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THE USE OF PROTON-RECOIL SPECTROMETER
WITH PULSE SHAPE DISCRIMINATION FOR SPECTRUM
MEASUREMENTS IN WATER MODERATED REACTORS

J. E. Powell

IDAHO NUCLEAR CORPORATION
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ABSTRACT

Proton and gamma ray rate-of-rise distributions were measured in the core of the Advanced Reactivity Measurement Facility II (ARMF-II) to demonstrate the feasibility of using a proton-recoil neutron spectrometer with pulse shape discrimination for spectrum measurements in a thermal reactor.

A hydrogen filled proportional counter was used to obtain the data for proton energies over the range of 5 keV to 100 keV. A high residual gamma ray background present in the ARMF-II core prevented measurements below 5 keV. No gamma ray events were observed in the rate-of-rise distributions above 60 keV.

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I. INTRODUCTION

Proton-recoil detectors have been used for many years to measure fast neutron spectra. The various devices used to detect the recoiling protons such as organic scintillators, gas filled counters, nuclear emulsions, cloud chambers, and recoil telescopes cover a wide range of uses and it is up to the experimenter to choose the type detector that best suits his needs. Marion and Fowler¹ give a good discussion of some of the problems associated with each of these detectors.

The gas filled proportional counter is a very useful device for making in-pile fast neutron spectrum measurements. Its chief disadvantage is its high sensitivity to gamma rays. In the past approximately 100 keV was considered the lowest practical energy that could be measured in a reactor with these counters since gamma events could not be distinguished from recoil proton events. Recently, however, Bennett²⁻⁹ has shown that the useful energy range of the gas counter can be extended down to a few keV by using a pulse shape discrimination system to reject gamma events. These events are due primarily to conversion electrons from the counter wall. The electrons have relatively long track lengths in the gas relative to those of recoil protons and consequently have slower rising pulses⁴. By recording the total energy deposited in the counter in coincidence with the amount of charge collected in the first few nanoseconds (rate-of-rise) proton events below 100 keV can be distinguished from gamma events and the neutron spectrum can be measured down to a few keV.

The upper energy limit of a recoil gas counter depends upon the stopping power of the gas, the gas pressure and the size of the counter. If the recoil-protons are not completely stopped in the counter, edge effects appear in the proton spectrum that create systematic errors in final neutron spectrum. The upper energy limit of the practical hydrogen counter is about 150 keV. Measurements can be made above 150 keV by using relatively larger counters filled with a gas with high stopping power such as methane.

The work presented in this report is a study of the problems encountered in measuring neutron spectra with a proton-recoil counter in the core of a thermal reactor. The major problem is gamma ray background. Most reactor spectrum measurements at Argonne with proton-recoil counters have been made in the fast criticals ZPR-3, -6, and -9 which have highly self-shielding cores. In these reactors gamma to neutron ratios are small and background subtraction can be made with reasonable accuracy. However, in a thermal reactor minimum self-shielding of fission gammas coupled with capture gamma rays from thermal neutrons cause much higher gamma to neutron ratios and the background correction becomes much more difficult.

Other problems encountered in proton-recoil spectroscopy such as uncertainties in the energy loss per ion pair of the gas, edge effects, distortion due to count rate and reduction of proton-recoil data will receive less attention in this report since they have been discussed in detail previously²⁻⁹.

II. ELECTRONICS

To study the gamma-proton separation problems that arise when making spectrum measurements in a thermal reactor, rate-of-rise

distributions for proton events in a narrow energy window were taken with the pulse shape discrimination system shown in Figure 1.

Signals from the detector were sent to a low-noise preamplifier which was attached as closely as possible to the detector to reduce input capacity. After amplification the signal was split and sent to a fast channel which determined the rate-of-rise of the pulse and a slow channel which determined the pulse height or ionization of the event.

In the fast channel the pulse was differentiated, amplified, and stretched. A 3.5 microsecond delay line followed the stretcher so that the fast and slow channel pulses would be in coincidence. The linear amplifier following the delay line was used as a gain control for the multichannel analyzer.

In the slow channel the pulse from the preamp was sent to a delay line amplifier with a 3 microsecond clipping time, an inverting amplifier for additional gain, a single channel analyzer, and a coincidence gate generator. This pulse gated the multichannel analyzer for those ionization events falling in the window set by the single channel analyzer. When gated the analyzer stored the rate-of-rise of the event.

