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Noise-power studies of the nearly commensurate quasi-one-dimensional conductor (N-methylphenazinium)$_x$(phenazine)$_{1-x}$(7,7,8,8-tetracyano-*p*-quinodimethane) [(NMP)$_x$(Phen)$_{1-x}$(TCNQ)]

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We report the noise power of (NMP)$_x$(Phen)$_{1-x}$(TCNQ) as a function of temperature ($100 \leq T \leq 300$ K), frequency ($1 \leq f \leq 10^4$ Hz), electric field ($0 \leq E \leq 300$ V/cm), and conduction-electron density ($0.49 \leq x \leq 0.59$). The results for the commensurate, doped commensurate, and incommensurate regimes are similar. The magnitude of the $1/f$ noise is in considerable excess of typical scaled values for other materials, suggesting the role of large units in the fluctuations. A thermally activated spectral feature is reported. Excess non-Gaussian noise is detected immediately following the formation of a microcrack, though this contribution to the noise decays with time.

I. INTRODUCTION

Quasi-one-dimensional systems have been the subject of extensive research for the past decade.[1] These systems frequently undergo a Peierls distortion leading to a semiconducting ground state. As a commensurate Peierls distortion is lower in energy than an incommensurate distortion, the addition of a few extra electrons or holes to a commensurate system results in the breaking up of the chains into commensurate regions separated by discommensurations which are delocalized over several lattice sites.[2] These charged domain walls or solitons may be either pinned or mobile. The success of this model has been demonstrated in the case of *trans*-(CH)$_x$, a one-half-filled-band system with moderate on-site Coulomb repulsion, U, as compared to the bandwidth, W.[1,3–6] Recent work by Rice and Mele[7,8] predicts the formation of solitons of half-integer charge, $e/2$, in highly correlated one-dimensional charge-transfer salts near the $\frac{1}{4}$-filled-band limit as a result of light doping, photoexcitation, or thermal excitation. It was further shown by Kivelson and Schrieffer[9] that this fractional charge is a sharp quantum observable and not just an average. Similar results have been proposed for one-third-filled-band systems.[10]

We report here the results of an extensive study of the behavior of the noise power in a system that is a physical realization of a highly correlated quasi-one-dimensional system near the commensurate one-quarter-filled-band limit. The family of charge-transfer salts examined in this study is (N-methylphenasinium)$_x$(phenazine)$_{1-x}$(TCNQ) [(NMP)$_x$(Phen)$_{1-x}$(TCNQ)], with x between 0.49 and 0.59, Fig. 1(a). Previous work has shown the $x = 0.50$ member of this family to be a highly correlated quasi-one-dimensional system near the commensurate one-quarter-filled-band limit and verified the existence of solitons in samples with $0.50 \leq x \leq 0.57$.[6,11] For $x \geq 0.57$, an incommensurate ground state forms. The samples in which solitons have been introduced through chemical doping have been shown to have an excess conductivity in agreement with a model developed by Conwell and Howard.[11,12] Detailed diffuse x-ray scattering studies have demonstrated that this is a large-U system with a crossover to a $U < W$ regime for $x \geq 0.67$.[13]

The experimentally measured voltage noise power spectral density, $S(f)$, at constant current, includes Johnson noise, amplifier noise, and noise with an approximately $1/f$ spectrum.[14] This $1/f$ noise scales as the square of the applied voltage in the Ohmic regime and thus is apparently due to resistance fluctuations. Shot noise (i.e., noise due to carrier number fluctuations with kinetics determined by electrical transport) is not observable in these samples because the screening length is small compared with the sample size. Fluctuations in number of carriers with generation-recombination kinetics should be present and may in fact contribute to the $1/f$ noise. However, the magnitude of the $1/f$ noise was larger than could be accounted for by generation-recombination noise if the conductivity were simply proportional to the number of free carriers. Regardless of the kinetic mechanism of the carrier number fluctuations the $1/f$ noise is too large to allow such fluctuations to be used to determine the charge of the carriers.

Noise with an approximately $1/f$ spectrum has been observed in some salts of TCNQ at temperatures ranging

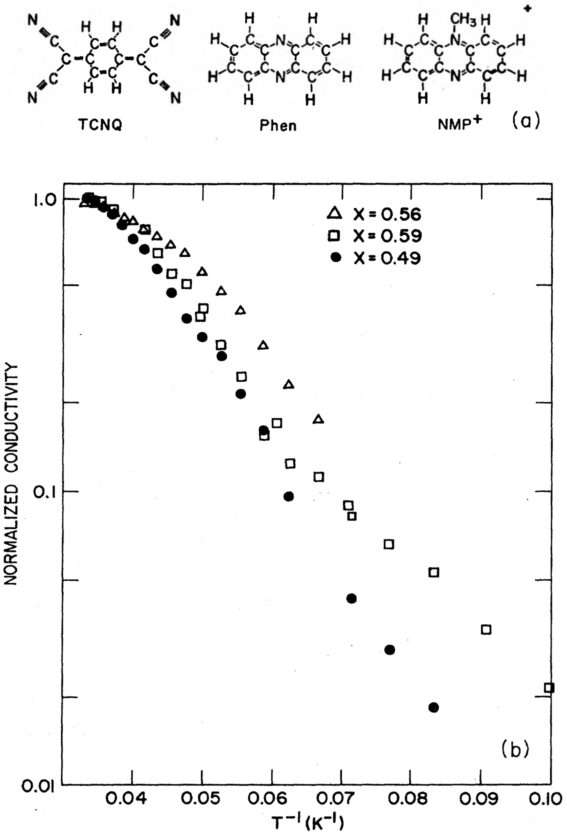


FIG. 1. (a) Molecular structure of tetracyanoquinodimethane (TCNQ), phenazine (Phen), and N-methylphenazinium (NMP^+). (b) Logarithm of the normalized conductivity vs T^{-1} for $(\mathrm{NMP})_x(\mathrm{Phen})_{1-x}(\mathrm{TCNQ})$ samples with $x=0.49$, 0.56, and 0.59.

from 105 K (Ref. 15) to 250 K (Ref. 16). These salts are not unique in exhibiting resistance fluctuations with a power spectrum inversely proportional to frequency. Such $1/f$ noise is found in most resistors, including metals, semimetals and semiconductors.[17-20] Since except perhaps in special cases, this noise is not well understood, one must use some caution in drawing inferences from its properties. A few facts, however, are well established in many systems. These points are discussed below.

The noise in many instances behaves like a resistance fluctuation that is only sampled, not created, by the current flow.[17-22] In all cases for which reliable data exist, the spatial correlation length of the underlying fluctuations is small compared with experimental resolution, which is often in the range of several microns or even smaller.[23-26] As a result, the noise magnitude typically scales inversely with volume, with corrections in some cases for surface effects.[17-21,27] Extrapolation of the noise magnitude down to the smallest volumes for which it makes sense to speak of resistance fluctuations (a region with dimensions comparable to a mean-free path or a screening length, depending on the cause of the fluctuations) ordinarily still gives fractional fluctuations substantially less than unity, so there is no problem in describing the noise as a simple linear superposition of local noise sources. In nearly all mechanically stable samples, the noise voltage is a Gaussian random variable by several tests,[28] which again is consistent with many independent local sources.

Such independent local sources cannot be identified with the charge carriers themselves. In essentially all cases observed, mobile carriers are swept out of the observed region, or diffuse out of it, in times less than the reciprocal of the highest observed $1/f$ noise frequency. The fluctuations must then be in something not swept along with the carriers, such as the occupancy of electron trapping states or the positions of defects, although theories attempting to attribute the noise to some independent events at separate mobile carriers are still quite common. Such theories are usually based on the expression proposed by Hooge[20] for metals and semiconductors:

$$S_v = 2\times 10^{-3} V^2/N_c f \,, \tag{1}$$

where V is the dc voltage across the sample, N_c the number of charge carriers in the sample, and f the frequency. Although this expression is not generally valid, it does often serve as a useful rule of thumb. In special cases it is possible that nonlinear instabilities may lead to $(1/f)$-like noise that lacks most of the properties described above, but this phenomenon has not been established experimentally for ordinary resistors.

