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1 **Correlation between deformation and total entropy change at the first-order magnetic**
2 **transition of Fe₂P-based magnetocaloric materials**

3 F. Guillou¹, H. Yibole^{1,*}, B. Narsu¹, and V. Hardy²

4 1- College of Physics and Electronic Information, Inner Mongolia Key Laboratory for Physics
5 and Chemistry of Functional Materials, Inner Mongolia Normal University, 81 Zhaowuda Road,
6 Hohhot 010022, Inner Mongolia, People's Republic of China

7 2- Normandie University, ENSICAEN, UNICAEN, CNRS, CRISMAT, 14000 Caen, France

8 *hyibole@imnu.edu.cn

9 **Highlights :**

- 10 - latent heat or transition entropy are key parameters in giant magnetocaloric materials
11 - a general scaling of ΔS_{tr} with $\Delta(c/a)$ is observed in Fe₂P-related materials family
12 - deformation has a crucial role even in volume preserving FOMTs

13 **Abstract:**

14 While there is a growing consensus that lattice is an important source of entropy change at
15 structural or elastic first-order magnetic transitions (FOMT) with finite volume change, the case
16 of volume preserving transitions ($\Delta V = 0$) remains more controversial. Here, the evolution of the
17 total transition entropy change within the Fe₂P family is presented as a function of the
18 discontinuity on the ratio of the cell parameters. A striking correlation between ΔS_{tr} and $\Delta(c/a)$ is
19 observed. This relationship is a first step towards a systematization of the FOMT properties in
20 the Fe₂P materials system. It also demonstrates that deformation can play a leading role in
21 volume preserving FOMT.

22 **Keywords:**

23 Latent heat; First-order Magnetic Transition; Magnetism ; Magnetocaloric effect ;
24 Thermomagnetic materials

25 Magnetic transitions often involve simultaneous changes in the electronic (S_{el}), lattice (S_{latt}), and
26 magnetic (S_{mag}) properties. The expression $S = S_{latt} + S_{el} + S_{mag}$ is commonly employed to express
27 how these degrees of freedoms and their entropy are expected to sum up. By extension, at first-
28 order magnetic transition (FOMT) with transition temperature (T_{tr}), the transition entropy $\Delta S_{tr} =$
29 L/T_{tr} related to the latent heat (L) is expected to originate from one or several of these
30 contributions. Unfortunately, estimating individually each term is challenging. On top of that, the
31 above summation relies on a strong and disputable assumption that the degrees of freedom are
32 independent, *i.e.* there is no cooperativity between them.

33 Understanding the driving mechanisms for the latent heat of giant magnetocaloric materials is
34 of outmost importance for applications, as the optimization primarily consists in triggering a large
35 latent heat for an external magnetic field change as small as possible. Following the discovery
36 of a giant magnetocaloric effect with magneto-structural FOMT in $Gd_5Si_2Ge_2$, a structural entropy
37 change representing about half of the magnetocaloric effect was proposed as primary reason
38 for overcoming the performances of elemental Gd [1,2]. This led to a general scaling that the
39 larger the relative volume change $\Delta V/V$, the stronger the lattice contribution and therefore the
40 higher the magnetocaloric effect [3]. This approach may however be confusing as it considers
41 the isothermal entropy change induced by a magnetic field change (referred to as ΔS), whose
42 relationship with the transition entropy discontinuity in zero field (referred to as ΔS_{tr}) is indirect.
43 In addition, an accurate determination of ΔS can be challenging at FOMT due to the spike
44 artefact. A $\Delta V/V$ scaling of the magnetocaloric effect appears also applicable to isotropic
45 magneto-elastic FOMT such as in $La(Fe,Si)_{13}$. For this system, after some early controversies
46 on whether the lattice entropy change counteracts the magnetic one [4], direct insights using
47 inelastic resonant x-ray scattering techniques have led to a consensus that the lattice entropy
48 change adds up to the magnetic contribution and may be responsible for nearly half the
49 isothermal entropy change [5-8]. However, ΔV or $\Delta V/V$ is not a convenient parameter for
50 characterizing magneto-elastic anisotropic FOMT as in hexagonal Fe_2P compounds where the
51 contraction on the a axis is compensated by an expansion along the c axis leading to nearly
52 negligible volume changes.

53 In view of the strong interest in Fe_2P compounds [9-28], insights into the mechanism of their
54 FOMT are highly desirable. Fe_2P -based compounds can exhibit ferromagnetic transitions with

55 extreme behaviors. Depending on chemical compositions, it is possible to achieve: *i*) second-
56 order transitions (typically $\text{Mn}_{2-x}\text{Fe}_x\text{P}_{0.5}\text{Si}_{0.5}$ with $x < 0.7$) [9]; *ii*) FOMT with particularly small
57 hysteresis and latent heat (case of the Fe_2P binary parent) [10,11]; *iii*) FOMT with small
58 hysteresis but significant latent heat (best compositions for magnetocaloric or thermomagnetic
59 applications, e.g. $\text{MnFe}_{0.95}\text{P}_{0.585}\text{Si}_{0.34}\text{B}_{0.075}$) [12]; and *iv*) up to giant hysteresis and giant latent
60 heat as in $\text{MnFe}_{0.95}\text{P}_{2/3}\text{Si}_{1/3}$ [13]. In all these materials the volume discontinuity is either limited
61 ($\Delta V/V < 0.2\%$) or down to virtually zero. For the Fe_2P -based family, no consensus has ever
62 emerged about the dominant(s) contribution(s) to ΔS_{tr} and even the most recent reports still led
63 to puzzling results. First, there is a one order of magnitude difference on the integrated magnetic
64 entropy between Fe_2P and $\text{MnFe}_{0.95}\text{P}_{0.585}\text{Si}_{0.34}\text{B}_{0.075}$ [11,16]. This is hardly understandable in
65 view of their comparable saturation magnetizations (M_{sat} approximately 2.9 and 4.0 $\mu_B/\text{f.u.}$,
66 respectively). Second, in contrast to early theoretical studies pointing out that the latent heat has
67 mostly a magnetic origin [17], recent phonon calculations and inelastic scattering experiments
68 suggest that nearly all the transition entropy (ΔS_{tr}) has a structural origin [18,19]. Finally, former
69 attempts at scaling the FOMT in Fe_2P -based materials (either via L , hysteresis or even ΔS) failed
70 to encompass the broad variety of properties observed in this system. Dung *et al.* pointed out
71 that isothermal entropy changes (ΔS) are correlated with $|\Delta a/a|$ and $|\Delta c/c|$ in a couple of
72 $(\text{Mn,Fe})_2(\text{P,Si})$ samples [25]. In $\text{MnFe}(\text{P,Si,B})$ compounds, Maschek *et al.* found that the thermal
73 hysteresis varies like $\Delta(c/a)$, but no specific correlation could be established for ΔS [22]. In
74 $(\text{Mn,Fe})_2(\text{P,Si})$ compounds, You *et al.* reported a linear relation between hysteresis and c/a (after
75 a given threshold), while they pointed an absence of correlation between L and (c/a) [29]. Miao
76 *et al.* claimed the existence of a striking relationship between thermal hysteresis and elastic
77 strain energy for a large panel of Fe_2P compounds [20]. It must be emphasized, however, that
78 all these previous observations carry some ambiguities. First, even though ΔS is correlated with
79 ΔS_{tr} , it also involves other parameters such as the sensitivity of the transition to the magnetic
80 field $T_{tr}(B)$ or even extrinsic ones like the transition width. Second, thermal hysteresis can also
81 not be regarded as an intrinsic quantity for a FOMT. Indeed hysteresis is known to be impacted
82 by external features like the microstructure and is even not a necessity for FOMTs, as materials
83 with nearly negligible hysteresis but sizable latent heat can be observed like in
84 $(\text{Mn,V,Fe})_2(\text{P,Si,B})$ [23]. Actually, ΔS_{tr} (or $L = T_{tr}\Delta S_{tr}$) are more genuine intrinsic quantities, directly
85 connected to the Ehrenfest definition of first-order transitions.

86 Seeking to bring back together the diversity in FOMTs observed in Fe₂P materials, **Figure 1**
87 presents the transition entropy ΔS_{tr} as a function of the elastic deformation quantified as the
88 discontinuity in the cell parameters ratio $\Delta(c/a)$. The MnFeP_{0.66-x}Si_{0.34}B_x series is particularly
89 important as it covers a wide ΔS_{tr} range while keeping chemical substitutions limited [13]. Results
90 for Fe₂P, MnFe(P,Si) and MnFe(P,Ge) were included depending upon availability of ΔS_{tr} and
91 temperature dependent structural data. The criteria used to determine $\Delta(c/a)$ and ΔS_{tr} as well as
92 the list of the eighteen considered samples are presented in Supplementary Materials.

