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AEC RESEARCH AND
DEVELOPMENT REPORT

GA-9275

NEUTRON CROSS-SECTION MEASUREMENTS

SUMMARY REPORT

March 1, 1968 through February 28, 1969

Prepared under
Contract AT(04-3)-167
Project Agreement No. 11
for the
San Francisco Operations Office
U. S. Atomic Energy Commission

March 27, 1969

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Gulf General Atomic Project 221

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1. INTRODUCTION

Neutron cross-section research at Gulf General Atomic under Contract AT(04-3)-167, Project Agreement 11, and with company support, has been directed primarily toward obtaining accurate resonance parameters through capture, self-indication, and transmission measurements in the resolved resonance energy region. Continuing efforts to upgrade the performance of the LINAC pulsed neutron source, to develop high-efficiency capture gamma-ray detectors and a computer-based on-line data acquisition system, and to devise rigorous analysis codes to extract the basic information from the measurements have resulted in a strong program in this area. Publications⁽¹⁻¹⁵⁾ in the past three years of the results of this research attest to the success of the program.

During the past year, our capabilities to perform cross-section research have been considerably expanded. Motivated by the increasing demand for cross-section information at the higher energies required for shielding and fast reactor applications and by the continuing dearth of reliable data in the difficult energy region above 1 keV, we have now developed the means to measure capture cross sections to about 3-MeV neutron energy using the 220-meter flight-path facility. Intensive efforts to improve capabilities for neutron flux measurements in the energy region above 10 keV have paid large dividends in this undertaking. Our first results for Gd and Au indicate that we can achieve high-resolution measurements of capture cross sections with an uncertainty of about 10% over a neutron energy range of some eight orders of magnitude. Publications⁽¹⁶⁻²⁰⁾ of the fast neutron work are now emerging.

The following sections of this report describe the progress of the various cross-section investigations underway (Sections 2.1 to 2.5), recent improvements to the experimental facility (Section 2.6), and the direction of future work (Section 3).

2. RESEARCH PERFORMED

2.1 GADOLINIUM RESONANCE PARAMETERS

Considerable progress has been made toward satisfying existing needs for improved gadolinium resonance parameters (cf. request Nos. 205, 207, 209 in WASH-1078). Capture measurements using two natural gadolinium samples (see Table 1) were analyzed with a new shape-analysis code CASHA to obtain neutron and radiation widths for levels between 3 and 20 eV. The experimental procedures and analysis methods for these measurements of resolved resonances are, by and large, similar to those discussed in previous reports under this contract, and we will not repeat the details of these techniques here.

The data were accumulated with the CDC-1700 on-line computer which stored the data in channels that had a fixed energy width of 0.05 eV. This scheme allows a relatively large energy region to be covered with good energy resolution, as opposed to the usual method of storing data in constant time-width channels.

Above 20 eV the combined effects of resolution and Doppler broadening make shape-analysis techniques unsatisfactory. In addition, the high level density in ^{155}Gd and ^{157}Gd make the use of enriched isotopes highly desirable. For these reasons the resolved-resonance data between 20 eV and 185 eV were taken with samples highly enriched in one of these two isotopes. In this manner contributions due to resonances not contained in the isotope under study are strongly suppressed.

The ^{155}Gd and ^{157}Gd materials were available only as oxide powders, and hence the materials had to be encapsulated in thin-wall aluminum containers. A thick and a thin capture sample, and a thick self-indication sample were made from each of the two enriched oxides. (See Table 1 for the sample thicknesses and Table 2 for isotopic enrichments.)

Table 1
SAMPLES USED IN CAPTURE AND
SELF-INDICATION MEASUREMENTS

	Nuclei/barn ($\times 10^3$)	Use ^a
Nat. Gd	0.2514	1
Nat. Gd	0.7584	1
¹⁵⁵ Gd ₂ O ₃	0.5176	2
¹⁵⁵ Gd ₂ O ₃	1.5835	2, 4
¹⁵⁵ Gd ₂ O ₃	1.4754	3
¹⁵⁷ Gd ₂ O ₃	0.4485	2
¹⁵⁷ Gd ₂ O ₃	1.2968	2, 4
¹⁵⁷ Gd ₂ O ₃	1.2056	3

^aUse: 1. Shape analyses 3-20 eV
2. Capture area 20-185 eV
3. Self-indication filter 20-185 eV
4. Average cross sections 185 eV-20 keV.

Table 2
ISOTOPIC ENRICHMENTS
(Supplied by ORNL Isotopes Division)

Isotope	% Batch A ^a	% Batch B ^a
152	< 0.05	< 0.03
154	0.61 ± 0.05	0.09 ± 0.03
155	91.77 ± 0.10	1.54 ± 0.05
156	5.14 ± 0.10	4.31 ± 0.05
157	1.13 ± 0.05	88.63 ± 0.10
158	0.94 ± 0.05	4.61 ± 0.05
160	0.40 ± 0.05	0.82 ± 0.05

^aBatch A is referred to as the ¹⁵⁵Gd material and Batch B as the ¹⁵⁷Gd material.

From 20 to 185 eV, thick and thin capture data were taken, as well as thick self-indication data. The area analysis of capture data yields an accurate neutron width, and when this is combined with the self-indication data, an accurate radiation width can be obtained, except in the case of a very weak resonance or overlapping resonances. In this way the number of levels with known radiation widths has been greatly extended, and because of the inherently higher sensitivity of the capture technique, several previously undetected levels have been measured.

To date only the data between 20 and 100 eV have been analyzed, and the results of this analysis, along with the shape analysis below 20 eV, are listed in Table 3.

From 185 eV to 20 keV average capture cross-section data were taken for the isotopes ^{155}Gd and ^{157}Gd . Upon completion of the resolved-resonance analysis between 100 eV and 185 eV, and the analysis of the average capture cross section data, the resonance-parameter statistics will be analyzed to obtain best values of the average level spacing, neutron width, radiation width, and strength function, which in turn will be employed in the resonance integral calculations. All of these data will be supplied in tabular form to the Sigma Center of Brookhaven National Laboratory.

2.2 PRECISION NEUTRON FLUX MEASUREMENTS

With the successful operation of a capture gamma-ray detector at the 220-meter flight-path facility, our capability for measuring capture events now covers the neutron energy range from 0.01 eV to about 3 MeV. However, a cross section determination from time-of-flight capture data also requires knowledge of the energy dependence of the incident neutron flux $\phi(E_n)$, and uncertainties in the flux often constitute the major source of error in determinations of capture cross sections at higher energies. For absolute cross sections, we must also be able to normalize the

Table 3
PRELIMINARY RESONANCE PARAMETERS BETWEEN
3 eV AND 100 eV

E_o (eV)	^{155}Gd Γ_v (meV)	$2g\Gamma_n$ (meV)
3.60 ± 0.01		0.030 ± 0.002
6.30 ± 0.03	115 ± 2	2.54 ± 0.10
7.74 ± 0.04	112 ± 3	1.36 ± 0.06
11.53 ± 0.07		0.441 ± 0.025
11.98 ± 0.07	101 ± 22	1.24 ± 0.08
14.47 ± 0.09	111 ± 4	2.38 ± 0.10
17.73 ± 0.12	93 ± 75	0.54 ± 0.02
19.87 ± 0.15	129 ± 10	4.2 ± 0.3
21.02 ± 0.04	101 ± 5	19.3 ± 1.2
23.65 ± 0.04	167 ± 14	3.94 ± 0.1
27.57 ± 0.05		0.844 ± 0.02
29.55 ± 0.06	93 ± 21	5.8 ± 0.4
30.10 ± 0.06	105 ± 11	12.4 ± 0.9
31.72 ± 0.06	73 ± 57	1.35 ± 0.04
33.10 ± 0.07		1.42 ± 0.2
33.50 ± 0.07		1.28 ± 0.12
34.83 ± 0.07		4.60 ± 0.17
35.45 ± 0.07		2.32 ± 0.12
37.13 ± 0.08	147 ± 18	5.6 ± 0.2
39.00 ± 0.08		1.41 ± 0.04
43.92 ± 0.10	136 ± 9	11.9 ± 0.4
46.05 ± 0.10		2.6 ± 0.2
46.82 ± 0.10	84 ± 12	6.5 ± 0.2
47.65 ± 0.11		0.45 ± 0.04
51.30 ± 0.07		13.5 ± 0.7

Table 3 (Continued)

E_o (eV)	Γ_y (meV)	$2g\Gamma_n$ (meV)
52.05 $\pm$ 0.07		12.2 $\pm$ 0.6
52.95 $\pm$ 0.08		1.56 $\pm$ 0.06
53.68 $\pm$ 0.08	72 $\pm$ 10	9.63 $\pm$ 0.45
56.17 $\pm$ 0.08	61 $\pm$ 55	2.71 $\pm$ 0.11
59.32 $\pm$ 0.09		8.06 $\pm$ 0.22
62.74 $\pm$ 0.09	82 $\pm$ 11	9.8 $\pm$ 0.4
64.00 $\pm$ 0.09		0.36 $\pm$ 0.02
65.15 $\pm$ 0.10		0.84 $\pm$ 0.04
69.50 $\pm$ 0.10	151 $\pm$ 36	7.9 $\pm$ 0.3
76.90 $\pm$ 0.12		2.10 $\pm$ 0.08
77.70 $\pm$ 0.12		0.97 $\pm$ 0.05
78.80 $\pm$ 0.12		5.6 $\pm$ 0.8
80.05 $\pm$ 0.12		0.56 $\pm$ 0.16
80.80 $\pm$ 0.12		0.93 $\pm$ 0.09
84.05 $\pm$ 0.13		6.89 $\pm$ 0.23
84.95 $\pm$ 0.13		2.28 $\pm$ 0.12
90.50 $\pm$ 0.14		1.63 $\pm$ 0.06
92.40 $\pm$ 0.14		3.0 $\pm$ 0.3
92.90 $\pm$ 0.15		4.0 $\pm$ 0.4
94.10 $\pm$ 0.15		0.68 $\pm$ 0.04
95.75 $\pm$ 0.15		4.94 $\pm$ 0.34
96.45 $\pm$ 0.15		4.4 $\pm$ 0.3
	^{157}Gd	
16.25 $\pm$ 0.11		0.51 $\pm$ 0.05
16.85 $\pm$ 0.12	106 $\pm$ 4	15.9 $\pm$ 1.0
20.56 $\pm$ 0.04	94 $\pm$ 5	15.3 $\pm$ 0.8
21.65 $\pm$ 0.04		0.44 $\pm$ 0.03
23.33 $\pm$ 0.04		0.59 $\pm$ 0.02

Table 3 (Continued)

<u>E_o (eV)</u>	<u>Γ_Y (meV)</u>	<u>$2g\Gamma_n$ (meV)</u>
25.40 $\pm$ 0.05		2.17 $\pm$ 0.07
40.15 $\pm$ 0.09		0.93 $\pm$ 0.04
44.20 $\pm$ 0.10	87 $\pm$ 8	11.4 $\pm$ 0.6
48.72 $\pm$ 0.11	86 $\pm$ 8	30.7 $\pm$ 1.4
58.31 $\pm$ 0.08	111 $\pm$ 7	39.1 $\pm$ 3.7
66.57 $\pm$ 0.10	64 $\pm$ 16	11.2 $\pm$ 1.0
81.30 $\pm$ 0.12		14.5 $\pm$ 3.8
82.15 $\pm$ 0.13		7.1 $\pm$ 3.1
87.20 $\pm$ 0.14	112 $\pm$ 54	12.2 $\pm$ 1.1
96.59 $\pm$ 0.15	102 $\pm$ 42	14.3 $\pm$ 1.8

product $\epsilon(E_n)\phi(E_n)$ at some energy, where $\epsilon(E_n)$ is the capture gamma-ray detection efficiency. The usual normalization techniques are:

1. The saturated-resonance method⁽²¹⁾
2. The use of a resonance capture area where the resonance parameters are well known.
3. The use of a well known thermal capture cross section.

