# Reply to ''Comment on 'Observation of vortex-lattice melting in $YBa_2Cu_3O_{7-\delta}$ by Seebeck-effect measurements' ''

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The rapid rise in the Seebeck effect that we observed in single crystals of YBCO in the mixed state was interpreted by us [H. Ghamlouch, M. Aubin, R. Gagnon, and L. Taillefer, Phys. Rev. B **54**, 9070 (1996)] as a manifestation of vortex-lattice melting. We maintain this interpretation despite the skepticism of the Comment [M. Ausloos, H. Bougrine, M. Houssa, and M. Pekala, Phys. Rev. B, preceding paper] who suggest that percolation or even experimental artifacts may be responsible. We point out the studies on various types of YBCO single crystals studied by our technique which all yielded plausible results. Recalling the resistivity measurements of Fendrich *et al.* we argue that percolation, if relevant in our measurements would only exist over ~160 mK and would be hidden in the observed transition. We also present as yet unpublished Nernst effect results as suggested by Ausloos *et al.* which corroborate our earlier interpretation.
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The Comment by Ausloos *et al.*[1] at times broadens the discussion to points more general than those directly related to the paper and one can only agree with those sections. On the other hand, the Comment questions the validity of our observation[2] as well as our interpretation of the jump in the Seebeck effect of YBCO single crystals as being due to vortex-lattice melting and proposed Nernst effect measurements to clarify the situation. New arguments will be presented to reinforce our case. We even have (as yet unpublished) Nernst effect data as proposed in the Comment. These are presented below and confirm our earlier interpretation.

We recall that the Seebeck effect measurements in question were performed on high quality untwinned single crystals of YBCO in the presence of various magnetic fields. Our technique is an ac one[2,3] allowing a small temperature gradient due to its high sensitivity. We observed a rapid initial increase of the Seebeck coefficient $S$ with temperature, a phenomenon which we attributed to vortex-lattice melting. This rapid initial rise was studied as a function of magnetic field with the aim of constructing a phase diagram of the melting transition. A consistent criterion was required to determine the melting temperature since the results of several $S(T)$ curves would be compared. We chose the maximum of the derivative of each curve for lack of a better criterion. This amounts to defining the lattice melting temperature as being near the midpoint of the steep region of $S(T)$, a choice which is contested by Ausloos *et al.* and we acknowledge that they are right. But since the width of the transition varies from 0.25 to 0.75 K depending on the magnetic field, the error in absolute value is minimal. In any case, the absolute value of the temperature read in a Seebeck effect measurement cannot be precise due to the existence of a temperature gradient. Relative temperature values are however more reliable. Finally, the effect on the phase diagram is imperceptible since one normally plots the melting field versus reduced temperature $t_m = T_m/T_c$ as in Fig. 3 of Ref. 2 and any discrepancy due to our criterion is much smaller than the size of the points illustrated in the diagram. Here $T_m$ and $T_c$ are the melting and critical temperatures, respectively.

The Comment also suggests that our observed transition may be a manifestation of percolation rather than melting. A review of recent literature reveals that very few authors discuss percolation in the context of high $T_c$ superconductors. Numerical simulations were used[4] to show in these materials the relation between the onset of the $c$-axis resistivity and the percolation transition of vortex lines in the ab plane. Some of the authors of the Comment drew phase diagrams of the percolation temperature following Seebeck effect and resistivity measurements[5] on Bi/Pb2223 ceramics. The only experimental work concerning percolation in the $a$-$b$ plane of single crystals we found in the literature was by Fendrich *et al.*[6] who performed resistivity (and simultaneous magnetization) measurements on untwinned YBCO. At very low currents, they observe a resistanceless temperature interval of 160 mK at the beginning of the melting process which they interpreted as a percolation region. Such an interval is too small to be observed in a Seebeck effect measurement in which a temperature gradient must be applied. Even our sensitive ac technique required a temperature difference across the sample approximately equal to the reported 160 mK percolation interval which therefore could not be detected. In the $c$-axis direction one may speak of intrinsic Josephson junctions between adjacent planes.[7]

