COO-2231-38

MASTER

# ENERGETIC-NEUTRON SPECTROMETRY

Progress Report
for period

1 June 1976 to 31 August 1977

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PREPARED FOR THE U.S. ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

UNDER CONTRACT E(11-1)-2231

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# DISCLAIMER

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## ABSTRACT

Advances in instrumentation and techniques for energetic-neutron spectrometry include the development of large-volume scintillators and a mean-timer electronic module to provide subnanosecond timing resolutions for time-of-flight measurements with improved energy resolutions, new determinations of the light response to protons (relative to electrons) of NE-228, NE228A, NE-224, and NE-102 scintillators, and the development of a multiplexing technique to permit the operation of several different counters simultaneously with our transportable data-acquisition system. Measurements demonstrating and utilizing these advances include neutron energy and angular distributions from 710-MeV alphas stopping in thick targets, and neutron spectra and yields from the nuclear capture of negative pions. Included also is a discussion of a planned experiment to measure neutron spectra from heavy-ion reactions at the Lawrence Berkeley Bevalac.

## 1. INTRODUCTION

This report describes progress made during the past year under contract EY-76-S-02-2231 with Kent State University. The scope of the investigations under this program include the development and improvement of instrumentation, detectors, and techniques for measurements of neutron energy spectra and yields in the energy region from a few MeV to several hundred MeV, and the demonstration and utilization of the apparatus and techniques in applications pertinent to ERDA programs.

## 2. RESEARCH ACCOMPLISHMENTS

The research accomplishments include the following:

### 2.1 The Development of Large-Volume Scintillators with Subnanosecond Timing Resolution

The Kent State Users Group has significantly improved its ability to measure neutron yields and spectra for experiments with low count rates by developing large plastic (NE-102) scintillators with subnanosecond timing resolution. Three large (5 in. x 4 in. x 40 in.) counters have been constructed, tested, and used in an experimental run. Since these counters have about ten times the volume (with about the same time-resolution) of our 5 in. diam. x 4 in. thick counters, they provide an improvement in counting rates of about a factor of ten.

The fast-timing ability ($\lesssim 1$ nsec) has been achieved by using a mean-timing technique previously reported by Evers et al (1975), Giordano et al (1976), Takeutchi et al (1975), and Bhowmik et al (1976). A module (see section 2.2 below) measures the mean time $\bar{t} = (t_1 + t_2)/2$ where $t_1$, $t_2$ are the photon transit times from the scintillation event to 5 in. diam. (Amperex XP 2041) photo-multiplier tubes (coupled to 6 in. lucite light pipes) at each end of the 40 in. long scintillator. We have observed subnanosecond timing with these large counters for both gamma-rays and high-energy (116 MeV) neutrons in an experimental run from 135 MeV protons bombarding a thin carbon target.

In addition to providing the two signals necessary to perform mean-timing, the summed signal from photomultiplier tubes on each end of the long scintillator has a much smaller variation in amplitude than the signal from a single photomultiplier tube as a function of the irradiated position along the long dimension of the scintillator. As shown in Fig. 1, the relative light output from the summed anode signals from the two ends vary by less than 10 percent as a function of the irradiated position along the length of the scintillator; on the other hand, the relative light output from a single photomultiplier tube varies by 60 percent over the length of the scintillator.

An abstract on the development of these large detectors has been submitted to the 1977 Fall Meeting of the Nuclear Division of the American Physical Society.

### 2.2 Design, Construction, and Testing of a Mean-Timer Module

We have adopted the mean-timing technique (see section 2.1 above) in order to obtain subnanosecond timing with large volume scintillation counters. The neutron counters are 4 in. deep x 5 in. high x 40 in. long NE-102

