the channels (collisional excitation and ionization) remains to be investigated. Experiments for determining the threshold kinetic energy of the penetrating atom and also the charge state of the penetrating component would be useful in understanding the nature of the phonomena involved.

The author is grateful to B. Domeij, F. Brown, J. A. Davies, E. V. Kornelson, and G. R. Piercy for helpful discussions and for the opportunity of studying their experimental results prior to publication.

---

*Work performed under the auspices of the U. S. Atomic Energy Commission.

[1] B. Domeij, F. Brown, J. A. Davies, E. V. Kornelson, and G. R. Piercy, Phys. Rev. Letters, preceding Letter [Phys. Rev. Letters 12, 363 (1964)].

[2] M. T. Robinson and O. S. Oen, Bull. Am. Phys. Soc. 7, 171 (1962); Appl. Phys. Letters 2, 30 (1963); Phys. Rev. 132, 2385 (1963).

[3] J. R. Beeler, Jr., and D. G. Besco, Proccedings of the Symposium on Radiation Damage in Solids and Reactor Materials (International Atomic Energy Agency, Vienna, 1962), Vol. 1, p. 43.

[4] G. R. Piercy, F. Brown, J. A. Davies, and M. McCargo, Phys. Rev. Letters 10, 399 (1963); also references to earlier work given therein.

[5] H. Lutz and R. Sizmann, Phys. Letters 5, 113 (1963).

[6] C. Lehmann and G. Leibfried, J. Appl. Phys. 34, 2821 (1963).

[7] M. T. Robinson, Oak Ridge National Laboratory Report No. ORNL-3493 (unpublished).

INFRARED QUANTUM COUNTER ACTION IN Er-DOPED FLUORIDE LATTICES

M. R. Brown
Ministry of Aviation, Signals Research and Development Establishment, Christchurch, Hampshire, England

and

W. A. Shand*
Department of Natural Philosophy, University of Aberdeen, Aberdeen, Scotland

(Received 24 February 1964)

In our previous reports of infrared quantum action,[1] the fluorescent and pump radiations were in the visible range while the signal was in the near infrared. In this Letter we report action in Er^{3+} doped 1% in LaF_3, SrF_2, CaF_2, and BaF_2 at room temperatures in which both the pump and signal are in the near infrared, while the fluorescent output from the combined schemes is clearly visible to the eye. The actual color of the fluorescence depends on the host lattice, viz., LaF_3 green, SrF_2 reddish orange, CaF_2 red, and BaF_2 yellowish orange.

Er^{3+} in these host lattices fluoresces in both the red (${}^4F_{9/2}$ to ${}^4I_{15/2}$) and the green (${}^4S_{3/2}$ to ${}^4I_{15/2}$). If the ions are excited to ${}^4S_{3/2}$ or higher, then both these fluorescences appear. The relative magnitudes depend on the lattice; for example, in the LaF_3 lattice the green is approximately 30 times stronger than the red, while in the SrF_2 lattice it is a factor of two weaker. If the ions are excited to ${}^4F_{9/2}$, then only the red fluorescence appears. The schemes have therefore been separated into two sets depending on the fluorescent output.

Five of the schemes identified are shown in Figs. 1 and 2. The energies given are the average for each of the multiplets and are only approximate for there are shifts between the various host lattices. The multiplet notation used in these schemes was assigned by analogy with other work on erbium.[2]

It is convenient to discuss the results for the four doped lattices by considering the two sets of schemes in turn.

Red output.—The two schemes positively identified in all four lattices are shown in Fig. 1. Scheme 1 [Fig. 1(a)] is inverted with respect to scheme 2 [Fig. 1(b)] in that the longer wavelength is absorbed as the second transition rather than as a transition from the ground state in the conventional scheme 2. We feel that an "inverted" scheme of this type in which the transition from the ground state is pumped by a strong visible pump and the infrared signal is the second transition could have advantages under certain circumstances over the conventional scheme for the detection of low-level signals. A third scheme, not shown, was found in the SrF_2 and CaF_2 lattices in which 973-mμ and 1.15μ wavelength radiations were needed. This scheme has been tentatively fitted as a hybrid of schemes 1 and 2 in which there is relaxation from ${}^4I_{11/2}$ to ${}^4I_{13/2}$.

