Magnetocaloric performance of $\text{RE}_{11}\text{Co}_4\text{In}_9$ (RE = Tb, Er)

Stanisław Baran,¹ Altifani Rizky Hayyu,¹ Yuriy Tyvanchuk,² and Andrzej Szytula¹

¹M. Smoluchowski Institute of Physics, Jagiellonian University, prof. Stanisława Łojasiewicza 11, PL-30-348 Kraków, Poland
²Department of Analytical Chemistry, Ivan Franko National University of Lviv, Kyryla i Mejodya 6, UA-79005 Lviv, Ukraine

(Dated: February 21, 2022)

The magnetocaloric effect in $\text{RE}_{11}\text{Co}_4\text{In}_9$ (RE = Tb, Er) has been studied by means of magnetometric measurements in the function of temperature and applied magnetic field. The maximum magnetic entropy change ($-\Delta S_{\text{tr}}^\text{max}$) at magnetic flux density change ($\Delta \mu_0 H$) 0-9 T has been determined to be $5.51\ \text{Jkg}^{-1}\text{K}^{-1}$ at $47.4\ \text{K}$ for Tb₁₁Co₄In₉ and $14.28\ \text{Jkg}^{-1}\text{K}^{-1}$ at $12.3\ \text{K}$ for Er₁₁Co₄In₉, while temperature averaged entropy change (TEC) with $3\ \text{K}$ span equals $5.50$ and $14.14\ \text{Jkg}^{-1}\text{K}^{-1}$ for RE = Tb and Er, respectively. The effective cooling power (RCP) and refrigerant capacity (RC) equal respectively $522.1$ and $391.2\ \text{Jkg}^{-1}$ in Tb₁₁Co₄In₉ and $605.2$ and $463.1\ \text{Jkg}^{-1}$ in Er₁₁Co₄In₉.

**keywords:** rare earth intermetallics, magnetocaloric effect, magnetic entropy change, relative cooling power, refrigerant capacity

### I. INTRODUCTION

Magnetocaloric effect (MCE) is nowadays of great scientific interest due to its application in magnetic refrigeration (MR) [1]. Recently, promising magnetocaloric properties have been reported for $\text{RE}_{11}\text{Co}_4\text{In}_9$ (RE = Gd, Dy, Ho) [2]. The $\text{RE}_{11}\text{Co}_4\text{In}_9$ (RE = Gd–Er) intermetallics are known to crystallize in an orthorhombic crystal structure of the Nd₁₁Pd₄In₉-type (space group $Cnmnm$) [2,3]. Within the $ab$-plane, the structure consists of the $\text{RECo}_2$ (AlB₂-type) and $\text{REIn}$ (CsCl-type) fragments in the 9:2 ratio [3]. Along the $c$-axis, the layers composed of the rare earth atoms ($z=0$) are separated by layers containing the Co and In atoms ($z=\frac{1}{2}$). In this complex crystal structure the rare earth atoms occupy five nonequivalent Wyckoff sites.

The measurements of magnetization vs temperature, undertaken at magnetic flux density $\mu_0 H$ of $2\ \text{T (20 kOe)}$, show a transition from para- to ferromagnetic state at $86, 37$ and $20\ \text{K}$ for RE = Gd, Dy and Ho, respectively [2]. The more recent measurements, performed at a low magnetic flux density of $0.005\ \text{T (50 Oe)}$, reveal a cascade of magnetic transitions at $95, 85, 70$ and $35\ \text{K (RE = Tb)}, \text{ 88, 28}$ and $19\ \text{K (RE = Dy)}, \text{ 33 and 10 K (RE = Ho)}$ with only exception for RE = Er, where a single transition, characteristic of formation of an antiferromagnetic order below $5.4\ \text{K}$, is observed [4]. The effective magnetic moments in $\text{RE}_{11}\text{Co}_4\text{In}_9$ (RE = Gd–Er) are close to the values expected for the free RE$^{3+}$ ions, indicating that magnetism in the investigated compounds is related to the rare earth magnetic moments while the Co atoms remain either non-magnetic or their magnetic moments are tiny and negligible when compared to high rare earth moments. Isothermal magnetization curves do not show saturation for RE = Gd, Dy and Ho at $T = 3\ \text{K}$ and $\mu_0 H = 7\ \text{T (70 kOe)}$ [2] as well as for RE = Tb, Dy, Ho and Er at $T = 2\ \text{K}$ and $\mu_0 H = 9\ \text{T (90 kOe)}$ [4]. It is worth noting that the primary isothermal magnetization curve for RE = Er, collected at $2\ \text{K}$, shows a metamagnetic transition at $0.06\ \text{T (0.6 kOe)}$, indicating that the low-temperature antiferromagnetic order can be turned into a ferromagnetic one by application of relatively low magnetic field [4].

