for each set and since, in the frame of reference moving with velocity $+u$, ω^1 and ω^2 are both positive energy while ω^3 and ω^4 are both negative energy in a frame of reference moving with velocity $-u$, it follows that the nonlinear set of equations has only bounded solutions for these short systems.

For a weak ion beam system in a strong magnetic field and for $\omega/\omega_{pe} \ll k_\parallel \lambda_{De}$,

$$\epsilon(\vec{k},\omega) = 1 + \frac{1}{k^2\lambda_{De}^2} - \frac{k_\parallel^2 \omega_{pi}^2}{k^2}\left[\frac{1}{\omega^2} + \frac{\eta}{(\omega - k_\parallel u)^2}\right]. \quad (8a)$$

Here $\lambda_{De} = \bar{v}_e/\omega_{pe}$ is the electron Debye length, ω_{pi} is the ion plasma frequency, $\eta \ll 1$ is the ratio of the ion-beam density to the total density, $k_\parallel$ is the wave vector along the field, and $k^2 = k_\parallel^2 + k_\perp^2$. All modes of (8a) are linearly stable if $\bar{v}_e^2 \gg u^2 > (m/M)\bar{v}_e^2$. However, again many resonances induce nonlinear growth. For beam velocities in the linearly stable regime, the four solutions are

$$\omega_k^1 = k_\parallel u + k_\parallel \omega_{pi}\eta^{1/2}(k^2 + 1/\lambda_{De}^2 - \omega_{pi}^2/u^2)^{-1/2},$$

$$\omega_k^2 = k_\parallel u - k_\parallel \omega_{pi}\eta^{1/2}(k^2 + 1/\lambda_{De}^2 - \omega_{pi}^2/u^2)^{-1/2},$$

$$\omega_k^3 = -\omega_k^4 = k_\parallel (m/M)^{1/2}\bar{v}_e(1 + k^2\lambda_{De}^2)^{-1/2}. \quad (8b)$$

The interaction $\omega_k^1 + \omega_{k'}^3 + \omega_{k''}^2 = 0$ is nonlinearly unstable but, as the system is shortened, stops resonating for $k_\parallel \gtrsim \omega_{pi}/u$. The coupling $\omega_k^3 + \omega_{k'}^4 + \omega_{k''}^2 = 0$ is also unstable but has a critical wave number of $k_\parallel \gtrsim 2\omega_{pi}/u$. For shorter systems only modes ω^1 and ω^2 interact, but they are both positive energy in a frame moving with velocity u, and hence in a short system the interactions of the low-phase-velocity mode are completely stable. However, in addition to these low-phase-velocity modes, (8b), this system has linearly stable electron plasma oscillations

$$\omega_k^{\pm} \cong \pm(k_\parallel \omega_{pe}/k)[1 + \tfrac{3}{2}(k\lambda_{De})^2 + \cdots].$$

A resonance of the form $\omega_k^3 + \omega_{k'}^+ + \omega_{k''}^2 = 0$ can take place and is nonlinearly unstable. This interaction is only stopped when the ω_k^+ mode becomes ill defined, i.e., $k\lambda_{De} \approx 1$; however, the matrix element $|V_{kk'k''}^{3+2}|^2$ is extremely small for this resonance and associated nonlinear growth rates are initially slow.

Similar extensions of the instability regions by resonant scattering occur for other beam-plasma systems. It is apparent that these extensions are important for the understanding of basic experiments and in the theory of the structure of shock waves in collisionless plasmas.

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ELECTROLUMINESCENCE OF KI AT 77°K*

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The majority of electroluminescence studies undertaken have been on semiconductors.[1] The theories put forth to explain the excitation of this phenomenon involve (1) the injection of charges into the crystal by the electrodes,[2] (2) direct field ionization of impurities[3] or of the valence band itself,[4] and (3) the acceleration of charged carriers to optical energies.[5,6] We make use of the first and last of these mechanisms to explain the intrinsic electroluminescence of pure KI at 77°K.

A voltage of 2500 V rms at 500 cps was applied across a crystal 0.5 mm thick using one Ag and one In electrode. The emitted light was observed perpendicular to the field at 1000 cps by using a phase-sensitive amplifier. The signal was found to be 90° out of phase with the reference frequency. The resulting spec-

trum is shown in Fig. 1. It is identical to the photoluminescent spectrum of pure KI at 77°K observed previously.[7]

When the electric field is applied across the crystal, it is thought that electrons are injected into the conduction band by quantum-mechanical tunneling from the two electrodes on alternate half cycles of the ac field. (The ensuing electroluminescence is seen to disappear if thin sheets of Mylar are interposed between the electrodes and the crystal. This fact serves also to rule out direct field ionization of the valence band.) These electrons are then accelerated by the field to optical energies, which enable them to ionize valence electrons through inelastic collisions. It is worthwhile at this point to remember that this excitation process may lead to sufficient electron multiplication so that dielectric breakdown occurs in the crystal. Obviously, the field in the interior of the crystal is somehow reduced so that equilibrium is maintained. The fact that the electroluminescence is observed to take place in front of the two electrodes suggests that the field is localized there and that a Mott-Schottky-type exhaustion layer, well known to occur in semiconductors, is formed in the crystal. The applied fields used in this experiment are at least an order of magnitude smaller than those found by von Hippel[8] to cause breakdown in the alkali halides.