All of these normalization methods are feasible only at low energies, $E_n \lesssim 100$ eV. Consequently, (n, γ) measurements at 1-MeV energy require knowledge of the variation of the neutron flux over an energy range of about four to eight orders of magnitude. This knowledge has previously been very difficult to obtain, primarily because no single method has existed for accurate neutron flux measurements over such a large energy range.

Therefore, a substantial part of this year's effort to extend the capture measurements to higher energies has been devoted to improving the experimental methods for neutron flux measurements over a wide range of energies and to monitoring the flux concurrently with capture measurements at the 220-meter flight-path facility. As a result of this development effort, we can now use ^3He gas proportional counters that are calibrated against the $^{10}\text{B}(n, \alpha)^7\text{Li}$ reaction and the $n+p$ scattering interaction for neutron flux measurements in the energy intervals ≤ 80 keV and 80-800 keV, respectively. The over-all uncertainty in a neutron flux measurement with the ^3He counters over the entire neutron energy range is less than 10%. We are now working on the problem of extending the range of the flux measurements to about 3 MeV. Measurements with a methane, proton-recoil detector are discussed briefly below, and the ^3He proportional counters are described in Section 2.5.

The $n+p$ scattering cross section has been intensively investigated in fundamental studies of the nucleon-nucleon interaction. A description

of the $n+p$ interaction was developed by Schwinger⁽²²⁾ and Bethe⁽²³⁾ that agrees with the experimental determinations to better than 1% over the entire energy from thermal to 10 MeV. Neutron capture is the only non-elastic channel open to the $n+p$ interaction, and this reaction becomes negligible compared to elastic scattering at energies above thermal. Consequently, there is much to support the conclusion that the $n+p$ scattering cross section is presently the best standard cross section available for fast neutron physics.

However, the practical difficulty of detecting low-energy protons has limited the widespread use of this cross section for neutron energies below ~ 1 MeV. Hydrogen and methane gas proportional counters have been used for accurate ($\sim 3\%$) neutron flux measurements with monoenergetic neutron sources to as low as 40-keV neutron energy.⁽²⁴⁾ However, to our knowledge, the intrinsic precision of hydrogenous gas counters has not been previously employed with time-of-flight techniques, primarily because of the inherent time jitter of gas counters and because of the difficulty in determining the detection efficiency (for a given electronic threshold) of a counter with a pulse-height spectrum that is a function of neutron energy, and hence of neutron flight time. In this work, such problems were minimized with the use of the long (220-meter) flight path and a special, two-parameter (pulse height and time of flight) data-acquisition system implemented with the CDC-1700 on-line computer.

A methane gas proportional counter (2-in. diam, 24-in. long, 2 atm gas pressure) placed at the end of a 220-meter flight path yields a timing resolution of 3 nsec/meter, which is more than adequate for neutron flux measurements. The two-parameter mode of data acquisition is used to extract from the raw data a proton-recoil pulse-height spectrum for any given time-of-flight interval so that the detection efficiency can be determined as a function of neutron energy.

The data acquisition system is programmed to accept two words of information per event, one from a time encoder (t) and one from a

4096-channel pulse-height digitizer (h). The digital information t and h correspond to the time of flight and pulse height of a neutron interaction in the methane gas proportional counter. The word pairs (t,h) are stored in "ping-pong" tables within the magnetic core memory of the CDC-1700 computer. A live display of pulse-height and time-of-flight spectra is updated from the data tables prior to their transfer into magnetic disc memory. At the conclusion of the measurement, the data on disc are sorted in such a way as to extract a proton-recoil pulse-height spectrum

$$\int_{t_1}^{t_2} \frac{d^2 N}{dt dH} (t, h) dt$$

resulting from neutrons with energies between $E_1(t_1)$ and $E_2(t_2)$. From the dimensions and gas density of the counter and the n + p scattering cross section, it is possible to accurately relate portions of the pulse-height spectra to the incident neutron flux.

In this manner, neutron flux measurements have been obtained with the methane counter with an over-all precision of 5% in the energy range 80 to 800 keV. This capability will have important applications both in the capture cross-section measurements and in measurements of important neutron-induced reactions such as $^3\text{He}(n, p)\text{T}$, $^{10}\text{B}(n, \alpha)^7\text{Li}$, and $^6\text{Li}(n, \alpha)\text{T}$.

2.3 FAST NEUTRON CAPTURE

2.3.1 Experimental Procedures and Data Reduction

The techniques described in Section 2.2 for the determination of neutron flux were applied to time-of-flight measurements of $\text{Au}(n, \gamma)$ and $\text{Gd}(n, \gamma)$ over the neutron energy range 1-700 keV. These data were taken with the pulsed neutron source and 220-meter flight-path facility described below in Sections 2.6.1 and 2.6.2. Additional data for Gd used for

normalization purposes were taken at the 20-meter flight-path facility, which has been described previously in detail.⁽³⁾ At the 220-meter station, capture gamma rays are detected with a 600-liter liquid scintillator (Section 2.6.2), which is similar, except for size, to the 4000-liter scintillator located at the 20-meter station.

While the efficiency of the large gamma-ray detector can be shown⁽²⁵⁾ to be relatively insensitive to the gamma-ray cascade mode, this is not necessarily true for the smaller 600-liter detector at the 220-meter station. However, this detector facility was designed primarily for measurements at neutron energies of 1 keV to 1 MeV. There, capture measurements for heavy elements usually represent an average over many levels of the compound nucleus, principally because the energy resolution is inadequate to resolve individual resonances. Consequently, only an average detection efficiency is involved in this type of measurement, and this average efficiency changes only slowly with neutron bombarding energy.

A block diagram of the instrumentation for the 600-liter detector is shown in Fig. 1. The discriminator threshold was set to reject scintillator pulses that correspond to deposited gamma-ray energies of less than 4 MeV. (This adjustment was made with the aid of the 4.44-MeV gamma-ray emitted by a Pu-Be neutron source.) The time history of the (n, γ) events was stored in a multichannel analyzer using constant time intervals of 2 μ sec. The flight path and the LINAC burst width for these measurements were 232.78 meters and 2 μ sec, respectively. Since the gamma-ray detector response time is small (~ 30 nsec), and since the neutron-source effects on the instrumental energy resolution are also small, the experimental conditions result in a triangular time response with a 2 μ sec FWHM. The resulting over-all neutron energy resolution is illustrated in Fig. 2.

Possible overloading effects of the LINAC bremsstrahlung pulse on the instrumentation were investigated by the following procedure. Two measurements of count rate versus flight time were made using a

600-LITER CAPTURE γ -RAY DETECTOR

Figure 1. Schematic illustration of instrumentation for 600-liter scintillator.

Figure 2. Over-all energy resolution of capture measurements at the 220-meter facility.

0.25-in.-thick carbon sample, with and without a ^{24}Na gamma-ray source placed near the sample but outside the neutron beam. The difference between these two measurements should be the constant count rate observed from the radioactive ^{24}Na source. Since the discriminator threshold was set at 4 MeV, which is near the total gamma-ray energy (4.1 MeV) from the ^{24}Na source, this test is very sensitive to any gain changes induced in the instrumentation by the bremsstrahlung pulse. The recovery of the system was found to be complete in about 10 μsec after the LINAC pulse, which is equivalent to a neutron energy of about 2.7 MeV.

Typical time-of-flight capture gamma-ray data for Au measured with the 220-meter facility are shown in Fig. 3. The thickness of the Au sample was 0.100 in. (0.01504 nuclei/barn), and that of the natural Gd sample was 0.040 in. (0.003028 nuclei/barn). Also shown in Fig. 3 are the backgrounds that have been subtracted from the capture data. The ambient background, which arises primarily from cosmic-ray interactions with the detector and from the natural radioactivity present in the detector and its environment, is determined by a count-rate measurement with the linear accelerator turned off. The time-dependent LINAC-associated background is that background above ambient which is observed with the accelerator on and with no sample in the neutron beam. Its magnitude is proportional to the intensity of the neutron beam and is primarily due to neutrons scattered and captured in the vicinity of the collimator placed just in front of the detector.

The scattered neutron background is the result of neutrons that are scattered by the sample and are subsequently captured in the detector materials. A measure of this background was obtained by substituting a 0.25-in. carbon sample and scaling the observed gamma-ray counts by the ratio of the scattering probabilities for a representative neutron energy of 200 keV. The proper scattering ratio is not known exactly since the mean lifetime of neutrons scattered into the liquid scintillator is about 150 μsec . Consequently the time-dependent background from this source

Figure 3. Time-of-flight capture data for gold and associated gamma-ray backgrounds.

at any flight time is primarily due to neutrons scattered at earlier flight times. Furthermore, the capture sample is surrounded by a natural boron sleeve 0.6 in. thick by 20 in. long which is progressively less transparent to lower energy neutrons having longer flight times. The over-all result is a scattered neutron background which varies slowly with flight time and which is proportional to an average scattering probability determined by the scattering properties of the sample in the upper-keV neutron energy range.

To check the effectiveness of our procedures for background subtractions, we made an auxiliary capture measurement in which we introduced a thick sodium "notch" filter in the neutron beam between the source and the capture sample. The count rate observed in the bottom of the transmission dip (due to the 2.85-keV resonance in ^{23}Na) agreed within 2% with the sum of the measured backgrounds at that neutron energy. We estimate a probable systematic uncertainty for the capture data of 5% due to background subtractions.

The sample-out and scattered-neutron backgrounds were smoothed prior to subtraction by grouping these data into intervals of $\Delta E_n = 0.2 E_n$ and $0.5 E_n$, respectively. The net capture counts at lower neutron energies (< 40 keV) were grouped into intervals of $\Delta E_n = 0.05 E_n$, and at higher energies the interval is determined by the analyzer time channel width of $2 \mu\text{sec}$. The total statistical uncertainty in the net capture data (as illustrated in Fig. 3), including contributions from the statistical uncertainties of the backgrounds, attains a maximum near 50 keV of 5% for Au and 6% for Gd, and it diminishes to about 3% at the lowest and highest energies.

