

Origin of the anomalous Hall effect in a disordered ferromagnetic $\text{Ho}_{1.25}\text{Au}_{0.75}\text{Si}_{1.55}$ single crystal

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The anomalous Hall effect (AHE) serves as a pivotal transport phenomenon for deciphering the interplay between magnetic spin textures and topological bands in magnetic materials, with its origin attributed to intrinsic (momentum-space Berry curvature linked to Weyl or Dirac point) and extrinsic (spin-dependent scattering, i.e., skew scattering and side-jump) mechanisms. The complex magnetic structure and strong spin-orbit coupling effect of rare-earth magnetic materials make them an important platform for studying AHE. Here, we report a disordered $\text{Ho}_{1.25}\text{Au}_{0.75}\text{Si}_{1.55}$ single crystal and investigate its magnetic and transport properties. In this single crystal, Ho-Au mixed occupancy on the $2c$ site and vacancies on the Si $2b$ sublattice give rise to pronounced chemical disorder. $\text{Ho}_{1.25}\text{Au}_{0.75}\text{Si}_{1.55}$ belongs to the rare-earth ferromagnetic material with a magnetic ordering temperature of 8 K (T_c) and easy magnetization along the c axis. The magnetoresistance (MR) of $\text{Ho}_{1.25}\text{Au}_{0.75}\text{Si}_{1.55}$ exhibits different behaviors at high and low temperatures in the $H \parallel ab$ and $I \parallel c$ configurations. At 3 K ($T < T_c$), the MR is initially positive and becomes negative with the magnetic field further increasing. This is due to the gradual disappearance of magnetic domain-wall scattering as the magnetization process approaches saturation. At 100 K ($T > T_c$), the MR remains negative as a result of the suppression of the scattering from spin fluctuations. With regard to the AHE, considering the scaling behavior between the anomalous Hall resistivity ρ_{xz}^A and the longitudinal resistivity ρ_{xx} , the origin of the AHE in $\text{Ho}_{1.25}\text{Au}_{0.75}\text{Si}_{1.55}$ can be described by the skew scattering mechanism. The dominance of skew scattering is likely driven by the structural disorder present in $\text{Ho}_{1.25}\text{Au}_{0.75}\text{Si}_{1.55}$: the Ho-Au mixed occupancy and Si vacancies create a random potential landscape and break local chemical periodicity, which are expected to enhance asymmetric carrier scattering. The anomalous Hall angle Θ_{AH} and anomalous Hall factor S_H of $\text{Ho}_{1.25}\text{Au}_{0.75}\text{Si}_{1.55}$ are 0.49% and 0.03 V^{-1} , respectively, at 3 K, and both decrease as the temperature rises. The small Θ_{AH} and S_H are attributed to the finite s - f exchange coupling in this $4f$ localized-moment ferromagnet and to the enhanced scattering environment associated with Ho-Au mixed occupancy and Si vacancies. This work establishes disordered $\text{Ho}_{1.25}\text{Au}_{0.75}\text{Si}_{1.55}$ as a platform for studying the role of structural disorder in skew-scatter-dominated AHE in rare-earth localized-moment ferromagnets.

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I. INTRODUCTION

The anomalous Hall effect (AHE) refers to the phenomenon whereby, in magnets, even in the absence of an external magnetic field, the net magnetization can induce a spontaneous Hall effect [1]. As a pivotal transport phenomenon in magnetic materials, it acts as a direct probe for deciphering the interplay between magnetic spin textures and topological band [2]. The Hall resistivity in ferromagnetic (FM) materials increases dramatically with the increase of the external magnetic field and finally saturates in the high-field

regime [3,4]. The origin of the AHE has gradually become clear with the introduction of these concepts of topology and geometry related to the AHE. The AHE originates from two microscopic mechanisms, intrinsic and extrinsic ones. The intrinsic contributions derived from the momentum-space Berry curvature, which is tightly linked to band topological features such as Weyl or Dirac points [5–8]. The extrinsic contributions stem from spin-dependent scattering, including skew scattering and side-jump [9–11]. Recently, the AHE has attracted considerable attention in the study of rare-earth magnetic materials. On the one hand, the localized magnetic moments of $4f$ electrons in rare-earth elements and the itinerant electronic magnetism of transition metals collectively give rise to complex magnetic ordered states. On the other hand, rare-earth elements exhibit a strong spin-orbit coupling effect

