

LUMINESCENCE IN KI:Tl

By J. E. ALDERSON* and S. E. WILLIAMS*

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Summary

Freshly cleaved single crystals of KI:Tl containing various concentrations of Tl have been irradiated in a vacuum monochromator in the 2800–1100 Å region at temperatures between –140 and 45 °C. The relative luminescence efficiencies in the Tl absorption bands and the host crystal fundamental absorption show that energy is transferred from host crystal to impurity centre to produce luminescence at room temperatures. To the high energy side of a threshold, which appears to depend on activator concentration, the luminescence efficiency is superlinear above about 15 °C for KI:Tl (0·0005%). Luminescence production shows a slow build-up which has been analysed in detail for irradiation at 1608 and 1216 Å. The build-up curve is found to have the form

$$L_t = L_s \{A(1 - e^{-yt}) + B(1 - e^{-zt})\},$$

where L_s is the saturation luminescence, L_t the luminescence t seconds after illumination starts, and A , B , y , and z are parameters associated with two processes for luminescence production involving recombination and the attainment of equilibrium in the filling of traps. The efficiency of the first process is superlinear and of the second approximately linear. As in the case of AgBr-AgI examined by Moser and Urbach, there is no observable phosphorescent decay. Thermal escape from traps followed by radiationless de-excitation has been observed by investigating the changes of the instantaneous component of luminescence production with varying intervals of darkness. An explanation is proposed in terms of the migration of holes from shallower to deeper traps near luminescence centres followed by recombination with free electrons.

I. INTRODUCTION

Studies of the luminescence in activated alkali halides fall roughly into three classes. Luminescence produced by absorption in the impurity bands of the activator has been interpreted as involving a simple monomolecular process occurring entirely within the impurity centre (Williams and Johnson 1959) although this has been questioned by others (Ewles and Joshi 1960). Luminescence produced by, or following X-ray or γ -ray excitation (Bonanomi and Rossel 1951; Smaller and Avery 1953) involves heterogeneous excitation energies as well as the production of lattice defects, which makes analysis of the luminescence mechanisms very complex. Finally, the luminescence resulting from irradiation of the crystal by photons whose energies lie within the fundamental absorption band of the host crystal has been examined by Teegarden (1957), by Lushchik and his collaborators (Lushchik *et al.* 1960), and by Ueta and Ishii (1959) and Tomura and Kaifu (1960). The upper limit of photon energy in these cases has been about 7·5 eV, which includes the exciton bands and part of

* Department of Physics, University of Western Australia, Nedlands, W.A.

the ionization region. The latter studies have provided evidence that energy transfer from host crystal to luminescence centre is an important factor in luminescence production.

The work described below involved the excitation of single crystals of KI:Tl by photons of energy up to 11 eV at temperatures between -140 and 45 °C. There was no visible evidence for the formation of colour centres even after several days' exposure to the highest intensities used. The luminescence phenomena observed at room temperatures closely resemble those recorded by Moser and Urbach (1957) for mixed crystals of AgI-AgBr at liquid air temperatures. They are similarly explainable on the assumption that free electrons and holes are produced and trapped even though attempts to observe photoconductivity in the alkali halides (Taylor and Hartmann 1959; Ewles and Joshi 1960; Meharry, personal communication) have been unsuccessful. While there are indications that similar processes persist into the exciton absorption band, the irradiation intensities at present available have not allowed a decisive investigation of this region.

II. INSTRUMENTAL

The vacuum monochromator has previously been described (Bolton and Williams 1953). Modifications include external focusing adjustments and means of controlling the specimen temperature. The normal vacuum is about 2×10^{-5} mm and with the hydrogen arc operating about 10^{-3} mm. The pass band is about 2 Å. Growth and decay of luminescence were recorded either photographically using a galvanometer of period 0.1 s and film speed 1 cm/s or by a recording milliammeter and a.c. amplifier. The a.c. signal was obtained by chopping the photomultiplier first dynode with a 270 c.p.s. square signal. No correction has been made for scattered light, which was approximately constant between 500 Å and the long wavelength limit of observation. The error introduced by this neglect is a maximum in the region between 1800 and 2000 Å, where the intensity of the arc is low and a wide exit slit is necessary to maintain constant intensity (for example in the luminescence efficiency observations of Fig. 1) and also in regions such as the exciton band, where the luminescence efficiency is low. For the maximum slit width used in these regions, scattered light, as measured at 500 Å, produced a maximum error of 5% in the luminescence efficiency. A KCl window was used when needed to eliminate second-order effects in the region above 2000 Å. Early observations on the growth of luminescence showed a lack of consistency which was eventually traced to contamination of the crystal face by oil from the backing pump. This was eliminated by inserting a liquid air trap in the backing line.

The KI:Tl specimens and a sodium salicylate monitor were mounted on a movable arm enabling either to be placed in the light beam. The KI:Tl crystals could be cooled to about 130 °K by conduction to a liquid air reservoir, but the monitor was always used at room temperature, since its efficiency is temperature dependent. Since high absorption restricts luminescence production to a thin surface layer, freshly cleaved single crystals were used, of a size 10 by 2 mm by 1.5 mm thick.

