Visualizing band selective enhancement of quasiparticle lifetime in a metallic ferromagnet

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Electrons navigate more easily in a background of ordered magnetic moments than around randomly oriented ones. This fundamental quantum mechanical principle is due to their Bloch wave nature and also underlies ballistic electronic motion in a perfect crystal. As a result, a paramagnetic metal that develops ferromagnetic order often experiences a sharp drop in the resistivity. Despite the universality of this phenomenon, a direct observation of the impact of ferromagnetic order on the electronic quasiparticles in a magnetic metal is still lacking. Here we demonstrate that quasiparticles experience a significant enhancement of their lifetime in the ferromagnetic state of the low-density magnetic semimetal EuCd\textsubscript{2}As\textsubscript{2}, but this occurs only in selected bands and specific energy ranges. This is a direct consequence of the magnetically induced band splitting and the multi-orbital nature of the material. Our detailed study allows to disentangle different electronic scattering mechanisms due to non-magnetic disorder and magnon exchange. Such high momentum and energy dependence quasiparticle lifetime enhancement can lead to spin selective transport and potential spintronic applications.
The development of long-range electronic order has a strong impact on electronic structure and transport properties of quantum materials. For charge density wave (CDW) and spin density wave (SDW) orders that are characterized by a finite-$q$ wave vector, this is a result of band folding and FS reconstruction due to new (larger) periodicity in the crystal. This has been observed in a number of systems including NbSe$_2$, Fe pnictides, Fe$_3$GeTe$_2$, and CeSb. In contrast, for ferromagnetic (FM) order the periodicity remains unchanged, but instead the bands experience a FM exchange splitting, leading to different FSs for majority and minority carriers. The effect of such band splitting on the properties of itinerant carriers and the impact of their coupling to fluctuations of the magnetic moments are important open questions that we address here. Previous studies have focused on itinerant magnets with 3$d$ transition metals, where electronic bands are broad due to the strongly correlated nature of the system and the observed effects on quasiparticle properties are small. The phenomenon of FM band splitting was demonstrated, for example, in elemental Ni, and a more recent study of Fe$_3$GeTe$_2$ also revealed FM exchange splitting with reduced quasiparticle coherence. Rare-earth-based FM materials with local magnetic moments and weakly correlated conduction electron bands are a much better platform for studying the impact of FM order on electronic quasiparticle properties. Here, we investigate a FM variant of EuCd$_2$As$_2$, which has received much attention recently as a candidate magnetic Weyl semimetal displaying FM exchange splitting with reduced quasiparticle coherence. In addition to the band splitting, we also observed a large enhancement of quasiparticle lifetime that accompanies the FM transition. This can be clearly seen in the raw data shown in Fig. 1e, f, where a very sharp band is present only below $T_C$. In Fig. 2a–j we show the detailed temperature evolution of the band dispersion measured using 6.79 eV photons at selected temperatures between 5 and 60 K. The results were reproduced using several samples and temperature cycling. As the sample undergoes a FM transition around $T_C = 26$ K, two significant features can be observed. One is the enhancement of the quasiparticle lifetime at the inner hole pocket, and the other is the downward shift of the fully occupied band centered at $\Gamma$ with decreasing temperature below $T_C$. A key observation is that the enhancement of quasiparticle lifetime occurs predominantly for the inner hole band and only over a limited energy range, which changes with temperature. This can be seen in Fig. 2a–d, where the hole band forming the inner circular Fermi pocket is sharp until it reaches the binding energy that roughly corresponds to the top of the fully occupied center hole band (indicated by the black/red/orange arrows). This effect suggests a significant interband scattering between the inner hole band and the center hole band, while intraband scattering is strongly suppressed below $T_C$. As we show in our theory modeling below, the increased lifetime of the inner band can be associated with a reduced impurity scattering rate of majority carriers (compared to minority carriers) due to phase space constraints.

