NUCLEAR INSTRUMENTS AND METHODS 151 (1978) 445-450 ; © NORTH-HOLLAND PUBLISHING CO.

THE RESPONSE OF NE-228A, NE-228, NE-224, AND NE-102 SCINTILLATORS TO PROTONS FROM 2.43 TO 19.55 MeV

RICHARD MADEY, FRANK M. WATERMAN*, ALAN R. BALDWIN, JAMES N. KNUDSON

Department of Physics, Kent State University, Kent, Ohio 44242, U.S.A.

J. D. CARLSON† and J. RAPAPORT

Department of Physics, Ohio University, Athens, Ohio 45701, U.S.A.

Received 26 September 1977

The response of NE-228A, NE-228, NE-224, and NE-102 scintillators to protons from 2.43 to 19.55 MeV has been measured relative to electrons. The NE-228A scintillator has the same high hydrogen content ($CH_{2.11}$) as NE-228; but it has a 30% higher light output. Proton recoils in this energy range were obtained by elastically scattering (20.76 ± 0.13) and (26.08 ± 0.06) MeV neutrons from protons in the scintillators through angles of 20°, 30°, 45°, and 60°. The neutrons were obtained from the T(d, n)α reaction. The measured response (in units of electron energy) for protons above 5 MeV in NE-102 is about 8% higher than that assumed in popular computer programs for calculating the neutron detection efficiency of plastic scintillators. The response of NE-228A is equivalent to that of NE-228. The response of NE-224 differs from that of either NE-102 or NE-228.

1. Introduction

The light output and therefore the pulse height from an organic scintillation counter is known to be a linear function of the energy deposited by an electron above about 100 keV. Since the light output produced in an organic scintillator by a more heavily-ionizing particle such as a proton is not a linear function of the energy lost by the particle, it is necessary to calibrate the response of the scintillator as a function of the energy deposited by the particle. It is customary to state the response of a scintillator to a charged particle in terms of an equivalent-electron energy. The electron energy equivalent to a particle is the energy that produces the same light output or pulse-height from the scintillation counter as the particle.

In this paper, we report measurements of the response (relative to electrons) of four organic scintillators to protons with energies in the interval from about 2 to 20 MeV. The four scintillators were obtained commercially from Nuclear Enterprises, Inc. One is NE-102 plastic; and the other three are NE-224, NE-228, and NE-228A liquids. The NE-228A liquid was developed by Nuclear Enterprises at the request of the Users Group from Kent State University for a scintillator with the same high hydrogen content ($CH_{2.11}$) as NE-228 but with a higher light output in order to improve the pulse-height resolution. The light output of NE-228A is about 30% higher than that of NE-228. Madey et al.[1]) have used NE-228A as the first detector in a self-contained time-of-flight spectrometer for neutrons from about 5 to 200 MeV. The response measurements on the four scintillators were carried out at the Ohio University Tandem Van de Graaff accelerator.

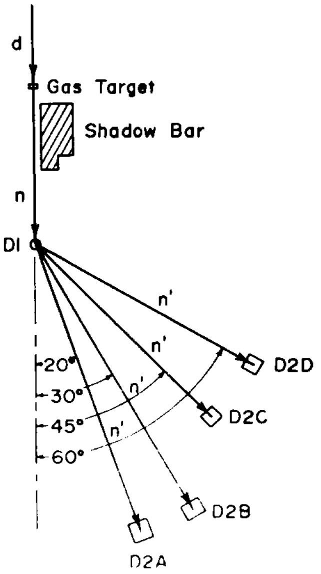

Fig. 1. Experimental arrangement.

---

* Present address: Department of Radiology, The University of Chicago, Chicago, Illinois 60637, U.S.A.

† Present address: Lord Corporation, Erie, Pa. 16512, U.S.A.