III. LUMINESCENCE EFFICIENCY

The curves shown in Figure 1 indicate luminescence efficiency variation with wavelength at about 26 °C. They were obtained by a point-to-point survey comparing the saturation luminescence efficiency from KI:Tl with the intensity from the monitor. Because there is a non-linear dependence of saturation luminescence intensity on excitation intensity over certain regions of the spectral range, it was necessary to adjust the excitation intensity to a constant value by using the monitor before each measurement. A time of the order of 1 min

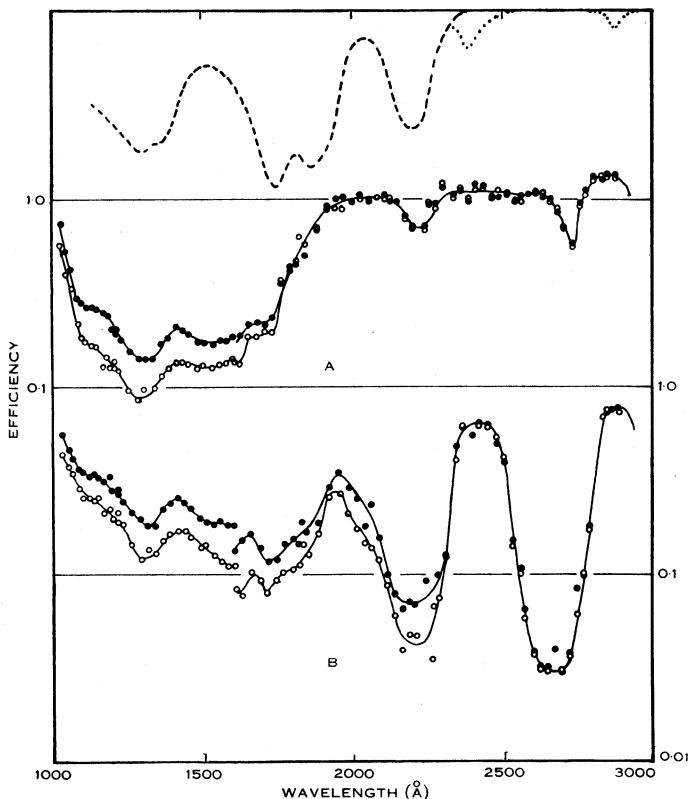


Fig. 1.—Variation of luminescence efficiency with irradiating wavelength.
 (A) KI:Tl (5%); (B) KI:Tl (0.0005%). ●●● Intensity 200.
 ○○○ Intensity 50. Broken line shows approximate variation of transmission of pure KI.

was needed for the luminescence to attain saturation. The figure shows also an approximation to the transmission of KI in this region (Schneider and O'Bryan 1937; Eby, Teegarden, and Dutton 1959), because the simple assumption that luminescence is produced by absorption of radiation at Tl centres implies that the luminescence efficiency should be proportional to the mean free path of the photons in the host crystal.

In the case of the 0.0005% Tl sample (curve B) the onset of KI fundamental absorption at 2300 Å divides the observations into two distinct regions. To the

long wavelength side of this edge, absorption takes place only at the Tl impurity centres, producing luminescent emission in a band centred at about 4000 Å (von Meyeren 1929). (Transmitted light is not detected since its wavelength is below the transmission limit of the photomultiplier window at 3000 Å.) Luminescence efficiency then follows the absorption of the activated crystal.

Below 2300 Å the luminescence efficiency shows a tendency to follow the main features of the KI transmission. This is most clearly apparent at the exciton peak at 2200 Å and at the absorption peak at 1290 Å. However, the two peaks at 1730 and 1870 Å are not resolved and there is a marked divergence between 1750 and 1350 Å, where the efficiency fails to rise with the transmission. The long wavelength limit of this region corresponds to the threshold for external photoemission and the short wavelength limit to the saturation emission of electrons (Taylor and Hartmann 1959). (The discontinuity at 1600 Å marks a division between two runs of observations.) This correlation of luminescence efficiency and transmission agrees with the results of Teegarden (1957) and Ueta and Ishii (1959) over the range of energies to 8·2 eV.

The 5% Tl sample (curve A) shows very similar variations between 1750 Å and the short wavelength limit. The peaks of high efficiency corresponding to impurity absorption at 2870 and 2380 Å are very much broadened without any apparent increase in efficiency as compared with the low impurity concentration samples. The drop in efficiency at the exciton peak is much less for this sample.

IV. SUPERLINEARITY

Figure 1 shows that in some regions the luminescence efficiencies are not constant for different exciting intensities. All samples show this departure from a linear relationship between excitation and luminescence intensity in the spectral range through which they show similar efficiency variations, i.e. below about 1750 Å, but for the low impurity sample the departure extends through longer wavelengths to about 2280 Å.

