Conf - 346 - 11

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Instrumentation for Fission Fragment Energy Correlation Experiments

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Abstract

CMPLIN REFERENCE NUMBER

AND-Conf-63-201-10

Experiments have been performed at the Oak Ridge National Laboratory in which the kinetic energies of correlated fragment pairs from thermal- and resonance-neutron-induced fission have been measured. In addition, a three-parameter ternary fission experiment has been performed in which the energies of correlated fragments were measured in coincidence with the energy of a third emitted particle, usually a long-range alpha particle. The detectors were large-area silicon surface barrier detectors. The instrumentation associated with these experiments is discussed in detail. The complete system is described, with attention given to the problems of background reduction (fast-coincidence requirements), stability, linearity, and resolution. Particular attention is given to the reduction of spectrum distortion by pile-up pulses, e.g., alpha-on-fission pile-up within the amplifier resolving time. Methods and limitations of pile-up detection are discussed. A new method for inspection and removal of pile-up pulses, which may be useful in a wide variety of applications, is presented.

International Conference on
Nuclear Physics with Reactor
Neutrons
Argonne, Illinois
October 15-17, 1963

Facsimile Price \$ 1.60

Microfilm Price \$.80

Available from the
Office of Technical Services
Department of Commerce
Washington 25, D. C.

*Now with Oak Ridge Technical Enterprises Corporation, Oak Ridge, Tennessee

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1. Introduction

Experiments have been performed at the Oak Ridge National Laboratory in which the kinetic energies of correlated fragment pairs from thermal- and resonance-neutron-induced fission have been measured.^{1,2)} In addition, a three-parameter ternary fission experiment has been performed¹⁾ in which the energies of correlated fragments were measured in coincidence with the energy of a third emitted particle, usually a long-range alpha particle.

Results of these experiments permit a detailed study of the kinetics of fission, including, for example, mass and energy distributions, mass-vs-energy correlations, and total kinetic energy-vs-mass correlations. It is the purpose of this paper to discuss in detail the instrumentation associated with these experiments. The complete system will be described, with particular attention to the problems of background reduction (fast-coincidence requirement), alpha particle pile-up (accidental alpha-on-fission pulses), linearity, and resolution. The new inspection circuit for pile-up reduction described below may be useful in a wide variety of applications.

2. System

A block diagram of the multi-parameter system is shown in Fig. 1. The system is shown as a three-parameter system; it may also be operated with any parameter singly or with any two parameters. Pulses from the large-area silicon surface barrier detectors are amplified in charge-sensitive pre-amplifiers followed by double-delay-line amplifiers. These pulses are delayed by 2 microseconds to allow the coincidence and inspection circuits to function; they then

are split, and proceed into the monitor analyzer, and into the analog-to-digital converters from which information is read onto punched paper tape, event by event.

In all of the experiments to date, inspection for pile-up has been necessary in only two parameters, as shown in Fig. 1. Unshaped signals from the appropriate pre-amplifiers are fed into fast (20 nsec) delay-line shaping amplifiers followed by discriminators whose outputs are of constant amplitude, say X . These pulses are then added, and the sum pulse enters a single channel analyzer which produces an output if the amplitude of the sum pulse is equal to the amplitude X ; if the amplitude of the sum pulse is $2X$, no output pulse from the single channel is produced. This anti-coincidence pulse, produced for each singles (non-coincident) event in a detector, is 4 microseconds long and prohibits analysis in the ADC units for that length of time. As shown in the figure, the fast coincidence is performed on pulses from the single-channel analyzer and cross-over pick-off circuits.

A description of each of the units and its operation follows.

3. Pre-Amplifiers and Amplifiers

The principal requirements placed on the pre-amplifiers are that they be charge-sensitive to provide stability and minimum noise, and that they maintain a fast rise-time of the output pulse, even when connected to a large capacitance (500 pf) detector. These requirements were met by the Tennelec Model 100A pre-amplifiers, with an increase in feedback capacity of 82 pf, added in parallel with the existing 4.7 pf capacitor. Without the added feedback capacity, a 20% change in detector

capacity would cause a 1% change in pulse height, whereas, with the added feedback the corresponding change in pulse height would be approximately 0.05%. This added feedback reduces the charge sensitivity and improves the rise-time of the output pulse; however, it creates a small short term ringing on the peak of the pulse which may be damped out by the addition of a small (82 pf) capacitor to ground from the grid of the White cathode follower in the input loop. The output rise-time requirement is imposed by the inspector circuit input requirements, described later.

The linear amplifiers are of the A-8 type³⁾, with double delay-line differentiation for base-line restoration. This type of amplifier is chosen for its stability, count rate capability, and zero crossing characteristic, even though the rms noise component is 2 to 4 times worse than that of an RC clipped amplifier. The amplifiers are modified to provide a fine gain adjust in order to balance accurately the gains of the system. The system is checked frequently by inserting a known amount of charge into each pre-amplifier from a precision pulse generator; the fine gain controls are used to compensate for small drifts.