To better visualize the band splitting and suppression of the scattering effect at the FM transition, we performed a detailed analysis summarized in Fig. 3. Panel (a) shows momentum distribution curves (MDCs) at the Fermi energy measured at various temperatures. The changes in the electronic structure at the magnetic transition temperature of $\sim 26$ K are quite prominent. Two well-separated bands at low temperatures merge into one broad band above the transition temperature. In addition, broad peak appears at $k_y = 0$ due to upward shift of the fully occupied center band. To demonstrate quantitatively the enhancement of quasiparticle lifetime, we plotted the full-width half maximum (FWHM) of the inner hole band extracted by using Lorentzian fitting to MDC in Fig. 3c. We also plotted the FWHM of the left side of bands, extracted from multi-peak Lorentzian fits to MDCs (shown in Fig. 3a), as a function of temperature in panel (g). The open red triangles represent the broad outer band, and the black filled squares represent the inner sharp band. Interestingly, the graph somewhat resembles the temperature-dependent resistance graph, shown in Fig. 1b, especially for the sharp band: slight upturn above the transition temperature followed by rapid decrease of FWHM below the $T_C$. Although both outer and inner
bands experience sharpening of the band, the effect is about three
times larger for the inner band. If we compare the data from
inner band at 5 to 30 K data, the FWHM is about six times
smaller. The other interesting feature is the continuous downward
shift of the center hole band with the decreasing temperature
below the magnetic transition. As we can see from Fig. 2, the top
of the center hole band almost touches the Fermi level and stays
at the same energy above 26 K. As the sample temperature
decreases, the center hole band continuously moves downward
and reaches around 150 meV below Fermi level at 5 K. In Fig. 1b,
we plot the EDC at the Γ point for several temperatures above
and below $T_C$. While the EDCs measured above $T_C$ look very similar,
significant changes occur upon entering FM state. The higher
energy peak disappears and the main peak moves significantly to

Fig. 1 Electronic structure and Fermi surface cuts of EuCd$_2$As$_2$ from ARPES and DFT in para- and FM phase, crystal structure, and resistivity. a Crystal structure of EuCd$_2$As$_2$. b Temperature-dependent normalized resistivity, $\rho(T)/\rho(300K)$, where $\rho(300K) \approx 4 \times 10^{-4} \, \Omega \, \text{cm}$. c, d FS results from ARPES measurements at 40 and 10 K, respectively, where $T_C = 26$ K is FM transition temperature. e, f ARPES intensity along the black dashed lines in (c, d) measured at 40 and 10 K, respectively. The orange arrow points to the bands crossing the Fermi level; the green arrow points to the fully occupied hole band at the center; the black arrow points to a possible splitting of the bands at 40 K. The color scale shows relative photoelectron intensity in panels (c-f). g, h FS calculated using DFT in paramagnetic and FM states, respectively. Color scale shows probability of finding available electronic state. i, j Band dispersion from DFT calculations along the black dashed line in (c). Bands undergo approximately $k$-independent rigid (Zeeman) energy shifts in the FM phase.

Fig. 2 Temperature evolution of electronic band dispersion in EuCd$_2$As$_2$. a-j Band dispersion of measured using 6.79 eV photons at indicated temperatures between 5 and 60 K. The arrows mark the energy above which enhancement of quasiparticle lifetime occurs. Black filled circles denote the top of an inner hole band, which continuously drops in energy below $T_C$. Blue stars point out the splitting of hole bands occurs on the right side. Red crosses mark the energy at which the splitting of hole bands occurs on the right side of Γ point.
higher binding energies. Below ~15 K, an additional shoulder appears and increases in intensity until it reaches intensity of the main peak. The energy location of the top of the center hole band seems to follow an order parameter like behavior of the magnetic ordering in EuCd₂As₂. By extracting the peak positions of the energy distribution curves, i.e., the top of the center hole band, we plotted the result in Fig. 3d showing a clear transition and enhancement of the Zeeman splitting that is a response to increasing internal field (i.e., FM order parameter) as the temperature is decreased. Figure 3e, f shows MDCs for the right side of the hole bands marked with blue stars in Fig. 2. A single band splits into two components below the transition temperature. Furthermore, the splitting point of two bands gets close to 𝐸_𝐹 as temperature approaches to the transition temperature.

The enhancement of the quasiparticle lifetime below 𝑇_𝐶 reflects changes in the imaginary part of self-energy. Via a Kramers-Kronig relation, it is related to the real part of the self-energy, which contributes to the quasiparticle binding energy. The energy shift arising from the real part of the self-energy, however, is a relatively small effect [estimated to be of the order of meV or less(F18)] compared to band shifts due to the magnetic Zeeman splitting and electron-lattice interactions (e.g., due to magnetostriiction), which move the central band to higher binding energies.

Discussion
To gain insight into the experimentally observed phenomenon of band and energy-dependent quasiparticle lifetimes in the FM state, we consider a phenomenological model of itinerant holes coupled to magnetic Eu moments by exchange constant 𝐽. The Eu moments (spin 𝑆 = 7/2) interact ferromagnetically with each other with exchange constant 𝐽_𝐸. Comparison to ARPES and DFT results (see Fig. 1), suggests using a quadratic hole-like dispersion 𝜖_𝐤 = −ℏ^2𝐤^2/(2𝑚_𝑣) + 𝜇 with momentum 𝐾, electron mass 𝑚_𝑣, and chemical potential 𝜇. We also include potential disorder that arises, for example, from Eu vacancies(F12). Importantly, all model parameters are set by comparison to experiment: 𝜇 is determined by the carrier density 𝑛, which we choose to be close to the value obtained from Hall measurements 𝑛_𝐻 ≈ 2.35 × 10^26 m^−3, 𝑆_𝐵 = 165 meV follows from the observed (Zeeman) band shift in the FM state, 𝑆_𝐵^2 = 0.15 meV is set by the experimental FM transition temperature 𝑇_𝐹 = 26 K, and the disorder strength is fixed from the observed quasiparticle lifetime ≈ 0.04 ps of the majority band at low temperatures.

We calculate the spin-dependent electronic scattering rates in the FM phase, Γ_σ = 1/(2𝜏_σ) with lifetime 𝜏 and  𝜂 = ↑, ↓, within the second-order Born approximation (see “Methods” and SI for details). These rates can be directly compared to the ARPES results shown in Fig. 3 [see panel (g)]. There are two scattering channels for holes in the FM phase, impurity scattering and magnetic scattering involving magnon exchange: Γ_σ = Γ_σ,imp + Γ_σ,mag. Both acquire an explicit spin dependence in the FM phase as we explain next. To first order in the electron-magnon coupling ℱ, the hole bands split into majority (minority) bands, where the electronic spin projection is (anti-)parallel to the magnetization: 𝜖_𝐤 → 𝜖_𝐤,σ − 𝜎(𝑇) with 𝜎(𝑇) = 𝐿_μ ≈ −0.33 (ℏ_olute band Exp., Mag. carrier Exp., Imp.,~carrier Tc) [3/2].

The second term accounts for the reduction of saturation magnetization due to fluctuations. This results in different densities 𝑛_σ for majority (𝜂 = ↑) and minority (𝜂 = ↓) carriers and different Fermi wave vectors 𝑘_𝐹,↑ < 𝑘_𝐹,↓ for hole pockets [see Fig. 4a]. Due to this band shift the impurity scattering rates of majority and minority carriers become unequal as Γ_σ,imp,↑ ≠ Γ_σ,imp,↓ is proportional to the density of states at the Fermi energy(F19). Majority hole carriers have a smaller FS volume and therefore experience less impurity scattering, Γ_σ,imp,↑ < Γ_σ,imp,↓ due to a reduced scattering phase space. An explicit spin dependence of the magnetic

![Fig. 3 Detailed temperature evolution of the electronic structure of EuCd₂As₂ obtained using ARPES.](image-url)

- (a) MDCs at the Fermi energy measured at temperatures between 5 and 60 K. The dashed lines are a guide to eye-marking locations of MDC peaks. Comparing peak position at 7 ≥ 25 K and T = 5 K, note that hole peak (spin) splits into two peaks in opposite directions. The dashed lines are a guide to eye-marking locations of MDC peaks. Comparing peak position at 7 ≥ 25 K and T = 5 K, note that hole peak (spin) splits into two peaks in opposite directions.
- (b) EDCs at 𝑘_𝑥 = 0 at temperatures between 5 and 50 K. Black lines mark locations of peaks. Note that the central peak is (spin) split into two at low temperatures.
- (c) Full-width half maximum (FWHM) data obtained from Lorentzian fitting the width of the peaks. The solid lines are theory results of the spin-dependent scattering rates of minority (red) and majority (black) carriers. We find good agreement under the assumption that the width in energy and in momentum space is proportional to each other.

![Intensity (arb. units)](image-url)

- (d) Hole Band Top E_{h,σ}(T) at 5 and 15 K, T_c = 26 K. Blue stars indicate the peak position. MDCs for which the two peaks merge are marked in blue.
- (e) FWHM of the MDC peaks on the left side in (a) as a function of temperature. Red triangles represent the very left peak (broad outer band), and black squares represent the second left peak (very sharp inner band). Error bars represent the standard deviation of fitting the width of the peaks. The solid lines are theory results of the spin-dependent scattering rates of minority (red) and majority (black) carriers. We find good agreement under the assumption that the width in energy and in momentum space is proportional to each other.