2. Experimental arrangement

The experimental arrangement is shown in fig. 1. The scintillator to be calibrated is designated as D1. Monoenergetic 20.76 MeV neutrons generated by the T(d, n)α reaction were scattered elastically from protons in D1. We measured the pulse height of the proton recoil in D1 whenever the scattered neutron was detected in the D2A, D2B, D2C, or D2D scintillation counters. These four scintillation counters were positioned to detect neutrons scattered in D1 through angles of 20°, 30°, 45°, and 60° with respect to the direction of the incident neutrons. Since the incident neutrons are monoenergetic, the kinetic energy of the recoil protons is specified kinematically by the neutron scattering angle. For 20.76 MeV incident neutrons, these angles correspond to recoil proton energies of 2.43, 5.20, 10.40, and 15.60 MeV, respectively. The corresponding recoil proton energies for 26.08 MeV incident neutrons are 3.05, 6.52, 13.04, and 19.55 MeV, respectively.

Monoenergetic neutrons of 20.8 and 26.08 MeV were produced by bombarding a tritium filled gas cell[2]) with 4.40 and 9.00 MeV deuterons. The T(d, n)α reaction has a Q-value of 17.586 MeV. Table 1 lists the energy lost by the deuteron beams in the 5 μm molybdenum entrance foil and in the 3 cm long tritium gas cell; the deuteron beam energy at the center of the target; and the energy of the neutrons produced at 0° with respect to the direction of the deuteron beam. In addition to the monoenergetic neutrons from the T(d, n)α reaction, there exists also a continuum of low-energy neutrons from such reactions as T(d, np) and T(d, 2n)^{3}He with three particles in the final state. Poppe, Holbrow, and Borchers[3]) have reported measurements of the neutron continuum which show that the number of low-energy neutrons produced at a deuteron bombarding energy of 4.00 MeV is much smaller than that at 9.00 MeV; in fact, at 4.00 MeV, the deuteron bombarding energy is below the threshold of the T(d, 2n)^{3}He reaction.

The D1 scintillator was positioned one meter from the center of the gas target at an angle of 0° with respect to the direction of the deuteron beam. The distance from the center of D1 to the centers of the D2A and D2B detectors was 2.0 m; the corresponding distance from D1 to the D2C and D2D detectors was 1.6 m. The position of each detector was determined with a transit located at the position of the D1 detector. An 18″ by 8″ by 4″ thick copper shadow bar shielded the D2A, D2B, D2C, and D2D detectors from the target. The (2½″ diam by 2½″ high) NE-102 and NE-228 D1 scintillators were mounted on Amperex 56AVP and 56DVP photomultipliers, respectively, by 2″ high lucite light pipes that tapered from a diameter of 2½″ to 1¾″. The (2″ diam by 2″ high) NE-228A and NE-224 D1 scintillators were mounted directly on Amperex 56DVP and 56AVP photomultipliers, respectively. The scintillator dimensions and the scintillator type used for the D2A, D2B, D2C, and D2D detectors are listed in table 2.

Fig. 2 is a block diagram of the electronic apparatus used to measure the recoil proton pulse-height spectra. The pulse-height of an event in the D1 detector was recorded only when a coincidence existed between an event in D1 and an event in either D2A, D2B, D2C, or D2D within a time interval comparable to the flight time of the scattered neutron. The electronic system shown in fig. 2 functions in the following manner. The linear fanout provides two outputs of the D1 photomultiplier anode signal. One output is fed into a constant-fraction-timing discriminator which generates a fast negative logic output signal approximately 4 ns wide. The photomultiplier anode

TABLE 1

The energy lost by the 4.40 and 9.00 MeV deuteron beams in traversing the 5 μm molybdenum entrance foil and the 3 cm long tritium gas cell; the mean deuteron bombarding energy; and the resulting neutron energy at 0°.