Capture cross sections were obtained from the observed gamma-ray counts by dividing by the incident neutron flux and by applying corrections for multiple scattering and resonance self-shielding. The net capture counts $\left[\frac{dN}{dt} (E_n) \Delta t \right]$ observed in the time-of-flight interval Δt at the time

corresponding to the energy E_n can be written

$$\frac{dN}{dt}(E_n)\Delta t = \epsilon(E_n)S T_\gamma \frac{d\phi}{dt}(E_n)\Delta t \langle P_o(E_n) + P_s(E_n) \rangle, \quad (1)$$

where $\epsilon(E_n)$ is the gamma-ray detection efficiency, S the sample area, T_γ a constant which accounts for the attenuation of capture gamma rays by the sample, $\frac{d\phi}{dt}(E_n)$ the incident neutron flux per unit area per unit time of flight, and P_o and P_s are the first-collision and multiple-scattered capture probabilities, respectively. The brackets denote an average over an energy interval typical of the experimental resolution. For the natural Gd sample, the difference in detection efficiency for capture events following one or more elastic collisions can be ignored and the average efficiency for a mixture of isotopes may be expressed as

$$\epsilon(E_n) = \frac{\sum_i a_i \sigma_{\gamma i}(E_n) \epsilon_i(E_n)}{\sum_i a_i \sigma_{\gamma i}(E_n)}, \quad (2)$$

where the i^{th} isotope has an abundance a_i and a capture cross section $\sigma_{\gamma i}$.

When many levels of the compound nucleus contribute to the measurement, the gamma-ray detection efficiency does not vary appreciably with the incident neutron energy until the energy becomes an appreciable fraction of the binding energy U less the scintillator threshold energy of 4 MeV. We write the energy variation as

$$\epsilon(E_n) = \epsilon_o \alpha(E_n), \quad (3)$$

and $\alpha(E_n)$ increases slowly from unity at high energies, say $E_n \gtrsim 100$ keV. For the natural Gd sample we use a sum over isotopes (i),

$$\epsilon_o \equiv \frac{\sum_i a_i \bar{\sigma}_{\gamma i} \epsilon_i^{(o)}}{\sum_i a_i \bar{\sigma}_{\gamma i}}, \quad (4)$$

where $\bar{\sigma}_{\gamma i}$ are typical isotopic capture cross sections at low energies (~ 10 keV). (Differences in the efficiencies ϵ_i for different isotopes were ignored in the correction for resonance self shielding.) The correction $\alpha(E_n)$ for Gd was then calculated using isotopic capture cross sections estimated with the code SESH (see below) from average statistical parameters, and using an estimate of the variation of the efficiency of the 600-liter scintillator with incident neutron energy. This efficiency estimate was made assuming the gamma-ray pulse-height distribution $f_i(E_\gamma, E_n)$ for each isotope (i) is stretched linearly with the total energy available for gamma de-excitation,

$$f_i(E_\gamma, E_n) = f_i\left(\frac{U_i}{U_i + E_n} E_\gamma, 0\right),$$

where U_i is the binding energy. The correction $\alpha(E_n)$ is then

$$\alpha(E_n) = \frac{\left[\sum_i a_i \bar{\sigma}_{\gamma i}(E_n)\right]^{-1} \sum_i a_i \bar{\sigma}_{\gamma i}(E_n) g_i(E_B, E_n)}{\left(\sum_i a_i \bar{\sigma}_{\gamma i}\right)^{-1} \sum_i a_i \bar{\sigma}_{\gamma i} g_i(E_B, 0)},$$

where $g_i(E_B, E_n)$ is the gamma-ray pulse-height spectrum fraction above the scintillator discriminator level E_B ,

$$g_i(E_B, E_n) = \frac{\int_{E_B}^{U_i + E_n} f_i(E_\gamma, E_n) dE_\gamma}{\int_0^{U_i + E_n} f_i(E_\gamma, E_n) dE_\gamma}, \quad (5)$$

and the $\sigma_{\gamma i}$ are estimated isotopic capture cross sections. For Gd, the correction $\alpha(E_n)$ is about 1.01 at 200 keV and increases to about 1.05 at 700 keV. For Au, the correction is given directly by the change in the spectrum fraction for different E_n and varies from 1.03 to 1.10 for neutron energies from 200 to 700 keV.

In the present measurements, the gamma-ray transmission through the sample (T_γ) does not vary appreciably with the energy of the incident neutrons, and for Gd T_γ is given by an isotopic average similar to that of Eq. 4. For example, for gammas of about 1 MeV energy a change as large as 30% in the gamma energy would change the transmission of gammas passing through the full thickness of the Au sample by less than 5%.⁽²⁶⁾

If we express the un-normalized incident flux spectrum measured by the ^3He gas proportional counters as

$$\frac{d\tilde{\phi}}{dt}(E_n) \equiv \frac{1}{C} \frac{d\phi}{dt}(E_n) , \quad (6)$$

where C is the normalization constant, then the capture probability is determined from the measured quantities according to

$$\langle P_o(E_n) + P_s(E_n) \rangle = \frac{\frac{dN}{dt}(E_n)}{\alpha(E_n)(\epsilon_o ST_\gamma C) \frac{d\tilde{\phi}}{dt}(E_n)} . \quad (7)$$

The normalization of the capture probability is thus determined by the product $(\epsilon_o ST_\gamma C)$, which can be found by the "saturated-resonance" method.⁽²¹⁾ In this method, capture data are examined for a low-energy resonance for which the left-hand side of Eq. 7 approaches unity near the resonance energy and hence becomes insensitive to the neutron and radiation widths that characterize the resonance. At the expense of a somewhat greater reliance on the resonance parameters, the full capture area A_{obs} of the resonance can be used to achieve a greater statistical precision; and resonances at

energies E_n in an isotope (i) determine the quantities ($\alpha = 1$)

$$A_{\text{obs}} \equiv \sum_k \frac{dN}{dt}(E_k) \Delta t_k = \epsilon_i ST_{\gamma i} C \frac{d\tilde{\phi}}{dt}(E_n) \int_{t_1}^{t_2} dt <P_o + P_s>, \quad (8)$$

where the variation of $d\tilde{\phi}/dt$ over the interval (t_1, t_2) is small. In the present work the integral

$$\int_{t_1}^{t_2} dt <P_o + P_s>$$

was calculated with the area-analysis code TACASI.⁽²⁷⁾ (This Monte Carlo code calculates Doppler and resolution broadened areas including contributions from adjacent resonances for a flux represented as $d\phi/dt = KE_n^x$, so that capture areas calculated with $\epsilon_i SK = 1$ and $x = 0$ give the desired integral.) The quantities $(\epsilon_i ST_{\gamma i} C)$ are then determined by comparing the ratio of the observed and calculated areas to the measured flux, and for Gd an average of these factors for different isotopes according to Eq. 4 yields the desired factor $(\epsilon_o ST_{\gamma} C)$.

While Au has six suitable normalization resonances above 100 eV, useful resonances in the Gd isotopes lie at energies below 35 eV. Since the range of the capture data taken with the 220-meter flight path does not extend to neutron energies below 70 eV, the saturated-resonance method was employed for Gd by taking additional capture data for the same sample with the 4000-liter scintillator at the 20-meter flight path facility. These data span the energy region 2 eV to 10 keV and overlap the data taken at 220 meters. To improve the accuracy of the normalization, the shape of the neutron flux observed at the 20-meter facility was first smoothed to eliminate small statistical variations by fitting with a minimum χ^2 criterion the flux obtained from the ^3He and BF_3 counters with the expression

$$\frac{d\hat{\phi}}{dt}(E_n) = C'e^{-\beta/\sqrt{E}} E^\gamma, \quad (9)$$

and the optimum values of β and γ were found to be $\beta = 1.39$ and $\gamma = 0.592$. The observed and analytical flux ($d\hat{\phi}/dt$) for the 20-meter data are compared in Fig. 4.

The normalization factors ($\epsilon_i ST_{\gamma i} C$) for the 20-meter Gd capture yields were then obtained from low-energy resonances according to Eq. 8, where $d\phi/dt \equiv C d\hat{\phi}/dt$. For ^{155}Gd , the resonance energies were 2.568, 6.30, 7.75, 14.47, and 27.52 eV. For ^{156}Gd , the 33.2 eV resonance was suitable, and for ^{157}Gd we used the resonances at 2.825, 16.82, and 25.4 eV. The resonance at 22.4 eV in ^{158}Gd was used for both ^{158}Gd and ^{160}Gd , since the latter isotope had no suitable resonance for calibration.

The capture areas

$$\int_{t_1}^{t_2} dt \langle P_o + P_s \rangle$$

for ^{155}Gd and ^{157}Gd were obtained from the resonance parameters of the present work (Section 2.1), and those for the even isotopes obtained from Ref. 28. The agreement of the observed and calculated resonance shapes was excellent, as is illustrated for a typical case in Fig. 5. Of the ten Gd resonances, only that at 2.568 eV in ^{155}Gd was "saturated" ($\langle P_o + P_s \rangle \gtrsim 0.95$ at the resonance energy), although the normalization constants obtained from all the resonances agree closely. For ^{155}Gd the five resonances gave an average normalization factor ($\epsilon_i ST_{\gamma i} C$) of 2.20 ± 0.07 (RMS error), and for ^{157}Gd we obtained 2.36 ± 0.07 , in units convenient to the experiment. The normalization factor for ^{156}Gd was 1.97 ± 0.16 , and that for ^{158}Gd was 1.97 ± 0.10 , where the uncertainties include both the statistical probable error and that due to the quoted⁽²⁸⁾ uncertainty in the neutron width. The isotopic average according to Eq. 4

Figure 4. Neutron flux at 20-meter flight path. The curve is the fit to the data using the expression given in the text with $\beta = 1.39$ and $\gamma = 0.592$.

Figure 5. Capture resonance observed at 20-meter flight path facility. The curve is the calculated quantity $\epsilon_i S T_{\gamma i} C \frac{d\phi}{dt} (E_0) < P_0(E_n) + P_s(E_n) >$ with the factor $(\epsilon_i S T_{\gamma i} C)$ adjusted to reproduce the observed area of the resonance between energy E_1 and energy E_2 .

then determined the normalization for the 20-meter Gd capture data, $(\epsilon_o ST_Y C) = 2.14 \pm 0.05$. The normalization factors for the Gd capture data taken at the 220-meter facility were then determined by matching the quotient of the capture data and the flux data to the normalized capture yields taken at 20 meters. The two data sets were matched in the energy region 3-8 keV with an estimated maximum uncertainty of 3% in judging their relative normalizations. (The statistical uncertainties of the 220-meter flux data are less than 3% at all energies.)

