Journal Club for Condensed Matter Physics DOI:10.36471/JCCM_March_2022_03
https://www.condmatjclub.org

Flux Quantization Cubed

Discovery of charge-4e and charge-6e superconductivity in kagome superconductor CsV_3Sb_5

Authors: Jun Ge, Pinyuan Wang,Ying Xing, Qiangwei Yin, Hechang Lei, Ziqiang Wang, Jian Wang

arXiv:2201.10352

Recommended with a Commentary by Chandra Varma, University of California, Berkeley -Visitor.

What a wonderful life we have as condensed matter physicists to be handed a big surprise by experiments every few years! The latest are provided by experiments in the recently discovered [1] compound CsV_3Sb_6 in an extended fluctuation regime above the superconducting resistivity transition at about 1.1 K. This is a family of compounds in which Cs can be replaced by other alkali atoms, K and Rb. All of them crystalize such that V-ions which provide the metallic states sit on a two-dimensional Kagome lattice. The structure is reproduced in Fig. (1). All these compounds have a transition at high temperatures, varying with different A, near 100 K to a state which breaks translational symmetry so that the low temperature structure has 2×2 unit-cells of the high temperature structure.

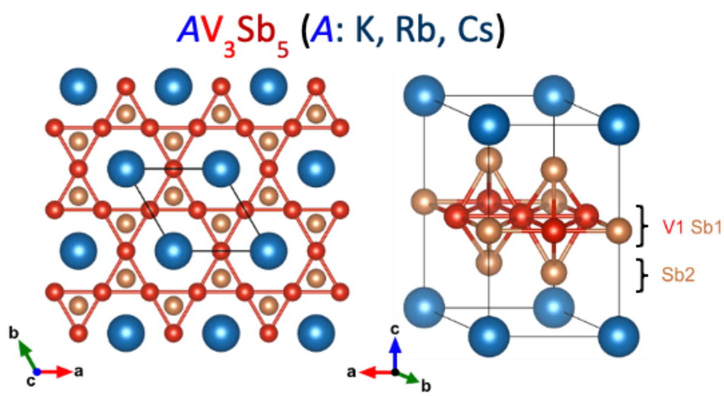

Figure 1: Crystal structure of the compounds CsV_3Sb_6.

This requires that the instability is at three different **Q** vectors which are oriented along the three hexagonal directions of the Kagome lattice. The instability is known through NMR experiments to be not of the spin-density wave type although there is plenty of evidence of time-reversal breaking. These results have been reviewed recently in the Journal club [2]. I will come back to them because they most likely provide the clue to the surprising discovery in the highlighted article.

Jun Ge et al. (article featured above) measured flux quantization in and above the superconducting state, for which they fabricated the geometry shown in Fig. (2), together with the resistivity below about 4 K. A ring with hole of about 200 nm linear dimension joins strips which are similar in size, making it an imperfect Little-Parks interferometer. A magnetic field is applied and the resistivity is measured as a function of flux through the ring. The results at various temperatures and fields are shown in Fig. (3). A Fourier transform of the resistivity with flux at various temperatures is shown also.

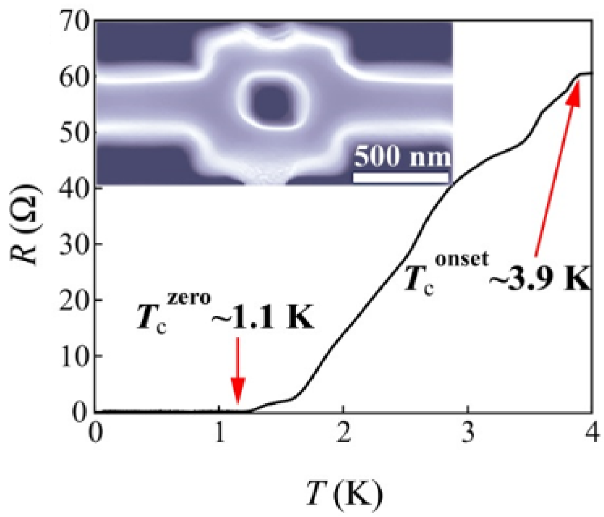

Figure 2: The resistance at zero applied magnetic field below 4 K measured in the geometry shown.

The expected quantization observed in the superconducting state below 1 K is not very impressive in its clarity. It is around the usual charge 2e of the Cooper pair with considerable other structure, as seen in the Fourier transform of the amplitude of the structure in resistivity plotted in Fig. (3-i) as a function of the flux quantums. A large enough field is required to observe it. That is not surprising because the sample has to be close to the superconducting transition to observe resistivity fluctuations as in the Little-Parks experiment. The fact that satellites are observed may be due to interference between different channels, expected because the strips connecting the holes have widths (probably) larger than the coherence length. But there may be more going on there as there are mysterious signals in the Josephson effects observed earlier in STM experiments [3] using a Nb tip. The most impressive results in Fig. (3) are in the region of superconducting fluctuations which appears to be over an unusually large temperature range - resistivity starts dropping fairly rapidly below about 4 K. Clear 6e quantization of the oscillatory part of the resistivity above a positive magneto-resistivity background is observed starting at about 3 K and it is seen starting from 0 field. Its amplitude increases as temperature is decreased. Below some temperatures but still in the fluctuation regime, 4e quantization joins in with complicated satellites around it. Note also the step-like features in the resistivity at zero field shown in Fig. (2). In the superconducting state, only the dirty 2e quantization starting above a magnetic field which sensibly depends on temperature survives.