Deuteron energy	T_d (MeV)	4.40	9.00
Energy lost in foil	ΔT_d foil (keV)	335	210
Energy lost in gas	ΔT_d gas (keV)	210	111
Energy at center of cell	T_d (MeV)	3.96	8.73
Neutron energy at 0°	T_n (MeV)	20.76±0.13	26.08±0.06

TABLE 2

The scintillator dimensions and the scintillator type used for the D2A, D2B, D2C, and D2D detectors.

Detector	Scintillator	Dimensions
D2A	NE-213	5″ diam × 5″ h.
D2B	NE-102	5″ diam × 4″ h.
D2C	NE-228	4″ diam × 4″ h.
D2D	NE-102	4″ diam × 4″ h.

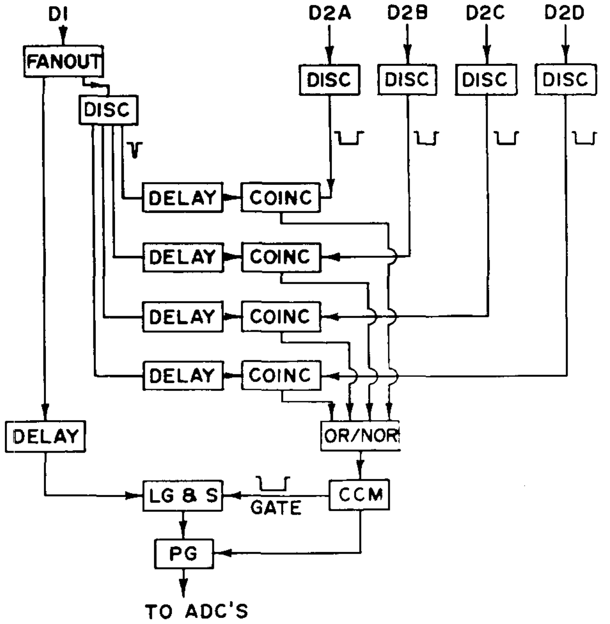

Fig. 2. Block diagram of the electronic apparatus.

signals from the D2A, D2B, D2C, and D2D detectors are fed into separate leading-edge discriminators. The logic output signals from each of these discriminators were increased in width to 20 ns (by an adjustable width control). Output signals from the D2A, D2B, D2C, and D3D discriminators are fed into separate coincidence modules together with a delayed signal from D1. Each D1 signal was delayed so that a D1 signal generated by a recoil proton arrives at the coincidence module within the wide D2 signal. A coincidence between an event in D1 and an event in either D2A, D2B, D2C, and D2D generates a coincidence output signal which triggers the coincidence control module (CCM). A logic output pulse (150 ns wide) generated by the coincidence control module opens the linear gate and stretcher (LG & S). A delayed D1 photomultiplier anode signal from another output of the linear fanout arrives at the stretcher after the gate is open. Signals from the individual coincidence modules were used to multiplex four analog-to-digital converters (ADCs). By multiplexing the ADCs, it was possible to store the recoil-proton pulse-height spectra associated with neutrons that scattered into D2A, D2B, D2C, and D2D in separate 1024 channel segments of the multichannel analyzer memory.

One of us (ARB) designed and constructed the pulse-height measuring system used for this experiment. This system has a linear dynamic range of 200 to 1 and consists of the photomultiplier base, the linear fanout, the linear gate and stretcher, the coincidence control module and the pedestal generator (PG). This system is described in detail elsewhere[1,4]).

3. Calibration with compton electrons

Compton spectra of gamma-rays from ^{137}Cs, ^{54}Mn, ^{22}Na, and ^{228}Th were generated in the D1 scintillator to serve as calibration points for determining the light output of recoil protons relative to that of electrons. The electronic apparatus shown in fig. 2 was used for these measurements; however, the linear gate and stretcher was switched to the ungated mode and a coincidence was not required between D1 and the D2A, D2B, D2C, and D2D detectors. The gamma-ray sources were positioned a few centimeters from the center of the D1 scintillator.

