Controlling unconventional superconductivity in artificially engineered $f$-electron Kondo superlattices

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Unconventional superconductivity and magnetism are intertwined on a microscopic level in a wide class of materials, including high-$T_c$ cuprates, iron pnictides, and heavy-fermion compounds. A new approach to this most fundamental and hotly debated subject focuses on the role of interactions between superconducting electrons and bosonic fluctuations at the interface between adjacent layers in heterostructures. A recent state-of-the-art molecular-beam-epitaxy technique has enabled us to fabricate superlattices consisting of different heavy-fermion compounds with atomic thickness. These Kondo superlattices provide a unique opportunity to study the mutual interaction between unconventional superconductivity and magnetic order through the atomic interface. Here, we design and fabricate hybrid Kondo superlattices consisting of alternating layers of superconducting CeCoIn$_5$ with $d$-wave pairing symmetry and nonmagnetic metal YbCoIn$_5$ or antiferromagnetic heavy fermion metals, such as CeRhIn$_5$ and CeIn$_3$. In these Kondo superlattices, superconducting heavy electrons are confined within the two-dimensional CeCoIn$_5$ block layers and interact with the neighboring nonmagnetic or magnetic layers through the interface. In CeCoIn$_5$/YbCoIn$_5$ superlattices, the superconductivity is strongly influenced by the local inversion symmetry breaking at the interface. In CeCoIn$_5$/CeRhIn$_5$ and CeCoIn$_5$/CeIn$_3$ superlattices, the superconducting and antiferromagnetic states coexist in spatially separated layers, but their mutual coupling via the interface significantly modifies the superconducting and magnetic properties. The fabrication of a wide variety of hybrid superlattices paves a new way to study the relationship between unconventional superconductivity and magnetism in strongly correlated materials.

I. INTRODUCTION

Superconductivity found in several classes of strongly correlated electron systems, including cuprates\[1,2\], iron pnictides/chalcogenides\[3,4\] and heavy fermion compounds\[5,6\] has attracted researchers over the past three decades. There is almost complete consensus that superconductivity in these systems cannot be explained by the conventional electron-phonon attractive pairing interactions \[5,6\]. As the superconductivity occurs in the vicinity of the magnetic order, it is widely believed that magnetic fluctuations, which arises from purely repulsive Coulomb interactions, act as the source of electron pairing. Moreover, the highest superconducting transition temperature $T_c$ is often found near a quantum critical point (QCP), at which a magnetic phase vanishes in the limit of zero temperature, indicating that proliferation of critical magnetic excitations resulting from the QCP plays a significant role in determining superconducting properties \[10,11\]. In these materials, a microscopic coexistence of superconducting and magnetically ordered phases both involving the same charge carriers is a striking example of unusual emergent electronic phases. Despite tremendous research, however, the relationship between superconductivity and magnetism has remained largely elusive.

The strongest electron correlation is realized in heavy-fermion compounds, containing $f$ electrons ($4f$ for lanthanide and $5f$ for actinide), especially in materials containing Ce, Pr, U and Pu atoms \[17,23\]. At high temperature, $f$ electrons are essentially localized with well-defined magnetic moments. As the temperature is lowered, the $f$ electrons begin to delocalize due to the hybridization with conduction electron band ($s$, $p$, $d$ orbital), and Kondo screening. At yet lower temperature, the $f$ electrons become itinerant, forming a narrow conduction band with heavy effective electron mass (up to a few hundred to a thousand times the free electron mass). Strong Coulomb repulsion within a narrow band and the magnetic interaction between remnant unscreened $4f$ or $5f$ moments leads to notable many-body effects, and superconductivity mediated by magnetic fluctuations. The hybridized $f$ electrons are not only responsible for long-range magnetic order, but are also involved in superconductivity. Therefore, the heavy-fermion compounds offer a fascinating playground where magnetism and unconventional superconductivity can both compete and coexist.

Among heavy fermion compounds, CeMIn$_5$ (where $M =$ Co, and Rh) with layered structure are ideal model systems due to their rich electronic phase diagrams in which an intricate interplay between superconductivity and magnetism is observed \[24,26\]. At ambient pressure, CeCoIn$_5$ is a superconductor ($T_c = 2.3$ K) with $d_{x^2-y^2}$-wave symmetry \[27,31\]. The normal state displays non-Fermi-liquid properties associated with a nearby underlying QCP \[32,33\]. In contrast, CeRhIn$_5$ orders antiferromagnetically at ambient pressure ($T_N = 3.8$ K) \[34\]. Its magnetic transition is suppressed by applying pressure and the ground state becomes a purely superconducting state at $P > P \approx 1.7$ GPa, suggesting a possible presence

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of a pressure-induced QCP [11, 13, 35, 39].

It has been shown that interactions between superconducting electrons and bosonic excitations through an atomic interface may have a profound influence on Cooper pairing. For example, when a monolayer FeSe film grown on a SrTiO$_3$ substrate, the coupling between the FeSe electrons and SrTiO$_3$ phonons enhances the Cooper pairing, giving rise to the highest $T_c$ among all known iron-based superconductor, which is almost an order of magnitude higher than that of the bulk FeSe [5, 40–43]. This raises the possibility of a magnetic analog in which the pairing interaction is influenced by magnetic fluctuations though an interface between an unconventional superconductor and a magnetic metal. This concept is illustrated schematically in Figs. 1(a) and 1(b). Besides allowing a new approach to revealing the entangled relationship between magnetism and unconventional superconductivity, this concept has the advantage that magnetic excitations are tunable as a magnetic transition is driven toward zero temperature, unlike phonon excitations in SrTiO$_3$.

In this review, we discuss the recent advances of Kondo superlattices which consist of alternating layers of heavy-fermion superconductor and heavy-fermion antiferromagnet. We focus on mutual interactions between $d$-wave superconductivity and magnetic order through the atomic interface, in particular paying attention to how the pairing interaction is influenced by magnetic fluctuations injected from the neighboring layers through the atomic interface. For this purpose, we have designed and fabricated two types of superlattices formed by alternating atomically thick layers of CeCoIn$_5$ and (1) conventional non-magnetic metal YbCoIn$_5$ and (2) antiferromagnetic (AFM) heavy fermion metals, such as CeRhIn$_5$ and CeIn$_3$. In these Kondo superlattices, superconducting heavy electrons are confined within the two-dimensional (2D) CeCoIn$_5$ block-layers (BLs) and interact with the neighboring nonmagnetic or magnetic layers through the interface. In CeCoIn$_5$/YbCoIn$_5$ superlattices, local inversion symmetry breaking at the interface enables Rashba spin-orbit coupling to play a key role in superconductivity [44–47]. In CeCoIn$_5$/CeRhIn$_5$ and CeCoIn$_5$/CeIn$_3$ Kondo superlattices, the superconducting and AFM states coexist in spatially separated layers [48, 49]. The AFM ordering temperature of CeRhIn$_5$ and CeIn$_3$ BLs can be tuned to zero by applying hydrostatic pressure, leading to a magnetic QCP. In these superlattices, we show that the superconducting and non-superconducting magnetic layers can interact with each other. In particular, in CeCoIn$_5$/CeRhIn$_5$ superlattices, upon suppressing the AFM order, the force binding superconducting electron pairs acquires an extreme strong coupling nature superlattices, demonstrating that superconducting pairing can be tuned nontrivially by magnetic fluctuations injected through the interface.

II. KONDO SUPERLATTICE

A. Kondo superlattice

Recently, the state-of-the-art molecular beam epitaxy (MBE) technique enables the realization of high quality hetero-interface of heavy fermion systems through the fabrication of Ce-based compounds [44, 50, 51]. Superlattices consisting of alternating layers of superconductor CeCoIn$_5$, nonmagnetic metals, such as YbCoIn$_5$ and YbRhIn$_5$, and AFM heavy fermion metals, such as CeRhIn$_5$ and CeIn$_3$ [38, 39] with atomic layer thicknesses have been fabricated.

Here we design and fabricate three kinds of superlattices formed by alternating atomically thick layers of CeCoIn$_5$ and (1)YbCoIn$_5$, (2)CeRhIn$_5$ and (3)CeIn$_3$. YbCoIn$_5$ and CeMIn$_5$ ($M =$ Co and Rh) crystalize in the tetragonal HoCoGa$_5$ structure. CeMIn$_5$ can be viewed as alternating layers of CeIn$_3$ and MIn$_2$ stacked sequentially along the tetragonal c-axis. CeIn$_3$ has a cubic AuCu$_3$-type structure with a 3D Fermi surface. It should be noted that as disorder may greatly influence physical properties, especially near a QCP, there is a great benefit in examining quantum critical systems that are stoichiometric and hence relatively disorder free; these heavy fermion compounds are examples of a small number of such systems.