For Au, the 220-meter capture yields were normalized directly to the resonance capture areas at 107.2, 144.65, 151.6, 190.4, 241.1, and 262.8 eV using the resonance parameters in Ref. 28. Uncertainties in the normalization factors due to statistics and quoted⁽²⁸⁾ uncertainties in the resonance parameters ranged from $\pm 3\%$ to $\pm 12\%$ for the different resonances, and the average normalization factor deduced by comparing the measured flux shape to that inferred by the capture areas was judged to be determined to within $\pm 5\%$.

The average capture cross sections $\langle \sigma_Y(E_n) \rangle$ were then obtained from the normalized probabilities $\langle P_o(E_n) + P_s(E_n) \rangle$ by taking into account the effects of multiple scattering and resonance self-shielding. These effects increase in importance with increasing sample thickness and decreasing neutron energy, and give rise to corrections of up to 20% in the present data at energies between 5 and 100 keV. The corrections were calculated with the Monte Carlo program SESH⁽²⁹⁾ which generates a Doppler-broadened resonance cross-section environment for the neutron energy at each collision in a cylindrical sample from distributions of the resonance parameters determined from specified statistical parameters (strength functions, average level spacings, and average radiation widths). The s-, p-, and d-wave strength functions used for Au were 2.0, 0.2, and 0.4×10^{-4} , respectively, as inferred from various sources. (The d-wave contribution is actually negligible in the energy region where the self-shielding correction is significant.) The strength functions used for the

Gd isotopes were taken from Ref. 30. The average radiation width at low energy for Au was judged to be 0.124 eV from the data in BNL 325, (28) and the average radiation widths used for the Gd isotopes were the present values and those from Ref. 28. The average observed level spacings at low energy and Au and Gd for $\ell = 0$ were taken to be those given in Ref. 31, and the spacings for ^{158}Gd and ^{160}Gd were adjusted to give the best agreement with our data and found to be about 25 eV. The average level spacings for $\ell = 1$ and $\ell = 2$ were obtained from the $\ell = 0$ spacing by assuming the spacing to vary inversely as $\sum_J (2J+1)$, where the sum is over all possible values of the total angular momentum J which are compatible with ℓ . Potential-scattering radii were obtained from Ref. 30. These various parameters produce reasonable agreement with the observed capture probabilities in the energy region where the resonance self-shielding effect is significant.

The resonance self-shielding effect is caused by the resonance structure of the cross section in conjunction with the nonlinear relationship between the cross section and the capture probability. For example, the energy average of the first-collision capture probability P_o is

$$\begin{aligned} \langle P_o \rangle &= \left\langle \left(1 - e^{-n\sigma_T} \right) \frac{\sigma_Y}{\sigma_T} \right\rangle \\ &\equiv \left[1 - \delta(E_n) \right] \left(1 - e^{-n\langle \sigma_T \rangle} \right) \frac{\langle \sigma_Y \rangle}{\langle \sigma_T \rangle}, \end{aligned} \quad (10)$$

where σ_Y and σ_T are the capture and total cross sections, respectively (Doppler broadened and summed over isotopic contributions), and n is the sample thickness (nuclei per unit area). The difference in $\langle P_o \rangle$ from that given by the average cross sections is then expressed by the positive number $\delta(E_n)$, and $\delta(E_n) = 0$ only when the cross sections vary smoothly over the energy interval of averaging. For Au, calculations

with the statistical parameters mentioned above give δ (1 keV) = 0.44, δ (2 keV) = 0.28, δ (5 keV) = 0.19, and $\delta < 0.1$ for $E_n \geq 10$ keV. For the Gd sample, δ (1 keV) = 0.19, δ (3 keV) = 0.05, and $\delta < 0.025$ for $E_n > 7$ keV.

The calculated fractional multiple scattering contribution $\langle P_s \rangle / \langle P_o + P_s \rangle$ for Au was 30% for $E_n = 1$ keV, 25% at 20 keV, and $< 20\%$ for $E_n > 125$ keV. For Gd, $\langle P_s \rangle / \langle P_o + P_s \rangle$ was 10% at 1 keV and less than 5% for $E_n > 100$ keV. For energies higher than the region of important resonance self-shielding effects, say $E_n > 20$ keV for Au and $E_n > 10$ keV for Gd, it proved unnecessary to carry out Monte Carlo calculations of the multiple scattering contribution, and an analytical calculation could be used which neglects the effects of neutron energy loss, finite sample radius, and motion of the sample nuclei. Contributions from neutrons captured after one or more inelastic collisions with the sample nuclei were estimated and found to be negligible.

The combined correction for multiple scattering and self-shielding (both resonant and nonresonant) can be expressed by writing

$$n \langle \sigma_\gamma(E_n) \rangle = D(E_n) \langle P_o(E_n) + P_s(E_n) \rangle, \quad (11)$$

where D is the total correction to the observed capture probability $\langle P_o + P_s \rangle$ and n is the sample thickness. Self-shielding leads to $D > 1$ and multiple scattering to $D < 1$. For Au, typical values are D (1 keV) = 1.73 ± 0.18 , D (5 keV) = 1.11 ± 0.09 , D (10 keV) = 0.92 ± 0.05 , and D (20 keV) = 0.85 ± 0.02 , where the uncertainties are due to the finite number of Monte Carlo histories used in the calculation. At higher energies, D slowly approaches unity as the effects of (nonresonant) self-shielding and multiple scattering diminish. For Gd, D (1 keV) = 1.03 ± 0.03 , D (3 keV) = 0.95 ± 0.02 , and D (7 keV) = 0.98 ± 0.03 .

The average capture cross sections and their total statistical uncertainties are illustrated in Fig. 6. The final data will be supplied in

Figure 6. Preliminary average neutron capture cross sections for Au and Gd.

tabular form to the Sigma Center of Brookhaven National Laboratory. The statistical uncertainties were obtained by adding in quadrature the statistical uncertainties in the capture and flux data and the uncertainty in the Monte Carlo calculation of $D(E_n)$ described above. In addition to these uncertainties, the total "absolute" uncertainty in the normalization of $\langle \sigma_Y(E_n) \rangle$ is estimated to be 10% for both elements. This was obtained by adding the systematic uncertainties due to background subtractions, the uncertainties in the normalization constants ($\epsilon_{oSTY C}$), and for Gd the uncertainty in judging the normalization of the 220-meter yields relative to the 20-meter data. The large variations in the Au data below 10 keV are well outside the probable relative errors and are due to partially resolved resonances.

Also shown in Fig. 6 are most of the previous measurements of the capture cross sections for Au and Gd. Our results for Au are in reasonable agreement with previous data below 20 keV, fall between the data of Cox⁽³²⁾ and Pönitz⁽³³⁾ from 20 to 200 keV, and lie close to most of the previous data above 200 keV. Our Au results are in serious disagreement with the data of Gibbons, et al.,⁽³⁴⁾ which show a large dip in the cross section near 100-keV energy that is not borne out by the present measurements. Our results for Gd below 10 keV lie lower than the data of Block, et al.,⁽³⁵⁾ and at energies above 100 keV our results are higher than the data of Gibbons, et al.⁽³⁴⁾

2.3.2 Statistical-Model Analysis

The present data give detailed information on the shape of the capture cross section from 10 to 700 keV and are thus ideally suited for a critical examination of the current theory of fast-neutron capture. Previous analyses of data obtained in activation experiments have been seriously hampered by the paucity and uncertainty of data at the lower energies (say < 100 keV), and analyses at higher energies are usually encumbered by diminishing information on the levels of the target nucleus,

which must be known to account for competition from inelastic scattering. Analysis of the present data has led to a basic change in the model for this reaction that affects the variation of the capture cross section with neutron energy and which has consequently eluded previous investigations focused on a narrower or different region of energy. For neutron energies near the peak of a fast-reactor spectrum (~ 0.5 MeV), this change in the model results in capture cross sections that differ by almost a factor of two from those calculated conventionally.

A brief description of this analysis has been submitted for publication as a Letter, and a full description will be published together with our final data. Our finding is essentially that the capture cross sections demand a new energy dependence of the parameters that describe the decay of the compound nucleus by gamma emission, and this is interpreted to imply a new energy dependence for the total radiation width in the continuum. The present analysis does not identify the underlying mechanism responsible for this energy dependence, and it seems likely that such information will be gained not from further studies of capture cross sections but rather from a detailed analysis of capture gamma-ray spectra over a neutron energy region similar to that considered here. Nonetheless, it is clear that the present, phenomenological result can have immediate practical consequences in the extrapolation and evaluation of data important to fast reactor systems. To insure the applicability of the present result for nuclei in the Ti-Ni region and to U and Pu, the phenomenological analysis should be extended to a few selected data sets in order to verify the universality of the result. For purposes of making predictions where no data exist whatsoever, such as for fission fragments, some additional study should also be made of the ability of the statistical/optical-model treatment to reproduce the observed normalization of the capture cross sections from confident values of low-energy resonance parameters. In particular, the choice of optical-model parameters will prove to be quite important in determining the normalization.

2.4 ZIRCONIUM RESONANCE PARAMETERS

Zirconium and Zircaloy (zirconium alloys) have found wide application in reactor technology because of their good mechanical properties, high-temperature stability, and low neutron absorption. However, accurate calculations of the neutron absorption by zirconium have been hampered by a lack of precise cross-section data and resonance parameters. This need is underlined by the numerous priority 1 and 2 requests for this type of information listed in WASH-1078. The major part of neutron absorption in natural zirconium is due to capture by ^{91}Zr , the only stable odd isotope. Below a neutron energy of 2000 eV, only one out of nine observed resonances is due to an even isotope (^{96}Zr). Above 2000 eV the observed levels of all isotopes are predominantly scattering resonances, i. e., $\Gamma_n \gg \Gamma_\gamma$. Consequently, the high-energy contribution to a calculated resonance integral is determined primarily by the radiation widths of the zirconium resonances.

We have measured capture cross sections for natural zirconium and ^{91}Zr in the thermal energy region and have also obtained resonance parameters for ^{91}Zr for neutron energies up to 2000 eV.⁽¹⁴⁾ However, the conclusion of this work has been delayed because of the lack of sufficient ^{91}Zr metal to allow an accurate normalization of these results using the saturated resonance method.⁽²¹⁾ Consequently, all of our earlier results have been plagued with a 20% systematic uncertainty.

In the latter part of 1968, we obtained 57 grams of ^{91}Zr (89% enrichment) in the form of zirconium-oxide powder. With this amount of material, we were able to apply the saturated-resonance method for a neutron-flux normalization with the 181-eV resonance. This flux normalization was then combined with an earlier thin-sample measurement of the capture area CA (observed for both thick and thin samples) of the weak 240-eV resonance in ^{91}Zr using the relation between the neutron flux $\phi(E_0)$ at the resonance energy E_0 and the capture area,

$$\varphi(E_o) = k \frac{CA}{n} (1 + \delta) , \quad (12)$$

where k is a constant containing the resonance parameters, n is the sample thickness, and δ is a small correction for second-order sample thickness effects such as multiple scattering and sample self-shielding. The thick- and thin-sample capture areas for the 181-eV resonance were then fit to calculated areas with the code TACASI⁽²⁷⁾ using Γ_γ and $2g\Gamma_n$ as free parameters. The results of this analysis are shown in Fig. 7. The 10% uncertainty in $2g\Gamma_n$ is primarily due to the statistical uncertainty of all the capture areas involved in the analysis and the uncertainty in the instrumental resolution function that is used in the saturated-resonance flux normalization.