4. Single Channel Analyzer and Cross-Over Pick-Off

Each of the A-8 linear amplifier outputs is applied in parallel to one of the inputs of a unit which consists of three improved⁴⁾ anti-walk single channel analyzers⁵⁾, and to one of the ADCs through a temporary delay line storage. The amplifiers and single channel analyzers are adjusted such that the time shift of the single channel output is less than 5 nsec for a pulse height range of 8 to 1. The fission fragment

energies cover only about half of this range (30 to 130 Mev). The anti-walk characteristic of this single channel analyzer is not affected by discriminator bias settings or by pulses whose amplitude is less than the lower level discriminator bias setting or more than the upper level bias setting. Coincidences involving low energy alpha pulses (5 to 6 Mev) are prevented by setting the lower level of the single channel above the alpha pulse height but below the minimum fission fragment pulse height.

5. Fast Coincidence Unit

In the coincidence unit, a fast coincidence ($2\tau = 40$ nsec) is required between the outputs of the single channel analyzers. The output from this unit is applied to the ADCs and serves as the coincidence enabling requirement to open the linear gates so that analysis of the coincident events may be performed. In these experiments, it has not been necessary to reduce the coincidence resolving time below 40 nsec; this time is easily and reliably attained, and improvement serves only to reduce the accidental fission rate. Such accidentals are already largely removed by the inspect function.

An output from this unit is prevented for a period of 4 μ sec following each non-coincident event (alpha or fission) by means of the anti-coincidence section. The 4 μ sec inhibit pulse originates in the inspection system.

6. Inspection System for Pile-Up Reduction

When pulse height analysis is performed on pulses occurring at random time intervals, some distortion of the pulse height distribution, created by one pulse falling upon another, will exist. To first approximation, the number of pile-up pulses per unit time is given by $R_D = R_1 R_2 (\tau_1 + \tau_2)$ where R_D is the pile-up pulse rate, R_1 and R_2 are the input rates, and τ_1 and τ_2 are the effective pulse widths. In this consideration the rates are the alpha rate and the fission fragment rate, and in general, for delay line shaping, $\tau_1 = \tau_2 =$ twice the amplifier clipping time. Since, however, analysis is performed on the positive portions of the pulses only, the effective pile-up time (T_p) is $1.5 \tau_1$ or 3 times the amplifier clipping time. This effective pile-up time may be reduced by detecting and removing a portion of the pile-up pulses, as discussed in the following paragraphs.

Probably the most straightforward approach to the detection of pile-up is to examine the pulses for shape change.⁶⁾ Graphical analysis of pile-up pulses as shown in Fig. 2a and 2b shows that when pile-up of positive-on-positive occurs, the crossover point is shifted by a time that is equal to, or greater than $(T_r/2)(E_2/E_1)$. Here T_r is the rise-time of the amplifier, and E_2 is the pulse that is piled upon E_1 . For the case of E_2 arriving on the tail of E_1 as is shown in Figs. 2c and 2d, there may be a double crossing of the base-line but there is no time shift of the crossover point or points. There is, however, a pulse height distortion when the second pulse is the one of interest. The pile-up time associated with this condition may be somewhat less than the amplifier clipping time, depending on the bandwidth of the peak detector in the analog-to-digital converter.

Some practical limits of pile-up detection by this method may be derived. With a rise-time of 200 nsec and a ratio of $E_2/E_1 = 1/20$, it is necessary to detect a time shift of the crossover point of 5 nsec for the positive-on-positive case. Detection of a 5 nsec time shift would be possible if a time reference of this accuracy existed; however, the only time reference presently available is the leading edge of the pre-amplifier output pulse which has a rise-time of ~ 100 nsec. The timing inaccuracies associated with the crossover pickoff and the leading edge trigger preclude the use of this method. The amount of positive-on-positive pile-up which may be removed by coincidence only, in multiple particle experiments, is limited by timing inaccuracies in particle detection, e.g., variation in particle flight times.

The method employed here consists of clipping the pre-amplifier pulses with a 20 nsec clipping line, then triggering a fast discriminator with these pulses. The outputs of the fast discriminators are then placed in anti-coincidence in such a way that if only one has been triggered the circuit will inhibit the coincidence output requirement, derived from the crossover pickoff signals (see Fig. 1).

The circuits used to perform this function consist of the inspector amplifier and discriminator circuit shown in Fig. 3 and the 0.1 μ sec single channel analyzer shown in Fig. 4. The pre-amplifier pulses enter the inspector amplifier through the cathode follower T_1 and are amplified by the transistors Q_1 and Q_2 . They are then clipped by a 20 nsec clipping line and reamplified by transistors Q_3 , Q_4 , and Q_5 . Transistors Q_6 and Q_7 form the fast discriminator which is set to trigger on all pulses,

both alpha particles and fission fragments. The outputs of the two discriminators are summed and fed to the 0.1 μ sec single channel analyzer, where the lower level is set below the amplitude of a single pulse and the upper level below the amplitude of the sum. By this means an anti-coincidence signal, 4 μ sec in duration, is created each time there is a single event in either detector but not when coincident events occur within the resolving time of the inspector circuit.