The magnetocaloric properties have been reported only for RE = Gd, Dy and Ho [2]. In the vicinity of the respective Curie temperature, the magnetic entropy change reaches $10.95, 4.66$ and $12.29\ \text{Jkg}^{-1}\text{K}^{-1}$ for RE = Gd, Dy and Ho, respectively. The temperature averaged entropy change (TEC) with $3\ \text{K}$ span shows the values of $10.93\ (\text{RE = Gd}), \text{ 4.64 (Dy) and 12.09 Jkg}^{-1}\text{K}^{-1}\ (\text{Ho})$. Relative cooling power (RCP) and refrigerant capacity (RC) are found to be $538.1$ and $405.9\ \text{Jkg}^{-1}$ (RE = Gd), $213.9$ and $165.9\ \text{Jkg}^{-1}$ (Dy) and $475.2$ and $357.4\ \text{Jkg}^{-1}$ (Ho).

In this work, the magnetocaloric properties of Tb₁₁Co₄In₉ and Er₁₁Co₄In₉ are reported, as derived from measurements of magnetization in the function of temperature and applied magnetic field (up to $9\ \text{T}$). These results extend the knowledge on magnetocaloric properties to all members of the $\text{RE}_{11}\text{Co}_4\text{In}_9$ (RE = Gd–Er) family of compounds.

### II. MATERIALS AND METHODS

The samples investigated in this work are the same samples as those reported in the previous study [4]. The reader interested in synthesis procedure and crystal structure parameters can find all this information in Ref. [4].

The magnetocaloric effect in $\text{RE}_{11}\text{Co}_4\text{In}_9$ (RE = Tb, Er) has been investigated with the use of a vibrating sample magnetometer (VSM) option of the Physical Proper-

*stanislaw.baran@uj.edu.pl*
ties Measurement System by Quantum Design, equipped with a superconducting magnet running up to 9 T. In order to collect the data, the following procedure has been performed:

- Demagnetization in the paramagnetic state by decreasing oscillating magnetic field.
- Cooling down to 2 K.
- Setting the desired value of magnetic flux density (the data were collected at 0.5, 1.0, ..., 9.0 T).
- Collecting magnetization vs temperature data up to 200 K (Tb\(_{11}\)Co\(_4\)In\(_9\)) or 70 K (Er\(_{11}\)Co\(_4\)In\(_9\)).
- Repetition of the above steps for the next value of magnetic flux density.

### III. RESULTS AND DISCUSSION

![FIG. 1. Magnetization vs temperature curves for (a) Tb\(_{11}\)Co\(_4\)In\(_9\) and (b) Er\(_{11}\)Co\(_4\)In\(_9\). The curves were collected at selected values of magnetic flux density ranging from 0.5 to 9.0 T.](image)

![FIG. 2. Magnetization vs magnetic flux density curves for (a) Tb\(_{11}\)Co\(_4\)In\(_9\) and (b) Er\(_{11}\)Co\(_4\)In\(_9\), as calculated from the raw data shown in Fig. 1.](image)

Fig. 1 shows the magnetization vs temperature curves collected for RE\(_{11}\)Co\(_4\)In\(_9\) (RE = Tb, Er) at selected values of magnetic flux density. All the curves have an inflection point characteristic of the transition from para- to ferro-/ferrimagnetic state. A maximum visible in the \(\sigma(T)\) curves for Tb\(_{11}\)Co\(_4\)In\(_9\) indicates the development of an antiferromagnetic contribution to the magnetic structure at low temperatures. With the increase of the applied magnetic field, the maximum shifts to lower temperatures and finally disappears, indicating the suppression of the antiferromagnetic component by applying a high magnetic field.

This result is in agreement with the magnetization vs magnetic flux density curves presented in Fig. 2. The curves for Tb\(_{11}\)Co\(_4\)In\(_9\), collected at the lowest temperatures, show a distinct metamagnetic transition indicating that antiferromagnetic contribution to the magnetic order is turned into the ferro/ferrimagnetic one by application of the external magnetic field. The metamagnetic transition disappears with increasing temperature.

