

TABLE VII. The first, second, and third derivatives of  $\tilde{c}_{hk}$  and  $\tilde{\epsilon}_{hk}$  with respect to temperature at 20°C; confidence coefficient: 90%.

	First diff. coeff. in 10 <sup>6</sup> cm <sup>2</sup> sec <sup>-2</sup> °C <sup>-1</sup>	One-half of the second diff. coeff. in 10 <sup>4</sup> cm <sup>2</sup> sec <sup>-2</sup> °C <sup>-2</sup>	One-sixth of the third diff. coeff. in 10 <sup>2</sup> cm <sup>2</sup> sec <sup>-2</sup> °C <sup>-3</sup>
$\tilde{c}_{11}$	-0.77 ± 0.46	-3.2 ± 2.1	-0.32 ± 0.45
$\tilde{c}_{33}$	-15.32 ± 0.60	-14.0 ± 2.8	-0.30 ± 0.59
$\tilde{c}_{44}$	-7.529 ± 0.038	-1.17 ± 0.10	-0.113 ± 0.078
$\tilde{c}_{66}$	8.076 ± 0.096	0.85 ± 0.26	-0.29 ± 0.19
$\tilde{c}_{13}$	-5.15 ± 0.51	-0.67 ± 0.52	-0.63 ± 0.81
$\tilde{c}_{14}$	-2.273 ± 0.019	-0.015 ± 0.051	0.107 ± 0.038
$\tilde{\epsilon}_{11}^2$	-0.23 ± 0.10	-0.33 ± 0.26	0.55 ± 0.21
$\tilde{\epsilon}_{14}^2$	-0.018 ± 0.020	-0.013 ± 0.045	0.018 ± 0.035
$\tilde{\epsilon}_{11}\tilde{\epsilon}_{14}$	0.065 ± 0.041	0.07 ± 0.11	-0.103 ± 0.084

where  $y_T$  stands for each of the values of  $\tilde{c}_{hk}$  and  $\tilde{\epsilon}_{hk}$  at a temperature rise  $T$  above 20°C, and  $y_{20}$ ,  $\dot{y}_{20}$ , etc., for its value and its first, second, and third differential coefficient with respect to the temperature at 20°C, respectively. All the necessary data for these calculations are given in (35) and Table VII.

On the other hand, the thickness  $a_T$  is quite closely given by

$$a_T = a_{20} [1 + n^2(7.48 \times 10^{-6} \times T + 0.86_9 \times 10^{-8} \times T^2) + (1 - n^2)(13.74 \times 10^{-6} \times T + 1.20_4 \times 10^{-8} \times T^2)]. \quad (45)$$

As Atanasoff and Hart<sup>1</sup> reported experimental results on the frequency-temperature relations of X-cut and Y-cut plates up to very high temperatures, the present writers tentatively computed them up to temperatures above 100°C, where (44) is not necessarily valid any more, because all terms of the fourth and the higher powers of temperature  $T$  have been dropped. The full lines in Fig. 1 are the reproduction of Atanasoff and Hart's results and the broken lines show the computed values. It is rather surprising to discover that the computed values are very close to the measured results up to about 200°C in the case of X-cut plates, and even up to temperatures above 300°C in the case of Y-cut plates.

## Energy Storage in ZnS and ZnCdS Phosphors\*†

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The deficiency area above a rise curve of fluorescence due to excitation by high-energy electrons is a measure of the total amount of energy stored in traps. In order to investigate the rate of decay of this energy, rise curves were taken for six phosphors of various luminescent properties and activation after various dark decay periods following excitation to equilibrium and after de-excitation by exposure to infrared light and heat. For all phosphors the trap concentration was found to be of the order of 10<sup>15</sup>/cc independent of the type of activator. In addition, the rates of decay of stored energy were determined and were found to be similar; from 20% to 60% of the energy remained in the phosphors after 1 week. This slow rate of decay is explained by predominant retrapping in traps of various depths.