B. Layered heavy-fermion CeCoIn$_5$ and CeRhIn$_5$

CeCoIn$_5$ is a heavy-fermion superconductor with $T_c = 2.3$ K, which is the highest among Ce-based heavy-fermion superconductors [52]. Related to the layered structure, de Haas–van Alphen experiments on CeCoIn$_5$ reveal a corrugated cylindrical Fermi surface [52, 53]. In addition, nuclear magnetic resonance (NMR) relaxation rate $T_1$ measurements indicate the presence of anisotropic (quasi-2D) AFM spin fluctuations in the normal state [54, 55]. A large Sommerfeld constant $\gamma = C/T = 290$ mJ mol$^{-1}$K$^{-2}$ is observed just above $T_c$ [56]. The normalized jump in heat capacity $\Delta C/C \gamma T_c \sim 4.5$ suggests that CeCoIn$_5$ exhibits very strong coupling superconductivity compared with the BCS value of 1.43 [57]. The normal state possesses non-Fermi-liquid properties in zero fields, including $T$-linear resistivity, indicating a nearby underlying QCP [52, 58]. It is well established by several experiments that the superconducting gap has $d_{x^2-y^2}$-wave symmetry, which is a strong indication for magnet-
superconductivity appears [11]. At higher pressures, the AFM phase and the superconducting phase coexist, and $T_c$ increases with pressure but $T_N$ decreases [71]. Above the pressure $P^*$ where $T_c = T_N$, the AFM order suddenly disappears and the pressure-induced transition to superconductivity appears to be first order, thus avoiding a QCP. Apparent deviations from Fermi liquid behavior have been observed in $\rho(T)$ over a wide temperature and pressure range [37]. The $P-T$ phase diagram is displayed in Fig. 2(b).

C. Antiferromagnetic heavy fermion CeIn$_3$

At ambient pressure, CeIn$_3$ undergoes an AFM transition at $T_N = 10.1$ K with an ordered magnetic moment of 0.48 $\mu_B$ and a commensurate wave vector $q = (0.5, 0.5, 0.5)$ [59]. A dome-like superconducting phase appears with $T^\text{max}_c = 0.2$ K around the critical pressure $P_c = 2.6$ GPa, which indicates that the superconductivity is believed to be mediated by quantum critical spin fluctuations [10, 73]. The normal state resistivity near the critical pressure shows non-Fermi liquid behavior [74], $\rho(T) \propto T^\alpha$ with $\alpha = 1.6$, which strongly deviate from the Fermi liquid value of $\alpha = 2$. This critical exponent $\alpha$ near $P_c$ is close to 3/2 reflecting 3D AFM magnetic fluctuations [75], indicating the existence of 3D AFM QCP. The $P-T$ phase diagram is displayed in Fig. 2(c).

D. Non-magnetic metal YbCoIn$_5$

The Yb-ions in YbCoIn$_5$ are divalent and form the closed-shell 4$f$ configuration [76]. As a result, YbCoIn$_5$ is a nonmagnetic compound, showing conventional metallic behavior in resistivity and magnetic susceptibility [77]. No superconducting transition has been reported in bulk and thin film YbCoIn$_5$ at ambient and under pressure [48, 77].

III. EXPERIMENTAL METHOD

A. Molecular beam epitaxy systems

MBE is essentially a refined ultra-high-vacuum evaporation method, which helps to prevent contamination of the surface and oxidation of elements such as Ce. Thus, high-quality thin films of Ce based compounds can be grown using MBE. MBE enables a slow growth rate of 0.01–0.02 nm/s that permits very precise control of layer thickness. Consequently, abrupt material interfaces can be achieved, enabling the fabrication of heterostructures such as superlattices. The typical pressure in the MBE chamber is maintained at < 10$^{-7}$ Pa during the fabrication of thin films, enabling powerful diagnostic techniques such as reflection high-energy electron diffraction.
Magnesium fluoride MgF$_2$ is used as the substrate. MgF$_2$ has a rutile-type tetragonal structure with a lattice parameter $a = 0.462$ nm, which matches the lattice parameters $a = 0.468$, $0.453$, $0.461$ and $0.465$ nm for CeIn$_3$, YbCoIn$_5$, CeCoIn$_5$ and CeRhIn$_5$, respectively. Furthermore, because MgF$_2$ does not contain oxygen, the oxidation of Ce compounds during the growth can be avoided. Thus, single-crystal MgF$_2$ is a suitable substrate material to support the epitaxial growth of CeIn$_3$ and CeCoIn$_5$ thin films. To relax the lattice mismatch and improve the quality of the superlattice, we first grow buffer layers. Initially, 30 nm of CeIn$_3$ buffer layers were grown at 450°C. Subsequently, 15 nm of YbCoIn$_5$ buffer layers were grown at 550°C. On top of these, superlattice layers were grown. For CeCoIn$_5$/CeIn$_3$ superlattices, $\sim 5$ nm of the cobalt is deposited as a capping layer at room temperature to avoid the oxidization of samples.

In what follows, we denote a superlattice with alternating layers of $n$-UCT CeCoIn$_5$ and $m$-UCT CeRhIn$_5$ as CeCoIn$_5(m)/$CeRhIn$_5(n)$. The left panel of Fig. 3 displays high-resolution cross-sectional transmission electron microscope (TEM) image of CeCoIn$_5(1)/$YbCoIn$_5(5)$ superlattice, where 1-UCT CeCoIn$_5$ layer are sandwiched by 5-UCT YbCoIn$_5$ layers. The bright dot arrays are identified as the Ce layers and the less bright dots are Yb atoms, which is consistent with the designed superlattice structure. As shown in the right panel of Fig. 3, the intensity integrated over the horizontal width of the image plotted against the vertical position indicates a clear difference between the Ce and Yb layers, showing no discernible atomic interdiffusion between the neighboring Ce and Yb layers. 

Figures 4(a) and 4(b) display high resolution cross-sectional TEM images of CeCoIn$_5(5)/$CeRhIn$_5(5)$ and CeCoIn$_5(7)/$CeIn$_3(13)$ superlattices, respectively. A clear interface between CeCoIn$_5$ and CeRhIn$_5$ or CeIn$_3$ layers is observed. Figures 4(c) and 4(d) display electron energy loss spectroscopy (EELS) images of CeCoIn$_5(5)/$CeRhIn$_5(5)$ and CeCoIn$_5(7)/$CeIn$_3(13)$ superlattices, respectively. The EELS images clearly resolve CeCoIn$_5$, CeRhIn$_5$ or CeIn$_3$ BLs, demonstrating sharp interfaces with no atomic interdiffusion between the neighboring BLs.

For all the above Kondo superlattices, streak patterns of the RHEED image were observed during the whole growth of the superlattices, indicating good epitaxy. In addition, the atomic-force-microscope measurements reveal that the surface roughness of both superlattices is within $\pm 1$ nm, which is comparable to 1–2 UCT along the c axis of the constituents. Because atomically flat regions extend over distances of $\sim 0.1 \mu$m, it can be expected that transport properties are not seriously influenced by the roughness. Superlattice structures were also confirmed by the satellite peaks of the x-ray diffraction patterns for all superlattices. These results demonstrate the successful fabrication of epitaxial superlattices with sharp interfaces, revealing that the MBE technology is well suited for achieving our goal of designing Kondo superlattices.

### B. Pressure experiments

In-plane resistivity measurements under pressure were performed with a commercial piston-cylinder-type high-pressure cell (CT Factory, Ltd.) [78]. We used Daphnet7373 oil as the pressure medium. We applied...
a load with a 20 tons hydraulic pressure machine at room temperature. The pressure inside the pressure cell was determined by the superconducting transition of lead (Pb), which was obtained by the quasi-four terminal resistivity measurement. A long and narrow shaped Pb installed inside the sample space is sensitive to the pressure gradient for the axial direction of the cell, which can be known by examining the width of the superconducting transition. In this study, the transition width was within 20 mK, indicating a good hydrostatic condition.

IV. HEAVY FERMION SUPERCONDUCTIVITY
AT THE METALLIC INTERFACE

A. 2D confinement of heavy fermion superconductivity

In CeCoIn$_5$/YbCoIn$_5$ superlattices, the Ruderman-Kittel-Kasuya-Yosida (RKKY) interaction between the Ce atoms in neighboring CeCoIn$_5$ BLs is substantially reduced [29]. Moreover, the superconducting proximity effect between CeCoIn$_5$ and YbCoIn$_5$ layers is negligibly small due to the large Fermi velocity mismatch [30]. Then an important question is whether the superconducting electrons in the superlattices are heavy and if so what their dimensionality is. When the thickness of the CeCoIn$_5$ BL is comparable to the perpendicular coherence length $\xi_c$ (about 2.1 nm for CeCoIn$_5$), and the separation of superconducting layers ($\sim$3.7 nm for CeCoIn$_5(n)$/YbCoIn$_5(5)$ superlattices) exceeds $\xi_c$, each CeCoIn$_5$ BL acts as a 2D superconductor [44, 45, 81].

Figure 5(a) depicts the magnetic-field dependence of resistivity for CeCoIn$_5(3)$/YbCoIn$_5(5)$ superlattice at several field angles from $\theta = 0$ ($\mathbf{H} \perp ab$) to 90 ($\mathbf{H} \parallel a$) at $T=150$ mK. Figure 5(b) shows the anisotropy of upper critical field $H_{c2}/H_{c2,1}$, where $H_{c2}$ and $H_{c2,1}$ are critical field parallel and perpendicular to the $ab$ plane, as a function of reduced temperature $T/T_c$ for CeCoIn$_5(n)$/YbCoIn$_5(5)$ superlattices with $n=3,5$ and 7 and for the bulk CeCoIn$_5$. $H_{c2}$ is determined by the mid-point of the resistive transition. Unlike the almost $T$-independent anisotropy seen in single crystal of CeCoIn$_5$, anisotropy in the superlattice shows a divergent increase toward $T_c$. This diverging anisotropy is characteristic of 2D superconductivity, in which $H_{c2,1}$ increases as $\sqrt{T_c - T}$ due to the Pauli paramagnetic limiting, but $H_{c2}$ increases as $T_c - T$ due to orbital limiting near $T_c$.

