Comment

Comment on: The interpretation of room-temperature superconductivity experiments in LK-99

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In their recent manuscript [1], Lee *et al.* have claimed the experimental demonstration of superconductivity at the ambient pressure and temperatures well above the room temperature. The Meissner effect manifested by a magnetic levitation has been demonstrated by the same group in the follow-up paper [2]. These studies have attracted a tremendous interest. If confirmed, the discovery of room temperature superconductivity would become one of the major scientific events of the XXIst century. Tens of laboratories are now busy repeating the experiments of Lee *et al*. Every day brings new comments and discussions around these findings.

So far, the comments from the scientific community to the new findings are controversial: while some groups have confirmed zero resistivity (although at Lower Tc) [3] and magnetic levitation in LK-99 [4], other groups while succeeded in the synthesis of the LK-99 structure could not detect superconductivity and could find only the diamagnetism and magnetic phases transitions [5]. Zhu et al [16] performed a set of conductivity and magnetic susceptibility measurements on a system very similar to LK-99 and observed a hysteresis behaviour at high temperatures which they interpreted as the first order phase transition between two crystal phases. They did not observe zero resistivity and they conclude against superconductivity. Still, the failure of other groups to immediately reproduce the effect observed in a polycrystalline material with a complex morphology such as LK-99 cannot immediately conclude the issue, and the interesting physics revealed by LK-99 needs to be properly understood in any case.

Here we address some of the issues that need to be clarified, and especially we focus on:

i) the experimental methods for precise measurements of the superconducting T_c in case of small superconducting fraction in LK-99, in metallic and insulating matrices,

ii) the theoretical interpretation of the observed phenomena in the framework of the newly suggested hybrid exciton-phonon mechanism of pairing in superconducting quantum wells.

Low magnetic field microwave absorption (LFMA) as an ultrasensitive test for superconductivity

It is crucially important to characterise LK-99 using most sensitive ultimate test for superconductivity, namely, the LFMA (also referred to as MMMA) known since the discovery of high temperature superconductivity (HTSC) [6–8] and recently used for search of multiphase superconductivity in Pnictides [9] and even in meteorites [10].

This LFMA (MMMA) test is easily performed in either usual electron spin resonance (ESR) spectrometer or in an even simpler set-up where temperature is scanned through Tc in a microwave cavity placed in the magnetic field [10]. LFMA is more sensitive than SQUID and it enables one to detect T_c (or several T_c in multiphase SCs) in nanogram or cubic nanometer amounts of the superconducting (SC) phase in any non-SC matrix.

Surprisingly, while the authors of [1] have used the ESR spectroscopy, they did not study LFMA. Although Fig. 3, (g,f) of Ref. [1] shows ESR spectra measured across a wide range of fields, all the measurements are done in the temperature range below the claimed T_c. The emergence of a strong LFMA signal in the vicinity of T_c has not been reported. The published ESR spectra

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1369-7021/ https://doi.org/10.1016/j.mattod.2023.08.008

are confusing and actually misleading, since the observation of g = 2 signal at the magnetic field of H = 3500 Oe is the proof of a normal phase which microwaves easily penetrate (while in the SC phase microwaves are screened and g = 2 signal is suppressed).

The new "Exciton-Phonon hybrid pairing" theoretical model for the interpretation of high T_c in QW structures

Several theoretical groups confirmed by ab-initio calculations the formation of nearly flat bands at the Fermi level in LK-99 and a similar material doped with gold [11]. Flat bands ensure high electronic densities of states that are paramount for the enhancement of Cooper pairing within the Bardeen-Cooper-Schrieffer (BCS) mechanism of superconductivity. We believe, this is a strong argument in favour of the room-temperature superconductivity in LK-99. Still, the key questions remains to answer: what binds electronic pairs together in this material? Why the extremely high critical temperature coexists with modest critical current and critical magnetic field?