If the saturation value of the luminescent output, L_s , of the phosphor is related to the exciting intensity I_e , by the equation $L_s = c.I_e^x$, where c is a constant, the phosphor is superlinear if x exceeds unity. Through the range of wavelengths indicated in Figure 1, x varies between unity and 1·5 at room temperature. However, except at wavelengths of high intensity, namely, 1216 and 1608 Å, the accuracy with which x can be measured is too low to give more than an indication of its manner of variation with wavelength.

Both the luminescence efficiency and the linearity (x) vary rapidly with temperature in the 0–50 °C range. The luminescence efficiency decreases by half as the temperature rises from 8 to 30 °C and by a further quarter between 30 and 45 °C. At 1608 Å, with an incident intensity range of 20 : 1, x is 1·23 at 28 °C, 1·06 at 18 °C, and 0·94 at –15 °C. The fall in luminescence efficiency at high temperatures makes accurate determination of the maximum value of x difficult, but up to 45 °C it is about 1·5. While the observation at –15 °C could have been affected by condensation of oil or water vapour on the crystal, subsequent measurements at a pressure 5×10^{-5} mm with a liquid air trap on the pumping line show that the KI:Tl becomes linear at about 15 °C.

V. GROWTH AND DECAY OF LUMINESCENCE IN KI:Tl (0·0005%)

When irradiated by wavelengths below about 2250 Å the low impurity concentration crystal does not immediately produce its maximum luminescence intensity. There is a slow build-up of luminescence which is analysed below in detail. The threshold wavelength for slow build-up for a crystal of KI:Tl containing 0·05% Tl was 2100 Å. In this case a KCl absorber was used to exclude second-order effects. Reasonable assumptions regarding the relative intensities of the scattered, first- and second-order light falling on the crystal with 0·0005% Tl do not explain the longer wavelength of the threshold and, since the threshold for KI:Tl (5%) is at 1750 Å, some effect of activator concentration on threshold seems to be indicated.

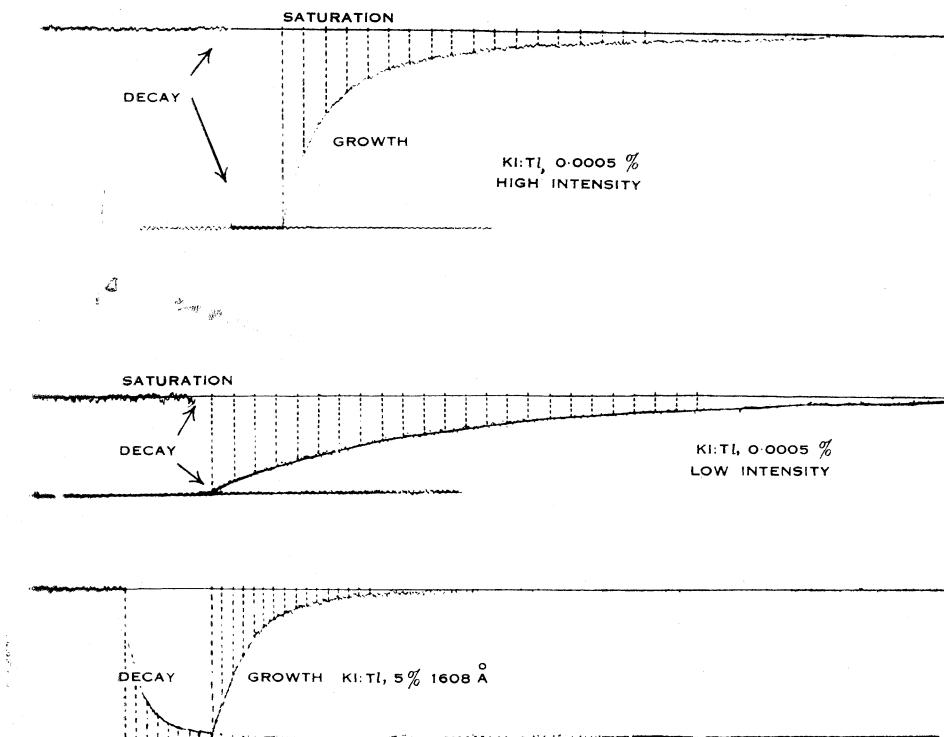


Fig. 2.—Photographically recorded growth and decay of luminescence in KI:Tl. Vertical broken lines are at 1 s intervals for KI:Tl (0·0005%) and at 0·5 s intervals for KI:Tl (5%).

Figure 2 shows typical records of the growth and decay of luminescence for low and high exciting intensities at 1608 Å for the 0·0005% Tl crystal compared with the 5% Tl crystal. It is clear that the decay is very fast relative to the growth and also that the time variation of the growth is intensity dependent. Neither of these characteristics is consistent with the assumption that the mechanism involved is the monomolecular process assumed by Williams and Johnson (1959) to be responsible for the production of luminescence in KCl:Tl irradiated in the impurity absorption bands.

