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THE PROBLEM OF MEASURING THE ABSOLUTE YIELD OF 14-Mev NEUTRONS BY MEANS OF AN ALPHA COUNTER

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ABSTRACT

The assumptions used to derive the total neutron yield per detected alpha particle (from the D-T reaction) which were derived in an earlier report are re-examined in the light of additional experimental information. It is concluded that, for an alpha counter at 90° to the incident beam direction, the assumptions introduce practically no difficulties. Therefore, for precise monitoring in the absence of certain target information, it is recommended that this configuration be used. For counters at angles different from 90°, nonuniformity of target loading contributes the most serious error to the computed yield.

INTRODUCTION

In UCRL-4266,[1] an expression was derived for the total neutron yield per detected α particle.

$$N = \frac{4\pi \int_0^E \frac{\sigma_{cm}(\theta,\epsilon)}{\frac{d\epsilon}{dx}}\, d\epsilon}{\Delta\Omega_\alpha \int_0^E \frac{\sigma_{cm}(\theta,\epsilon)}{\frac{d\epsilon}{dx}} \left(\frac{d\omega_{cm}}{d\omega_{lab}}\right)_\alpha d\epsilon} \equiv \frac{4\pi}{\Delta\Omega_\alpha} R_\alpha , \qquad (1)$$

where $\Delta\Omega_\alpha$	is the solid angle subtended by the α counter,
$\sigma_{cm}(\theta, \epsilon)$	is the differential cross section for the D-T reaction in the center-of-mass system,
$d\epsilon/dx$	is the rate of energy loss of deuterons in the target material,
$d\omega_{cm}/d\omega_{lab}$	is the solid angle conversion factor from the center-of-mass to the laboratory system for the detected α particles, and
E	is the incident deuteron energy.

Implicit in the derivation of this expression are the following assumptions:

1. The reaction products are isotropically distributed in the cm system for the incident deuteron energies to 500 kev.
2. $d\epsilon/dx$ is fairly well known in the region $0 < \epsilon < E$.
3. Uniform loading of tritium atoms to a depth at least equal to the range of incident deuterons.
4. No scattering of incident deuterons.

Subsequent experience in measuring absolute cross sections for 14-Mev neutron interactions has cast some doubt on the reliability of this calculated calibration. This report presents the results of the investigation to determine the validity of the expression and the factors that contribute to it.

DISCUSSION OF THE ASSUMPTIONS

1. Data available at the writing of UCRL-4266[1] led to the assumption of isotropy, in the cm system, of reaction products for incident deuteron energies up to 500 kev. More recent information, however, shows a measurable anisotropy above 200 kev. In Fig. 1 are presented the data of Bame and Perry[2] on the angular distribution of neutrons in the cm system for several bombarding energies. The angular dependence may be represented as

①* $$\frac{\sigma_n(\theta)}{\sigma_n(0)} = 1 \qquad E < 200 \text{ kev}$$

②* $$\frac{\sigma_n(\theta)}{\sigma_n(0)} = 0.998 + 0.0213 \cos\theta_n - 0.0190 \cos^2\theta_n \qquad E = 350 \text{ kev}$$

③* $$\frac{\sigma_n(\theta)}{\sigma_n(0)} = 0.992 + 0.0382\, \theta_n - 0.0303 \cos^2\theta_n \qquad E = 500 \text{ kev.}$$

Since, in the cm system, $\theta_n = \pi - \theta_\alpha$ the α-particle distribution is given by

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[*] The circled numbers refer to similarly numbered curves in Fig. 1.

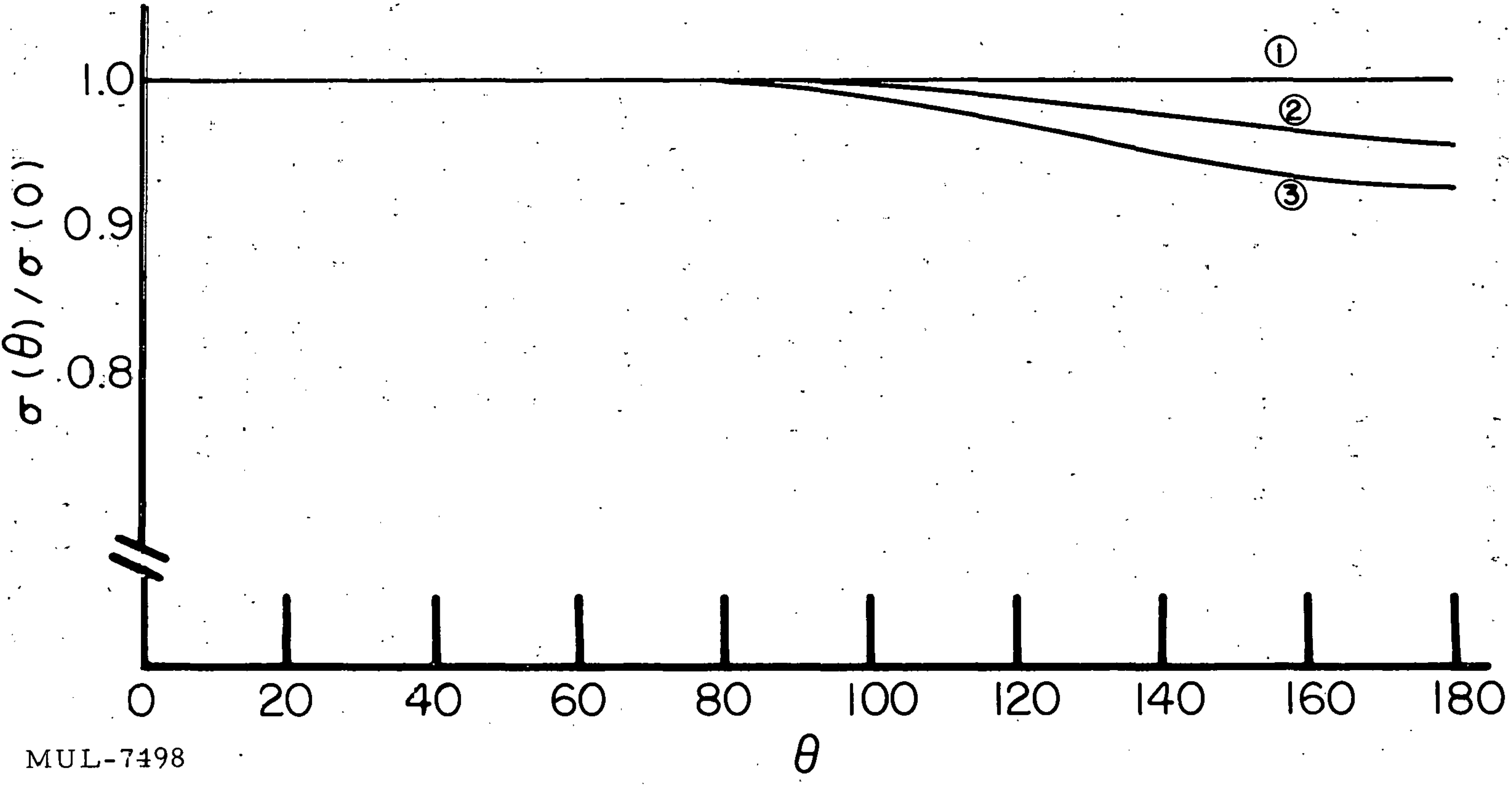

Fig. 1. Angular distribution of neutrons from T(d, n)He^4 reaction.

