kcal/mole in the sodium chloride structure, -135.4 - 7.25 = -142.65 kcal/mole in the cesium chloride structure, <u>so that cesium iodide is stable in the cesium chloride modification</u> (difference about 3 kcal/mole).

Rubidium chloride. — The Born-Mayer lattice energy is -159.1 kcal/mole in the NaCl structure, -149.4 kcal/mole in the CsCl structure, favoring the sodium chloride modification by about 9.7 kcal/mole. For the three-body exchange interactions we find,

for NaCl, $\Delta E = 12(-0.08)2.3\alpha + 3(0.08)2\alpha$

$$= -1.728\alpha, \text{ i.e., } -5.27 \text{ kcal/mole;}$$

for CsCl, $\Delta E = 12(-0.16)2.8\alpha + 4(0.08)2\alpha$

$$= -4.736\alpha, \text{ i.e., } -14.00 \text{ kcal/mole.}$$

Therefore, even including three-body interactions, the <u>sodium chloride structure is more stable,</u> by about 0.9 kcal/mole. For the transition pressure[2] P_t we find, for $P_t \Delta V = 0.9$ kcal/mole, that $P_t = 6300$ atm, compared with the experimental value $P_t = 4900$ atm. On the basis of pair potentials only the transition pressure is about 35 000 atm.

It appears, therefore, that the stability of alkali halide crystals can be explained on a quantitative basis in terms of three-body exchange interactions between the ions and their symmetry properties. Detailed results will be given in another publication.

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SURFACE BARRIER IN TYPE-II SUPERCONDUCTORS*

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(Received 7 October 1963)

Flux penetration in type-II superconductors is believed to occur in the form of quantized, flux-enclosing, supercurrent vortices (or "flux threads").[1] Using this concept, Abrikosov[1] considered an infinitely large specimen and predicted magnetization curves which have been largely verified by experimental results on bulk samples.[2-4] However, some of these results suggest that the specimen surface may be influencing the magnetic behavior,[5] in particular, by causing a low-field hysteresis in the magnetization curves of even well-annealed, single-phase specimens [see Fig. 8(b) of reference 4]. As a possible explanation of these experimental results, we present here an elementary treatment of the interaction between a flux thread and the specimen surface.

Consider a semi-infinite type-II superconductor with a flux thread within it lying parallel to the single plane surface. There are two sep-arate forces which the flux thread feels near the surface:

(1) Image force. — The necessary boundary condition of zero current normal to the surface is satisfied by adding an image flux thread, of opposite sign, outside the surface [Fig. 1(a)]. There is thus an <u>attractive</u> force to the surface, and the energy E per unit length of the flux thread increases with x, the distance from the surface, as shown in Fig. 2 for $H = 0$. From the interaction energy between two flux threads,[1] for $x \gg \xi$ and $\lambda \gg \xi$, $E(x) = \epsilon - (\varphi_0/4\pi\lambda)^2 K_0(2x/\lambda)$. Here ξ is the coherence length, λ is the penetration depth, ϵ is the energy per unit length of a single flux thread far from the surface and is approximately[6] equal to $(\varphi_0/4\pi\lambda)^2 \log(\lambda/\xi)$, φ_0 is the flux quantum, and K_0 is a modified Bessel function of the second kind. For $x \gg \xi$, the image term in $E(x)$ vanishes as $e^{-2x/\lambda}$. For $x \approx \xi$, $E(x)$ must be altered so that E goes smoothly to zero

IMAGE FORCE
ATTRACTIVE
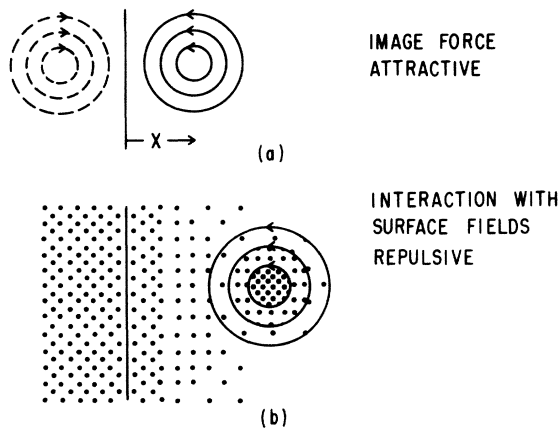
(a)

INTERACTION WITH
SURFACE FIELDS
REPULSIVE

(b)

FIG. 1. Schematic representation of the forces on a flux thread near a specimen surface: (a) attractive force produced by an "image" flux thread of opposite sign. (b) Repulsive force from interaction with the surface fields (density of dots represents density of local field).

FIG. 2. Dependence of the line energy E of the flux thread on x, distance from the surface, for various applied fields. Results presented are for $\lambda = 10\xi$.

as $x \to 0$ rather than going to $-\infty$ with K_0.

(2) External field.—An external field H penetrates into the superconductor [Fig. 1(b)] as $H^{-x/\lambda}$. If this field is of the same sign as the fields of the flux thread, this produces a repulsive force from the surface, and a contribution to $E(x)$ of $\varphi_0 H e^{-x/\lambda}/4\pi$. This interaction energy is obtained by straightforward integration of the total energy of the superposed fields and currents of the flux thread and the surface layer. Note that for any nonzero H, this term will eventually dominate the image contribution to $E(x)$ for $x \gg \lambda$.