The slow build-up of luminescence has been observed by Randall and Wilkins (1945), by Levialdi and Luzatti (1947), by Hoogenstraten (1953), and by Hoogenstraten and Klasens (1953) for luminophors which showed also a slow phosphorescent decay. Except for the present case of KI:Tl, slow build-up together with very fast decay has only been observed for mixed AgI-AgBr by Moser and Urbach (1957).

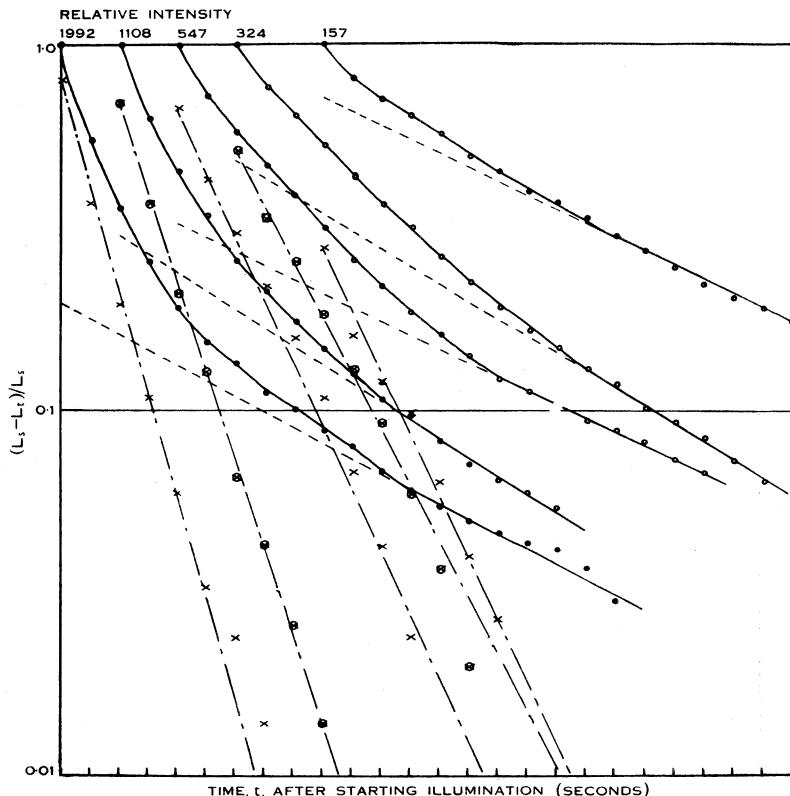


Fig. 3.—Growth of luminescence in KI:Tl (0.0005%) for various intensities of irradiation by 1216 Å. Growth curves for different intensities of irradiation have been separated along the time axis. Dissection of the curves shown by the broken lines is described in the text.

The growth curves have been analysed by a simpler method than that used by Schön (1954), although, as in his case, it has been assumed that the slow build-up is associated with the trapping of electrons and holes. An analysis of the curves is possible at 1216 and 1608 Å because of the high intensities available for excitation at these wavelengths. In Figures 3 and 4 the full lines show the difference between the saturation luminescence intensity L_s and the luminescence L_t , at time t after starting illumination at constant intensity. The curves have been displaced, for clarity, along the time axis. It is seen that with increasing intensity the growth curve departs from the simple exponential form. The broken lines show how the curves have been dissected. The straight part of the

curve for large t has been extrapolated to zero time and subtracted from the full curve to give the second component. At both 1216 and 1608 Å the growth curves are then found to separate into two exponential components, so that the full curve can be represented by the formula

$$L_t = L_s \{A(1 - e^{-yt}) + B(1 - e^{-zt})\}, \text{ where } A + B = 1.$$

That the growth curves for luminescent SiO_2Cd could be represented as the sum of two exponentials, was recognized by Levialdi and Luzzati (1947). The numerical values are listed in Table 1.