The areas under curves of phosphorescent emission were compared to the deficiency areas above rise curves taken immediately

after the end of decay. For four of the phosphors these two areas are nearly equal to each other. One phosphor, especially activated with Ni and with practically no phosphorescence exhibited, however, a rate of energy decay similar to the phosphorescent phosphors. This means that the decay of stored electrons can take place radiatively and/or nonradiatively and that the rate for both processes is of the same order of magnitude.

The areas under curves of visible light stimulated by infrared irradiation were compared with areas above rise curves taken immediately after the end of stimulation. If all stored electrons were released radiatively, these two areas would be equal. For only one phosphor (specially Pb activated ZnS) was this the case. All others exhibited only from 0.6% to 5% radiative recombinations. Thus the light sum under a stimulation curve does not give a true picture of the trap population.

### I. INTRODUCTION

**E**LECTRONS which are stored in traps can be removed by the addition of thermal energy or infrared irradiation. The resulting recombinations are often radiative so that a correspondence has been made between the area under a glow curve<sup>1-3</sup> or under

a stimulation curve<sup>4-6</sup> and the total number of electrons which were originally in the traps. Both of these methods suffer from the fact that nonradiative transitions are induced along with the radiative ones so that determinations of trap population can be in error. Several investigators have found, for instance, that the area under a stimulation curve is many times greater than the corresponding area under a glow curve.<sup>4-6</sup> Information about electrons stored for long periods of

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<sup>1</sup> J. T. Randall and M. H. F. Wilkins, Proc. Roy. Soc. (London) **A184**, 366, 390 (1945).

<sup>2</sup> G. F. J. Garlick and M. H. F. Wilkins, Nature **161**, 565 (1948).

<sup>3</sup> R. H. Bube, Phys. Rev. **80**, 655, 764 (1950).

<sup>4</sup> R. T. Ellickson, J. Opt. Soc. Am. **36**, 264 (1946).

<sup>5</sup> G. F. J. Garlick and D. E. Mason, J. Electrochem. Soc. **96**, 90 (1949).

<sup>6</sup> C. Bull and D. E. Mason, J. Opt. Soc. Am. **41**, 718 (1951).

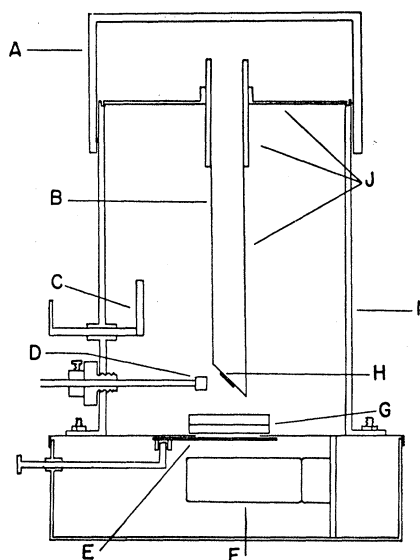


FIG. 1. Experimental apparatus for viewing beta-induced luminescence; A, light-tight screw-on cap; B, hollow copper tube; C, rotary lead shield; D, retractable beta source; E, sliding light shield; F, photomultiplier, Type 1P28; G, filters; H, sample; I, steel cylinder; J, removable sample holder.

time can be collected from investigation of the rise curve of fluorescence.<sup>7-9</sup> This method enables one to determine from the deficiency area<sup>9</sup> how long electrons remain excited in the sample and to infer the number of traps which are empty at the onset of excitation. In this paper, the rise-curve method is used to analyze the distribution in lifetime<sup>10</sup> of excited electrons which are stored in the sample. A quantitative comparison of deficiency areas with respective areas below curves of decay of phosphorescence and below curves of stimulation provides information on the fraction of non-radiative transitions occurring during the two recombination processes.