To determine the response of a scintillator to electrons, it is necessary to know the electron energy of some feature in the Compton spectrum. Many authors associate the half-height of the Compton spectrum with the maximum Compton electron energy. In a previous paper[5]), we associated the peak of the Compton spectrum with the maximum Compton electron energy. Knox and Miller[6]) have determined the electron energies that correspond to the peak and the half-maximum of the Compton spectra of gamma-rays from ^{137}Cs and ^{22}Na in a 2" diameter by 2" high NE-213 scintillator mounted on an RCA 8575 photomultiplier. In the Knox and Miller work, the half-height of the Compton spectrum corresponds to an electron energy 11.7 ± 3.4 percent higher than that of the maximum electron energy; and the peak of the Compton spectrum corresponds to an electron energy $(4.9 \pm 1.7)\%$ lower than the maximum Compton electron energy. The advantage of using the peak of the Compton spectrum as a calibration point rather than the half-maximum is that the location of the peak channel is less sensitive than the position of the half-maximum to the pulse-height resolution of the scintillation counter.

In this experiment, we used the peaks of gamma-ray Compton spectra as calibration points, and we associated the peak channel with an electron energy equal to 0.95 that of the maximum Compton electron energy. The gamma-ray sources used were ^{137}Cs, ^{54}Mn, ^{22}Na, and ^{228}Th. The electron energies associated with Compton peaks of the

0.51, 0.66, 0.84, 1.28, and 2.62 MeV gamma-rays are 0.32, 0.46, 0.61, 1.01, and 2.27 MeV, respectively. The multichannel analyzer display was calibrated in units of electron energy from a plot of the channel numbers of the Compton peaks versus the corresponding energies. The equivalent-electron-energy corresponding to a channel number in the recoil-proton pulse-height spectrum is given by this calibration.

4. Results

Fig. 3 is an illustrative example of a recoil-proton pulse-height spectrum. Specifically, fig. 3 shows the recoil-proton pulse-height spectrum in NE-224 from 20.76 MeV neutrons that scattered through an angle of 45°. The peak channel 2384±6 corresponds kinematically to a recoil proton energy of 10.38 MeV. The level of background from chance or accidental coincidences can be seen on either side of the recoil proton peak. The level of background from accidental coincidences was small at a neutron energy of 20.76 MeV; however, at 26.08 MeV, the background from accidental coincidences was so large that the recoil proton peaks at 20° and 30° were generally obscured. The accidental coincidences at 26.08 MeV increased as a result of the large number of low-energy neutrons produced in the T(d, 2n)^{3}He reaction.

In table 3, we list the recoil proton energy and the electron energy for equal pulse height obtained for NE-228A, NE-228, NE-224, and NE-102 scintillators. The listed uncertainties in the recoil proton energy result from the uncertainties in the incident neutron energy and the neutron scattering angle. The listed uncertainties in the electron energy reflect the uncertainty in determining the peak channel for the recoil proton and the uncertainty in calibrating the pulse-height spectrum in units of electron energy. It is evident from the values listed in table 3 that the recoil proton and electron energies that give equal pulse height are the same in NE-228A and NE-228 scintillators. Although the response of protons relative to that of electrons is the same in NE-228A and NE-228, the light output for a given proton or electron energy is greater in NE-228A. The fact that the light output in NE-228A is higher is evidenced by the improved pulse-height resolution observed with NE-228A. In the above context, light output is

TABLE 3

The response of NE-228A, NE-228, NE-224, and NE-102 scintillators to protons.

