

tion in the fundamental absorption band<sup>5</sup> is not required. In order to keep the sample in essentially the same state of activity for photo-emission, all subsequent work on activation and deactivation effects was carried out using photon energies less than 3.0 ev.

Figure 2 shows the enhancement of photo-emission starting from a state (A) which was less active for photo-emission than the sample in Fig. 1(A). Thirty minutes irradiation at  $h\nu=3.37$  ev changed the sample to state (B). At  $h\nu=1.8$  ev a 1000-fold increase was observed, whereas at  $h\nu=2.5$  ev the increase was by a factor of 30. It is apparent that the effect of irradiation is considerably greater near the photoelectric threshold than for higher energies. This feature of the enhanced photo-emission from BaO differs from the effect<sup>4</sup> in KI, in which the increase occurs simultaneously for all wavelengths.

At 300°K the enhancement effect decays slowly with time but at different rates for the various wavelengths, Fig. 3. Wave-

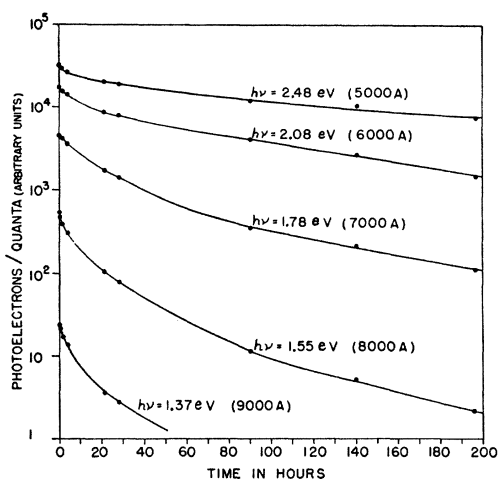


FIG. 3. Decay of enhanced photo-emission from BaO at 300°K at various wavelengths.

lengths near the photoelectric threshold for which the enhancement effect is most pronounced have the greater decay rate. This decay increases rapidly with higher temperatures; at 600°K complete deactivation takes place in 30 minutes. It is apparent that the decay does not have a simple exponential time dependence nor does it seem to obey a second-order reaction law. If one assumes that the decay rate has an initial exponential dependence on  $E/kT$ , where  $E$  is the activation energy, and uses  $1/t$ , as a measure of the decay rate, where  $t$  is the time required for the photo-current to fall to one-half value, an activation energy may be evaluated. At  $h\nu=1.8$  ev this activation energy is 0.92 ev and at  $h\nu=2.5$  ev the energy is 1.07 ev.

Although it is perhaps too early to attempt a complete interpretation of this enhanced photo-emission effect, it seems likely that incompletely filled donor levels lying in a region 1 ev below the conduction band together with a few low lying levels above the filled band will account qualitatively for the observed phenomena. This enhanced photo-emission effect has been observed on three BaO cathodes although all of the data presented here are for a single sample.

The author acknowledges the helpful advice of Professor Albert Eisenstein and his assistance in the preparation of this manuscript.

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<sup>1</sup> J. E. Dickey and E. A. Taft, Phys. Rev. **80**, 308 (1950).

<sup>2</sup> Mallinckrodt Ultra Pure BaCO<sub>3</sub>, containing less than 1 ppm Sr, sprayed onto a pure nickel base and converted to the oxide in vacuum. Coating thickness about  $10^{-3}$  cm.

<sup>3</sup> L. Apker, Phys. Rev. **78**, 352 (1950).

<sup>4</sup> L. Apker and E. Taft, Phys. Rev. **79**, 964 (1950).

<sup>5</sup> W. W. Tyler, Phys. Rev. **76**, 1887 (1949).

## Angular Distributions of Neutrons from $(\alpha, n)$ and $(d, n)$ Reactions

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BEFORE interpreting the data of Allen, *et al.*<sup>1</sup> on the angular distributions of the neutrons from  $(\alpha, n)$  and  $(d, n)$  reactions, as measured with sulfur detectors, two very important corrections must be applied: (1) a correction for the variation of the solid angle in the center-of-mass system, and (2) a correction for the fraction of the neutrons detectable by a threshold detector at various angles.

The first of these is described by Taschek and Hemmendinger,<sup>2</sup> and their formulas can be used. The second arises as follows. A neutron produced in an  $(\alpha, n)$  reaction on element  $A$  will have different energies in the laboratory and the center-of-mass systems. These are related by the formula (with the masses in atomic units)

$$E_c = \frac{1}{2} \left[ (2E_L)^{\frac{1}{2}} - \left( \frac{M_a}{M_a + M_A} \right) (2E_a/M_a)^{\frac{1}{2}} \cos\theta_c \right]^2 \quad (1)$$

An ideal threshold detector detects all neutrons with  $E_L$  greater than its threshold,  $B$ . Assuming the neutrons to be emitted with an energy distribution

$$I(E) \propto e^{-E/T}, \quad (2)$$

the total number of neutrons detected is

$$N \approx \int_{E_{\min}}^{E_{\max}} E e^{-E/T} dE, \quad (3)$$

where

$$E_{\min} = \frac{1}{2} \left[ (2B)^{\frac{1}{2}} - \left( \frac{M_a}{M_a + M_A} \right) (2E_a/M_a)^{\frac{1}{2}} \cos\theta_c \right]^2, \quad (4)$$

$E_{\max}$  = maximum energy in the center-of-mass system.