With the aid of the computer-based, two-parameter on-line data acquisition system, we have recently obtained data that will determine the detection efficiency for capture by the 300-eV resonance in ^{96}Zr relative to that for resonances in ^{91}Zr . This information should allow an accurate determination of the resonance parameters, $g\Gamma_n$ and Γ_γ , for the 300-eV level. The parameters for this resonance in ^{96}Zr are important for two reasons: (1) the level makes a significant contribution to the resonance integral of natural zirconium, and (2) the determination of Γ_γ for this level may help justify the assumption that Γ_γ is the same for all the zirconium isotopes. The constancy of Γ_γ is presently assumed in calculating the high-energy contribution to the resonance integral for natural zirconium.

The work that remains to be done on the problem of neutron capture in zirconium is as follows:

1. Renormalize earlier resonance-parameter results⁽¹⁴⁾ to the new, more precise value of $2g\Gamma_n$ for the 181-eV resonance.

Figure 7. Curves defined in the $(2g\Gamma_n, \Gamma_\gamma)$ plane by experimental capture areas of the 181-eV resonance obtained with thick ($n = 0.033$ nuclei/barn) and thin ($n = 0.00215$ nuclei/barn) samples of zirconium enriched in ^{91}Zr (89%).

2. Complete the analysis for resonance parameters of the 300-eV level in ^{96}Zr .
3. Calculate the infinite-dilution resonance integral for natural zirconium using the results from Steps 1 and 2 above.
4. Prepare a description of this work for publication.

2.5 $^3\text{He}(n, p)\text{T}$ CROSS SECTION

The large magnitude and nearly "1/v" behavior of the $^3\text{He}(n, p)\text{T}$ cross section as well as favorable properties of ^3He gas proportional counters suggest the use of ^3He as a neutron standard. Its usefulness, however, has been hampered by the lack of accurate direct experimental measurements of the cross section, mainly in the 10 keV to 1 MeV incident neutron energy range. To help remedy this situation, a measurement of the $^3\text{He}(n, p)\text{T}$ cross section has been made in the energy region 300 keV - 1.16 MeV (this work is pertinent to request No. 8 in WASH-1078).

2.5.1 ^3He Gas Proportional Counters

A gas proportional counter that makes use of the $^3\text{He}(n, p)\text{T}$ reaction has many features that recommend it as a neutron flux detector for time-of-flight measurements. This counter can be made more efficient (with high gas pressure) than the $^{10}\text{BF}_3$ counter, and it also has a smaller "time jitter" (charge collection time).

Four 1-in. diam by 6-in. long (active length) ^3He -filled proportional counters were used in these measurements. The counters were obtained from Reuter-Stokes Electronic Components, Inc., who furnished the following information:

1. The ^3He pressure is 150 psi $\pm$ 1%
2. The isotopic purity of ^3He is > 99.9%
3. The temperature of the room at the time of filling was 34°C.

4. The anode is 0.004-in. diam tungsten
5. The cathode is 1100 F aluminum with a 0.032-in. wall.

Since the neutron energy resolution for time-of-flight measurements with these proportional counters depends on the time jitter of the counter, a measurement to determine this property was made. A delayed coincidence technique was used as illustrated by the block diagram in Fig. 8. This technique has been described previously in detail.⁽³⁶⁾ The results of this measurement, also shown in Fig. 8, give a time jitter of 2.5 μ sec.

In the $^3\text{He}(n, p)\text{T}$ reaction the triton and proton share a total energy of $Q = 764$ keV plus the energy of the incident neutron. A pulse is formed in the counter that is directly proportional to the total energy. Figure 9 shows a typical pulse-height spectrum obtained with the ^3He counter in an isotropic flux of thermal neutrons. The plateau (A in Fig. 9) is formed by particles that do not lose all their energy in the sensitive volume of the counter. The "knee" in the spectrum (B in Fig. 9) results from events that occur near the surface of the wall, where the proton enters the wall and the triton, which carries $Q/4$ in kinetic energy, goes in to the sensitive gas volume. When fast neutrons with energy E_n initiate the reaction, the peak of the pulse-height distribution will be located at a point $(Q + E_n)$. Smaller pulses will also result from ^3He nuclei recoiling from elastically scattered neutrons.

2.5.2 Method of Obtaining the $^3\text{He}(n, p)\text{T}$ Cross Section and Calculation of Wall Effects

In an "ideal" ^3He counter (one with no wall effects) and for mono-energetic neutrons with energies below the threshold of the $^3\text{He}(n, d)\text{D}$ reaction (4.36 MeV in the laboratory system), the pulse-height spectrum will be composed of two parts: A peak centered at about $(Q + E_n)$, where E_n is the neutron energy, and a pulse-height distribution from zero to

(a)

(b)

Figure 8. Delayed coincidence measurement of time jitter.

Figure 9. Pulse-height spectrum for thermal neutrons.

($3E_n/4$) due to the ^3He recoils from elastic scattering. If self-shielding is negligible, which is the case for the present work, then the total number of counts $C_T(E_n)$ in the pulse-height spectrum is determined by the product

$$C_T(E_n) = \phi(E_n)\sigma_T(E_n) , \quad (13)$$

where $\phi(E_n)$ is the number of neutrons that enter the sensitive volume and $\sigma_T(E_n)$ is the total neutron cross section at E_n . The number of counts in the peak is similarly determined:

$$C_{np}(E_n) = \phi(E_n)\sigma_{np}(E_n) , \quad (14)$$

where σ_{np} is the $^3\text{He}(n, p)\text{T}$ cross section. Thus $\sigma_{np}(E_n)$ is given by the ratio of the counts in the peak to the total counts times the total cross section (the latter is known to $\sim 3\%$ in the present energy range):

$$\sigma_{np} = \frac{C_{np}}{C_T} \sigma_T .$$

There are, of course, important differences between the actual situation and the ideal case described above. One major difficulty in previous attempts to use this method below $E_n = 1$ MeV has been that the recoil spectrum was superimposed on a large background contribution from epithermal neutrons. In the present experimental arrangement at the 220-meter flight path facility, this source of background is negligible, as was verified by placing two 1-in. -diam ^3He counters just outside the region of the neutron flux. The counting rate outside the flux was less than 3% of the counting rate inside the flux.

In the actual counter all the pulses from the (n, p) reaction are not concentrated in a peak, since some of the charged particles from the reaction can lose energy in the wall of the counter as well as in the sensitive

volume. These events contribute to a tail ("wall effect") in the (n, p) pulse-height distribution, and a portion of this tail overlaps the ^3He recoil spectrum. In order to obtain the total number of (n, p) counts, it is necessary to extrapolate the tail to zero pulse height through the ^3He recoil spectrum. To facilitate this extrapolation, a simple Monte Carlo code was written which calculates an (n, p) pulse-height spectrum for a given range of incident neutron energies. To check the code, a calculation was performed for slow neutrons so that the entire wall effect may be seen in the absence of ^3He recoils. The results of this calculation are shown in Fig. 9, and the fit to the experimental data is seen to be very good. This code was then used to obtain the number of counts in the tail under the ^3He recoil spectrum at higher neutron energies. A typical calculation of the pulse-height spectrum for fast neutrons is compared to data in Fig. 10.

Electronic noise prevents very small pulses in the spectrum from being unambiguously observed. Consequently, it is also necessary to extrapolate the ^3He recoil spectrum to zero pulse height. For this purpose the spectrum was calculated using the results of a phase-shift analysis done by Meyerhof and McElearney.⁽³⁷⁾ Since the ^3He -recoil pulses lost in the noise constitute a small part of the total counts, the uncertainty in this calculation has a small effect on the determination of the (n, p) cross section. Figure 10 shows the fit to the data achieved with the phase shifts given in Ref. 37.

2.5.3 Results of the Measurement

Results of the pulse-height analysis of data from the ^3He counters are given in Table 4 and illustrated in Fig. 11. For neutron energies below 300 keV a large portion of the ^3He recoil spectrum cannot be observed due to electronic noise, and such data are not included. The upper limit of our data (1.15 MeV) is determined by the effect of the gamma flash from the neutron source which influences the shape of the pulse-height

Figure 10. Pulse-height spectrum for fast neutrons.

Figure 11. $^3\text{He}(n,p)\text{T}$ cross section.

distribution at higher neutron energies. Above 500 keV the range of the neutron energy for each cross-section value was selected such that the neutron time-of-flight interval equalled the time jitter of the counter, which is the limiting factor in this region. The quoted uncertainties were obtained by adding in quadrature the statistical uncertainties, the uncertainties in the extrapolations (assuming 20% accuracy in the calculations), and the uncertainties in the total cross section. Also shown in Fig. 11 are previous results for the $^3\text{He}(n, p)\text{T}$ cross section. Except perhaps at the lowest energy, where our measurement becomes more uncertain due to the preponderance of electronic noise, the present data agree quite well with most of the previous results and contribute a significant improvement in accuracy.

Table 4
 $^3\text{He}(n, p)\text{T}$ CROSS SECTION

Incident Neutron Energy Range (MeV)	Average Cross Section (barn)
0.300 to 0.400	0.896 ± 0.068
0.400 to 0.500	0.908 ± 0.051
0.503 to 0.642	0.882 ± 0.044
0.642 to 0.840	0.899 ± 0.045
0.840 to 1.16	0.929 ± 0.046

2.6 GENERAL EXPERIMENTAL IMPROVEMENTS

A considerable amount of effort has been devoted this past year to the completion of an operational facility tailored to the measurement of high-energy capture cross sections. The following subsections describe the new pulsed neutron source, 220-meter facility, data acquisition system, and the linear electron accelerator; all of which are components of the facility for high-energy measurements.*

* Since the 20-meter flight path facility has been previously described in detail, only a description of the new 220-meter facility is given.

2.6.1 Pulsed Neutron Source

Neutrons are generated by the (γ, n) reaction for time-of-flight experiments in the form of intense, short-duration pulses by bombarding high-Z targets with bursts of 30- to 60-MeV electrons from the linear accelerator. The electron burst width can be varied from 10 nsec to 5 μ sec, which results in a neutron pulse of the same width, provided the target is small and does not contain moderating materials. The neutron yield can be as large as $\sim 10^{11}$ neutrons/burst and has an energy spectrum very similar to that of a fission spectrum, which peaks at ~ 1 MeV.