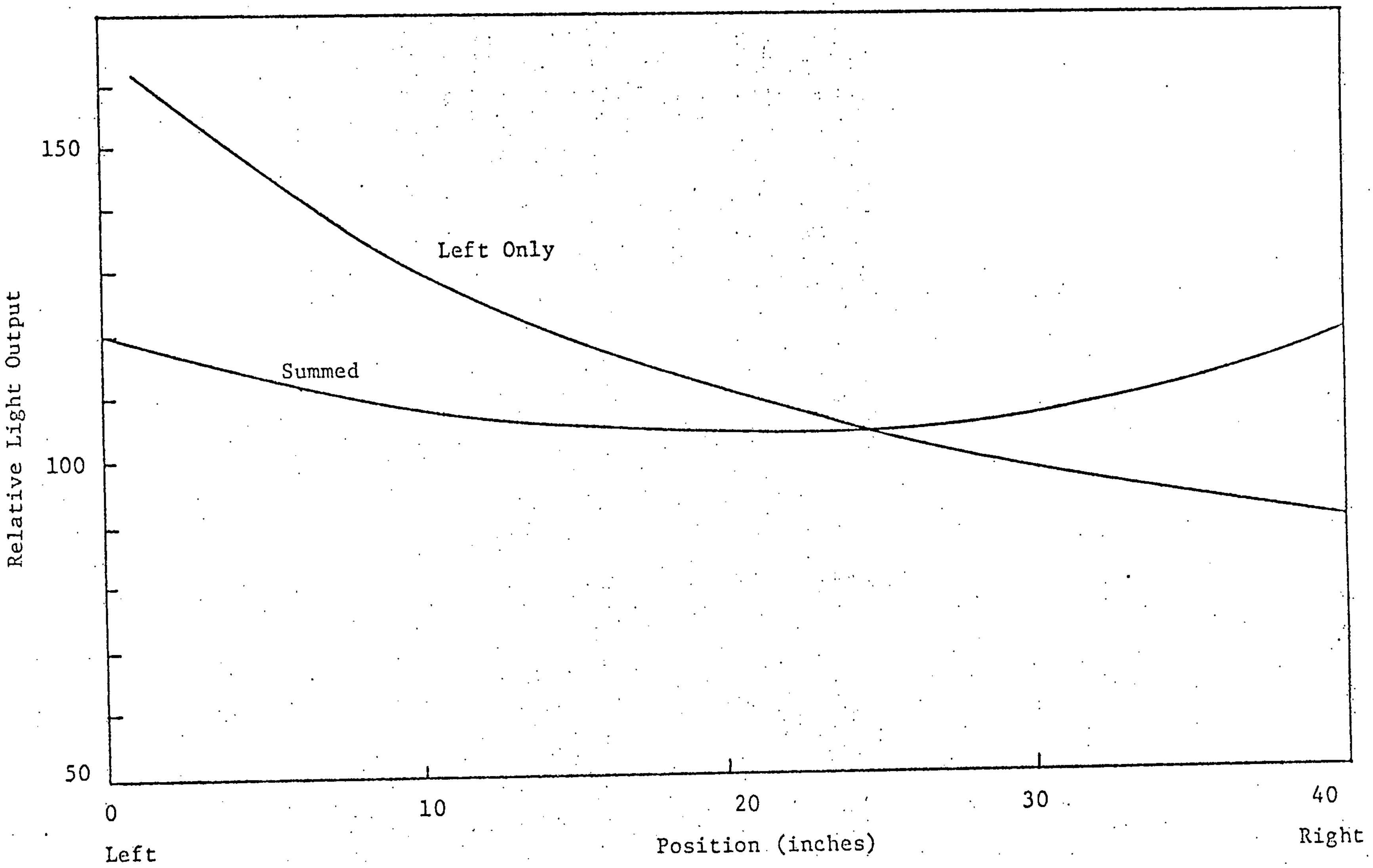

Fig. 1. Relative light output of a 5 in x 4 in x 40 in NE-102 scintillator with 6 in. light pipes on each end as a function of irradiated position along the long dimension.

scintillators with an Amperex XP2041 5 in. diam photomultiplier tube (PMT) mounted on each end. Since the transit times of scintillation light from a point of neutron interaction in the scintillator to the photocathodes at each end may be significantly different in such long counters, an electronic module was constructed to determine the mean arrival time of light at both ends from the anode pulses of the PMTs. This mean-detection time is theoretically independent of the position of the event in the scintillator.

The mean-timer can be described functionally as two independent (but equal) current sources (each triggered by one of the input timing pulses), a resistor-capacitor current integration network, and a level discriminator which generates an output pulse when the voltage at the integration network reaches a preset value. The level discriminator output pulse occurs at a predetermined fixed time after the mean-time of the two input pulses.

The mean-timer module has been tested in conjunction with a 40 in. long scintillator with a photomultipler mounted on each end. The two timing signals to the mean-timer module are derived from the anode signals from these two photomultiplers. We observed (fwhm) timing resolutions as follows: (1) 0.8 ns for a 3:1 dynamic range of pulse-heights from a $^{60}$Co γ-source illuminating a large scintillator from a distance of four feet in coincidence with a small scintillator with a very narrow dynamic range; (2) 0.65 ns for γ-rays with energies greater than 2 MeV produced by 135-MeV protons on a thin carbon target; and (3) 0.8 ns for the ground (and unresolved first excited) state (at 116 MeV neutron energy) from the $^{12}$C(p,n)$^{12}$N reaction at 135 MeV incident proton energy. The latter two measurements include an estimated time jitter of 0.5 nsec from the width of the proton burst from the Indiana University Cyclotron Facility and shifts in the time of arrival of the proton burst on the target relative to the phase of the cyclotron rf signal.

