

Giant Thermopower Changes Related to the Resistivity Maximum and Colossal Magnetoresistance in EuCd_2P_2

Judith Grafenhorst¹, Sarah Krebber², Kristin Kliemt², Cornelius Krellner²,
Elena Hassinger^{3,1,4} and Ulrike Stockert^{1,4,3,*}

¹*Technische Universität Dresden, 01062 Dresden, Germany*

²*Kristall-und Materiallabor, Physikalisches Institut, Goethe-Universität Frankfurt, 60438 Frankfurt/M, Germany*

³*Institute for Quantum Materials and Technologies, Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany*

⁴*Max Planck Institute for Chemical Physics of Solids, 01187 Dresden, Germany*



(Received 2 March 2026; accepted 9 July 2026; published 4 September 2026)

We present the thermopower of EuCd_2P_2 , a material which exhibits a large resistivity peak with significant magnetic field dependence in the temperature range of 10–25 K. In the same region, we observe a highly unusual behavior of the thermopower with two sign changes and giant extrema. The overall variation of the thermopower exceeds 4000 $\mu\text{V/K}$ and takes place in an extremely narrow temperature region of less than 5 K. The anomaly is suppressed completely in a small magnetic field of 0.5 T. We discuss this observation using a simple drift-diffusion picture and taking into account that the temperature gradient inducing the thermopower voltage is accompanied by a gradient of the electrical resistivity. Our simple estimation yields the correct magnitude, shape, and field dependence of the thermopower anomaly observed in EuCd_2P_2 . These results open a new route to giant thermopower values via gradients of electronic properties.

DOI: 10.1103/95x8-3wtb

Thermoelectric materials have a large potential for applications based on the conversion of thermal to electrical energy and reverse [1]. The efficiency of these processes is determined by the thermoelectric figure of merit $zT = \sigma S^2 T / \kappa$, which depends on the electrical and thermal conductivities σ and κ , respectively, the thermopower S , and temperature T . A high zT and, therefore, also a large S is a prerequisite for profitable thermoelectric cooling and appreciable enhancement of the overall power efficiency of technical processes by using waste heat for voltage generation. Beyond that, materials with a large thermopower could be used in thermocouple sensors. A strong field dependence of $S(T)$ would even allow one to design thermoelectric devices and sensors controlled by magnetic fields [2]. This motivates the exploration of preconditions and mechanisms allowing for large thermopower values and changes.

The thermopower S of conventional metals and semiconductors contains two contributions, namely, from phonon drag S_{drag} and charge carrier diffusion S_{diff} . Large

thermopower values exceeding 1000 $\mu\text{V/K}$ and in some cases even 100 000 $\mu\text{V/K}$ are usually caused by the phonon drag effect due to momentum transfer from phonons to charge carriers via electron-phonon coupling [3], e.g., in TiO_2 (200 000 $\mu\text{V/K}$) [4,5] and $\text{Dy}_{1-x}\text{Sr}_x\text{MnO}_3$ (220 000 $\mu\text{V/K}$) [6]. However, the related good thermal conductivity is detrimental to high values of zT and applications. By contrast, the diffusion thermopower S_{diff} is typically much smaller, being of the order of 10 $\mu\text{V/K}$ for metals and a few hundred $\mu\text{V/K}$ for semiconductors below room temperature [7]. In a simple picture, it arises from a change of the number and velocity of the mobile charge carriers with temperature T due to the energy dependence of the density of states and the T dependence of the Fermi distribution [8]. The resulting imbalance in the presence of a temperature gradient ∇T leads to diffusion of charge carriers and development of an internal electrical field E limited by a reverse Ohmic current $j = \sigma E$.

Within the semiclassical Boltzmann picture, the thermopower of metals and degenerate semiconductors is given by the Mott expression:

$$S_{\text{diff}} = \frac{\pi^2 k_B^2 T}{3q} \left(\frac{d \ln \sigma(\epsilon)}{d\epsilon} \right)_{E_F}. \quad (1)$$

This equation relates S_{diff} to the logarithmic energy derivative of the conductivity $\sigma(\epsilon)$ at the Fermi level E_F . k_B denotes the Boltzmann constant and q the charge of the carriers including

* Contact author: ulrike.stockert@tu-dresden.de

Published by the American Physical Society under the terms of the Creative Commons Attribution 4.0 International license. Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI. Open access publication funded by the Max Planck Society.

sign. Equation (1) has the drawback that $\sigma(\epsilon)$ is not directly accessible by experiments. Therefore, it is often further simplified to estimate the magnitude and temperature dependence of S . For simple metals, which can be described as a free electron gas with an energy-independent relaxation time, the derivative of Eq. (1) is of the order of $1/E_F$ [9]. This yields a linear T dependence $S \propto T/E_F$ with small absolute values due to the large Fermi energy in normal metals [10,11]. By contrast, the thermopower of nondegenerate semiconductors exhibits an inverse temperature proportionality $S \propto E_g/T$ with the gap width E_g [12].

These simple concepts cannot be applied to materials with a strong temperature dependence of their electronic properties as, for instance, charge carrier density, chemical potential, valence, or mobility. In such a situation, any temperature gradient is accompanied by non-negligible gradients of the electronic properties of the material. In this Letter, we demonstrate how this can give rise to giant thermopower values by presenting both experimental results and a simple model taking into account such secondary gradients. In fact, it has been shown previously that a shift of the chemical potential with T related to a strongly T -dependent valence gives rise to an additional thermopower contribution in the intermediate-valence materials EuIr_2Si_2 and EuNi_2P_2 [13]. Similarly, the rapidly changing charge carrier mobility with T in $\text{Co}_{0.999}\text{Ni}_{0.001}\text{Sb}_3$ goes along with a considerable enhancement of $S(T)$ [8]. However, in both cases the overall effects have been moderate, leading to absolute thermopower values of at most 50 and 300 $\mu\text{V/K}$, respectively. Here, we investigate $S(T)$ of EuCd_2P_2 , a material with a huge temperature and magnetic field dependence of its electrical resistivity ρ at low T , suggesting dramatic changes of the charge carrier mobility and/or number of free charge carriers. In the same regime, we observe giant thermopower values in zero magnetic field exceeding those of the above-mentioned examples by a factor of more than 10. They can be related directly to $\rho(T)$ based on a simple drift-diffusion picture. Our findings open a new route to giant thermopower values by using gradients of electronic properties.

EuCd_2P_2 belongs to a group of trigonal 122 compounds with CaAl_2Si_2 structure (space group $P\bar{3}m1$) that have been studied in the past as potential thermoelectrics [14–18]. More recently, this class of materials—in particular, with composition EuT_2Pn_2 containing transition metals $T = \text{Cd}, \text{Zn}$ and pnictides $\text{Pn} = \text{P}, \text{As}, \text{Sb}$ —arouse considerable interest due to the discovery of unconventional electronic and transport properties related to the interplay of band structure topology and magnetism [19]. The most prominent representative is EuCd_2As_2 usually classified as a topological Weyl semimetal [20]. Recently, the material has been also suggested as a rare example to host a three-dimensional Van Hove singularity [21]. Other members of the family exhibit a colossal magnetoresistance (CMR) effect, e.g., EuZn_2P_2 [22], EuZn_2As_2 under pressure [23], and the hereinafter investigated material EuCd_2P_2 [24].

Magnetism in EuCd_2P_2 arises from Eu^{2+} moments that order antiferromagnetically at about $T_N = 11$ K [24–26]. The electrical resistivity exhibits a considerable sample dependence with semiconducting or weakly metallic behavior above about 50 K and a moderate anisotropy for the current within and perpendicular to the ab plane [24,26]. The band structure of EuCd_2P_2 has a gap at the Fermi level as determined consistently by angle-resolved photoemission spectroscopy (ARPES) experiments [26,27] and band structure calculations [26,28]. Independent of the behavior at higher T , a pronounced maximum in $\rho(T)$ is observed between about 10 and 25 K in zero magnetic field with the resistivity changing by more than one order of magnitude. A moderate magnetic field $B = \mu_0 H$ of 1 T is sufficient to suppress the resistivity at the maximum by more than 2 orders of magnitude with some dependency on crystal quality and growth conditions [24,26,27]. The origin of the resistance maximum and CMR effect is a subject of ongoing discussions. It has been shown that ferromagnetic interactions play an important role [29] and slight modifications in the growth conditions induce a ferromagnetic ground state via charge carrier doping [28]. The most likely scenario appears to be formation and percolation of magnetic polarons [30]. Despite these open questions, EuCd_2P_2 with its huge peak and field dependence of ρ appeared an ideal candidate to study the relation between electrical

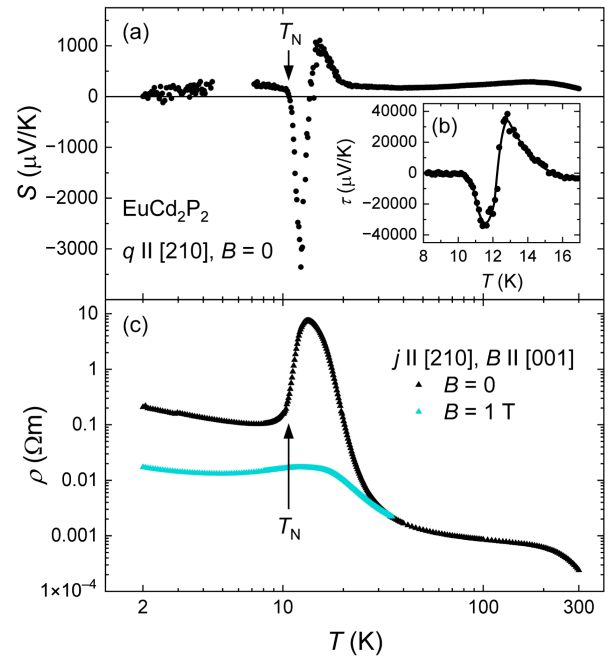


FIG. 1. (a) Temperature dependence of the thermoelectric power S of EuCd_2P_2 measured along [210]. The antiferromagnetic ordering temperature T_N is indicated by an arrow. (b) Thomson coefficient τ in the T range between 8 and 17 K. The line is a guide to the eye. (c) Electrical resistivity $\rho(T)$ measured on the same sample and contacts as $S(T)$ in zero magnetic field and $B = \mu_0 H = 1$ T.

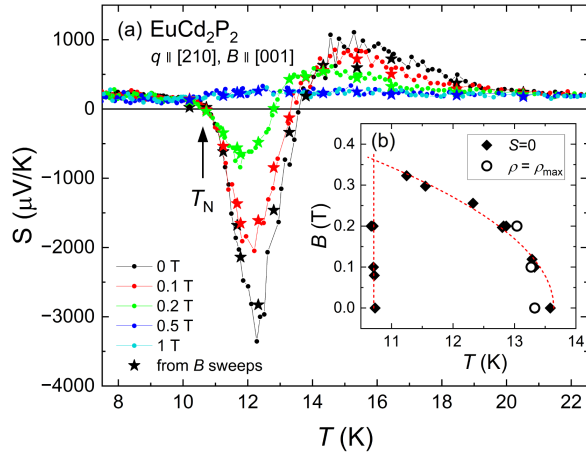


FIG. 2. (a) Temperature dependence of the thermoelectric power S of EuCd_2P_2 at different magnetic fields. The results from T sweeps (lines with small symbols) are in good agreement with those from B sweeps (asterisks). (b) Comparison of maxima in $\rho(T)$ and points at which S changes sign in T and B sweeps. The lines are guides to the eye.

conductivity $\sigma = 1/\rho$ and thermopower in a situation with an extreme T dependence of the electrical transport properties. Details of our contacting and measurement procedure are given in Supplemental Material [31].

Results—The thermopower $S(T)$ of EuCd_2P_2 is plotted in Fig. 1(a) on a logarithmic temperature scale. Above 25 K, EuCd_2P_2 has a positive thermopower with relatively weak temperature dependence. This is in line with holelike charge carriers as inferred from Hall effect measurements in the same T range [28,29], ARPES [27], and band structure calculations [26,28]. Below 25 K, the thermopower behavior changes dramatically: In a very narrow temperature region between 10 and 20 K, $S(T)$ assumes huge absolute values and switches sign twice. Below 10 K, the weak temperature dependence of $S(T)$ with positive values is recovered. Figure 1(c) shows the electrical resistivity measured on the same sample and contacts for comparison. In zero magnetic field, $\rho(T)$ changes overall by more than 4 orders of magnitude and exhibits the characteristic maximum around 15 K observed on antiferromagnetic EuCd_2P_2 samples [24,26,28]. The maximum is dramatically suppressed in a relatively small magnetic field of 1 T.

The region between 8 and 22 K is expanded in Fig. 2(a). It shows $S(T)$ in zero magnetic field and in magnetic fields $B = \mu_0 H$ up to 1 T. In this plot, one can trace the giant changes of the thermopower of EuCd_2P_2 in zero field, which to our knowledge are so far unprecedented concerning the combination of magnitude, sign changes, and extremely narrow T range: Starting from moderate positive values at 10 K, the thermopower changes sign upon heating around 10.7 K, goes through a huge minimum at about 12.3 K, switches back to positive values around 13.6 K, reaches a maximum at 15.4 K, and slowly decreases toward higher T . That is, in a T range of less than 5 K, the

thermopower changes sign twice and alters overall by more than 4000 $\mu\text{V/K}$. The giant slope of $S(T)$ goes along with a huge Thomson coefficient $\tau = TdS/dT$ of up to 35 000 $\mu\text{V/K}$. It is shown in Fig. 1(b) and exceeds those of up-to-date Thomson cooler materials by more than a factor of 30, for instance, Ni-doped FeRh alloy (900 $\mu\text{V/K}$) [32], YbInCu₄ (400 $\mu\text{V/K}$) [33], and FeSb₂ (800 $\mu\text{V/K}$) [34]. The large slope of $S(T)$ necessitates special measurement conditions as, for instance, an extremely small temperature difference ΔT along the sample with $\Delta T/T < 0.12\%$ to determine the intrinsic behavior. We estimate the uncertainty of our thermopower in regions with a large slope dS/dT to be at most 18% as explained in Supplemental Material [31]. In addition, the behavior of $S(T)$ has been confirmed on a second sample from a different batch. The respective data are shown in Supplemental Material [31].

Application of magnetic fields leads to a rapid suppression of the huge thermopower anomaly between 10 and 20 K; cf. Fig. 2(a). The strong field dependence is also seen in B sweeps shown in Fig. 3. A field of about 0.3 T is sufficient to eliminate negative thermopower values. In 0.5 T, the anomaly has disappeared completely and the thermopower remains positive without significant T dependence.