The 2D superconductivity is also confirmed from the angle variation of $H_{c2}(\theta)$ shown in Fig. 5(c). For 3D anisotropic mass model, $H_{c2}(\theta)$ is represented as [82]

$$H_{c2}(\theta) = \frac{H_{c2}}{(\sin^2 \theta + \gamma_m^2 \cos^2 \theta)^{1/2}}, \quad (2)$$

where $\gamma_m = H_{c2}/H_{c2,1}$. In this model, $H_{c2}$ varies smoothly with field orientation. We note that when $H_{c2}$ is limited by Pauli paramagnetic effect as represented by Eq. (1), $H_{c2}$ also varies smoothly as a function of $\theta$. On the other hand, for 2D superconductor and Josephson coupled layered superconductors, $H_{c2}(\theta)$ is represented by Tinkham’s formula as [83]

$$|H_{c2}(\theta) \cos \theta/H_{c2,1}| + |H_{c2}(\theta) \sin \theta/H_{c2,1}|^2 = 1. \quad (3)$$

At $\theta = 90^\circ$, $H_{c2}(\theta)$ exhibits a sharp cusp. The solid blue and red lines in Fig. 5(c) are the fits to Eq. (2) and Eq. (3), respectively. A clear cusp at $\theta = 90^\circ$ is observed at $T=0.8$ and 1.0 K, indicating the 2D superconductivity. The cusp-like behavior of $H_{c2}(\theta)$ becomes less pronounced well below $T_c$, which is the opposite trend to the $H_{c2}(\theta)$ behavior of conventional multilayer systems. This suggests that $H_{c2}(\theta)$ at low temperatures is dominated by the Pauli effect in any field directions.

Figure 6 shows $H-T$ phase diagram of CeCoIn$_5(n)$/YbCoIn$_5(5)$ superlattices with $n=3, 5$ and 7 in magnetic field parallel (open symbols) and perpendicular (closed symbols) to the $ab$ plane. For
the comparison, the results of the bulk CeCoIn$_5$ are also plotted. At low temperatures $H_{c2\perp}$ and $H_{c2\parallel}$ of the superlattices are significantly larger than those in conventional superconductors with similar $T_c$. The zero-temperature value of the orbital upper critical field in perpendicular field $H_{c2\perp}^{\text{orb}}(0)$ reflects the effective electron mass in the plane $m_{\perp}^{\text{orb}}$, $H_{c2\perp}^{\text{orb}}(0) \propto m_{\perp}^{\text{orb}}$. Here, $H_{c2\perp}^{\text{orb}}(0)$ is determined from the initial slope of $H_{c2\perp}(T)$ at $T_c$ through the relation [54],

$$H_{c2\perp}^{\text{orb}} \approx 0.69T_c(-dH_{c2\perp}/dT)|_{T_c}.$$  \hfill (4)

$H_{c2\perp}^{\text{orb}}(0)$ is estimated to be 6, 11 and 12 T for CeCoIn$_5$(n)/YbCoIn$_5$(5) with $n=3$, 5 and 7, respectively. These magnitudes are comparable with or of the same order as $H_{c2\perp}^{\text{orb}}(0) (=14T)$ in bulk CeCoIn$_5$. [41].

Based on these results, we conclude the 2D confinement of the superconducting ‘heavy’ electrons in the CeCoIn$_5$/YbCoIn$_5$ superlattices.

**B. Local inversion symmetry breaking**

In Fig. [7], $H_{c2\perp}$ normalized by $H_{c2\perp}^{\text{orb}}(0)$ for CeCoIn$_5$(n)/YbCoIn$_5$(5) superlattices with $n=3$, 5 and 7 is plotted as a function of the normalized temperature $T/T_c$. Two extreme cases, i.e., the result of the bulk single crystal of CeCoIn$_5$ dominated by Pauli paramagnetic effect and the Werthamer-Helfand-Hohenberg (WHH) curve with no Pauli effect [53], are also shown. For all superlattices, $H_{c2\perp}/H_{c2\perp}^{\text{orb}}(0)$ is much larger than that of single crystal CeCoIn$_5$, indicating that Pauli paramagnetic pair breaking effect is reduced in these superlattices. More importantly, $H_{c2\perp}/H_{c2\perp}^{\text{orb}}(0)$ is strikingly enhanced with decreasing $n$.

Recently, it has been suggested that the inversion symmetry breaking (ISB), together with strong spin-orbit interaction, can dramatically affect the superconductivity [-69]. It has also been pointed out that such phenomena are more pronounced in strongly correlated electron systems. The inversion symmetry imposes important constraints on the pairing states: In the presence of inversion symmetry, Cooper pairs are classified into a spin-singlet or triplet state, whereas in the absence of inversion symmetry, an asymmetric potential gradient $\nabla V$ yields a spin-orbit interaction that breaks parity, and the admixture of spin-singlet and triplet states is possible. For instance, asymmetry of the potential in the direction perpendicular to the 2D plane $\nabla V \parallel [011]$ induces Rashba spin-orbit interaction

$$\alpha_{Rg}(k) \cdot \sigma \propto (k \times \nabla V) \cdot \sigma,$$ \hfill (5)

where $g = (-k_y, k_x, 0)/k_F$, $k_F$ is the Fermi wave number, and $\sigma$ is the Pauli matrix. Rashba interaction splits the Fermi surface into two sheets with different spin structures [87][89]. The energy splitting is given by $\alpha_R$, and the spin direction is tilted into the plane, rotating clockwise on one sheet and anticlockwise on the other. When the Rashba splitting exceeds the superconducting gap energy ($\alpha_R > \Delta$), the superconducting properties are dramatically modified. As the spin-orbit interaction is generally significant in Ce-based superconductors, the introduction of ISB makes the systems a fertile ground for observing exotic properties. Moreover, theoretical studies suggest that when the interlayer hopping integral is comparable to, or smaller than, the Rashba splitting ($t_c \leq \alpha_R$), the local ISB plays an important role in determining the nature of the superconducting state[86]. This appears to be the case for the CeCoIn$_5$/YbCoIn$_5$ superlattices.

Although these superlattices maintain centrosymmetry, it has been suggested that the local ISB at the interface between two compounds influences the superconducting. Figure [8](a) represents the schematic representation of CeCoIn$_5$(n)/YbCoIn$_5$(5) superlattice. The middle CeCoIn$_5$ layer in a given CeCoIn$_5$ BL indicated by the gray plane is a mirror plane. The green (small) arrows represent the asymmetric potential gradient associated with the local ISB, $-\nabla V_{\text{local}}$. The Rashba splitting occurs at the interface between the CeCoIn$_5$ and YbCoIn$_5$ due to the local ISB. The spin direction is rotated in the $ab$ plane and is opposite between the top and bottom CeCoIn$_5$ layers. Because the fraction of noncentrosymmetric interface layers increases with decreasing $n$, the observed remarkable enhancement of $H_{c2\perp}/H_{c2\perp}^{\text{orb}}(0)$ with decreasing $n$ shown in Fig. [7] is attributed to the increased importance of the local ISB.

![FIG. 7: Out-of-plane upper critical field $H_{c2\perp}$ normalized by the orbital-limited upper critical field at $T = 0\ K$, $H_{c2\perp}/H_{c2\perp}^{\text{orb}}(0)$, for CeCoIn$_5$(n)/YbCoIn$_5$(5) and CeCoIn$_5$(n)/CeRhIn$_5$(n) superlattices with $n=7$, 5, and 3 are plotted as a function of the normalized temperature $T/T_c$. Two extreme cases, i.e., the result of the bulk CeCoIn$_5$ dominated by Pauli paramagnetic effect and the WHH curve with no Pauli effect, are also shown. In CeCoIn$_5$(n)/YbCoIn$_5$(5), $H_{c2\perp}/H_{c2\perp}^{\text{orb}}(0)$ is enhanced with decreasing $n$, indicating the importance of the local ISB. In contrast, in CeCoIn$_5$(n)/CeRhIn$_5$(n), $H_{c2\perp}/H_{c2\perp}^{\text{orb}}(0)$ is independent of $n.$](image-url)
influence the magnetic properties in non-superconducting Kondo superlattices. In CeRhIn$_5$/YbRhIn$_5$ superlattices, with reducing the thickness of magnetic CeRhIn$_5$ BLs, the Néel temperature is suppressed and the quasiparticle mass is strongly enhanced, implying dimensional control toward a magnetic QCP [90].

C. Tricolor Kondo superlattices

Recently, it has been reported that the magnitude of the Rashba spin-orbit interaction arising from the ISB is controllable by fabricating two types of Kondo superlattices[40] [91]. One is the introduction of the thickness modulation of YbCoIn$_5$ BLs that breaks the inversion symmetry centered at the superconducting block of CeCoIn$_5$. The other is the ‘tricolor’ superlattices, in which CeCoIn$_5$ BLs are sandwiched by two different nonmagnetic metals, YbCoIn$_5$ and YbRhIn$_5$, as illustrated in Fig. 8(b). These two types of Kondo superlattices, the weakening of the Pauli paramagnetic pair breaking effect is more pronounced than that in ‘bicolor’ CeCoIn$_5$/YbCoIn$_5$ superlattices, as revealed by the further enhancement of $H_{c2\perp}/H_{c2\parallel}(0)$.