## II. EXPERIMENTAL PROCEDURE

Samples<sup>11</sup> were prepared as in reference 9 but on glass microscope slides. The apparatus was changed in order to be able to make stimulation-curve measurements as well as rise curves at various temperatures and to introduce neutral density and/or color filters for control of intensity and wavelength of light reaching the photomultiplier (see Fig. 1). The dc amplifier had provision for measuring a range of four orders of magnitude. Zero adjustments before all readings were made after sliding

<sup>7</sup> A. Levaldi and V. Luzzati, *J. phys. radium* **8**, 306, 341 (1947).

<sup>8</sup> W. Hoogenstraaten, *J. Electrochem. Soc.* **100**, 356 (1953).

<sup>9</sup> H. Kallmann and G. M. Spruch, *Phys. Rev.* **103**, 94 (1956).

<sup>10</sup> Lifetime here means the reciprocal of the probability per unit time of recombination of stored electrons. This is a function of the instantaneous state of excitation of the sample. We do not speak of the lifetime of a trap since the lifetime we refer to depends on retrapping.

<sup>11</sup> The materials used for this investigation were selected to cover a variety of luminescent properties and activation. A complete description will be found in reference 9, Table I.

the light shield over the face of the phototube. All samples were exposed to infrared light of  $\lambda \geq 7700 \text{ \AA}$  (Corning 7-56) and heat for about 60 minutes so that complete de-excitation was achieved.<sup>12</sup> Rise curves were made with an incident intensity of about 1500 roentgens per hour from a 10-mC Sr<sup>90</sup>-Y<sup>90</sup> beta source about 10 mm distant. Electron excitation has several advantages over ultraviolet excitation. First, because of the excitation of channels within the phosphor which is characteristic of excitation by fast particles, the emitted light intensity at the onset of excitation jumps immediately to an initial value which varies from 10% to 30% of the equilibrium value depending on the phosphor. This is quite different from the situation with ultraviolet excitation where the initial point is at zero and the fluorescence rises in an S-shaped curve to the equilibrium value.<sup>8,13</sup> The initial point of a rise curve obtained with fast electrons is a very sensitive measure of the state of de-excitation of the phosphor and enables

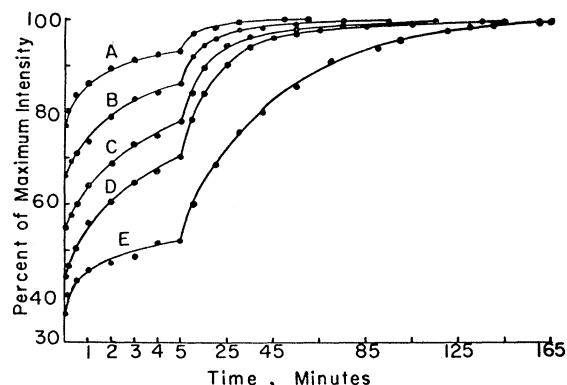


FIG. 2. Rise of fluorescence of ZnS-LG as a function of time of excitation for varying dark periods since preceding excitation to equilibrium. A, 10 minutes; B, 1 hour; C, 1 day; D, 1 week; E, de-excited. The de-excited curve was obtained after exposure to heat and infrared light of  $\lambda \geq 7700 \text{ \AA}$  for one hour. The discontinuity at  $t=5$  minutes is due to the change in time scale.

one to check its initial state of excitation. In addition it gives information on the channel radius as will be reported by J. Dresner of this laboratory. Second, ultraviolet light, which excites electrons from the valence band, is strongly absorbed in a small thickness thereby producing layers of quite different excitation along the thickness of the sample. Fast electrons, with an average energy of 1.2 Mev, lose only a small fraction of their energy in going through a sample of average density 20 mg/cm<sup>2</sup>, thus assuring more uniform excitation of the sample. Third, the state of excitation of the phosphor during the rise curve is not too much changed with electron excitation (since the initial point is already about 20% of maximum), while with light excitation this change is very considerable (since the initial point is zero). Since the probability for nonradi-

<sup>12</sup> Further irradiation and heating left the initial value in the rise curve unchanged. See also reference 9.