Proton energy (MeV)	Electron energy (in MeV) for equal pulse height. NE-228A	NE-228	NE-224	NE-102
2.43±0.06	0.58±0.05	0.58±0.08	0.77±0.04	0.64±0.04
5.20±0.08	1.97±0.09	1.96±0.14	2.42±0.10	2.17±0.09
6.52±0.10				3.05±0.12
10.40±0.09	5.26±0.28	5.43±0.33	6.21±0.20	5.55±0.14
13.04±0.12	6.97±0.50			7.40±0.25
15.60±0.06	8.83±0.43	9.07±0.53	10.30±0.33	9.27±0.20
19.55±0.08	11.60±0.60			12.35±0.31

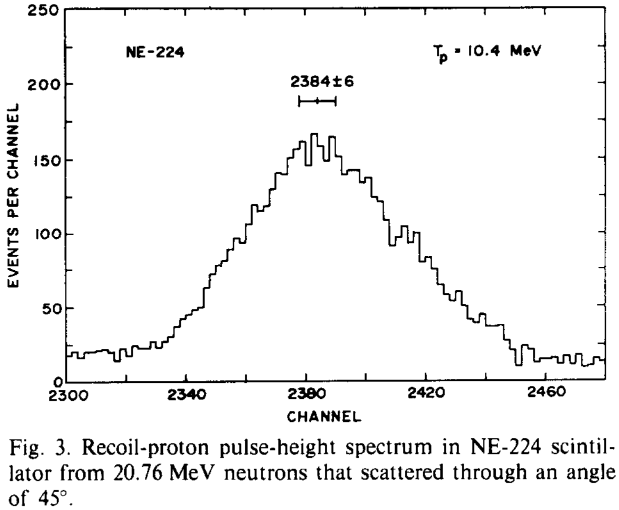

Fig. 3. Recoil-proton pulse-height spectrum in NE-224 scintillator from 20.76 MeV neutrons that scattered through an angle of 45°.

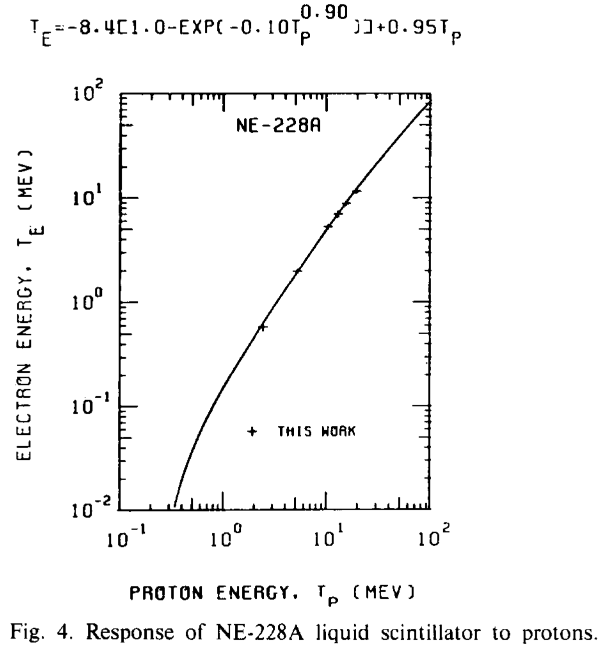

Fig. 4. Response of NE-228A liquid scintillator to protons.

equivalent to the number of photons that produce photoelectrons in the photocathode.

Figs. 4–7 are plots of the measured response of NE-228A, NE-228, NE-224, and NE-102, respectively. These curves plot the electron energy on the ordinate that yields the same height as the proton energy on the abscissa. Since the uncertainty in the recoil proton energy is small, error bars are shown only for the uncertainty in the electron energy. Plotted also in figs. 5–7 are the previous measurements of Madey and Waterman[5]) of the response of NE-228 and NE-102 scintillators to 3.5, 5.8, and 10.5 MeV protons. In the previous work, the peaks of the gamma-ray Compton spectra were taken to be equivalent to the maximum Compton electron energy; however, in figs. 5 and 7, we have reduced by 5% the values reported previously for the electron energy to reflect the conclusion of Knox et al.[6]) that the peak of the Compton spectrum is equivalent to 0.95 that of the maximum Compton electron energy. The previous measurement at 10.5 MeV proton energy is about 11% lower than the present measurement for NE-228 and about 4% lower for NE-102. The difference between the present and previous measurements is most likely a result of differences in the apparatus used to measure the pulse-height spectra. The photomultiplier base[1]) used in the present experiment has a dynamic range more than 5 times greater than that used previously. The apparatus used in the present experiment is linear to within 2% over the range of pulse heights measured. We estimate that the apparatus used in the previous experiments was linear only to about 10%. Another difference is that the de-

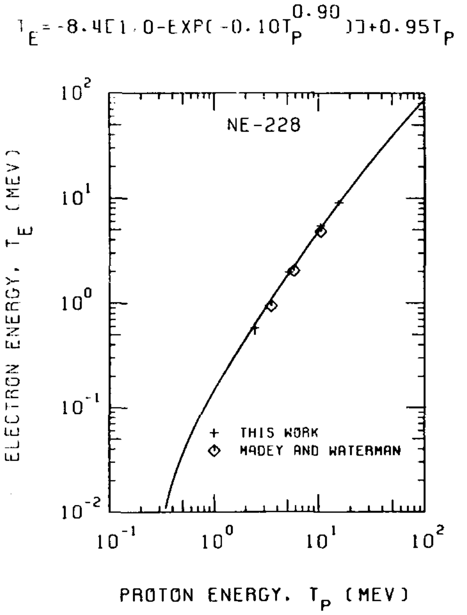

Fig. 5. Response of NE-228 liquid scintillator to protons. Shown also are the previous measurements of Madey and Waterman[5]).

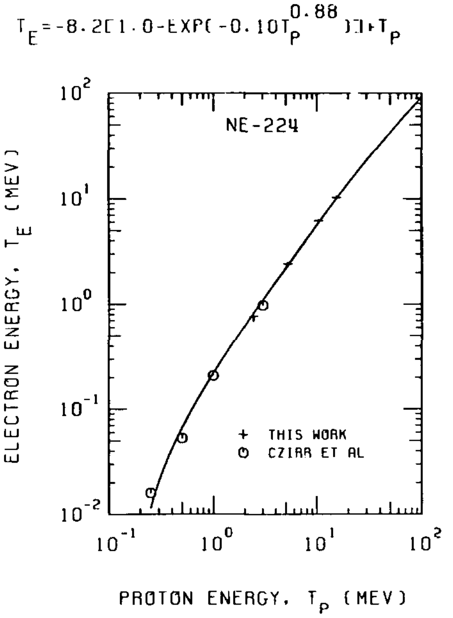

Fig. 6. Response of NE-224 liquid scintillator to protons. Shown also are the previous measurements of Czirr et al.[7]).

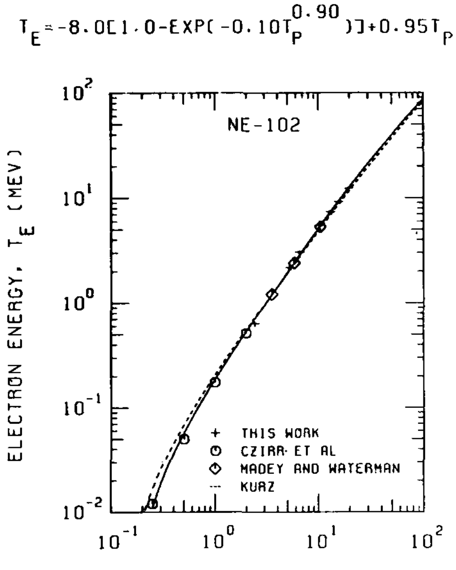

Fig. 7. Response of NE-102 plastic scintillator to protons. Shown also are the previous measurements of Madey and Waterman[5]) and Czirr et al.[7]). The dashed curve is the response of NE-102 to protons used in the computer codes of Kurz[11]) and Stanton[8]).

TABLE 4

Values of the coefficients used in eq. (1) to determine the light output of recoil protons in NE-102, NE-224, NE-228, and NE-228A scintillators.

Scintillator	Coefficients			
	a_1	a_2	a_3	a_4
NE-102	−8.0	−0.10	0.90	0.95
NE-224	−8.2	−0.10	0.88	1.0
NE-228 & NE-228A	−8.4	−0.10	0.90	0.95

tector positions which correspond to the neutron scattering angles were determined more accurately (with a transit) in the present experiment.

In figs. 6 and 7, we have plotted also the previous measurements by Czirr et al.[7]) of the response of 0.5, 1.0, and 2.0 MeV protons in NE-224 and NE-102, respectively. These values are in agreement with the extrapolated curve of our measurements.

NE-102 plastic scintillator is commonly used as a neutron detector. The neutron detection efficiency can be calculated with a Monte Carlo computer program written by Stanton[8]) [and revised by McNaughton et al.[9]) and by Del Guerra[10])]. The Monte Carlo program is based on an earlier analytical program written by Kurz[11]). The Monte Carlo version retains the empirical expressions used by Kurz to compute the light output of recoil protons and alpha particles. The expression relating the light output of a recoil proton to that of an electron has the form

$$T_e = a_1 \left[1 - \exp(-a_2 T_p^{a_3})\right] + a_4 T_p , \qquad (1)$$

where T_p is the recoil proton energy in MeV, T_e is the electron energy in MeV that gives the same light output, and a_1, a_2, a_3, and a_4 are empirically-determined coefficients. The values of the coefficients used by Kurz are $a_1 = -10.68$, $a_2 = -0.07$, $a_3 = 0.89$, and $a_4 = 0.929$.

We carried out a fine-grid χ^2 search to find values of the coefficients a_1, a_2, a_3, and a_4 that would give the best fit of eq. (1) to our measurements and to those of Czirr et al. The values of the coefficients determined in this manner are listed in table 4. The solid lines in figs. 5–7 represent eq. (1) with the coefficients determined from our χ^2 search. The measured and calculated values agree within experimental error.

5. Conclusion

A comparison of the values given by eq. (1) with the coefficients of Kurz and our measurements at Ohio University shows that the Kurz coefficients underestimate the light output in NE-102 for protons above 5 meV by about 8%. A comparison of eq. (1) with the measurements of Czirr et al. for NE-102 shows that the Kurz coefficients overestimate the light output by about 15% at 1 MeV and by about 40% at 0.25 MeV. The response of NE-228A is equivalent to that of NE-228. The response of NE-224 differs from that of either NE-102 or NE-228.

This work was supported in part by the Energy Research and Development Administration under Contract E(11-1)-2231.

References

[1]) R. Madey, F. M. Waterman and A. R. Baldwin, Nucl. Instr. and Meth. **133** (1976) 61.

[2]) J. D. Carlson, Nucl. Instr. and Meth. **113** (1973) 541.

[3]) C. H. Poppe, C. H. Holbrow and R. R. Borchers, Phys. Rev. **129** (1963) 733.

[4]) A. R. Baldwin and R. Madey, Nucl. Instr. and Meth. **128** (1975) 557.

[5]) R. Madey and F. M. Waterman, Nucl. Instr. and Meth. **104** (1972) 253.

[6]) H. H. Knox and T. G. Miller, Nucl. Instr. and Meth. **101** (1972) 519.

[7]) J. B. Czirr, D. R. Nygren and C. D. Zafiratos, Nucl. Instr. and Meth. **31** (1964) 226.

[8]) N. Santon, COO-1545-92 (1971).

[9]) M. W. McNaughton, N. S. P. King, F. B. Brady and J. L. Ullmann, Nucl. Instr. and Meth. **129** (1975) 241.

[10]) A. Del Guerra, Nucl. Instr. and Meth. **135** (1976) 337.

[11]) R. J. Kurz, UCRL-11339 (1964).