The target will also emit a prompt, intense burst of bremsstrahlung, which can produce undesirable effects in the neutron detection systems used in time-of-flight experiments. Consequently, the targets are designed to enhance the neutron-to-bremsstrahlung ratio and to modify the neutron energy spectrum to suit the needs of a particular experiment. For measurements of fast neutron capture, we have designed a target configuration that consists of a small, water-cooled, fansteel target surrounded by a larger cylindrical depleted uranium shield, shown in Fig. 12. The shield serves the dual purpose of absorbing bremsstrahlung and degrading the primary neutron energy spectrum by the inelastic scattering process.

Calculations with the one-dimensional transport code 1DF indicate that neutron multiplication by fast neutron fission approximately compensates for neutron absorption in the depleted uranium shield. Since gamma-ray attenuation is greater with a uranium shield than with a lead shield of the same dimensions, the ratio of neutron/bremsstrahlung yield is greater for the depleted uranium target configuration than that obtained with an earlier lead target configuration. A 1-in. -thick slab of polyethylene is placed adjacent to the uranium cylinder and normal to the 220-meter flight path described below. The polyethylene moderator provides neutrons extending in energy down to the eV region. It was expected that we would

Figure 12. LINAC pulsed neutron source.

observe a time-independent background from delayed neutron emission from the uranium shield. This component of background was investigated by measuring the ambient counting rate observed at a time interval preceding the LINAC burst with various neutron detectors and with the liquid scintillators (containing capture samples) at 20 meters and at 220 meters. No significant increase in background was observed for the uranium relative to that observed for earlier lead shield.

Since the uranium cylinder and the polyethylene slab are several transport mean free paths in extent, the effects of these materials on the neutron pulse were calculated. Timing uncertainties introduced by slowing down effects in the polyethylene slab have been found to limit the fractional energy resolution to $\sim 10^{-4}$. For the 6-in. right circular cylinder of uranium, slowing-down effects may be neglected since a neutron can only lose $\leq 1.7\%$ of its kinetic energy per elastic collision. From simple diffusion theory, and by neglecting absorption, fission and inelastic scattering, we find that the uranium cylinder limits the fractional energy resolution to $\sim 10^{-3}$ for neutron energies of $\gtrsim 1$ MeV. For lower energies, the transmission of the polyethylene slab is low, and transmitted neutrons are degraded to energies where the time spread introduced by the uranium is insignificant.

2.6.2 220-Meter Flight Path Facility

The evacuated neutron flight path for this facility consists of a 12-in. -diam, 385-ft-long section and a 24-in. -diam, 321-ft-long section. A vacuum of < 0.1 torr is maintained over its entire length, and the entrance and exit windows consist of 12-mil Mylar. The length of the flight path has been precisely measured by a team of professional surveyors who employed a geodimeter. The calibrated distances along the flight path are permanently marked by brass plugs set in concrete slabs. Various collimators and antiscatter baffles contained within both sections of the flight path define a 4-in. -diam beam that passes through a 5-in. -diam

drift tube located in the center of a 600-liter liquid scintillator. This detector is similar in construction to the 4000-liter scintillator used at the 20-meter flight-path facility, which has been described in previous reports under this contract. An aluminum container (7-in. -diam) filled with ^{10}B powder (0.452 g/cm^2) is placed in front of the first collimator to remove neutrons with energies below 10 eV. This allows operation of the LINAC at a 180 pulse/sec repetition rate with no significant overlap of neutrons from previous pulses.

2.6.3 Computer for Data Acquisition

A CDC-1700 computer serves as the central element in our "on-line" data acquisition system. Some of the features of this computer are:

1. 16 k-word magnetic core memory size
2. 18 bits/word, which includes one parity bit and one memory protect bit.
3. $1.1\text{-}\mu\text{sec}$ memory cycle time
4. 14 interrupt data channels, with priority under program control.
5. 1.5×10^6 -word storage in a removable magnetic disk-pack.

The capabilities for high-speed data acquisition, coupled with the large storage area of the magnetic disk, allow simultaneous storage of several time-of-flight spectra.

For the average capture cross-section measurements described in Section 2.3, the data acquisition system was used to store either capture data or neutron flux data obtained simultaneously at the 220-meter flight path facility with two separate detection systems: (1) the 600-liter liquid scintillator for capture gamma rays, and (2) a bank of ^3He gas proportional counters for the neutrons. The time-of-flight information from either detection system goes to a time encoder which generates binary

numbers identifying the flight time of the observed events. These binary numbers are stored in the magnetic core memory of the computer via an interrupt data channel. Each detection system uses a unique interrupt line, and the data are stored in separate arrays corresponding to each interrupt line. During the course of the experiment, the time information in these arrays may be converted to energy, grouped into equal lethargy intervals ($\Delta \ln E$), and displayed on an oscilloscope. At the end of a measurement, the information is transferred to the magnetic disk and stored until it is needed for further data processing. For the measurements of neutron flux with the proton-recoil gas proportional counter (Section 2.2), a two-parameter mode of data acquisition was used in which the neutron flight time and pulse height for each proton-recoil event were stored as a pair of binary numbers.

For all the measurements discussed in the preceding sections, corrections for electronic dead time were made "automatically" by the various computer codes employed for data processing. In most cases, the data acquisition rates were so low that these corrections were negligible ($< 1\%$). Exceptions to this were measurements that employed the two-parameter mode of data acquisition. For these cases the analog-to-digital converter introduces a large, variable dead time. Consequently, the data accumulation rate was electronically limited to a maximum of one event per LINAC pulse to simplify the correction for missed events. Then the average data arrival rate was adjusted so that the magnitude of the correction was $\leq 20\%$ over the neutron energy range of interest.

2.6.4 Linear Accelerator

During the past year many improvements were made in the overall performance of the LINAC. The two new high-power L-band, constant-gradient waveguides have given excellent performance during this year. These waveguides replaced two constant-impedance doorknob-coupled waveguides that were able to accept about 10-MW rf input power. The

construction of the 20-MW modulators has been completed, and three of the four waveguide sections now use the higher power tubes. Further waveguide experiments and installation are scheduled for 1969. The high-current injector system was tested to 25 amperes output current, and 15 amperes has been accelerated through one section.

The four sections of LINAC are operating together on a routine basis in the high-current, short-pulse mode, with only small losses of current between the two LINACs. Over-all performance of 58-MeV electron energy and 7 amperes peak beam current have been attained at short beam pulse widths (0.020-0.050 μ sec). It is expected that increases in peak current and peak energy will be attained during the next year as our improvement program continues. For the four sections, we expect to achieve currents on target in the neighborhood of 10 amperes.

3. FUTURE WORK

In addition to completion of the analysis of resonant capture in Gd and Zr, work will be initiated on the determination of the Rh capture cross section from 0.01 eV to about 1 MeV. Particular emphasis will be placed upon accurate determination of the radiation widths so that an accurate resonance capture integral for rhodium can be obtained. These measurements will satisfy the request Nos. 161 and 162 in WASH-1078. Rhodium is in the mass region where a peak in the p-wave neutron strength function occurs. Previous measurements made at this laboratory and elsewhere⁽³⁸⁾ for nuclei in this mass region indicate that there is a difference in the intensity of high energy gamma-ray transitions resulting from p-wave neutron capture and that due to s-wave neutron capture. This phenomenon is a result of the selection rules for gamma-ray transitions. It is expected that this difference will also be observed for rhodium and will allow parity determinations to be made for a large number of resonances. The two-parameter data-taking procedures will allow average gamma-ray pulse-height distributions to be obtained simultaneously for many resonances.

The information obtained from this analysis on the widths and spacings of the Rh resonances, combined with a measurement of the high-energy capture cross section where the contribution from p-wave resonances will be large, should allow a substantial improvement in the determination of the p-wave neutron strength function. It should also be possible to determine whether the radiation width is dependent on the parity of the capturing state. Since ¹⁰³Rh has a ground-state spin of 1/2, it will be possible to determine the spins of many capturing states through shape and area analysis for low-energy resonances and with the self-indication method of spin assignments at higher energies if the resonances are not

too weak. If enough resonances can be analyzed in this manner, it may be possible to examine quantitatively the dependence of the radiation width and neutron strength function on spin.

Previous measurements^(6, 39) have indicated that there are anomalies in the value of p-wave radiation widths for nuclei in the mass region $A \approx 90$. However, the large uncertainties in many of the measurements do not allow a detailed determination of the dependence of the radiation width upon atomic number or neutron number. Measurements of the radiation width of selected p-wave resonances for several nuclei in this mass region are planned in order to look for any mass or shell effects that might be present.

Measurement of the average capture cross section of Rh from 10 keV to 1 MeV will afford another set of data for a monoisotopic element that can be compared to our revised model for fast neutron capture (Section 2.3.2). Comparison of the high-energy data with calculations based on accurate values of the average radiation width and s-wave level spacing for Rh should be of great value in judging the ability of the statistical-model treatment to reproduce the observed normalization of the average capture cross sections. Also, accurate s- and p-wave strength-function data can be compared to values predicted by the optical-model potential used to characterize the neutron channels in the capture calculation. As indicated in Section 2.3.2, it is also desirable to make a limited number of statistical-model calculations for selected data sets other than those currently being measured at this laboratory.

REFERENCES

1. E. Haddad, F. H. Fröhner, W. M. Lopez, and S. J. Friesenhahn, "Neutron Capture Cross Section Measurements and Resonance Parameters," Vol. II, Proc. of the National Topical Meeting of the American Nuclear Society, San Diego, Feb. 7-9, 1966, A. J. Goodjohn and G. C. Pomraning, Eds., MIT Press, pp. 125-150 (1966).
2. F. H. Fröhner, E. Haddad, W. M. Lopez, and S. J. Friesenhahn, "Accuracy of Resonance Parameters from Combined Area and Self-Indication Measurements," Book 1, Conf. on Neutron Cross Section Technology, Washington, D. C., March 22-24, 1966, P. B. Hemmig, Ed., TID-4500, CONF-660303.
3. S. J. Friesenhahn, E. Haddad, F. H. Fröhner, and W. M. Lopez, "The Neutron Capture Cross Section of the Tungsten Isotopes from 0.01 to 10 eV," Nucl. Sci. and Eng. 26, 487 (1966).
4. F. H. Fröhner and E. Haddad, "Least-Squares Analysis of Neutron Capture, Self-Indication and Transmission Data," Bull. Am. Phys. Soc., 11, 101 (1966).
5. W. M. Lopez, E. Haddad, S. J. Friesenhahn, and F. Fröhner, "Niobium Resonance Parameters from (n, γ) Measurements to 1500 eV," Bull. Am. Phys. Soc., 11, 742 (1966).
6. W. M. Lopez, E. Haddad, S. J. Friesenhahn, and F. Fröhner, "Niobium Resonance Parameters," Nucl. Phys., A93, 349 (1966).
7. F. H. Fröhner, "Calculation of Doppler-Broadened Cross Sections Directly from Doppler- (and Resolution-) Broadened Cross Sections Corresponding to a Lower Temperature," Nucl. Instr. Methods, 49, 89 (1967).
8. S. J. Friesenhahn, F. H. Fröhner, W. M. Lopez, D. A. Gibbs, and E. Haddad, "Cross Sections of the Rhenium Isotopes from 0.01 eV to 30 keV," Bull. Am. Phys. Soc. 12, 596 (1967).