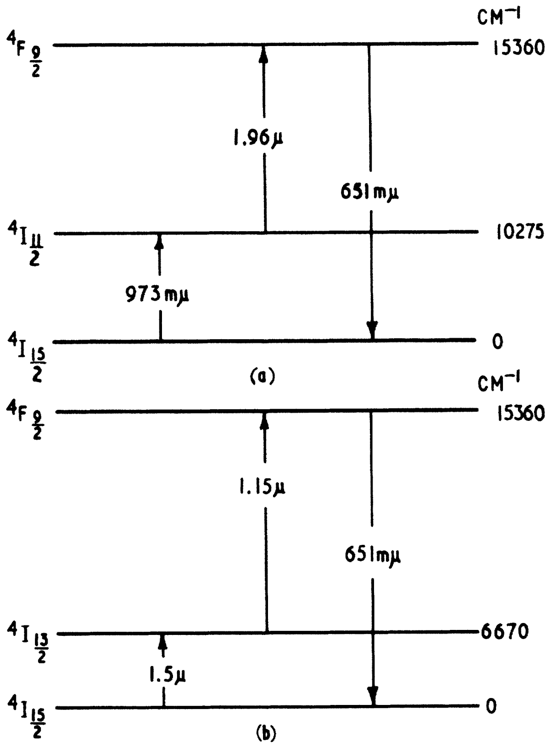

FIG. 1. The infrared quantum counter schemes giving a red fluorescent output. Only the relevant energy level of the Er^{3+} ion are shown.

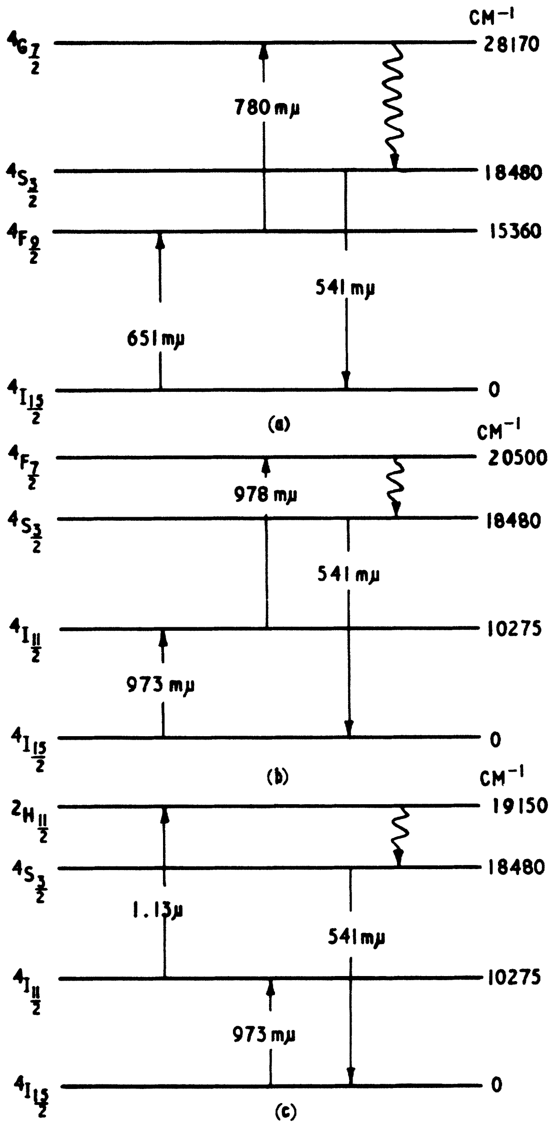

FIG. 2. The infrared quantum counter schemes giving a red and green fluorescent output. Only the relevant energy levels of the Er^{3+} ion are shown.

Red and green output.—The three schemes positively identified in all four host lattices are given in Fig. 2, showing the green output alone for clarity. In scheme 3 [Fig. 2(a)], the energy of the upper level ($^4G_{7/2}$) as found from the scheme was within 200 cm^{-1} of the value we measured for each of the lattices. We feel this to be good agreement in view of the crudeness of the filtering. In scheme 4 [Fig. 2(b)], the signal and pump radiations are very close to one another giving a doubling effect. For the particular case of the SrF_2 lattice, the match between signal and pump is exact, within the linewidth, at 975 mμ. Scheme 5 is the fifth example of a scheme in which both signal and pump are in the infrared. There is some evidence that a sixth scheme involving 973 mμ ($^4I_{15/2}$ to $^4I_{11/2}$) and 1.22 μ ($^4I_{11/2}$ to $^4S_{3/2}$), exists but it could not be positively identified due to the difficulty of discriminating with the filters available.

It has not been possible to measure the relative intensities of these schemes because of the width of the pass band of the filters used and the difficulty of matching the two beams in the crystal over a range of wavelengths. However, it can be said that the schemes collectively are sufficiently strong to give an output clearly visible to the eye with only one source fitted with an infrared filter. Figure 3 shows a photograph of the effect in which the light from a xenon source, after filtering, was focused onto the Er^{3+}-doped SrF_2 crystal to give the visible fluorescence. The way in which the color of this visible fluorescence varies with the host lattice may be explained qualitatively:

(i) Er^{3+} ions in the LaF_3 lattice give green because not only do ions decaying down to $^4S_{3/2}$ give

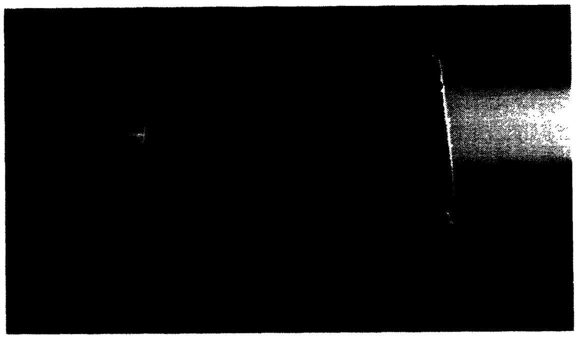

FIG. 3. Infrared quantum counter action in an Er^{3+}-doped SrF_2 single crystal showing the band of visible fluorescence produced by the focused infrared radiation. The source in this case was a xenon lamp.

30 times more green fluorescence than red, but the quantum efficiency of the $^4S_{3/2}$ level is twice that of the $^4F_{9/2}$ level.

(ii) The case is almost the reverse in the CaF_2 lattice in that the color is red due to the decay processes giving three times more red fluorescence than green and the quantum efficiency of the $^4F_{9/2}$ level is 10 times that of $^4S_{3/2}$.

(iii) With the SrF_2 and BaF_2 lattices the colors are reddish orange and yellowish orange, respectively, a situation intermediate between (i) and (ii). The decay processes give roughly equal amounts of red and green fluorescence, while the quantum efficiency of the $^4F_{9/2}$ level is five to 10 times that of the $^4S_{3/2}$. This situation biases the color mixture towards the red.

These results show that the quantum counter, as a means of measuring the energies of levels involved in the scheme, is capable of giving reasonably accurate values and that it can be used to make infrared radiation visible. An obvious application of the latter is night viewing, and in this context perhaps the acronym VISOR is suitable, that is, Visible from Infrared by the Summation of Radiation.

We wish to thank Miss S. Collier for assistance with the spectroscopy and the Royal Radar Establishment, Malvern, England together with the University of Aberdeen, Aberdeen, Scotland, for providing the crystals used in this work.

---

*On detached duty at Signals Research and Development Establishment, Christchurch, Hampshire, England.

[1] M. R. Brown and W. A. Shand, Phys. Rev. Letters 11, 366 (1963); Phys. Letters 8, 19 (1964).

[2] B. G. Wybourne, J. Chem. Phys. 32, 639 (1960).

TRAPPING LEVELS AND THERMOLUMINESCENCE OF CsI DOPED WITH VARIOUS ACTIVATORS*

Prudencio Martinez, Frank E. Senftle, and Marlys Page
U. S. Geological Survey, Washington, D. C.

(Received 5 March 1964)

In two recent communications[1,2] describing the thermoluminescence of thallium-activated alkali halides, it was shown that the main trapping levels are characteristic of the host crystal rather than of the thallium. In addition, Hersh and Hadley[1] have ascribed the emission of the main thermoluminescence peaks to the release of holes from V_k centers (halogen molecule ions) and subsequent annihilation with an electron trapped at or near an impurity. Schlesinger and Halperin,[2] however, found the emission spectra for the pure alkali halides to be characteristic of the crystal, whereas the emission for the thallium-doped crystals was characteristic of thallium. They point out the incompatibility of this evidence with a V_k center hypothesis and explain the main thermoluminescence emission as being due to an electron, which was originally in the ground state of the Tl^+ ion, but, as a result of excitation, becomes trapped in a negative ion vacancy in close proximity to the Tl^+ ion. Emission can take place when the electron is thermally raised to the excited state of the Tl^+ ion and then returns to the ground state by a radiative transition.

Experiments with cesium iodide in this laboratory over the past few years confirm the importance of the host crystal in establishing the trapping levels, but they do not support the trapped-electron hypothesis of thermoluminescence emission for this particular alkali halide. Thermoluminescence curves of pure cesium iodide as well as crystals doped with silver, indium, copper, and thallium activated with 58 kV, 6 mA x rays for 30 sec at 77°K are shown in Fig. 1. The main peaks are seen in all the crystals at the same temperatures. These results, in agreement with those of previous workers, imply that the main trapping levels are characteristic of

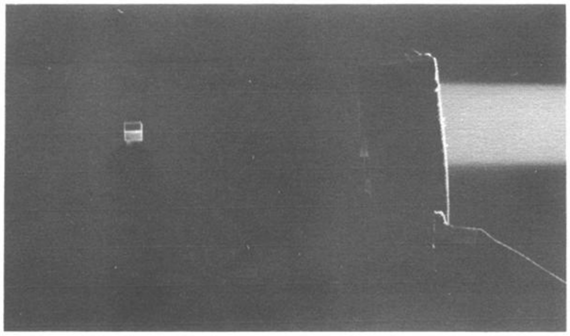

FIG. 3. Infrared quantum counter action in an Er^{3+}-doped SrF_2 single crystal showing the band of visible fluorescence produced by the focused infrared radiation. The source in this case was a xenon lamp.