<sup>13</sup> F. Moser and F. Urbach, *Phys. Rev.* **106**, 852 (1957).

ative transitions depends upon the state of excitation to some extent this variation of nonradiative transitions during the rise is minimized with fast electrons.

The experiment is started by opening the lead shutter and pushing the beta source into its predetermined position. This procedure may introduce an inaccuracy of about one second in the first point of the rise curve.<sup>14</sup> Since there is very little increase of fluorescent intensity in the time between 2 and 3 seconds no effort was made to go to earlier times. That this is a safe procedure is confirmed by the fact that the 2.5-msec value as reported in reference 9 is about the same as the 2-second value. Stimulation measurements were made one hour after excitation to equilibrium, the beta source having been retracted and shielded during that time. The sample was rotated now to face another window in which a Corning 7-69 filter was placed to pass  $\lambda \geq 7200$  Å from an infrared source. Because of the rapid variation in stimulated light intensity a dc scope was used as recorder.

TABLE I. Percent of total traps remaining filled after various dark decays and deficiency area for de-excited sample.

Phosphor	Percent of traps remaining filled after					Normalized deficiency area above de-excited rise curve (in arbitrary units)
	10 min	30 min	1 hour	1 day	1 week	
ZnS <i>LG</i>	93.3	86.6	85.1	77.8	61.4	95.6 <sup>a</sup>
ZnCdS <i>K</i>	88.5	87.7	85.3	70.3	45.5	13.5
ZnCdS <i>L</i>	84.1	75.6	49.8	40.2	40.2	15.3
ZnS <i>M</i>	78	65.4	54	39.5	32.7	28.2
ZnS <i>N</i>	78	78	76.6	57.5	32.7	13.5
ZnS <i>R</i>	77.6	62.5	60.3	43.9	23.3	45

<sup>a</sup> The fraction of total incident energy lost in traps for this phosphor indicates that this number is equivalent to  $3 \times 10^{15}$  empty traps/cc. This confirms the result of reference 9.

### III. RISE CURVE RESULTS

A sample family of rise curves is presented in Fig. 2. The area below the equilibrium value (normalized to 100%) and above a given rise curve represents the number of empty traps which were filled during the excitation to equilibrium. It therefore also measures the number of stored electrons which had recombined during the dark decay period since the preceding excitation to equilibrium. This area is called the deficiency area. The discontinuity in the curves at  $t=5$  minutes is due to a change in time scale, the earlier part of the rise curve being expanded for easier analysis. Table I presents the fraction of traps still filled after various dark decay periods. Since these phosphors have different luminescent efficiencies and different thicknesses the absolute values of the deficiency area do not give immediate information about the amount of energy stored in different phosphors. In order to get

<sup>14</sup> This statement also applies to the measurements of phosphorescence except that the time error there is due to the retraction and shielding of the beta source.

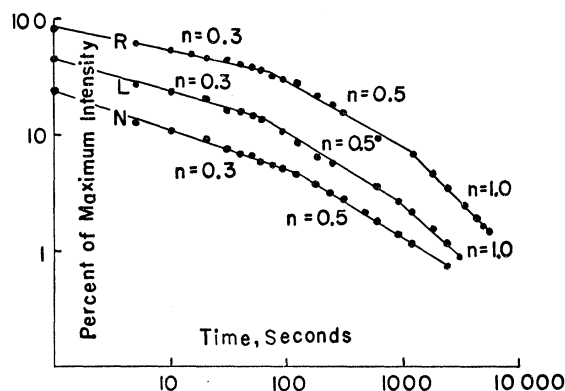


FIG. 3. Decay of phosphorescence of phosphors *R*, *L*, and *N* as a function of time. Values of  $n$  in the relation  $I=K/t^n$  are indicated.

this information the equilibrium currents for all phosphors have been normalized to the same value. The resultant normalized deficiency areas are given in the last column of Table I in arbitrary units of  $\mu\text{-sec}/(\text{mg}/\text{cm}^2)$ . They are a rough measure of the energy stored in a phosphor per unit volume if the emission efficiencies of these phosphors do not differ too much from each other. It can be further noted that for all six phosphors investigated, electrons remain excited over very long times (even after one week in darkness from 23% to 61% had not yet recombined).<sup>15</sup>

### IV. DECAY CURVE RESULTS

The curves of decay of phosphorescence for three of the six phosphors are shown in Fig. 3 plotted on log-log paper. The general shape of these curves follows a  $1/t^n$  law, where  $n$  changes from 0.3 to 1 as time increases. The area under these curves when plotted on linear paper corresponds to the number of electrons that recombine radiatively during the dark decay time. It should be noted that the first sharp drop occurs in about 1 second and therefore does not contribute very much to the total area. The sharp drop means that during this part of the decay recombination occurs mainly for those electrons which are in the conductivity

TABLE II. Light sum under curves of decay of phosphorescence up to various times (after beta excitation to equilibrium). Normalized areas in same units as last column of Table I.

Phosphor	10 min	30 min	1 hour
ZnS <i>LG</i>	6.7	12.4	16.9
ZnCdS <i>K</i>	0	0	0
ZnCdS <i>L</i>	1.9	3.1	3.8
ZnS <i>M</i>	6.1	9.7	13.7
ZnS <i>N</i>	1.8	3.1	...
ZnS <i>R</i>	10	16.7	22

<sup>15</sup> An analysis was made of the rise curves published in reference 9 for the *R* phosphor. A comparison of the area above curve *C* in their Fig. 1 with the area above curve *A* showed that 44% of the excited electrons were still in traps after 24 hours. This agrees with the figure given here in Table I.

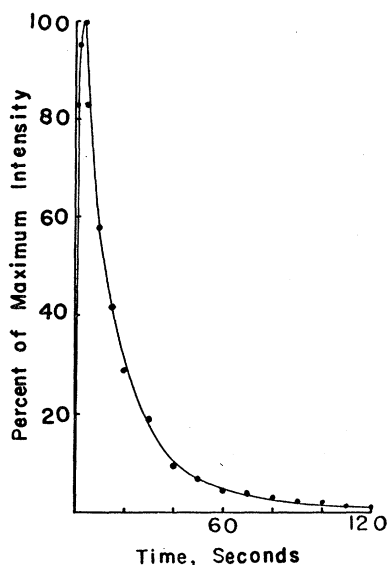


FIG. 4. Variation of luminescence stimulated by infrared light of  $\lambda \geq 7200 \text{ \AA}$  in ZnS-R as a function of time of exposure to infrared. The stimulation began after a 1-hour dark period following excitation to equilibrium.

band immediately after the end of excitation so that only a small number of trapped electrons have recombined. The areas were determined for decay times of 10 minutes, 30 minutes, and 1 hour. Table II presents these areas in the same units as the last column of Table I. Note that the ratios of the phosphorescence areas for one phosphor are nearly the same as the corresponding ratios for the other phosphors. This is an indication that the law of decay is very similar for all these phosphors, except during the very first seconds.

## V. STIMULATION MEASUREMENT RESULTS

A sample stimulation curve is presented in Fig. 4. Such stimulation releases some<sup>16</sup> of the excited electrons still stored in the phosphor after 1 hour dark time. The area under the curve measures only that portion of the released electrons which recombine in a radiative manner. Stimulation curves for the six phosphors under investigation are analyzed in Table III. The areas in the last column are in the same units as in Tables I and II. All these phosphors show typical stimulation behavior in which the peak is reached only after a finite time.