9. S. J. Friesenhahn, D. A. Gibbs, E. Haddad, F. H. Fröhner, and W. M. Lopez, "Neutron Capture Cross Sections and Resonance Parameters of Rhenium from 0.01 eV to 30 keV," J. Nucl. Energy **22**, 191 (1968).
10. F. H. Fröhner, "Monte Carlo Reinterpretation of Gold Sphere Transmission Data at 24 keV Neutron Energy," J. Nucl. Energy (in press).
11. F. H. Fröhner, "Recursion Formulae for Semianalytical Multiple Scattering Calculations in Slab Geometry," Nucl. Inst. and Methods **62**, 113, 1968.
12. S. J. Friesenhahn, "Radiation Width of the 2.85-keV Level in ^{23}Na ," Neutron Cross Sections and Technology, March 4-7, 1968, Washington, D. C., NBS Special Publication 299, Vol. II, p. 695.
13. F. H. Fröhner, J. L. Russell, Jr., and J. C. Young, "Temperature Dependence of the Average Transmission of Tungsten Between 2 keV and 2 MeV Neutron Energy," Cross Sections and Technology, March 4-7, 1968, Washington, D. C., NBS Special Publication 299, Vol. I, p. 61.
14. W. M. Lopez, et al., "Cross Section Measurements of Zirconium," Neutron Cross Sections and Technology, March 4-7, 1968, Washington, D. C., NBS Special Publication 299, Vol. II, p. 857.
15. W. M. Lopez, "A Computer System for Neutron Cross-Section Measurements," Proc. of the Conference on Computer Systems in Experimental Nuclear Physics, Skytop, Pennsylvania, March 3-6, 1969.
16. M. P. Fricke and W. M. Lopez, "Radiation Width for Fast Neutron Capture," (Submitted for publication in Phys. Rev. Letters).
17. D. G. Costello, et al., " $^3\text{He}(n,p)\text{T}$ Cross Section," (Contributed to the Spring APS Meeting, Washington, D. C., 1969)(to be published).
18. W. M. Lopez, et al., "Neutron Capture Cross Sections in the Energy Range 1-700 keV," (Contributed to the Spring APS Meeting, Washington, D. C., 1969)(to be published).
19. M. P. Fricke, et al., "Analysis of Average Neutron Capture Cross Sections," (Contributed to the Spring APS Meeting, Washington, D. C., 1969)(to be published).

20. W. M. Lopez, et al., "Radiative Capture of 1-700 keV Neutrons by Gd, W, Re, and Au, " (to be published in the Phys. Rev.).
21. E. R. Rae and E. M. Bowey, "Gamma-Ray Yields from the Resonant Capture of Slow Neutrons, " J. Nucl. Energy 4, 179 (1957).
22. J. S. Schwinger, "A Variational Principle for Scattering Problems, " Phys. Rev. 72, 742 (1947).
23. H. Bethe, "Theory of the Effective Range in Nuclear Scattering, " Phys. Rev. 76, 38 (1949).
24. P. H. White, "The Hydrogen Gas Recoil Counter for Neutron Flux Measurements Below 100 keV, " Symposium on the Absolute Determination of Neutron Flux in the Energy Range 1-100 keV, EANDC - 33 (U), p. 25 (1963).
25. E. Haddad, et al., "A High Efficiency Detector for Neutron Capture Cross Section Measurements, " Nucl. Instr. and Methods, 31, 125 (1964).
26. U. Fano, et al., "Penetration and Diffusion of X-rays, " Handbuch der Physik, Vol. 38/2, p. 660, Springer-Verlag, Berlin (1959).
27. F. H. Fröhner, "TACASI - A FORTRAN-IV Code for Least Squares Area Analysis of Neutron Resonance Data, " General Atomic Report GA-6906, August 1966 (unpublished).
28. D. Goldberg, et al., "Neutron Cross Sections, Vol. IIA - Z equals 21 to 40, Vol. IIB - Z equals 41 to 60, Vol. IIC - Z equals 61 to 87, " Brookhaven National Laboratory Report BNL 325, 2nd ed., Supplement 2 (1966).
29. F. H. Fröhner, "SESH - A FORTRAN-IV Code for Calculating the Self-Shielding and Multiple Scattering Effects for Neutron Cross Section Data Interpretation in the Unresolved Resonance Region, " Gulf General Atomic Report GA-8380, January 1968 (unpublished).
30. K. K. Seth, et al., "s-, p-, and d-wave Neutron Strength Functions, " Phys. Rev. Letters 13, 70 (1964).
31. A. Gilbert and A. G. W. Cameron, "A Composite Nuclear-Level Density Formula with Shell Corrections, " Can. J. Phys. 43, 1446 (1965).

32. S. A. Cox, "Fast Neutron Activation Cross Section of ^{197}Au , " Phys. Rev. 122, 1280 (1961).
33. W. P. Pönitz, D. Kompe, and H. O. Menlove, EANDC(E) 84 "S" (1967).
34. J. H. Gibbons, et al., "Neutron Radiative Capture Measurements, " Phys. Rev. 122, 182 (1962).
35. R. C. Block, et al., Neutron Time-of-Flight Methods (Saclay Conference), p. 203 (1961); and ORNL-3085, p. 48 (1961).
36. O. K. Harling, "Detector Time Jitter in ^3He and BF_3 Proportional Counters, " Nucl. Instr. and Methods 34, 141 (1965).
37. W. E. Meyerhof and J. N. McElearney, "Phase Shift Analysis of $^3\text{He}(p, p)$, $^3\text{He}(p, n)$ and $^3\text{He}(n, n)$ Reactions, " Nucl. Phys. 74, 533 (1965).
38. H. E. Jackson, "Properties of Capture Gamma-Ray Spectra of s-Wave and p-Wave Resonances in Zr, Nb and Mo, " Phys. Rev. 131, 2153 (1963).
39. H. E. Jackson, "Total Radiation Widths for s-Wave and p-Wave Neutron Capture in ^{93}Nb , " Phys. Rev. Letters 11, 378 (1963).
40. V. A. Konks, et al., "Cross Sections for Radiative Capture of Neutrons with Energies up to 50 keV by ^{139}La , ^{181}Ta , and ^{197}Au , " Soviet Phys. - JETP 19, 59 (1964).
41. A. A. Grench, et al., Private Communication to D. Goldberg (1966), (see p. 79-D-18 in Ref. 28).
42. S. A. Cox, "Fast neutron Activation Cross Section of ^{197}Au , " Phys. Rev. 122, 1280 (1961); and see Ref. 28.
43. J. Barry, "The Radiative Capture Cross Section of ^{197}Au for Neutrons in the Energy Range 0.12-1.8 MeV, " J. Nucl. Energy 18, 491 (1964).
44. K. K. Harris, et al., "The $^{197}\text{Au}(n, \gamma)^{198}\text{Au}$ Cross Section from 13 keV to 683 keV, " Nucl. Phys. 69, 37 (1965).
45. J. A. Miskel, et al., "Neutron Activation Cross Sections, " Phys. Rev. 128, 2717 (1962); and see Ref. 28.

46. A. E. Johnsrud, et al., "Energy Dependence of Fast Neutron Activation Cross Sections," Phys. Rev. 116, 927 (1959); and see Ref. 28.
47. M. C. Moxon and E. R. Rae, "A Gamma-Ray Detector for Neutron Capture Cross Section Measurements," Nucl. Instr. and Methods 24, 445 (1963); and see Ref. 28.
48. I. Bergqvist, "Fast Neutron Radiative Capture Cross Sections in Ag, Ta, W, Au, Hg, and U," Arkiv Fysik 23, 425 (1963); and see Ref. 28.
49. E. G. Bilpuch, et al., "Neutron Capture Cross Sections in the keV Region, Part I - Methods of Measurement and Analysis," Ann. Phys. 10, 455 (1960); and see Ref. 28.
50. B. C. Diven, et al., "Radiative Capture Cross Sections for Fast Neutrons," Phys. Rev. 120, 556 (1960).
51. J. Als-Nielsen, Newsletter No. 6, Neutron Data Compilation Centre, European Nuclear Energy Agency (1967).
52. R. Batchelor, R. Ames, and T. H. R. Skyrme, "Helium-3 Filled Proportional Counter for Neutron Spectroscopy," Rev. Sci. Instr. 26, 1037 (1955).
53. J. H. Gibbons and R. L. Macklin, "Total Neutron Yields from Light Elements under Proton and Alpha Bombardment," Phys. Rev. 114, 571 (1959).
54. J. E. Perry, E. Haddad, R. L. Henkel, G. A. Jarris and R. J. Smith, "The $T(p, n)^3\text{He}$ Reaction and Its Inverse," reported in J. D. Seagrave, Proc. of Conference on Nuclear Forces and the Few Nucleon Problem, London 1959, Vol. II, p. 583, Pergamon Press, Oxford (1960).
55. A. R. Sayres, K. W. Jones and C. S. Wu, "Interaction of Neutrons with ^3He ," Phys. Rev. 122, 1853 (1961).
56. J. D. Seagrave, L. Cranberg and S. E. Simmons, "Elastic Scattering of Fast Neutrons by Tritium and ^3He ," Phys. Rev. 119, 1981 (1960).

APPENDIX

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A COMPUTER SYSTEM FOR
NEUTRON CROSS-SECTION MEASUREMENTS

by

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I. INTRODUCTION

This paper describes a computer-based data acquisition and analysis system that was developed with the idea in mind that it should be kept simple enough to be useful in a wide variety of the diverse measurements possible with an electron LINAC facility. Some initial considerations were as follows:

1. Only one experiment would control the system at any one time.
2. Programming would be done in FORTRAN wherever possible.
3. Instrumental logic decisions (such as coincidence requirements, data tagging, or data routing) would be done external to the system interface wherever possible.

Under these constraints, the system has evolved during the past 18 months into a data acquisition system that is very versatile and easy to use, and consequently it has been readily accepted by experimentalists working in various areas of neutron physics. After a brief description of the system hardware and software, a few applications to neutron cross-section measurements are presented.

II. THE DATA ACQUISITION SYSTEM

The central processor of the system consists of a CDC-1700 computer with a 16 K-word memory. The main features of this computer are:

1. 16 bits/word plus one parity bit and one memory protect bit.
2. 16 unique interrupt levels with priority under program control.
3. 1.1 μ sec memory cycle time.