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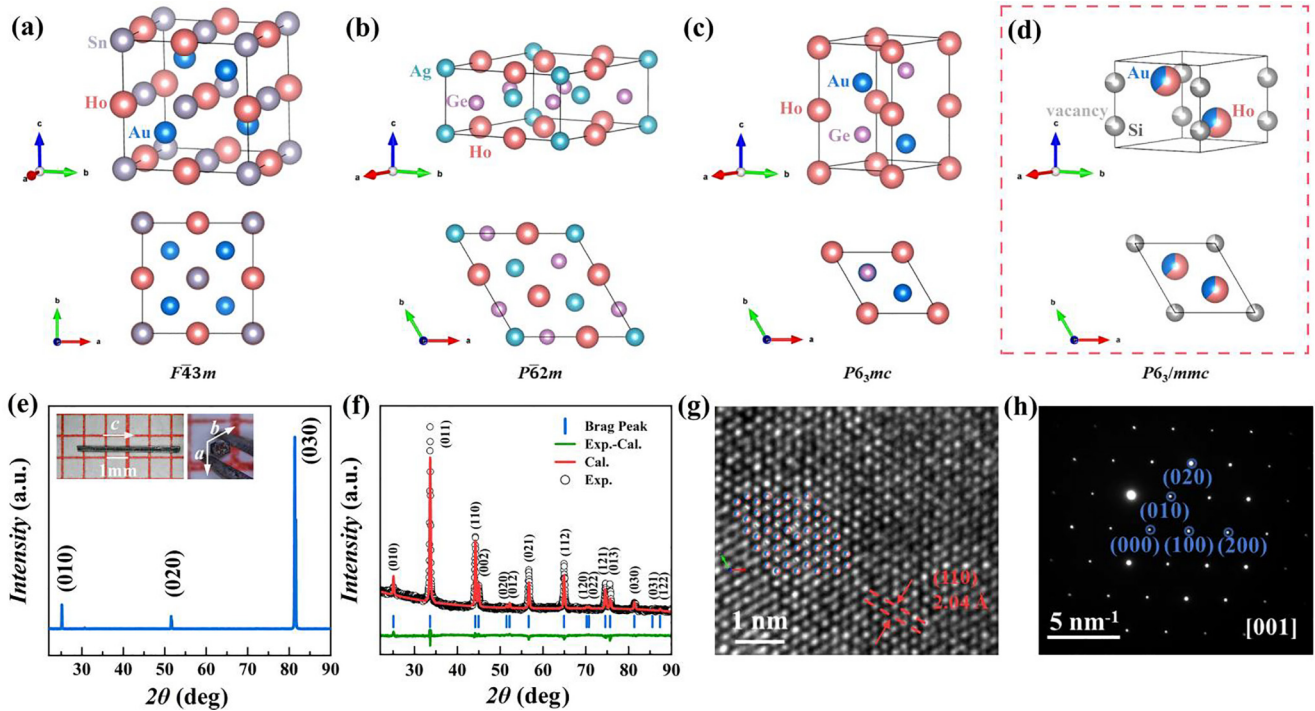


FIG. 1. Several typical crystal structures of the HoTX series, including (a) HoAuSn, (b) HoAgGe, and (c) HoAuGe. (d) The crystal structure of Ho_{1.25}Au_{0.75}Si_{1.55}. (e) X-ray diffraction (XRD) pattern of a single crystal measured on the (010) surface. Inset shows the photographs of an Ho_{1.25}Au_{0.75}Si_{1.55} single crystal. (f) The experimental and calculated results of the powder XRD patterns of crushed Ho_{1.25}Au_{0.75}Si_{1.55} crystals based on $P6_3/mmc$ at room temperature. (g) Transmission electron microscopy (TEM) image of Ho_{1.25}Au_{0.75}Si_{1.55} single crystal taken along the [001] zone direction. The red, blue, silver, and white spheres represent Ho, Au, Si, and a vacancy, respectively. Scale bar = 1 nm. (h) Electron-diffraction patterns of an Ho_{1.25}Au_{0.75}Si_{1.55} single crystal taken along [001].

due to their relatively large atomic masses. Both types of factors can significantly modulate the AHE response, making these materials an ideal system for investigating AHE mechanisms [12–15].

Among rare-earth magnetic materials, the RTX family (R = rare earths, T = transition metals, and X = p -block elements) represents a system characterized by diverse crystal structures and a wealth of novel physical phenomena [16–18]. The RTX series incorporates $4f$ electron correlation as well as a variety of crystal symmetries (twisted kagome [19], half-Heusler [20,21], polar LiGaGe-type [18], etc.), a wide range of magnetically ordered temperatures (ranging from extremely low temperatures [22] to 510 K [23,24]), and non-trivial electronic properties (Kondo effect [25], heavy fermion behavior [26,27], superconductivity [28,29], large magnetoresistance [20,30], etc.). In the RTX family, the HoTX subclass has received increasing attention due to its complex magnetic structure and magnetic effects [18,31–34]. The $4f^{11}$ electron configuration of Ho atoms exhibits strong correlation effects coupled with diverse crystal structures, which enable the HoTX series materials to exhibit interesting physical properties. The crystal structures of several typical materials in this system are shown in Figs. 1(a)–1(c). Among them, HoAuSn belongs to the half-Heusler structure ($F\bar{4}3m$ space group), which is semiconducting in the ground state and transforms into a Weyl semimetal under magnetic field induction, presenting a high mobility and a huge negative magnetoresistance [20,30,35]. In addition, HoAgGe belongs to the ZrNiAl-type structure (space group $P\bar{6}2m$), and the

Ho atoms in the ab plane form a twisted kagome lattice, which endows it with topologically nontrivial properties (e.g., quasitwo-dimensional bands and Dirac intersections), and the Fermi surface topology can be modulated by the magnetic field [19,36]. Recently, researchers [18] observed the AHE in polar semimetallic HoAuGe corresponding to a two-step variable magnetic transition co-driven by delta-lattice magnetoresistance frustration and magnetostrictive coupling. The AHE of HoAuGe mainly stems from intrinsic contributions, possibly related to the Berry curvature in the electron bands induced by the time-reversal symmetry breaking and the polar lattice. Although equimolar HoTX compounds (1 : 1 : 1) such as HoAuSn and HoAuGe exhibit rich topological effects and AHE characteristics, research on the HoTX system remains largely confined to the 1 : 1 : 1 stoichiometry. The structural diversity of nonequimolar HoTX derivatives and their corresponding physical effects have been scarcely explored. Moreover, as localized $4f$ electron systems, the structure-property correlations in these compounds remain poorly understood. As a key magnetoelectric transport phenomenon, the AHE sensitively reflects the interaction between intrinsic spin structures and charge transport, making it an effective tool for investigating the intrinsic properties of nonequimolar HoTX compounds.

In this paper, we report a disordered Ho_{1.25}Au_{0.75}Si_{1.55} single crystal based on the HoTX family and systematically investigate its structural, magnetic, and transport properties. Structural refinement reveals pronounced chemical disorder, including Ho-Au mixed occupancy on the $2c$ site and

vacancies on the Si $2b$ sublattice. Magnetization and heat-capacity measurements indicate a ferromagnetic transition at $T_c = 8$ K, with the c axis serving as the easy magnetization axis. A pronounced AHE is observed in $\text{Ho}_{1.25}\text{Au}_{0.75}\text{Si}_{1.55}$, and scaling analyses of the resistivity and conductivity show that the AHE is dominated by skew scattering. This skew-scatter-dominated AHE is intimately connected to, and likely driven by, the structural disorder present in this compound: the Ho-Au mixed occupancy and Si vacancies create a random potential landscape and break local chemical periodicity, which are expected to enhance asymmetric carrier scattering. This work establishes disordered $\text{Ho}_{1.25}\text{Au}_{0.75}\text{Si}_{1.55}$ as a platform for studying the role of structural disorder in skew-scatter-dominated AHE in rare-earth localized-moment ferromagnets.

II. EXPERIMENT DETAILS

The single crystals of $\text{Ho}_{1.25}\text{Au}_{0.75}\text{Si}_{1.55}$ were grown by the flux method. High-purity Ho powder, Au powder, Si powder, and Sn powder were weighed and placed into a clean corundum crucible according to the molar ratio of Ho : Au : Si : Sn of 1 : 1 : 2 : 15 and then sealed in a quartz tube. The quartz tubes were heated to 1100 °C and held for 12 h, then cooled at a rate of 2 °C/h to 900 °C. The crystals were separated from the Sn flux by centrifugation. The crystals were separated from the tin flux by centrifugation at 900 °C. Finally, gray-black rod-like single crystals were obtained. The surface of the single crystal is bright, and the crystal size is $5 \times 0.3 \times 0.3 \text{ mm}^3$.

Single-crystal and powder x-ray diffraction (XRD) data collection was performed at room temperature on the PANalytical X'Pert diffractometer with Cu K_α radiation ($\lambda = 0.15406 \text{ nm}$) by a conventional scan for a crystal mounted on a sample holder. Rietveld refinement of XRD data was carried out using the Rietica software. The structural characterization has been performed by a Tecnai TF-20 transmission electron microscope (TEM). Electrical transport and heat-capacity measurements were carried out in a Physical Properties Measurement System (Quantum Design, PPMS-9 T, $0 \text{ T} \leq H \leq 9 \text{ T}$, $2 \text{ K} \leq T \leq 400 \text{ K}$). The electrical resistivities were measured via the standard four-probe method with the electric current along the crystallographic c axis on the resistivity mode. The traditional Hall resistivities were measured using the standard seven-probe method at different temperatures and magnetic fields in the ACT mode. The magnetization measurement was carried out by using a Quantum Design Magnetic Property Measurement System (MPMS-XL5, $0 \text{ T} \leq H \leq 5 \text{ T}$, $2 \text{ K} \leq T \leq 400 \text{ K}$).

III. RESULTS AND DISCUSSION

Figure 1(d) illustrates the crystal structure of $\text{Ho}_{1.25}\text{Au}_{0.75}\text{Si}_{1.55}$, which could be well indexed based on the $P6_3/mmc$ space group. For detailed structural refinement information, see Supplemental Material [37]. The refined structure reveals pronounced chemical disorder in $\text{Ho}_{1.25}\text{Au}_{0.75}\text{Si}_{1.55}$. Ho and Au randomly occupy the $2c$ Wyckoff site with respective occupancies of 62.6% (Ho) and 37.4% (Au), while approximately 23% vacancies exist on

the Si $2b$ sublattice. Although the average crystallographic structure is well described by the $P6_3/mmc$ space group, the compound lacks long-range chemical order on the mixed Ho-Au and partially occupied Si sublattices. The random distribution of Ho atoms carrying localized $4f$ moments and nonmagnetic Au atoms gives rise to spatial disorder of local magnetic moments. In rare-earth-based intermetallic compounds, localized $4f$ moments are generally coupled through indirect exchange interactions mediated by conduction electrons [16]. Therefore, the Ho-Au site disorder and Si vacancies are expected to perturb the local exchange environment and make the magnetic exchange interactions spatially nonuniform. Meanwhile, such chemical disorder provides additional scattering centers for conduction electrons and thus can influence carrier-scattering processes. The single-crystal XRD results were collected from the shining surface of the crystals and found to be in the (0/0) family, as shown in Fig. 1(e), and the inset is a photograph of the $\text{Ho}_{1.25}\text{Au}_{0.75}\text{Si}_{1.55}$ single crystal. In addition, in order to obtain accurate structural parameters, we performed the powder XRD measurements for the $\text{Ho}_{1.25}\text{Au}_{0.75}\text{Si}_{1.55}$ (by grinding the $\text{Ho}_{1.25}\text{Au}_{0.75}\text{Si}_{1.55}$ single crystals into powders) and refined them with Rietveld analysis software, as shown in Fig. 1(f). According to the fitting results of the powder XRD, the crystal structure with the $P6_3/mmc$ space group of $\text{Ho}_{1.25}\text{Au}_{0.75}\text{Si}_{1.55}$ single crystal was confirmed, and the lattice constants ($a = b = 4.1049(3) \text{ \AA}$, $c = 4.0223(2) \text{ \AA}$, $\alpha = \beta = 90^\circ$, $\gamma = 120^\circ$) are obtained. As shown in Fig. 1(g), $\text{Ho}_{1.25}\text{Au}_{0.75}\text{Si}_{1.55}$ single crystal was characterized by TEM along the [001] direction at room temperature, and the atomic arrangement is completely consistent with the (001) plane of $\text{Ho}_{1.25}\text{Au}_{0.75}\text{Si}_{1.55}$. The corresponding selected area electron diffraction (SAED) pattern along the [001] direction is shown in Fig. 1(h), which is bright and sharp, demonstrating the good crystallinity in the current study.

As illustrated in Figs. 2(a) and 2(b), the temperature-dependent magnetization $M(T)$ was measured under 0.01 T with the applied magnetic field oriented parallel to the ab plane ($H \parallel ab$) and the c axis ($H \parallel c$). The pronounced disparity between M_{ab} and M_c provides evidence of notable magnetic anisotropy in low-temperature regime, indicating that the extended c axis is more susceptible to magnetization. Based on the $M(T)$ curve, it was determined that $\text{Ho}_{1.25}\text{Au}_{0.75}\text{Si}_{1.55}$ is an FM material with a Curie temperature of 8 K. The temperature dependence of inverse magnetic susceptibility $\chi^{-1}(T)$ curve was fitted by the Curie-Weiss law [38] within the temperature range of $T = 100$ to 300 K and extended to 0 K:

$$\chi(T) = \chi_0 + \frac{C}{T - T_\theta}, \quad (1)$$

where χ_0 is the temperature-independent term encompassing the contribution from the core diamagnetism and the Van Vleck paramagnetism, C is the Curie constant, and T_θ is the Weiss temperature. From the fitting of Eq. (1), the value of $T_\theta \approx 18.76 \text{ K}$ with $H \parallel ab$ and -8.58 K with $H \parallel c$ are obtained, respectively. C is $12.36 \text{ emu K mol}^{-1} \text{ Oe}^{-1}$ ($H \parallel ab$) and $14.87 \text{ emu K mol}^{-1} \text{ Oe}^{-1}$ ($H \parallel c$). The effective magnetic moments are estimated with the relation $\mu_{\text{eff}} = \sqrt{8C/1.25}$.

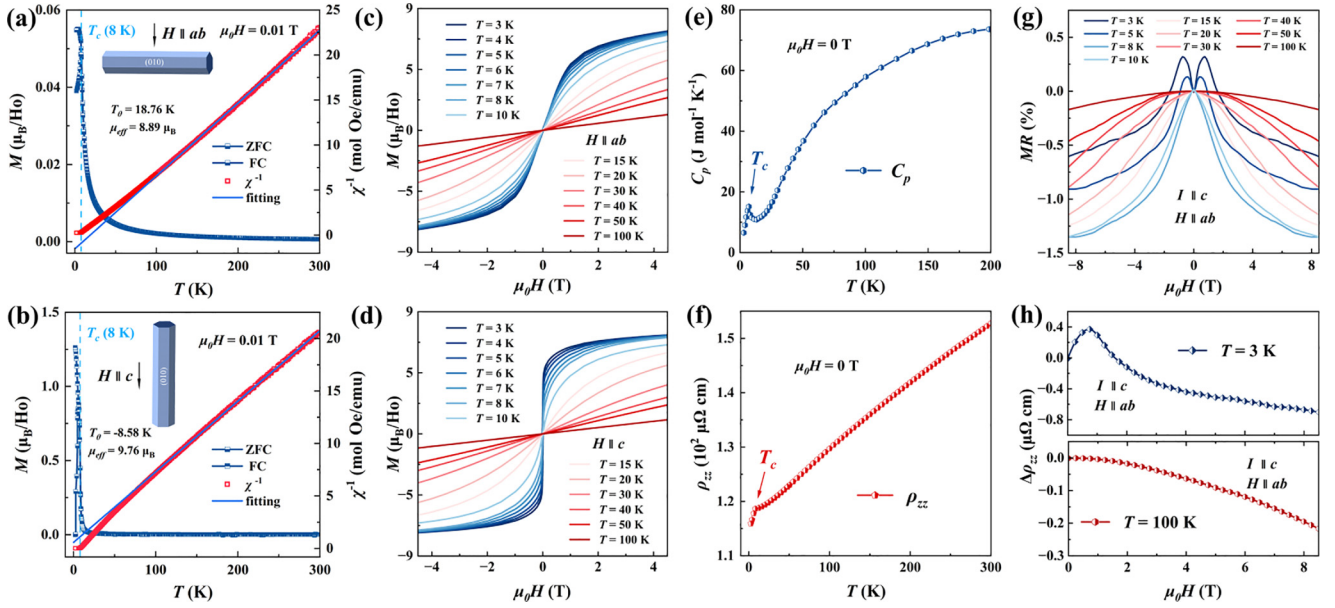


FIG. 2. (a) The temperature-dependent magnetization and inverse magnetic susceptibility curves of $\text{Ho}_{1.25}\text{Au}_{0.75}\text{Si}_{1.55}$ single crystal for $H \parallel ab$ under 0.01 T. (b) The temperature-dependent magnetization and inverse magnetic susceptibility curves of $\text{Ho}_{1.25}\text{Au}_{0.75}\text{Si}_{1.55}$ single crystal for $H \parallel c$ under 0.01 T. (c), (d) Isothermal magnetization curves at different temperatures for $H \parallel ab$ and $H \parallel c$, respectively. Temperature-dependent curves for the (e) specific heat capacity and (f) resistivity of $\text{Ho}_{1.25}\text{Au}_{0.75}\text{Si}_{1.55}$ single crystal. (g) Magnetoresistance at different temperatures. (h) The field-dependent change in resistivity at 3 and 100 K.

Therefore, the effective magnetic moment with $H \parallel ab$ is $8.89 \mu_B$ and becomes $9.76 \mu_B$ with $H \parallel c$. Isothermal magnetization $M(H)$ curves in the $\text{Ho}_{1.25}\text{Au}_{0.75}\text{Si}_{1.55}$ single crystal with H applied parallel to the ab plane ($H \parallel ab$) and along the c axis ($H \parallel c$) are respectively shown in Figs. 2(c) and 2(d). The magnetization along the c direction is easier to saturate than when it is in the ab plane, further indicating that the c axis is the easy magnetization axis. The temperature-dependent heat capacity data of $\text{Ho}_{1.25}\text{Au}_{0.75}\text{Si}_{1.55}$ measured in zero field is shown in Fig. 2(e) for $3 \text{ K} \leq T \leq 200 \text{ K}$. A λ -like anomaly in $C_p(T)$ with a peak at 8 K confirms the occurrence of ferromagnetic ordering. The expected Dulong-Petit limiting value of $C_v = 3nR = 88.54 \text{ J mol}^{-1} \text{ K}^{-1}$, where $R = 8.314 \text{ J mol}^{-1} \text{ K}^{-1}$ is the gas constant and $n = 3.55$ is the total number of atoms per formula unit for $\text{Ho}_{1.25}\text{Au}_{0.75}\text{Si}_{1.55}$. The specific heat reaches $73.61 \text{ J mol}^{-1} \text{ K}^{-1}$ at 200 K, which is still not a saturation value. To characterize the electrical transport properties, we have measured the longitudinal resistivity ρ_{zz} and magnetoresistance MR of $\text{Ho}_{1.25}\text{Au}_{0.75}\text{Si}_{1.55}$. As shown in Fig. 2(f), it is clear that $\text{Ho}_{1.25}\text{Au}_{0.75}\text{Si}_{1.55}$ shows typical metallic behavior over the whole temperature range. A turning point in the ρ_{zz} appears at 8 K, which corresponds to the magnetic phase transition. The resistivity shows no obvious transition at all temperatures except 8 K. In combination with the absence of distinct extraneous diffraction peaks in the previous XRD measurements, and the fact that no characteristic superconducting signals (e.g., zero-resistance transition [39], Meissner effect [40]) have been detected in both electrical transport and magnetic measurements, it is confirmed that there are no impurities such as Sn in the sample in this work, and all subsequent data from other measurements are derived from the sample itself. It should be emphasized, however, that the absence

of extrinsic impurity phases does not exclude the intrinsic chemical disorder revealed by the structural refinement. The random Ho-Au occupation and Si vacancies constitute static disorder in the conducting lattice and can provide elastic-scattering centers for conduction electrons. Therefore, the transport behavior should be interpreted in the presence of this intrinsic disorder, while the field-dependent MR discussed below reflects the additional contribution from magnetic scattering processes. Figure 2(g) demonstrates the magnetoresistance MR at different temperatures. The MR is calculated using the equation: $\text{MR} = \Delta\rho_{zz}/\rho_{zz}(T, 0) = [\rho_{zz}(T, H) - \rho_{zz}(T, 0)]/\rho_{zz}(T, 0)$, where $\rho_{zz}(T, 0)$ and $\rho_{zz}(T, H)$ are the longitudinal resistivity at zero and nonzero field. It is observed that above T_c , a negative MR is manifested, while below T_c , a positive MR first appears and then turns negative as the magnetic field is enhanced, with comparable behavior found in systems such as HoPdSi [41] and Fe_3GeTe_2 [42]. In ferromagnets, MR is primarily collectively governed by the modulation of spin scattering and the suppression of spin fluctuations. Figure 2(h) shows the magnetic field dependence curves of the change in resistivity ($\Delta\rho_{zz}$) at 3 and 100 K. At $T = 3 \text{ K}$, the positive $\Delta\rho_{zz}$ at low field originates from spin scattering [43] during spin flips in the external magnetic field and the scattering at domain walls [44,45]. As the magnetic field increases, the magnetization process gradually saturates, and the spin scattering and domain-wall scattering diminish, after which only negative $\Delta\rho_{zz}$ is observed. For the high-field negative $\Delta\rho_{zz}$, it arises from the significant suppression of spin-disorder scattering, a universal mechanism in $4f$ local-moment ferromagnetic systems. Its essence lies in the fact that high magnetic fields significantly suppress both s - f exchange scattering between conduction electrons and localized magnetic moments and electron-magnon scattering, leading

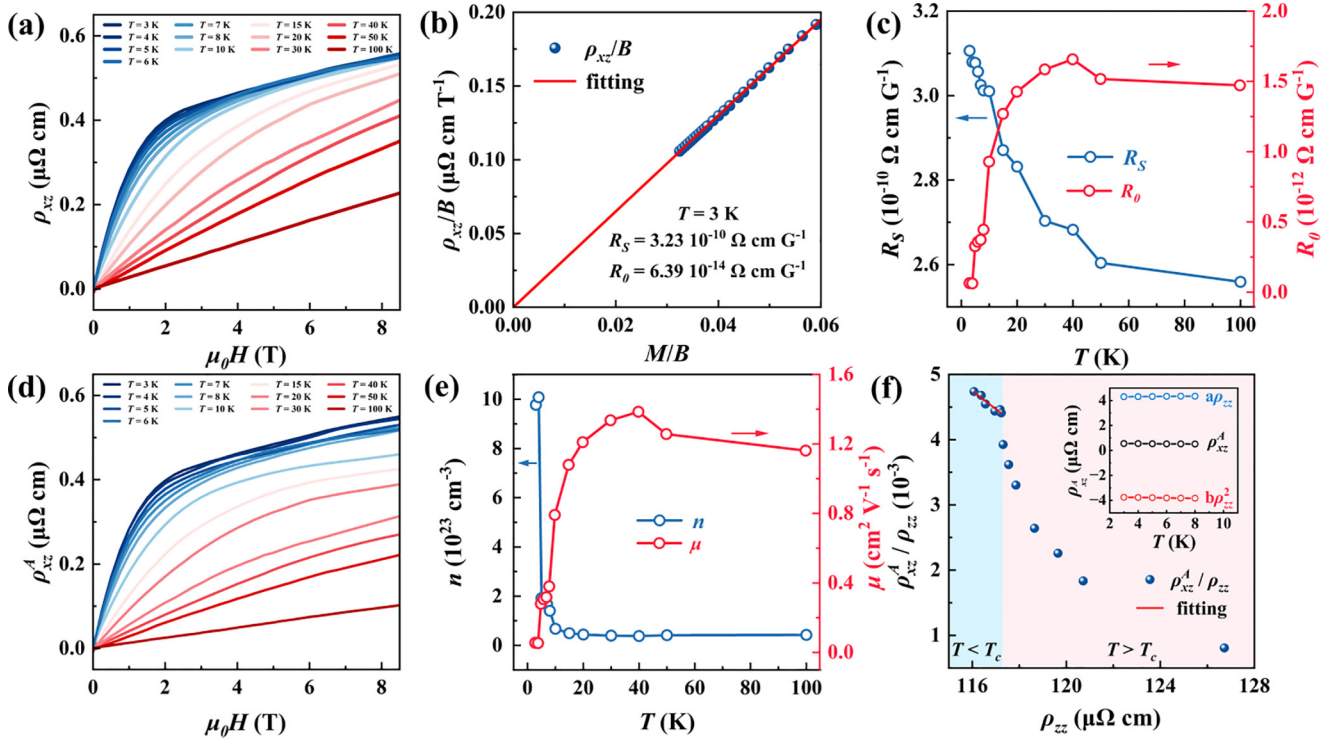


FIG. 3. Hall effect measurements on Ho_{1.25}Au_{0.75}Si_{1.55} single crystal. (a) The field dependence of Hall resistivity ρ_{xz} at various temperatures. Inset shows the configuration of Hall resistivity measurements: $I \parallel c$ axis (z axis) and $H \parallel b$ axis (y axis). (b) Analysis of the same anomalous Hall-effect data by using Eq. (3). (c) Temperature-dependent anomalous Hall coefficient R_s and ordinary Hall coefficient R_0 . (d) The field dependence of anomalous Hall resistivity ρ_{xz}^A at various temperatures. (e) Temperature-dependent carrier concentration n and mobility μ . (f) Linear fitting of anomalous Hall resistivity ρ_{xz}^A / ρ_{zz} vs ρ_{zz} curve at $T \leq 8 \text{ K}$ under 8.5 T. Inset shows different contributions in ρ_{xz}^A with temperature are plotted on the same scale.

to a continuous decrease in resistivity and thus manifesting as negative $\Delta\rho_{zz}$ [46–50]. At 100 K, Ho_{1.25}Au_{0.75}Si_{1.55} is in the paramagnetic phase, and its $\Delta\rho_{zz}$ exhibits positive curvature at low fields and negative $\Delta\rho_{zz}$ at high fields, which stems from the dynamic disorder of $4f$ localized magnetic moments induced by thermal excitation, while an external magnetic field suppresses this disorder and reduces scattering on conduction electrons [51].

The Hall effect was also used on Ho_{1.25}Au_{0.75}Si_{1.55}, which is demonstrated in Fig. 3. Figure 3(a) and its inset illustrate the field-dependent Hall resistivity (ρ_{xz}) and the experimental configuration for the Hall effect ($I \parallel z$ axis and $H \parallel y$ axis), respectively. Combined with the magnetization curves, it indicates that there is an AHE in Ho_{1.25}Au_{0.75}Si_{1.55}. The total Hall resistivity ρ_{xz} in ferromagnets consists of two components [38,52],

$$\rho_{xz} = \rho_{xz}^N + \rho_{xz}^A = R_0 B + \mu_0 R_s M, \quad (2)$$

where the first term ρ_{xz}^N is the ordinary Hall resistivity contributed from the Lorentz force, and the second term ρ_{xz}^A is the AHE component. R_0 and R_s are ordinary and anomalous Hall coefficients, respectively. For materials with saturated magnetization under high magnetic fields, the ordinary Hall coefficient R_0 can be obtained from the slope and the anomalous Hall resistivity ρ_{xz}^A from the intercept via linear fitting of ρ_{xz} under high magnetic field conditions. For materials that have not achieved magnetization saturation under high magnetic fields, it can be used for fitting with the following

modified equation [53]:

$$\frac{\rho_{xz}}{B} = R_0 + \mu_0 R_s \frac{M}{B}. \quad (3)$$

As shown in Fig. 3(b), the data at 3 K were fitted using Eq. (3). From that fitting of ρ_{xz}/B vs M/B in the high-field regime, we can determine the slopes and Y -axis intercepts, which provide us the temperature-dependent values of R_s and R_0 , respectively, as shown in Fig. 3(c). According to the formula $\rho_{xz}^A = \mu_0 R_s M$, we obtain the correct ρ_{xz}^A , as depicted in Fig. 3(d). Based on the relationships $R_0 \approx 1/(en)$ and $\mu = 1/(en\rho_{(0T)})$, the variation relationships of carrier concentration and mobility with temperature are obtained, as shown in Fig. 3(e).