## 2.3 Determination of Light Response Curves of Four Scintillators to Protons

We have analyzed the measurements of the response (relative to electrons) of NE-228A, NE-228, NE-224, and NE-102 scintillators to protons from 2.43 to 19.55 MeV. The data have been fit with a semi-empirical function to provide analytical expressions respresenting the results. The results for NE-102 were fit simultaneously with the data of Czirr et al (1964) at lower proton energies. A comparison of this fitted curve with an earlier curve due to Kurz (1964), which has been used in popular computer codes for calculating neutron detector efficiencies, shows that the Kurz response curve under-estimates the light output for protons above 5 MeV by about 8%, and overestimates the light output at 1 MeV by about 15% and at 0.25 MeV by about 40%. The response of NE-228A is the same as that of NE-228. The response of NE-224 differs from that of either NE-102 or NE-228. Since the different scintillators are observed to have different response curves, it is important that measurements be performed for each kind of scintillator used in a neutron counter and not assume, as has been done, that the response curves are all identical. Response curves for these four scintillators are presented in Figs. 1 through 4. A full paper reporting the measurements and the analysis of the results will be submitted to Nulear Instruments and Methods.

### 2.4 Neutron Production from 710-MeV Alphas in Thick Targets

We measured the spectra and yields of neutrons produced at nine angles from 0° to 150° by 710-MeV alphas stopping in targets of C, Pb, $H_2O$, and steel. A telescope counted each alpha particle in the beam at the Space Radiation Effects Laboratory and provided a timing signal to measure the neutron flight-time to one of six organic scintillation counters operated in a muliplexing mode with a PDP-11/15 computer. Neutron yields above about 8 MeV were measured with five NE-102 plastic scintillators with flight paths of 5 m at forward angles, 3 m at 60°, and 2 m for angles greater than 60°; neutron yields from about 3 to 10 MeV were measured with a small (2 in. diam x 2 in. long) NE-213 liquid scintillator (with $n$-$\gamma$ pulse-shape discrimination) at a distance of 1 m. The energy resolution varied from 8% at 3 MeV to about 18% at 300 MeV. Our measured neutron spectra at 0° and 90° from lead are shown in Fig. 5. At 0° and 6° we observed neutron yield above the 178 MeV kinetic energy per nucleon of the incident alpha up to about 300 MeV. The spectra at 0° and 6° also show a peak at about 115 MeV which is more pronounced in the light (C and $H_2O$) targets.

These measurements will provide data needed for shielding design considerations at new heavy-ion accelerators such as the Oak Ridge Facility and the proposed Michigan State University superconducting cyclotron facility. Recent Monte-Carlo intranuclear cascade model calculations by Bertini et al (1974, 1976) predict that an appreciable number of neutrons would be emitted with energies greater than the incident energy per nucleon at all angles from heavy-ion reactions. Such high-energy yields would require a large amount of shielding around the beam stop at any heavy-ion accelerator facility.

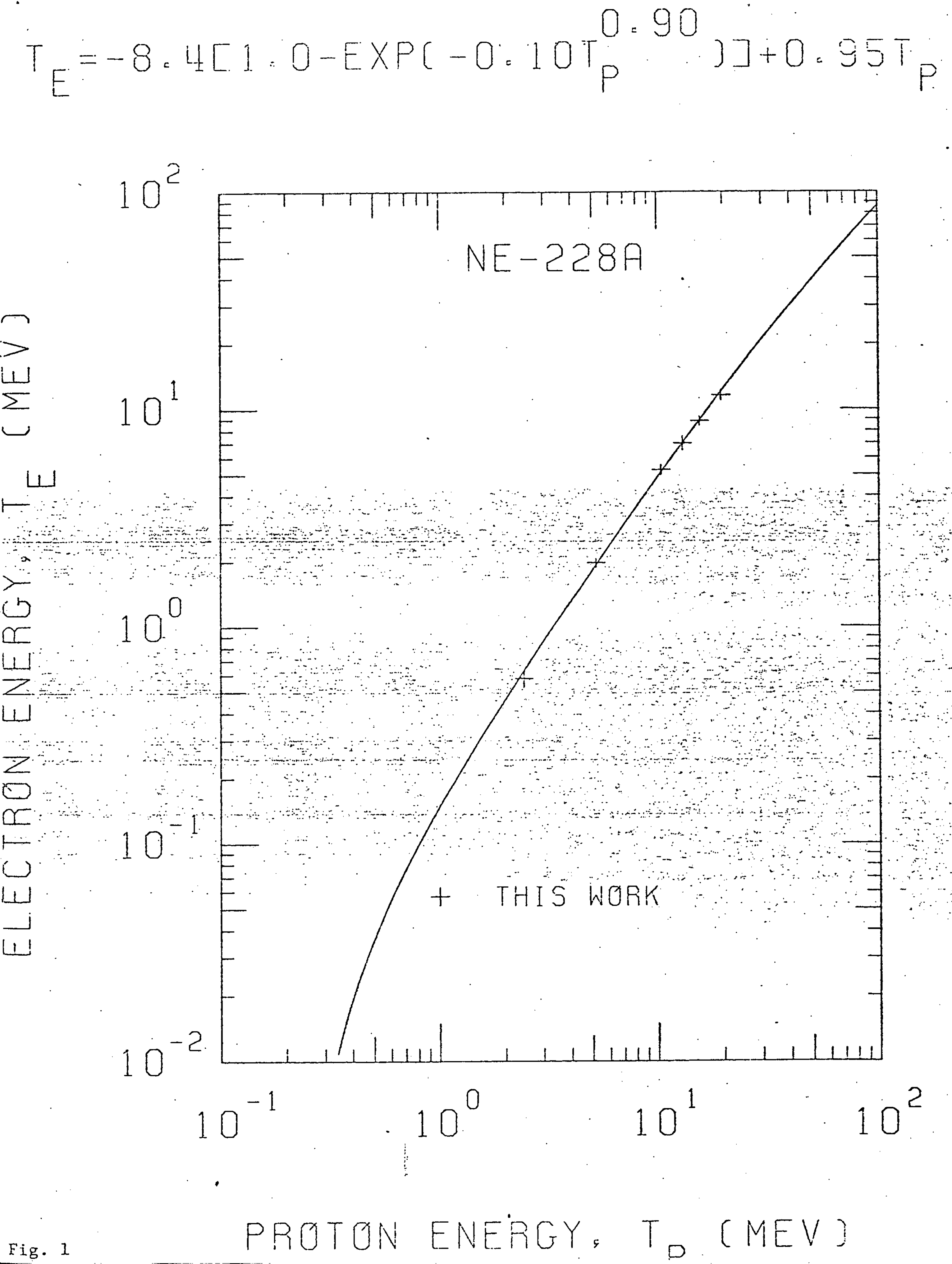
$T_E = -8.4[1.0-EXP(-0.10T_P^{0.90})]+0.95T_P$
NE-228A
+ THIS WORK
$10^{2}$
$10^{1}$
$10^{0}$
$10^{-1}$
$10^{-2}$
$10^{-1}$
$10^{0}$
$10^{1}$
$10^{2}$
ELECTRON ENERGY, $T_E$ (MEV)
PROTON ENERGY, $T_P$ (MEV)

Fig. 1

$$T_E = -8.4[1.0 - \mathrm{EXP}(-0.10\,T_P^{0.90})] + 0.95\,T_P$$

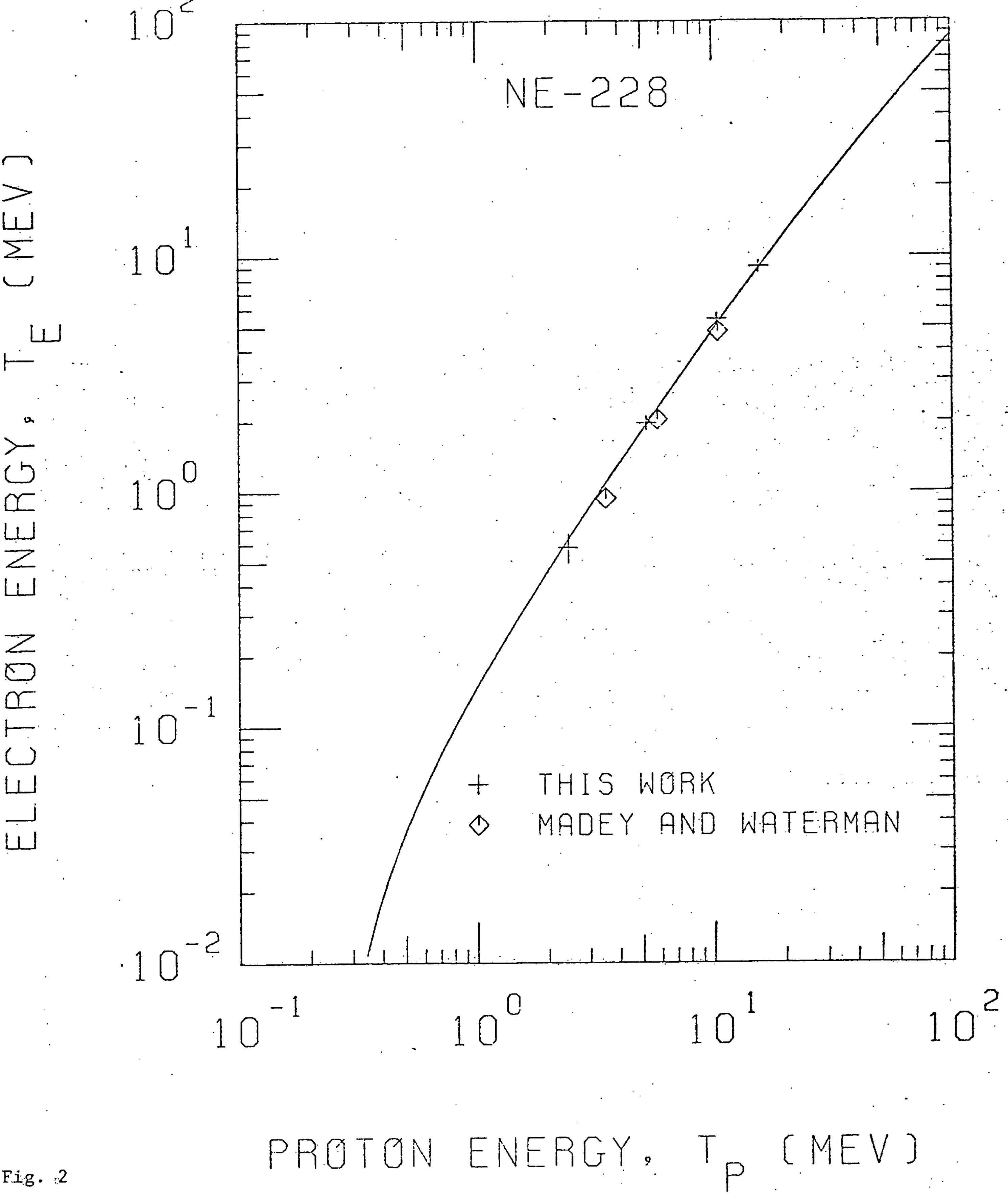

Fig. 2

$$T_E = -8.2[1.0 - EXP(-0.10 T_P^{0.88})] + T_P$$

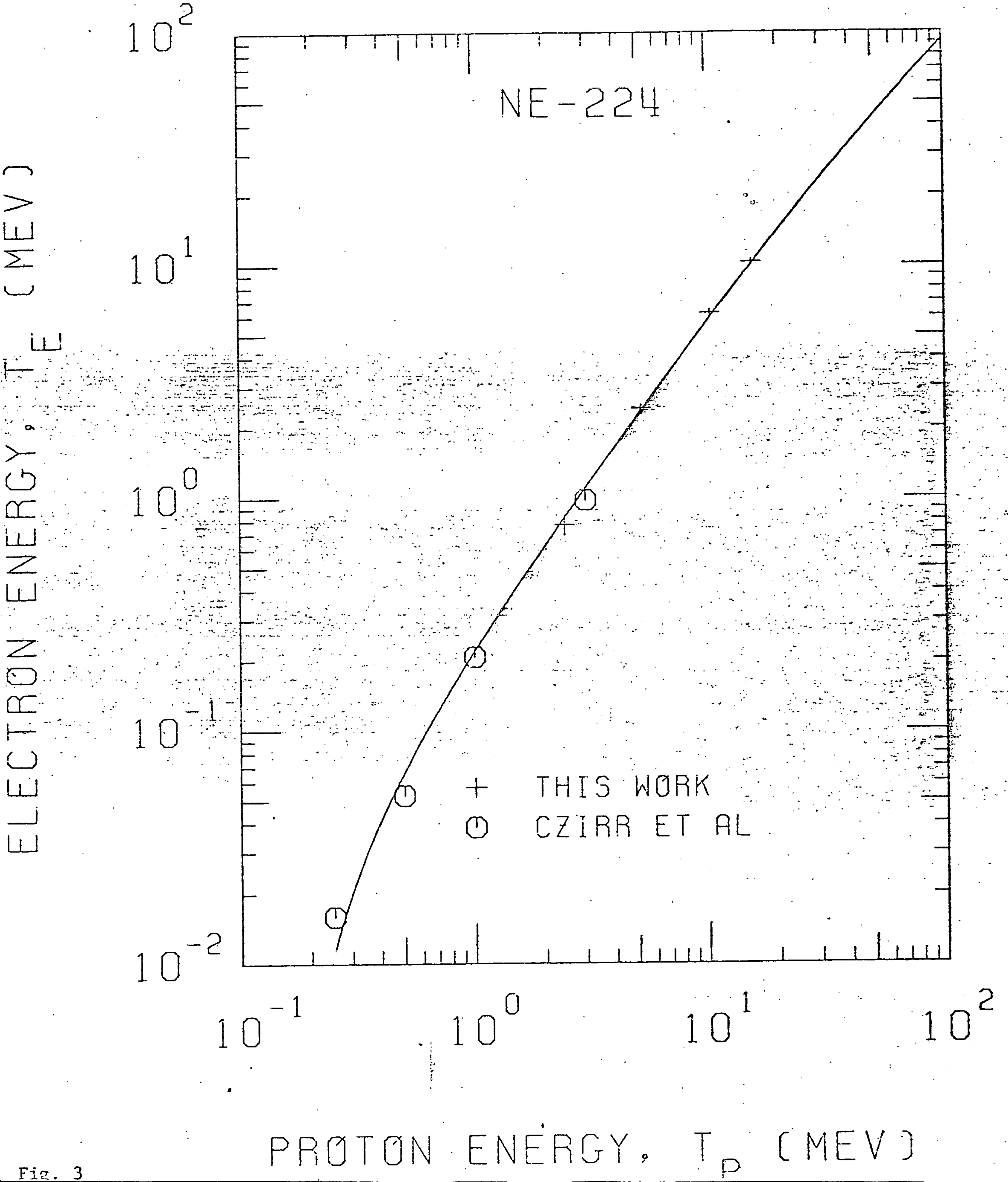

Fig. 3

$$T_E = -8.0[1.0-\mathrm{EXP}(-0.10T_P^{0.90})]+0.95T_P$$

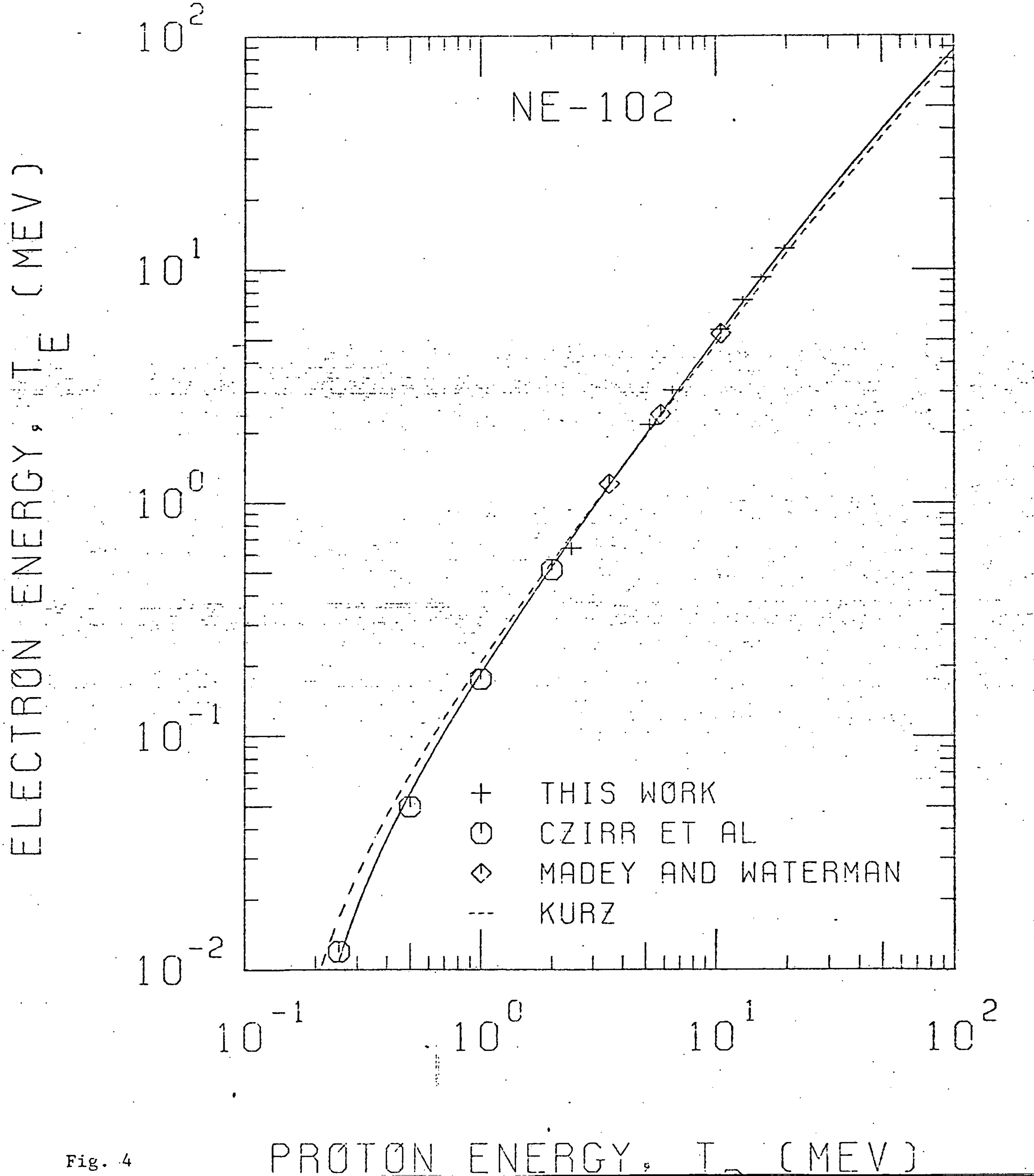

Fig. 4

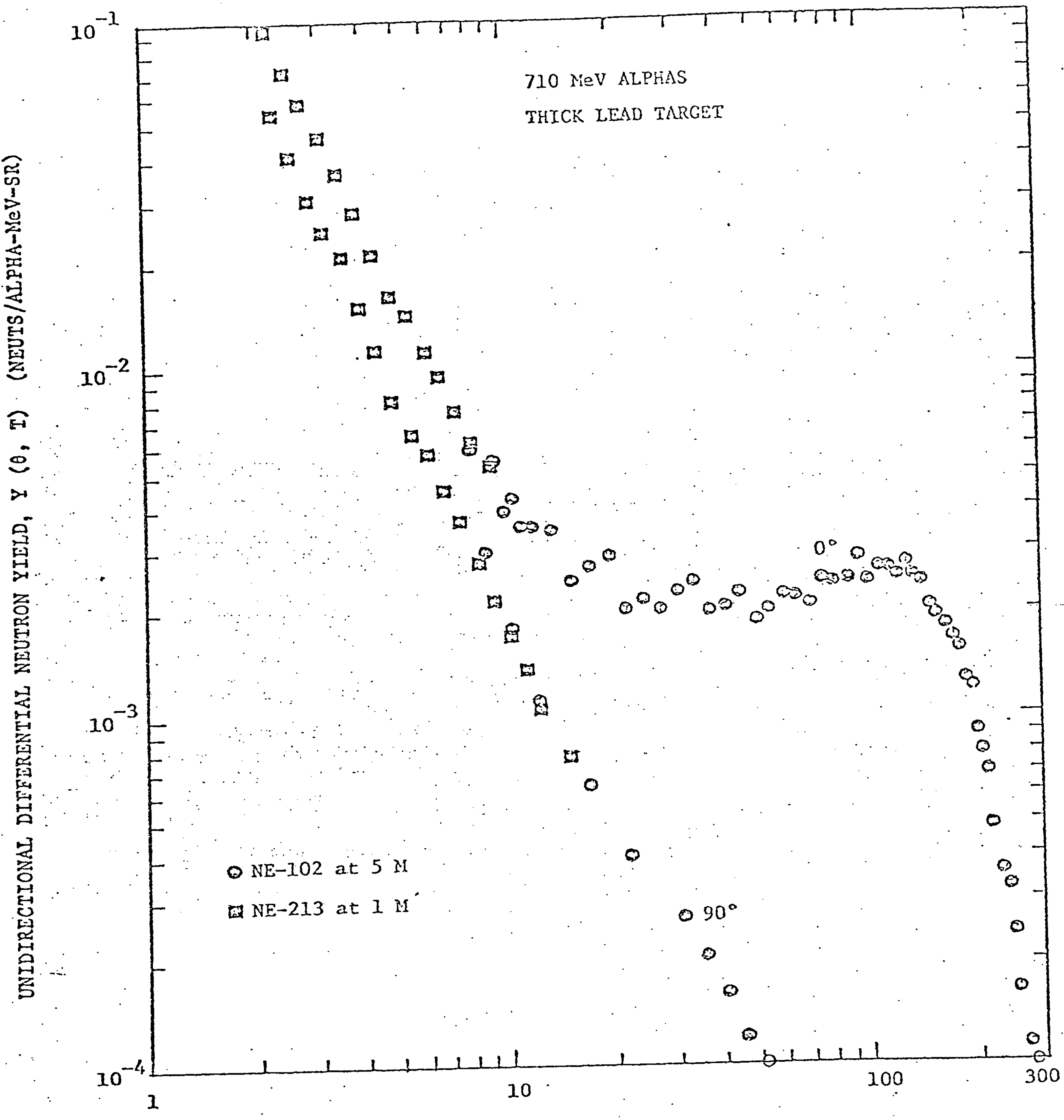

Fig. 5 Differential neutron spectra at 0° and 90° from 710-MeV alphas stopping in a thick lead target.

As reported above, we see appreciable yields above the average energy per nucleon only at the very forward angles from stopping alphas. Monte-Carlo intranuclar-cascade-model calculations will be performed by Armstrong (1977) to compare directly with our results to check his code. Calculations will also be performed with another intranuclear-cascade code at ORNL for comparison with our results.

These data are useful also to evaluate the likelihood that heavy-ion beams might provide a more favorable neutron yield (multiplicity) than proton beams for use in accelerator-breeder schemes for conversion of fertile material to fissile-fuel and for energy production. The neutron total yield measurements of West and Wood (1971) show that there is about 20% more neutron yield from the same energy deuterons as protons. Our alpha-particle data is being analyzed to see if this trend in increased neutron yield will continue.

The results of these measurements will be presented at the 1977 Fall Meeting of the Nuclear Division of the American Physical Society.

## 2.5 Neutron Spectra Above 1 MeV from Nuclear Capture of Negative Pions.

We have measured the energy spectra and yields of neutrons above 1 MeV emitted following nuclear capture of negative pions stopped in C, N, Al, Cu, Ta, Pb, Bi, a tissue-equivalent liquid, and a bone-equivalent powder at the Columbia University Nevis Laboratory. Energies in the region from 1 to 120 MeV were determined from the neutron flight-time between the production target and one of four organic scintillation counters. Flight paths ranged from 1.3 to 2.5 m. Timing was obtained from a pion telescope, which contained a Cerenkov counter to reject electrons. The measured spectra above 5 MeV from C, O, N, and tissue-equivalent targets are identical within experimental errors. Also, the spectra above 5 MeV from C, N, and Pb are in reasonable agreement with the data of Hattersley et al (1965), but disagree with the measurements of Anderson et al (1964), Dey et al (1976), and Venuti et al (1964).