In many materials, there is good evidence that the kinetics of some or all of the noise is thermally activated.[17,25,29-31] The $1/f$ spectrum then arises from a fairly flat distribution of activation enthalpies, although distributions of attempt rates can also be present. Dutta and Horn[17] have demonstrated that, given several conditions, nearly $1/f$ noise with thermally activated kinetics obeys a simple relation between the spectral slope and the temperature dependence of the magnitude. The mechanical instabilities of the $(\mathrm{NMP})_x(\mathrm{Phen})_{1-x}(\mathrm{TCNQ})$ samples as they are cooled do not allow for sufficiently accurate measurements of the intrinsic temperature dependence of the noise magnitude to test this relation. However, for sufficiently narrow spectral features, one can directly see the shifting of characteristic frequencies with temperature, and this technique turns out to be applicable to $(\mathrm{NMP})_x(\mathrm{Phen})_{1-x}(\mathrm{TCNQ})$.

The results of the noise power studies of $(\mathrm{NMP})_x(\mathrm{Phen})_{1-x}(\mathrm{TCNQ})$ revealed[15] a rich array of phenomena. The data for the commensurate $(x\simeq 0.50)$, doped commensurate $(x\simeq 0.56)$, and incommensurate $(x\simeq 0.59)$ regimes proved quite similar. The magnitude of the $1/f$ noise was in considerable excess of that predicted by Hooge.[20] Several unusual features were observed including a crossover from $S \propto V^2$ to $S \propto V$ at electric field strengths, E, of ~ 5 V/cm, coincident with the onset field for a severalfold decrease in sample resistance. This behavior is different from that reported earlier for charge-density wave transport in TaS_3 (Ref. 32) and interparticle hopping in granular composites.[33] Excess noise power is observed after formation of "microcracks." This excess noise is found to "anneal out" after several minutes, with the final noise power scaling with the resistance change. These microcracks and the resulting sudden increase in the resistance of the

$(NMP)_x(Phen)_{1-x}(TCNQ)$ samples during the temperature variation, do not allow for a sufficiently accurate measurement of the intrinsic temperature dependence of the noise magnitude to test the relation between the spectral slope and the temperature dependence of the noise magnitude. However, a narrow, thermally activated spectral feature is observed with an activation energy of ~ 0.25 eV. These phenomena are compared with available models and directions for further work are indicated. The magnitude of the flicker noise obviated direct observation of the shot noise (and hence direct measure of the electronic charge of the carrier) in this system.

In Sec. II we describe the experimental details and techniques. In Sec. III we present the results for the noise power as a function of electron concentration, temperature, and electric field. Section IV contains a discussion of our results together with our conclusions. Section V summarizes our work.

II. EXPERIMENTAL DETAILS AND TECHNIQUES

The material system studied is based on (NMP)(TCNQ) and is realized by substituting neutral phenazine, $Phen^0$, for NMP.[34] The $Phen^0$ is of similar size, shape, and polarizability to NMP^+, but unlike NMP^+ it does not contribute carriers. The overall segregated stack crystal structure of (NMP)(TCNQ) remains unchanged for $0.50 \leq x \leq 1.00$. For $x = 0.50$ the NMP^+ and phenazine alternate in a regular lattice.[13,35] The number of conduction electrons per unit cell to be shared among the donors and the TCNQ molecules is equal to the fraction, x, of NMP in the "alloy." Electron spin resonance g-value studies demonstrate that essentially all of the conduction electrons are on the TCNQ chain for $0.5 \leq x \leq 0.6$. Generally, the values of x, which are determined by solution absorption spectra, are accurate to ± 0.02. In cases where solution analysis yields results $x = (0.50 - \delta)$ with $\delta \sim 0.01$, concerted studies suggest that for these samples x is equal to or slightly larger than 0.50, that is, very close to stoichiometric. An example of such a composition is the $x = 0.49$ sample discussed below.

