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# Correlative motion of vortices near the vortex lattice melting point in $Bi_2Sr_2CaCu_2O_{8+x}$ single crystals

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**Abstract.** Voltage noise of the $Bi_2Sr_2CaCu_2O_{8+x}$ single crystal below $T_c$ is analysed by an asymptotic power spectrum method. The low-frequency noise power, $S_v(T)$, shows a peak at $T = T_p$. This peak is found to be closely related to the vortex lattice melting temperature. Near the peak $T = T_p$ the power spectrum, $S_v(f)$, exhibits a power-law fall-off, while at much lower temperatures $S_v(f)$ dramatically deviates from the power-law behaviour, showing some broad peaks which are superposed upon a background with an exponential-law characteristic. The estimated correlation dimension of the noise data reveals that the vortex motion is highly correlated at the early stage of melting, then develops into an extended dissipative dynamic system with self-organized criticality, showing a $1/f^{\alpha}$ behaviour. The correlated motion disappears when the lattice completely melts.

The recently discovered high-temperature superconductors (HTSs) are strong type-II superconductors with huge thermal fluctuations, weak pinning, and strong anisotropy, leading to interesting effects in the phase diagram of the vortex states. One of the useful tools to study vortex dynamics is to measure the voltage noise, $S_v$, arising from fluctuations of the vortex motion. Extensive studies have been made to reveal the origin of the voltage noise and its correlation with the vortex motion [1–5]. One of the most interesting phenomena observed is the noise peak near $T_c$, which has been interpreted as originating from vortex motion [1], transition between different vortex states [2], thermal fluctuations [3], critical current fluctuations [4], and granularity [5]. Most of these studies have concentrated on the temperature dependence of the $1/f$ noise power spectrum, few paying attention to the detailed changes of the spectrum itself around the noise peak. Recently D'Anna *et al* [6] have investigated the vortex motion below the quasistatic melting transition in a detwinned $YBa_2Cu_3O_{7-y}$ (Y-123) single crystal by measuring the differential resistance and the voltage noise. They found that with a magnetic field parallel to the $CuO_2$ planes, the noise power spectrum is dominated by the surfaces and that the vortices appear to be flowing in channels, resulting in unusually sharp and distinct peaks in the noise power spectrum, which are periodic in frequency. Lee *et al* [7] studied the spatial correlation of the vortex motion in Y-123 and $Bi_2Sr_2CaCu_2O_{8+x}$ (Bi-2212) films and single crystals by measuring the flux noise using two dc superconducting quantum interference devices (SQUIDs). Their results revealed that the vortices moved as rigid rods.

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As pointed out previously for the low-$T_c$ superconductors [8, 9], the noise voltage is produced by a sequence of random, overlapping pulses arising from the motion of flux lines or bundles of flux lines. This type of model emphasizes the motion of the individual flux line which is driven by the Lorentz force, and provides a suitable description for the vortex motion in superconductors with strong flux pinning. For a system with high anisotropy and weak pinning, the vortex lattice melting process plays an important role in the vortex motion, and the collective motion may be dominant [10]. Numerical simulation for some simple vortex systems has revealed that the vortex motion is highly correlated and highly self-organized [11, 12]. Analysis of asymptotic power spectra and calculation of the correlation dimensions provide an effective way to find a possible temporal correlation of the motion from the noise data, to distinguish whether the motion is deterministic or highly random. In this paper, we investigate the temporal correlation of the vortex motion by analysing the noise power spectrum in Bi-2212 single crystals with a magnetic field perpendicular to the $CuO_2$ planes to determine possible collective motions of the vortices during the vortex lattice melting process.

The Bi-2212 single crystals used in this study were prepared by a travelling solvent floating-zone method. The dimensions of a typical sample in the $a$, $b$ and $c$ directions are 6.1, 2.3, and 0.09 mm, respectively. The $T_c$ (the onset transition from susceptibility measurements) was 95.74 K by a SQUID magnetometer measurement at 10 Oe. The zero-resistivity temperature measured by the dc four-probe method at $H = 0$ was 95.79 K. Noise power at fixed frequencies was measured by a lock-in technique. In order to obtain detailed information, the noise spectral density was obtained by a fast Fourier transformation of the discretely sampled data measured by a high-resolution digital voltmeter for a fixed time interval. A testing current was fed into the *ab* plane along the $a$ direction and a magnetic field was applied perpendicular to both the current and the *ab* plane. The phase diagram for the melting line of the vortex lattice was determined from ac susceptibility measurements with a dc magnetic field (in the direction of the $c$ axis) perpendicular to the ac field (in the *ab* plane) as proposed by Pastoriza *et al* [13].

Figure 1 shows a typical voltage noise power, $S_v(T)$, measured at 7 Hz. The testing current is 1 mA, which is equivalent to a current density of 483 mA cm$^{-2}$. The applied magnetic field is 60 Oe. There is a noise peak occurring at $T_p = 95.61$ K, which is consistent with the report of Han *et al* [14] that an anomalously enhanced noise peak near $T_c$ was found. In order to exclude thermal fluctuations $S_t(T) \propto (\mathrm{d}R/\mathrm{d}T)^2$, as a possible origin of the peak, $(\mathrm{d}R/\mathrm{d}T)^2$ measured at the same magnetic field is also plotted in figure 1 and compared with $S_v$. It is evident that $T_p$ is significantly lower than the temperature at which the peak of $S_t(T)$ occurs, indicating that the noise peak does not originate from thermal fluctuations. This is slightly different from the results of Kim *et al* [15] for Y-123 thin films in which an additional noise peak was found at the maximum of $S_t(T)$. However, the effect of the thermal fluctuations on $S_v(T)$ can still be seen as the noise peak shown in figure 1 is broadened in the temperature region where the thermal fluctuations play a significant role. In the normal state, the noise power curve can be fitted to Johnson noise, $S_J = 4k_BRT$, which vanishes at the zero-resistivity temperature and is thus not the cause of the peak. The noise peak in Bi-2212, as in Y-123 thin films [14], is magnetic field dependent, i.e. the magnitude and position of the peak vary with the applied field and the peak disappears at $H = 0$. This suggests that the peak is related to vortex motion, and is probably an indication of the melting transition of the vortex lattice as concluded by other authors [2].

In the inset of figure 1, we plot the variation of the noise peak position $T_p$ with applied magnetic field. For comparison, the melting line $T_m(H)$ determined by the ac susceptibility

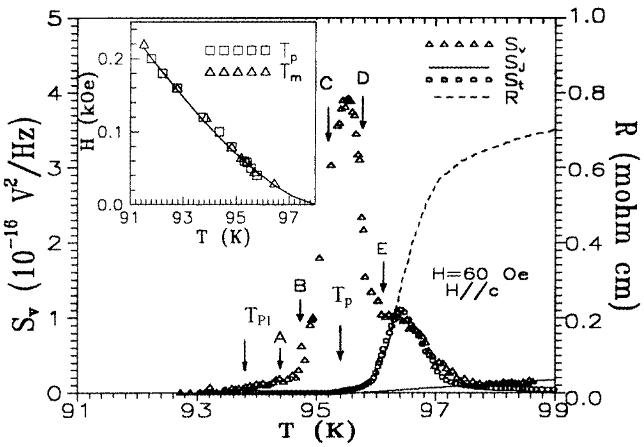


**Figure 1.** The noise power measured at 7 Hz and 60 Oe together with the resistivity, Johnson noise, $S_j$, and thermal fluctuations, $S_t$. Points A–E are selected for comparing their power spectra and/or correlation dimensions. Inset, the magnetic field dependence of the noise peak temperature, $T_p$, and melting temperature, $T_m$. The solid line represents the relation $H = H_0(1 - T/T_{c0})^{1.45}$.

measurements is also plotted. It is evident that $T_p(H)$ and $T_m(H)$ are very close and both of them can be described approximately by the relation $H = H_0(1-T/T_{c0})^n$ with $n = 1.45$ and $H_0 = 11$ kOe, where $T_{c0}$ is the mean-field transition temperature. This further illustrates that the noise peak shown in figure 1 is associated with the melting transition of the vortex lattice in the Bi-2212 single crystals. As can be seen in figure 1, the noise power appears at $T_{pl} < T_p$, which can be regarded as the early stage of vortex lattice melting.