$$\frac{\sigma_a(\theta)}{\sigma_a(0)} = 0.998 - 0.0213 \cos \theta_a - 0.0190 \cos^2 \theta_a \qquad E = 350 \text{ kev}$$

$$\frac{\sigma_a(\theta)}{\sigma_a(0)} = 0.992 - 0.0382 \cos \theta_a - 0.0303 \cos^2 \theta_a \qquad E = 500 \text{ kev.}$$

This lack of isotropy does not affect the value obtained for the numerator of Eq. (1) since it represents the total yield of neutrons. The denominator, however, can be affected because it is evaluated at a particular angle. Calculation shows that the observed anisotropy would affect the contribution of 500 kev deuterons to the integral by about 1% and of 350-kev deuterons by about 0.5%. Since the yield of α particles by deuterons in the 300-500 kev range is about one-seventh of the total, it is clear that the assumption of isotropy in calculating R has contributed an error no larger than a small fraction of 1%.

2. The rate of energy loss of deuterons in the titanium-tritium target material was calculated from the expression

$$\frac{d\epsilon}{dx} = \frac{48}{48 + 3\mathcal{N}} \left(\frac{dE}{dx}\right)_{Ti} + \frac{3\mathcal{N}}{48 + 3\mathcal{N}} \left(\frac{dE}{dx}\right)_{T} ,$$

where $(dE/dx)_{Ti}$ and $(dE/dx)_T$ refer to deuterons in normal titanium and tritium, and $\mathcal{N}$ represents the number of tritium atoms per titanium atom.

The rate of energy loss of protons in hydrogen was used to derive $(dE/dx)_T$, down to a deuteron energy of about 25 kev. $(dE/dx)_{Ti}$ was derived by interpolating between proton data for aluminum and copper and, assuming that dE/dx was only a function of the velocity of the particle, changing the energy scale to apply to deuterons. Since proton data was available only down to 50 kev, deuteron data could be derived only to 100 kev. Since the peak yield of the D-T reaction occurs near 100 kev, it might be feared that an extrapolation below 100 kev would be a little risky. This is not quite the case because $d\epsilon/dx$ appears in both the numerator and denominator of R. Calculation shows that a 50% error in $d\epsilon/dx$ below 100 kev yields a 2% change in R.

$d\epsilon/dx$ also depends on the loading factor, the ratio of tritium to titanium atoms. In early calculations a loading factor of 1 was assumed.

Later experience showed that it was not unusual to have loading factors of 1/2 or less. It is easy to compute that a change of a factor of 3 in the loading factor will yield a 10% change in $d\epsilon/dx$, while an infinite change (no tritium at all) will yield but a 15% change. It is clear, however, that, because $d\epsilon/dx$ appears in both the numerator and denominator of R, a change in the magnitude of $d\epsilon/dx$ affects R not at all. Only a change in the shape, that is, the energy dependence of $d\epsilon/dx$, is important. Since the energy dependence of $d\epsilon/dx$ is a very weak function of the loading factor, and since even a 50% change in $d\epsilon/dx$ in a sensitive part of the yield curve gave only a 2% change in R, the loading factor can be expected to have an unimportant influence on R.

3. The tritium distribution with depth in the target was assumed constant in the absence of any other information. It is possible to imagine, however, a surface layer lacking in tritium atoms existing on fresh targets or being built up with bombardments. The existence of a surface layer would have the effect of lowering the value of the upper limit on the integrals and reducing the value of R.

4. Thomas[3] has calculated that for deuterons of 400 kev incident on a zirconium-tritium target the rms multiple scattering angle will be 20 degrees after a loss of 300 kev in the target material. Since the factor $d\omega_{cm}/d\omega_{lab}$ in the denominator of Eq. (1) is derived from kinematical considerations in which the reacting deuteron direction is taken to be that of the beam, neglect of multiple scattering can be expected to affect the accuracy of this term. $d\omega_{cm}/d\omega_{lab}$ is a cosine-like term which is given approximately by

$$\frac{d\omega_{cm}}{d\omega_{lab}} \approx \left(\frac{\cos\phi + K}{K}\right)^2 ,$$

where ϕ is the angle which the α particle makes with the incident deuteron direction and K is a constant (>> 1) determined by the kinematics. Multiple scattering would yield a scatter of ϕ's about the α observation angle. This suggests that no correction for multiple scattering would be necessary for an α observation angle about which this function is closely linear. Such an angle is 90 degrees. For α's observed at 135 degrees the correction due to this effect has been estimated as less than 0.5%.

MEASUREMENTS

If we drop the assumption of uniform loading of the target, the expression for R becomes

$$R' \equiv \frac{\int_0^E n(x) \frac{\sigma_{cm}(\theta,\epsilon)}{\frac{d\epsilon}{dx}} d\epsilon}{\int_0^E n(x) \frac{\sigma_{cm}(\theta,\epsilon)}{\frac{d\epsilon}{dx}} \left(\frac{d\omega_{cm}}{d\omega_{lab}}\right)_\alpha d\epsilon} \quad (2)$$

Now, it turns out that for an α detector at 90 degrees, $d\omega_{cm}/d\omega_{lab}$ is a very slowly varying function of energy (e.g., from 0 to 500 kev the ratio goes from 1 to 0.9775, and the weighted average of $d\omega_{cm}/d\omega_{lab}$ in the denominator integral, if n(x) is constant, is 0.9911 at 500 kev and 0.9926 at 350 kev). Thus for a 90-degree α detector we may write

$$R'_{90°} \equiv \frac{\int_0^E n(x) \frac{\sigma_{cm}(\theta,\epsilon)}{\frac{d\epsilon}{dx}} d\epsilon}{\left(\frac{d\omega_{cm}}{d\omega_{lab}}\right)_{90°} \int_0^E n(x) \frac{\sigma_{cm}(\theta,\epsilon)}{\frac{d\epsilon}{dx}} d\epsilon} \quad (3)$$

$$\equiv \frac{1}{\left(\frac{d\omega_{cm}}{d\omega_{lab}}\right)_{90°}},$$

practically independent of our knowledge of the loading factor and of $d\epsilon/dx$. This feature makes it possible to devise a rather sensitive experimental method for evaluating R and testing the assumptions on which the calculations were based.