During the noise power studies, the current was supplied by batteries in series with wire-wound or quiet metal-film resistors. Both the number of batteries in series and the size of the series resistor was switchable, allowing selection of constant currents ranging from 1 to 80 microamps. Noise signals were amplified with Princeton Applied Research (PAR) 113 amplifiers. Spectra and cross spectra were taken with a PAR 4520 Fast Fourier Transform processor (manufactured by Unigon). The processor is interfaced to a Digital Equipment Corporation LSI-11/23 computer. The processor averager is used for small bundles of transforms (e.g., 16) while further averaging is done in the computer. The computer discards any bundles which are much different from the running average, so that long averages may be taken without risk of the data being ruined by an occasional glitch, which would otherwise be a serious problem in mechanically unstable samples. Averaged spectra were recorded on disk. Spectra were analyzed by summing into octave intervals, which gives adequate frequency resolution for $(1/f)$-like spectra while compressing the data into manageable form. In some cases it was necessary to edit out 60 Hz and harmonic spikes before computing the octave sums. Resistance data were taken directly on the LSI-11/23 using a 12-bit (binary digit) analog-to-digital converter.

All measurements were taken in a helium flow-through cryostat, part of an S.H.E. variable-temperature magnetometer. The long-term temperature stability of this instrument is approximately 0.1 K over most of the range in which data were taken, but stabilization times can be long (e.g., 30 minutes). Much of the resistivity data therefore have an extra degree or so of temperature uncertainty, since full stabilization times were not used.

Samples were typically 1.5×10^{-1} cm in length, 7.5×10^{-4}-cm thick, and roughly cylindrical in shape. These crystals were supported from the ends of 0.5-mil diameter gold wires using silver paint (du Pont 4922) in a five-probe configuration. The other end of each gold wire was mounted onto a quartz block using an insulating varnish (GE 7031) after being connected to aluminum wires using silver paint. The contact length relative to the spacing between contacts was ≤ 0.2.

The use of five-probe measurements with cross-correlation between two disjoint regions provides a method of distinguishing between noise in the sample itself and noise produced at the contacts. This distinction is harder to make for whisker-shaped samples than for planar samples, for which voltage sensing contacts may be removed entirely from the current path. Even when a contact (such as our center contact) carries no net current, it provides a local shunt to the current, which may cause spurious noise. When the noisy contact is a member of the two voltage sensing pairs (i.e., our center contact) the spurious noise in the two pairs will ordinarily be highly correlated. Noise arising from the sample fiber itself, however, is almost totally uncorrelated between the two sections. We found, in fact, that at room temperature the noise was clearly dominated by contact noise, while below 200 K the correlation dropped to a few percent, consistent with genuine sample noise being dominant. This conclusion was confirmed by an association between the onset of nonlinear current dependencies in the noise and in the differential resistance, as discussed below, which would be very unlikely if the noise were to come from the contacts.

In addition to the noise spectra, information on the higher moments of the noise voltage was recorded. For each spectrum, the standard deviation of the noise power in each octave was measured. These standard deviations become anomalously large if the noise is bursty or shows certain other non-Gaussian properties.[28] Occasionally, more complete statistical data were taken, consisting mainly of a covariance matrix for the noise power in different octaves.[28] This covariance matrix depends on four-point correlation functions which are sensitive to non-Gaussian properties of the noise.

