We have also calculated derivatives of k_1 and k_2 with respect to the lattice parameter c. For $c/b=(8/3)^{\frac{1}{2}}$, we find

$$dk_1/dc=(-1.10721\pm0.00006)q/b^4, \qquad (5)$$
$$dk_2/dc=(-1.60363\pm0.00010)q/b^5.$$

For a face-centered cubic crystal of cubic lattice parameter a, the potential takes the form,

$$V=q/r+(8\pi/3)qr^2/a^3$$
$$+k_4[x^4+y^4+z^4-3(x^2y^2+x^2z^2+y^2z^2)]+\ldots, \qquad (6)$$

where coordinate axes are chosen parallel to cube edges, and

$$k_4=(-7.653\pm0.035)q/a^5. \qquad (7)$$

The arrangement of ions in a hexagonal close-packed crystal with ideal ratio of c/b is very similar to that in a face-centered cubic crystal. For the case $a=\sqrt{2}b$, the ions in each crystal have 12 nearest neighbors, with the same spacing, and almost the same arrangement. Nevertheless, not only does the hexagonal potential have extra terms, but even the 4th degree harmonics in the two cases differ in both form and magnitude.

In assuming a uniform distribution of conduction electrons, the model we have used neglects screening by these electrons. This screening is likely to be different for the different harmonics or multipoles.

[1] H. A. Bethe, Ann. Physik 3, 133 (1929).
[2] M. Born and M. Goeppert-Mayer, Handbuch' der Physiki (Springer, Berlin, Germany, 1933), Vol. XXIV, Part 2, p. 709.
[3] M. Born and M. Goeppert-Mayer, Handbuch der Physik (Springer, Berlin, Germany, 1933), Vol. XXIV, Part 2, p. 710.

Photoconductivity of Trapped Electrons in KBr Crystals at Room Temperature

J. J. OBERLY
Crystal Branch, Metallurgy Division, Naval Research Laboratory, Washington, D. C.
(Received October 26, 1951)

THE room temperature photoconductivity of all the stable color center absorption bands attributed to electrons trapped at lattice defects has been reported briefly for KCl[1] and for KBr.[2] The quantitative data for KBr generally verified the initial findings with KCl and allowed a comparison of the product ηw—quantum yield times electron range—for the various bands. This note will discuss the KBr results in more detail. The crystals were colored by x-rays from a Machlett AEG-50A tube having a tungsten target and beryllium window and were polarized by 500 volts dc while continuous records of photocurrent vs wavelength were made.

Soft x-rays produce the F-absorption band and a much weaker M-absorption band, both of which are photoconductive. After a very short x-irradiation, when the M-band is too weak to be observed, a peak is found in the photoresponse (photocurrent/incident energy) at the M-band wavelength which is 500 times weaker than the F-peak. Further x-irradiation strengthens both absorption bands and their photoresponse until the condition shown in Fig. 1 is obtained. The splitting of the F-peak can be attributed to the inhomogeneous distribution of F-centers produced by soft x-rays. Since F-centers are good electron traps, the range being inversely proportional to F-center concentration, they make the photoresponse smaller at the center of the band where the monochromatic light is absorbed in a high concentration of F-centers near the entrance surface. Unstable centers (F'), which have a lifetime of the order of a second, form and decay during the measurement, raising the photoresponse nonuniformly. This is evident in the difference between the two curves obtained by sweeping in opposite directions through the spectral region.

Illuminating the crystal with F-light (F-bleach) weakens the F-band and also affects the M-band and forms the R-, N-, and
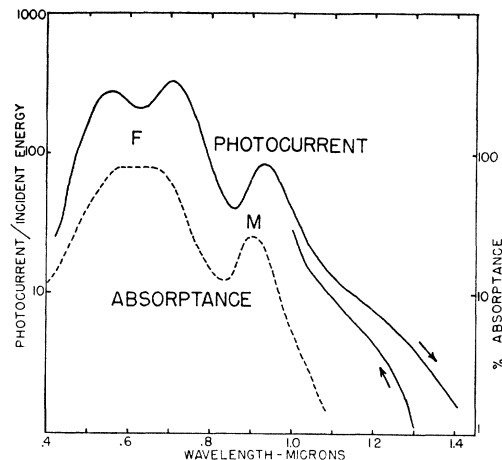

FIG. 1. Photoresponse and absorptance of F- and M-centers in KBr after long exposure to soft x-rays.