In particular, in the tricolor Kondo superlattices, the Rashba spin-orbit interaction induced global inversion symmetry breaking is largely tunable by changing the layer thicknesses of YbCoIn$_5$ and YbRhIn$_5$, leading to profound changes in the superconducting properties of 2D CeCoIn$_5$ BLs. Remarkably, the temperature dependence of $H_{c2\perp}$ of YbCoIn$_5(5)/$CeCoIn$_5(n)/$YbRhIn$_5(3)$, in which 3-UTC YbCoIn$_5$, 5-UTC CeCoIn$_5$ ($n = 5$ and 8) and 3-UTC YbRhIn$_5$ are stacked alternatively, in-plane upper critical field exhibits an anomalous upturn at low temperatures, which is attributed to a possible emergence of a helical or stripe superconducting phase [91]. These results demonstrate that the tricolor Kondo superlattices provide a new playground for exploring exotic superconducting states in the strongly correlated 2D electron systems with the Rashba effect.

The fabrication of tricolor superlattices containing $d$-wave superconducting layers offers the prospect of achieving even more fascinating pairing states than bulk CeCoIn$_5$, such as helical and stripe superconducting states [92], a pair-density-wave state [93], complex stripe state [94], a topological crystalline superconductivity [95, 96], and Majorana fermion excitations [97–101], in strongly correlated electron systems.

V. TUNING THE PAIRING INTERACTION THROUGH THE INTERFACE

A. CeCoIn$_5$/CeRhIn$_5$ Kondo superlattices

FIG. 9: (a) Temperature dependence of the resistivity of CeCoIn$_5$ thin film at ambient pressure and at $P = 2.1$ GPa. (b), (c) Temperature dependence of the resistivity (solid lines, left axes) and its temperature derivative $dp(T)/dT$ (dotted lines, right axes) for CeRhIn$_5$ thin film and CeCoIn$_5(5)/$CeRhIn$_5(3)$ superlattice at ambient pressure and at $P = 2.1$ GPa, respectively. The peak of $dp(T)/dT$ corresponds to AFM transition. (d), (e) $P$-$T$ phase diagrams of thin films and single crystals of (d) CeCoIn$_5$ and (e) CeRhIn$_5$. 

FIG. 8: (a) Schematic representation of bicolor Kondo superlattice CeCoIn$_5(m)$/$YbCoIn$_5(5)$. The center of a CeCoIn$_5$ BL (ash plane) is a mirror plane. The green (small) arrows represent the asymmetric potential gradient associated with the local ISB, $-\nabla V_{\text{local}}$. The Rashba splitting occurs at the interface between the CeCoIn$_5$ and YbCoIn$_5$ BLs due to the local ISB. The spin direction is rotated in the $ab$ plane and is opposite between the top and bottom CeCoIn$_5$ BLs. (b) Schematic representation of noncentrosymmetric tricolor Kondo superlattices YbCoIn$_5(3)/$CeCoIn$_5(3)/$YbRhIn$_5(3)$. The orange (large) arrows represent the asymmetric potential gradient $-\nabla V_{\text{global}}$. In the tricolor superlattices, all layers are not the mirror planes. The orange arrows represent the asymmetric potential gradient $-\nabla V_{\text{global}}$ due to the global broken inversion symmetry. The amplitude of Rashba splitting at the top layer of CeCoIn$_5$ BL is larger than that at the bottom of the BL, owing to the presence of $-\nabla V_{\text{global}}$ shown by the green small arrows.
dependence of $T_c$ and $T_N$ for CeCoIn$_5$ and CeRhIn$_5$ thin films, along with those for single crystals, are shown in Figs. 9(d) and 9(e). The $P-T$ phase diagrams of both films are essentially similar to those of single crystals. However, $T_c (=2.0$ K) in the CeCoIn$_5$ thin film is slightly reduced from the bulk value, whereas $T_N (=3.7$ K) of CeRhIn$_5$ thin film is almost the same as that in a single crystal. With applying pressure, $T_c$ of the CeCoIn$_5$ thin film increases and shows a broad peak near $P \sim 1.7$ GPa. Similar to CeRhIn$_5$ single crystals[13,192], superconductivity in the thin films develops at $P \gtrsim 1$ GPa, where it coexists with magnetic order. In analogy to CeRhIn$_5$ single crystals, there appears to be a purely superconducting state at $P \gtrsim 2.1$ GPa, which is a slightly higher pressure than that required to remove evidence for AFM order in single crystals.

Figure 10(a) shows the $P$-dependence of $T_c$ and $T_N$ determined by the peak in $\mathrm{d} \rho(T)/\mathrm{d}T$ for CeCoIn$_5(5)/$CeRhIn$_5(5)$ superlattice. At $P \sim 2$ GPa, $T_c$ is at a maximum, forming a dome-shaped $P$-dependence. With pressure, $T_N$ gradually decreases at low $P$ and decreases sharply when it exceeds $P \gtrsim 1$ GPa. At $P \gtrsim 1.6$ GPa, evidence of magnetic order is hidden beneath the superconducting dome. Although there is large ambiguity in determining a critical pressure $P_c$, a simple extrapolation of $T_N$ gives $P_c \sim 2$ GPa, where $T_n$ has a maximum. Furthermore, this critical value is very close to the $P_c$ of CeRhIn$_5$ single crystal.

The $T_c$ and $T_N$ of the hybrid superlattice are lower than those of the CeCoIn$_5$ and CeRhIn$_5$ thin films, suggesting that the reduction in dimensions affected the electronic structure. However, these values are higher than the corresponding CeCoIn$_5$/YbCoIn$_5$ and CeRhIn$_5$/YbRhIn$_5$, indicating the importance of interaction between CeCoIn$_5$ and CeRhIn$_5$ BLs.

B. Superconductivity and antiferromagnetism in specially separated layers

We show that 2D superconductivity is realized in the CeCoIn$_5$ BLs in the whole pressure regime in CeCoIn$_5(5)/$CeRhIn$_5(5)$ superlattice. Figure 10(b) depicts the $T$-dependence of the upper critical field determined by the midpoint of the resistive transition in a magnetic field $H$ applied parallel ($H_{c2||}$) and perpendicular ($H_{c2\perp}$) to the $ab$ plane. Figure 10(c) shows the $T$-dependence of the anisotropy of upper critical fields, $H_{c2||}/H_{c2\perp}$. Unlike the almost $T$-independent anisotropy seen in single crystals and thin films of CeCoIn$_5$, anisotropy in the superlattice shows a divergent increase toward $T_c$. This diverging anisotropy is characteristic of 2D superconductivity, in which $H_{c2||}$ increases as $\sqrt{T_c-T}$ due to the Pauli paramagnetic limiting, but $H_{c2\perp}$ increases as $T_c - T$ due to orbital limiting near $T_c$. Considering this result and the fact that the 5-UCT of the CeCoIn$_5$ BL is comparable to the superconducting coherence length in the $c$-axis direction $\xi_c \sim 3$–4 nm, the 5-UCT of the CeCoIn$_5$ BL effectively act as a 2D superconductor[44]. The 2D superconductivity is also confirmed from the angle variation of $H_{c2}(\theta)$. Figure 10(d) and its inset show $H_{c2}(\theta)$ below and above $P^*$. For both pressures, at temperature well below $T_c$, $H_{c2}(\theta)$ in the regime $|\theta| \lesssim 30^\circ$ is enhanced with decreasing $|\theta|$ and exhibits a sharp cusp at $\theta = 0$. This cusp behavior is typical of Josephson-coupled layered superconductors[82].

It should be noted that in contrast to single crystals and thin films of CeRhIn$_5$, the CeRhIn$_5$ layers in CeCoIn$_5$/CeRhIn$_5$ hybrid superlattices do not become fully superconducting even under pressure where AFM order is suppressed. As a result, 2D superconductivity occurs in a wide pressure regime. In fact, as shown in Fig. 10(d), at $P = 1.8$ GPa where CeRhIn$_5$ thin film does not show bulk superconductivity, the hybrid superlattice shows an angular dependence with a cusp structure near $\theta = 0$. Essentially similar cusp-like behavior is observed at $P = 2.1$ GPa above $P_c$, suggesting that 2D superconductivity derived from the CeCoIn$_5$ BLs is realized below and above $P_c$.

When the number of BL thickness is reduced, superconductivity survives in CeCoIn$_5$, but is suppressed in CeRhIn$_5$. This difference may be related to the ordering vector $q = (0.5, 0.5, 0.297)$ of the incommensurate magnetic structure of CeRhIn$_5$. In CeCoIn$_5$, on the other hand, the AFM fluctuations are dominated by $q = (0.45, 0.45, 0.5)$[59]. This commensurability along the $c$-axis would match well with the superconducting struc-
tured, and as a result, the superconductivity is robust against the decrease in the BL thickness \[47, 103\]. Recent site-selective NMR measurements on CeCoIn\(_5\)/CeRhIn\(_5\) superlattices have shown that AFM order is not induced in the CeCoIn\(_5\) BLs \[103\]. The pressure suppresses magnetic order in CeRhIn\(_5\) and CeCoIn\(_5\) approaches the Fermi liquid state, so it is unlikely that AFM order is induced in the CeCoIn\(_5\) BLs in the superlattice under pressure. We comment on the reversal of \(H_{c2}\) of the CeCoIn\(_5\)/(CeRhIn\(_5\)) superlattice at low temperature under pressure (Fig. 10(b)). Such a reversed anisotropy of \(H_{c2}\) can be seen in CeRhIn\(_5\) single crystal in a high pressure region where AFM order is completely suppressed. However, similar reversed anisotropy \(H_{c2} > H_{c2}^\perp\) is preserved at \(P = 1.8\) GPa, where \(H_{c2\parallel}\) exceeds \(H_{c2\perp}\) in the CeRhIn\(_5\) single crystal and thin film. This result suggests that the reversal of \(H_{c2}\) occurs in 5-UCT CeCoIn\(_5\) BLs. From the above results, we conclude that 2D superconductivity of CeCoIn\(_5\) couples by the Josephson effect within a BL is realized in the whole pressure regime.