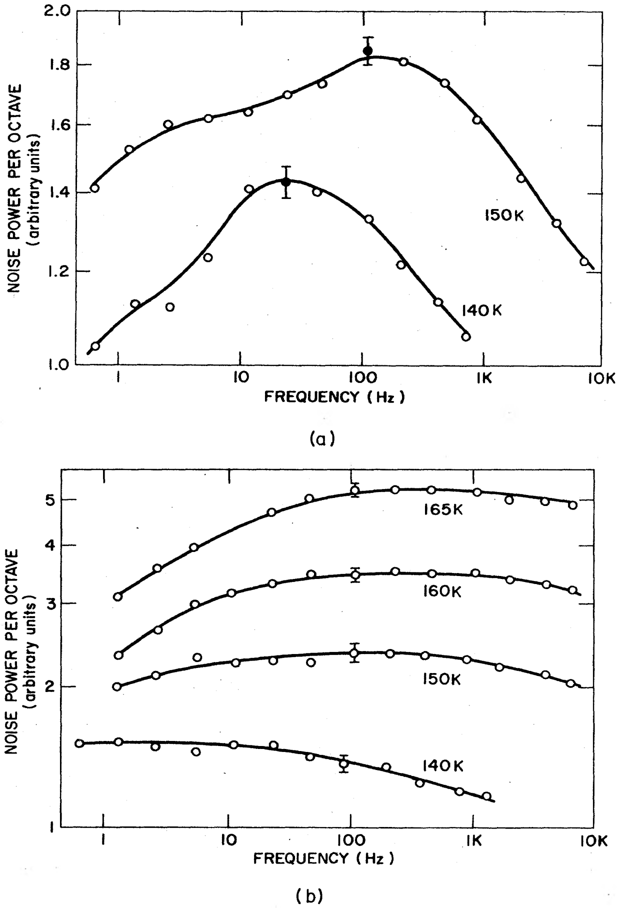
III. EXPERIMENTAL RESULTS

The temperature dependence of the normalized conductivity, $\sigma_n(T) = \sigma(T)/\sigma(295\ \text{K})$, for samples of composition $x = 0.49$, 0.56, and 0.59, is shown in Fig. 1(b) with

TABLE I. Values of room-temperature conductivity for various compositions of $(\mathrm{NMP})_x(\mathrm{Phen})_{1-x}(\mathrm{TCNQ})$.

x	$\sigma_{295\ \mathrm{K}}$ (S/cm)
0.49 ± 0.02	29.27
0.56 ± 0.02	18.27
0.59 ± 0.02	12.09

absolute values of the room temperature conductivity given in Table I. During the course of an experiment, sudden irreversible nonreproducible increases in sample resistance would occur. These are associated with microcracks formed in the fragile crystals, causing a portion of the sample to be removed from the current path. Since the concommitant large non-Gaussian effects on the noise anneal out after a short, finite time as discussed below, the conductivity data have been corrected to account for these jumps. Comparison with earlier data[11] shows these crystals to be representative of this class of charge-transfer salts.



(a)

(b)

FIG. 2. Noise power per octave vs frequency for $(\mathrm{NMP})_x(\mathrm{Phen})_{1-x}(\mathrm{TCNQ})$. The temperature of the sample is indicated for each curve. (a) $x=0.53$ (magnified by a factor of 10 relative to frequency) and (b) $x=0.59$ (magnified by a factor of 4 relative to frequency).

The noise power was approximately proportional to $f^{-\alpha}$ with $\alpha\sim1.0$ for all x, T, and E studied. However, the detailed noise spectra were not perfectly $1/f$ and were not identical from sample to sample. For all three electron concentrations studied, deviations from the $1/f$ law were observed. On two samples, $x=0.53$ and 0.56, sufficiently broadband spectra with a recognizable spectral feature were obtained at several temperatures. This permitted the determination of the temperature dependence of the feature's kinetics. The spectra are shown in Fig. 2. The characteristic frequencies clearly increase with increasing temperature. For one sample the temperature was not a monotonic function of time, so the effect cannot be attributed to some temporal instability.

Since it was possible to take spectra on intact samples without significant contact noise over only a limited temperature range, detailed fits of the temperature dependencies of the characteristic frequencies to specific theoretical models would be impossible even if such models were available. However, the temperature dependencies are too large to be fit reasonably except by assuming thermally activated kinetics,

$$f_{\max}=f_0\exp(-\Delta H/k_BT)\ . \tag{2}$$

The activation enthalpy, ΔH, is approximately 0.25 eV, implying attempt rates, f_0, of about 10^9 Hz.