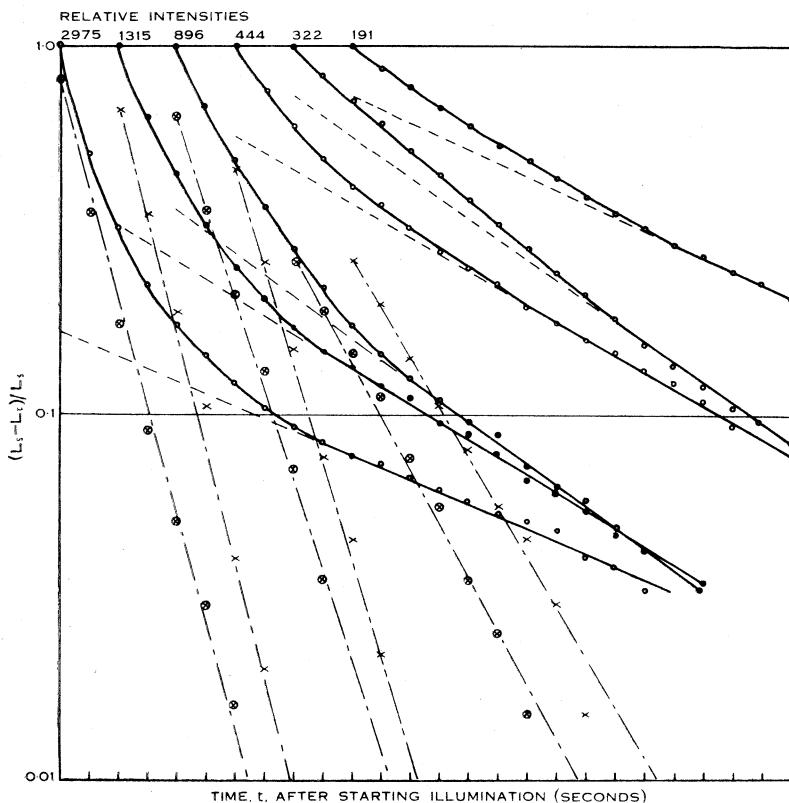


Fig. 4.—Growth of luminescence in KI:Tl (0.0005%) for various intensities of irradiation by 1608 Å.

It appears from this analysis that the intensity dependence of the growth curves results from a change in the relative importance of two processes for producing luminescence, designated by the parameters A and y , and B and z . The former increases in importance with increasing excitation intensity, the latter consequently decreases. Since A and B are the fractions of L_s produced by each of the two processes, then $A.L_s/I_e$ and $B.L_s/I_e$ are the respective luminescence efficiencies. The table shows that, while the efficiency for the first process increases rapidly, in fact about as $I_e^{1.5}$, the efficiency for the second process is

approximately constant, showing a small decrease at the highest intensities. The original superlinearity, then, arises from the superlinear character of the first process. Further discussion is included below.

The available excitation intensity would not allow such a detailed examination of the intensity dependence of the luminescence growth at other wavelengths, but a slow build-up has been observed to extend into the exciton band region to the thresholds mentioned above.

TABLE I
ANALYSIS OF GROWTH CURVES

| Incident Intensity, I_e (from Monitor) | Saturation Lumin-escence Intensity, L_s | A | y | $A.L_s/I_e$ | B | z | $B.L_s/I_e$ |
|---|---|------|------|-------------|------|-------|-------------|
| <i>(a) At 1216 Å (Fig. 3)</i> | | | | | | | |
| 1992 | 530 | 0.81 | 0.67 | 0.21 | 0.19 | 0.10 | 0.05 |
| 1188 | 296 | 0.70 | 0.55 | 0.17 | 0.30 | 0.12 | 0.07 |
| 547 | 121 | 0.68 | 0.37 | 0.15 | 0.32 | 0.09 | 0.07 |
| 324 | 65 | 0.52 | 0.34 | 0.11 | 0.48 | 0.11 | 0.09 |
| 157 | 26 | 0.28 | 0.34 | 0.05 | 0.72 | 0.09 | 0.12 |
| <i>(b) At 1608 Å (Fig. 4)</i> | | | | | | | |
| 2975 | 1258 | 0.82 | 0.74 | 0.35 | 0.18 | 0.075 | 0.075 |
| 1315 | 468 | 0.67 | 0.74 | 0.24 | 0.33 | 0.10 | 0.12 |
| 896 | 296 | 0.63 | 0.59 | 0.18 | 0.37 | 0.12 | 0.12 |
| 444 | 109 | 0.46 | 0.53 | 0.11 | 0.54 | 0.10 | 0.13 |
| 322 | 69 | 0.26 | 0.33 | 0.06 | 0.74 | 0.12 | 0.16 |
| 191 | 34 | 0.26 | 0.31 | 0.05 | 0.74 | 0.08 | 0.13 |

VI. INSTANTANEOUS COMPONENTS OF LUMINESCENCE GROWTH

An instantaneous component can be observed at wavelengths lower than 1700 Å by illuminating the sample after a relatively short time in darkness following a previous illumination to saturation at the same intensity. Similar observations were made by Moser and Urbach (1957). The dependence of the magnitude of this instantaneous component relative to the saturation luminescence on the time since the crystal was previously illuminated is shown in Figure 5. The rate of decay is the same at 26 °C at both 1216 and 1608 Å, but it is greatly reduced by a decrease in the crystal temperature, as the curve for 1608 Å excitation at 15 °C shows.

When the temperature is lowered to, say, -100 °C the growth curve associated with the first illumination has a form determined by the time interval since the previous illumination and the start of cooling and the temperature during that interval. However, subsequent illuminations at the same intensity after periods up to 15 min in darkness at low temperature show a completely instantaneous rise in luminescence.