Figure 7 displays \(H_{c2\perp}(T)/H_{c2\perp}(0)\) of CeCoIn\(_5\)/(CeRhIn\(_5\)) and CeCoIn\(_5\)/(YbCoIn\(_5\)) superlattices plotted as a function of \(T/T_c\). Here \(H_{c2\parallel}(0)\) is calculated by the initial slope of \(H_{c2\parallel}(T)\) at \(T_c\) by using Werthamer-Helfand-Hohenberg (WHH) formula, \(H_{c2\parallel}(0) = -0.69T_c/dH_{c2\parallel}/dT \). For comparison, we also include two extreme cases: \(H_{c2\perp}(0)\) for bulk CeCoIn\(_5\) \[103\], in which \(H_{c2}\) is dominated by Pauli paramagnetism, and the WHH curve with no Pauli effect. In CeCoIn\(_5\)/(YbCoIn\(_5\)), \(H_{c2\perp}/H_{c2\parallel}(0)\) increases with decreasing \(n\). This is because the local inversion symmetry breaking suppresses the Pauli pair-breaking effect at the interfaces between BLs. As \(n\) decreases, the contribution of the interface increases and the relative importance of orbital pair-breaking effect compared with Pauli pair-breaking effect increases. On the other hand, \(H_{c2\perp}/H_{c2\parallel}\) is almost independent on \(n\) in CeCoIn\(_5\)/(CeRhIn\(_5\)), suggesting that the local inversion symmetry breaking in not important in the superlattices in which both substances constituting the superlattice are Ce-based compounds.

### C. Enhancement of superconducting pairing strength

The superconducting properties of the hybrid superlattice change dramatically when pressure is applied. Figure 11(a) depicts the \(T\)-dependence of \(H_{c2\perp}/H_{c2\parallel}(0)\) of CeCoIn\(_5\)/(CeRhIn\(_5\)) for several pressures. Remarkably, near the critical pressure of \(P_c \sim 2\) GPa where AFM order vanishes, \(H_{c2\perp}/H_{c2\parallel}\) almost coincides with WHH curve, indicating that \(H_{c2\perp}\) is determined only by the orbital pair-breaking effect.

The fact that \(H_{c2\perp}\) reaches the orbital limit has important implications for the superconducting properties of the hybrid superlattice. In CeCoIn\(_5\)/YbCoIn\(_5\), where YbCoIn\(_5\) is a conventional metal, Pauli pair-breaking effect is weakened in the superlattice compared with the bulk due to local inversion symmetry breaking at the interfaces, where the Fermi surface splits with spin momentum locking due to anisotropic Rashba spin-orbit interaction. This leads to anisotropic suppression of the Zeeman effect which may be partly responsible for the observed reversed anisotropy \(H_{c2\perp}/H_{c2\parallel} < 1\) at low temperatures (Fig. 10(d)). However, this effect is less important in CeCoIn\(_5\)/(CeRhIn\(_5\)) superlattices compared with CeCoIn\(_5\)/YbCoIn\(_5\), which is evidenced by the fact that \(H_{c2\perp}/H_{c2\parallel}(0)\) does not strongly depend on \(n\) (Fig. 7).

Further, such an effect is not expected to show significant pressure dependence. Therefore, there must be a different mechanism that significantly enhances \(H_{c2\perp}\) given by Eq. (1).

An enhancement of \(H_{c2\perp}\) is not due to a dramatic suppression of \(g\). As \(g\) is enhanced by pressure in both CeCoIn\(_5\) and CeRhIn\(_5\) \[102\], \(g\) is expected to be enhanced with pressure in the superlattice. Therefore, a significant increase in the superconducting gap is thought to be the origin of the increase in \(H_{c2\perp}\). This is also supported by the sharp increase in \(H_{c2\perp}/T_c\) upon approaching \(P_c\) shown in Fig. 11(a). Because \(H_{c2\perp} \approx H_{c2\perp}^{\text{Pauli}} < H_{c2\perp}^{\text{orb}}(0)\) in the low \(P\) regime and \(H_{c2\perp} \approx H_{c2\perp}^{\text{orb}}(0) < H_{c2\perp}^{\text{Pauli}}\) near \(P \sim P_c\), the enhancement of \(H_{c2\perp}/T_c\) directly indicates an enhancement of \(H_{c2\perp}^{\text{Pauli}}/T_c\) and hence \(\Delta/k_B T_c\). This behavior is significantly different from CeCoIn\(_5\) single crystal, in which \(H_{c2\perp}/T_c\) monotonically decreases with pressure, approaching the Fermi liquid state. The enhancement of \(\Delta/k_B T_c\) is caused as a consequence of the enhancement of pairing interaction. In the spin fluctuation mediated mechanism, the pairing interaction is brought about by high-energy spin fluctuations well above \(\Delta\), while low-energy fluctuations cause the pair-breaking. High-energy fluctuations have the effect of increasing \(T_c\), while low-energy fluctuations decrease \(T_c\), so that the enhancement of pairing interaction can give rise to increase in \(\Delta/k_B T_c\) without accompanying a large enhancement of \(T_c\). Therefore, these results demonstrate that the critical magnetic fluctuations developed in CeRhIn\(_5\) near its critical pressure are injected into CeCoIn\(_5\) BLs through the interface and enhance the pairing interaction of the CeCoIn\(_5\) BLs.

It has been established that normal and superconducting properties are greatly affected by quantum fluctuations in many classes of unconventional superconductors. The common behavior is that the effective mass of quasiparticle diverges as the system approaches a QCP, as reported in cuprates, pnictides and heavy-fermion systems \[16, 38, 106\]. Such an increase in effective mass gives rise to a corresponding enhancement \(H_{c2}^{\text{orb}}\), which is proportional to \((m^* \Delta)^2\), the CeCoIn\(_5\)/CeRhIn\(_5\) superlattices show different behavior. In contrast to the CeRhIn\(_5\) single crystal, which shows a sharp peak at the critical pressure, the \(H_{c2\perp}^{\text{orb}}\) of the CeCoIn\(_5\)/(CeRhIn\(_5\)) superlattices with \(n = 4\) and \(5\) does not show much \(P\)-dependent behavior, and there is no anomaly in \(P_c\). Compared to a monotonic decrease of effective mass in CeCoIn\(_5\) single
crystal, the result of the hybrid superlattice is consistent with an enhancement of $\Delta$, indicating that there is no mass enhancement in CeCoIn$_5$ BLs. Such behavior is in contrast to what is expected for usual quantum criticality, and is a subject for future research.

VI. COUPLING BETWEEN SUPERCONDUCTIVITY AND ANTIFERROMAGNETISM

To further examine how $d$-wave superconductors and antiferromagnets interact through the interface, we designed another hybrid superlattice using a different AFM metal CeIn$_3$ [19]. The cubic CeIn$_3$ forms 3D AFM order with the ordered magnetic moment of 0.48 $\mu_B$ occurs with a commensurate wave vector $q = (0.5, 0.5, 0.5)$ at $T_N = 10$ K, where $\mu_B$ is the Bohr magneton [72]. This is contrast to CeRhIn$_5$, which forms an incommensurate helical AFM order with $q = (0.5, 0.5, 0.239)$ at $T_N = 2.3$ K. On the other hand, both are Ce-based heavy-fermion AFM metal with AFM QCP under pressure [10][22]. Therefore, it becomes possible to investigate the effect of different types of antiferromagnetism on $d$-wave superconductivity by measuring the $H_{c2}$ for CeCoIn$_5$/CeIn$_3$ superlattice under pressure, as have done for CeCoIn$_5$/CeRhIn$_5$.

A. Robust magnetism against thickness reduction

Figure 12(a) depicts the temperature dependence of the resistivity $\rho$ of CeCoIn$_5$(7)/CeIn(n) superlattices with $n = 3, 4, 6$ and 13. We also show $\rho$ of CeCoIn$_5$ and CeIn$_3$ thin films grown by MBE. The mean free path of these superlattices is difficult to estimate because of the parallel conductions of CeCoIn$_5$ and CeIn$_3$ BLs. However, the mean free path in each BL is expected to be shorter than the atomically flat regions extending over distances of $\sim 0.1 \mu m$, because of the following reasons. In CeCoIn$_5$ and CeIn$_3$ single crystals, the mean free path determined by the de Haas-van Alphen oscillations is $\sim 0.2 \mu m$ [107][108]. The residual resistivity ratio of CeCoIn$_5$ and CeIn$_3$ thin films with $100 \text{ nm}$ thickness is 4–5 times smaller than that of the single crystals. Therefore, the mean free path of CeCoIn$_5$ and CeIn$_3$ BLs in the superlattices is expected to be much shorter than $0.1 \mu m$, suggesting that the transport properties are not seriously influenced by the surface roughness. The resistivity of CeCoIn$_5$(7)/CeIn(n) superlattices follows the typical heavy-fermion behavior. With decreasing temperature, $\rho(T)$ increases below $\sim 150$ K due to the Kondo scattering but then begins to decrease due to strong $c$-$f$ hybridization between $f$-electrons and conduction ($c$) band electrons, leading to the narrow $f$-electron band at the Fermi level. The Kondo coherence temperature $T_{coh}$, at which the formation of heavy-fermion occurs, is estimated from the maximum in $\rho(T)$.

