysis was performed on these times, and both times were recorded for each event.

The electronics used in the muon-gamma-neutron time of flight experiment were the same as those used in the neutron pulse height experiment, with the exceptions described below. Refer to Figures 3, 4, and 5.

Neutrons in counter 7 were identified in the coincidence circuit XXI by the coincidence $7T, 7, \bar{8}$, where the $7T$ pulse arrives last and thus determines the timing of the output pulse.

The counter 5 gamma pulse from coincidence circuit XV and the counter 7 neutron pulse from coincidence circuit XXI were sent to the coincidence circuit XXIII, which generated an output when a pulse occurred in counter 7 between 20 nanoseconds before and 40 nanoseconds after a pulse occurred in counter 5.

The pulse from the coincidence circuit XV, which pulse was only 1 nanosecond wide, was widened to 60 nanoseconds by the discriminator XVII and sent to the time to pulse height converter XVIII, together with the counter 7 neutron pulse from the coincidence circuit XXI. The amplitude of the output of the time to pulse height converter was proportional to the overlap in time of its two inputs. Although this

operation was double-valued, the operation was made effectively single-valued by the timing requirements of the coincidence circuit XXIII. The time to pulse height converter output represented the time between the capture of a muon in the target and the arrival of a neutron in counter 7. The zero time was determined by using events in which gamma rays resulting from muon capture were detected in both counter 5 and counter 7.

The string of amplifiers in the two dimensional analyzer was connected to the signal from the time to pulse height converter. The pulse height discriminators to which the outputs of these amplifiers were connected were set so that their thresholds corresponded to particular neutron times of flight.

In the neutron time of flight experiment, the delayed pulse shape discriminator pulse passed through an inverter, the output of which was direct coupled to a coincidence input of the eight channel pulse height analyzer. This particular coincidence input applied only to channels two through eight. The inverter normally supplied the voltage level required for coincidence, and a pulse from the PSD, upon entering the inverter, removed this voltage level. Since neutrons produce a PSD pulse, and gammas do not, the coincidence level at the eight channel pulse height analyzer was removed when the particle was a neutron, and was present when the particle was a gamma.

As in the neutron pulse height experiment, the muon spin was precessed in a magnetic field. The direction in which a neutron was

emitted following muon capture exhibited an asymmetry with respect to the direction of the muon spin at the time of capture. The probability that a neutron would be detected in counter 7 was therefore a function of the angle between the muon spin at the time of capture and the direction from the target to counter 7.

The advantage of measuring the neutron asymmetry by this technique was that the energy of each neutron was determined explicitly, whereas the measurement of the neutron asymmetry by the recoil proton pulse height technique determined only the minimum energy of the neutron. Since the theoretically predicted neutron asymmetry is a function of the neutron energy, the precise determination of the energy of each neutron is of interest.

No values of the neutron asymmetry were obtained from the muon-gamma-neutron time of flight experiment for two reasons. The first reason was that the number of events observed was much smaller than the number which had been anticipated in planning the experiment. The second reason was that the background levels in counters 5 and 7 were much higher than had been anticipated.

The rate at which real muon-gamma events occurred was measured by removing the requirement that a pulse from counter 7 be detected. This rate was higher than had been assumed in planning the experiment. The number of neutrons per muon capture per unit energy interval was determined from the neutron pulse height experiment by

unfolding the pulse height spectrum as described in Chapter V. This number was larger than that which had been assumed in planning the experiment. By using the observed muon-gamma rate and the neutron emission probability, the solid angle of counter 7, and the probability that the neutron would produce a pulse above threshold in counter 7, the rate at which muon-gamma-neutron events would be expected was calculated. This calculation assumed that the emission of a neutron does not strongly reduce the probability of emission of a gamma. However, the number of observed muon-gamma-neutron events was approximately a factor of ten lower than the number computed on this basis.

In order to reduce the background, the measurements were made using a beam intensity which was a factor of three below full beam. The calculations of the expected real event rates were performed for the beam intensity and dead times actually used. The neutrons were sorted into three energy intervals. In the 5 to 12 MeV interval, the expected rate was 0.0144 real events per second; the actual rate was 0.0014 ± 0.0003 real events per second. In the 12 to 20 MeV interval, the expected rate was 0.00407 real events per second; the actual rate was 0.00052 ± 0.00016 real events per second. In the 20 to 35 MeV interval, the expected rate was 0.00112 real events per second; the actual rate was 0.00004 ± 0.00013 real events per second. The small ratios of the actual event rates to the computed event rates suggest that the emission of a neutron with energy above 5 MeV normally leaves the residual nucleus in its ground state.