To this end a target assembly was designed with two α arms (see Fig. 2) so that α particles could be detected simultaneously at 90 and 135 degrees. The ratio of the number of α's observed at 90 degrees to those observed at 135 degrees is

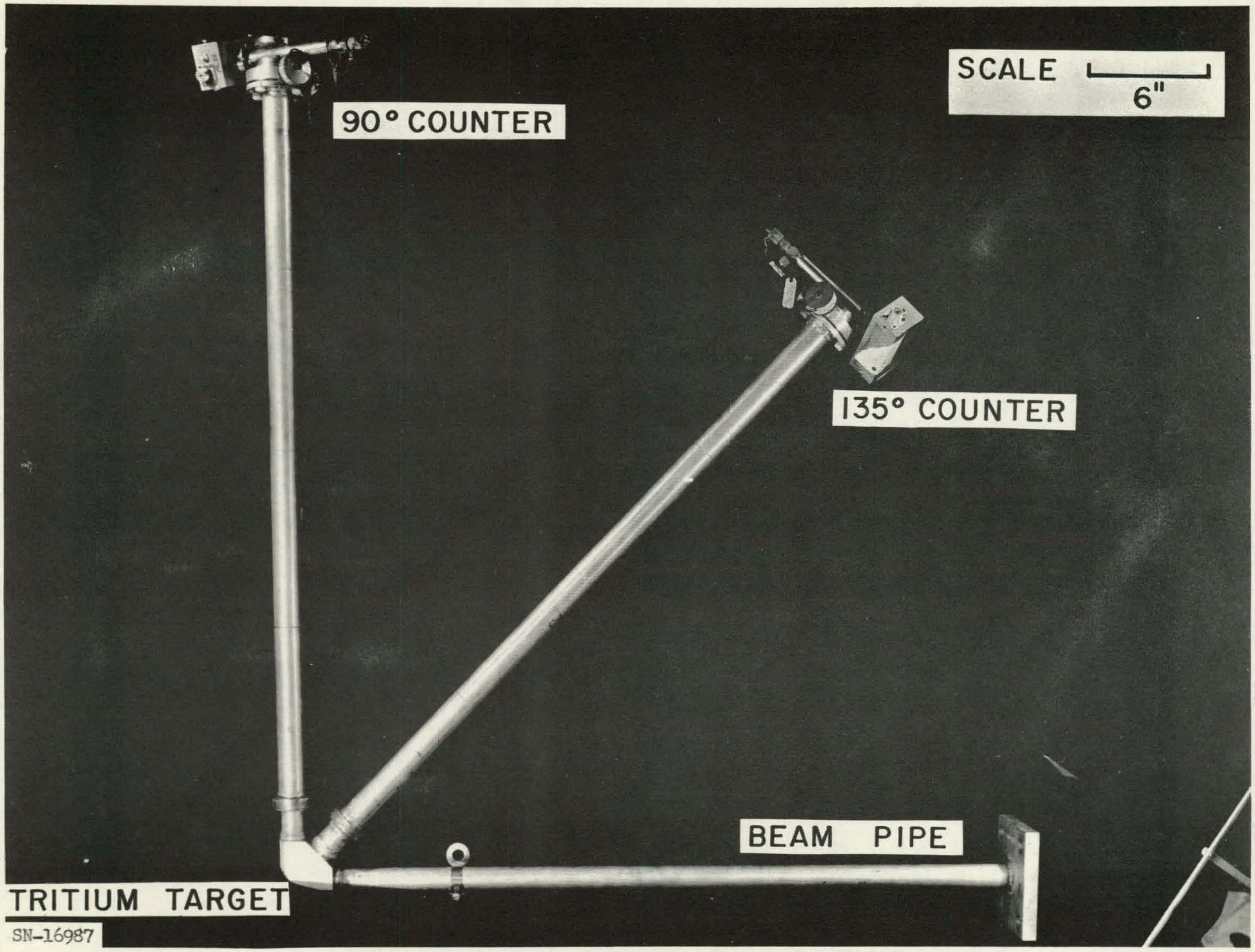

Fig. 2. 90-135° alpha counter assembly.

$$\frac{N_\alpha(90^\circ)}{N_\alpha(135^\circ)} = \frac{\Delta\Omega_{90^\circ}}{\Delta\Omega_{135^\circ}} \frac{\overline{\left(\frac{d\omega_{cm}}{d\omega_{lab}}\right)_{90^\circ}} \int_0^E n(x) \frac{\sigma_{cm}(\theta,\epsilon)}{\frac{d\epsilon}{dx}} \, d\epsilon}{\int_0^E n(x) \frac{\sigma_{cm}(\theta,\epsilon)}{\frac{d\epsilon}{dx}} \left(\frac{d\omega_{cm}}{d\omega_{lab}}\right)_{135^\circ} d\epsilon}$$

$$= \frac{\Delta\Omega_{90^\circ}}{\Delta\Omega_{135^\circ}} \overline{\left(\frac{d\omega_{cm}}{d\omega_{lab}}\right)_{90^\circ}} \; R'_{135^\circ} . \qquad (4)$$

Thus, a fundamentally simple measurement of the ratio of two numbers leads to a rather precise test of the calibration constant R'_α.

The 90-135 degree assembly was mounted on the 26-degree port of the Cockcroft-Walton. A collimator in the beam pipe insured that only the active part of the target was exposed to the beam. The α particles were detected in argon-CO_2 gas proportional counters after passing through 1 mg/cm^2 aluminum-coated Mylar foils. A remotely controlled shutter in each α arm made it possible to measure background contributions to the α spectrum. Background corrections were customarily less than 3%.

A schematic diagram of the α-monitoring electronics is shown in Fig. 3. The multichannel analyzer served primarily as a visual means for setting amplifier gains and discriminator levels quickly and accurately.

Figure 4 shows the pulse-height distributions of the alpha particles in the two counters for several different deuteron bombarding energies. The shift of the peak toward lower energies as the incident energy increases is due to the fact that the most prolific deuterons (those in the neighborhood of 100 kev) are being formed deeper in the target material. Furthermore, it is suggested that the larger low-energy tail observed in the 90° counter is due to the fact that, in our geometry, 90° alphas had to travel through 40% more target material before being detected. Scattering could increase this considerably with consequent appreciable losses of energy. Below about 400 kev this behavior of the spectrum gave no difficulty in setting the discriminator level for precise monitoring of the yield. Above 400 kev, however, the separation between significant portions of the alpha spectrum and noise was not as clean and the same degree of confidence could not be held for the measured number.

