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ENERGETIC-NEUTRON SPECTROMETRY

Progress Report

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ABSTRACT

The self-contained time-of-flight spectrometer has been used successfully to measure neutron spectra from both thick and thin targets. Neutron spectra produced by 740 MeV protons on a 30-cm thick uranium target have been measured from 20 to 500 MeV at 50 degrees and from about 2 to 140 MeV at 130 degrees. Comparison of these results with the predictions of the nucleon-meson transport code (NMTC) show that the intranuclear cascade model underestimates the production of cascade neutrons at wide angles; furthermore, these comparisons show that this discrepancy increases with increasing angle of emission.

The high-energy limit of the spectrometer has been extended to about 1 GeV by adding a counter telescope to detect the recoil proton from the n-p elastic scattering event in the first detector. Neutron spectra above about 175 MeV produced by 724 MeV protons on thin beryllium and copper targets have been measured at 0 degrees with this modified spectrometer. Comparison of these results with the intranuclear cascade calculation indicates that the intranuclear cascade model underestimates the neutron production both in the quasi-elastic peak and in the continuum between 300 MeV and the 175 MeV cut-off energy of the spectrometer.

1. Introduction

This technical progress report summarizes the research accomplishments and progress during the past year in the program of energetic-neutron spectrometry carried out under Contract AT(11-1)-2231 at Kent State University. The research accomplishments can be classified into the following categories:

- a. Analysis and publication of existing data and techniques.
- b. Measurement of neutron spectra from thin targets.
- c. Extension of the neutron spectrometer to higher energies.
- d. Development of auxiliary instrumentation.
- e. Preparation of manuscripts for publication or presentation.

The specific accomplishments in each of these categories are described in section 2.

2. Research Accomplishments

a. Analysis and publication of existing data and techniques.

We completed the analysis of existing data from measurements made at the National Research Council, Ottawa, Canada and at the Lawrence Berkeley Laboratory under Contract AT (30-1)-3914. Then we prepared the following manuscripts for publication:

1. "The Response of NE-228 Liquid Scintillator to 3.5, 5.8, and 10.5 MeV Protons," Nucl. Instr. and Meth. 104, 253-256 (1972). A reprint of this paper is appended as C00-2231-6. *Reviewed*
2. "A Time-of-Flight Spectrometer for Neutrons from 1 to 500 MeV," Nucl. Instr. and Meth. 106, 89-101 (1973). A reprint of this paper is appended as C00-2231-7. *Reviewed*
3. "High-Energy Neutrons Produced by 740 MeV Protons on Uranium" (Ph.D. Dissertation of Frank M. Waterman submitted to Clarkson College of Technology; journal publication to be submitted.) The Ph.D. Dissertation Abstract of Frank M. Waterman is appended as C00-2231-9. *Reviewed*

b. Measurement of neutron spectra from thin targets.

An experiment was designed and carried out at the Lawrence Berkeley Laboratory 184-inch cyclotron to measure

the neutron spectra at 0 degrees from 724 MeV proton bombardment of thin beryllium and copper targets. The experimental arrangement for these measurements and some preliminary results are described in the appended documents C00-2231-1 and C00-2231-2. The purpose of these measurements and the subsequent analysis was to investigate the production spectra from these thin targets and to generate data to test the validity of the intranuclear cascade calculation at a production angle of zero degrees. Comparison of experiment and theory indicates that the intranuclear cascade calculation underestimates the magnitude of the quasi-elastic peak and the number of neutrons emitted with energies between 300 MeV and the cut-off energy at about 175 MeV. The position of the quasi-elastic peak is observed at the proton bombarding energy in agreement with the intranuclear cascade calculation. The experimental results for copper show a substantial contribution to the spectrum in the continuum between 300 MeV and the cutoff energy at about 150 MeV, whereas the intranuclear cascade calculation does not show this contribution.

The intranuclear cascade calculations for comparison with these data were made by H. Bertini at the Oak Ridge National Laboratory.

c. Extension of the neutron spectrometer to higher energies.