![Intensity (arb. units)](image-url)

- (f) Intensity (arb. units) of MDCs at the Fermi energy measured at temperatures between 5 and 60 K. Black lines mark locations of MDC peaks. Comparing peak position at 7 ≥ 25 K and T = 5 K, note that hole peak (spin) splits into two peaks in opposite directions. The dashed lines are a guide to eye-marking locations of MDC peaks. Comparing peak position at 7 ≥ 25 K and T = 5 K, note that hole peak (spin) splits into two peaks in opposite directions.
theoretical model with function of $T$ pronounced in low-density semimetals such as EuCd$_2$As$_2$. Magnetic $T$ scattering rate, that the majority hole carriers experience a larger magnetic temperatures due to a reduced magnon density. The origin of the sharp increase of the resistivity close to $T_C$ can be explained by scattering with magnons that proliferate at the phase transition. c) Ratio of minority over majority quasiparticle scattering rates, $\Gamma_{\uparrow}/\Gamma_{\downarrow}$, as a function of $T$ for different carrier densities $n/\nu_0$. The ratio increases for decreasing $T$ and $n$, and is larger than unity. The blue dashed line marks the experimental value of $\Gamma_{\uparrow}/\Gamma_{\downarrow}$ at $T=5$ K extracted from Fig. 3g.

Using parameters describing EuCd$_2$As$_2$, we find in Fig. 4b, c that the majority hole carriers experience a larger magnetic scattering rate, $\Gamma_{\text{mag,}\uparrow} > \Gamma_{\text{mag,}\downarrow}$, but a smaller impurity scattering rate, $\Gamma_{\text{imp,}\uparrow} < \Gamma_{\text{imp,}\downarrow}$. Impurity scattering dominates in the FM state (except close to $T_C$), which explains why the majority band appears sharper, $\Gamma_{\uparrow} < \Gamma_{\downarrow}$ for $T \ll T_C$. The ratio of total scattering rates, $\Gamma_{\uparrow}/\Gamma_{\downarrow}$, increases as temperature is lowered and, at fixed temperature, as $n$ becomes smaller, making the effect more pronounced in low-density semimetals such as EuCd$_2$As$_2$. Magnetic scattering only dominates close to $T_C$ but is suppressed at lower temperatures due to a reduced magnon density. The origin of the experimentally observed majority band lifetime enhancement can thus be identified with lower impurity scattering rates for the majority compared to minority holes. On the other hand, the sharp increase of the resistivity close to $T_C$ can be explained by scattering with magnons, which peaks at the phase transition. Finally, taking interband scattering to additional bands into account, our model naturally accounts for the experimentally observed energy dependence of the quasiparticle scattering rates, and the rapid broadening observed at energies where elastic scattering to the central hole pocket exists [see red arrow in Fig. 2a–d].

To conclude, we report a direct observation of the evolution of quasiparticle properties into the FM phase of magnetic semimetal EuCd$_2$As$_2$. In addition to energy band shifts and renormalizations proportional to the magnetization, we observe a large enhancement of the electronic carrier lifetime in selected bands and energy ranges. Investigating the temperature dependence of the lifetimes allows us to quantify the importance of different electronic scattering mechanisms, and to quantitatively relate our experimental observations to the impact of magnetic order and magnetic fluctuations on the properties of the itinerant carriers. Our work provides a direct link between quasiparticle lifetimes and loss-of-spin disorder suppression of the resistivity, and reveals a mechanism towards spin selective transport via lifetime tuning of spin-polarized carriers.

**Methods**

Crystal growth and electrical transport. Single crystals of EuCd$_2$As$_2$ were grown using flux growth method as described in ref. 12. Temperature-dependent electrical transport measurements were carried out in a Quantum Design Physical Property Measurement System (PPMS) for 1.8 K $\leq T \leq$ 300 K. The samples for electrical transport measurements were prepared by attaching four Pt wires using DuPont 4929N silver paint. The current was applied in ab plane with $I=1$ mA and $f=17$ Hz.