Before discussing an alternative scenario for the unusual thermopower of EuCd_2P_2 , we would like to rank the observed values and field dependence. In the literature, the terms “giant” or “colossal” thermopower have been used for a wide range of absolute values. Some of the largest thermopowers in bulk materials have been observed in manganates as $\text{Dy}_{1-x}\text{Sr}_x\text{MnO}_3$ (220 000 $\mu\text{V/K}$) [6] and $\text{Gd}_{1-x}\text{Sr}_x\text{MnO}_3$ (35 000 $\mu\text{V/K}$) [35], in TiO_2 (200 000 $\mu\text{V/K}$) [4], and in FeSb₂ (45 000 $\mu\text{V/K}$) [36]. However, as mentioned in our Introduction, the thermopower in these systems is at least to some extent enhanced by phonon drag [5,6,37]. By contrast, the diffusion thermopower in metals and semiconductors is typically 3 orders of

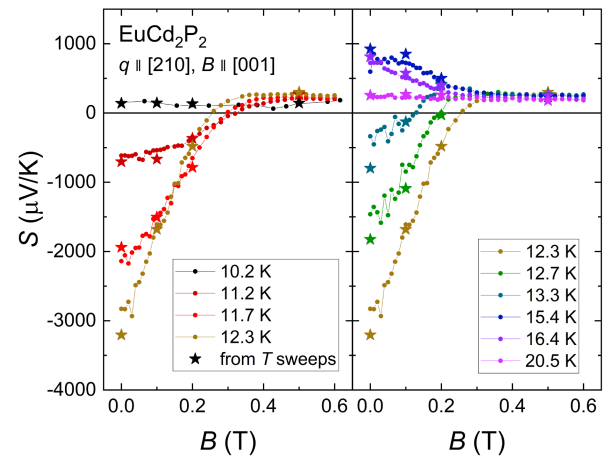


FIG. 3. Field dependence of the thermoelectric power S of EuCd_2P_2 at different temperatures. B sweeps (lines with small symbols) and T sweeps (asterisks) exhibit the same behavior.

TABLE I. Materials claimed to exhibit a giant magnetothermopower. The maximum reported value $dS_{\max} = |S(B) - S(0)|$ is given together with the corresponding temperature $T(dS_{\max})$ and field $B(dS_{\max})$, at which it was determined. In addition, the steepest slope $|dS/dB|_{\max}$ calculated from published data $S(B)$ is specified.

Material	$dS_{\max}$ [$\mu\text{V/K}$]	$T(dS_{\max})$ [K]	$B(dS_{\max})$ [T]	$ dS/dB _{\max}$ [$\mu\text{V/KT}$]	Reference
EuCd ₂ P ₂	3600	12	0.5	13 000	This Letter
InAs	10 000	8	29	800	[39]
Bi	4000	7	5	1500	[40]
NbP	800	50	9	150	[41]
Ag _{2-δ} Te	470	110	7	150	[42]

magnitude lower with values of 10–100 $\mu\text{V/K}$ [7]. Based on this scale, the thermopower of 400 $\mu\text{V/K}$ observed in the clathrate system Ba₈(Cu, Zn)_xGe_{46-x} has also been labeled as “giant” [38]. The observation of absolute values exceeding 3000 $\mu\text{V/K}$ in EuCd₂P₂ is, therefore, clearly remarkable.

Besides the large absolute values of S observed in EuCd₂P₂ in zero magnetic field, the dramatic suppression in relatively small magnetic fields is also remarkable. Typically, giant magnetothermopower values defined as $|S(B) - S(0)|$ are claimed for applied fields of several Tesla. Some examples are summarized in Table I in comparison to EuCd₂P₂. Besides the maximum change of S in magnetic fields, also the steepest slope $|dS/dB|_{\max}$ is given. The values in Table I demonstrate that EuCd₂P₂ is indeed exceptional, concerning both the low field required to induce a large magnetothermopower and the huge slope of $S(B)$. Interestingly, the absolute values of $S(T)$ of EuCd₂P₂ decrease with increasing magnetic field, while all other materials mentioned in Table I exhibit an opposite field dependence.

In summary, the thermopower of EuCd₂P₂ in the T range of 10–20 K is highly unconventional with respect to four facts: (i) huge absolute values primarily not due to phonon drag, (ii) an extremely strong temperature dependence with the slope exceeding 2000 $\mu\text{V/K}^2$, (iii) a dramatic suppression of S in exceptionally small magnetic fields, and (iv) an overall unusual T dependence with two sign changes within 3 K.

Discussion—Since the thermopower anomaly of EuCd₂P₂ is not due to phonon drag, at least not exclusively, we have to search for an alternative explanation. Comparing the thermopower to the electrical resistivity reveals that both properties exhibit highly unconventional behavior in a very similar temperature and field range. It appears most natural that both effects should be related: The giant T dependence of ρ —changing for instance by more than an order of magnitude upon cooling from 20 to 15 K—leads to a sizable

resistivity gradient in the presence of a temperature gradient. This, in turn, is expected to have an impact on the diffusion thermopower. Consistently, the maximum in $\rho(T)$ at 13.5 K coincides with a sign change and, therefore, also small values of $S(T)$. This is demonstrated in Fig. 2(b). It shows the positions of the maxima in $\rho(T)$ and where $S = 0$. The second sign change in $S(T)$ at lower T occurs close to the ordering temperature T_N . It has been determined from specific heat measurements on samples from the same batch to be $T_N = 10.6$ K in zero magnetic field with an only weak field dependence up to 0.4 T [26].