Nothing like this has ever been observed in any compound before, although 4e quantization has been invoked [3] in relation to specific heat and Seebeck effect above the superconducting transition in $Ba_{1-x}K_xFe_2As$, and feeble effects associated with equally feeble charge density waves in some cuprates [4] well above the superconducting transition. However, the theoretical idea in the supplementary section of Ref. [3] may be of interest in the present context. Worth knowing also are the symmetry considerations given in Ref. [5]. Of direct

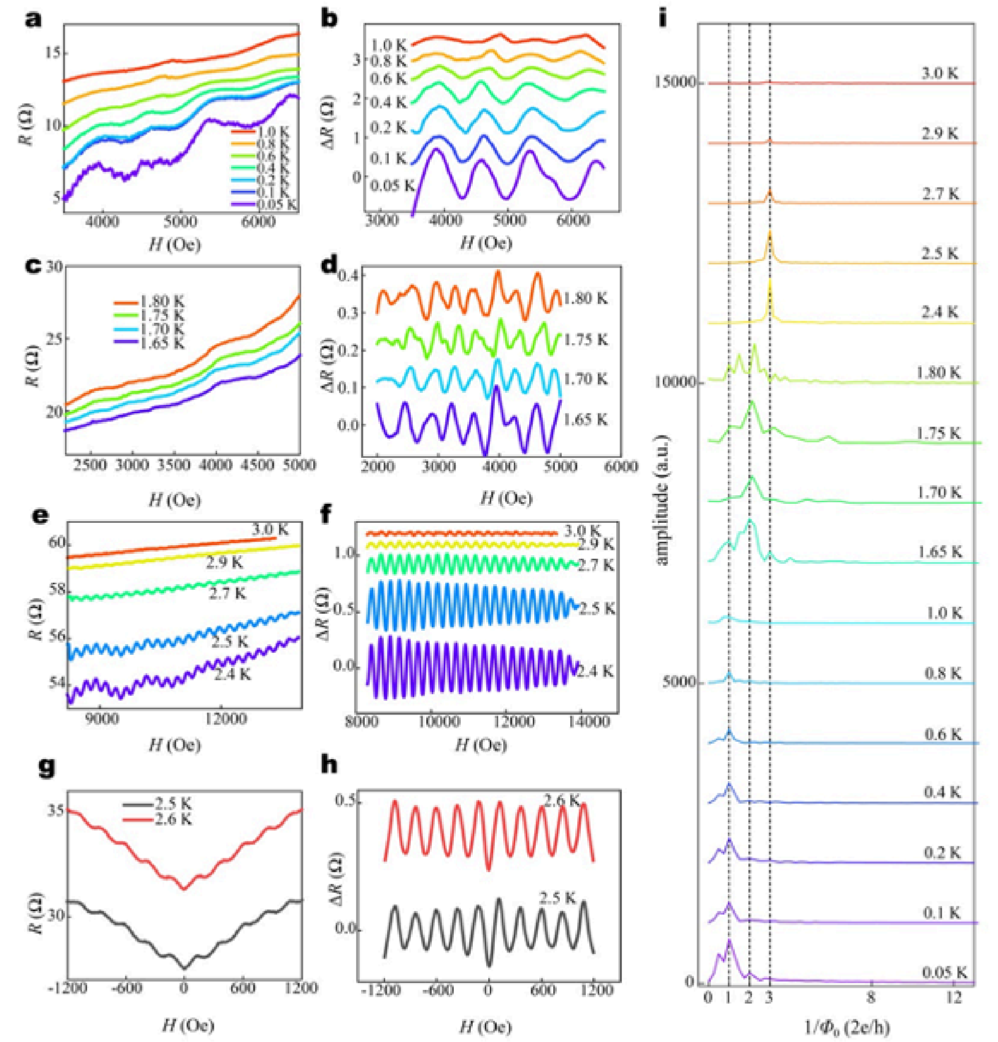

Figure 3: The principal experimental results in the featured article. (**a**) to (**h**) show the magneto-resistance (R the total resistance and ΔR after removing the uniform background) at various temperatures below and above the superconducting transition at about 1.1 K. (**i**) is the Fourier transform of the amplitude of the oscillatory signal as a function of the Cooper pair flux quantum.

interest is Ref. [6].

What could possibly be going on? For mysteries of superconductivity, one must look always to going-ons in the normal state. There is evidence from the large anomalous Hall effect, through magnetic field dependent chirality observed in STM experiments, through Kerr effects and muSR measurements that the translational symmetry breaking is accompanied below the high temperature transition or below it with loop-currents, as a generalization of what was proposed for the cuprates. (For references to these, please see [2]. It should be added that some of these experimental results are contested.) Mean-field calculations suggest [6] that in the electronic structure of the Kagome lattice, such states are favored. The Kagome structure, if only the nearest neighbor transfer is considered, provides a band with flat dispersion at the edge of the metallic states and van Hove singularities inside. In the same approximation, the states near the van-Hove singularities have interference effects such that the on-site interactions are negligible compared to next neighbor interactions [7]. The van Hove singularity persists for more general kinetic energy and it is reasonable that in the more general model the nearest neighbor interactions remain more important. Nearest neighbor interactions favor instability to loop-currents. In the models proposed, each of the three $\mathbf{Q}$ vectors for translational symmetry breaking has a phase factor [5]. Is it possible that any of the simple Cooper pairing of the quasi-particles of such states as a leading instability is not favored in relation to other states because of the interference of such phases or other energetic reasons. A wave-function with product of three Cooper pairs may be chosen not to have such an obstruction? Can 6e superconductivity itself only exist in a fluctuating state and not be able to condense? How does ordinary Cooper pairing re-assert itself at lower temperatures.

The experiments raise these and many more questions. At this point more experiments would be very helpful. At the present, the normal states with different A atoms appear not to be behave identically in experiments, and the flux quantization experiments have been done only in the Cs compound?

I wish to thank Ziqiang Wang for very helpful discussions.

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