In order to ensure that the magnetic transition corresponding to the maximum magnetic entropy change is the second-order phase transition (SOPT), not the first-order phase transition (FOPT), and therefore no thermal hysteresis of magnetic entropy change is expected, the Arrott curves at selected temperatures have been calculated (see Fig. 3). The theory predicts that the sign of the slope of Arrott curve corresponds to the character...
FIG. 3. The $\sigma^2(\mu_0 H/\sigma)$ Arrott curves at selected temperatures for (a) Tb$_{11}$Co$_4$In$_9$ and (b) Er$_{11}$Co$_4$In$_9$.

of the magnetic phase transition, i.e. it is positive for SOPT and negative for FOPT. It is clearly visible in Fig. 3 that all curves for Er$_{11}$Co$_4$In$_9$ have positive slope and only some low-temperature curves for Tb$_{11}$Co$_4$In$_9$ have negative slope within a limited range. Therefore, the FOPT in Tb$_{11}$Co$_4$In$_9$ is related to the appearance of the low-temperature antiferromagnetic contribution to the magnetic order. It has to be mentioned that all Arrott curves in the vicinity of temperatures at which magnetic entropy change reaches its maximum (i.e. 47.4 K in Tb$_{11}$Co$_4$In$_9$ and 12.3 K in Er$_{11}$Co$_4$In$_9$ for magnetic flux density change 0-9 T) have positive slope, indicating that the corresponding magnetic phase transition is SOFT.

In order to calculate the magnetic entropy change under isothermal conditions, the following well-known equation has been used:

$$\Delta S_M(T, \Delta \mu_0 H) \equiv \int_{\mu_0 H_i}^{\mu_0 H_f} \left( \frac{\partial \sigma(T, \mu_0 H)}{\partial T} \right)_{\mu_0 H} \, d\mu_0 H$$

(1)

where $\Delta \mu_0 H$ is a change of the magnetic flux density, defined as a difference between the final ($\mu_0 H_f$) and initial ($\mu_0 H_i$) flux densities, while $\left( \frac{\partial \sigma(T, \mu_0 H)}{\partial T} \right)_{\mu_0 H}$ is a derivative of magnetization over temperature at fixed magnetic flux density $\mu_0 H$. As it is commonly assumed to report magnetic entropy change with respect to the initial magnetic flux density equal to zero ($\mu_0 H_i = 0$), the same convention is used in the current study. Fig. 4 shows magnetic entropy change in function of temperature for selected values of the magnetic flux density change. The maximum magnetic entropy change for $\Delta \mu_0 H = 0-9$ T reaches 5.51 J·kg$^{-1}$·K$^{-1}$ at 47.4 K for Tb$_{11}$Co$_4$In$_9$ and 14.28 J·kg$^{-1}$·K$^{-1}$ at 12.3 K for Er$_{11}$Co$_4$In$_9$. The values of maximum magnetic entropy change for different magnetic flux density changes between 0-1 up to 0-9 T are listed in Table 1.

Another, recently introduced parameter characterizing a magnetocaloric material is the temperature averaged magnetic entropy change (TEC) over a given temperature span $(\Delta T_{\text{lift}})$, defined by the following equation:

$$T E C(\Delta T_{\text{lift}}, \Delta \mu_0 H) =$$

$$\frac{1}{\Delta T_{\text{lift}}} \int_{T_{\text{mid}} - \frac{\Delta T_{\text{lift}}}{2}}^{T_{\text{mid}} + \frac{\Delta T_{\text{lift}}}{2}} \Delta S_M(T, \Delta \mu_0 H) \, dT$$

(2)

where the integral is maximized with respect to the $T_{\text{mid}}$ parameter which is a center of the temperature span.
refrigerant capacity (RC) \[9\] and relative cooling power (RCP) \[10\], defined as follows:

\[
RC = \int_{T_1}^{T_2} | - \Delta S_M(T) | \, dT
\]

\[
RCP = -\Delta S_M^{\text{max}} \times \delta T_{\text{FWHM}}
\]

where \( T_{\text{FWHM}} \) denotes full width at half-maximum of the \(-\Delta S_M(T)\) curve while \( T_1 \) and \( T_2 \) refer respectively to the lower and higher limits of the \( \delta T_{\text{FWHM}} \) range.