In the course of a run, counts were observed in the 90° and 135°

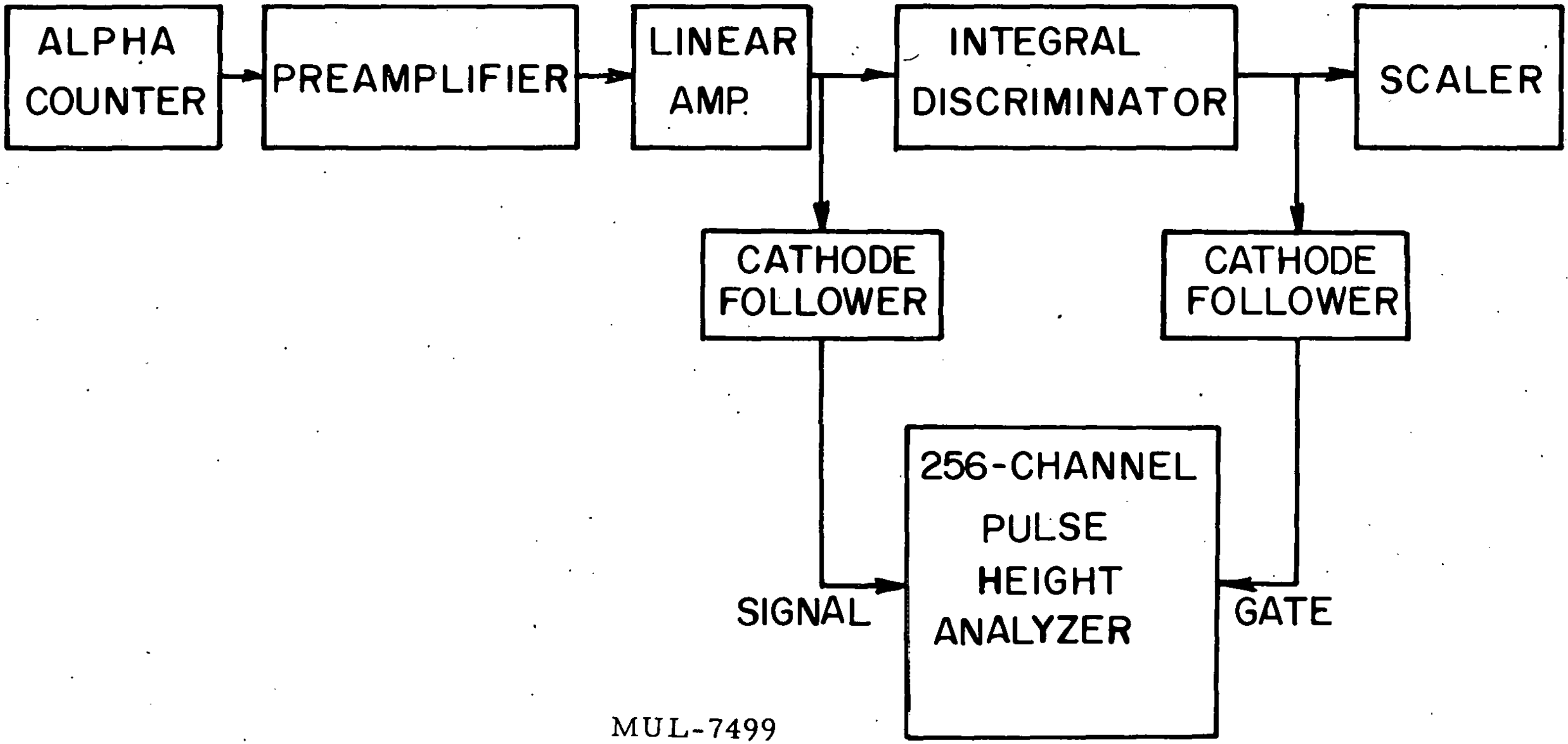

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Fig. 3. Alpha-monitoring electronics.

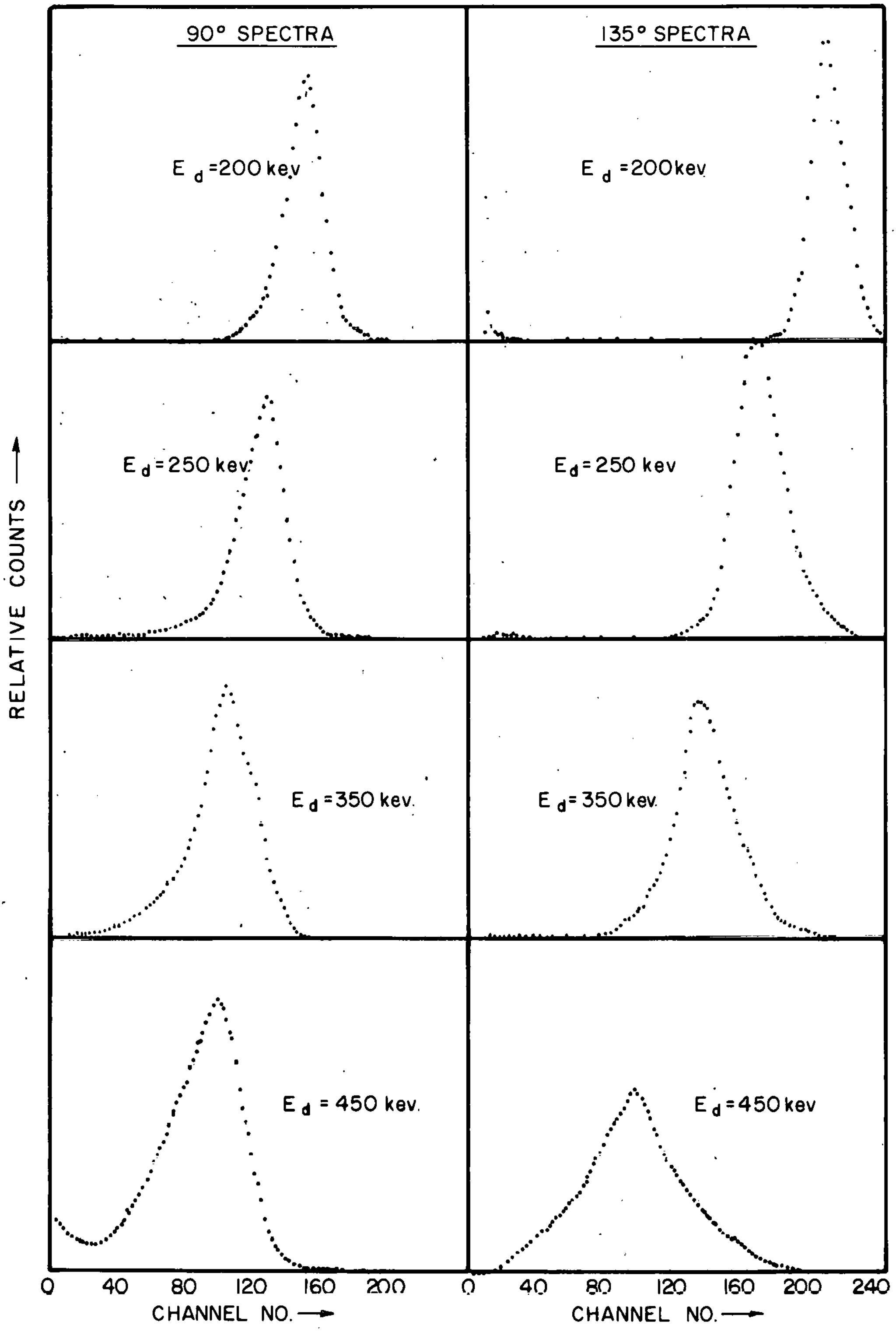

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Fig. 4. Change in shape and channel position of alpha spectrum as E_d is varied.

alpha counters simultaneously. Then the shutters were inserted and, using a neutron detector as monitor, background counts were observed. Net alpha counts were deduced after both observations had been corrected for dead-time in the system.