## VI. ANALYSIS OF RESULTS

### A. Rise Curve Measurements

1. For these phosphors, which are quite different in activation and in decay and stimulation properties, the total number of excited electrons per unit volume which can be stored in these samples is of the same order of

<sup>16</sup> As is indicated later on, irradiation by infrared light alone does not release all electrons stored in traps.

magnitude.<sup>17</sup> The last column of Table I indicates that between the most stimuable phosphor (*LG*) and that with the strongest quenching properties (*K*) this number differs by at most a factor of seven. In addition, the relative trap populations may be compared to the corresponding values published in Table II of reference 9 for the same six phosphors. The differences in the relative magnitudes are probably due to the following: (1) In this paper normalization for different thicknesses was achieved by assuming that the phosphor is transparent to its own radiation. Since there is some self-absorption the light output is not exactly proportional to the thickness of the sample. (2) Our present de-excitation procedure is more effective. It was found that for some substances infrared irradiation alone does not empty the traps completely, the addition of heat being a necessary adjunct. This will be reported on more fully in the future. Since phosphor *LG* is especially sensitive to the de-excitation procedure its deficiency area increases at a greater rate than the other phosphors.

2. The relative rates of decay of the stored energy for all these phosphors differ by not more than a factor of 3. This can be seen by examining Columns 2-6 of Table I. In view of the fact that the *K* phosphor exhibits no phosphorescence this must mean that the recombination process during the decay for that phosphor is completely nonradiative. The uniformity of decay is noteworthy since the phosphors display quite different properties with respect to decay of phosphorescence, decay of photoconductivity (see later), stimulability, and type of activation.

3. The observed decay of stored energy can be explained by assuming electrons are trapped in levels varying over a range of energies. If one assumes no retrapping the traps must be very deep to account for the extremely slow decay. On the other hand, the existence of retrapping would permit shallower traps to explain the slow decay since the retrapping process would remove electrons from the recombination process and thereby cause an apparent lifetime longer than that associated with the actual energy depth.

It is difficult to accept the assumption of no retrapping and the consequent necessity for very deep traps

TABLE III. Analysis of stimulation curves induced by infrared,  $\lambda \geq 7200 \text{ \AA}$ , 1 hour after excitation to equilibrium. Area in same units as Tables I and II.

Phosphor	Time to reach peak sec	Peak amplitude $\mu\text{a}$	Time to decay to 1% sec	Normalized area
ZnS <i>LG</i>	0.2	850	20	43.7
ZnCdS <i>K</i>	0.3	0.041	20	0.04
ZnCdS <i>L</i>	2.0	0.38	200	0.21
ZnS <i>M</i>	3.5	1.5	90	0.63
ZnS <i>N</i>	2.0	0.44	70	0.057
ZnS <i>R</i>	3.5	6.8	120	1.2

<sup>17</sup> Rise curves made under varying conditions of excitation on de-excited phosphors all give similar results for the number of empty traps per unit volume.

in view of the experimental facts that warming to 100°C or exposure to 25 000 Å for long enough time is sufficient to empty all traps.<sup>18</sup> These experiments clearly indicate that retrapping is a predominant factor. In addition, a calculation which assumes dominant retrapping, by R. Herman of this laboratory, predicts the proper shape of the curve of decay of phosphorescence.

### B. Comparison of Deficiency Area with Area under Phosphorescent Decay Curve

The deficiency areas measure the number of stored electrons which had recombined during the dark decay period since the preceding excitation to equilibrium.<sup>19</sup> A comparison of this area with the light sum under a curve of decay of phosphorescence up to the same dark decay time will determine the proportion of radiative transitions occurring in the normal decay process. A comparison between appropriate areas in Tables I and II is presented in Table IV. The values for the deficiency area in Column 4 are calculated from the figures given in Table I.