The individual electronic components will be discussed only briefly here since a report¹⁰ is in progress which describes them in detail. The preamp was a pole-zero corrected charge sensitive device with a 30 Mc bandwidth. It used two field effect transistors in parallel for the first stage which set the noise levels for the fast and slow channels. The high frequency noise measured at the output of the stretcher was approximately 200×10^{-18} coulombs rms referred to

Figure 1 - Proton-recoil pulse shape discrimination system

the input of the preamp. The slow channel noise measured at the output of the delay line amplifier was 75×10^{-18} coulombs rms referred to the preamp input.

The differentiator was a R-C type with a time constant that could be varied depending upon the energy of the event under consideration. The overall band width of the fast channel into the stretcher was 20 Mc.

For measurements less than 20 keV it was necessary for the delay line amplifier in the slow channel to withstand overloads of at least a thousand. Recovery within 50 microseconds with a minimum of base line shift was necessary to minimize spectrum distortion due to high count rates. This was accomplished by matching the delay line amplifier to the pole-zero corrected preamp¹⁰.

The coincidence gate following the single channel analyzer generated a square pulse 10 volts high with a width that was variable from 2 to 10 microseconds. Throughout the experiment the gate width was maintained at 3 microseconds with the fast channel signal coming 1.5 microseconds after the start of the gate pulse.

The time constant of the differentiator as well as the clipping time of the delay line amplifier was determined by observing the profiles of the pulses out of the preamp. Figure 2 shows a typical pulse from the hydrogen filled detector. Most of the pulses observed had rise times that varied from 50 to 150 nanoseconds. The parts of the curve labeled (1) and (2) indicate the regions of pulse where the fast and slow channels respectively extract the rate-of-rise and ionization information.

Figure 2 - Typical pulse from hydrogen filled proportional counter.

III. COUNTER CONSTRUCTION AND CALIBRATION

The counter used in this experiment was manufactured and filled commercially* to the specifications of the author. The cathode was constructed from a stainless steel cylinder 0.933 in. OD, 4.5 in. long with 0.030 in. thick walls. The anode was a 0.001 in. stainless steel wire held coaxially with the cathode by means of a ceramic feed-through insulator on one end and a ceramic terminating insulator on the other end. The terminating insulator was inside the counter and a filling tube extended from the end containing this insulator. Hypodermic-type tubing 0.001 in. in diameter protruding 0.75 in. into the counter volume from each end was used to define a sensitive volume in the counter 3 in. long. After construction the counter was baked at 500°C for several hours. After cooling the tube was loaded to a pressure of 10 cm Hg of nitrogen for calibration, 20 cm Hg of methane for quenching and 200 cm Hg of hydrogen to supply the protons. A photograph of the counter is shown in Figure 3.

Calibration was accomplished by placing the counter in a thermal neutron beam of 10^6 neutrons/cm²-sec from the MTR Crystal Spectrometer and observing the 615 keV proton from the $N^{14}(n,p)C^{14}$ reaction. Assuming 35 eV per ion for hydrogen gas 1.76×10^4 initial ion pairs are created in the counter from this reaction. Since this is substantially more than the 30 or so pairs created by a 1 keV proton it is necessary to increase the counter multiplication to bring 1 keV events into the range of the analyzer. By using the counter as a gain control optimum signal to noise ratios can be preserved in the electronic system.

*Reactor Controls Co.
P. O. Box 427,
Oak Ridge, Tennessee

Figure 3 - Hydrogen proportional counter tube.

A relation between the multiplication A and the high voltage on the anode V has been established by Diethorn¹¹ which is accurate for A values in the range of 10 to $10^{5.5}$. If $\frac{\ln A}{V}$ is plotted as a function of $\ln V$ a line is obtained that can be extrapolated with reasonable accuracy to high values of multiplication. Figure 4 is a plot for the hydrogen counter in Figure 3. No data were taken above 3100 volts because the characteristic line of the $N^{14}(n,p)C^{14}$ reaction was very broad and no accurate determination of the peak could be made.

The multiplication A was determined by measuring the height of the pulses from the $N^{14}(n,p)C^{14}$ reaction out of the linear amplifier and working backwards in gain to determine the input charge from the counter to the first stage of the preamp. This charge Q is related to the preamp output voltage by

$$E_{out} = Q/C_f$$

where C_f is the feedback capacity of the preamp ($= 0.46$ pf). Q is in turn related to A by $Q = 0.5 eIA$ where e is the charge on the electron and I is the initial number of ion pairs from the $N^{14}(n,p)C^{14}$ reaction. The factor 0.5 is approximate and depends on the clipping time constants of the amplifier.