On integrating (3) and assuming that  $E_{\max} \gg T$ , we find that

$$N \approx (E_{\min} + T) \exp(-E_{\min}/T). \quad (5)$$

Use of (4) in (5) gives a large correction factor in many cases. As an example, Fig. 1 shows the correction to the intensities at 90° and 180° with respect to 0° using sulfur detectors ( $B \sim 3$  Mev), plotted against the parameter  $T$  (effective nuclear temperature).<sup>3,4</sup>

Table I shows the result of applying these corrections to the  $(\alpha, n)$  data of reference 1. Column 4 shows the value of  $T$  required

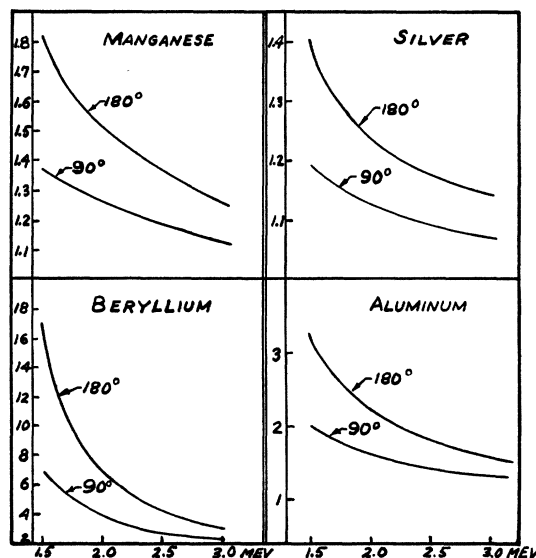


FIG. 1. Correction factors for detector activities at 90° and 180° with respect to 0° activity for  $(\alpha, n)$  angular distributions. Abscissa is the effective nuclear temperature of the outgoing neutrons.

TABLE I. Relative neutron yields from ( $\alpha, n$ ) reactions at 0°, 90°, and 180°.

(1)	(2)	(3)	(4)	(5)
Target element	Observed ratio <sup>a</sup>	Yield at 180°/Yield at 0°		Yield 90° (corrected)
		Corrected for CM solid angle <sup>b</sup>	T required to remove asymmetry	
Beryllium	0.13	0.60	>4.0 Mev <sup>c</sup>	~0.7
Manganese	0.55	0.70	1.5-2.0	0.77
Silver	0.76	0.87	1.4-2.3	0.80
Gold	0.93	0.99	1.0-∞	0.74
Bismuth	0.98	1.03	1.0-∞	0.81
Columbium	0.78	0.92	1.5-2.8	0.81
Aluminum	0.39	0.67	2.3-2.8	0.80
Copper	0.70	0.89	2.2-4.0	0.81
Cadmium	0.74	0.84	1.4-2.1	0.81
Cobalt	0.82	1.05	>3.5	0.73

Av. = 0.79 ± 0.04

<sup>a</sup> See reference 1.<sup>b</sup> See reference 2.

<sup>c</sup> This is much larger than the observed value of 2.3 Mev (reference 5). It is probably caused by the fact that the 180° intensity is so small that the effect of scattered neutrons is important. Beryllium was neglected in obtaining the average in column (5).

to make the ratio of the intensities at 180° and 0° equal to 1.0 ± 0.1. The values are in good agreement with the measured values<sup>5</sup> and theoretical estimates of the effective nuclear temperature.<sup>4</sup> This, taken together with column 5 of Table I, gives strong support to Wolfenstein's theory<sup>6</sup> of the angular distributions from compound nucleus reactions, which predicts<sup>5</sup> symmetry about 90°, maxima at 0° and 180°, and minima at 90°.

The correction factors are so sensitive to the value of  $T$  that the assumption of equal intensities at 0° and 180° provides a quick method of determining  $T$ . This can be done much more accurately using higher energy threshold detectors (e.g., the 24.5-min activity in silver,  $B \sim 11$  Mev), since the center-of-mass solid angle correction is smaller and the dependence on temperature is stronger.

Table II shows the observed<sup>1</sup> 180°/0° intensity ratio for ( $d, n$ )

TABLE II. Relative neutron intensities at 180° and 0° from deuteron bombardment.

