Reply to “Comment on ‘Dephasing of conduction electrons due to zero-point fluctuation’ ”

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We point out that the central theme in the paper by Wang, Xiong, and Wang [Phys. Rev. B **61**, R5090 (2000)] is the inseparability of electron degrees of freedom and those of electromagnetic field (EMF). The dephasing of conduction electrons due to zero-point fluctuation (ZPF) of EMF is because experiments probe electron degrees of freedom only. The treatment of ZPF of EMF in the above paper is oversimplified, and a proper handling of the effects of electron-EMF coupling is required.

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The preceding comment² by Wu and Lin questions the possibility of zero-temperature dephasing of conduction electrons, in particular, that by the zero-point fluctuation (ZPF) of electromagnetic field (EMF). Wu and Lin reached their conclusion simply after they realized that we, unfortunately, used the electron-diffusion constant given in the paper by Mohanty *et al.*³ Its value, due to an error, is too large for a typical disordered metal.

In the Rapid Communication¹ under discussion, we proposed a zero-temperature dephasing mechanism for conduction electrons based on ZPF of the EMF in vacuum and the electron-EMF interaction through Aharonov-Bohm (AB) phase. It is well known that electron degrees of freedom cannot be separated from that of an EMF. This means that an electronic state cannot be a true eigenstate of a system because electrons by themselves do not form a closed system. This point has also been made in other work.⁴ Many fundamental physics phenomena such as the spontaneous emission and the Casimir force are due to the electron-EMF interaction. For example, an excited electronic state in a system is not a true eigenmode of the system because of this interaction. Thus, the ZPF of the EMF can induce electron transitions from the excited state to lower energy states (the spontaneous emission). At the ground state, the system energy cannot be lowered further because the system has no place to go, but the values of other observables might change through the interaction. According to quantum mechanics, all observables are expectation values of Hermitian operators. Due to the electron-EMF coupling, an electron phase alone cannot be the eigenvalue of the phase operator. The meaning of an electron phase in classical sense is clear. Ironically, its operator form in quantum mechanics is still unknown. A beautiful discussion on this subject can be found in a recent book⁵ by Mandel and Wolf, *Optical Coherence and Quantum Optics*. The lack of an exact definition of the phase operator fails our attempts to have a fully quantum-mechanical treatment of the electron phase. But it shows that, the argument that electron-EMF interaction has no effect on the electron phase

is oversimplified.

With the above general remarks on the electron-EMF interactions, let us come back to the second critique of the preceding comment about our work.¹ Obviously, the issue of discussion is more on the technicality of the proper way of handling the coupling rather than the principle of our approach. In Ref. 1, we treated EMF as a classical field, and the EMF affects an electron through adding the AB phase to the electron. We assumed that the vector potential **A** is spatially uncorrelated for mathematical convenience. To be sure, the ZPF of EMF in metals does not satisfy this assumption. A more severe problem is on the spectrum of EMF in a metal. We know that low-frequency EMF modes are not allowed in a good metal. Thus, there is no ZPF of such low-frequency EMF modes in a metal. However, it is assumed in Ref. 1 that a mode of arbitrary frequency can dephase an electron. Therefore, it is not surprising that electron dephasing by the ZPF of EMF has been greatly overestimated in Ref. 1. We believe that the issue should be on how to calculate correctly the effects of the ZPF of an EMF in a metal on electron dephasing, and how large this effect is.

In conclusion, the treatment of vacuum fluctuation of the EMF in Ref. 1 is oversimplified. The preceding comment reveals that our simple-minded consideration of zero-point motion of EMF is not enough. The issue of possible dephasing of electrons due to the fluctuating EMF is still there. One should distinguish the technicality of calculation with the principles of dephasing due to the interaction between an electron and zero-point motion of EMF.

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