As shown in Fig. 12(a), $T_{coh}$ of CeCoIn$_5$(7)/CeIn(n) superlattices is nearly independent of $n$ and is closer to $T_{coh}$ of CeCoIn$_5$ thin film than $T_{coh}$ of CeIn$_3$ thin film, suggesting that $T_{coh}$ is mainly determined by CeCoIn$_5$ BLs. Figure 12(b)-(f) depict $\rho(T)$ at low temperatures. All superlattices show the superconducting transition at $T \approx 1.5$ K. For the $n = 3$ and 4-superlattices, $\rho(T)$ decreases with increasing slope, $d\rho(T)/dT$, as the temperature is lowered below 12 K down to $T_c$.

The lattice parameters along the $a$-axis of CeCoIn$_5$, CeRhIn$_5$, and CeIn$_3$ are 4.613, 4.653, and 4.690 Å, respectively. Therefore, a large tensile strain along the $a$-axis is expected in CeCoIn$_5$ BLs of CeCoIn$_5$/CeIn$_3$ compared to CeCoIn$_5$/CeRhIn$_5$. It has been shown that the uniaxial pressure dependence of $T_c$ along the $a$-axis for CeCoIn$_5$ is $dT_c/dP_a = 290$ mK/GPa (109), indicating that $T_c$ decreases by tensile strain. However, $T_c$ of CeCoIn$_5$/CeIn$_3$ ($T_c \sim 1.5$ K) is larger than that of CeCoIn$_5$/CeRhIn$_5$ ($T_c \sim 1.4$ K). We note that the lattice parameter along the $a$-axis for CeCoIn$_5$ BLs in CeCoIn$_5$/CeIn$_3$, which is estimated from x-ray diffraction, well coincides with that in CeCoIn$_5$/CeRhIn$_5$. These results suggest that the strain effect at the interfaces is not important for determining $T_c$. Figure 12(g)-(k) display the temperature derivative of the resistivity $d\rho(T)/dT$. As shown by the arrows in Fig. 12(g), $d\rho(T)/dT$ of CeIn$_3$ thin film exhibits a distinct kink at $T_N = 10$ K [72]. Similar kink structures are observed in all superlattices at the temperatures indicated by arrows, showing the AFM tran-
FIG. 12: (a) Temperature dependence of the resistivity $\rho(T)$ in CeCoIn$_5$(7)/CeIn$_3$(n) superlattices for $n = 3, 4, 6,$ and 13, along with $\rho(T)$ for CeIn$_3$ (black solid line) and CeCoIn$_5$ (black dashed line) thin films. Inset illustrates the schematics of CeCoIn$_5$(7)/CeIn$_3$(n) superlattice. (b)-(f) $\rho(T)$ at low temperatures. (g)-(f) Temperature derivative of the resistivity, $d\rho(T)/dT$, as a function of temperature. The arrows indicate the Néel temperature $T_N$.

FIG. 13: The Néel temperature $T_N$ for CeCoIn$_5$(7)/CeIn$_3$(n) as a function of $n$. For comparison, $T_N$ for CeIn$_3$(n)/LaIn$_3$(4) and CeCoIn$_5$(n)/CeRhIn$_5$(n) are shown. Open square and triangle are $T_N$ of bulk CeIn$_3$ and CeRhIn$_5$ single crystals, respectively.

of the CeCoIn$_5$(7)/CeIn$_3$(n) superlattices. For comparison, the data sets of CeIn$_3$(4)/LaIn$_3$(n), where LaIn$_3$ is a nonmagnetic conventional metal with $n$-electrons, and CeCoIn$_5$(n)/CeRhIn$_5$(n) are also included in Fig. 13. Remarkably, the observed thickness dependence of $T_N$ in CeCoIn$_5$/CeIn$_3$ is in striking contrast to that in CeIn$_3$/LaIn$_3$; While $T_N$ is strongly suppressed with decreasing $n$ and vanishes at $n = 2$ in CeIn$_3$/LaIn$_3$, $T_N$ is nearly independent of $n$ in CeCoIn$_5$(7)/CeIn$_3$(n). This suggests that CeIn$_3$ BLs are coupled weakly by the RKKY interactions through the adjacent LaIn$_3$ BL, but they can strongly couple through the adjacent CeCoIn$_5$ BL. This is even more surprising, as the distance between different CeIn$_3$ BLs is larger in the CeCoIn$_5$(7)/CeIn$_3$(n) superlattices than in the CeIn$_3$(n)/LaIn$_3$(4) superlattices. We thus conclude that small but finite magnetic moments are induced in CeCoIn$_5$ BS in CeCoIn$_5$/CeIn$_3$, which mediate the RKKY-interaction. On the other hand, because of the absence of strongly interacting $f$-electrons in LaIn$_3$, which can form magnetic moments, the RKKY interaction in CeIn$_3$/LaIn$_3$ can be expected to be much weaker. To clarify this, a microscopic probe of magnetism, such as NMR measurements, is required. We note that as shown in Fig. 13, the reduction of $T_N$ is also observed in CeCoIn$_5$(n)/CeRhIn$_5$(n) superlattices [48], suggesting that the RKKY interaction between CeRhIn$_5$ BLs through adjacent CeCoIn$_5$ BL is negligibly small. This is supported by the recent site-selective NMR measurements which report no discernible magnetic moments induced in the CeCoIn$_5$ BS while magnetic fluctuations are injected from CeRhIn$_5$ BS into one or two layers of CeCoIn$_5$ in CeCoIn$_5$/CeRhIn$_5$ [104].

B. Tuning AFM fluctuations via pressure

The pressure dependence of the superconducting and magnetic properties provide crucial information on the mutual interaction between superconductivity and magnetism through the interface. Figure 14(a) depicts the pressure dependence of $T_N$ and $T_c$ for CeCoIn$_5$(7)/CeIn$_3$(n) superlattices for $n = 6$ and 13. With applying pressure, $T_N$ decreases rapidly. For comparison, $T_N$ of a single crystal CeIn$_3$ is also shown by the solid line [10]. The pressure dependence of $T_N$ of both superlattices is very similar to that of the bulk CeIn$_3$ single crystal. In bulk CeIn$_3$, the AFM QCP is located at $P_c \approx 2.6$ GPa. It is natural to expect, therefore, that the AFM QCP of the superlattices is close to 2.6 GPa. Thus, at 2.4 GPa, the superlattices are in the vicinity of the AFM QCP. This is supported by the temperature dependence of the resistivity under pressure. The resistivity can be fitted as

$$\rho(T) = \rho_0 + AT^\epsilon. \quad (6)$$

Figure 14(b) shows the pressure dependence of $\epsilon$ obtained from $d\ln\Delta\rho/d\ln T$, where $\Delta\rho = \rho(T) - \rho_0$. The magnitude of $\epsilon$ decreases with pressure. In bulk CeIn$_3$ single crystal, $\epsilon$ decreases with pressure and exhibits a minimum at the AFM QCP [107, 74]. On the other hand, applying pressure to CeCoIn$_5$ leads to an increase of $\epsilon$, which is attributed to the suppression of the non-Fermi liquid behavior, $\rho(T) \propto T$, and the development of a Fermi liquid state with its characteristic $\rho(T) \propto T^2$ dependence [32, 33]. Therefore, the reduction of $\epsilon$ with...
pressure arises from the CeIn$_3$ BLs, indicating that the CeIn$_3$ BLs approach the AFM QCP.

As shown in Figs 14(a), $T_c$ increases, peaks at $\sim 1.8\, \text{GPa}$, and then decreases when applying pressure. This pressure dependence bears a resemblance to that of CeCoIn$_5$ bulk single crystals [32]. An analysis of the upper critical field provides important information about the superconductivity of CeCoIn$_5$ BLs. Figure 15 depicts the temperature dependence of the upper critical field determined by the midpoint of the resistive transition in a magnetic field $H$ applied parallel ($H_{c2||}$) and perpendicular ($H_{c2\perp}$) to the layers. The inset of Fig 15 shows the anisotropy of the upper critical fields $H_{c2||}/H_{c2\perp}$ at ambient pressure. The 2D feature is revealed by the diverging anisotropy of $H_{c2||}/H_{c2\perp}$ of the superlattice on approaching $T_c$, in sharp contrast to the CeCoIn$_5$ thin film. Thus, each CeCoIn$_5$ BL in CeCoIn$_5$/CeIn$_3$ superlattice effectively behaves as a 2D superconductor.

![FIG. 14: (a) Pressure dependence of $T_N$ and $T_c$ of CeCoIn$_5(7)/$CeIn$_3(n)$ superlattices for $n = 13$ and 6. For comparison, $T_N$ of CeIn$_3$ and $T_c$ of CeCoIn$_5$ single crystals are shown by solid lines. (b) Pressure dependence of the exponent $\varepsilon$ in $\rho(T) = \rho_0 + A T^\varepsilon$, obtained from $d\ln \rho / d\ln T$ ($\Delta \rho = \rho(T) - \rho_0$), for the CeCoIn$_5(7)/$CeIn$_3(n)$ superlattices for $n = 13$ and 6. For comparison, $\varepsilon$ for bulk CeIn$_3$ and CeCoIn$_5$ single crystals is shown.