RESULTS

In order to determine whether target parameters were important, a rather broad selection of targets was studied, with stress laid on obtaining a good sampling of loading parameters and dates of preparation. Table I presents the target data.

Table I. Characteristics of targets.

Target No.	Tritium (cc)	Titanium (mg)	Loading factor Tr/Ti	Zeus meter reading of β activity
818	1.13	11.7	0.414	240
1037	1.55	7.7	0.861	350
1018	1.52	5.9	1.102	1100
813	1.22	12.7	0.432	235
1012	2.58	10.9	1.014	1000
1015	3.47	13.5	1.100	1000
1010	1.94	7.9	1.052	600
993	2.14	8.5	1.078	600
1008	2.56	13.7	0.800	600
1016	4.12	16.0	1.102	900
815	1.22	12.6	0.414	250
742	4.25	24.4	0.746	1200
807	1.23	12.1	0.436	- -
705	1.61	12.5	0.551	700
814	1.23	12.8	0.412	240
822	1.80	11.4	0.676	450
809	1.73	14.3	0.518	700
823	1.90	12.0	0.678	500

For each target, observations of the 90-135° ratio were made at several deuteron bombardment energies in the range $150 \leq E \leq 450$ kev. These ratios appear in Table II.

Table II. Ratio $N_a(90°)/N_a(135°)$ for various targets and E_d's.

Target	Incident deuteron energy E_d (kev)						
No.	150	200	250	300	350	400	450
818	1.355	1.341	1.384		1.349		1.266
1037		1.302	1.357		1.403		1.406
1018		1.392			1.407		1.431
1010	1.365	1.380	1.40		1.412		1.417
813		1.342	1.374		1.321		1.234
1012	1.363	1.388	1.395		1.408		1.427
1015	1.350	1.391	1.373		1.407		1.407
993	1.360		1.390		1.411		1.415
1008	1.358		1.385		1.410		1.409
742		1.380	1.370	1.340	1.274	1.237	1.194
814		1.3750	1.355	1.337	1.314	1.274	1.20
705		1.362	1.351	1.346	1.304	1.212	1.172
807		1.351	1.342	1.350	1.333	1.309	1.264
815		1.330	1.318	1.318	1.292	1.272	1.258
822		1.338	1.336	1.320	1.318	1.282	1.226
823		1.336	1.328	1.325	1.298	1.279	1.236

Figures 5a and 5b are graphical representations of these ratios after having been converted to R's by means of Eq. (4). The data have been displayed separately for those targets that behaved as expected theoretically and those that behaved anomalously. The precision of the measurements is ± 1% as determined by the measurements of the solid angles and counting statistics and verified by their reproducibility.

Figure 5a shows that one group of targets yields an energy dependence for $R'_{135°}$ very similar to that expected from the evaluation of the integral in Eq. (1). However, the magnitude of $R'_{135°}$ turns out to be consistently 1.5% to 2.5% lower than that calculated. Within the precision of the measurements, this lowering could be understood in terms of the existence of a surface

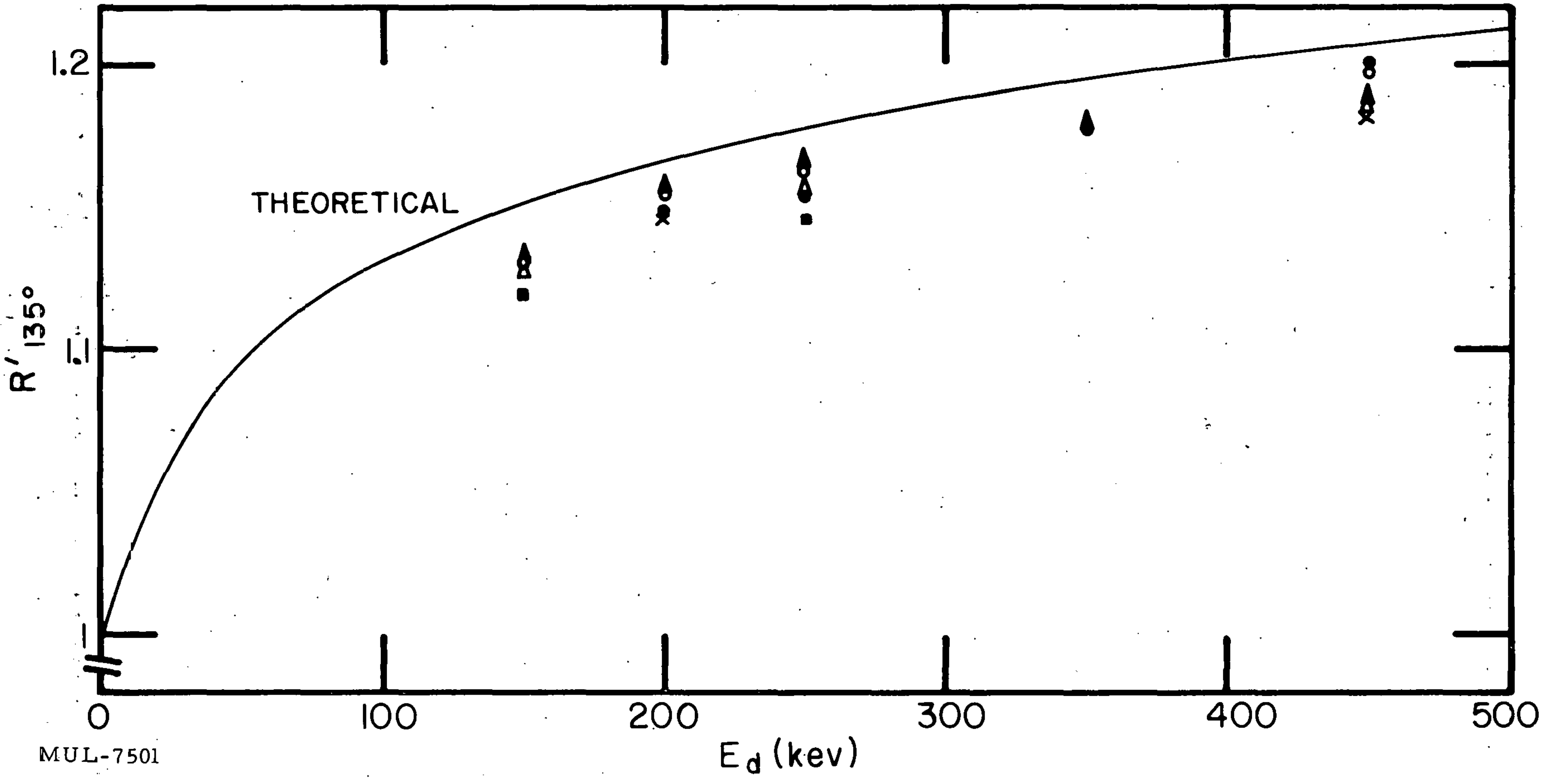

Fig. 5a. $R'_{135°}$ vs E_d for normal targets.