93 A striking correlation is observed between the transition entropy ΔS_{tr} and the deformation $\Delta(c/a)$.
94 We emphasize, however, that this correlation does not imply a predominant lattice component
95 in the entropy change; it neither addresses the respective weights of the magnetic, lattice or
96 electronic contributions within the net ΔS_{tr} value. First of all, one must keep in mind that the
97 experimental determinations of ΔS_{tr} can only yield a global quantity incorporating all the degrees
98 of freedom. Second, we stress that even when using additional experimental data, the aim at
99 separating the various contributions in ΔS_{tr} is basically impossible owing to the intrication
100 between degrees of freedom that characterizes FOMTs. Recently, it has been proposed that the
101 elastic deformation energy could be expressed as $\Delta U_{elastic}/V_{mol} \approx (c_{11}+c_{12})\epsilon_1^2+2c_{13}\epsilon_1\epsilon_3+(c_{33}\epsilon_3^2)/2$
102 where ϵ_{ij} denotes the strains and c_{ij} the elastic constants [20]. Considering the theoretical elastic
103 constants for MnFeSi_{0.33}P_{0.58}B_{0.08} [21] and the experimental strains for MnFe_{0.95}P_{0.595}Si_{0.33}B_{0.075}
104 [13], the above equation leads to a $\Delta S_{elastic} = \Delta U_{elastic}/T_{tr}$ estimated in the range 8 – 18 J kg⁻¹ K⁻¹,
105 which would be compatible with the experimental $\Delta S_{tr} = 16$ J kg⁻¹ K⁻¹. Nevertheless, the above
106 equation involves squared strains, whereas ΔS_{tr} appears to linearly scale with $\Delta(c/a)$. Even
107 though large uncertainties make it difficult to distinguish the two possibilities, a ΔS_{tr} - $\Delta(c/a)$
108 scaling was found to be the most reliable.

109 The main result of Figure 1 is that the deformation appears as the source of the *total* transition
110 entropy change ΔS_{tr} . But no complementary information about the various contributions to this
111 overall result is accessible. Let us also specify that the correlation appears so far limited to Fe₂P
112 materials. Considering iso-structural FOMTs in other hexagonal materials, (Sc,Ti)Fe₂ ($\Delta(c/a) \approx$
113 0.004 and $\Delta S_{tr} \approx 7$ J kg⁻¹ K⁻¹ [31]) would be close to fit in, but (Hf,Ta)Fe₂ ($\Delta(c/a) \approx 0.014$ and ΔS_{tr}
114 ≈ 4 J kg⁻¹ K⁻¹ [32]) strongly departs from the trend. This might reflect that each materials family
115 has its own underlying FOMT mechanism, leading to distinct ΔS_{tr} -deformation relations.

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132 **References**

- 133 [1] V. K. Pecharsky, K. A. Gschneidner, Jr., Giant magnetocaloric effect in $\text{Gd}_5\text{Si}_2\text{Ge}_2$. *Phys.*
134 *Rev. Lett.* 78 (1997) 4494–4497. <https://doi.org/10.1103/PhysRevLett.78.4494>
- 135 [2] V.K. Pecharsky, A. P. Holm, K. A. Gschneidner, Jr., and R. Rink, Massive Magnetic-Field-
136 Induced Structural Transformation in Gd_5Ge_4 and the Nature of the Giant Magnetocaloric
137 Effect. *Phys. Rev. Lett.* 91 (2003) 197204. <https://doi.org/10.1103/PhysRevLett.91.197204>
- 138 [3] K. A. Gschneidner Jr, Y. Mudryk, V. K. Pecharsky. On the nature of the magnetocaloric
139 effect of the first-order magnetostructural transition. *Scr. Mater.* 67 (2012) 572–577.
140 <https://doi.org/10.1016/j.scriptamat.2011.12.042>
- 141 [4] L. Jia, G. J. Liu, J. R. Sun, H. W. Zhang, F. X. Hu, C. Dong, G. H. Rao, B. G. Shen, Entropy
142 changes associated with the first-order magnetic transition in $\text{LaFe}_{13-x}\text{Si}_x$. *J. Appl. Phys.* 100
143 (2006) 123904. <http://dx.doi.org/10.1063/1.2404468>
- 144 [5] M. E. Gruner, W. Keune, B. Roldan Cuenya, C. Weis, J. Landers, S. I. Makarov, D. Klar,
145 M. Y. Hu, E. E. Alp, J. Zhao, M. Krautz, O. Gutfleisch, H. Wende, Element-Resolved
146 thermodynamics of Magnetocaloric $\text{LaFe}_{13-x}\text{Si}_x$. *Phys. Rev. Lett.* 114 (2015) 057202.
147 <https://doi.org/10.1103/PhysRevLett.114.057202>
- 148 [6] J. Landers, S. Salamon, W. Keune, M. E. Gruner, M. Krautz, J. Zhao, M. Y. Hu, T. S.
149 Toellner, E. E. Alp, O. Gutfleisch, H. Wende, Determining the vibrational entropy change in the
150 giant magnetocaloric material $\text{LaFe}_{11.6}\text{Si}_{1.4}$ by nuclear resonant inelastic x-ray scattering. *Phys.*
151 *Rev. B* 98 (2018) 024417. <https://doi.org/10.1103/PhysRevB.98.024417>

- 152 [7] A. Terwey, M. E. Gruner, W. Keune, J. Landers, S. Salamon, B. Eggert, K. Ollefs, V.
153 Brabänder, I. Radulov, K. Skokov, T. Faske, M. Y. Hu, J. Zhao, E. E. Alp, C. Giacobbe, O.
154 Gutfleisch, H. Wende, Influence of hydrogenation on the vibrational density of states of
155 magnetocaloric $\text{LaFe}_{11.4}\text{Si}_{1.6}\text{H}_{1.6}$. *Phys. Rev. B* 101 (2020) 064415.
156 <https://doi.org/10.1103/PhysRevB.101.064415>
- 157 [8] Jia-Zheng Hao, Feng-Xia Hu, Zi-Bing Yu, Fei-Ran Shen, Hou-Bo Zhou, Yi-Hong Gao, Kai-
158 Ming Qiao, Wen-Hui Liang, Jia Lib, Cheng Zhang, Jing Wang, Jun He, Ji-Rong Sun, Bao-Gen
159 Shen, The sign of lattice and spin entropy change in the giant magnetocaloric materials with
160 negative lattice expansions. *J. Magn. Magn. Mater.* 512 (2020) 166983.
161 <https://doi.org/10.1016/j.jmmm.2020.166983>
- 162 [9] N. H. Dung, Z.Q. Ou, L. Caron, L. Zhang, D.T. Cam Thanh, G.A. de Wijs, R.A. de Groot,
163 K.H.J. Bushow, E. Brück. Mixed Magnetism for Refrigeration and Energy Conversion. *Adv.*
164 *Energy Mater.* 1 (2011) 1215–1219. <https://doi.org/10.1002/aenm.201100252>
- 165 [10] O. Beckman, L. Lundgren, P. Nordblad, P. Svedlindh, A. Törne. Specific Heat of the
166 Ferromagnet Fe_2P . *Phys. Scr.* 25, 679 (1982). <https://doi.org/10.1088/0031-8949/25/6A/005>
- 167 [11] M. Hudl, D. Campanini, L. Caron, V. Höglin, M. Sahlberg, P. Nordblad, and A. Rydh.
168 Thermodynamics around the first-order ferromagnetic phase transition of Fe_2P single crystals
169 *Phys. Rev. B* 90 (2014) 144432. <https://doi.org/10.1103/PhysRevB.90.144432>
- 170 [12] F. Guillou, G. Porcari, H. Yibole, N.H. van Dijk, E. Brück. Taming the First-Order Transition
171 in Giant Magnetocaloric Materials. *Adv. Mater.* 26 (2014) 2671–2675.
172 <https://doi.org/10.1002/adma.201304788>
- 173 [13] F. Guillou, H. Yibole, N.H. van Dijk, E. Brück, Effect of boron substitution on the
174 ferromagnetic transition of $\text{MnFe}_{0.95}\text{P}_{2/3}\text{Si}_{1/3}$. *J. Alloys Compd.* 632 (2015) 717–722.
175 <https://doi.org/10.1016/j.jallcom.2015.01.308>
- 176 [14] X. F. Miao, H. Sepehri-Amin, K. Hono, Structural origin of hysteresis for hexagonal
177 $(\text{Mn,Fe})_2(\text{P,Si})$ magneto-caloric compound, *Scripta Mater.* 138 (2017) 96-99.
178 <https://doi.org/10.1016/j.scriptamat.2017.05.043>