Unlike most stable, well-characterized $1/f$ noise sources, the $(\mathrm{NMP})_x(\mathrm{Phen})_{1-x}(\mathrm{TCNQ})$ samples usually showed sowewhat non-Gaussian statistics. A typical symptom was cross-correlation coefficients between noise power fluctuations in neighboring octaves of roughly 0.05, where Gaussian samples give zero. However, such effects were not completely reproducible. When major breaks occurred in the crystal, as judged by resistivity, non-Gaussian effects were often much larger, with some recovery in time, probably reflecting an annealing of the sample near the break. Since every sample showed at least some sign of microcracks, we cannot be sure that any non-Gaussian effects would remain in a completely intact sample. The shape of the noise spectra did not show any major change after the formation of the cracks, although the magnitude increased. The increase in the variance of the noise with bandwidth is characteristic of variance due to an amplitude modulation of the noise.

There are several indications that the microcracks are

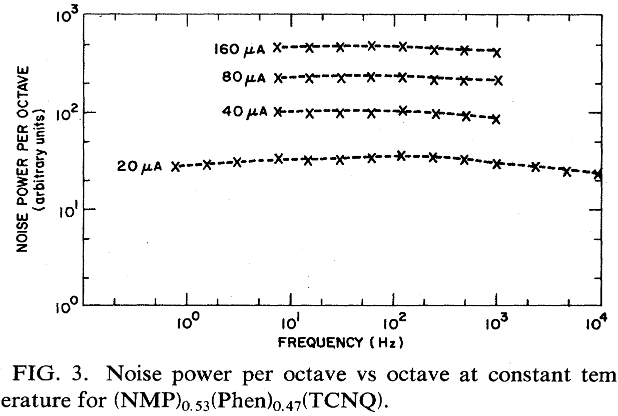
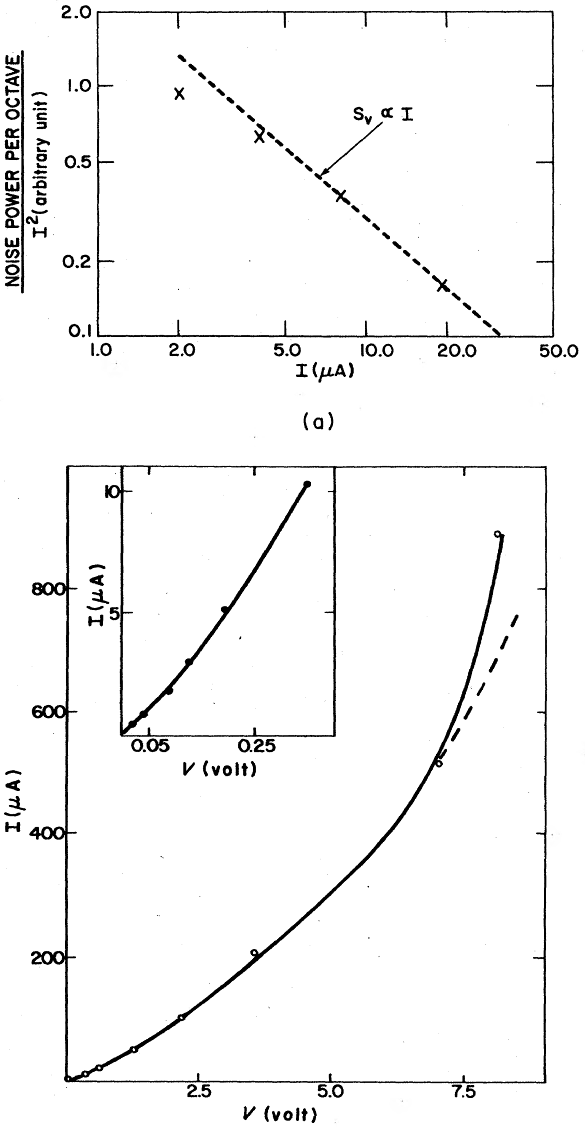


FIG. 3. Noise power per octave vs octave at constant temperature for $(\mathrm{NMP})_{0.53}(\mathrm{Phen})_{0.47}(\mathrm{TCNQ})$.