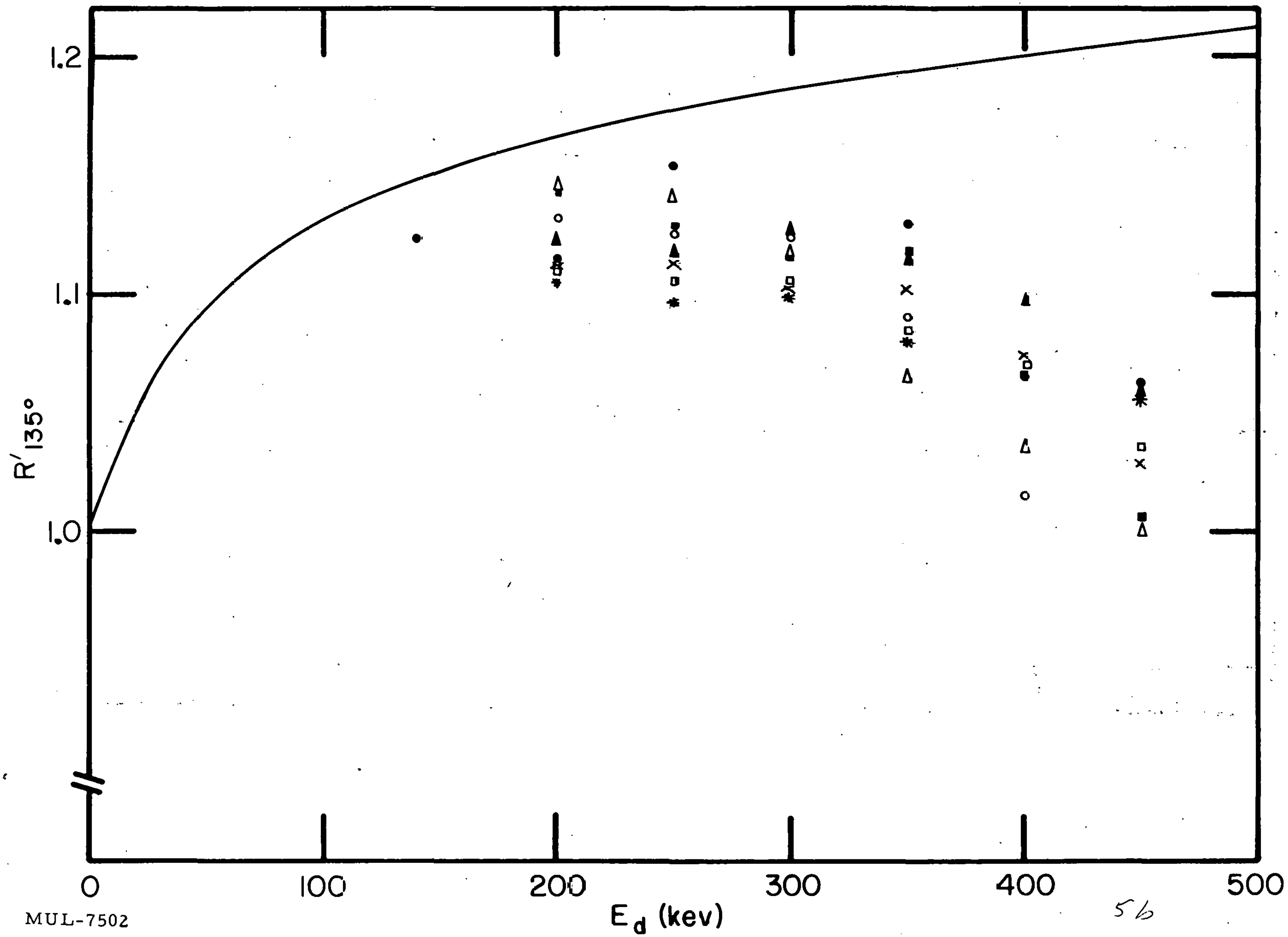

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Fig. 5b. $R'_{135°}$ vs E_d for anomalous targets.

layer, about 50 kev thick, depleted in tritium. The assumption of isotropy also yields a discrepancy in the right direction; however, it is expected to be about 1% at 500 kev and to decrease rapidly with decreasing energy. Likewise, the effect of scattering of the incident deuterons is to give a smaller value to $R'_{135°}$. The correction was estimated to be less than 0.5% at 500 kev and one would expect this to decrease with decreasing energy. The possibility that counts were lost from the 90° detector by absorption or scattering of the alpha particles emerging from the target has been ruled out on the basis of our observations of alpha pulse-height distributions. Important effects of this sort would be made obvious by the ragged appearance of the lower edge.

The behavior of the targets displayed in Fig. 5b is understandable in terms of nonuniform loading with the tritium concentration increasing rapidly with depth. A simple test for uniformity of loading would be to plot the loading factor N_T/N_{Ti} vs the weight of titanium. Uniform loading would show N_T/N_{Ti} = constant, while if the tritium were concentrated in a relatively thin layer one would expect N_T/N_{Ti} to decrease monotonically with the weight of titanium.

Figure 6 shows that the "good" targets, those that behave as expected with regard to the energy dependence of $R'_{135°}$, do indeed indicate that the loading is uniform. Unfortunately, there is not a sufficiently large range of titanium weights for the "anomalous" targets to show conclusively that the tritium was not uniformly distributed. We may only conclude that the average loading was relatively low and the best evidence for nonuniform loading remains the observed energy dependence of $R'_{135°}$.

CONCLUSIONS

In examining the assumptions made for calculating the calibration constant for an alpha counter monitor, it is concluded that:

1. For an alpha counter at 90° to the incident beam direction, the assumptions introduce practically no difficulties; therefore, for precise monitoring in the absence of certain target information, it is recommended that this configuration be used. Above an incident deuteron energy of about 400 kev, however, the alpha spectrum degenerates on the low side so that one must take considerable care to insure proper monitoring conditions.