The high-energy limit of the spectrometer has been

extended upward to about 1 GeV by adding a counter telescope to detect the recoil proton from the n-p elastic scattering event in the first detector. The additional coincidence requirement reduces background from competing inelastic reactions by imposing kinematic and coplanarity requirements for n-p elastic scattering. The performance of this spectrometer was tested in measuring the 724 MeV quasi-elastic neutron peak produced at 0° from 724 MeV proton bombardment of beryllium. The observed resolution of 16% for a flight path of 5 meters is in agreement with the calculated resolution of 17%. The resolution can be improved approximately twofold with a 10 meter flight path. Loss in counting rate can be compensated for by using a larger collimator and a larger detector. A description of the modified spectrometer is given in the appended documents COO-2231-1 and COO-2231-2. *Revised*

d. Development of auxiliary instrumentation.

1. A 350 MHz decade scaler.

The thin target measurements made at the Lawrence Berkeley Laboratory required scalers with higher counting rate capabilities than our (Ortec 430) 16 MHz scalers. To meet this need, a 350 MHz decade scaler was designed and used to expand the counting rate capabilities of the Ortec 430 scalers. The scaler counts at pulse rates up to 350×10^6 per second with

a pulse pair resolution of less than 3 nanoseconds. The operating features include on/off control, external gating of the scaler, pushbutton reset and external reset input, read out of the scaler count onto data lines, and system interconnection capabilities. A detailed description of the 350 MHz scaler is given in the appended preprint COO-2231-10. *Removed*

2. A fast (temperature-stable) linear gate.

During the development of a pulse-shape discrimination (PSD) system for the separation of neutrons and gamma rays, it became apparent that a technique for increasing the analysis efficiency and rate would be to employ fast gating of the anode signal ahead of the PSD system. In the PSD analysis, this gated signal would be integrated, shaped, and analyzed. Experimentally we found that the pedestal voltage (i.e., the output voltage in the absence of a signal during the gate interval) of commercially available high-speed diode linear gates have a temperature drift on the order of 1 millivolt per degree centigrade; however, we found that a shift of less than 2 millivolts would distort low-level pulse-shape signals to unusable proportions. This investigation culminated in a fast linear gate with pedestal shifts more than an order of magnitude smaller than commercial high-speed linear gates.

The high-stability linear-gate circuit was designed for a system requiring fast gating and a very stable baseline. The gate amplifier provides unity gain from dc to 100 megahertz with a baseline drift of less than 30 microvolts per degree centigrade. The linear gate has an opening and closing time of 10 nanoseconds with gate generated transients of less than 15 millivolts. The input offset voltage is less than 50 microvolts and the output pedestal voltage is adjustable to any point between ± 10 millivolts of zero volts. The linear gate will operate with negative pulses up to 2 volts in amplitude. The alternation of the closed gate is typically 10^3 at 100 megahertz and greater than 10^5 at dc.

Preliminary tests using the high-speed linear gate and a PSD system indicate that operation at input data rates up to 10^6 pulses per second, which is an order of magnitude higher than ungated systems, is readily achievable. Initial results show that for a 20 to 1 dynamic range of pulse heights, the neutron peak-to-valley ratios are 135 to 1 for a 250 nanosecond gate interval and 60 to 1 for a 100 nanosecond gate interval.

e. Preparation of manuscripts for publication or presentation.

During the past year, the following manuscripts have been prepared for publication or presentation in addition

to those listed in section 2a:

1. "Neutron Spectrometry from 1 MeV to 1 GeV,"
Richard Madey and F.M. Waterman, IAEA/sm-167/47.
(To be published in the Proceedings of the IAEA
Symposium on Neutron Monitoring for Radiation
Protection Purposes, Vienna, Austria, 11-15 *Revised*
December 1972.) A reprint of this paper is ap-
pended as COO-2231-1.
2. "High-Energy Neutrons Produced by 740 MeV Protons
on Uranium," F.M. Waterman and Richard Madey, Bull. *Revised*
Am. Phys. Soc. 17, 581 (April 1972). This abstract
is appended as COO-2231-3.
3. "Neutron Spectrometry from 200 MeV to 1 GeV,"
Richard Madey and F.M. Waterman, Bull. Am. Phys. *Revised*
Soc. 18, 617 (April 1973). This abstract is ap-
pended as COO-2231-8.
4. "A 350 Megahertz Decade Scaler," Alan R. Baldwin
and Richard Madey, (submitted to Nucl. Instr. and *Revised*
Meth.). A preprint of this paper is appended as
COO-2231-10.