To investigate the origin of the AHE in Ho_{1.25}Au_{0.75}Si_{1.55}, one needs to first understand its various generating mechanisms. In general, there exist three kinds of mechanisms contributing to the origin of AHE: skew scattering, side jump, and intrinsic Berry curvature [5,10,11,54]. Ideally, the anomalous Hall resistivity and longitudinal resistivity associated with the AHE arising from skew scattering follow the relation [55–57] $\rho_{xz}^A \propto \rho_{zz}$, whereas the AHE resulting from side jump and intrinsic Berry curvature conforms to $\rho_{xz}^A \propto \rho_{xx}^2$ [5,11,58]. In practical scenarios, the AHE of a material typically stems from the combined effect of multiple mechanisms, leading to deviations from the aforementioned relation, and thus requires further analysis. As shown in Fig. 3(f), fitting the ρ_{xz}^A / ρ_{zz} vs

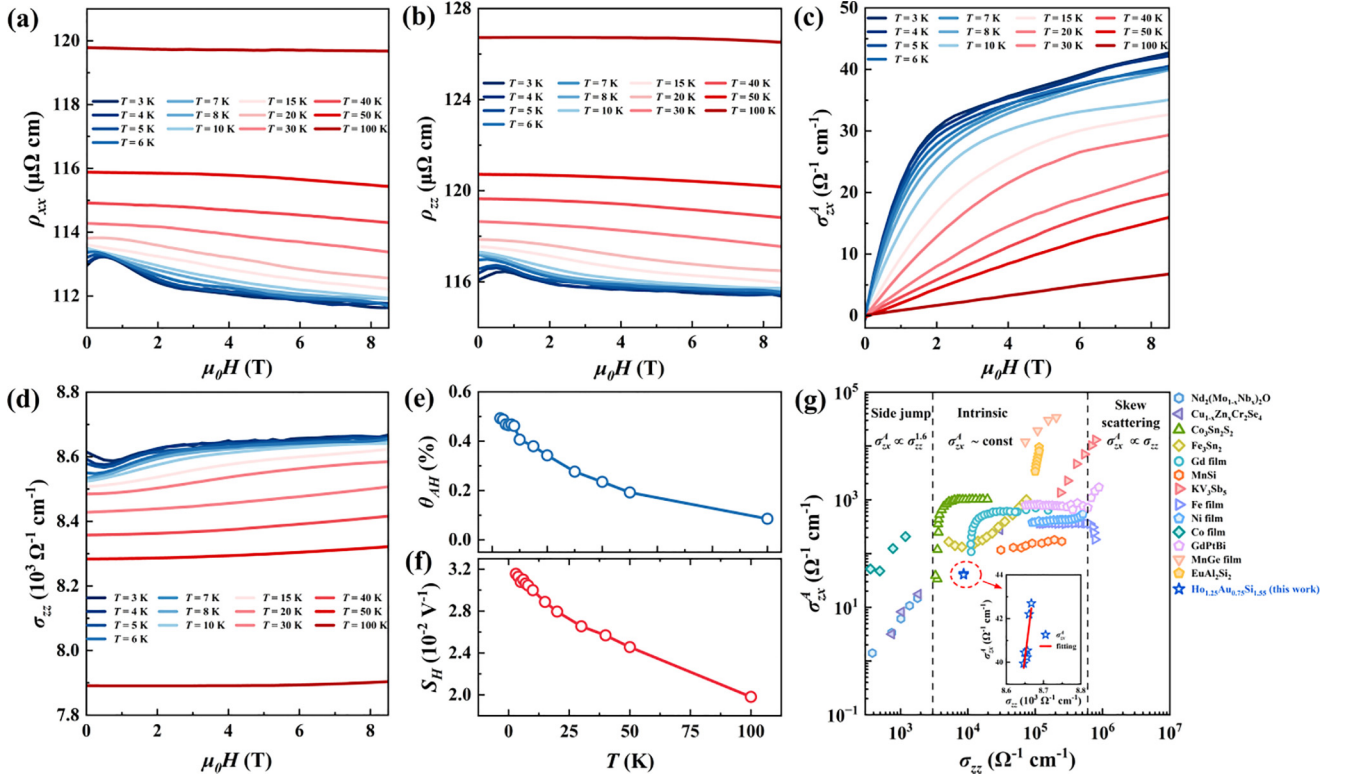


FIG. 4. (a) The field dependence of resistivity ρ_{xx} at various temperatures. (b) The field dependence of resistivity ρ_{zz} at various temperatures. (c) The field dependence of anomalous Hall conductivity σ_{xx}^A at various temperatures. (d) The field dependence of longitudinal conductivity σ_{zz} at various temperatures. (e) Temperature-dependent anomalous Hall angle Θ_{AH} at 8.5 T. (f) Temperature-dependent anomalous Hall factor S_H at 8.5 T. (g) Full logarithmic plot of σ_{xx}^A vs σ_{zz} for a variety of materials spanning the various AHE regimes from the side-jump mechanism through the intrinsic and skew-scattering regimes [12,62–68]. Inset shows the fitting curve of σ_{xx}^A vs σ_{zz} at $T \leq 8$ K under 8.5 T.

ρ_{zz} curve with the relation [59–61]

$$\rho_{xz}^A / \rho_{zz} = a + b\rho_{zz}, \quad (4)$$

in which the skew scattering term ($a\rho_{zz}$) and side-jump plus intrinsic term ($b\rho_{zz}^2$) are obtained. The inset of Fig. 3(f) illustrates the different contributions in ρ_{xz}^A , and the results show that several mechanisms coexist in the system, with the skew scattering mechanism dominating. Additionally, Figs. 4(a) and 4(b) present the resistivity ρ_{xx} and ρ_{zz} , which are used for calculating the anomalous Hall conductivity (AHC), respectively. The AHC σ_{xx}^A can be calculated from ρ_{xz}^A and ρ_{zz} using the equation

$$\sigma_{xx}^A = \frac{\rho_{xz}^A}{\rho_{xx}\rho_{zz} + (\rho_{xz}^A)^2}. \quad (5)$$

The field-dependent σ_{xx}^A for each temperature is displayed in Fig. 4(c).