In an experiment in which the sample was allowed to warm up gradually as it was alternately irradiated to saturation and left in the dark, it was found

that, following irradiation at -15°C and 12 min in darkness while the temperature rose to 3°C , the diminution of the instantaneous component was negligible. After irradiation to saturation at 3°C followed by 13 min in darkness, during which time the temperature rose to 18°C , the instantaneous component had completely disappeared when the sample was next irradiated. It appears that the process responsible for decay of the instantaneous component becomes much less probable when the temperature falls below about 10°C . The decay curves of Figure 6 can be expressed as the sum of two exponentials, namely,

$$L_{\text{inst.}} = L_s(0.58e^{-0.1t} + 0.42e^{-0.002t}) \text{ at } 26^{\circ}\text{C},$$

and

$$L_{\text{inst.}} = L_s(0.36e^{-0.06t} + 0.64e^{-0.008t}) \text{ at } 15^{\circ}\text{C},$$

where t is the time in the dark.

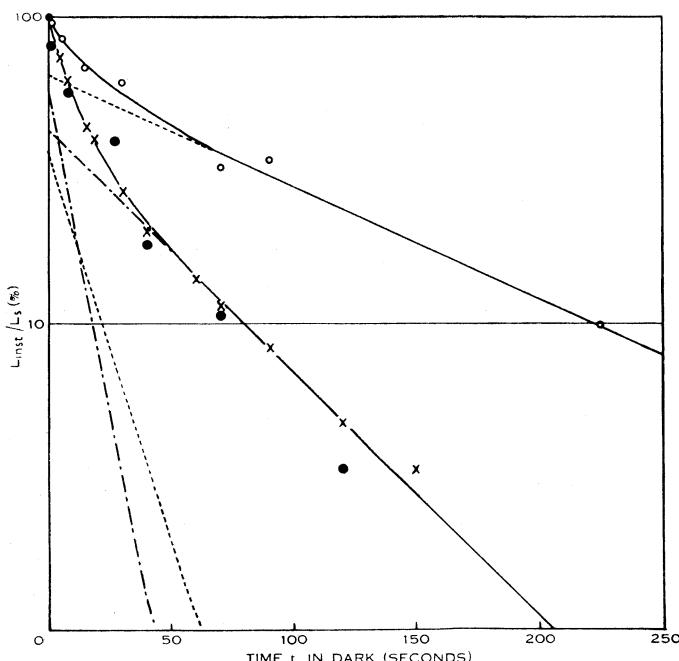


Fig. 5.—Decay of the instantaneous component of luminescence in KI:Tl (0.0005%). Irradiated by 1216 Å at 26°C , $\times \times \times$ irradiated by 1608 Å at 26°C , $\circ \circ \circ$ irradiated by 1608 Å at 15°C . Dissection of the curves by the broken lines is described in the text.

VII. GROWTH AND DECAY OF LUMINESCENCE IN KI:Tl (5%)

Some observations were made on the growth and decay of luminescence in the high impurity concentration crystal at about 26°C . The most significant feature was the appearance of a phosphorescent decay whose half-life was shorter than the corresponding growth "half-life". A typical curve for excitation by 1608 Å radiation is shown in Figure 2, and Figure 6 shows typical growth

and decay curves. The form of the decay does not change very much when the exciting intensity is increased by 25 times. The corresponding growth curves show some change with intensity, but the growth is so rapid (about 5 times faster) that it was not possible with the available equipment to observe the growth accurately enough to justify an analysis similar to that of Figures 3 and 4. Nor could it be determined whether any instantaneous component exists after short periods in darkness.

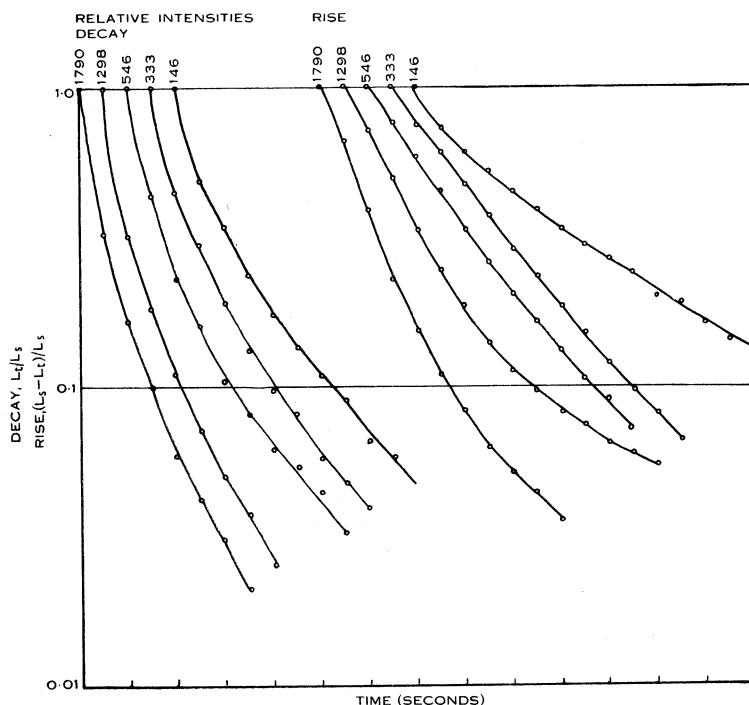


Fig. 6.—Curve of growth and decay of luminescence in KI:Tl (5%) irradiated by various intensities at 1608 Å. Curves displaced along time axis for clarity.