A schematic drawing of the data flow between the central processor and the input/output peripherals is shown in Fig. 1. Data transfers are in parallel at 16 bits per transfer. The units interfaced to the system for on-line data acquisition purposes are shown in the upper half of Fig. 1. These consist of one time encoder with 5-nsec resolution over a maximum time span of about 5 msec, two data channels that accept plug-in function-determining modules, and one oscilloscope display channel. The plug-in

Figure 1. Schematic drawing of the data flow between the computer central processor and external input/output devices.

modules usually used are 4096-channel pulse-height digitizers, but others are available such as multiscalers or additional time encoders. Since most of the plug-in modules do not require 16 bits of information per digitized event, provision is made for entering additional bits of "tagging" information that originate in the external instrumental logic.

The transfer of information between the central processor and the external units is relatively simple and straightforward. An address loaded by the program into a register selects the external device via the Address and Control Trunk as shown in Fig. 1. The program then executes an input (or output) instruction which strobes the external device with a read (or write) pulse. The device then sends back a reply pulse which initiates the data transfer via the Bi-directional Data Trunk and then terminates this operation. The execution of the input-output instruction and subsequent data transfer takes about 4-6 μ sec. For on-line data input transfers the above procedure is initiated by an interrupt command from the external device (or devices) that selects the appropriate subroutine for the input operation.

The on-line operation of the system is presently disc oriented. A small section of a disc (160 K-words) is used to store user relocatable object programs. The remainder of the disc (1.34×10^6 words) is available to the user for on-line data storage. Experiments that require one word or more of storage per event normally use core memory for buffering between the input devices and the disc. When a disc becomes filled with data, it can be dumped onto a magnetic tape in about five minutes. A 2400-ft reel of magnetic tape can hold the contents of three discs. It is not unusual for an experiment to fill two or three magnetic tapes in a 24-hour period.

An on-line data-acquisition program can be written in ASA FORTRAN-IV by using a special FORTRAN statement that allows insertion of on-line machine language coding. This feature allows one to enable or inhibit the interrupt system and to perform on-line input/output operations with the data input channels or the oscilloscope display channel, all within the context of a FORTRAN program. Input subroutines written in this way typically require about 100 μ sec to process an event. The actual data transfer from the external device normally occurs about 20 to 30 μ sec after the interrupt command initiates the input subroutine. These processing times are fast enough to satisfy most experimental requirements.

III. SOME EXPERIMENTAL APPLICATIONS

Neutron Total Cross Sections - Total cross-section measurements are, in principle, relatively straightforward. However, measurements that strive to attain high accuracy and high energy resolution with neutron time-of-flight techniques in the MeV energy region can place some stringent demands on the data acquisition system. For this type of measurement, one normally needs a very large number of time channels and the ability to handle relatively high data rates. To meet these needs for a recent total cross-section measurement of natural iron, ⁽¹⁾ the data acquisition system was programmed to behave as an 8192-channel time analyzer with 5 nsec/channel resolution as determined by the time encoder* shown in Fig. 1. A very fast input subroutine was coded in symbolic language which, when coupled to the dual-buffer derandomizer contained in the time encoder, resulted in a net system deadtime of 8 μ sec/event over a 24- μ sec time span. Since the experimenters used a 200-meter flight path and a 7-nsec LINAC burst width, the over-all result was a high resolution (0.035 nsec/m) total cross-section measurement which covered an energy span of 0.5 MeV to 10 MeV. The measurement was made with a data rate of about 0.4 events per LINAC pulse while maintaining deadtime losses to about 24% or less. A portion of the data obtained in this experiment is shown in Fig. 2.

Neutron Flux Measurements - A program has recently been initiated at Gulf General Atomic for applying hydrogenous gas proportional counters to the measurement of neutron flux with time-of-flight techniques in the energy region 1 keV to about 1 MeV. The goal of this program is to achieve an accuracy of about 3% for absolute neutron flux measurements. This capability is important to measurements of reaction cross sections such as (n, γ) , (n, α) , and (n, p) .

For a recent experiment, ⁽²⁾ the data acquisition system was programmed to accept two words of information per event, one from the time encoder (t) and one from a 4096-channel pulse-height digitizer (h). The digital information t and h corresponded to the time-of-flight and pulse-height of a neutron interaction in a methane gas proportional counter that was located 200 meters from the LINAC pulsed neutron source. The word pairs (t, h) were stored in "ping-pong" tables within the magnetic core memory. A live display of pulse-height and time-of-flight spectra were updated from the data tables prior to their transfer into magnetic disc memory. At the conclusion of the measurement, the data on disc were sorted in such a way as to extract a proton-recoil pulse-height spectrum

* Manufactured by Eldorado Electronics, Concord, California.

Figure 2. Preliminary neutron total cross section of natural iron obtained by Carlson and Cerbone⁽¹⁾ with a 220-meter flight path, an electron LINAC pulsed neutron source, and a fast computerized data-acquisition system. The complete data span an energy region of 0.5 MeV to about 10 MeV.

$$\int_{t_1}^{t_2} \frac{d^2 N}{dt dh} (t, h) dt$$

resulting from neutrons with energies between $E_1(t_1)$ and $E_2(t_2)$. Four typical recoil pulse-height spectra obtained in this manner are shown in Fig. 3. From the dimensions and gas density of the counter and the well known n+p scattering cross section, ⁽³⁾ it is possible to accurately relate portions of the pulse-height spectra shown in Fig. 3 to the incident neutron flux. ⁽⁴⁾

The $^3\text{He}(n, p)\text{T}$ Cross Section - The two-parameter data acquisition program described above was also applied to time-of-flight and pulse-height measurements of neutron interactions in a ^3He gas proportional counter that was located at the end of a 225-meter neutron flight path. Three typical pulse-height spectra obtained from the data (after sorting in the manner described above) are shown in Fig. 4. In this case one can relate portions of these pulse-height spectra to the elastic scattering and (n, p) cross sections. Since the total number of pulses is related to the total neutron cross section for ^3He , which has been measured with a precision of about 3%, ⁽⁵⁾ one can determine the partial cross sections to an accuracy of about 5-10% for neutron energies of 0.5 to 1 MeV.

Gamma-Ray Production Cross Sections - A more sophisticated version of the two-parameter data acquisition program described above has been coded for use with a Ge(Li)-NaI three-crystal pair spectrometer. This detector configuration may be operated simultaneously in the following three modes:

1. Singly-operated Ge(Li) detector
2. Compton suppression spectrometer
3. Three-crystal pair spectrometer.

By means of coincidence criteria, events from the detector can be tagged as belonging to one or more of these modes of operation. The tags can be stored along with pulse-height information by using the extra bits available in the 16-bit word of the input data channel.

A digital gain and zero-stabilization subroutine was also incorporated into this program to preserve the inherent gamma-ray energy resolution of the Ge(Li) detector during long experimental time periods. This is accomplished by using two highly stable reference pulses that are routed through the Ge(Li) detector amplifier system and subsequently processed

Figure 3. Proton-recoil pulse-height spectra obtained with a methane gas proportional counter at the end of a 227-meter flight path, an electron LINAC pulsed neutron source, and a two-parameter data acquisition system. (2) The data are compared to proton-recoil spectra (solid curves) calculated with a Monte Carlo computer code written by Parker, et al. (8)

Figure 4. Three pulse-height spectra vs neutron time of flight obtained with ^3He gas proportional counters, a 220-meter flight path facility, and a two-parameter mode of data acquisition. (2)

by the data acquisition system. These reference pulses are uniquely tagged so that the stabilization routine can separate them from the real photon events.

Measurements of capture gamma-ray production in natural tungsten have recently been obtained by V. J. Orphan, *et al.*,⁽⁶⁾ with this detector system located at the end of a 16-meter neutron flight path. Some of their preliminary pair spectrometer data are shown in Fig. 5. From this type of data, gamma-ray intensities from neutron capture in natural tungsten have been obtained for neutron energy groups in the range 0.02 eV to 100 keV.

This data acquisition program has also been used with a single 30-cm³ Ge(Li) detector (located at a 50-meter neutron flight path) to measure gamma-ray production in oxygen and nitrogen over a neutron energy range from 0.5 MeV to about 16 MeV. In this energy region, special electronic instrumentation is employed to suppress gain shifts induced by the LINAC bremsstrahlung rays scattered into the Ge(Li) detector. A portion of preliminary gamma-ray spectrum data from nonelastic neutron interactions in oxygen obtained by Orphan, *et al.*,⁽⁷⁾ is shown in Fig. 6. In spite of the additional instrumental complexity required for this measurement, the inherent energy resolution of the Ge(Li) detector is not greatly degraded, as is evidenced by an 11-keV width (FWHM) of the 6.128-MeV gamma-ray observed from the ¹⁶O(n, n' γ) reaction (see Fig. 6).

IV. CONCLUSIONS

The few examples of experimental data-acquisition applications given here were selected to illustrate the impact on cross-section measurements made by a relatively unsophisticated on-line computer system. We see that the marriage of this system with an electron LINAC has improved the quality of experiments and extended their scope into areas usually associated with Van de Graaff accelerators. In a situation that involves a rapid turnover of diverse experiments and heavy usage of the experimental facility, it has been our experience that it is indeed important to de-emphasize the level of complexity of both the hardware and software.

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Figure 5. Preliminary capture gamma-ray spectra from tungsten obtained by Orphan, *et al.*, (6) with a Ge(Li)-NaI three-crystal pair spectrometer, a 16-meter flight-path facility, and a two-parameter data acquisition system that uses digital gain stabilization.

Figure 6. Preliminary gamma-ray spectra from nonelastic neutron interactions in oxygen for the neutron energy range 9.57 MeV to 14.95 MeV. These data were obtained by Orphan, *et al.*,⁽⁷⁾ with a 30-cm³ Ge(Li) detector, a 50-meter flight path, and a two-parameter data acquisition system that uses digital gain stabilization.

C. G. Hoot, J. John, and J. R. Beyster for allowing the presentation of some of their preliminary data prior to publication in order to illustrate some applications of the data acquisition system.

REFERENCES

1. A. D. Carlson and R. J. Cerbone, private communication (1969); to be published.
2. W. M. Lopez, M. P. Fricke, D. G. Costello, and S. J. Friesenhahn, National Aeronautics and Space Administration Report NASA CR-72474, September 30, 1968 (unpublished).
3. J. L. Gammel, Fast Neutron Physics, Part II, Eds. J. B. Marion and J. L. Fowler, Interscience Publishers, Inc., New York, p. 2185 (1963).
4. A. T. G. Ferguson, Fast Neutron Physics, Part I, Eds. J. B. Marion and J. L. Fowler, Interscience Publishers, Inc., New York, p. 179 (1960).
5. Los Alamos Physics and Cryogenics Groups, Nucl. Phys. 12, 291 (1959).
6. V. J. Orphan and J. John, Gulf General Atomic Report GA-9121, December 31, 1968 (to be published).
7. V. J. Orphan, C. G. Hoot, A. D. Carlson, J. John, and J. R. Beyster, private communication (1969); to be published.
8. J. B. Parker, et al., Nucl. Instr. and Methods, 23, 61 (1963).