The 0.1 μ sec single channel analyzer needs little explanation. It consists of an emitter follower input, two Schmitt-trigger level discriminators, an inhibit gate, and two output pulse generators. The fast output produces a 2v negative pulse, approximately 50 nsec wide. The slow output produces either a positive or negative pulse, 10v in amplitude and 4 μ sec in duration. The integral linearity of the circuit is shown in Fig. 5. The temperature stability has proved to be better than 0.15 mv/ $^{\circ}$ C between 20 $^{\circ}$ C and 50 $^{\circ}$ C. The variable capacitor between the collector of Q₆ and the base of Q₇ provides a means for adjustment such that input pulse widths of approximately 10 to 80 nsec may be used. The input rise-time, however, must be maintained at less than 15 nsec for correct operation.

7. Inspector Circuit Test Results

A series of tests were performed to check the operation of this circuit. The tests were designed to simulate the conditions of the fission experiments, except that the random alpha rate was increased to check the circuit operation at high rates. The test consists of the analysis of a pulser spectrum obtained in the presence of a high

background ($1.6 \times 10^4/\text{sec}$) of Am^{241} alphas. The results of these tests are shown in Fig. 6; the amplitude of the pulser signals corresponds to an energy of ~ 76.5 Mev. Figure 6a shows a single side spectrum where the only requirement is that the energy be greater than 2 times the alpha energy. The pile-up distortion is readily evident in the pulser-plus-alpha and the pulser-minus-alpha wings. Figure 6b shows the results obtained under the same conditions, but with a 40 nsec coincidence requirement added. Figure 6c shows the results obtained with the inspect function turned on (the 40 nsec coincidence requirement is maintained); Fig. 6d shows the results obtained with the inspect function on, but without a fast coincidence.

From these data the effective pile-up time $T_p = 3.3 \pm 0.1 \mu\text{sec}$ is obtained for the uninspected case. With inspection this pile-up time T_{PI} is reduced to $T_{PI} = 0.55 \pm 0.03 \mu\text{sec}$, an improvement of a factor of ~ 6 . By circuit optimization, it should be possible to reduce T_{PI} to approximately 140 nsec, i.e., two times the inspector amplifier clipping time (40 nsec) plus the charge sensitive pre-amplifier rise time (100 nsec).

8. Analog-to-Digital Converters and Data Acquisition System

The correlation analyzer consists of a pair of analog-to-digital converters (ADCs), utilizing the standard lengthener, ramp generator, comparator, and oscillator countdown technique. Upon receipt of a coincident event the ADC units provide (to a paper-tape punch control) outputs in binary code representing the channel numbers into which each

of the coincident pulse amplitudes fall. The tape punch-control unit translates the parallel information into serial hexadecimal code which is then recorded on paper tape. The tape format is such that the analyzer may be used with 128 x 128 or 256 x 256 channels, and a third parameter containing a maximum of 16 channels is added for the ternary experiments. The uncorrelated spectra are monitored on a separate analyzer.

The data recorded on paper tape are processed by a high-speed computer coded to sort and sum the events into a matrix of channel combinations. A typical 128 x 128 channel matrix thus produced is shown in Fig. 7. This matrix, containing $\sim 10^6$ events, shows the energy correlation spectrum for fragments from the thermal-neutron-induced fission of U^{235} . Contours are drawn for several numbers of events per box; outside the contour for 10 events per box (a box is a unit square in the matrix, one channel by one channel), the actual numbers of events are entered so that locations of the less frequent events are evident. The energy scales indicated are approximate. From these data, appropriately calibrated, transformations may be made; mass and energy distributions, mass-energy correlations, and other kinetic parameters important in the physics of fission may be obtained. Such results and their interpretations are the subject of forthcoming publications.

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FIGURE CAPTIONS

Figure 1. Block diagram of instrumentation for fission fragment energy correlation measurements.

Figure 2. Graphical representation of certain pile-up conditions.
See text.

Figure 3. Inspector amplifier and discriminator circuit diagram.

Figure 4. 0.1 μ sec single channel analyzer circuit diagram.

Figure 5. Plot of integral linearity for 0.1 μ sec single channel analyzer.

Figure 6. Pulse height spectra for pulser (60 cps) plus alpha particles (1.5×10^4 c/sec), for a single side of the two parameter system:

- (a) No coincidence, no inspection;
- (b) Coincidence only;
- (c) Coincidence and inspection;
- (d) Inspection only.

Figure 7. Spectrum of correlated fission fragment pulse heights for thermal-neutron-induced fission of U^{235} . The matrix contains 128 x 128 channels; the energy scales are approximate.

Block Diagram for Fission Energy Correlation Measurements.

FIGURE 1

FIGURE 2

FIGURE 4

Plot of Integral Linearity

FIGURE 5

FIGURE 6

FIGURE 7