The relation between resistivity and thermopower anomalies in EuCd₂P₂ cannot be understood from simple diffusion pictures for normal metals or semiconductors as given by the Mott equation. The latter assumes a temperature-independent diffusivity, which clearly does not apply here because of the huge temperature dependence of the electrical resistivity: For example, around 11 K, i.e., close to the largest slope of $\rho(T)$, a temperature difference of 1% gives rise to more than 20% change in resistivity. This effect is much stronger than, e.g., thermal broadening of the Fermi-Dirac distribution, which is the main source for the thermopower in the Mott relation.

In order to evaluate the influence of the resistivity anomalies of EuCd₂P₂ on the diffusion thermopower, we start from a macroscopic transport picture. At this point, we are interested in only the impact of the strong changes in $\rho(T)$ on S_{diff} . The material is treated as being single phase with homogeneous properties apart from its strongly T -dependent electrical transport. That is, we do not consider local inhomogeneities arising from ferromagnetic-cluster or magnetic-polaron formation. In this picture, the thermopower results from a balance between two currents: a diffusion current j_{diff} due to a change of electronic and transport properties with T and a drift current j_{drift} arising from the developing electrical field E . In our evaluation of the thermopower, we allow explicitly for a variation in the charge carrier density n and diffusion coefficient D along the sample. The latter is usually assumed constant or quasi-constant in the literature, which is an important difference to our calculation. The situation with variable n and D is described by the Stratton equation [43]. The total electrical current along a specific direction (e.g., x) amounts to

$$j_x = j_{\text{diff}} + j_{\text{drift}} = \sigma E_x - q \frac{\partial(nD)}{\partial x}. \quad (2)$$

For simplicity, we ignore anisotropies of transport coefficients and omit the corresponding subscripts. In thermopower measurements, the net current is zero, and the diffusion and drift currents have opposite direction: $j_{\text{diff}} = -j_{\text{drift}}$. Assuming a constant temperature gradient along the sample, we may replace the derivative with respect to x by the one with respect to T : $\partial(nD)/\partial x = \partial(nD)/\partial T \cdot \nabla T$. In addition, we use the relations between diffusion coefficient D , mobility μ , and electrical conductivity σ to replace $D = \mu k_B T / q$ by

$\sigma = n\mu q$, with the Boltzmann constant k_B . Thus, we get a direct relation between the diffusion thermopower and electrical conductivity:

$$S_{\text{diff}} = \frac{E}{\nabla T} = \frac{k_B}{q} \frac{1}{\sigma} \frac{\partial(\sigma T)}{\partial T} = \frac{k_B}{q} \left(1 + \frac{\partial \ln \sigma}{\partial \ln T} \right). \quad (3)$$

Although this equation and, in particular, the derivative resembles the Mott relation, Eq. (1), its origin is completely different: namely, a spatial change of σ arising from ∇T instead of the energy derivative related to thermal broadening of the Fermi-Dirac distribution.

In a trigonal system as EuCd_2P_2 , electrical conductivity and resistivity along high-symmetry directions are directly inverse; i.e., for j along [210], we can take $\sigma = 1/\rho$. Therefore, Eq. (3) allows a calculation of the diffusion thermopower from the electrical resistivity. The results obtained for EuCd_2P_2 are plotted in Fig. 4. We assumed holelike charge carriers in agreement with ARPES, which did not reveal notable changes of the electronic structure across the full temperature range of the anomaly [26]. The resemblance of calculation and data is extremely good, taking into account the simplicity of our assumptions. In fact, Eq. (3) predicts the correct shape, sign, magnitude, and field dependence of the thermopower. The main difference is the width of the anomalies in $S(T)$. The strongest temperature dependence is observed in a more narrow regime than predicted by Eq. (3). Possibly, the effective resistivity gradient seen by the carriers in the percolation regime is steeper than the one measured macroscopically, which would result in a sharper anomaly. Alternatively, these deviations can be attributed to the simplicity of our drift-diffusion picture of classical particles, which does not account for impact from different scattering or transport

channels, local inhomogeneities due to ferromagnetic domain or polaron formation, percolation effects, and variations in the chemical potential with T . The relevance of these factors might be evaluated by systematically studying the thermopower of crystals grown under different conditions. In fact, it has been shown that small variations in the charge carrier concentration may lead to dramatic changes in the magnetic and transport properties of the material [28]. Moreover, we cannot exclude that phonon drag plays a certain role in the material and gives rise to an additional contribution to $S(T)$.

Altogether, our very simple model is able to account for all four of the above-mentioned aspects of the highly unconventional thermopower of EuCd_2P_2 . In particular, we emphasize that there is no free parameter in our calculation: The only ingredients are the electrical resistivity and the charge carrier type, while the microscopic origin of the strong T dependence of $\rho(T)$ and the CMR are not considered. Therefore, the similarity between the calculated and measured thermopower curves is indeed impressive. It clearly demonstrates that the unusual temperature and field dependencies of S in EuCd_2P_2 are caused by the strong changes of the electrical resistivity with T and B .

Despite the large thermopower observed in EuCd_2P_2 , the thermoelectric figure of merit zT is very small—about 10^{-7} at 12 K. This is mainly due to the extremely high electrical resistivity of the material. For the same reason, the material is also not suitable for Thomson cooling. In general, usage of the presented effect in thermoelectric devices is limited by the small temperature region of the thermopower enhancement. It is directly related to the strong T dependence of the electrical resistivity, which cannot be perpetuated over a large T range. This drawback might be overcome to some extent by the material's customization to operating environments. Independent of these limitations, our finding proves the direct relation between thermopower and resistivity anomalies in EuCd_2P_2 . This shows that, in general, it is possible to generate a large thermopower as needed for decent zT values via secondary gradients of electronic properties. A possible direction for exploitation of this mechanism is the search for materials with secondary gradients of other electronic properties or the use of internal compositional gradients induced via position-dependent doping.

Acknowledgments—We thank B. Fauqué and K. Behnia for clarifying discussions. We acknowledge funding from the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) through the Collaborative Research Centers CRC 288 (No. 422213477, Project No. A03) and CRC 1143 (No. 247310070, Project No. C10) and through the Würzburg-Dresden Cluster of Excellence ctd.qmat—Complexity, Topology and Dynamics in Quantum Matter (EXC 2147, Project-ID

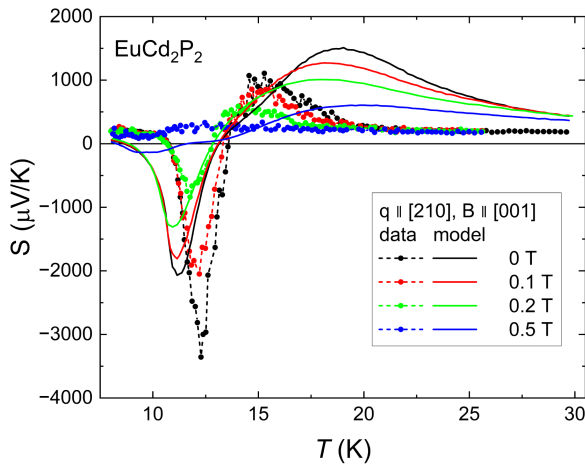


FIG. 4. Temperature dependence of the thermoelectric power S of EuCd_2P_2 at different magnetic fields. Lines are calculations for a drift-diffusion model as explained in the main text.

No. 390858490). We acknowledge financial support from the Max Planck Society through the Physics of Quantum Materials department and the research group “Physics of Unconventional Metals and Superconductors (PUMAS).”

Data availability—The data that support the findings of this manuscript are openly available [44].

- [1] D. Crane, B. Poudel, W. Li, and G. Joshi, Thermoelectric applications, innovations, and impact across industries, *MRS Bull.* **50**, 902 (2025).
- [2] K. Wang, L. Wang, and C. Petrovic, Large magnetothermopower effect in Dirac materials (Sr/Ca)MnBi₂, *Appl. Phys. Lett.* **100**, 112111 (2012).
- [3] J. M. Ziman, *Electrons and Phonons: The Theory of Transport Phenomena in Solids* (Oxford University Press, New York, 2001).
- [4] W. R. Thurber and A. J. H. Mante, Thermal conductivity and thermoelectric power of rutile (TiO₂), *Phys. Rev.* **139**, A1655 (1965).
- [5] J. Tang, W. Wang, G.-L. Zhao, and Q. Li, Colossal positive Seebeck coefficient and low thermal conductivity in reduced TiO₂, *J. Phys. Condens. Matter* **21**, 205703 (2009).
- [6] B. S. Nagaraja, A. Rao, and G. S. Okram, Structural, electrical, and colossal thermoelectric properties of Dy_{1-x}Sr_xMnO₃ manganites, *J. Supercond. Novel Magn.* **28**, 223 (2015).
- [7] H. J. Goldsmid, *Introduction to Thermoelectricity*, Springer Series in Materials Science Vol. 121 (Springer-Verlag, Berlin, 2010).
- [8] P. Sun, B. Wei, J. Zhang, J. M. Tomaczak, A. M. Strydom, M. Sondergaard, B. B. Iversen, and F. Steglich, Large Seebeck effect by charge-mobility engineering, *Nat. Commun.* **6**, 7475 (2015).
- [9] S. Paschen, Thermoelectric aspects of strongly correlated electron systems, in *Thermoelectrics Handbook: Macro to Nano*, edited by D. M. Rowe (CRC Press, Taylor & Francis Group, Boca Raton, FL, 2006).
- [10] K. Behnia, D. Jaccard, and J. Flouquet, On the thermoelectricity of correlated electrons in the zero-temperature limit, *J. Phys. Condens. Matter* **16**, 5187 (2004).
- [11] A. Akrap, N. Barišić, L. Forró, D. Mandrus, and B. C. Sales, High-pressure resistivity and thermoelectric power in Yb₁₄MnSb₁₁, *Phys. Rev. B* **76**, 085203 (2007).
- [12] A. P. Gonçalves and C. Godart, in *New Materials for Thermoelectric Applications: Theory and Experiment*, edited by V. Zlatić and A. Hewson (Springer Netherlands, Dordrecht, 2013), pp. 1–24.
- [13] U. Stockert, S. Seiro, N. Caroca-Canales, E. Hassinger, and C. Geibel, Valence effect on the thermopower of Eu systems, *Phys. Rev. B* **101**, 235106 (2020).
- [14] A. Artmann, A. Mewis, M. Roepke, and G. Michels, AM₂X₂-Verbindungen mit CaAl₂Si₂-Struktur. XI. Struktur und Eigenschaften der Verbindungen ACd₂X₂ (A: Eu, Yb; X: P, As, Sb), *Z. Anorg. Allg. Chem.* **622**, 679 (1996).
- [15] H. Zhang, J.-T. Zhao, Y. Grin, X.-J. Wang, M.-B. Tang, Z.-Y. Man, H.-H. Chen, and X.-X. Yang, A new type of thermoelectric material, EuZn₂Sb₂, *J. Chem. Phys.* **129**, 164713 (2008).
- [16] H. Zhang, L. Fang, M.-B. Tang, H.-H. Chen, X.-X. Yang, X. Guo, J.-T. Zhao, and Y. Grin, Synthesis and properties of CaCd₂Sb₂ and EuCd₂Sb₂, *Intermetallics* **18**, 193 (2010).
- [17] A. F. May, M. A. McGuire, D. J. Singh, J. Ma, O. Delaire, A. Huq, W. Cai, and H. Wang, Thermoelectric transport properties of CaMg₂Bi₂, EuMg₂Bi₂, and YbMg₂Bi₂, *Phys. Rev. B* **85**, 035202 (2012).
- [18] T. Wubieneh, P. Wei, C. Yeh, S. Chen, and Y. Chen, Thermoelectric properties of Zintl phase compounds of Ca_{1-x}En_xZn₂Sb₂ (0 ≤ X ≤ 1), *J. Electron. Mater.* **45**, 1942 (2015).
- [19] K. Kliemt, Chemical pressure due to impurities in trigonal compounds EuT₂Pn₂ (T = Cd, Zn; Pn = P, As, Sb), *Progr. Cryst. Growth Charact. Mater.* **71**, 100667 (2025).
- [20] J.-Z. Ma *et al.*, Spin fluctuation induced Weyl semimetal state in the paramagnetic phase of EuCd₂As₂, *Sci. Adv.* **5**, eaaw4718 (2019).
- [21] W. Wu *et al.*, The discovery of three-dimensional Van Hove singularity, *Nat. Commun.* **15**, 2313 (2024).
- [22] S. Krebber, M. Kopp, C. Garg, K. Kummer, J. Sichelschmidt, S. Schulz, G. Poelchen, M. Mende, A. V. Virovets, K. Warawa, M. D. Thomson, A. V. Tarasov, D. Y. Usachov, D. V. Vyalikh, H. G. Roskos, J. Müller, C. Krellner, and K. Kliemt, Colossal magnetoresistance in EuZn₂P₂ and its electronic and magnetic structure, *Phys. Rev. B* **108**, 045116 (2023).
- [23] S. Luo, Y. Xu, F. Du, L. Yang, Y. Chen, C. Cao, Y. Song, and H. Yuan, Colossal magnetoresistance and topological phase transition in EuZn₂As₂, *Phys. Rev. B* **108**, 205140 (2023).
- [24] Z.-C. Wang, J. D. Rogers, X. Yao, R. Nichols, K. Atay, B. Xu, J. Franklin, I. Sochnikov, P. J. Ryan, D. Haskel, and F. Tafti, Colossal magnetoresistance without mixed valence in a layered phosphide crystal, *Adv. Mater.* **33**, 2005755 (2021).
- [25] I. Schellenberg, U. Pfannenschmidt, M. Eul, C. Schwickert, and R. Pöttgen, A ¹²¹Sb and ¹⁵¹Eu Mössbauer spectroscopic investigation of EuCd₂X₂ (X = P, As, Sb) and YbCd₂Sb₂, *Z. Anorg. Allg. Chem.* **637**, 1863 (2011).
- [26] D. Y. Usachov, S. Krebber, K. A. Bokai, A. V. Tarasov, M. Kopp, C. Garg, A. Virovets, J. Müller, M. Mende, G. Poelchen, D. V. Vyalikh, C. Krellner, and K. Kliemt, Magnetism, heat capacity, and electronic structure of EuCd₂P₂ in view of its colossal magnetoresistance, *Phys. Rev. B* **109**, 104421 (2024).
- [27] H. Zhang, F. Du, X. Zheng, S. Luo, Y. Wu, H. Zheng, S. Cui, Z. Sun, Z. Liu, D. Shen, M. Smidman, Y. Song, M. Shi, Z. Zhong, C. Cao, H. Yuan, and Y. Liu, Electronic band reconstruction across the insulator-metal transition in colossally magnetoresistive EuCd₂P₂, *Phys. Rev. B* **108**, L241115 (2023).
- [28] X. Chen, Z. Wang, Z. Zhou, W. Yang, Y. Liu, J.-Y. Lu, Z. Ren, G.-H. Cao, F. Tafti, S. Dong, and Z.-C. Wang, Manipulating magnetism and transport properties of EuCd₂P₂ with a low carrier concentration, *Phys. Rev. B* **109**, 224428 (2024).
- [29] V. Sunko, Y. Sun, M. Vranas, C. C. Homes, C. Lee, E. Donoway, Z.-C. Wang, S. Balguri, M. B. Mahendru, A. Ruiz, B. Gunn, R. Basak, S. Blanco-Canosa, E. Schierle, E. Weschke, F. Tafti, A. Frano, and J. Orenstein, Spin-carrier

- coupling induced ferromagnetism and giant resistivity peak in EuCd_2P_2 , *Phys. Rev. B* **107**, 144404 (2023).
- [30] M. Kopp, C. Garg, S. Krebber, K. Kliemt, C. Krellner, S. Balguri, M. Mahendru, F. Tafti, T. L. Breeze, N. P. Bentley, F. L. Pratt, T. J. Hicken, H. Luetkens, J. A. Krieger, S. J. Blundell, T. Lancaster, M. V. Ale Crivillero, S. Wirth, and J. Müller, Robust magnetic polaron percolation in the anti-ferromagnetic CMR system EuCd_2P_2 , *npj Quantum Mater.* **11**, 22 (2026).
- [31] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/95x8-3wtb>, which contains descriptions of the experimental methods, additional resistivity and thermal conductivity data, and thermopower results on a second sample.
- [32] R. Modak, M. Murata, D. Hou, A. Miura, R. Iguchi, B. Xu, R. Guo, J. Shiomi, Y. Sakuraba, and K.-i. Uchida, Phase-transition-induced giant Thomson effect for thermoelectric cooling, *Appl. Phys. Rev.* **9**, 011414 (2022).
- [33] Z. Chen, X. Zhang, S. Zhang, J. Luo, and Y. Pei, Demonstration of efficient Thomson cooler by electronic phase transition, *Nat. Mater.* **24**, 34 (2025).
- [34] P. Negi, S. Wu, T. K. Panigrahi, A. Pancholi, S. S. S. Gadhavajhala, K. Samanta, B. Srinivasan, Y. Pan, and S. Roychowdhury, Beyond Kelvin's relation: A giant transverse Thomson response for efficient cryogenic cooling, *J. Am. Chem. Soc.* **148**, 18118 (2026).
- [35] S. Sagar, V. Ganesan, P. A. Joy, S. Thomas, A. Liebig, M. Albrecht, and M. R. Anantharaman, Colossal thermoelectric power in Gd-Sr manganites, *Europhys. Lett.* **91**, 17008 (2010).
- [36] A. Bentien, S. Johnsen, G. K. H. Madsen, B. B. Iversen, and F. Steglich, Colossal Seebeck coefficient in strongly correlated semiconductor FeSb_2 , *Europhys. Lett.* **80**, 17008 (2007).
- [37] M. Battiato, J. M. Tomczak, Z. Zhong, and K. Held, Unified picture for the colossal thermopower compound FeSb_2 , *Phys. Rev. Lett.* **114**, 236603 (2015).
- [38] I. Bednar, E. Royanian, S. Bühler-Paschen, E. Bauer, N. Nasir, A. Grytsiv, N. Melnychenko-Koblyuk, and P. Rogl, Giant thermopower at low temperatures in novel clathrates $\text{Ba}_8\{\text{Cu}, \text{Zn}\}_x\text{Ge}_{46-x}$, *J. Electron. Mater.* **39**, 1687 (2010).
- [39] A. Jaoui, G. Seyfarth, C. W. Rischau, S. Wiedmann, S. Benhabib, C. Proust, K. Behnia, and B. Fauqué, Giant Seebeck effect across the field-induced metal-insulator transition of InAs , *npj Quantum Mater.* **5**, 94 (2020).
- [40] J. H. Mangez, J. P. Issi, and J. Heremans, Transport properties of bismuth in quantizing magnetic fields, *Phys. Rev. B* **14**, 4381 (1976).
- [41] U. Stockert, R. D. dos Reis, M. O. Ajeesh, S. J. Watzman, M. Schmidt, C. Shekhar, J. P. Heremans, C. Felser, M. Baenitz, and M. Nicklas, Thermopower and thermal conductivity in the Weyl semimetal NbP, *J. Phys. Condens. Matter* **29**, 325701 (2017).
- [42] Y. Sun, M. B. Salamon, M. Lee, and T. F. Rosenbaum, Giant magnetothermopower associated with large magnetoresistance in $\text{Ag}_{2-\delta}\text{Te}$, *Appl. Phys. Lett.* **82**, 1440 (2003).
- [43] R. Stratton, Diffusion of hot and cold electrons in semiconductor barriers, *Phys. Rev.* **126**, 2002 (1962).
- [44] [10.17617/3.vejght](https://arxiv.org/abs/10.17617/3.vejght).