In order to obtain information for the correlation of the vortex motion during vortex lattice melting, the characteristics of the noise spectrum around the peak have been examined. By studying carefully the power spectral density, $S_v(f)$, around the peak, it is found that some characteristics of the spectrum are changed as the temperature increases from $T_{pl}$ to $T_p$. Typical results are shown in figure 2, in which four points around $T_{pl}$ and $T_p$ (denoted as A–D in figure 1) are selected for the comparison of their characteristics of the noise spectrum. The corresponding temperatures of these points are 94.32, 94.79, 95.21, and 95.72 K from A to D, respectively. At temperatures above and close to $T_p$ (see point D), $S_v(f)$ is a typical $1/f^\alpha$ spectrum with $\alpha = 0.73$ (see figure 2(d)). Such a power-law behaviour of the so-called $1/f$ noise is observed at all applied magnetic fields as shown in the figure. At a temperature slightly lower than $T_p$ (point C), a roughly power-law behaviour can still be seen, but the fitting of a $1/f^\alpha$ curve is not as good as for point D; in particular as the magnetic field decreases to 10 Oe no power-law behaviour can be found (see figure 2(c)). At lower temperatures (points A and B), a log–log plot of power spectra cannot be fitted as a straight line, indicating that the power-law behaviour no longer holds. In addition, some broad peaks appear in these spectra, since the peaks are so broad that they cannot be regarded as the dominant frequencies in the spectra. However, it is interesting to find that the trends of the spectra can be approximately described by a exponential law (see the solid lines in figure 2(a) and (b)). Therefore, the noise spectra at points A and B have the feature of broad-band structure superposed upon a background with an exponential-law characteristic. Deviations from power-law behaviour may have several possible origins, such as a Lorentzian contribution as observed in [6], chaotic motion, and even experimental noise. The first can be excluded for the following reasons: (i) the peak is far from a Lorentzian form; (ii) the frequencies of the peaks do not follow the ratio of 1:2:3; (iii) the frequencies of the peaks change randomly with magnetic field; (iv) we have failed to find any sharp frequencies by either Fourier transformation or the maximum-entropy method [16]. The experimental noise, including that from the original data collection as well as from the spectrum analysis, may be the source of the broad-band structure shown in figure 2(a) and (b). However, the following correlation dimension analysis shows that this is not the dominant factor. Broad-band structure without a dominant peak may also be a characteristic of the power spectrum of a chaotic-dynamic system in the low- to moderate-frequency regimes. Especially, the background with an exponential-law characteristic indicates a chaotic motion [17]. As is well known, exponential decay of the power spectral density is indicative of a low- or moderate-dimensional chaotic state, while a power-law decay is indicative of a system in which small-scale processes contribute significantly to global behaviour [17]. Thus it is suggested that the vortex motion is highly correlated at the early stage of vortex lattice melting, while it becomes more chaotic and moves like an extended dissipative dynamic system with self-organized criticality [18] as vortex lattice melting further develops. The observed $1/f$ noise in the later case is a temporal 'fingerprint' of this self-organized criticality [18].

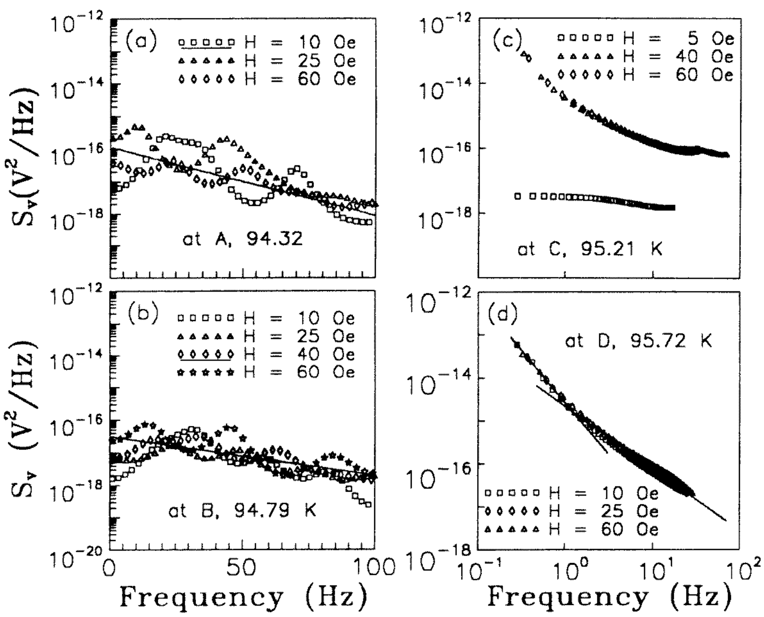


**Figure 2.** The power spectral densities at points (a) A, (b) B, (c) C, and (d) D (see figure 1). The solid lines in (a) and (b) show an exponential decay of the background. The lines in (d) are guides for the eyes.