These data are needed in order to evaluate the undesirable radiation damage in negative pion radiotherapy resulting from the interaction of neutrons in healthy tissue outside the treatment volume. Additional objectives are to resolve discrepancies existing in previous measurements and to assess the degree of validity of predictions of Monte Carlo intranuclear cascade calculations. An abstract reporting these results will be presented at the 1977 Fall meeting of the Nuclear Division of the American Physical Society. This work was supported also by a grant from the National Institute of Health.

## 2.6 Planning a Measurement of Neutron Spectra and Yields from Medium-Energy Heavy-Ion Reactions at the Bevalac Accelerator.

In collaboration with workers at the Lawrence Berkeley Laboratory, we have designed and prepared an experiment to measure neutron spectra and yields from medium-energy heavy-ion reactions at the Bevalac accelerator. The experimental run has been allocated beam time by the Program Advisory Committee at the Bevalac and is scheduled for the late fall of 1977. These experiments will be the first step in a series of measurements of neutron yields from heavy-ion reactions at the Bevalac by the Kent State Users Group.

In these experiments, we plan to observe neutrons from heavy-ion beams interacting in thick and thin targets. The first experiment will measure neutron spectra and yields from neon beams interacting in a thin uranium target. The results will be compared with the recent experiment of Gutbrod et al (1976) which measured the energy spectra of protons and other charged particles emitted by neon beams of 250, 400, and 2100 MeV/nucleon bombarding a thin uranium target. The measurements will be performed with the new large volume neutron detectors (see 2.1 above) developed by the Kent State Users Group to minimize the required beam time. Three of these counters have been tested in an actual experimental run at the Indiana University Cycloton Facility. The neutron detectors, electronics, and data-acquisition system will be provided by the Kent State Users Group. The uranium target and beam telescope will be provided by the Berkeley collaboators.

The series of experiments at the Bevalac will provide direct information on the spectra and yields of emitted neutrons useful for shielding considerations at the new heavy-ion facilities such as at Oak Ridge. In particular, these experiments will continue the investigation (see 2.5 above) by our Users Group to see whether the Monte-Carlo intranuclear cascade calcultations of Bertini et al (1974, 1976) are correct in predicting an appreciable number of emitted neutrons with energies greater than the incident energy per nucleon at all angles for heavy-ion reactions. The measurements on thin targets will further test the "fireball" model of Westfall et al (1976) which seemed to be fairly successful in reproducing the emitted proton energy spectra of Gutbrod et al (1976) for such reactions. The thick-target measurements will also be useful for evaluating the use of heavy-ion beams in accelerator-breeder schemes for energy production and for evaluating the undesirable radiation damage in heavy-ion radiotherapy resulting from the interaction of neutrons in healthy tissue outside the treatment volume.

These measurements are an excellent example of the kind of experiment which can be performed quickly and reliably by our Users Group with its development of different kinds of neutron detectors, improved electronics for fast-counting applications, and experience in neutron spectral measurements.

## 3. ACTIVITIES IN PROGRESS

During the remainder of this contract period and the forthcoming year, we plan to continue work in progress leading to publications on the following topics:

(1) The response of NE-228A, NE-228, NE-102, and NE-224 scintillators to protons from 2.43 to 19.55 MeV.

(2) The design and performance of an electronic circuit to perform mean-timing.

(3) The design and development of large-volume plastic scintillators with subnanosecond timing resolution.

(4) Improved Monte-Carlo calculations of neutron detector efficiencies of organic scintillators.

(5) Neutron spectra and yields from 710-MeV alphas stopping in C, Pb, water, and steel targets.

(6) Integrated neutron yields for 710-MeV alphas stopping in C, Pb, water, and steel targets as a function of the neutron threshold energy.

(7) Neutron spectra from the nuclear capture of negative pions.

We plan also to continue with the necessary preparations for performing the measurements of neutron spectra and yields from heavy-ion reactions at the Lawrence Berkeley Laboratory Bevalac accelerator. These preparations include the construction of more large-volume scintillator neutron detectors and some improvements to our existing hardware and software.

## 4. CONTRACT COMPLIANCE

During the 1976-77 academic year, the principal investigator devoted more than 17.5 percent of his time and two faculty associates each devoted more than 10 percent of their time. The principal investigator and the two faculty associates expect to continue to devote this effort during the 1977-78 academic year. During the summer of 1977, the principal investigator devoted more than one-sixth of his time, Assistant Professor Bryon Anderson devoted more than one-third of his time, and Assistant Professor Thomas Witten devoted more than one-twelfth of his time. To the best of our knowledge, there have been no failures to comply with the contract requirements.

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