L-bands (R_1 and R_2 are not usually resolved in KBr at room temperature; L designates the short wavelength companion of the F-band). It is found that F photoresponse is not proportional to absorptance during F-bleach. This is shown in Fig. 2(a) for a crystal x-rayed through $\frac{1}{16}$-inch aluminum to produce a more homogeneous distribution of F-centers. The rate of weakening during bleaching is much greater in F photoresponse than in F absorptance, and a decrease in the rate of weakening during bleaching is evident in both. This greater effect on photoresponse
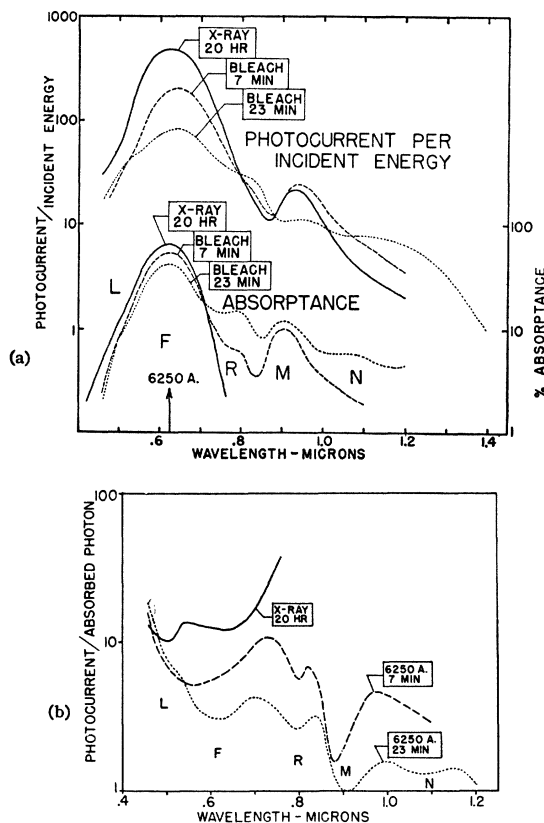

FIG. 2. Trapped electron centers in KBr after long exposure to hard x-rays and subsequent F-bleach: (a) photoresponse and absorptance; (b) product of quantum yield and electron range (ηw) in arbitrary units.

is also evident in Fig. 2(b) where the ordinate is proportional to the ratio photocurrent absorbed photon and thus to the product ηw. If the destruction of F-center electron traps were the only process during bleaching, ηw would increase rather than decrease as observed. A similar decrease observed in additively colored KCl has been attributed to colloidal electron traps[3] which, however, are not expected in these x-ray crystals. It is possible that the other centers formed during F-bleach are even better traps than F-centers, but this would not readily account for the decrease in rate of weakening.

On the other hand, both the greater weakening rate for photoresponse and the decrease in the rate can be explained by the existence of two kinds of centers which together produce the F-absorption as suggested by Przibram.[4] These will be called "soft" and "hard," the bleachable-photoconductive and the nonbleachable-nonphotoconductive, respectively. X-rays form both with the relative amounts depending on the nature of the x-rays. The superposition of two absorption bands is also indicated by the familiar small shift of the absorption peak during bleaching which is not apparent in this figure. Petroff[5] recently reported that F-centers in additively colored KCl transform into M-centers by way of an intermediate stage (B-centers) whose absorption coincides with the F-band, but no such genetic relationship is yet apparent between soft and hard centers. The changing stability of the F-band during bleaching has recently been attributed to a changing capture cross section of V-centers for the electrons freed from F-centers,[6] the stability increasing with decreasing cross section. However, such a mechanism would produce an increase in ηw during bleaching, rather than the observed decrease, since the decreasing cross section would allow the range of the electron to increase.

The photoconductivity of the other color center bands is also shown in Figs. 2(a) and 2(b). The well-known increase and decrease of the M-band during F-bleach is evident in Fig. 2(a) in both photoresponse and absorptance, the height above the general curve level being significant in the latter case. The greater decrease in photoresponse compared to absorptance during F-bleach, and the occurrence of the same effect during M-bleach (with M-light), indicate the existence of soft and hard M-centers also. Thus, the F- and M-bands are similar in having both soft and hard components; their similarity is also evident in their greater stability to heat than the R- and N-bands and in their rapid growth while the R- and N-bands disappear during a short x-irradiation. The L-, R-, and N-bands all have corresponding photoresponse peaks which become more prominent during F-bleach.

The corresponding values of the product ηw are shown in Fig. 2(b). If the range w were the same for electrons freed from the various types of centers, each curve would show relative quantum yield. The minima located at the band centers would result if for any reason the photoresponse peaks are flatter than the absorptance peaks or if some more efficient photoconductive process is present over the whole spectral range. The R'-band is broad and photoconductive but it has been observed only in additively colored KCl.[7] In the L-region the product is not greatly affected by F-bleach, but elsewhere it changes by a fairly constant factor during the second bleaching interval. In both of the bleached conditions the quantum yields in the F and R regions are equal and about 3 times the yields in the R and N regions, if the range is assumed constant for all.

When F-bleach is continued still further, a minimum appears in the photoresponse curve at the F region which is then similar to the curve in Fig. 1. The appearance of such a minimum after bleaching can be attributed only to absorption by hard F-centers remaining after the soft centers near the surface entered by the light are bleached away. As shown in Fig. 3 where the photocurrent has not been corrected to an equal energy basis, further F-bleach weakens the F photocurrent still more and at the same time weakens the M and builds up the N to a fixed value. While these changes take place, the R photocurrent remains constant. This unusual stability of photoconductivity is even more evident
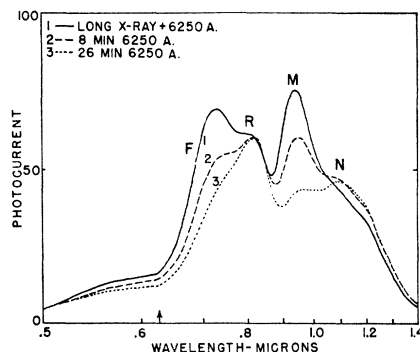

FIG. 3. Effect of further F-bleach on photoconductivity of the trapped electron centers in KBr.

during irradiation with R-light for several hours; the R photo current changes very little, while F and M photocurrent o-either side weaken considerably.

The writer wishes to express his appreciation to Elias Burstein for the suggestion of this problem and for his continued interest in the work.

[1] J. J. Oberly and E. Burstein, Phys. Rev. 79, 217 (1950).
[2] J. J. Oberly, Phys. Rev. 83, 228 (1951).
[3] G. Glaser, Gött. Nachr., Fachgruppe II, 3, 31 (1937).
[4] K. Przibram, Z. Physik 68, 403 (1931).
[5] St. Petroff, Z. Physik 127, 443 (1950).
[6] Casler, Pringsheim, and Yuster, J. Chem. Phys. 18, 887 (1950).
[7] A. B. Scott and L. P. Bupp, Phys. Rev. 79, 341 (1950).

Equivalence of the S-Matrix in Different Representations

L. M. YANG
University of Edinburgh, Edinburgh, Scotland
(Received October 5, 1951)

SINCE the first formulation of the S-matrix[1] in the interaction representation, the corresponding S-matrix in the Heisenberg representation has been defined by Yang and Feldman,[2] and shown to be equivalent to the S-matrix of Dyson. It will be pointed out in this note that the equivalence of the S-matrix in different representations can be directly inferred to hold generally from kinematical considerations without having to go through explicit transformation for each particular set of fields. For this purpose one observes that a matrix element of the type $\langle \chi(\sigma) | F(\sigma) | \Psi(\sigma) \rangle$, where $\Psi(\sigma)$, $\chi(\sigma)$ are two state vectors of the system referring to the same space-like surface σ and $F(\sigma)$ any dynamical variable of the system, corresponds to a measurement on the surface σ; its value for the same σ is therefore independent of the representation used. For convenience we assume that the surface corresponds to $t =$ constant and that the interaction is turned on and off at t_i and t_f, respectively. (In the limit one can have $t_i \rightarrow -\infty$ and $t_f \rightarrow +\infty$.) In particular, when $t = t_f$ we have

$$\langle \chi_I(t_f, t_i) | F_I(t_f, t_i) | \Psi_I(t_f, t_i) \rangle = \langle \chi_H(t_f) | F_H(t_f, t_i) | \Psi_H(t_f) \rangle,$$

where the subscripts I and H indicate operators and state vectors in the interaction and Heisenberg representation, respectively. To go from the Heisenberg to the interaction representations, one uses the unitary operator $S(t, t_i)$ defined by

$$i\hbar(\partial/\partial t)S(t, t_i) = V_I(t)S(t, t_i), \quad S(t_i, t_i) = 1,$$

where $V_I(t)$ is the interaction energy in the interaction representation. Thus for any time t between t_i and t_f, we have

$$| \Psi_I(t, t_i) \rangle = S(t, t_i) | \Psi_H(t) \rangle,$$
$$F_H(t, t_i) = S^\dagger(t, t_i)F_I(t, t_i)S(t, t_i).$$