3. Bibliography

This bibliography lists papers, presentations, pre-
prints, and reports prepared under Contract AT(11-1)-
2231. Reprints of these documents are appended to this
report.

1. COO-2231-1

Neutron Spectrometry from 1 MeV to 1 GeV, Richard Madey and F.M. Waterman, International Atomic Energy Agency Reprint IAEA/SM-167/47, IAEA Symposium on Neutron Monitoring for Radiation Protection Purposes, Vienna, Austria, 11-15 December 1972.

2. COO-2231-2

Neutron Spectrometry from 1 MeV to 1 GeV, Remarks prepared for presentation on 11 December 1972 by Richard Madey at the International Atomic Energy Agency Symposium on Neutron Monitoring for Radiation Protection Purposes at Vienna, Austria.

3. COO-2231-3

High-Energy Neutrons Produced by 740 MeV Protons on Uranium, Richard Madey and F.M. Waterman, Bull. Am. Phys. Soc. 17, 581 (April 1972).

4. COO-2231-4

High-Energy Neutrons Produced by 740 MeV Protons on Uranium, Remarks prepared for presentation by Richard Madey at the Washington, D.C., meeting of the American Physical Society on 27 April 1972.

5. COO-2231-5

High-Energy Neutrons Produced by 740 MeV Protons on Uranium, Remarks prepared for presentation by Richard Madey at a physics colloquium at the Los Alamos Scientific Laboratory on 4 May 1972, and also at the summer study session for the Indiana University Cyclotron Facility at Boulder, Colorado, 12-16 June 1972.

6. COO-2231-6

The Response of NE-228 Liquid Scintillator to 3.5, 5.8, and 10.5 MeV Protons, R. Madey and F.M. Waterman, Nucl. Instr. and Meth. 104, 253-256 (1972).

7. C00-2231-7

A Time-of-Flight Spectrometer for Neutrons from 1 MeV to 500 MeV, Richard Madey and Frank M. Waterman, Nucl. Instr. and Meth. 106, 89-101 (1973).

8. C00-2231-8

Neutron Spectrometry from 200 MeV to 1 GeV, Richard Madey and F.M. Waterman, Bull. Am. Phys. Soc. 18, 617 (April 1973).

9. C00-2231-9

High-Energy Neutrons Produced by 740 MeV Protons on Uranium, Frank M. Waterman, Ph.D. Dissertation Abstract, Clarkson College of Technology (May 1973).

10. C00-2231-10

A 350 Megahertz Decade Scaler, Alan R. Baldwin and Richard Madey, Nucl. Instr. and Meth. (submitted). *Removed*

11. C00-2231-11

Energetic-Neutron Spectrometry, Richard Madey and Frank M. Waterman, Progress Report for the period 1 April 1972 through 31 March 1973.

4. Activities in Progress

Activities in progress include the preparation of the following papers for publication:

- a. "Neutron Spectra at 0° from 724 MeV Protons on Be and Cu," F.M. Waterman and Richard Madey, (to be submitted to Phys. Rev.).
- b. "A Time-of-Flight Spectrometer for Neutrons from about 200 MeV to 1 GeV," F.M. Waterman and Richard Madey, (to be submitted to Nucl. Instr. and Meth.).

Other activities involve preparations for a measurement at an accelerator.

5. Contract Compliance

The principal investigator devotes at least 15 percent of his time during the academic year and one summer session and full-time during another summer session to the project.

To the best of our knowledge, there have been no failures to comply with the contract requirements.