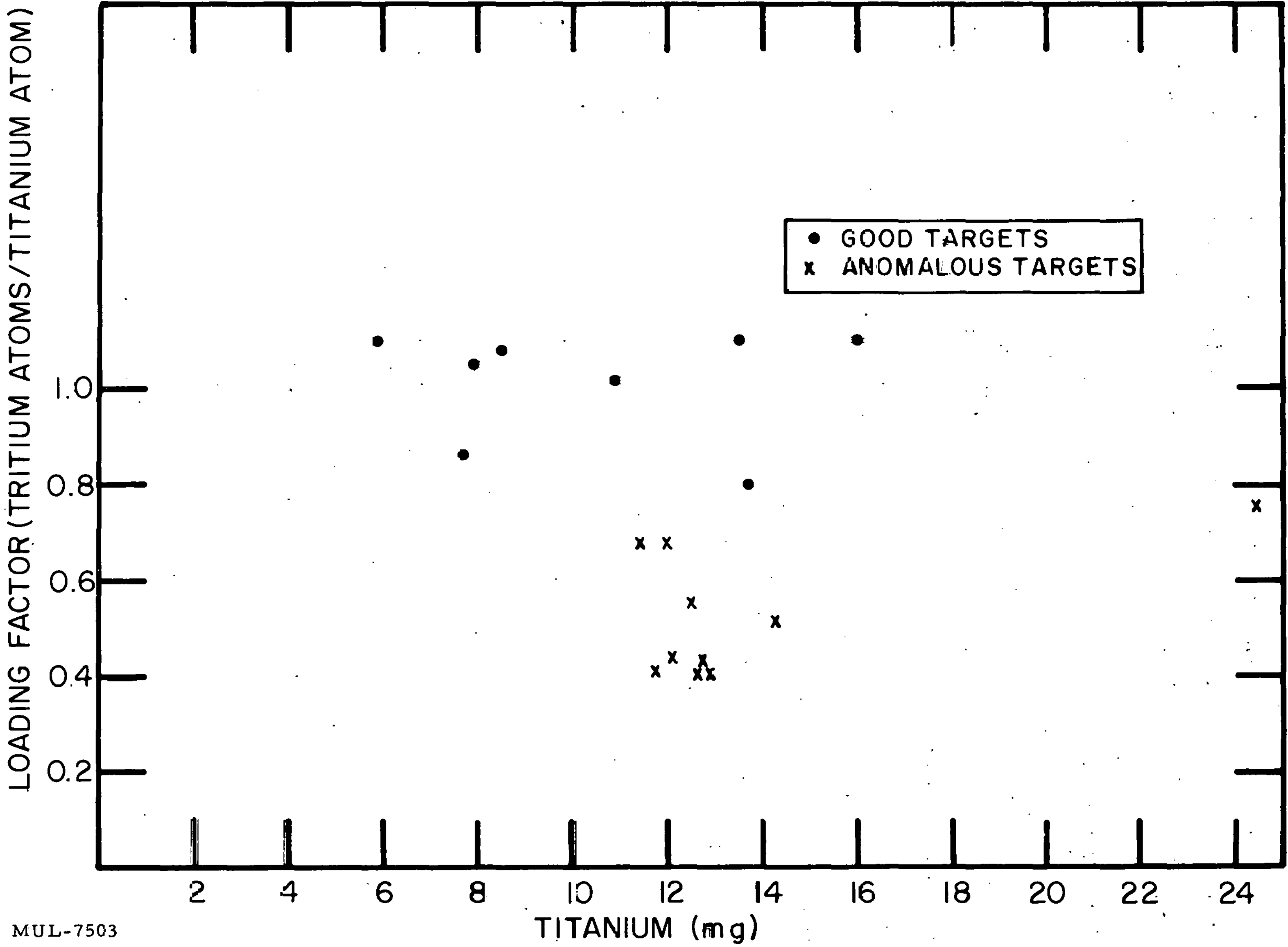

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Fig. 6. Loading factor vs weight of Ti.

2. For alpha monitors at angles different from 90°, it was shown experimentally that nonuniformity of target loading contributed the most serious error to the computed calibration constant.

3. For the targets investigated, those having a loading factor of at least 0.8 T atom per Ti atom were sufficiently uniformly loaded to yield calibration constants that behaved normally.

4. For uniformly loaded targets, a discrepancy in the observed and computed $R'_{135°}$ amounting to (2.0 ± 1)% was noted.

ACKNOWLEDGMENT

It is a pleasure to acknowledge the very helpful participation in this study of the Cockcroft-Walton crew under the direction of L. M. Erickson and R. V. Cedarlund.

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[2] S. J. Bame, Jr., and J. E. Perry, Jr., Phys. Rev. 107, 1616 (1957).

[3] R. G. Thomas, Private communication.

APPENDIX

CALIBRATION OF THE 174° α ARM

In our study of γ rays from 14-Mev-neutron interactions with various nuclei in ring geometry, it is desirable to use a target assembly that can be completely shielded from the view of the detector. To this end, a target assembly was constructed for monitoring alpha particles which were emitted in a direction making an angle of 174° with the incident beam (see Fig. 7).

Since the difficulties encountered with the calculation of the calibration constant for the 135° alpha counter are expected to be aggravated at 174°, no attempt was made to calculate R (174°). Rather the 174° assembly was calibrated against the 90° assembly using a neutron detector as intermediary.

Neutrons were detected in 1/2 in. × 1/2 in. cylindrical plastic scintillator placed directly in line with the incident deutron beam. To achieve insensitivity to gain shifts in the electronic amplifiers, the signals were passed through a differential discriminator set to select pulses in the flat region of the knock-on spectrum. The behavior of this system is displayed in Fig. 8. Long-term tests of this system showed that the ratio of neutron counts to alpha-particle counts was constant well within statistics.

The experimental procedure was to measure the number of alpha counts per detected neutron for first the 90° assembly, and then for the 174° assembly. In each case corrections were made for dead time. The ratio of the two measurements and knowledge of the 90° assembly calibration gives us the 174° assembly calibration.

Different targets were observed, in order to determine the extent of variation among them. Several completely separate runs were conducted to assure ourselves that our measurements were reliable and meaningful. All observations were made at a bombarding energy of 350 kev because it is at this energy that the gamma-ray work is being done.

Table III displays the results of our measurements. It appears that all but target No. 813 gave a ratio $N_\alpha(90°)/N_\alpha(174°) = 0.127$ within 1%.