The fact that the jump in the Seebeck effect has not been seen by ''any other author'' is not surprising. Our results were the first (and are still the only ones reported) on high quality untwinned single crystals of YBCO in the presence of a magnetic field. Our technique is also unique with its relatively small temperature gradient which does not wash out all structure in the superconducting transition. It is true that ac Seebeck effect measurements have given rise to anomalous peaks[8] in YBCO which were later attributed to the technique[3,9,10] [heating only one end of the sample leads to a peak proportional to the derivative of the $S(T)$ curve as one may show mathematically; similarly one may show that heating both ends alternatively as in our case, eliminates the artificial peak]. Even a dc technique yielded anomalous peaks but these were due to inhomogeneities in non-fully oxygenated polycrystalline samples.[11] The latter are labeled as nonintrinsic defects by Mosqueira *et al.*[11] contrary to Ref. 1. Our technique has been applied to various types of YBCO single crystals, heavily twinned,[12] unidirectionally twinned,[13] untwinned but measured in the *a* and *b* directions.[2] The results were different in each case with a plausible explanation so that the technique may be considered reliable.

Ausloos *et al.*[1] were initially surprised by the high value of $T_c$ considering the apparent positive sign of $S$. They acknowledge our private communication in which it was pointed out that the reported data represented absolute values. This was inevitable with an ac technique but we should have pointed out this more clearly in the text. A follow-up dc measurement did indicate that $S$ is indeed negative in this sample.

Reference 1 suggests that Nernst effect measurements could constitute a better tool to investigate the transition. In particular the fine structure could help characterize the melting process. We have such data taken from a similar sample although it was not completely detwinned. These were acquired by an ac technique as in our Seebeck effect measurements. These results are still unpublished and appear in Fig. 1. The Nernst signal rises very rapidly from zero over 0.5–0.6 K at 3 and 5 T and then rises more slowly to its maximum. This could be compared to the initial slow rise at 4 T for the Bi/Pb 2223 ceramic[5] followed by a more rapid rise to the maximum. In that case, the Comment seems to imply that the initial increase is due to a moving solid. But in Fig. 1 we observe initially a rapid increase which must be interpreted as lattice melting.

It is also mentioned in Ref. 1 that it is not trivial to distinguish between vortex motion dissipation and quasiparticle scattering. This may be the case but in Ref. 14 that is cited, the latter contribution increases gradually with temperature and not suddenly as in our data.

Finally, we note that we performed measurements of resistivity, Seebeck and Nernst effects on a sample similar to that discussed in the paper and that a jump was observed in each case. If our Seebeck technique were at the origin of an anomaly, it is highly unlikely that it would appear in a similar fashion in all three measurements. On the other hand, as mentioned above, measurements made on other types of YBCO single crystals exhibited different behaviors which have been interpreted in a coherent manner. Ausloos *et al.*[1] mention the possibility of a transition from a static lattice to a moving lattice upon increasing the temperature. They may have in mind the resistivity curves of Fendrich *et al.*[6] on YBCO single crystals discussed above and which revealed such a behavior at high currents but at low currents an extremely narrow resistanceless percolation region appeared followed by a sharp rise at the end of the melting process. The latter case (low current) approaches that of Seebeck effect measurements which involve no transport current and one can dismiss the moving solid idea but accept the possibility of a narrow percolation region followed by melting, all within a fraction of a degree. Thus percolation, if it exists in our measurements, is hidden in the width of our quoted melting transition.

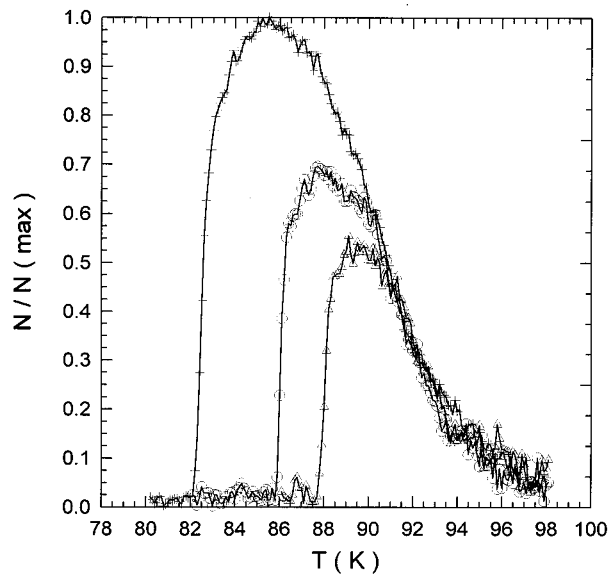


FIG. 1. Normalized Nernst effect of a YBCO single crystal along the *b* axis as a function of temperature for magnetic fields of 2, 3, and 5 T (from right to left).

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