The values of RC and RCP for the whole RE\(_{11}\)Co\(_4\)In\(_9\) (RE = Gd–Er) family of compounds are listed in Table \[\text{II}\].

For a fixed value of the flux density change \((\Delta \mu_0 H)\), RC and RCP decrease with the increasing number of the \(4f\) electrons, reaching a local minimum for RE = Dy, and afterwards for RE = Ho, Er they increase to the values comparable with those found for RE = Gd.

The magnetocaloric performance of the RE\(_{11}\)Co\(_4\)In\(_9\) (RE = rare earth) intermetallics is comparable to that of the best known magnetocaloric materials \[11, 12\], making RE\(_{11}\)Co\(_4\)In\(_9\) good candidates for low-temperature magnetocaloric refrigeration.

### IV. CONCLUSIONS

The magnetocaloric effect in RE\(_{11}\)Co\(_4\)In\(_9\) (RE = Tb, Er) has been investigated by magnetometric measurements in the function of temperature and applied magnetic field. Based on these data, the following parameters characterizing magnetocaloric performance have been determined: \(-\Delta S_M^{\text{max}}\), TEC, RC and RCP. Comparison of these parameters for the whole RE\(_{11}\)Co\(_4\)In\(_9\) (RE = Gd–Er) family of compounds leads to the conclusion that the intermetallics with RE = Gd, Ho and Er show high and comparable one to another magnetocaloric performance, much higher than that found for RE = Tb and Dy. It is worth noting that although the parameters characterizing MCE in RE = Gd, Ho and Er take similar values, the corresponding maximum magnetic entropy changes appear at different temperatures which are closely related to the magnetic transition temperatures of individual compounds. The maximum of \(-\Delta S_M\) is found around 90, 20 and 10 K for RE = Gd, Ho and Er, respectively.

### DECLARATION OF COMPETING INTEREST

The authors declare no conflict of interest.

### ACKNOWLEDGEMENTS

The research was partially carried out with the equipment purchased thanks to the financial support of the...
European Regional Development Fund in the framework of the Polish Innovation Economy Operational Program (contract no. POIG.02.01.00-12-023/08).

[1] V. Franco, J. S. Blázquez, J. J. Ipus, J. Y. Law, L. M. Moreno-Ramírez, A. Conde, Magnetocaloric effect: From materials research to refrigeration devices, Prog. Mater. Sci. 93 (2018) 112–232. doi:10.1016/j.pmatsci.2017.10.003.

[2] Z. Zhang, P. Wang, N. Wang, X. Wang, P. Xu, L. Li, Structural and cryogenic magnetic properties of rare earth rich RE\textsubscript{11}Co\textsubscript{4}In\textsubscript{9} (RE= Gd, Dy and Ho) intermetallic compounds, Dalton Trans. 49 (2020) 8764–8773. doi:10.1039/D0DT01213B.

[3] Yu. Tyvanchuk, M. Dzevenko, Ya. Kalychak, R\textsubscript{11}Co\textsubscript{4}In\textsubscript{9} (R = Gd, Tb, Dy, Ho, Er) – the first representatives of Nd\textsubscript{11}Pd\textsubscript{4}In\textsubscript{9} structure type in R–Co–In systems, Visnyk Lviv Univ., Series Chem. 53 (2012) 127–132. Ukrainian.

[4] S. Baran, Yu. Tyvanchuk, A. Szytuła, Crystal structure and magnetic properties of R\textsubscript{11}Co\textsubscript{4}In\textsubscript{9} (R = Tb, Dy, Ho and Er) compounds, Intermetallics 130 (2021) 107065. doi:10.1016/j.intermet.2020.107065.

[5] L. Sojka, M. Manyako, R. Černý, M. Ivanyk, B. Belan, R. Gladyshevskii, Ya. Kalychak, Nd\textsubscript{11}Pd\textsubscript{4}In\textsubscript{9} compound a new member of the homological series based on AlB\textsubscript{2} and CsCl types. Intermetallics 16 (2008) 625–628. doi:10.1016/j.intermet.2008.01.001.

[6] B. K. Banerjee, On a generalised approach to first and second order magnetic transitions, Phys. Lett. 12 (1964) 16–17. doi:10.1016/0031-9163(64)91158-8.

[7] A. M. Tishin, Y. I. Spichkin, The Magnetocaloric Effect and its Applications, Institute of Physics Publishing, Bristol (UK) and Philadelphia (PA), 2003.