ARPES measurements. Samples used for ARPES measurements were cleaved in situ at 40 K under ultrahigh vacuum (UHV). The data were acquired using a tunable VUV laser ARPES system that consists of Omicron Scienta DA30 electron analyzer, a picosecond Ti: Sapphire oscillator, and fourth harmonic generator20. Data were collected with photon energies of 6.05–6.79 eV. Momentum and energy resolutions were set at $\approx 0.005$ Å$^{-1}$ and 2 meV. The size of the photon beam on the sample was $\approx 30$ μm. The measurements were reproduced using several single crystals and extensive temperature cycling to exclude possibility of sample aging effects.

DFT calculations. Band structures with spin-orbit coupling (SOC) in density functional theory (DFT)21,22 have been calculated using a PBE exchange correlation functional, a plane-wave basis set and projector augmented wave method24 as implemented in VASP25,26. For ferromagnetic (FM) EuCd$_2$As$_2$, a Hubbard-like27 U value of 5.0 eV is used to account for the half-filled strongly localized Eu 4f orbitals, while for non-magnetic (NM) EuCd$_2$As$_2$, the Eu 4f orbitals are treated as core electrons. For bulk band structures of a Monkhorst-Pack28 (11 x 11 x 7) k-point mesh with a Gaussian smearing of 0.05 eV including the $\Gamma$ point and a kinetic energy cutoff of 318 eV have been used. Experimental lattice parameters15 have been used with atoms fixed in their bulk positions. A tight-binding model based on maximally localized Wannier functions29–31 was constructed to reproduce closely the bulk band structure including SOC in the range of $E_{F} \pm 1$ eV with Eu $sdf$, Cd $sp$, and As $p$ orbitals. Then the 2D bulk band dispersions and FSs have been calculated with WannierTools32.

**Theoretical model.** Our minimal model to describe the observed band-selective sharpening of the ARPES line-width in the FM phase of EuCd$_2$As$_2$ is composed by three parts: $H = H_{J} + H_{\text{H}} + H_{\text{S}}$. The electronic component, $H_{J} = \sum_{j} \xi_{j} \hat{c}_{j}^{\dagger} \hat{c}_{j} + \sum_{k} \epsilon_{k} \sum_{\sigma} \hat{c}_{k\sigma}^{\dagger} \hat{c}_{k\sigma} e^{-i\mathbf{q}_{k} \cdot \mathbf{r}_{j}}$, accounts for electrons in a parabolic hole-like band, $\xi_{j} = h^{2}/(2m^{*}) + W - m_{o}$, with effective mass $m^{*} = m_{o}$. Here, $m_{o}$ denotes the rest-electron mass and $W$ denotes the energy associated with the top of the band. The electrons experience a random potential $\mathbf{v}(\mathbf{r}) = \sum_{m_{f}} \mathbf{v}_{m_{f}}(\mathbf{r}) \delta(\mathbf{r} - \mathbf{r}_{m_{f}})$ created by $N_{\text{imp}}$ point-like impurities at random sites $\mathbf{r}_{j}$. Besides, $H_{J} = -\sum_{j} \sum_{\sigma} S_{j} \cdot \mathbf{S}_{j}$ describes $N$ Eu $S=7/2$ magnetic moments on a hexagonal lattice12 with nearest-neighbor FM coupling $J_{1,2} > 0$. The interaction between the electrons and the localized moments takes the form $H_{J} = -\sum_{j} \sum_{\sigma} \hat{S}_{j} \cdot \sigma_{j} \mathbf{S}_{j}$, where $\hat{S}_{i} = \frac{3}{2} \sum_{k} \sum_{\sigma} e^{-i\mathbf{q}_{k} \cdot \mathbf{r}_{i}} \mathbf{c}_{k\sigma}^{\dagger} \mathbf{c}_{k\sigma}$ is the spin operator of the conduction electrons, and $\mathbf{R}_{i}$ denotes the position of site $i$. 