The probability for Tl ions to occupy adjacent cation sites in the lattice is much greater for the 5% Tl crystal. Adjacent Tl centres will introduce additional traps and at the same time, on the assumptions of the discussion below, the chance for radiationless de-excitation will be decreased in favour of phosphorescent emission.

VIII. DISCUSSION

If the luminescence resulting from excitation energies falling within the fundamental absorption band of the host crystal were solely the result of direct absorption at Tl centres, the intensity of the luminescence would be expected to show a considerable decrease compared with that for excitation in the impurity peaks where the host crystal is transparent. The luminescence efficiency could be expected to follow the transmission of the sample in a general way.

The high luminescence efficiency observed within the fundamental absorption band throws doubt on this simple assumption even when superlinearity, slow growth, and very fast decay are neglected. The number of impurity centres directly accessible to radiation of wavelengths in the fundamental absorption band should be decreased compared with the number accessible to radiation of wavelengths in the impurity bands by a factor approximately equal to the ratio of the absorption coefficients, provided the crystal is thick enough to absorb completely in both regions. The absorption coefficient in the fundamental band is of the order of $10^5/\text{cm}$ (Schneider and O'Bryan 1937; Eby, Teegarden, and Dutton 1959). The absorption coefficient in the impurity bands depends on the impurity concentration. The observed value for the 2870 \AA band for the 0.0005% Tl sample was about 100 cm^{-1} . At 2400 \AA it was of this order but could not be measured accurately for the thinnest specimens which could be cleaved (0.02 cm). (Proximity to the tail of the fundamental absorption band also tends to mask the impurity absorption in this region.) A similar difficulty existed for the 5% sample. However, it is clear that the ratio of the absorption coefficients is at least of the order of 1 : 500 while the observed ratio of the corresponding luminescence efficiencies is of the order of 10 : 1.

This discrepancy could be the result of one or more of three causes. Firstly, there may be an increase in the cross section of the Tl centre for direct excitation by photons of energies within the fundamental absorption band, though any such increase would probably not be considerable over more than a very restricted energy range. Secondly, a luminescent process for de-excitation of the host crystal following irradiation in the absorption band may exist. It is reported, however, that KI in the pure form does not normally show luminescence at room temperature (Teegarden 1957). If such luminescence were promoted by the presence of the Tl activator, new emission bands of high intensity compared with the Tl emission bands should be observed on illumination within the fundamental absorption edge, unless their wavelength was coincident with the 4000 \AA bands of Tl. No evidence has been reported for the existence of such bands, although Chatterjee (1950) and Smaller and Avery (1953), who used X-ray and γ -ray excitation, should have observed them if they existed. The remaining possibility is that the high luminescence efficiency results from the transfer of energy from the host crystal to the Tl ion responsible for luminescence emission. Such a transfer of energy is assumed to occur only in regions of the host crystal in the immediate neighbourhood of an impurity ion. To account for the increased luminescence efficiency, such regions must have a radius of the order of 5 lattice spacings.

Similar conclusions have been reached by other investigators. Tomura and Kaifu (1960) have concluded that at liquid air temperatures excitons produced in KI:Tl can transfer energy to the Tl ions to produce luminescence, though as the temperature rises the luminescence efficiency falls rapidly. Ewles and Joshi (1960) from a study of KCl:Tl concluded that, even for excitation in the impurity bands, transition between energy levels of a Tl ion cannot explain the characteristics of luminescence production. Johnson and Williams (1950) calculated from measurements of the variation of luminescence efficiency with

Tl concentration that the influence of the impurity extended over several lattice spacings. Lushchik and Pliavin (1959) have also proposed the occurrence of energy transport from host lattice to impurity centres.

In what follows, therefore, the details of luminescence production by a Tl ion have been ignored. The presence of an impurity ion in the lattice is assumed to cause the formation of a region in its vicinity containing trapping sites for electrons and holes additional to and probably deeper than those normally present in the remainder of the lattice. The analytical form of the growth curves, namely,

$$L = L_s \{ A(1 - e^{-yt}) + B(1 - e^{-zt}) \}$$

indicates that luminescence production depends on the processes involving the attainment of equilibrium in the filling of traps. The probability of emptying of traps by recombination or by thermal escape is then measured by the coefficients y and z , and saturation luminescence production is attained when the number of occupied traps in the vicinity of a luminescence centre is a maximum.

Moser and Urbach assumed that free electrons recombined with trapped holes to produce luminescence in AgI-AgBr. A similar assumption has been made by Lushchik (Lushchik *et al.* 1960), in regard to activated alkali halides irradiated by photons of energy up to 7 eV. From the present work it cannot be decided whether the two terms in the expression for L_t represent the recombination of free electrons with trapped holes and the recombination of free holes with trapped electrons, or involve a further trapping process such as would result from a secondary generation of F -centres. However, following the above-mentioned authors it is assumed that the first term, namely, $A(1 - e^{-yt})$ represents the luminescence resulting from recombination of free electrons with trapped holes within a few lattice spacings from a Tl ion so that energy transfer to the Tl ion can occur. This process is superlinear, the efficiency AL_s/I_e varying at room temperature approximately as $I_e^{3/2}$. The second term also represents a recombination process involving traps and energy transfer to Tl centres, but this process is approximately linear.