The calibration peaks for high voltage settings of 2500 and 2900 volts are shown respectively in Figures 5 and 6. The resolution which is an indication of gas purity, wire uniformity and electric field definition was 12% FWHM. Above 2800 volts as the voltage was increased (see Figure 6) the peak gradually broadened indicating a space charge saturation effect.³

There was a slight fast neutron background in the spectrometer beam which caused some proton-recoil events to be superimposed upon the

Figure 4 - Diethorn plot for hydrogen proportional counter.

Figure 5 - Pulse height distribution for 615 keV protons for hydrogen counter at 2500 volts.

Figure 6 - Pulse height distribution for 615 keV protons for hydrogen counter at 2900 volts.

calibration peak. These events were subtracted out of the distribution by taking a pulse height distribution with the counter cadmium covered and subtracting this distribution from a bare count. After subtracting the fast neutron background a non-Gaussian portion of the core remained (Figure 5) which can be attributed to the finite length of the counter. Tests with counters¹² of the same diameter and pressure but with 5 to 20 times the length produced Gaussian responses.

IV. RESULTS

The experimental data were taken in the Advanced Reactivity Measurement Facility-II¹³ (ARMF-II) which is a swimming pool reactor with a fully enriched U²³⁵ core composed of 21 plate-type fuel elements. The center element was replaced by a 2 inch diameter aluminum dry tube and the proton-recoil counter was inserted in the tube near the core center line. A cross section of the core is shown in Figure 7, and Figure 8 shows the location of the proton-recoil counter and preamp in the core. One-half inch of lead was placed around the counter to lower the gamma background and lead shot was placed in the bottom of the dry tube for weight and additional shielding.

The reactor was run at a power of 5×10^{-3} watts for a period of 6 hours to accumulate the data. Maximum counting rates were 12,000 c/s. Rate-of-rise distributions taken for proton events at 5, 10, 20, 40, and 100 keV are shown in Figures 9 through 13. The proton peaks are at the high pulse height positions on the right representing fast rates-of-rise. Separation between gamma and proton events is evident at 5 keV although the gamma peak is substantially higher. Below 5 keV gamma events far outnumbered proton events and discrimination was no longer possible.

Figure 7 - ARMF-II core loading 10-66.

Figure 8 - Proton recoil detector and preamp in ARMF-II core.

Figure 9 - Rate-of-rise spectrum for 5 keV protons.

Figure 10 - Rate-of-rise spectrum for 10 keV protons.

Figure 11 - Rate-of-rise spectrum for 20 keV protons.

Figure 12 - Rate-of-rise spectrum for 40 keV protons.

Figure 13 - Rate-of-rise spectrum for 100 keV protons.

Tests in the core before startup and after shutdown showed that most of the gamma background (1.6 r/hr) was from previous reactor operation. These tests also showed that very few gamma events were present above ionization levels equivalent to 60 keV.

V. CONCLUSIONS

Although many problems still need to be solved it seems practical to use a proton-recoil spectrometer to make spectrum measurements in a water moderated reactor. The pulse shape discrimination system that was used had the advantage of yielding information about gamma to neutron ratios without the use of a two parameter analyzer. These ratios are valuable in deciding what the energy limits of the spectrometer will be, the time constants to use in the differentiator, the type of counter to use, and so forth. However, this type of discrimination system is undesirable for spectrum measurements both from the standpoint of the time involved in accumulating the data and the quality of data received.

The pole-zero corrected preamp offered a distinct advantage over previously available amplifiers by minimizing spectrum distortion due to high counting rates. However, meaningful spectrum measurements below 10 keV will be essentially impossible even with the most sophisticated electronic system unless an initially clean core is available in which to do the measurement.

It may be necessary to use several counters for measurements over the energy range of 1 keV to 100 keV. Smaller counters can be used for the low energy measurements to enhance neutron to gamma ratios. For higher energy measurements it will be necessary to use larger counters to avoid spectrum distortion from edge effects.

The problems encountered in making measurements above 100 keV should be similar to those found in fast reactor spectrum work since very little gamma background will be present. However, data accumulations times will greatly increase since the $1/E$ nature of the fast flux will reverse the count rate problem found at low energies.

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