Fig. 4 Theoretical model results. a) Spin resolved carrier (hole) density $n_{\sigma}$ as a function of temperature $T$ below the magnetic transition $T_{C} \approx 26$ K in the theoretical model with $n = n_{\uparrow} + n_{\downarrow}$. We choose $n = 2 \nu_{0}/3$, where $\nu_{0} = 2.35 \times 10^{26}$ m$^{-3}$ is extracted from Hall measurements, $JS_{\uparrow}^{2} = 165$ meV, and $d_{\text{obs}}^{2} = 0.15$ meV. Inset shows Zeeman energy shift $\delta(\mathbf{r})$ proportional to magnetization in FM phase. b) Total minority and majority scattering rates $\Gamma_{\downarrow}$ and $\Gamma_{\uparrow}$ (solid) as a function of $T$, where $\Gamma_{\downarrow} = \Gamma_{\text{imp,}\downarrow} + \Gamma_{\text{mag,}\downarrow}$. Dashed lines show impurity scattering contributions, which dominate at low $T$. Upturn close to $T_{C}$ is caused by scattering with magnons that proliferate at the phase transition. c) Ratio of minority over majority quasiparticle scattering rates, $\Gamma_{\uparrow}/\Gamma_{\downarrow}$, as a function of $T$ for different carrier densities $n/\nu_{0}$. The ratio increases for decreasing $T$ and $n$, and is larger than unity. The blue dashed line marks the experimental value of $\Gamma_{\uparrow}/\Gamma_{\downarrow}$ at $T=5$ K extracted from Fig. 3g.
At low temperatures, the fluctuations about the ordered phases are small and we can map the previous Hamiltonian into an interacting electron-magnon problem via a Holstein-Primakoff transformation, which takes a simpler form for only a small number of magnons are excited in the system. The resulting electron-magnon interaction has four types of vertices that encode both spin-dependent interactions.

Within first-order perturbation theory, we find that the electron band is aligned with the magnetization direction, it is shifted downward and via a Holstein-Primakoff transformation, which takes a simpler form for only a small number of magnons are excited in the system. The resulting electron-magnon interaction has four types of vertices that encode both spin-dependent interactions.

To calculate the magnetic scattering rate we apply second-order perturbation theory in the coupling $J$, which results in

$$
\Gamma_{\text{magn}} = \frac{\pi J^2}{2} \int d\Omega \left( n_0(\Delta_1 + \Delta_2) + \frac{1}{2} \frac{n_0(\Omega)}{\sqrt{\Omega}} \right),
$$

where $\Delta = 0$ and $\delta = 1$ for spin-up. The integral in Eq. (4) was calculated numerically assuming a quadratic dispersion for the magnons $\Omega_0$. The magnetic impurities were treated via self-average and the impurity scattering was calculated using the first-order Born approximation, yielding (see Supplementary Information for details)

$$
\Gamma_{\text{imp}} = \frac{n_{\text{imp}} \mu^2}{h} \frac{1}{V} \sum_{\sigma} \delta(F_\sigma - \xi_{\text{imp}}),
$$

where $n_{\text{imp}} = N_{\text{imp}}/V$ denotes the impurity density, where $V$ is the system volume. We set $n_{\text{imp}} \mu^2 = 7.9 \times 10^{-14} \text{eV}^2 \text{cm}^2$ in Fig. 4, which we estimated from the experimental quasiparticle scattering rate $0.125 \text{ps}$ for the majority band.

Data availability

Relevant data for the work are available at the Materials Data Facility: https://doi.org/10.18126/1/mute-imp8.