A result of this comparison is that one can separate these phosphors into two groups based on the percent of radiative recombinations during the phosphorescence process; one group having close to 100% radiative recombination during the decay and the other having less than 100%. Within the limits of experimental and graphical error, the ZnS phosphors *LG*, *R*, *N*, and *M* seem to have completely radiative recombinations—or more accurately—the percentage of nonradiative re-

combinations along the rise curves and the decay curves is the same for times up to 1 hour. The ZnCdS phosphors, *K* and *L*, show the effects of the excess of nonradiative recombinations during phosphorescent decay; *K* having completely nonradiative recombinations while *L* has about 30% nonradiative. This analysis shows that the absence of phosphorescence for the *K* phosphor is due not to the absence of traps but to the preponderance of nonradiative transition processes at low emission levels. This also makes the nonlinear fluorescence efficiency of this phosphor understandable.

The rate of decay of stored energy of the phosphor *K* is of the same order of magnitude as that of the other phosphors although there is practically no phosphorescence. This could be interpreted to mean that the eventual radiative and nonradiative transitions which empty traps are similar processes. However, there are objections to this interpretation. The *K* phosphor also exhibits a sharp drop in photoconductivity after termination of excitation. *L* and *N* behave similarly. This is, in general, also true for all Ag-activated phosphors when subject to the same excitation conditions as the Cu-activated phosphors. A first attempt to explain such sharp drops in phosphorescence and photoconductivity assumes rapid recombinations of electrons from the conductivity band in radiative or nonradiative transitions. If this were so, one would observe a much faster decay of stored energy in these phosphors. This is not the case. A second attempt would ascribe the low phosphorescence and photoconductivity to traps which are almost filled to saturation. An examination of the equilibrium condition for the number of filled traps shows that when the traps are nearly all filled a slight emptying of traps causes the number of electrons in the conductivity band to drop sharply due to increased retrapping. It can thus be seen that for such a situation light emission and photoconductivity drop very quickly after termination of excitation while the traps empty quite slowly. The different behavior of the other phosphors would then be attributed to the existence of additional shallower traps which are not filled to saturation. This point of view agrees quite well with studies on Ag- or Cu-activated phosphors. As indicated above, all Ag-activated phosphors display this fast drop of light emission and photoconductivity during the decay. Experiments in this laboratory on other Ag-activated phosphors have shown that these Ag-activated phosphors have the same concentration of traps as Cu-activated phosphors and that they both remain occupied for as long periods of time. Phosphor *N*, which is activated with Ag and traces of Cu, does not have as steep a drop in phosphorescence as other Ag-activated phosphors. This may be attributed to the presence of Cu. Thus the second viewpoint indicates that Cu activators are responsible for shallower, partially filled traps and that the Ag activators are connected with deeper, saturated traps. This is in agreement with results of other investigators.<sup>8</sup> However, the

TABLE IV. Areas under phosphorescent decay curves for decay times up to 1 hour and comparison with deficiency areas above rise curves for same dark decay. Areas in same units as Tables I and II.

Phosphor	Dark decay min	Decay area	Deficiency area	$\left(\frac{\text{Decay area}}{\text{Deficiency area}}\right) \times 100$
ZnS <i>LG</i>	10	6.7	6.4	103
	30	12.4	13.2	95
	60	16.9	14.3	118
ZnCdS <i>K</i>	10	0	1.6	0
	30	0	1.7	0
	60	0	2	0
ZnCdS <i>L</i>	10	1.9	2.4	78
	30	3.1	3.7	83
	60	3.8	7.7	50
ZnS <i>M</i>	10	6.1	6.2	99
	30	9.7	9.8	99
	60	13.7	13	105
ZnS <i>N</i>	10	1.8	3	60
	30	3	3	102
	60	...	3.2	...
ZnS <i>R</i>	10	10	10	100
	30	16.7	17	98
	60	22	18	122

<sup>18</sup> Experiments performed in this laboratory.

<sup>19</sup> See the definition of deficiency area given in Sec. III.