C. Effect of magnetic fluctuations on superconductivity

It has been revealed that the $T$ dependence of $H_{c2\perp}$ provides crucial information on the effect of interfaces on the superconductivity of CeCoIn$_5$ BLs. In particular, the modification of the Pauli paramagnetic effect in the superlattice, which dominates the pair breaking in bulk CeCoIn$_5$ single crystals, provide valuable clues [35 40 48 91]. Figure 16(a) and (b) depict the $T$ dependence of the $H_{c2\perp}$ of CeCoIn$_5(7)/$CeIn$_3(13)$ superlattice at ambient pressure Fig 16(a) and under pressure Fig 16(b), normalized by the orbital-limited upper critical field at zero temperature, $H_{c2\perp}^{\text{orb}}(0)$, which is obtained from the WHH formula, $H_{c2\perp}^{\text{orb}}(0) = -0.69T_c(dH_{c2\perp}/dT)_{T=0}$.

![FIG. 15: Temperature dependence of upper critical fields in magnetic fields parallel ($H_{c2||}$, open symbols) and perpendicular ($H_{c2\perp}$, closed symbols) to the ab-plane for CeCoIn$_5(7)/$CeIn$_3(13)$ superlattice at ambient pressure and at 2.1 and 2.4 GPa. The inset shows anisotropy of the upper critical field, $H_{c2||}/H_{c2\perp}$. The data of CeCoIn$_5$ thin film at ambient pressure is shown by dotted line.

In figure 16(a) and 16(b), two extreme cases are also included; the WHH curve with no Pauli pair-breaking and $H_{c2||}$/$H_{c2\perp}^{\text{orb}}(0)$ for bulk CeCoIn$_5$ single crystal [105]. For comparison, $H_{c2\perp}^{\text{orb}}(0)$ for CeCoIn$_5$/YbCoIn$_5$ and CeCoIn$_5$/CeRhIn$_5$ are also shown [44 48].

![FIG. 16: (a) Upper critical field in perpendicular field normalized by the orbital limiting upper critical field, $H_{c2\perp}/H_{c2\perp}^{\text{orb}}(0)$, plotted as a function of $T/T_c$ (a) at ambient pressure and (b) under pressure about 2 GPa for CeCoIn$_5(7)/$CeIn$_3(13)$ superlattices. For comparison, $H_{c2\perp}/H_{c2\perp}^{\text{orb}}(0)$ for bulk CeCoIn$_5$ single crystal, CeCoIn$_5(5)/$YbCoIn$_5(5)$ and CeCoIn$_5(5)/$CeRhIn$_5(5)$ are shown. Orange dotted lines represent the WHH curve, which is upper critical field for purely orbital limiting.

At ambient pressure, $H_{c2\perp}/H_{c2\perp}^{\text{orb}}(0)$ is significantly increased from bulk CeCoIn$_5$ single crystal in both CeCoIn$_5$/YbCoIn$_5$ and CeCoIn$_5$/CeRhIn$_5$, indicating the suppression of the Pauli paramagnetic pair-breaking effect. However, we point out that the mechanisms of this
suppression in these two systems are essentially different. In CeCoIn$_5$/YbCoIn$_5$, as discussed in section IV-B, the enhancement of $H_{c21}/H_{c21}^{orb}(0)$ is caused by the local ISB at the interface. At $P = 2.2$ GPa, $H_{c21}/H_{c21}^{orb}(0)$ of CeCoIn$_5$/YbCoIn$_5$ nearly coincides with the WHH curve, indicating that $H_{c21}$ is dominated by the orbital pair breaking most likely due to the suppression of the Pauli paramagnetic pair-breaking effect by the Rashba splitting.

As shown in Fig. 7, in stark contrast to CeCoIn$_5$ single crystal. Here $g$ is assumed. Figure 17 depicts the pressure dependence of $q = \sqrt{2g_\mu_B H_{c21}/k_BT_c}$ for CeCoIn$_5$/CeRhIn$_5$ and CeCoIn$_5$/CeIn$_3$, along with $q$ for bulk CeCoIn$_5$ single crystal. Here $g = 2$ is assumed. Although this simple assumption should be scrutinized, the fact that $g = 4.2$ of the bulk CeCoIn$_5$ is larger than the BCS value of $g = 3.54$ is consistent with the strong coupling superconductivity, which is supported by the specific heat measurements that report $2\Delta/k_BT_c \approx 6$. The increase of $q$ with pressure in CeCoIn$_5$/CeRhIn$_5$ implies the increase of $2\Delta/k_BT_c$. This increase has been attributed to an enhancement of the force binding superconducting electron pairs. In this case, an increase of $2\Delta/k_BT_c$ occurs without accompanying a large enhancement of $T_c$, which is consistent with the results of CeCoIn$_5$/CeRhIn$_5$. Thus, the critical AFM fluctuations that develop in CeRhIn$_5$ BLs near the QCP are injected into the CeCoIn$_5$ BLs through the interface and strongly enhance the pairing interaction in CeCoIn$_5$ BLs.
the RKKY interaction through adjacent CeCoIn$_5$ BLs. Even in the vicinity of the AFM QCP of the CeIn$_3$ BLs, the superconducting state in the CeCoIn$_5$ BLs is very similar to that of CeCoIn$_5$ bulk single crystals. This indicates that the AFM fluctuations injected from CeIn$_3$ BLs do not help to enhance the force binding the superconducting electron pairs in CeCoIn$_5$ BLs. This is in stark contrast to CeCoIn$_5$/CeRhIn$_5$, in which the pairing force in CeCoIn$_5$ BL is strongly enhanced by the AFM fluctuations in CeRhIn$_5$ BLs [59], although the CeRhIn$_5$ BLs are magnetically only weakly coupled through CeCoIn$_5$ BLs.

We note that the superconducting phase appears under pressure in CeRhIn$_5$ single crystals and epitaxial thin films. On the other hand, in the CeRhIn$_5$/YbRhIn$_5$, zero resistivity is not attained even under pressure [48]. This result indicates that the superconductivity of CeRhIn$_5$ is suppressed when the thickness of the BLs was reduced. Similarly, in CeCoIn$_5$/CeRhIn$_5$ superlattices, 2D superconductivity derived from the CeCoIn$_5$ BLs is thought to be realized from ambient pressure to under pressure near QCP.

D. Contrasting behaviors between CeCoIn$_5$/CeIn$_3$ and CeCoIn$_5$/CeRhIn$_5$ superlattices

As discussed in the previous sections, CeCoIn$_5$/CeIn$_3$ and CeCoIn$_5$/CeRhIn$_5$ superlattices exhibit contrasting superconducting and magnetic properties. We point out that there are two possible important factors that determine whether magnetic fluctuations are injected through the interface; one is the magnetic wave vector and the other is the matching of the Fermi surface between two materials.

For CeCoIn$_5$, the Fermi surface is 2D-like and AFM fluctuations with wave vector $q_0 = (0.45, 0.45, 0.5$ are dominant [59]. The magnetic wave vector in the ordered phase of CeIn$_3$ is commensurate with $q_0 = (0.5, 0.5, 0.5)$ [72]. The evolution of the ordered moment below $T_N$ is consistent with mean field theory. While the wave number along the $c$ axis, $q_c$, of CeIn$_3$ is the same as that of CeCoIn$_5$, the 3D Fermi surface of CeIn$_3$ is very different from the 2D Fermi surface of CeCoIn$_5$. On the other hand, for CeRhIn$_5$, $q_0$ in the ordered phase is incommensurate $q_0 = (0.5, 0.5, 0.297$ at low pressure [34] and changes to $q_0 = (0.5, 0.5, 0.4$ above $\sim 1.0$ GPa [110]. Thus, the $q_c$ of CeRhIn$_5$ is different from the $q_c$ of CeCoIn$_5$. The evolution of the ordered moment below $T_N$ deviates from mean field behavior, likely due to 2D fluctuations. However, the 2D Fermi surface of CeRhIn$_5$ bears a close resemblance to that of CeCoIn$_5$.

The equality between the $c$ axis component of $q_0$ in CeCoIn$_5$ and CeIn$_3$ would explain why the magnetic coupling between CeIn$_3$ BLs through a CeCoIn$_5$ BL is stronger than that between CeRhIn$_5$ BLs. Thus, AFM order is formed in CeCoIn$_5(7)/$CeIn$_3(n)$ even for small $n$, for which the AFM order has already vanished in CeCoIn$_5(n)/$CeRhIn$_5(n)$. In magnetically mediated superconductors, the pairing interaction is expected to be strongly wave number dependent. Considering the good resemblance of the Fermi surface and the same $d_{x^2−y^2}$ superconducting gap symmetry of CeCoIn$_5$ and CeRhIn$_5$ [102], it is likely that the pairing interaction in both compounds has 2D character and peaks around the same wave number on the Fermi surface. Furthermore, it has been assumed that 2D magnetic fluctuations are strong in CeRhIn$_5$. Thus, superconductivity in the CeCoIn$_5$ BLs of CeCoIn$_5(n)/$CeRhIn$_5(n)$ is strongly influenced. On the other hand, in CeIn$_3$ with 3D Fermi surface, 2D AFM fluctuations are expected to be very weak. AFM fluctuations having 3D character in CeIn$_3$ may not play an important role for the pairing interaction in CeCoIn$_5$, resulting in little change of the superconductivity in CeCoIn$_5$/CeIn$_3$.

VII. CONCLUSION

We reviewed the most recent advances of Kondo superlattices containing atomic layers of strongly correlated heavy fermion superconductor CeCoIn$_5$ with $d$-wave symmetry, CeCoIn$_5$/YbCoIn$_5$, CeCoIn$_5$/CeRhIn$_5$ and CeCoIn$_5$/CeIn$_3$ grown by using a state-of-the-art MBE technique. In these Kondo superlattices, superconducting heavy electrons are confined within the 2D CeCoIn$_5$ block layers and interact with the neighboring nonmagnetic or magnetic layers through the interface.

In CeCoIn$_5$/YbCoIn$_5$ superlattices, the superconductivity is strongly influenced by the local ISB at the interface, which seriously reduces the Pauli paramagnetic pair-breaking effect. Our results demonstrate that the tricolor Kondo superlattices provide a new playground for exploring exotic superconducting states in the strongly correlated 2D electron systems with the Rashba effect.

CeCoIn$_5$/CeRhIn$_5$ and CeCoIn$_5$/CeIn$_3$ superlattices, the superconducting and antiferromagnetic states coexist in spatially separated layers, but their mutual coupling via the interface significantly modifies the superconducting and magnetic properties. In CeCoIn$_5$/CeRhIn$_5$ superlattices, the superconductivity in the CeCoIn$_5$ BLs is profoundly affected by AFM fluctuations in the CeRhIn$_5$ BLs. Upon suppressing the AFM order by applied pressure, the force binding superconducting electron pairs acquires an extreme strong coupling nature, highlighting that the pairing interaction can be maximized by the critical fluctuations emanating from the magnetic QCP. In CeCoIn$_5$/CeIn$_3$ superlattices, each CeIn$_3$ BL is magnetically coupled by RKKY interaction through the adjacent CeCoIn$_5$ BLs. In stark contrast to CeCoIn$_5$/CeRhIn$_5$ superlattices, the superconductivity in the CeCoIn$_5$ BLs in CeCoIn$_5$/CeIn$_3$ superlattices is barely influenced by the AFM fluctuations in the CeIn$_3$ BLs, even when the CeIn$_3$ BLs are tuned in the vicinity of the AFM QCP by pressure. The striking difference between the two Kondo
superlattices provides direct evidence that 2D AFM fluctuations are essentially important for the pairing interactions in CeCoIn$_5$.

Finally, we describe the future prospect of the Kondo superlattices. Cd- and Hg-doped CeCoIn$_5$ are known to show anomalous antiferromagnetic order at small doping levels\cite{111,113}. The fabrication of superlattices consisting of alternating layers of Cd- and Hg-doped CeCoIn$_5$ and pure CeCoIn$_5$ is expected to provide important information on the interplay between superconductivity and unusual magnetic order. The advantage of these superlattices is that the mismatch of the lattice constant is very small. Recently, strongly correlated electron systems with strong Rashba interaction are attracting much attention\cite{114,116}. Thus fabricating superlattices in strongly correlated electron systems and pure CeCoIn$_5$ forms a topological superconducting state owing to the strong Rashba interaction\cite{68, 09, 123, 124}. Most of the past research on topological superconductivity has focused on weakly correlated materials. The topological superconductivity in monolayer CeCoIn$_5$ will give an opportunity to study topological excitations, including Majorana fermions in strongly correlated d-wave superconductors. Moreover, it is an open question whether monolayer CeRhIn$_5$ exhibits magnetic order. It is highly challenging to study these issues by using the scanning tunneling microscopy measurements.

The fabrication of a wide variety of Kondo superlattices paves a new way to study the entangled relationship between unconventional superconductivity and magnetism in strongly correlated electron systems, offering a route to exploring the emergence of novel superconducting systems and the roles of their interface.

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**Data Availability**

The data that support the findings of this study are available from American Physical Society. Restrictions apply to the availability of these data, which were used under license for this study. Data are available from the authors upon reasonable request and with the permission of American Physical Society.

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[1] D. J. Scalapino, Rev. Mod. Phys. 84, 1383 (2012)
[2] B. Keimer, S. A. Kivelson, M. R. Norman, S. Úchida, and J. Zaanen, Nature 518, 179 (2015)
[3] P. J. Hirschfeld, M. M. Korshunov, and I. I. Mazin, Rep. Prog. Phys. 74, 124508 (2011)
[4] G. R. Stewart, Advances in Physics 66, 75 (2017)
[5] T. Shibauchi, T. Hanaguri, and Y. Matsuda, J. Phys. Soc. Jpn. 89, 102002 (2020)
[6] P. Thalmeier and G. Zwicknagl, Unconventional Superconductivity and Magnetism in Lanthanide and Actinide Intermetallic Compounds (Handbook on the Physics and Chemistry of Rare Earths, Vol. 34 (Elsevier, 2004) pp. 135 – 287)
[7] C. Pelleiderer, Rev. Mod. Phys. 81, 1551 (2009)
[8] M. Sigrist and K. Ueda, Rev. Mod. Phys. 63, 239 (1991)
[9] K. H. Bennemann and J. B. Ketterson, eds., Superconductivity Volume 1: Conventional and Unconventional Superconductors, Volume 2: Novel Superconductors (Springer Berlin Heidelberg, 2008).
[10] N. D. Mathur, F. M. Grosche, S. R. Julian, I. R. Walker, D. M. Freye, R. K. W. Haselwimmer, and G. G. Lonzarich, Nature 394, 39 (1998)
[11] T. Park, F. Ronning, H. Q. Yuan, M. B. Salamon, R. Movshovich, J. L. Sarrao, and J. D. Thompson, Nature 440, 65 (2006)
[12] P. Gegenwart, Q. Si, and F. Steglich, Nature Phys. 4, 186 (2008)
[13] G. Knebel, D. Aoki, J.-P. Brison, and J. Flouquet, J. Phys. Soc. Jpn. 77, 114704 (2008)
[14] Y. Nakai, T. Iye, S. Kitagawa, K. Ishida, H. Ikeda, S. Kasahara, H. Shishido, T. Shibauchi, Y. Matsuda, and T. Terashima, Phys. Rev. Lett. 105 (2010), 10.1103/physrevlett.105.107003
[15] K. Hashimoto, K. Cho, T. Shibauchi, S. Kas-
[108] N. Harrison, U. Alver, R. G. Goodrich, I. Vekhter, J. L. Sarrao, P. G. Pagliuso, N. O. Moreno, L. Balicas, Z. Fisk, D. Hall, R. T. Macaluso, and J. Y. Chan, Phys. Rev. Lett. 93 (2004), 10.1103/physrevlett.93.186405

[109] N. Oeschler, P. Gegenwart, M. Lang, R. Movshovich, J. L. Sarrao, J. D. Thompson, and F. Steglich, Phys. Rev. Lett. 91 (2003), 10.1103/physrevlett.91.076402

[110] S. Raymond, G. Knebel, D. Aoki, and J. Flouquet, Phys. Rev. B 77 (2008), 10.1103/physrevb.77.172502

[111] L. D. Pham, T. Park, S. Maquilon, J. D. Thompson, and Z. Fisk, Phys. Rev. Lett. 97 (2006), 10.1103/physrevlett.97.056404

[112] M. Nicklas, O. Stockert, T. Park, K. Habicht, K. Kiefer, L. D. Pham, J. D. Thompson, Z. Fisk, and F. Steglich, Phys. Rev. B 76 (2007), 10.1103/physrevb.76.052401

[113] C. H. Booth, E. D. Bauer, A. D. Bianchi, F. Ronning, J. D. Thompson, J. L. Sarrao, J. Y. Cho, J. Y. Chan, C. Capan, and Z. Fisk, Phys. Rev. B 79 (2009), 10.1103/physrevb.79.144519

[114] Y. Michishita and R. Peters, Phys. Rev. B 99 (2019), 10.1103/physrevb.99.155141

[115] K. Nogaki and Y. Yanase, Phys. Rev. B 102 (2020), 10.1103/physrevb.102.165114

[116] S. Wolf and S. Rachel, Phys. Rev. B 102 (2020), 10.1103/physrevb.102.174512

[117] E. Bauer, G. Hilscher, H. Michor, C. Paul, E. W. Scheidt, A. Gribanov, Y. Seropogin, H. Noël, M. Sigrist, and P. Rogl, Phys. Rev. Lett. 92 (2004), 10.1103/physrevlett.92.027003

[118] N. Kimura, Y. Muro, and H. Aoki, J. Phys. Soc. Jpn. 76, 051010 (2007)

[119] Y. Okuda, Y. Miyachi, Y. Ida, Y. Takeda, C. Tonohiro, Y. Ouchida, T. Yamada, N. D. Dung, T. D. Matsuda, Y. Haga, T. Takeuchi, M. Hagiwara, K. Kindo, H. Harima, K. Sugiyama, R. Settai, and Y. Onuki, J. Phys. Soc. Jpn. 76, 044708 (2007)

[120] S. Khim, J. F. Landaeta, J. Banda, N. Banon, M. Brando, P. M. R. Brydon, D. Hafner, R. Küchler, R. Cardoso-Gil, U. Stockert, A. P. Mackenzie, D. F. Agterberg, C. Geibel, and E. Hassinger, arxiv:2101.09522 (2021)

[121] M. Shahzad and P. Sengupta, J. Phys.: Condens. Matter 29, 305802 (2017)

[122] S. Okumura, Y. Kato, and Y. Motome, Physica B: Condensed Matter 536, 223 (2018)

[123] N. F. Yuan, C. L. Wong, and K. Law, Physica E: Low-dimensional Systems and Nanostructures 55, 30 (2014)

[124] N. Read and D. Green, Phys. Rev. B 61, 10267 (2000)