The interpretation of the remarkable properties of LK-99 given in Ref. [2] is based on the Brinkman-Rice-BCS (BR-BCS) model that implies formation of strongly bound small size electronic pairs due to the correlation induced charge density wave (CDW). We argue that this interpretation cannot explain the full variety of the presented data. In particular, strongly bound Cooper pairs are expected to resist magnetic fields up to several tens of Tesla, while the experimentally detected critical magnetic fields are well below 1 T, which is a signature of weakly bound Cooper pairs, like those in conventional BCS superconductors. However, the conventional phonon BCS mechanism would result in the critical temperature of superconductivity T_c well below the Debye temperature T_D, while in the present experiment T_c appears to be very close to T_D.

Our hypothesis: These inconsistencies may be circumvented if the phonon BCS coexisted with a different mechanism of Cooper pairing such as the exciton mechanism. The exciton mechanism proposed in 1970 s by Allender, Bray and Bardeen [12] and further advocated by Ginzburg [13] has been recently revisited in the context of the discovery of the Bose-Einstein condensation of exciton-polaritons at the room temperature [14,15]. We note that, as follows from the schematic band structure shown in Fig 3e of Ref. [1], LK-99 may sustain a significant concentration of excitons that are dipole-polarised along the superconducting quantum well (SQW) potential. These excitons would be created by electrons thermally excited to the size-quantized state of the SQW just above the Fermi level and holes from below the Fermi level, see the scheme in Fig. 1. If, as Lee *at al* suggest [2], the superconductivity in LK-99 is of a hole-type, the excitons would be created by holes excited above the hole Fermi level and electrons situated below the hole Fermi level. In both scenario, electron and hole envelopes would be given by eigen functions of the effective potential having an approximately triangular shape (see Fig. 1), i.e. by Airy functions. The electron and hole mass centers would be separated in real space, which is why excitons formed by them would possess significant dipole moments. It may also happen that while one type of the carriers (electrons or holes) remains confined in the SQW, the other type may be delocalised and rather situated in one of the barrier regions. This would also result in excitons with very large dipole moments. Due to these large dipole moments, the excitons may efficiently interact with free electrons (free holes). They would act as binding agents for Cooper pairs in the same way as phonons do, see the diagram in the inset to Fig. 1. The interplay between the exciton and phonon mechanisms of Cooper pairing may lead to the exponential enhancement of T_c as shown in [15]. Based on the formalism developed in Ref. [15] we performed simple estimations that yield the critical temperature, critical current and critical magnetic field close to the experimental values if the effective cut-off temperature characteristic of the exciton mechanism for superconductivity is significantly (couple of orders of magnitude) lower than the Debye temperature. We believe, this is very likely, as the excitonic dispersion in an SQW must be nearly flat, similar to the electronic dispersion [11]. We conclude that superconductivity in LK-99 may be a result of the interplay between the exciton and phonon BCS. In order to check this hypothesis we propose to measure the transmission spectrum of a thin film of LK-99 in the terahertz frequency range. Exciton resonances would strongly manifest themselves in these spectra. Combined with the proposed LFMA measurement, this would yield a comprehensive picture of the new phases in LK-99.

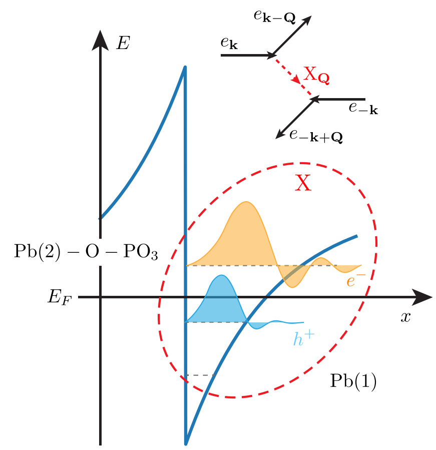

FIG. 1

Schematically shows the potential of asuperconducting quantum well (SQW) adapted from Fig. 3e of Ref. [1]. The energy quantization levels of the SQW and the wave functions of the would be highest occupied energy level (HOEL) and lowest unoccupied energy level (LUEL) at zero temperature are shown. An exciton (X) formed by an electron and a hole situated at HOEL and LUEL would play role of a binding agent between two electrons (two holes) situated at the Fermi level as the diagram in the inset shows. Such an exciton would be kicked by a first Fermi level electron (hole) to the virtual Q-state and then would return to its ground state passing the wave-vector Q to another electron (hole) of the pair.

Data availability

No data was used for the research described in the article.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Further reading

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