(b)

FIG. 4. For $(NMP)_{0.53}(Phen)_{0.47}(TCNQ)$: (a) Noise power/$I^2$ vs I for $f = 500$ Hz; (b) I vs V.

not essential to most of the noise. The sample-to-sample variations in resistance change due to the cracks were larger than were the fractional resistance fluctuations. Except after the occurrence of the largest of the microcracks, there were only small changes in the fractional noise of any particular sample after cracking. In addition, the detailed form of the noise spectrum for any particular sample was not changed by any but the largest microcracks, which gave a contribution steeper than $1/f$. Finally we note that the detailed temperature dependencies indicate processes with well-defined activation energies, which would be surprising for gross mechanical fluctuations near a crack.

The noise power at constant temperature, as exemplified in Fig. 3 for $(NMP)_{0.53}(Phen)_{0.47}(TCNQ)$, shows a quadratic current (I) dependence at low values of applied field with a crossover to a roughly I dependent functional form at higher fields. This result is typical of all samples studied. The value of the electric field at which this crossover occurs is a function not only of sample stoichiometry, but also of temperature. The electric field at which this crossover occurs corresponds to the field at which the resistance decreases, as shown for example in Fig. 4 for $(NMP)_{0.53}(Phen)_{0.47}(TCNQ)$. While it is tempting to associate this change in functional form with possible nonlinearities due to the motion of the discommensurations above a threshold field, for example, we do not have sufficient data to support this conclusion.

IV. DISCUSSION

The $1/f$ noise in $(NMP)_x(Phen)_{1-x}(TCNQ)$ shares some features with $1/f$ noise in other systems. In particular, the presence of broad thermally activated features in the $1/f$ spectra are similar to the broad features in the $1/f$ noise reported earlier by Dutta and Horn[17] for metal films and to the spectral features found in the noise in silicon-on-sapphire wafers by Black *et al.*[26] These spectral features suggest the possibility that the rate limiting steps in the $1/f$ kinetics themselves are thermally activated, with the approximate $1/f$ spectrum resulting mainly from a spread in activation enthalpies. For small currents, the noise power is close enough to quadratic in the current to indicate that the noise is present as a resistance fluctuation before being sampled by the current.

The principal feature of the noise which is highly unusual is the large magnitude (approximately a factor of 10^3 larger than that predicted by Hooge's equation). This precluded direct determination of the charge per carrier ($|e|$ for electrons and holes, $|e|/2$ for solitons) via measurement of noise from carrier number fluctuations. In one-dimensional conductors, a change in the magnitude of carrier number fluctuations might be expected to accompany any changes in the conduction mechanism. However, to be observed such noise must be approximately as large as both the Johnson noise and the $1/f$ noise in some range of voltage and frequency. Noise from fluctuations in the number of mobile carriers, regardless of the kinetic mechanism, contributes a fractional conductivity variance of less than $\sim 1/N$, where N is the number of carriers, barring peculiar cooperative effects in which more than one or two carriers appear and disappear together. (For samples larger than a screening length, number fluctuations are much smaller than this value unless two signs of charge carrier and/or immobile trapped states exist.) Since the number fluctuation line shape, on a noise per octave plot, is at least as broad as a Lorentzian, the maximum squared fractional fluctuation per octave from that source is less than $1/N$. However, we found more $1/f$ noise than that per octave, so that number fluctuation noise would not have been observable. This argument applies whether or not the kinetics are determined by the carrier transit time, as in the unlikely special case of simple shot noise.

If the ordinary inverse volume scaling of the mean-square fractional magnitude were to hold, the fluctuations would be of order unity in volumes of about 10^{-15} cm^3, which is much larger than a mean-free volume (i.e., the product of three mean-free paths, of which two are only a few angstroms) for the charge carriers. Either the volume scaling of the magnitude breaks down at surprisingly large distances or the net fluctuation is not expressible as a linear sum of local terms, because the local fluctuations are so large that they strongly affect the current through neighboring regions. We doubt that the latter explanation, involving nonlinear percolationlike effects is very important in determining the net noise magnitude, since if it were the rough reproducibility of the noise magnitude between samples would be surprising. That is, if the large magnitude resulted from fluctuations themselves reducing the available current paths, thus decreasing the effective sample volume, the fluctuations would have to be independent of both temperature and stoichiometry, an unlikely possibility. The similarity of our results to those obtained by another group[16] on a different salt of TCNQ [(N-methyl-N-(*n*-butyl)morpholinium)(TCNQ)$_2$] also suggests that we are not seeing any effects of being near a percolation threshold.