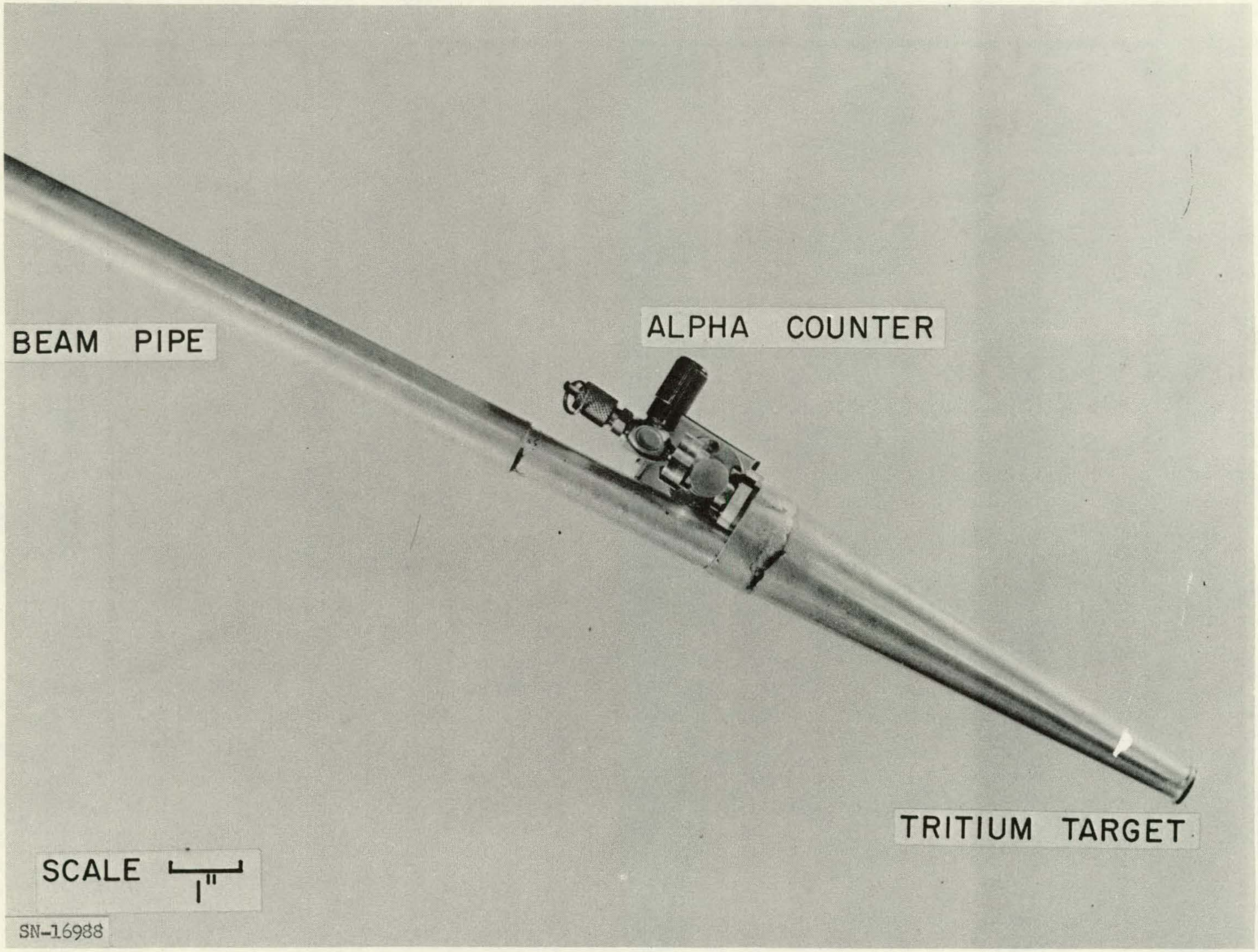

Fig. 7. 174° alpha counter assembly.

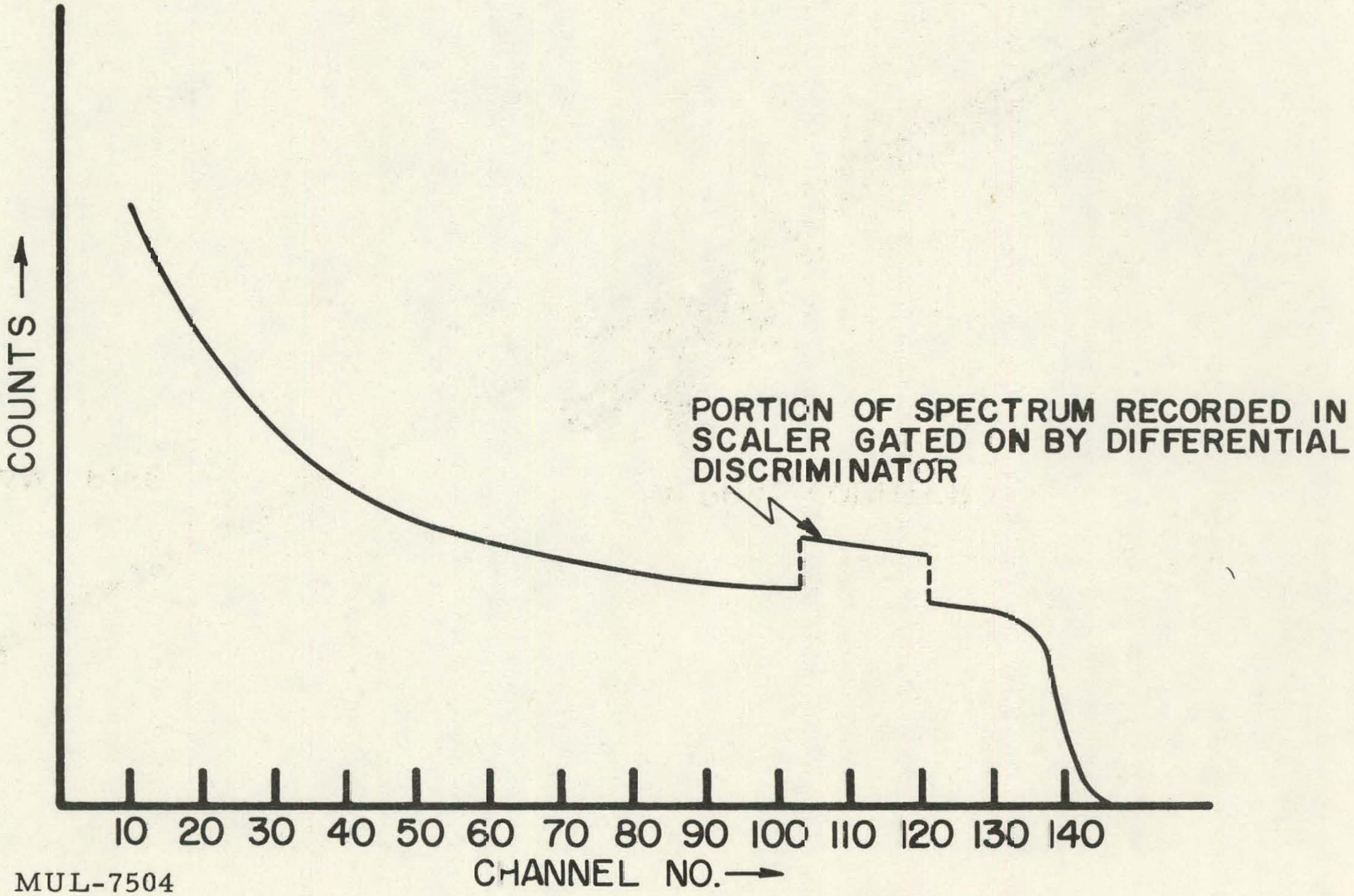

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Fig. 8. Neutron spectrum produced by knock-on protons in plastic scintillator.

This is not at all surprising since target No. 813 is the only one in the list which was previously revealed to behave anomalously.

Table III. Ratio $N_a(90°)/N_a(174°)$ for various targets and E_d = 350 kev.

Target No.	$\frac{N_a(90°)}{N_a(174°)}$
813	0.115
993	0.1263
1008	0.126
1016	0.128
1010	0.128
1018	0.1283
1012	0.127

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