To further investigate the correlation of the vortex motion, the correlation dimension, $d$, of the noise of the vortex motion is calculated using the method of Grassberger and Procaccia [19]. To do this, it is necessary to construct the phase space. The space may be reconstructed using the time-delay embedding method [20]:

$$x_i = [x(t_i), x(t_i + \tau), x(t_i + 2\tau), \dots, x(t_i + (D_E - 1)\tau)] \tag{1}$$

where $D_E$ is the embedding dimension, and $\tau$ is the time delay. This reconstructed geometrical structure has the same dimensional characteristics, such as the correlation dimension, of the attractor generated from the dynamic system (vortices) underlying the original scalar time series. Defining the correlation integral $C(l) = \lim_{N\to\infty} 1/N^2$, where $N$ is the number of $D_E$-dimensional vectors constructed from the scalar time series, $C(l)$ can be scaled as $l^d$, where $d$ is the correlation dimension. Usually, a saturation of $d$ with increasing embedding dimension $D_E$ indicates that the times series has a nonrandom component. Therefore, the $d$–$D_E$ relationship of a time series will give us an indication of whether it is completely random or whether it contains physical information on the motion with temporal correction.

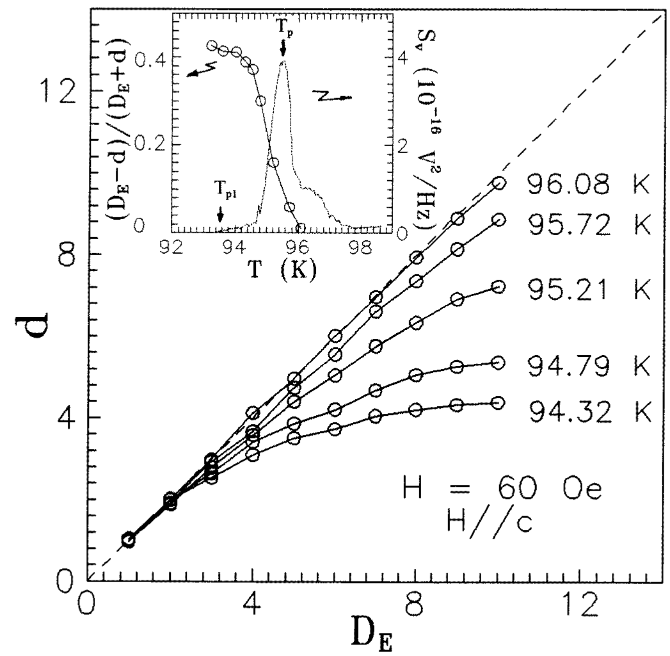


**Figure 3.** The relation between the correlation dimension $d$ and the embedding dimension $D_E$. The dashed line is the result of uncorrelated noise. Inset, the temperature dependence of $(D_E - d)/(D_E + d)$ and $S_v$ at $H = 60$ Oe.

Figure 3 shows the estimated correlation dimensions in different embedding dimensions for the noise data at points A–E shown in figure 1. For the noise signal at point A, the correlation dimension $d$ increases slowly with the embedding dimension and saturates gradually at $d = 4.2$. This strongly suggests that the nonrandom component other than random noise (including experimental noise) is dominant, thus indicating that the vortex motion is highly correlated at the early stage of vortex lattice melting, consistent with the exponential-law-like decay of $S_v(f)$ shown by the solid lines in figure 2(a) and (b). However, this correlation behaviour is greatly decreased by vortex lattice melting as the temperature approaches the peak point at $T = T_p$, and finally disappears at point E where the vortex lattice has completely melted. Here we introduce $w = \lim_{D_E\to\infty}(D_E - d)/(D_E + d)$ as a correlation degree of the noise data to describe the correlation of the vortex motion. $w$ is near unity for highly correlated motion, but near zero for uncorrelated motion. In this work, we used the value of $(D_E - d)/(D_E + d)$ at $D_E = 10$ to represent the value