The data seem rather to suggest a model in which the volume scaling of the magnitude breaks down at a surprisingly large volume. This effect can occur either if the noise arises from a relatively small number of special sites or if the noise arises uniformly, but with an unusually large correlation length. The noise magnitude is about what would be expected if the contribution to the conductance of each linear chain of molecules as a whole were randomly switched on and off. Previous workers looking at a similar system were led to the conclusion that the noise is due to the switching on and off of large entities, which they interpret as being single linear chains.[16] Though the volume associated with the fluctuations ($\sim 10^{-15}$ cm^3) corresponds approximately to the volume of a single chain between the voltage contacts ($\sim 10^{-1}$ cm), it is unlikely that the fluctuating unit involves only a single chain in such a complex system. The lack of cross correlation between noise in adjacent sample sections argues strongly against the fluctuation of single long chain contributions to the resistance as the source of the $1/f$ noise. The data are more consistent with the conductivity of shorter bundles of chains changing in a correlated manner.

We believe that the large magnitude of the noise provides some evidence that the deviations from a $1/f$ spectrum, which show activated kinetics, are not a distinct process superimposed on a true $1/f$ background, as has been previously conjectured.[16] The features themselves are so large as to require, like the $1/f$ noise, an anomalous coherence volume. Rather than postulate several such noise sources, we believe that it is more reasonable to assume that all the noise comes from a single process with a slightly nonuniform distribution of activation enthalpies. This approach is indirectly supported by the seeming ubiquity with which small activated deviations from the $1/f$ form appear in a variety of systems.[17,30] The associated nonlinearities in the I-V curve and in the noise power indicate that, unlike some composite systems,[35] the noise is arising from barriers or regions which contribute a significant amount to the resistivity.

The increase in conductivity with increasing electric field is reminiscent of that reported earlier for other quasi-one-dimensional conductors, including the analagous nearly commensurate, highly correlated system (quinolinium)(TCNQ)$_2$ [Qn(TCNQ)$_2$].[36] For Qn(TCNQ)$_2$ the non-Ohmic behavior becomes apparent at ~ 2 V/cm for all temperatures where observed. This threshold corresponds to the crossover from $S \propto I^2$ to $S \propto I$. The latter effect roughly agrees with $S \propto V^2$ after correction for the decrease of the sample resistance with increasing electric field. The reduced rate of increase of noise power with increasing electric field is in contrast to the behavior of charge-density-wave conductors such as NbSe$_3$,[37,38] TaS$_3$,[32] and K$_{0.30}$MnO$_3$,[39] where the broadband noise increases dramatically at the threshold for electric-field-dependent conductivity. The variation of noise power with current in (NMP)$_x$(Phen)$_{1-x}$(TCNQ) differs from its behavior in the Ni::Al$_2$O$_3$ granular composites.[33] In the latter systems, there is a crossover from $S \propto I^2$ to $S \propto I$ in the absence of any nonlinearity in the I-V characteristics.

V. SUMMARY

We have demonstrated the presence of excess $1/f$ noise in the highly anisotropic, quasi-one-dimensional system (NMP)$_x$(Phen)$_{1-x}$(TCNQ). This excess noise is insensitive to conduction electron concentration and the commensurate/incommensurate nature of the electric ground state. The magnitude of the noise precludes measurement of the shot noise and suggests that large units are involved in the fluctuations.

Thermally activated spectral features are found in the broadband $1/f$ noise. A sudden increase in the noise power is observed upon formation of microcracks. This additional noise contribution is attenuated after several minutes. The voltage noise power is observed to be approximately proportional to the square of the electric field even in the regime where the conductivity is electric field dependent.

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