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Reply to "Comment on 'Anomalous peak in the thermopower of $YBa_2Cu_3O_{7-\delta}$ single crystals: A possible fluctuation effect' "

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Howson *et al.* reported measurements of the thermopower using an ac optical heating technique. In this reply we show how the signal measured in this experiment is proportional to only the thermopower of the $YBa_2Cu_3O_7$ sample with respect to the Pb reference leads. The argument of Logvenov *et al.* that the signal has a contribution from the derivative of the thermopower, is shown to be incorrect.

In the experiment of Howson *et al.*[1] a flashing light source is used to heat a single-crystal sample of $YBa_2Cu_3O_x$ and a small dc temperature gradient is established. The hot end of the sample also has a small dc temperature oscillation at the same frequency as the flashing light source. The cold end of the sample is attached to a copper heat sink via the thick Pb lead referred to as thermal resistance R_1 by Logvenov *et al.* It is assumed that the cold end of the sample is at the fixed temperature of the heat sink. A lock-in detects the thermal emf generated at the first harmonic frequency of the flashing light.

Logvenov *et al.* argue that there are two components to the signal at the first harmonic frequency: one proportional to the thermopower and one proportional to the derivative of the thermopower. In fact, there is an error in their argument and we will show that the signal we measure is proportional to the thermopower only. The error arises because due account has not been taken of the spatial dependence of the thermopower along the crystal because of the temperature gradient. In Eq. (7) Logvenov *et al.* explicitly refer to $S(T_0)$ and $(\partial S/\partial T)_{T_0}$ where T_0 is some time-averaged temperature. In fact, since he has changed his integration variable to x, these should be $S(T(x))$ and $(\partial S/\partial T)|_{T(x)}$. Once the integral over x is carried out, the $\partial S/\partial T$ term at the frequency ω is then proportional to $S(T_0)$.

To see how the signal depends on the thermopower more clearly it is simple enough to evaluate the measured signal

$$V(t) \equiv \int_{T(t)}^{T'(t)} S(T)dT \ , \tag{1}$$

where $T'(t)$ refers to the temperature of the "hot" end of the crystal and $T(t)$ refers to the temperature of the "cold" end. Both depend on time t so that

$$T(t) = T_0 + \delta T \sin(\omega t) \quad \text{and} \quad T'(t) = T'_0 + \delta T' \sin(\omega t) \ . \tag{2}$$

At this point, Logvenov *et al.* change the integration variable to x but forget to write $S(T(x))$. However, if we simply write the indefinite integral as

$$v(T) = \int S(T)dT \ , \tag{3}$$

then Eq. (1) becomes

$$V(t) = v(T'(t)) - v(T(t)) \ . \tag{4}$$

Then Eq. (4) can be Taylor expanded using Eq. (2) to give

$$V(t) = [v(T'_0) - v(T_0)] + \left[\left[\frac{dv(T)}{dT} \right]_{T=T_0} \delta T' \sin(\omega t) - \left[\frac{dv(T)}{dT} \right]_{T=T_0} \delta T \sin(\omega t) \right] \ , \tag{5}$$

which reduces to

$$V(t) = \int_{T_0}^{T'_0} S(T)dT + [S(T'_0)\delta T' \sin(\omega t) - S(T_0)\delta T \sin(\omega t)] \ . \tag{6}$$

Here the first term is the dc component and the other two terms are the ac components. The second term arises because of the oscillating "hot" end while the third term arises if the temperature of the "cold" end is not fixed. The terms which depend on $\partial S/\partial T$ appear at the second harmonic and so are not detected by the lock-in. It is possible to pick up $\partial^2 S/\partial T^2$ from the $\sin^3(\omega t)$ term in the Taylor expansion which when factorized gives a $\sin(\omega t)$ contribution but this third-order term is likely to be too small to be important.

As regards to the temperature of the cold end of the sample, we believe, in fact, that it is fixed at pretty close to the heat sink temperature. There are two reasons for thinking this. The first point is, and this point was not made in the original paper, the sample is surrounded by half an atmosphere of helium exchange gas and thus the temperature decays exponentially along the crystal because the greater fraction of the heat absorbed by the crystal is transmitted to the helium exchange gas by conduction and convection. Only a very small fraction is conducted along the crystal to the cold end. If the thermal conductivity of the crystal is 5 W/mK and the heat transfer coefficient from the crystal to the surrounding helium gas is about 10^3 W/Km^2 then the exponential decay length is about 100 μm, this is about a tenth of the

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length of the crystal. The second point is that the ratio of the thermal resistance of the crystal to the thermal resistance of the Pb lead is about 500. Both these points help to ensure that the temperature of the cold end of the crystal is as near constant as possible.

Why this peak has not been seen in other work using a dc method is an interesting question. Logvenov *et al.* argue that Ri *et al.*[2] have measured the thermopower to a similar precision as ourselves using a dc method and do not see a peak.

It would be extremely difficult to make dc measurements with temperature gradients this small. The signal would be of the order of 10 nV. This level of precision along with high-quality samples are necessary to observe this peak.

Thus we are confident that our measurements of the thermopower are correct. The fact that we see a peak in the thermopower close to T_c is not an artifact of the ac technique. However, whether it is a fluctuation effect is open to controversy. Recently, we published data for the thermopower of an untwinned crystal.[1] We found the thermopower to be of opposed sign in the two crystallographic directions: positive in the "*a*" direction and negative in the "*b*" direction. The peak was only clearly seen in the "*a*" direction. We argued that this could be due to differences in the coherence length in the "*a*" and "*b*" directions. However, the very fact that the thermopower is opposite in sign could itself lead to peaks at T_c through a cancellation effect if the slopes of the thermopowers are different in the two directions. This could easily happen in the twinned crystals where the two thermopowers are in series. However, for an untwinned crystal it would need a significant misalignment of the crystal to produce a peak. We are looking at this at the moment.[3]

In summary we have shown that the Logvenov argument is incorrect and the measured signal only depends on the thermopower at the frequency ω. There is no contribution from $\partial S/\partial T$. We have also suggested that this peak was not been observed in dc measurements of the thermopower because the temperature gradient used is over an order of magnitude greater than that used in our ac technique.

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[1] M. A. Howson *et al.*, Phys. Rev. B **41**, 300 (1990); see also, A. J. Lowe, S. Regan, and M. A. Howson, *ibid.* **44**, 9757 (1991).

[2] H.-C. Ri *et al.*, Phys. Rev. B **43**, 13 739 (1991).

[3] A. J. Lowe, S. Regan, and M. A. Howson, J. Phys. Condens. Matter **4**, 8843 (1992).