TABLE V. Comparison of number of traps still filled after 1 hour dark decay as determined by difference between rise curve deficiency areas and by areas under stimulation curves. Area in same units as in Tables I and III.

Phosphor	Difference between deficiency areas	Area under stimulation curve	$\left(\frac{\text{Stimulation area}}{\text{Deficiency area}}\right) \times 100$
ZnS <i>LG</i>	34	49	110
ZnCdS <i>K</i>	6.7	0.04	0.6
ZnCdS <i>L</i>	7.7	0.21	2.8
ZnS <i>M</i>	15	0.63	4.2
ZnS <i>N</i>	6.5	0.057	0.88
ZnS <i>R</i>	27	1.2	4.5

*K* phosphor does not fit into this picture since it is Cu-activated but shows the very rapid drop in phosphorescence and photoconductivity characteristic of Ag-activated phosphors. There is another similarity between the *K* phosphor and the Ag-activated phosphor *N* which can be noted in the last column of Table III; the areas under their stimulation curves are much smaller than the corresponding areas for Cu-activated phosphors. All the other Cu-activated phosphors have slow decay of light and photocurrent; this means that their traps empty via the conductivity band and recombine in completely radiative transitions. Since the photocurrent in the *K* phosphor drops so rapidly while its traps are emptying at the same rate as the other phosphors, it can be assumed that its traps do not empty via the conduction band but instead empty via a nonradiative direct recombination with free holes. This transition can be attributed to the presence of Ni, which, as is well known, acts as a "killer" impurity. The similarity in the rate of trap emptying between the *K* and the other phosphors is then quite accidental.

### C. Comparison of Deficiency Area with Area under Stimulation Curve

The stimulation curves show a rather steep rise to maximum at the beginning followed by a decay which is given by a  $1/t^n$  law, with  $n$  approximately unity at the beginning and approximately two when the phosphor is nearly exhausted. This behavior is remarkably uniform if one considers that these phosphors behave completely differently with respect to the total amount of stimulated light emission (see Column 5 of Table III).

The area under a stimulation curve measures only that portion of the released electrons which recombine in a radiative manner. Since the infrared irradiation does not release all electrons in traps, we must determine how many electrons have been released by the infrared. This is done by taking a rise curve immediately after the end of the stimulation period and subtracting from this deficiency area the deficiency area for the rise curve after 1 hour dark time. If the recombinations induced by infrared light are completely radiative, the area under the stimulation curve will equal the forementioned difference in deficiency areas. A comparison of these areas for the various phosphors is presented in Table V. The values for Column 2 represent the number of traps emptied by the infrared stimulation process. A comparison of the areas in Columns 2 and 3 of Table V shows that predominantly nonradiative transitions are induced by the infrared stimulation process.

TABLE VI. Characterization of phosphors.

Type of phosphor	Percent radiative recombination in Phosphorescence	Stimulation	Number traps/cc	Percent of traps remaining filled after 1 week
Stimulable ( <i>LG</i> )	100%	100%	$3 \times 10^{15}$	61.4
Normal ( <i>L, M, N, R</i> )	100%	0.9-5%	$4 \times 10^{14}$ - $10^{15}$	23-40
Quenching ( <i>K</i> )	0%	0.6%	$4 \times 10^{14}$	45.5

Column 4 indicates the percentage of transitions which are radiative; *LG* phosphor is the most stimuable (100% of stimulation-induced transitions radiative) while all the others show roughly 2% radiative transitions. The overpowering effect of nonradiative transitions previously demonstrated in the phosphorescence decay of the *K* phosphor is once again evidenced in the very weak stimulability of this phosphor.

### VII. CONCLUSION

The phosphors under investigation divide most naturally into three groups, depending on their phosphorescence and stimulation behavior. This is summarized in Table VI.

It must be emphasized again that for these three types of phosphors, (1) the total number of traps per cc is about the same and (2) the rate of trap emptying at room temperature is about the same.