The addition of these two contributions to $E(x)$ will lead to different total $E(x)$ curves for various values of H. Curves calculated for $\lambda = 10\xi$ are seen in Fig. 2. Note that an energy barrier to flux motion into or out of the specimen exists at low fields. Without these surface effects, internal flux threads become energetically favorable[1] at a field H_{c1}, defined by $\varphi_0 H_{c1}/4\pi = \epsilon$ [i.e., in present terms, $E(0) = E(\infty)$]. However, the presence of this surface energy barrier suggests that with a perfect surface, at absolute zero, flux threads may not be able to enter until a higher field, H_S (see Fig. 2), at which the barrier to flux penetration no longer exists.[7] The barrier to flux escape, on the other hand, does not disappear completely until H is reduced to zero.

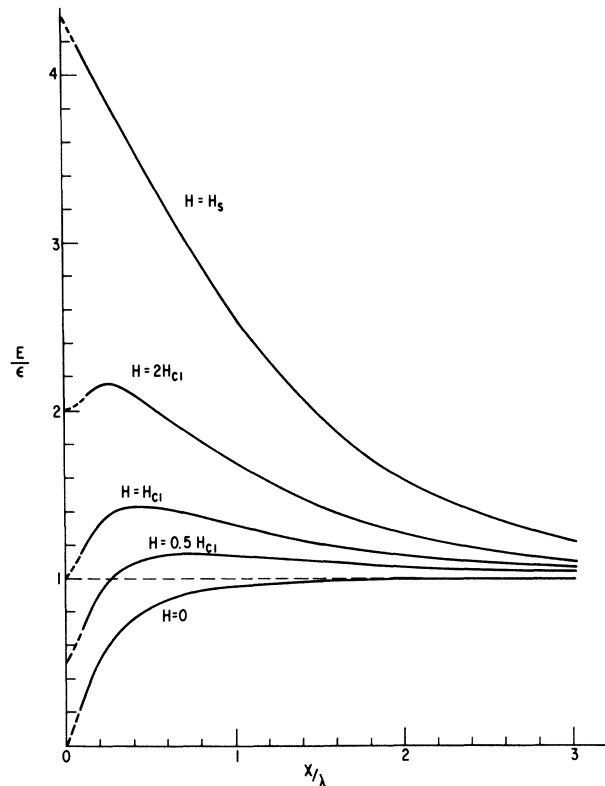Although the above considerations indicate

that a plane surface provides an energy barrier to flux thread motion, it is likely that field concentrations at specimen ends or surface irregularities may create local fields equal to H_S when the average applied field is considerably less. Thus flux may enter at these irregularities, and may then spread into the remainder of the specimen when it becomes energetically favorable, i.e., at H_{c1}. These same field concentrations, however, will block flux escape at these irregularities in decreasing fields. At other spots, surface concavities may produce lowered local surface fields that may encourage flux escape, but since a barrier to flux escape exists down to $H = 0$, flux escape should still be difficult. Thus with surface irregularities and end effects, the magnetization curve in increasing field may be nearly the thermodynamically reversible one (as is commonly assumed), whereas surface hysteresis in the form of delayed flux expulsion will appear in decreasing field. This is consistent with the form of the surface hys-

teresis observed.[4,5] Experiments are currently underway to see if improved surface preparation and avoidance of end effects will produce evidence of the large nucleation barrier to flux penetration calculated here.

The present elementary treatment has only considered $E(x)$ for a single flux thread. To calculate the detailed hysteresis curves expected, one must consider an assembly of flux threads and the interactions between them. For a more exact calculation of H_S and removal of the limitation $\lambda \gg \xi$, detailed consideration of the core of the flux thread and use of the Ginzburg-Landau equations will be required.

We gratefully acknowledge discussion with P. G. deGennes, who had independently considered the image flux thread and the resulting energy barrier.

*This research was supported in part by the Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio.

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[7]Our calculation of H_S in this approximation is inexact because of uncertainties in the image term in $E(x)$ for $x \lesssim \xi$. Choosing to cut off $K_0(2x/\lambda)$ at $x = \xi$, the maximum image force then occurs here, and we get $H_S = \varphi_0/4\pi\lambda\xi \approx H_C/\sqrt{2}$, where H_C is the thermodynamic critical field.

IONIC THERMOCONDUCTIVITY. METHOD FOR THE INVESTIGATION OF POLARIZATION IN INSULATORS*

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Polarization effects due to ionic motion in insulators have been studied over a great many years, essentially following two different methods: by considering the change in time of the electrical current in a sample subjected to a dc external field[1,2] or by measuring the dielectric losses[3]; these measurements are carried out at fixed temperature. Alkali halides were one of the subjects studied more extensively.

We propose here a different method of investigation; it is based on a phenomenon, analogous to thermoluminescence, which could be called ionic thermoconductivity (ITC). The method is as follows:

(1) The sample is first polarized in a static field E, for a time t, at a temperature T_p; the temperature should be enough to allow the complete orientation of all the dipoles that one wishes to consider, and not too high, in order to avoid heavy space-charge contributions. In alkali halides, reasonable polarization temperature is around $0°C$.

(2) The solid is cooled down to a temperature $T_0 \ll T_p$, where any ionic motion is completely

hindered, then the external field is taken off.

(3) The solid is subsequently warmed up at a constant rate b, and the discharge current is registered as a function of temperature. One expects "electrical glow" curves, similar to those characteristic of thermoluminescence[4] or of electronic glow.[5]

When the release of the electrostatic energy is due to relaxation of electric dipoles, the peaks of the function $i(T)$ correspond to various dipolar imperfections present in the crystal, and can give information as to relaxation time and number of dipoles. The situation is in some respects simpler than in the case of thermoluminescence, because the relaxation mechanism is monomolecular; the only exception to be expected is the case of release of the accumulated space charge, where decay is complex and slower.[6]

Briefly, the following information can be obtained by analyzing a peak of ITC: (1) The area delimited by the function $i(T)$ is proportional to the number of dipoles of a given kind present in the sample: