Discrete fluctuators and broadband noise in the charge-density wave in $NbSe_3$

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In small samples of $NbSe_3$ the broadband noise of the sliding charge-density wave (CDW) can be partially resolved into two-state and multistate fluctuators, which show strong sensitivity to the bias current and temperature. Explicit violations of detailed balance appear. Near the threshold bias for sliding, intermittent periods of noise occur, indicating that some or all of the sample fluctuates between the pinned and sliding states. The behavior of the discrete fluctuators under a variety of time-dependent bias conditions indicates that some particular configurations are available for the CDW in both sliding and pinned states, but with slower dynamics in the pinned state. The results are consistent with a model in which the noise comes from collective rearrangements of defects in the CDW.

I. INTRODUCTION

The broadband noise (BBN) found when charge-density waves (CDW's) are driven to slide[1] has been approached via two main categories of models: those based on equilibrium fluctuations in a random, frustrated system (the pinned CDW) or those based on nonequilibrium driven effects. The first type of model was proposed by Bhattacharya *et al.*,[2] and supported largely on the basis of a fluctuation-dissipation relation between the pinned ac conductivity and the sliding BBN in o-TaS_3.[3] Data showing the dependence of the BBN in $NbSe_3$ on sample geometry offer some support for the latter type of model.[4]

Subsequent measurements have confirmed the general features of the quasiequilibrium picture for BBN in o-TaS_3,[5,6] although mesoscopic measurements show that the sliding-state BBN actually comes from different detailed configurations at different biases.[7] In $NbSe_3$, however, the sensitivity of the BBN to the form of the time-dependent ac bias[8] suggests a more complicated interplay between driven and quasiequilibrium features than found in o-TaS_3.[7] Our first mesoscopic measurements in $NbSe_3$ showed that even at fixed bias current, the BBN dynamics were not a quasiequilibrium process.[9] Here we present more complete mesoscopic data to sort out the effects underlying the BBN in $NbSe_3$, briefly incorporating the prior results.

II. BACKGROUND

An ideal incommensurate CDW would have a single wave vector, with evenly spaced parallel wave front planes, free to slide. The CDW is pinned by randomly placed impurities, since each impurity tries to dictate the local CDW phase. Under the assumption that only the CDW phase need be considered in the resulting complicated minimization problem on a random Hamiltonian, Fukuyama, Lee, and Rice (FLR) worked out many of the properties of the pinned CDW.[10] The pinned CDW should have many metastable configurations, i.e., many phase arrangements.[11] In the FLR model, however, the sliding CDW would approach a unique state.[12]

In a real CDW the CDW amplitude as well as phase is affected by the random potential. If the CDW has topological defects, e.g., dislocations, which can only exist if the amplitude falls to zero in some regions, it is highly likely that some qualitative features of the CDW behavior will not be reproduced by a pure phase-distortion model. In the discussion that follows, when we refer to defects in the CDW we mean actual discontinuities of the phase fronts.

When a voltage greater than a threshold (V_T) is applied, the CDW starts to slide. This nonlinear excess conductivity is accompanied by two types of voltage fluctuations:[1] (1) a high-frequency periodic signal called narrow-band noise (NBN); and (2) the broadband low-frequency noise with a power spectral density $S(f)$ typically of the form $f^{-\gamma}$ with γ from 0.5 to 1.

The most natural explanation for the BBN would be slow, thermally activated switching among metastable configurations, analogous to the sources of $1/f$ noise in many other systems.[13] However, for the most part, the BBN is observed only in the sliding state, precisely the condition under which the FLR theory indicates that the metastable configurations should collapse. A central goal of these experiments is to sort out the extent to which metastable configurations nonetheless play a role in the sliding BBN, and the extent to which these configurations and their dynamics are related to those found in the pinned state. The main techniques employed will be combinations of mesoscopic noise analysis with studies of the effects of perturbations on the long-time correlations which underlie the low-frequency BBN.[14,9]

III. SAMPLE PREPARATION AND EXPERIMENTAL TECHNIQUES

The $NbSe_3$ crystals were grown by DiCarlo *et al.*[15] All detailed experiments presented here were made on a single sample. Four similar samples were studied; all showed individual discrete fluctuators very similar to those to be described here.

The sample is a single five-probe bridge device[6] of 2.0×0.7 μm^2 cross section and 240 μm length for each of the four intercontact arms. Although the use of a bridge sample increases the sample volume over that obtainable for two-probe samples (and thus slightly dilutes some of the mesoscopic effects) it allows us to make measurements with various time-dependent currents without overloading the input amplifiers. Most of the experiments to be described involve such techniques.

The $NbSe_3$ whisker was placed on a glass substrate, and held in place by drops of epoxy at each end (at least 1 mm from the nearest contact). The electrical contacts were then made by evaporating ~ 3 μm of Sn through a physical mask. Each contact had ~ 5-Ω resistance, and each arm had a ~ 320-Ω resistance at room temperature. As shown in Fig. 1, the *I-V* curve of the sample shows a clean transition to the sliding state, typical for good $NbSe_3$ samples, with no noticeable hysteretic switching effects at 90 K.

In similar experiments on thicker samples, we found that the magnitude of the BBN between closely spaced contacts was very low, indicating that the BBN was not a contact effect.[8] Contact effects should be a smaller fraction of the BBN in thin samples employed here.

In all the noise experiments to be described, the sample was held under nearly fixed current, using large series resistors, as shown in Fig. 2, and fluctuations are measured in the voltage. It is convenient to specify the bias in terms of the (easily measured) time average of the voltage produced on one arm of the sample by the current bias.

The experiments performed included standard BBN measurements, in which a dc current was used. For these we collected voltage noise spectra, $S(f)$, and often stored voltage time traces, $V(t)$. Usually higher-order statistical characterizations of the noise were also collected. In order to map out the detailed dependence of the BBN on bias and temperature, it proved convenient to record and display a single-parameter characterization of the noise, for which we used the net rms noise in a fixed bandwidth.

We performed several types of tests of the long time memory of the BBN under time-varying bias, while measuring the voltage at just one bias. For experiments

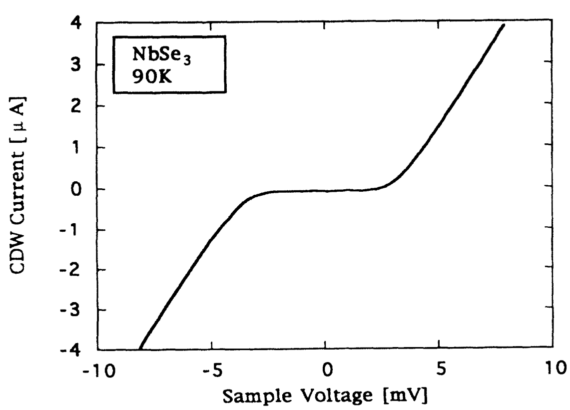

FIG. 1. CDW *I-V* curve of one arm from the five-contact $NbSe_3$ sample at 90 K. The linear part of the curve due to the normal electrons is subtracted by using the sample as one arm of a balanced resistor bridge.

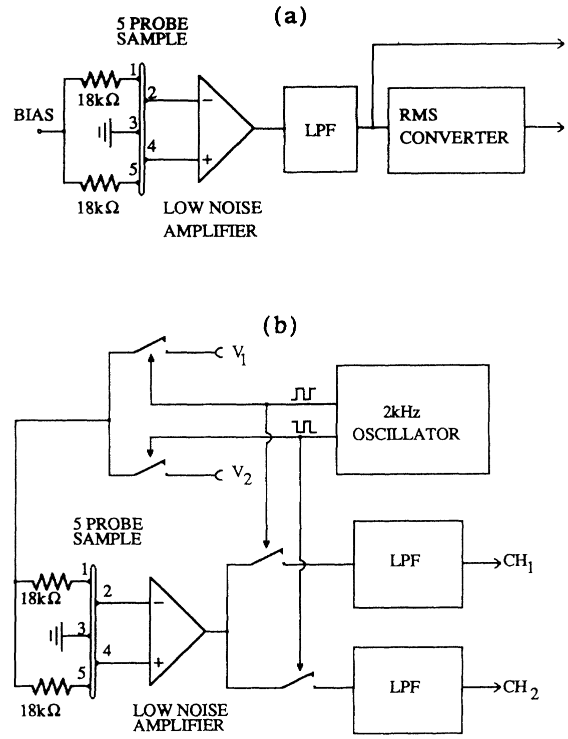

FIG. 2. (a) The standard setup for measuring the BBN. "LPF" stands for low-pass filter. The applied bias could be either dc or ac. We denote the average voltage between probes 2 and 3 of the sample as the sample bias. (b) The experimental setup used to examine the long-time memory of the low-frequency noise under the influence of fast periodic bias switching, using electronic switches. When V_1 (V_2) is applied on the bridge, the noise signal coming from the amplifier is connected to channel 1 (2) via a low-pass filter.

in which the bias was switched at rates of less than about 100 Hz, the different levels were directly set using a computer-controlled digital-to-analog converter (DAC). For more rapidly switched bias, the two levels were set by two different DAC and the switching circuit illustrated in Fig. 2(b) was employed.

We used this setup in several ways, each involving observations of channel 1. The simplest was to set $V_2=0$ while using values of V_1 selected to give clear two-state switching in the voltage. A second version used a swept V_2 and fixed V_1. In a third version V_2 was fixed and V_1 was varied.

IV. EXPERIMENTAL RESULTS

As previously reported, large individual fluctuators were evident in the voltage from the small samples at fixed dc bias.[9] Some of these fluctuators show distinct multilevel configurations with easily resolvable jumps between them. We refer to these repeated switchings between two or more voltage levels as random telegraph signals RTS's. The large peaks in the noise were superimposed on a background of BBN not resolved into individual fluctuators. Most of the large RTS's were found for biases between V_T and $2V_T$.

An approximate lower bound on the size of each typical fluctuating region Ω_f may be made using the extreme assumption that this region is a volume fluctuating between sliding and pinned. Assuming that the CDW current does not change by more than 100% in Ω_f, we have

$$\Omega_f > \Omega_s(\Delta V/I_c)(dI/dV) , \quad (1)$$

where ΔV is the measured voltage fluctuation, I_c is the current due to the electrons condensed in the CDW, and Ω_s is the sample volume.[7] For a typical measured ΔV this lower bound on the volume is $\sim 10^{-11}$ cm^3. The corresponding lower bound on the length of the large fluctuating regions is about 10 μm. The length is roughly consistent with our length estimates made from more subtle non-Gaussian effects in larger samples.[8] Since the apparent volume is smaller than in the thicker samples, it seems that the inherent correlation width for the fluctuations is larger than the thickness of the thin samples.

There are obvious signs of interactions between switching processes on different time scales, as shown in Fig. 3. (Similar results were found in o-TaS$_3$.[16]) This complicated record can be approximately decomposed into three fluctuators: (1) a slow two-level RTS whose levels are marked $a1$ and $a2$, (2) short downward spikes, marked b, and (3) periods without any of these events, marked c. Since the amplitude of the spikes is greater in $a2$ than in $a1$, and since both spikes and the $a1$-$a2$ transition are absent in the state c, it is clear that the constituent fluctuations are not independent.

Even small changes in dc bias or temperature give changes in the duty cycles and kinetics of the fluctuators, even though in macroscopic experiments on large samples the average spectrum is only weakly dependent on these parameters. As the temperature was changed, fluctuators entered and left our experimental frequency window. Each fluctuator had a different temperature dependence, with apparently random signs. (Similar results were found in o-TaS$_3$.[7]) Some typical dependences of spectral features on T are shown in Fig. 4.

Clearly the main effect of changing T is not simply to change the Arrhenius rate of thermal activation over a barrier. The properties of the configurations must themselves be strongly T dependent. For example, the height of energy barriers might depend on T. Both the duty cycle and the characteristic frequency of individual RTS's are obviously strongly bias dependent.

Figure 5 illustrates the rms noise voltage vs average bias voltage for different temperatures. Most discrete fluctuators are found in the measured frequency range only in a small area in the temperature bias (T-V) plane, approximately 0.02–0.5 K by 0.2–1.5 mV. Figure 5(a) exhibits a typical case of several fluctuators (one very prominent one) for which the bias voltage giving the maximum noise depends weakly, and not systematically, on T. Figure 5(b) demonstrates an unusual fluctuator: a little change in V can compensate for a change in T to keep this fluctuator active in our frequency window.

One of the simplest possible CDW parameters whose fluctuations can give BBN is V_T.[2] If V_T does fluctuate, it should be possible in a small sample to directly watch the CDW switch between pinned and sliding over a narrow range of bias. Voltage records near V_T are shown in Fig. 6. Just below V_T the sample BBN is small (residual noise is Nyquist noise and preamplifier noise). Above V_T the sample BBN is larger. At intermediate biases the BBN is

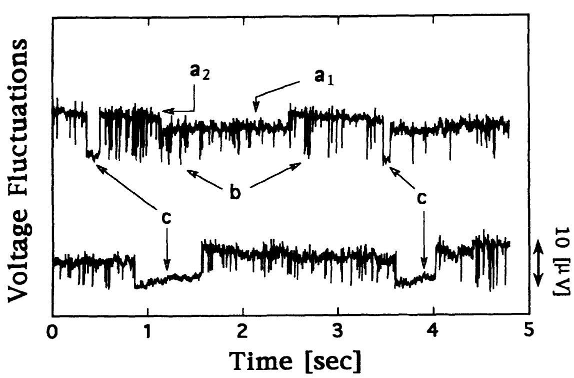

FIG. 3. Small portion of a time trace of voltage fluctuations exhibiting interaction between three fluctuators, as described in the text.

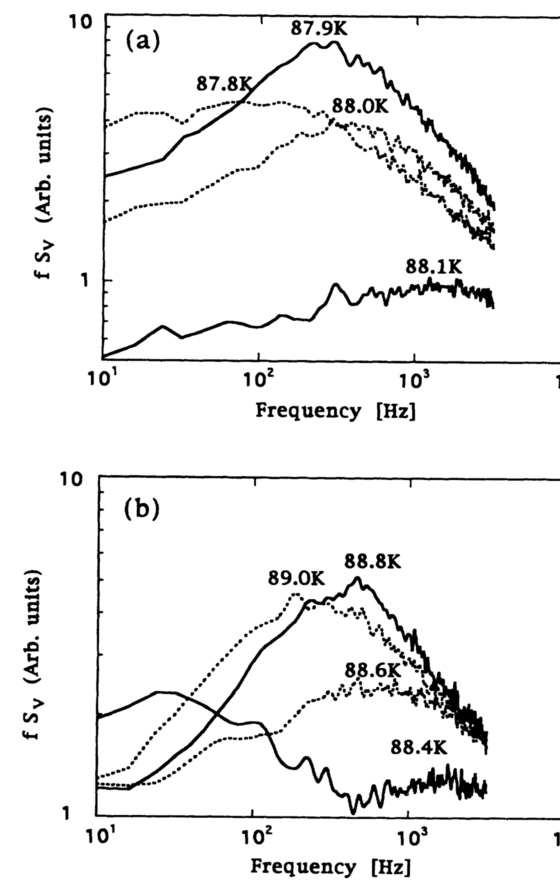

FIG. 4. $fS(f)$ at bias voltage 3.78 mV of two discrete fluctuators are shown. The characteristic frequencies exhibit (a) anomalously large positive T dependence and (b) negative T dependence.

intermittent. The noisy periods always have voltage with a single sign of deviation from that of the quiet periods. When increasing the bias, the quiet instances become shorter and the noisy ones become longer (and noisier). The total change in the I-V relation between the apparently sliding and quiet periods is too small to show up in I-V curves taken with our standard dc-coupled methods.

The intermittency illustrated in Fig. 6 could also be found by an automated technique—measuring the correlation coefficient of the fluctuations in noise power between separate octaves (e.g., 14–28 and 50–100 Hz), as a function of bias. A large peak (correlation coefficient 0.7) in this cross correlation appeared near threshold. Similar peaks were found at many but not all temperatures. For those T at which the noise rose smoothly near threshold, without intermittency, no feature appeared in the cross correlation between octaves. A scattering of smaller cross-correlation peaks appeared away from threshold. (Similar results were found in o-TaS_3.[16])

The actual dynamics observed in a typical BBN experiment on $NbSe_3$ are not describable by a quasiequilibrium model, since three-state discrete fluctuators are found to violate detailed balance.[9,17] The bias current thus plays a qualitatively important role in the dynamics of the noise. (Only more subtle effects of driven kinetics appeared in o-TaS_3.[7]) Since many features of the BBN in $NbSe_3$ resemble the apparently quasiequilibrium effects in o-TaS_3, we ran other tests to see if some form of the fluctuations would still be detectable in the absence of driving.

Since shear effects have been implicated in the BBN of $NbSe_3$, we measured BBN in mesoscopic samples with applied 1-MHz current with amplitudes from $0.9V_T$ to $1.9V_T$. As in macroscopic samples,[8] low-frequency noise appeared. It contained discrete fluctuators, as can be seen in Fig. 7. Under these conditions the CDW oscillates only about 0.23–1.5 of its wavelengths from its equilibrium position (calculated from the dielectric constant[1] and the CDW velocity[18]) so that velocity shear would not be expected to create the fluctuations.

To ensure that no large net dc electrical field is present when applying an ac bias, e.g., due to asymmetrical contacts, we measured the net dc voltage across the sample as a function of ac bias frequency and amplitude. With

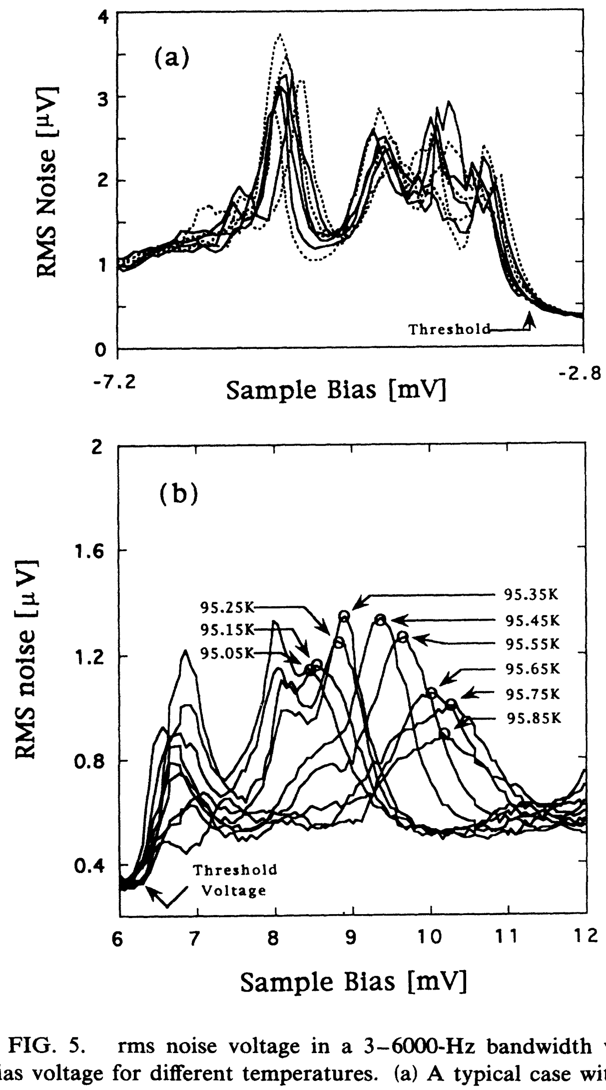

FIG. 5. rms noise voltage in a 3–6000-Hz bandwidth vs bias voltage for different temperatures. (a) A typical case with little systematic T dependence of the optimum bias. Eight curves were measured at temperatures from 91.05 to 91.75 K. (b) An unusual fluctuator with compensation in the temperature-bias plane: when changing the bias, one can compensate with temperature changes to keep this fluctuator active in the frequency window.

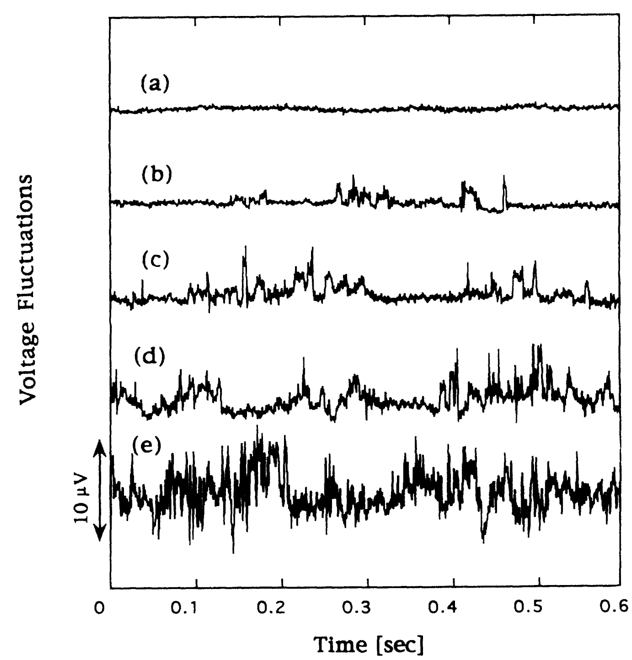

FIG. 6. $V(t)$ at 90 K for slightly different successive bias voltages near the nominal V_T: (a) $V_B/V_T=0.96$, (b) $V_B/V_T=1$, (c) $V_B/V_T=1.01$, (d) $V_B/V_T=1.02$, (e) $V_B/V_T=1.05$. In trace (a) the CDW is pinned, in trace (e) the CDW is sliding at a bias set to the center of the first rms noise peak above threshold. Between the two extreme traces one finds instances where the system is quiet and noisy alternately [trace (b), for example], an indication that at these biases some portion of the sample is jumping between sliding and pinned states.

1-MHz ac bias, the net dc voltage across the sample is negligible ($<0.1\ \mu V$). However, at lower bias frequencies, for which the CDW moves back and forth many wavelengths each ac cycle, small dc polarizations ($\sim 10\ \mu V$) form. The conditions for observing the low-frequency fluctuations appear to be just opposite to those which create a dc polarization.

To check for the presence of fluctuators in the pinned state like those seen in the BBN, we observed what happened in sliding-state RTS's when they spent time in the pinned state.[9] After finding a clear two-level RTS in the sliding state at bias V_1, we applied a bias alternating from V_1 to zero with periods much longer than the time constant of the RTS. For short pinned times, e.g., 0.5 s (still much longer than the RTS characteristic time constant), the RTS almost always returns to the state it was previously in. Thus in the pinned state the system keeps the memory of the specific configuration of the fluctuator longer than in the sliding state. As the pinned state time is increased, the probabilities of finding one transition increases, indicating that this fluctuator has a finite transition rate (one way) in the pinned state.[9] This behavior was found for four RTS's, and also in o-TaS_3.[16]

To compare the effects of changing the bias toward a more rapidly sliding state with those of comparable bias

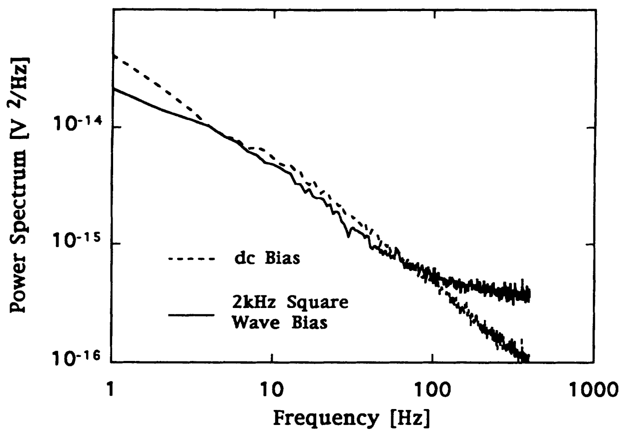

FIG. 8. Comparison of $S(f)$ in channel 1 in the dc case ($V_1=V_2=8$ mV) where the sample noise shows BBN without resolvable discrete fluctuators, and the ac case where the bridge voltage alternates between V_1 and $V_2=-V_1$.

voltage changes into the pinned state, we measured rms noise while the bias was switched at 2 kHz between $V_2=12$ mV and a range of different V_1, using the setup shown in Fig. 2(b). The rms noise was measured at the V_1 bias. As shown previously,[9] the large noise peaks found with dc bias were substantially reduced by this procedure, but the rms value of the background noise was not much changed. Nevertheless such switching affected the background BBN spectrum. Figure 8 illustrates the difference between $S(f)$ at 8 mV (at which no discrete fluctuator was found) and with an 8-mV amplitude 2-kHz square wave. Although the rms BBN in the 0.3–400-Hz bandwidth is scarcely affected, the ac switching causes some of the slow fluctuations to be lost, and a new higher-frequency component to appear.

The same experimental setup [Fig. 2(b)] was used to investigate the detailed dependence of individual fluctuators on ac bias. In Fig. 9 the time dependence of the sam-

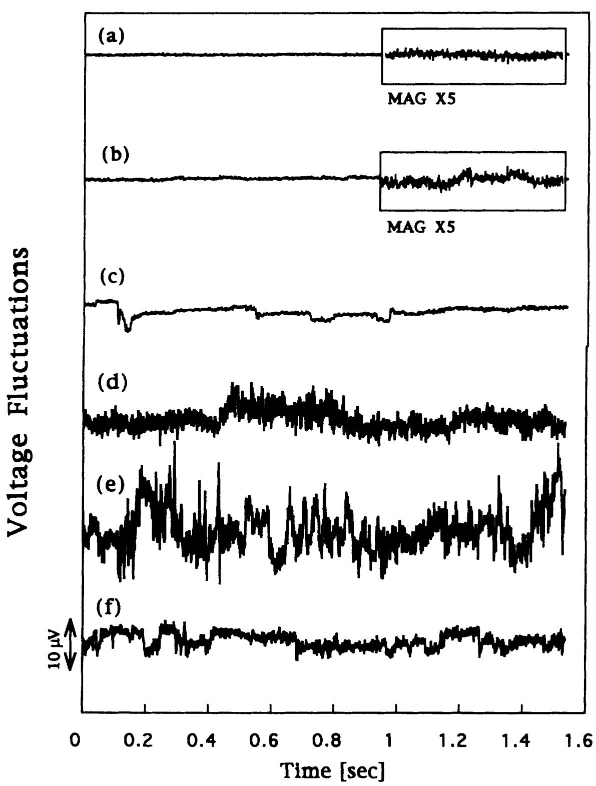

FIG. 7. Time traces of low-frequency noise (1–455 Hz) recorded under 1-MHz ac bias applied with increasing amplitude at $T=81$ K. The ratio of the 1-MHz amplitudes to the dc V_T (with about 5% calibration uncertainly, due to capacitative effects) are (a) 0, (b) 0.9, (c) 1.2, (d) 1.3, (e) 1.5, (f) 1.9. Discrete jumps and low-frequency noise are found, similar to time traces of discrete fluctuators found in the noise under dc bias.

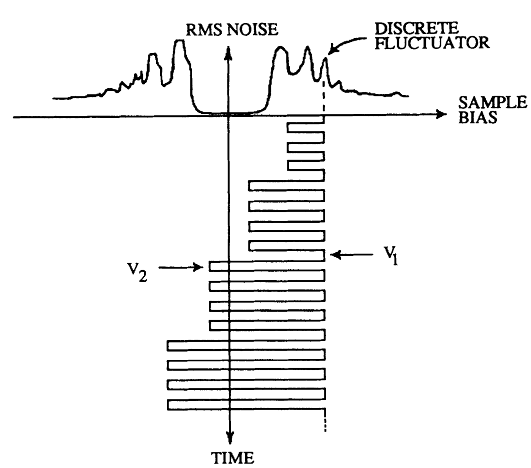

FIG. 9. Illustration of time evolution of the sample voltage for tracking the behavior of a slow discrete fluctuator under the influence audio frequency: pulses from the measurement voltage V_1 to V_2: V_1 is tuned to a voltage at which a clear two-level random telegraph was observed, V_2 is varied from V_1 to $-V_1$, time traces were taken from channel 1 [see Fig. 2(b)].

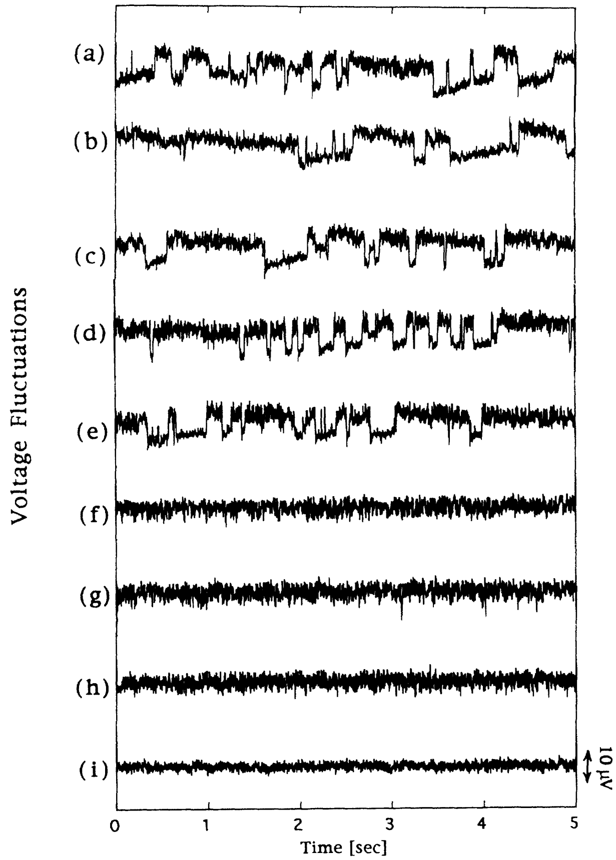

FIG. 10. Time traces of a slow discrete fluctuator at sample voltage 4.63 mV under the influence of 2-kHz switching to V_2 [see Fig. 2(b)]. Values of V_2 are (a) 4.63 mV, (b) 3.83 mV, (c) 2.60 mV, (d) 1.32 mV, (e) 0 mV, (f) −1.32 mV, (g) −2.60 mV, (h) −3.83 mV, and (i) −4.63 mV.

ple bias is illustrated: V_1 was set at a voltage where a clear two-level RTS was observed, V_2 was varied from V_1 to $-V_1$, and time traces were recorded from channel 1, i.e., from the V_1 setting only.

Although in ac bias experiments on macroscopic samples, only reversed sliding, i.e., $V_2 < -V_T$, was found to substantially eliminate the long-time memory of the BBN,[8] Fig. 10 illustrates a particular RTS which was wiped out for $V_2 < 0$. Although disappearance of the RTS for $V_2 < -V_T$ was more typical, reversal of the CDW current is clearly not essential for scrambling individual fluctuators.

V. DISCUSSION

The clear observation of many metastable configurations of the CDW via voltage noise in the sliding state confirms the idea of Bhattacharya *et al.*[2] that the BBN comes from switching among such configurations. Since theoretical considerations indicate that a sliding defect-free CDW described only by phase degrees of freedom would have no metastability in the sliding state,[12] such a phase model cannot describe the BBN. In all probability, various other slow relaxational phenomena which persist in the sliding state, such as internal friction,[19] also require descriptions allowing for topological defects in the CDW.

Once it is accepted that discontinuities in the phase fronts, i.e., defects, are necessary to describe the BBN and other slow relaxations, one still must account for the rather complex dependence of the BBN and its component RTS's on bias currents. Since each of the component RTS's appears only for a narrow window of dc bias current, the simplest version of the Bhattacharya hypothesis, in which the fluctuations measured in the sliding state are essentially the same as those present in the pinned state,[3] cannot be completely true.

The kinetics of the fluctuating configurations giving the RTS's in $NbSe_3$ obviously have a substantial driven, nonequilibrium contribution, since clear violations of detailed balance appear. Violations of detailed balance have previously been found in strongly driven noisy systems, e.g., in charge fluctuations in an amorphous insulating barrier with a strong nonequilibrium current.[17] In that case there was a nonequilibrium flow in real space of the stuff responsible for the fluctuations (the electrons). The most plausible interpretation of the detailed balance violations in the CDW BBN would also involve real-space flow of CDW defects.

The flowing CDW should exert a nonequilibrium drag force (not derivable from a potential) on its own defects, which then can be driven from regions of high stability to ones of low stability. In Fig. 11 we illustrate a possible example of cyclical creation and annihilation of defects. A CDW dislocation loop might be thermodynamically stable in position x_1 (configuration C) due to the random pinning potential. The drag of the moving CDW on the dislocation might cause a nonequilibrium transition to position x_2 (configuration A), at which the loop is metastable. A thermally activated transition to a dislocation-free configuration (C) could then occur. The resulting strain could then lead to a thermally activated creation of

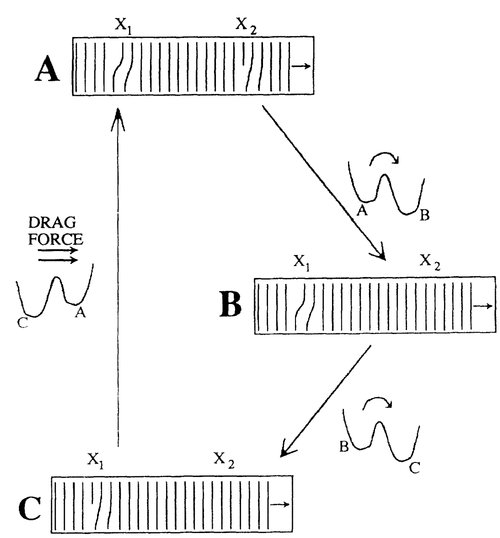

FIG. 11. A schematic model of how the nonequilibrium CDW drag could create predominantly cyclical kinetics, as described in the text.

a new dislocation loop at x_1. (A related picture, involving defect motion orthogonal to the current at contacts, has been proposed for a somewhat different type of noise found in o-TaS_3 samples with unusually large threshold fields.[20])

Given that the current helps drive the dynamics of at least the larger discrete fluctuators, an obvious question is whether any similar fluctuations would exist in the pinned state. Several prior considerations suggest that they would. Low-frequency internal friction persists in the pinned state, and it must be accompanied by low-frequency strain fluctuations, according to the fluctuation dissipation theorem. In very small samples of o-TaS_3 direct observation of discrete fluctuators in the pinned state has been possible.[21]

The strongest evidence connecting pinned-state fluctuations with BBN was the similarity of the dipole-moment fluctuation spectrum (inferred via the fluctuation-dissipation theorem from the ac conductivity) to the BBN spectrum in o-TaS_3.[3] This connection of the configuration fluctuations with dipole-moment fluctuations is expected, since such fluctuations require variations in the CDW wave vector, whose magnitude is directly proportional to the density of condensed electrons. Since the electric dipole moment should fluctuate with the configuration, the free-energy difference of two configurations will in general depend on the electric field. Thus it is not surprising that the set of active fluctuators, i.e., those which have two configurations with approximately equal free energies, is a function of the field.

Several features of our data also point to the existence of similar fluctuators in the pinned state. Some of the transition rates among the metastable configurations are nonzero in the pinned state but with slower dynamics compared to the sliding state, as shown by the sliding-pinned-sliding cycling experiments.[9] While we found only one-way relaxations in the pinned state, that is hardly surprising since the duty cycle of each fluctuator depends strongly on the bias voltage. The hypothetical pinned state fluctuators, which would of course have to have at least two nonzero rates, would not produce RTS's in the sliding state for precisely the same reason.

The closest approximation to directly measuring the fluctuations in quasiequilibrium without the effects of driving was obtained in the high-frequency ac driving experiments. It has long been known that, at least in the o-TaS_3, the ac conductance becomes nonlinear for voltages below the dc threshold.[3] If the nonlinearity below threshold has the same sort of random fluctuations as give rise to the "vector" BBN above threshold,[6] then subthreshold noise can probe configuration fluctuations.

Even with a net oscillatory motion of the CDW of less than a half wavelength, we found clear steps in the low-frequency voltage. The CDW jumps between configurations with different random rectifications of the applied current. Such a measurement is not made in true equilibrium, of course, but it does strongly indicate that the continuous generation of defects via velocity shear mechanisms is not necessary to drive the dynamics of the BBN or its larger mesoscopic features.

In the intermittent noise traces sometimes found near threshold, the quiet portions look like records taken in the pinned state, while the noisy portions resemble sliding-state records. The obvious interpretation is that the CDW is switching between the pinned state and a state in which at least part is sliding. Within the sliding state many metastable configurations are detectable. The occasional smaller, less obvious intermittency picked up away from threshold in the interoctave correlations is simply the expected consequence of coupled RTS's, such as those in Fig. 3.

Although it is not correct to simply treat the fluctuations as if they appear only in a single parameter, V_T, the intermittent traces show that V_T does indeed fluctuate substantially—up to about 5% in these small samples—as had been predicted.[2] To realistically estimate the volume of the fluctuating regions when the bias is well above V_T, it would be much more reasonable to treat the fluctuations as changing V_T by a few percent within that region, rather than as driving the entire region pinned (as we did in obtaining a lower-bound estimate). The resulting estimate of the coherently fluctuating volumes are then between 10^{-10} and 10^{-9} cm^3, i.e., roughly the volume of the whole sample.

The very strong temperature dependence of the individual fluctuators makes little sense unless large-scale collective effects are involved. The typical temperature correlation scale of the BBN, ~ 100 mK, roughly corresponds to changing the number of CDW wavelengths in the sample by one, due to the T-dependent wave vector.[22] As we have argued for o-TaS_3,[7] the most reasonable interpretation is that the CDW phase mediates interactions among CDW defects, so that the signs of the interactions are scrambled when the number of wavelengths in a coherent region changes by one.

Many of the fluctuators appear to be complicated multistate systems, which may perhaps be thought of as interacting few state systems. Such interactions would hardly be surprising, given that the individual fluctuations must include such large portions of the sample length that frequent overlap is inevitable.

Granted that the CDW defect configuration can be maintained even as the CDW itself is flowing, there remains the question of how that configuration can be partially maintained even as the CDW polarization is changed by changing the bias. Since the pulse overshoot effect demonstrates that the entire CDW polarization is reset when the CDW sliding direction is switched,[23] it might seem unlikely that any configurational memory would survive repeated repolarizations, which require moving on the order of ten wave fronts from one side of the sample to the other. Nevertheless, internal friction measurements in the presence of above-threshold ac bias show that some such long-time memory does persist.[19] In o-TaS_3, most of the BBN persisted in the presence of such switching bias,[6] while in $NbSe_3$ most of the low-frequency BBN was eliminated, except when the bias frequency was so high that little polarization could occur.[8] In $NbSe_3$ only the low-frequency memory associated with the background BBN, i.e., the part not resolved into discrete fluctuators, partially survives bias switching.

Although the CDW can retain its configurational memory while sliding, the data on the BBN under switched-bias conditions show some signs of reduced configurational memory in more rapidly sliding states. When stepping the bias from a value for which a discrete fluctuator is observed to zero bias for a time much longer than the fluctuator's time constant, the configuration changes much more slowly than while sliding. When the intervening bias pulses are to more slowly sliding states (of the same sign), they have little effect on the BBN. However, when these intervening pulses are to a much more rapidly sliding state, the large RTS's are greatly reduced.

VI. CONCLUSIONS

The main conclusions about the BBN in $NbSe_3$ that we can draw are that (1) the noise comes from configurational rearrangements, presumably requiring topological defects: (2) some of the rearrangements extend over regions comparable to our sample volumes; (3) the properties of th individual configurations are strongly affected by small temperature changes, presumably via effects on the wave vector; (4) the kinetics in the sliding state are partly driven, but the essential noise processes appear to persist in the pinned state; (5) all of the larger rearrangements are scrambled when the direction of current flow is reversed.

Very little evidence other than the experiments on cleaved $NbSe_3$ (Refs. 4 and 18) exists to sort out what causes topological defects to be present. Our results do not support an interpretation in which the BBN is a *direct* outcome of velocity shear, since BBN and some of the contributing rearrangements can occur in the absence of such shear. However, our interpretation is consistent with the idea that in very-high-quality samples with nonrectangular cross sections velocity shear is *indirectly* responsible for most of the BBN,[4] since in such samples velocity shear may be the principal source of topological defects. Once generated, a nonequilibrium ensemble of such defects might be hard to remove (without annealing to the Peierls temperature), and thus could serve as a source of fluctuating collective configurations even in quasiequilibrium.

Even for ideal rectangular geometries with weak pinning only, some defects are expected to result from dynamical shear due to the inherent statistics of the pinning.[24] The roles of occasional strong pinning sites in creating dynamical shear sites, and also in creating topological defects in pinned thermal equilibrium are not known. In fact, there is no proof that topological defects are absent in thermal equilibrium even when only weak pinning is present.

We have suggested that the BBN in o-TaS_3 might be described by a model of defects interacting via the CDW.[7] This model bears a strong resemblance to a Hamiltonian examined as an approach to spin glasses.[25] A similar model may prove adequate for $NbSe_3$ as well. A good theoretical treatment ought to provide a quantitative understanding of the greater nonequilibrium effects in $NbSe_3$. One possibly relevant distinction between $NbSe_3$ and o-TaS_3 is that the crystals of the o-TaS_3 are far less perfect, which might promote the formation of a set of true equilibrium topological defects in its CDW.

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