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References

1. Borisenko, S. V. et al. Two energy gaps and Fermi-surface "Arcs" in NbSe$_2$. Phys. Rev. Lett. 102, 166402 (2009).
2. Liu, C. et al. Evidence for a Lifshitz transition in electron-doped iron arsenic superconductors at the onset of superconductivity. Nat. Phys. 6, 419–423 (2010).
3. Kondo, T. et al. Unexpected Fermi-surface nesting in the pnictide parent compounds BaFe$_2$As$_2$ and CaFe$_2$As$_2$ revealed by angle-resolved photoemission spectroscopy. Phys. Rev. B 81, 060507 (2010).
4. Jo, N. H. et al. Anisotropic physical properties and pressure dependent magnetic ordering of CaRu$_2$Fe$_2$. Phys. Rev. B 94, 184413 (2016).
5. Kuroda, K. et al. A devil's transition of the electronic structures in CaSn. Nat. Commun. 11, 1–9 (2020).
6. Eastman, D. E., Himpel, F. J. & Knapp, J. A. Experimental band structure and temperature-dependent magnetic exchange splitting of nickel using angle-resolved photoemission. Phys. Rev. Lett. 40, 1514–1517 (1978).
7. Xu, X. et al. Signature for non-Stoner ferromagnetism in the van der Waals ferromagnet Fe$_3$GeTe$_2$. Phys. Rev. B 101, 201104 (2020).
8. Hua, G. et al. Dirac semimetal in type-IV magnetic space groups. Phys. Rev. B 98, 201116 (2018).
9. Wang, Lin-L. et al. Single pair of Weyl fermions in the half-metallic semimetal EuCd$_2$As$_2$. Phys. Rev. B 99, 245147 (2019).
10. Söhl, J.-R. et al. Ideal Weyl semimetal induced by magnetic exchange. Phys. Rev. B 100, 201102 (2019).
11. Ma, J.-Z. et al. Spin fluctuation induced Weyl semimetal state in the paramagnetic phase of EuCd$_2$As$_2$. Adv. Phys. 59, 4718 (2019).
12. Jo, N. H. et al. Manipulating magnetism in the topological semimetal EuCd$_2$As$_2$. Phys. Rev. B 101, 144002 (2020).
13. Taddei, K. M. et al. Spin-canting driven Weyl physics in EuCd$_2$As$_2$. Preprint at https://arxiv.org/abs/2012.01555 (2020).
14. Artmann, A., Mewis, A., Roepke, M. & Michels, G. AM$_2$X$_3$-Verbindungen mit CaAl$_2$Si$_2$-Struktur. XI. Struktur und Eigenschaften der Verbindungen AM$_2$X$_3$ (A: Eu, Yb; X: P, As, Sb). Z. f.är. anorganische und Allg. Chem. 622, 679–682 (1996).
15. Schellenberg, L., Pfannenschmidt, U., Eul, M., Schwickert, C. & Pöttgen, R. A.
16. Kohn, W. & Sham, L. J. Self-consistent equations including exchange and correlation effects. Phys. Rev. 140, A1133–A1138 (1965).
17. Perdew, J. P., Burke, K. & Ernzerholf, M. Generalized gradient approximation made simple. Phys. Rev. Lett. 77, 3865–3868 (1996).
18. Blöchl, P. E. Projector augmented-wave method. Phys. Rev. B 50, 17953–17979 (1994).
19. Kresse, G. & Furthmüller, J. Efficient iterative schemes for ab initio total-energy calculations using a plane-wave basis set. Phys. Rev. B 54, 11169–11186 (1996).
20. Kresse, G. & Furthmüller, J. Efficiency of ab-initio total energy calculations for metals and semiconductors using a plane-wave basis set. Computational Mater. Sci. 6, 15–50 (1996).
21. Dudarev, S. L., Botton, G. A., Savrasov, S. Y., Humphreys, C. J. & Sutton, A. P. Electron-energy-loss spectra and the structural stability of nickel oxide: an LSDA+U study. Phys. Rev. B 57, 1505–1509 (1998).
22. Monkkor, H. J. & Pack, J. D. Special points for Brillouin-zone integrations. Phys. Rev. B 13, 5188–5192 (1976).
23. Marzari, N. & Vanderbilt, D. Maximally localized generalized Wannier functions for composite energy bands. Phys. Rev. B 56, 12847–12865 (1997).
24. Souza, J., Marzari, N. & Vanderbilt, D. Maximally localized Wannier functions for entangled energy bands. Phys. Rev. B 65, 035109 (2001).
25. Marzari, N., Mostofi, A. A., Yates, J. R., Souza, I. & Vanderbilt, D. Maximally localized Wannier functions: theory and applications. Rev. Mod. Phys. 84, 1491–1475 (2012).
26. Wu, Q., Zhang, S., Song, H. F., Troyer, M. & Soluyanov, A. A. Wanniertools: an open-source software package for novel topological materials. Comp. Phys. Comm. 224, 405 (2018).
27. Auerbach, A. Interacting Electrons and Quantum Magnetism (Springer, 1994).
28. Jo, N. H. et al. Visualizing band selective enhancement of quasiparticle lifetime in a metallic ferromagnet. Materials Data Facility. https://doi.org/10.18126/1/mute-imp8 (2021).

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Author contributions

N.-H.J. and Y.W. contributed equally to the present work. N.H.J. and B.K. grew and characterized the samples under the supervision of S.L.B. and P.C.C. Y.W., N.H.J., K.L., and B.S. acquired and analyzed ARPES data under the supervision of A.K. L.-L.W. carried out the DFT calculations. T.V.T. and P.P.O. developed the theory modeling and performed analytical calculations. All authors contributed to writing the paper.

Competing interests

The authors declare no competing interests.