[8] L. D. Griffith, Y. Mudryk, J. Slaughter, V. K. Pecharsky, Material-based figure of merit for caloric materials, J. Appl. Phys. 123 (2018) 034902. doi:10.1063/1.5004173.

[9] M. E. Wood, W. H. Potter, General analysis of magnetic refrigeration and its optimization using a new concept: maximization of refrigerant capacity, Cryogenics 25 (1985) 667–683. doi:10.1016/0011-2275(85)90187-4.

[10] K. A. Gschneidner, Jr., V. K. Pecharsky, Magnetocaloric materials, Annu. Rev. Mater. Sci. 30 (2000) 387–429. doi:10.1146/annurev.matsci.30.1.387.

[11] K. A. Gschneidner, Jr., V. K. Pecharsky, A. O. Tsokol, Recent developments in magnetocaloric materials, Rep. Prog. Phys. 68 (2005) 1479–1539. doi:10.1088/0034-4885/68/6/R04.

[12] J. Lyubina, Magnetocaloric materials for energy efficient cooling, J. Phys. D: Appl. Phys. 50 (2017) 053002. doi:10.1088/1361-6463/50/5/053002.
TABLE I. The values of $-\Delta S_M^{\text{max}}$, TEC(3 K), TEC(5 K) and TEC(10 K) under various $\Delta \mu_0 H$ for RE$_{11}\text{Co}_4\text{In}_9$ (RE = Gd–Er). The data taken from Ref. [2] are shown in the $\Delta \mu_0 H$ range up to 0-7 T while those reported in this work in the range up to 0-9 T.

Gd$_{11}\text{Co}_4\text{In}_9$ (data from Ref. [2])

| $\Delta \mu_0 H$ [T] | $-\Delta S_M^{\text{max}}$ [J-kg$^{-1}$K$^{-1}$] | TEC(3 K) [J-kg$^{-1}$K$^{-1}$] | TEC(5 K) [J-kg$^{-1}$K$^{-1}$] | TEC(10 K) [J-kg$^{-1}$K$^{-1}$] |
|---------------------|---------------------------------|-----------------|-----------------|-----------------|
| 0-1                 | 2.92                            | 2.79            | 2.68            | 2.41            |
| 0-2                 | 5.03                            | 4.96            | 4.88            | 4.59            |
| 0-3                 | 6.55                            | 6.52            | 6.48            | 6.22            |
| 0-4                 | 7.86                            | 7.83            | 7.79            | 7.55            |
| 0-5                 | 9.01                            | 8.92            | 8.88            | 8.70            |
| 0-6                 | 10.02                           | 10.01           | 9.93            | 9.72            |
| 0-7                 | 10.95                           | 10.93           | 10.85           | 10.65           |

Tb$_{11}\text{Co}_4\text{In}_9$ (this work)

| $\Delta \mu_0 H$ [T] | $-\Delta S_M^{\text{max}}$ [J-kg$^{-1}$K$^{-1}$] | TEC(3 K) [J-kg$^{-1}$K$^{-1}$] | TEC(5 K) [J-kg$^{-1}$K$^{-1}$] | TEC(10 K) [J-kg$^{-1}$K$^{-1}$] |
|---------------------|---------------------------------|-----------------|-----------------|-----------------|
| 0-1                 | 0.45                            | 0.45            | 0.44            | 0.42            |
| 0-2                 | 1.16                            | 1.16            | 1.15            | 1.12            |
| 0-3                 | 1.91                            | 1.90            | 1.89            | 1.85            |
| 0-4                 | 2.61                            | 2.60            | 2.59            | 2.55            |
| 0-5                 | 3.25                            | 3.24            | 3.23            | 3.19            |
| 0-6                 | 3.85                            | 3.84            | 3.84            | 3.80            |
| 0-7                 | 4.43                            | 4.42            | 4.41            | 4.39            |
| 0-8                 | 4.98                            | 4.97            | 4.97            | 4.94            |
| 0-9                 | 5.51                            | 5.50            | 5.50            | 5.48            |

Dy$_{11}\text{Co}_4\text{In}_9$ (data from Ref. [2])

| $\Delta \mu_0 H$ [T] | $-\Delta S_M^{\text{max}}$ [J-kg$^{-1}$K$^{-1}$] | TEC(3 K) [J-kg$^{-1}$K$^{-1}$] | TEC(5 K) [J-kg$^{-1}$K$^{-1}$] | TEC(10 K) [J-kg$^{-1}$K$^{-1}$] |
|---------------------|---------------------------------|-----------------|-----------------|-----------------|
| 0-1                 | 0.38                            | 0.37            | 0.37            | 0.34            |
| 0-2                 | 1.14                            | 1.12            | 1.18            | 1.12            |
| 0-3                 | 2.09                            | 2.06            | 2.02            | 1.94            |
| 0-4                 | 2.88                            | 2.84            | 2.80            | 2.71            |
| 0-5                 | 3.53                            | 3.51            | 3.47            | 3.38            |
| 0-6                 | 4.09                            | 4.08            | 4.05            | 3.98            |
| 0-7                 | 4.66                            | 4.64            | 4.61            | 4.55            |

Ho$_{11}\text{Co}_4\text{In}_9$ (data from Ref. [2])

| $\Delta \mu_0 H$ [T] | $-\Delta S_M^{\text{max}}$ [J-kg$^{-1}$K$^{-1}$] | TEC(3 K) [J-kg$^{-1}$K$^{-1}$] | TEC(5 K) [J-kg$^{-1}$K$^{-1}$] | TEC(10 K) [J-kg$^{-1}$K$^{-1}$] |
|---------------------|---------------------------------|-----------------|-----------------|-----------------|
| 0-1                 | 0.91                            | 0.90            | 0.88            | 0.83            |
| 0-2                 | 2.95                            | 2.90            | 2.86            | 2.74            |
| 0-3                 | 5.23                            | 5.11            | 5.03            | 4.81            |
| 0-4                 | 7.34                            | 7.17            | 7.06            | 6.78            |
| 0-5                 | 9.22                            | 9.00            | 8.87            | 8.55            |
| 0-6                 | 10.84                           | 10.61           | 10.47           | 10.13           |
| 0-7                 | 12.29                           | 12.09           | 11.90           | 11.54           |

Er$_{11}\text{Co}_4\text{In}_9$ (this work)

| $\Delta \mu_0 H$ [T] | $-\Delta S_M^{\text{max}}$ [J-kg$^{-1}$K$^{-1}$] | TEC(3 K) [J-kg$^{-1}$K$^{-1}$] | TEC(5 K) [J-kg$^{-1}$K$^{-1}$] | TEC(10 K) [J-kg$^{-1}$K$^{-1}$] |
|---------------------|---------------------------------|-----------------|-----------------|-----------------|
| 0-1                 | 3.26                            | 3.18            | 3.06            | 2.67            |
| 0-2                 | 6.00                            | 5.86            | 5.69            | 5.16            |
| 0-3                 | 8.04                            | 7.88            | 7.71            | 7.18            |
| 0-4                 | 9.61                            | 9.44            | 9.31            | 8.82            |
| 0-5                 | 10.93                           | 10.72           | 10.61           | 10.18           |
| 0-6                 | 11.92                           | 11.77           | 11.69           | 11.31           |
| 0-7                 | 12.80                           | 12.66           | 12.60           | 12.29           |
| 0-8                 | 13.59                           | 13.44           | 13.39           | 13.13           |
| 0-9                 | 14.28                           | 14.14           | 14.10           | 13.87           |
TABLE II. The values of RCP and RC with $\Delta\mu_0 H$ of 0–2, 0–5 and 0–9 T for RE$_{11}$Co$_4$In$_9$ (RE = Gd–Er).

| Material | RCP [J·kg$^{-1}$] | RC [J·kg$^{-1}$] | Ref. |
|----------|-------------------|------------------|------|
|          | 0-2 T             | 0-5 T            | 0-9 T | 0-2 T | 0-5 T | 0-9 T |
| Gd$_{11}$Co$_4$In$_9$ | 106.3 | 357.9 | 81.5 | 269.9 | [2] |
| Tb$_{11}$Co$_4$In$_9$ | 44.6  | 179.5 | 522.1 | 34.5  | 139.5 | 391.2 | this work |
| Dy$_{11}$Co$_4$In$_9$ | 27.1  | 128.4 | 20.4  | 97.8  | [2] |
| Ho$_{11}$Co$_4$In$_9$ | 87.4  | 306.7 | 66.1  | 228.7 | [2] |
| Er$_{11}$Co$_4$In$_9$ | 84.6  | 265.1 | 605.2 | 66.2  | 205.3 | 463.1 | this work |