Thermal release from the traps will produce free holes or electrons, but the absence of phosphorescence indicates that these holes and electrons do not recombine in the vicinity of Tl centres to transfer energy to the Tl, but tend to leave the region in which energy transfer can take place to recombine by a radiationless process elsewhere. In the 5% Tl crystal, because of the smaller distance between Tl centres, the possibility for this is less than in the 0.0005% Tl crystal and phosphorescence should be produced. The observation of phosphorescence in these high impurity content crystals with a decay curve whose form is independent of exciting intensity supports this assumption.

The thermal emptying of traps produces the decay of the instantaneous coefficient of luminescence on the one hand and a fall in luminescence efficiency with rising temperature on the other. Since the saturation luminescence intensity is inversely proportional to the probability of a trap being emptied, both y and z should be temperature dependent. At constant intensity y should be the sum of the probability of recombination of a free electron with a trapped hole and a temperature-dependent probability for thermal release which is

observable as the exponential decay of the instantaneous component. Observations in the temperature range 18–45 °C tend to confirm this assumption, though the accuracy with which the growth and decay curves can be analysed is less than could be desired.

The observed superlinearity results from an increase in the efficiency $A.L_s/I_e$ of the relevant luminescence process, which makes $A.L_s$ increase approximately as $I_e^{1.5}$. $A.L_s$, the saturation luminescence intensity for this process, is proportionate to the equilibrium concentration of trapped holes near a Tl centre. At constant temperature, in the absence of any additional intensity-dependent influence, the concentration should be proportional to the incident intensity. Therefore to account for the observed superlinearity an additional intensity-dependent factor is required to raise the concentration of trapped holes suitably in the vicinity of Tl centres. The intensity-dependence of this factor is observed to increase from zero at about 10 °C, the threshold for superlinearity, to $I_e^{\frac{1}{2}}$ at room temperature and above. Since a rise in temperature will facilitate the migration of holes toward the deeper traps closest to Tl centres it is suggested that the intensity-dependent factor is to be associated with the process of hole migration.

IX. ACKNOWLEDGMENTS

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X. REFERENCES

- BOLTON, J. H., and WILLIAMS, S. E. (1953).—*Brit. J. Appl. Phys.* **4**: 6.
- BONANOMI, J., and ROSSEL, J. (1951).—*Helv. Phys. Acta* **25**: 725.
- CHATTERJEE, A. (1950).—*Indian J. Phys.* **24**: 331.
- EBY, J., TEEGARDEN, K. J., and DUTTON, D. B. (1959).—*Phys. Rev.* **116**: 1099.
- EWLES, J., and JOSHI, R. V. (1960).—*Proc. Roy. Soc. A* **254**: 358.
- HOOGENSTRATEN, W. (1953).—*J. Electrochem. Soc.* **100**: 356.
- HOOGENSTRATEN, W., and KLASENS, H. A. (1953).—*J. Electrochem. Soc.* **100**: 366.
- JOHNSON, P. D., and WILLIAMS, F. E. (1950).—*J. Chem. Phys.* **18**: 1477.
- LEVIALDI, A., and LUZZATI, V. (1947).—*J. Phys. Radium* **8**: 306, 341.
- LUSHCHIK, Ch. B., LIID'YA, G. C., YAEK, I. V., and THISLER, E. S. (1960).—*Optika i Spektrosk.* **9**: 77.
- LUSHCHIK, Ch. B., and PLIAVIN, I. K. (1959).—*Optika i Spektrosk.* **7**: 41.
- VON MEYEREN, W. (1929).—*Z. Phys.* **61**: 321.
- MOSER, F., and URBACH, F. (1957).—*Phys. Rev.* **106**: 852.
- RANDALL, J. T., and WILKINS, M. H. F. (1945).—*Proc. Roy. Soc. A* **184**: 366.
- SCHNEIDER, E. G., and O'BRYAN, H. M. (1937).—*Phys. Rev.* **51**: 293.
- SCHÖN, M. (1954).—*Physica* **20**: 930.
- SMALLER, B., and AVERY, E. (1953).—*Phys. Rev.* **92**: 233.
- TAYLOR, J. W., and HARTMANN, P. L. (1959).—*Phys. Rev.* **113**: 1421.
- TEEGARDEN, K. J. (1957).—*Phys. Rev.* **105**: 1222.
- TOMURA, M., and KAIFU, Y. (1960).—*J. Phys. Soc. Japan* **15**: 314.
- UETA, M., and ISHII, T. (1959).—*J. Phys. Soc. Japan* **14**: 857.
- WILLIAMS, F. E., and JOHNSON, P. D. (1959).—*Phys. Rev.* **113**: 97.