Element	Observed <sup>a</sup>	Corrected
Beryllium	0.06	0.56
Aluminum	0.12	0.26
Titanium	0.38	0.60
Chromium	0.28	0.40
Manganese	0.24	0.35
Cobalt	0.31	0.43
Copper	0.29	0.39
Columbium	0.34	0.40
Molybdenum	0.27	0.32
Cadmium	0.31	0.37
Tantalum	0.33	0.34
Gold	0.42	0.46
Lead	0.44	0.48
Bismuth	0.45	0.49
		0.42 ± 0.07

<sup>a</sup> See reference 1.

reactions and the corrected ratio using plausible and in some cases, measured values of  $T$ . It is evident that some process other than compound nucleus interaction is effective, and some sort of a deuteron stripping process is suggested.<sup>7</sup>

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<sup>1</sup> Allen, Nechaj, Sun, and Jennings, Phys. Rev. **81**, 536 (1951).<sup>2</sup> R. Taschek and A. Hemmendinger, Phys. Rev. **74**, 373 (1948).<sup>3</sup> V. Weisskopf, *Lecture Series in Nuclear Physics* (U. S. Govt. Printing Office, Washington, D. C., 1947).

<sup>4</sup> The effective nuclear temperature in this case is the nuclear temperature (reference 3) at an excitation of ( $E_{max} - E$ ), where  $E$  is the energy (in the center-of-mass system) which will be most effective in exciting the threshold detectors (reference 5).

<sup>5</sup> B. Cohen, Carnegie Inst. of Tech. Technical Report No. 4 (May 20, 1950), unpublished.

<sup>6</sup> L. Wolfenstein, Phys. Rev. **78**, 322 (1950).

<sup>7</sup> R. Serber, Phys. Rev. **72**, 1017 (1947); S. Dancoff, Phys. Rev. **72**, 1008 (1947).

## Photo-Luminescence Efficiency of ZnS:Cu Phosphors as a Function of Temperature\*†

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IN recent communications by the author, the luminescence and trapping of a series of cubic and hexagonal ZnS:[Zn]:Cu(0.0-0.3), [NaCl(2)] phosphors,<sup>1</sup> and the effects of infrared on these phosphors,<sup>2</sup> have been discussed. This letter presents additional data on the variation with operating temperature of the photo-luminescence efficiency of these phosphors during 3650A ultraviolet excitation.

The blue and green luminescence emission intensities have been recorded through Wratten 47 and 58A filters, respectively. Figure 1 shows the variation of photo-luminescence emission intensity through the green filter for the cubic and hexagonal phosphors, and Fig. 2 shows the variation obtained through the blue filter.

The curves of these figures show that the temperature for maximum green intensity starts to shift to lower temperatures with increasing copper proportion between 0.01 and 0.03 weight percent copper for the cubic phosphors, and between 0.03 and 0.1 percent Cu for the hexagonal phosphors. Similarly, the blue intensity starts to decrease rapidly and continuously to zero for copper proportions between 0.01 and 0.03 percent for the cubic phosphors, and between 0.03 and 0.1 percent for the hexagonal phosphors.

These results are further evidence of the critical change previously reported in the nature of the copper imperfection when the amount of copper activator has reached a certain amount. Between 0.01 and 0.03 percent copper for the cubic phosphors,

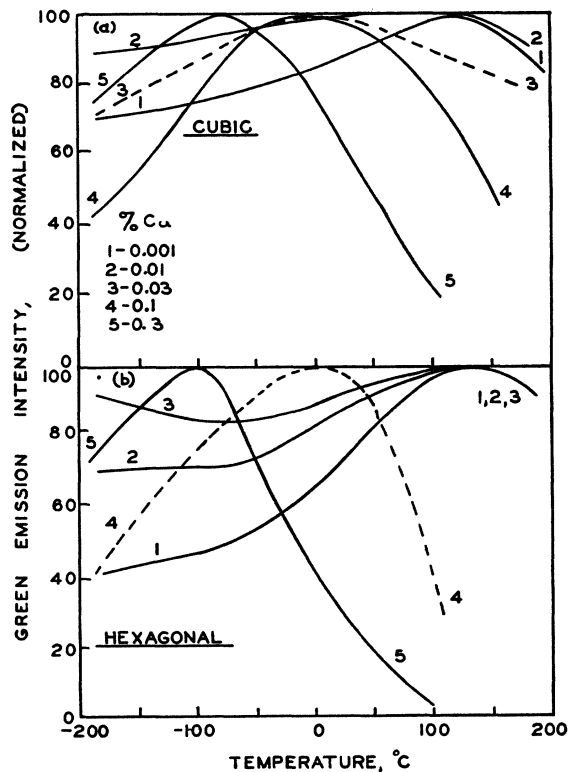


FIG. 1. Green photo-luminescence emission intensity, as observed through a Wratten 58A filter, as a function of operating temperature, for a series of increasing copper proportions in cubic and hexagonal ZnS:[Zn]:Cu phosphors.