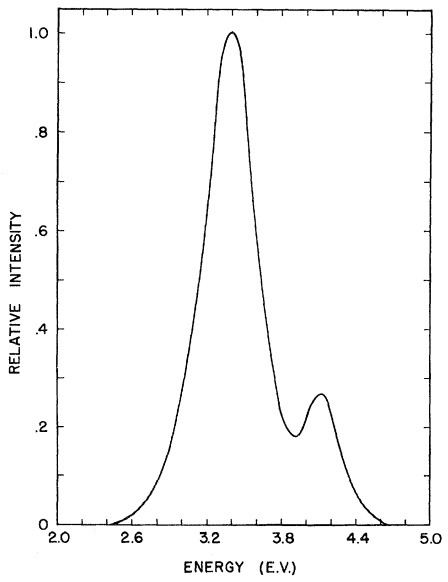

FIG. 1. Electroluminescence spectrum of pure KI at 77°K, obtained with an electric field of 5×10^4 V/cm rms.

The free holes and electrons produced in the above manner then undergo recombination via the V_k center, the well-known mechanism responsible for the intrinsic emission bands of the alkali halides.[9,10] These centers are unstable above 118°K, at which temperature both photoluminescence and electroluminescence are seen to disappear.

The electric field dependence of the luminescent intensity, shown in Fig. 2, is of the form derived by Taylor and Alfrey[11] for the electron-acceleration process in a semiconductor having a localized electric field enhanced by a Mott-Schottky exhaustion layer:

$$I = I_0 \exp(-c/V^{1/2}), \tag{1}$$

where V is the peak voltage applied to the crystal, and I_0 and c are appropriate constants.

One other possibility for the mechanism of electroluminescence is that both electrons and holes are injected from the same electrode into the crystal on alternate half cycles of the ac field. The holes would become trapped immediately by the lattice, since their mobility in an alkali-halide crystal is extremely low, and then recombine with the electrons by way

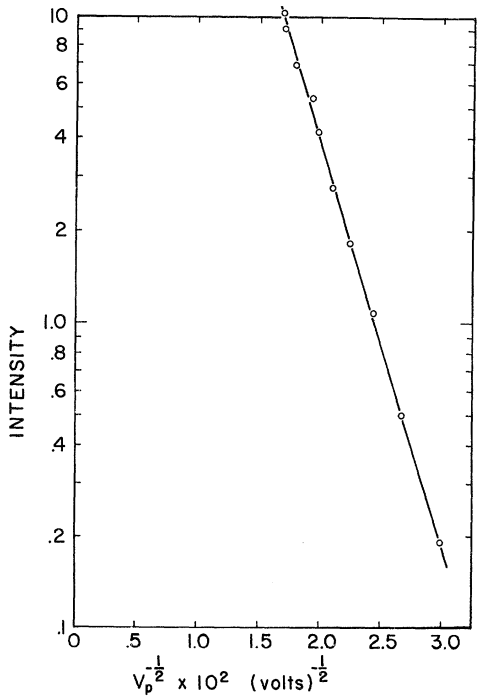

FIG. 2. The luminescent intensity plotted as a function of the inverse square root of the applied peak voltage for KI.

of the V_k center. Such a process requires no electron acceleration by the field. However, this situation should result in an emission intensity in phase with the reference signal at twice the field frequency, in contrast to that observed.

The application of a dc field of the same peak-to-peak value as the corresponding ac field failed to give any emission intensity on the same scale as the rms signal obtained with the ac field. This is attributed to the fact that the crystal is given the opportunity to polarize and build up sufficient space charge to effectively quench the electron acceleration in the crystal.

A study of other alkali halides is being undertaken to determine the dependence of the existence or magnitude of electroluminescence on the characteristic breakdown fields of these materials. It is also hoped that frequency-dependent measurements will yield some useful information on the transport of charge carriers in alkali-halide crystals.

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EFFECT OF APPLIED ELECTRIC FIELD ON THE ELECTRON PARAMAGNETIC RESONANCE SPECTRA OF DOPED FERROELECTRIC ROCHELLE SALT

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A linear shift of the epr lines of Cu^{2+}-doped Rochelle salt by an applied electric field has been observed in the high-temperature paraelectric phase. The shifts become asymmetric with respect to the polarity of the applied field in the ferroelectric phase and disappear at low temperatures in the antiferroelectric phase, demonstrating that it is only the instability of the crystal lattice connected with the ferroelectric transitions which makes the electric-field effect easily observable.

Bloembergen[1] was the first to point out that linear effects of the applied electric field on the epr spectra of ions occupying sites which lack inversion symmetry could be observed. The shifts should be particularly interesting and pronounced in ferroelectrics and in this Letter we report the first observation of this ferroelectric epr Stark effect.

Recent epr and optical studies[2-4] of Cu^{2+}-doped Rochelle salt[5] did not show significant changes in the spectra on going through the two Curie points but demonstrated that the Cu^{2+} ions are located on the sites of the Na atoms and that the $3d$ copper orbitals and the $2s$ and $2p$ orbitals of the four oxygen ligands (1, 7, 5, 10) form molecular orbitals with C_{2v} (and nearly D_{2h}) symmetry. Since the Cu^{2+} sites thus lack inversion symmetry, linear effects of the applied electric field on the epr spectra[1] should be observable.

The measurements were made on a $CuCl_2$-doped Rochelle-salt crystal, containing 0.05 wt.% of Cu^{2+} ions with the electric field applied along the ferroelectric a axis. Spontaneous polarization was observed between +16 and −11°C. The hysteresis loops were found to be displaced from the center in the x and y directions, indicating the presence of an internal bias of about 950 V/cm and the stabilization of a particular direction of the spontaneous polarization due to the Cu^{2+} impurities. In the absence of the applied electric field the epr spectra