The high background levels in counters 5 and 7, in addition to causing the loss of statistical significance of the data, caused ambiguities through the existence of half-real events. Such events consisted of real muons and gammas and accidental neutrons, and of real muons and neutrons and accidental gammas. These events had digital timing spectra of the same shape as the timing spectra of real events. This made it necessary to determine what fraction of the spectra were due to half-real events by calculations using measured real muon-gamma and real muon-neutron rates and using measured singles rates in counters 5 and 7. Such calculations are subject to large systematic errors. However, events consisting of real muons, accidental gammas, and accidental neutrons had digital timing spectra which were flat. These events could be identified unambiguously by the analysis of the total timing spectra, and caused only statistical errors.

The small real event rates and the large background rates made it impractical to measure the neutron asymmetry using the muon-gamma-neutron time of flight technique.

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TABLE I

Carbon Decay Electron Asymmetry

Bin	Minimum Pulse Height, Electron MeV	Maximum Pulse Height, Electron MeV	Asymmetry	Asymmetry Error	Chi Squared, Standard Deviations Above Expected
Sum of bins 2 - 8			-0.0502	0.0019	-0.73
2	3.5	6.0	-0.0397	0.0047	+0.52
3	6.0	9.0	-0.0288	0.0045	+1.55
4	9.0	12.0	-0.0366	0.0049	-1.26
5	12.0	16.0	-0.0487	0.0045	-0.84
6	16.0	20.0	-0.0641	0.0045	-0.19
7	20.0	25.0	-0.0737	0.0048	-0.49
8	25.0	40.0	-0.0916	0.0095	-0.00

TABLE II

Decay Electron Asymmetry Results

	Silicon	Sulfur	Calcium
C (Real event amplitude)	352,599 ±304	140,486 ±282	122,112 ±145
A (Asymmetry)	-0.04169 ±0.00043	-0.02999 ±0.00056	-0.03399 ±0.00079
L/C (Lead to real amplitude ratio)	0.0339 ±0.0017	0.0287 ±0.0022	0.0333 ±0.0025
D/C (Carbon to real amplitude ratio)	0.0076 ±0.0006	0.0082 ±0.0026	0.0125 ±0.0010
W/C (Random to real amplitude ratio)	0.0038 ±0.0001	0.0070 ±0.0012	0.0050 ±0.0005
R ₁ (Rate, per microsecond)	1.323 ±0.012	1.799 ±0.054	2.999 ±0.041
C/R ₁ (Real events observed)	13,326,000	7,809,000	4,072,000
ω (Precession freq., radians/microsec.)	18.09 ±0.07	35.67 ±0.21	35.61 ±0.35
$\emptyset$ (Precession phase, degrees)	113.46 ±0.58	110.15 ±1.05	107.95 ±1.31
χ^2 , number of standard deviations high	+2.42	+1.96	+0.10

TABLE III

Neutron Asymmetry Results *

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I	II	III	IV	V	VI	VII	VIII	IX	X
Element	E _{min} MeV	E _{max} MeV	C	A	L/C	W/C	C/R ₁	A ₁	No. Std. Dev.
Silicon	7.73	11.49	9634	+0.0038	+1.00	0.080	364,107	0.07	+0.69
			±26	±0.0029	±0.02	±0.001		±0.01	
	11.49	15.62	3658	+0.0237	+0.72	0.110	138,242	0.10	+0.06
			±17	±0.0049	±0.04	±0.001		±0.01	
	15.62	19.54	1357	+0.0456	+0.78	0.173	51,302	0.11	+1.18
			±11	±0.0085	±0.07	±0.002		±0.01	
	19.54	24.55	664	+0.0292	+0.75	0.295	25,108	0.11	+2.48
			±9	±0.0133	±0.10	±0.005		±0.01	
	24.55	29.41	232	+0.0498	+0.63	0.54	8,759	0.13	+0.77
			±6	±0.0258	±0.19	±0.02		±0.01	
	29.41	35.34	115	-0.0161	+0.42	0.94	4,363	0.09	+0.07
			±5	±0.0427	±0.30	±0.04		±0.01	
	35.34	52.53	69	+0.1043	-0.61	2.16	2,612	0.11	+0.29
			±6	±0.0763	±0.50	±0.19		±0.01	
Sulfur	7.73	11.49	5569	+0.0088	+0.90	0.079	309,574	0.11	+2.09
			±23	±0.0031	±0.02	±0.001		±0.01	
	11.49	15.62	2070	+0.0158	+0.77	0.111	115,063	0.16	-1.76
			±14	±0.0053	±0.03	±0.002		±0.01	
	15.62	19.54	700	+0.0250	+0.66	0.174	38,893	0.17	-0.40
			±9	±0.0096	±0.05	±0.004		±0.02	
	19.54	24.55	373	+0.0402	+0.61	0.279	20,757	0.17	-0.66
			±7	±0.0142	±0.08	±0.007		±0.02	
	24.55	29.41	124	+0.0092	+0.72	0.55	6,872	0.16	-0.53
			±5	±0.0285	±0.15	±0.02		±0.02	
	29.41	35.34	58	+0.0374	+0.84	1.00	3,236	0.19	+0.23
			±4	±0.0496	±0.27	±0.07		±0.02	
	35.34	52.53	30	-0.0578	+0.00	2.80	1,676	0.17	-0.28
			±5	±0.0987	±0.50	±0.47		±0.01	
Calcium	7.73	11.49	7737	+0.0055	+0.66	0.046	257,994	0.14	+0.92
			±29	±0.0034	±0.02	±0.001		±0.01	
	11.49	15.62	2783	+0.0158	+0.62	0.069	92,803	0.17	+1.20
			±19	±0.0059	±0.03	±0.001		±0.01	
	15.62	19.54	965	+0.0275	+0.52	0.106	32,177	0.17	-0.79
			±12	±0.0104	±0.04	±0.002		±0.02	
	19.54	24.55	483	+0.0009	+0.42	0.193	16,094	0.20	-0.42
			±9	±0.0158	±0.07	±0.004		±0.01	
	24.55	29.41	166	+0.0695	+0.56	0.34	5,540	0.18	-0.12
			±6	±0.0303	±0.13	±0.01		±0.02	
	29.41	35.34	82	-0.0741	+0.26	0.60	2,725	0.22	-0.03
			±5	±0.0481	±0.20	±0.04		±0.02	
	35.34	52.53	48	+0.1019	-0.06	1.46	1,602	0.16	-1.24
			±5	±0.0850	±0.33	±0.15		±0.01	

* See Chapter IV, Section A for symbol definitions.

TABLE IV

Thin Target Electron Asymmetries

Target Element	Target Thickness, g/cm ²	Asymmetry	Asymmetry Error
Calcium	4.0	-0.0340	0.0008
	2.0	-0.0309	0.0037
	1.0	-0.0284	0.0054
Sulfur	4.0	-0.0300	0.0006
	2.0	-0.0288	0.0026
	1.0	-0.0291	0.0043

TABLE V

Normalized Neutron Asymmetry Results

Target Element	Recoil Proton Energy, Min. MeV	Recoil Proton Energy, Max. MeV	Fraction of Max. Allowable Asymmetry	Error in Asymmetry	Asymmetry, Standard Deviations from Zero
Silicon	7.73	11.49	+0.030	0.023	+1.31
	11.49	15.62	+0.186	0.038	+4.88
	15.62	19.54	+0.357	0.067	+5.36
	19.54	24.55	+0.228	0.104	+2.19
	24.55	29.41	+0.390	0.202	+1.93
	29.41	35.34	-0.126	0.334	-0.38
	35.34	52.53	+0.817	0.597	+1.37
Sulfur	7.73	11.49	+0.096	0.034	+2.80
	11.49	15.62	+0.172	0.058	+2.98
	15.62	19.54	+0.272	0.105	+2.60
	19.54	24.55	+0.437	0.155	+2.83
	24.55	29.41	+0.100	0.310	+0.32
	29.41	35.34	+0.407	0.540	+0.75
	35.34	52.53	-0.629	1.074	-0.59
Calcium	7.73	11.49	+0.053	0.033	+1.60
	11.49	15.62	+0.152	0.057	+2.69
	15.62	19.54	+0.264	0.100	+2.64
	19.54	24.55	+0.009	0.151	+0.06
	24.55	29.41	+0.667	0.291	+2.29
	29.41	35.34	-0.711	0.462	-1.54
	35.34	52.53	+0.979	0.816	+1.20

TABLE VI

Neutron Energy Spectrum

Element	Minimum Energy, MeV	Maximum Energy, MeV	Neutrons Per Capture Per MeV	Error	Integral Spectrum	
					Neutrons Per Capture	Error
Silicon	7.73	11.49	0.0251	0.0044	0.232	0.041
	11.49	15.62	0.0138	0.0024	0.138	0.025
	15.62	19.54	0.0087	0.0015	0.081	0.015
	19.54	24.55	0.00461	0.00082	0.0469	0.0086
	24.55	29.41	0.00210	0.00039	0.0238	0.0045
	29.41	35.34	0.00132	0.00025	0.0136	0.0026
	35.34	52.53	0.000336	0.000065	0.0058	0.0011
Sulfur	7.73	11.49	0.0234	0.0041	0.210	0.037
	11.49	15.62	0.0132	0.0023	0.122	0.022
	15.62	19.54	0.0070	0.0012	0.068	0.013
	19.54	24.55	0.00401	0.00072	0.0403	0.0077
	24.55	29.41	0.00191	0.00037	0.0202	0.0041
	29.41	35.34	0.00114	0.00023	0.0109	0.0023
	35.34	52.53	0.000243	0.000056	0.00418	0.00096
Calcium	7.73	11.49	0.0210	0.0036	0.183	0.032
	11.49	15.62	0.0111	0.0019	0.104	0.019
	15.62	19.54	0.0062	0.0011	0.058	0.011
	19.54	24.55	0.00330	0.00059	0.0335	0.0063
	24.55	29.41	0.00152	0.00029	0.0170	0.0034
	29.41	35.34	0.00094	0.00019	0.0096	0.0020
	35.34	52.53	0.000233	0.000049	0.00401	0.00084

FIGURE CAPTIONS

1. Experimental arrangement.
2. Experimental arrangement, target vicinity.
3. Electronics block diagram.
4. Fast and slow logic block diagram. Solid dots at points where cables enter circuits signify anticoincidence. The letters "SC" signify connection to a scaler.
5. Two dimensional analyzer block diagram. Ellipses around cables signify multiple cables.
6. Silicon data, five channel sums. Bin 1 electrons and bin 4 neutrons.
7. Asymmetry in silicon, extracted sinusoidal component. Bin 1 electrons.
8. Asymmetry in silicon, extracted sinusoidal component. Bin 1 electrons and bin 4 neutrons. Five channel averages.
9. Silicon asymmetry.
10. Sulfur asymmetry.
11. Calcium asymmetry.
12. Results of other asymmetry experiments.
13. Pion capture neutron pulse height spectra due to two neutron energies. The points are experimental, and the solid curve is the result of a Monte Carlo calculation.
14. Muon capture neutron pulse height spectra due to two neutron energies. A smooth curve is fitted to the Monte Carlo points.
15. Silicon neutron pulse height spectrum.
16. Sulfur neutron pulse height spectrum.
17. Calcium neutron pulse height spectrum.

18. Muon decay electron energy spectra.
19. Silicon neutron energy spectrum.
20. Sulfur neutron energy spectrum.
21. Calcium neutron energy spectrum.
22. Response of NE 213 scintillant to protons.
23. Output of pulse shaping circuit for neutrons and gamma rays as a function of pulse height.
24. Energy deposited in counters 3 and 4 as a function of incident muon energy.
25. Time relationships of logic pulses.

FIG. 1

FIG. 2

FIG. 3

FIG. 4

FIG. 5

FIG. 6

ASYMMETRY PROJECTION

FIG. 7

ASYMMETRY PROJECTION

FIG. 8

FIG. 9

FIG. 10

FIG. 11

FIG. 12

FIG. 13

FIG. 14

FIG. 15

FIG. 16

FIG. 17

FIG. 18

FIG. 19

FIG. 20

FIG. 21

FIG. 22

FIG. 23

FIG. 24

FIG. 25