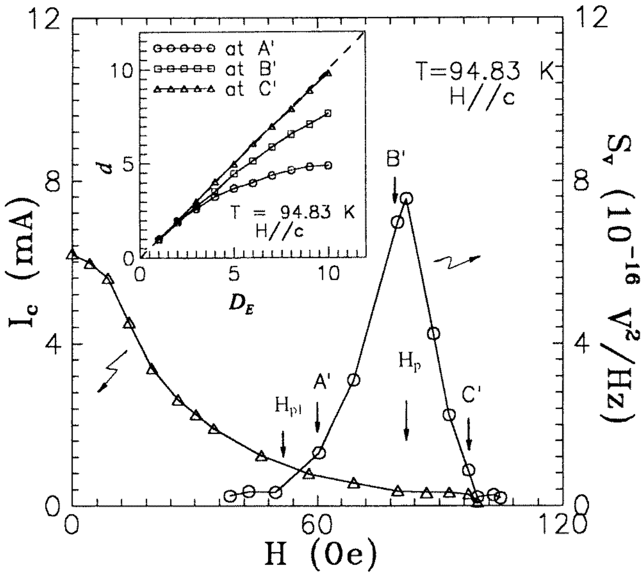


**Figure 4.** The magnetic field dependences of $I_c$ and $S_v$. The points A′–C′ are selected for comparing their power spectra and correlation dimensions. The inset is the $d$–$D_E$ relation for noise data at A′–C′, in which the dashed line is the result of uncorrelated noise.

of $w$. As show in the inset of figure 3, the value of $(D_E - d)/D_E + d)$ decreases slowly with temperature near $T_{p1}$ but rapidly as the temperature approaches $T_p$. This indicates that the vortex motion is highly correlated in the early stage of the vortex lattice melting, and then becomes random with development of the melting process. It is noticeable that a certain correlation of the vortex motion still exists at $T = T_p$ (see $d - D_E$ at point C). Very large noise, as well as the correlated motion in this region, indicates that this may be a plastic flow regime of the vortices suggested by Marley *et al* [10] for the layered low-$T_c$ superconductor.

Besides the noise peak in the $S_v$–$T$ relation, a noise peak is also observed in the $S_v$–$H$ relation. Figure 4 shows a typical result of $S_v(H)$ measured at 7 Hz and 94.83 K. It is evident that noise arises at $H_{p1}$ and reaches a maximum at $H_p = 82.3$ Oe. This is similar to the noise peak in $S_v(T)$. As found by Marley *et al* [10], the maximum of the noise power corresponds to plastic flow of the vortices. This means that some plastic deformation of the vortex lattice has taken place near $H_p$. It is interesting to note that the peak in $S_v(H)$ covers a range of magnetic fields where the critical current $I_c$ decreases slowly with the magnetic field (see also figure 4). As is well known, Bi-2212 is weak in flux pinning because of the lack of pinning centres. A low $J_c$ value of $\sim$2 A cm$^{-2}$ at a reduced temperature $T/T_{c0} = 0.98$ and zero field further supports the weak pinning of the sample. On this weak-pinning basis, the collective pinning caused by the plastic deformation of the vortex lattice may play a significant role as the vortex lattice melting point is approached. The coincidence of the noise peak with the flat region in the $I_c$–$H$ curve further supports the concept that plastic deformation of the vortex lattice has taken place near $H_p$.

The characteristics of the noise spectrum around the peak in $S_v(H)$ have also been examined. The results are similar to those obtained previously for the noise spectra around the peak in $S_v(T)$ (results are not shown here). For instance, near $H_{p1}$ (point A′ in figure 4), the noise spectrum shows some broad peaks superposed upon a background having an exponential-law characteristic, similar to the result shown in figure 2(a), suggesting a correlated vortex motion for this state. As $H$ increases to near $H_p$ (see point B′ in figure 4), the spectrum changes into a power-law behaviour. The correlation dimensions for the noise data at points A′–C′ are shown in the inset of figure 4: these have similar characteristics to those shown in figure 3, that is, the noise data are highly correlated at point A′ but nearly random at point C′; the noise data at point B′ is correlated but the correlation is smaller than that at point A′. These results are consistent with those of $S_v(H)$ and $I_c(H)$, which further confirms that the vortex motion is highly correlated at the early stage of vortex lattice melting, then changes into an extended dissipative motion with self-organized criticality, and finally becomes completely random motion.

In conclusion, we report on an analysis of the asymptotic power spectrum of the voltage noise for Bi-2212 single crystals. We find that the vortex motion is highly correlated at the early stage of vortex lattice melting, then changes into an extended dissipative motion with self-organized criticality, and finally becomes completely random motion. There is a wide range of magnetic fields for which plastic deformation of the vortex lattice exists, and this plays a significant role in the origin of the noise peak in $S_v(T)$ and $S_v(H)$ curves as well as collective pinning for the Bi-2212 crystals.

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