Superconductivity in Al-Zn-Mg quasicrystal

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Quasicrystal is expected, due to its unique geometry, to have an electronic state called critical state that is neither extended nor localized. This unique eigenstate emerges as a result of the competition between the broken translational invariance and the self-similarity of quasiperiodic structure. Besides extensive studies, the electronic state of quasicrystals is veiled in mystery. For example, no long-range-ordered state of electronic origin is established yet; to the best of our knowledge, there is no quasicrystal showing the long-range ordering such as ferromagnetism and superconductivity. Especially, superconductivity is an extraordinary phenomenon that occurs at low temperatures. It is therefore interesting to discover superconductivity in quasicrystal.

To present the convincing evidence for the emergence of superconductivity, we need to show not only zero resistance but also Meissner effect. To further evidence that the superconductivity is of bulk origin, we need to show the heat capacity jump at the transition temperature. Here we review our first observation of bulk superconductivity in Al-Zn-Mg quasicrystal [1]. The geometric structure of the Al-Zn-Mg alloy depends on the ratio of the three constituent elements. When reducing the Al content while keeping the Mg content almost constant, we confirmed that the alloy remains to be an approximant crystal, and further that, at 15% Al, the system transformed into a quasicrystal [1,2]. (A quasicrystal was previously reported to become superconducting, but it was later shown to be an approximant crystal, thus it is important to examine whether the material studied is an approximant or quasicrystal [1]. For this purpose, we carried out X-ray and electron diffraction experiments, and we actually confirmed the fivefold rotational symmetry for our quasicrystalline samples.) For the superconductivity, we found that all of the approximant crystals show bulk superconductivity at low temperatures; the transition temperature T_c decreases gradually from ~0.8 to ~0.2 K. At the critical concentration mentioned above, where the quasicrystal is formed, we observed that T_c goes down to ~0.05 K. This was the first report on the emergence of superconductivity, a typical example of the electronic long-range ordering, in quasicrystal.

In Fig.1, we show the relation between the superconducting transition temperature T_c and the inverse of the electronic specific heat coefficient γ for the Al-Zn-Mg quasicrystal. (Note that γ is proportional to the density of states at the Fermi energy $D(E_F)$.) We observe the linear relation between them, i.e., $\ln T_c \propto 1/\gamma$, for all the materials studied here, including the approximant and quasicrystal. According to the BCS theory of superconductivity, this indicates that the effective pairing interaction between electrons is kept attractive and its magnitude is invariant when the system is varied from the periodic to quasiperiodic crystals.

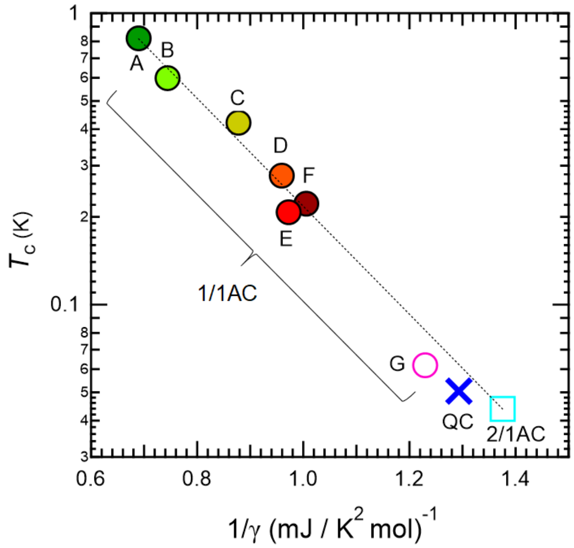

Figure 1. Correlation between the superconducting transition temperature T_c and the inverse of the electronic specific heat coefficient γ for the Al-Zn-Mg quasicrystal and its approximant crystals [1]. "A" to "G" denotes the 1/1 approximant crystal, "2/1AC" denotes the 2/1 approximant crystal, and "QC" indicates the quasicrystal.

The extremely low T_c of the quasicrystal explains why superconductivity in quasicrystals has proven so hard to achieve, and also shows that the quasicrystal has the low γ, i.e., the low $D(E_F)$. This low density of states at the Fermi energy can be ascribed to the pseudogap formation in the quasicrystal.

The observation of superconductivity in the quasicrystal raises an interesting question of whether the emerging superconductivity shows a weak-coupling, spatially extended Cooper pair or a strong-coupling, local pair (reflecting the possible critical state). We found that temperature dependences of the thermodynamic properties and the upper critical filed are understood within the weak-coupling framework of BCS theory [1], suggesting the formation of spatially extended pairs. However, this does not necessarily mean that the superconducting state of the quasicrystal is the same as that of periodic crystals. According to the recent theoretical study [3], the paring state of quasicrystal is expected to differ from the conventional Cooper pairing of the BCS theory. This novel superconductivity, which we call *fractal superconductivity*, may open the door to a new type of superconductivity.

1. K. Kamiya, T. Takeuchi, N. Kabeya, N. Wada, T. Ishimasa, A. Ochiai, K. Deguchi, K. Imura, N. K. Sato, *Nat. Commun*. **9**, (2018) 154.

2. T. Takeuchi and U. Mizutani, *Phys. Rev*. B **52**, (1995) 9300.

3. S. Sakai, N. Takemori, A. Koga, R. Arita, *Phys. Rev*. B **95**, (2017) 024509.