To further assess the strength of AHE in $\text{Ho}_{0.25}\text{Au}_{0.75}\text{Si}_{1.55}$, we estimated the two characteristic quantities, namely, the anomalous Hall angle (Θ_{AH}) and the anomalous Hall factor (S_H). $\Theta_{AH} = \sigma_{xx}^A / \sigma_{zz}$, measuring the strength of the transverse current generated with respect to the applied normal current [1]. $S_H = \sigma_{xx}^A / M$ estimates the relative magnitude of the anomalous Hall current with respect to the M [65]. Figure 4(d) shows the longitudinal conductivity σ_{zz} used for the calculation of Θ_{AH} . The curves of Θ_{AH} and S_H as a

function of temperature are shown in Figs. 4(e) and 4(f), respectively. For $\text{Ho}_{0.25}\text{Au}_{0.75}\text{Si}_{1.55}$ crystals, Θ_{AH} and S_H are moderately reduced with increasing temperature, and their maximum values are approximately 0.49% (for Θ_{AH}) and 0.03 V^{-1} (for S_H). The small Θ_{AH} and S_H of $\text{Ho}_{0.25}\text{Au}_{0.75}\text{Si}_{1.55}$ are attributed to the finite s - f exchange coupling in this $4f$ localized-moment ferromagnet and to the enhanced scattering environment associated with Ho-Au mixed occupancy and Si vacancies.

To understand the origin of the AHE, we plot σ_{xx}^A vs σ_{zz} for the typical materials spanning from the superclean regime to the dirty metal regime in Fig. 4(g). Based on the different intensities of carrier scattering, the mechanism of AHE is divided into three parts [66,69]: superclean regime ($\sigma_{zz} > 5 \times 10^6 \Omega^{-1} \text{cm}^{-1}$), good metal regime ($\sigma_{zz} \approx 10^4$ – $10^6 \Omega^{-1} \text{cm}^{-1}$), and dirty metal regime ($\sigma_{zz} < 10^4 \Omega^{-1} \text{cm}^{-1}$). Based on experience, the following patterns typically hold true: the superclean regime where the skew scattering mechanism dominates ($\sigma_{xx}^A \sim \sigma_{zz}$); the good metal regime where intrinsic mechanism dominates ($\sigma_{xx}^A \sim \text{const}$); and the dirty metal regime where localized hopping plays a role ($\sigma_{xx}^A \sim \sigma_{zz}^{1.6}$). However, the regime division of this phase diagram cannot serve as direct evidence for judging the AHE mechanism but only suggests a high probability that a certain mechanism is dominant in the material. The σ_{zz} value of $\text{Ho}_{0.25}\text{Au}_{0.75}\text{Si}_{1.55}$ is approximately $8.6 \times 10^3 \Omega^{-1} \text{cm}^{-1}$, which is located at the boundary

between the good metal regime and the dirty metal regime, far from the skew scattering regime in the phase diagram. Nevertheless, as shown in the inset of Fig. 4(g), the fitting based on the relationship $\sigma_{xx}^A \propto \sigma_{xx}^n$ yields $n = 0.89$, which is closer to the linear relationship ($n = 1$). Therefore, the results of conductivity fitting and resistivity fitting together confirm that the AHE in the $\text{Ho}_{1.25}\text{Au}_{0.75}\text{Si}_{1.55}$ system is dominated by the skew scattering mechanism. A similar phenomenon is also observed in the GdAuPb [70] and EuAl_2Si_2 [71] systems. These findings clarify that skew scattering dominates the AHE in $\text{Ho}_{1.25}\text{Au}_{0.75}\text{Si}_{1.55}$. This dominance is intimately connected to, and likely driven by, the structural disorder present in this compound. Specifically, the Ho-Au mixed occupancy and Si vacancies create a random potential landscape and break local chemical periodicity, which are expected to enhance asymmetric carrier scattering and favor the skew-scattering contribution to the AHE. This work establishes disordered $\text{Ho}_{1.25}\text{Au}_{0.75}\text{Si}_{1.55}$ as a platform for studying the role of structural disorder in skew-scatter-dominated AHE in rare-earth localized-moment ferromagnets with moderate conductivity.

IV. CONCLUSIONS

In conclusion, we have grown a disordered $\text{Ho}_{1.25}\text{Au}_{0.75}\text{Si}_{1.55}$ single crystal by the flux method and systematically investigated its structural, magnetic, and electrical transport properties. Structural refinement reveals pronounced chemical disorder, including Ho-Au mixed occupancy on the $2c$ site and Si vacancies on the $2b$ site. Magnetization and heat-capacity measurements indicate a ferromagnetic transition at $T_C = 8$ K, with the c axis serving as the easy magnetization axis. The longitudinal resistivity exhibits metallic behavior, while the different MR behaviors at low and high temperatures can be understood in terms of magnetic domain-wall scattering and spin-fluctuation scattering, respectively. Scaling analyses of resistivity and conductivity collectively confirm that the AHE in $\text{Ho}_{1.25}\text{Au}_{0.75}\text{Si}_{1.55}$ is dominated by skew scattering. Combined

with the structural refinement, this skew-scatter-dominated AHE is intimately connected to, and likely driven by, the pronounced structural disorder in this compound. The random Ho-Au occupation and Si vacancies perturb the local magnetic-exchange environment, create a random potential landscape, and break local chemical periodicity, thereby favoring asymmetric carrier scattering and an extrinsic skew-scattering contribution to the AHE. However, due to the finite s - f exchange coupling and the disorder-induced scattering environment associated with Ho-Au mixed occupancy and Si vacancies, both Θ_{AH} and S_H remain small. Our current results establish disordered $\text{Ho}_{1.25}\text{Au}_{0.75}\text{Si}_{1.55}$ as a rare-earth localized-moment ferromagnet for studying the role of structural disorder in skew-scatter-dominated AHE. Subsequent theoretical calculations and neutron diffraction experiments will help further clarify the magnetic structure of $\text{Ho}_{1.25}\text{Au}_{0.75}\text{Si}_{1.55}$ and the microscopic mechanism underlying its AHE.

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DATA AVAILABILITY

There are no publicly available research data or software supporting this paper. Requests for further information or data should be sent to the authors.

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