- 179 [15] J. Lai, X. Tang, H. Sepehri-Amin, K. Hono, Tuning transition temperature of
180 magnetocaloric $\text{Mn}_{1.8}\text{Fe}_{0.2}(\text{P}_{0.59}\text{Si}_{0.41})_x$ alloys for cryogenic magnetic refrigeration. *Scripta*
181 *Mater.* 183 (2020) 127-132. <https://doi.org/10.1016/j.scriptamat.2020.03.024>
- 182 [16] F. Guillou, R. Hamane, H. Yibole, J.Y. Xu, B. Narsu, V. Hardy, Heat capacity of a
183 $\text{MnFe}(\text{P},\text{Si},\text{B})$ compound with first-order magnetic transition. *J. Magn. Mater.* 541 (2022)
184 168513. <https://doi.org/10.1016/j.jmmm.2021.168513>
- 185 [17] P. Roy, E. Brück, R. A. de Groot, Latent heat of the first-order magnetic transition of
186 $\text{MnFeSi}_{0.33}\text{P}_{0.66}$. *Phys. Rev. B* 93 (2016) 165101. DOI: 10.1103/PhysRevB.93.165101
- 187 [18] B. Wurentuya, Shuang Ma, B. Narsu, O. Tegus, Zhidong Zhang. Lattice dynamics of
188 $\text{FeMnP}_{0.5}\text{Si}_{0.5}$ compound from first principles calculation. *J. Mater. Sci. Technol.* 35 (2019) 127.
189 <https://doi.org/10.1016/j.jmst.2018.09.009>
- 190 [19] D. Bessas, M. Maschek, H. Yibole, J.-W. Lai, S. M. Souliou, I. Sergueev, A. I. Dugulan, N.
191 H. van Dijk, E. Brück. Lattice dynamics across the magnetic transition in $(\text{Mn},\text{Fe})_{1.95}(\text{P},\text{Si})$.
192 *Phys. Rev. B* 97 (2018) 094303. DOI: 10.1103/PhysRevB.97.094303
- 193 [20] Xuefei Miao, Yong Gong, Fengqi Zhang, Yurong You, Luana Caron, Fengjiao Qian,
194 Wenhui Guo, Yujing Zhang, Yuanyuan Gong, Feng Xu, N. van Dijk, E. Brück, Enhanced
195 reversibility of the magnetoelastic transition in $(\text{Mn},\text{Fe})_2(\text{P},\text{Si})$ alloys via minimizing the
196 transition-induced elastic strain energy, *J. Mater. Sci. Technol.* 103 (2022) 165-176.
197 <https://doi.org/10.1016/j.jmst.2021.05.087>
- 198 [21] P. Roy, E. Torun, and R. A. de Groot. Effect of doping and elastic properties in
199 $(\text{Mn},\text{Fe})_2(\text{Si},\text{P})$. *Phys. Rev. B* 93 (2016) 094110. <https://doi.org/10.1103/PhysRevB.93.094110>
- 200 [22] M. Maschek, X. You, M. F. J. Boeije, D. Chernyshov, N. H. van Dijk, E. Brück, Charge
201 redistribution and the magnetoelastic transition across the first-order magnetic transition in
202 $(\text{Mn},\text{Fe})_2(\text{P},\text{Si},\text{B})$. *Phys. Rev. B* 98, 224413 (2018).
203 <https://doi.org/10.1103/PhysRevB.98.224413>

- 204 [23] J. Lai, X. You, J. Law, V. Franco, B. Huang, D. Bessas, M. Maschek, D. Zeng, N. van Dijk,
205 E. Brück, Ultra-low hysteresis in giant magnetocaloric $Mn_{1-x}V_xFe_{0.95}(P,Si,B)$ compounds. *J.*
206 *Alloys and Compds.* 930 (2023) 167336. <https://doi.org/10.1016/j.jallcom.2022.167336>.
- 207 [24] J.Y. Xu, F. Guillou, H. Yibole, V. Hardy, Peltier cell calorimetry “as an option” for
208 commonplace cryostats: Application to the case of $MnFe(P,Si,B)$ magnetocaloric materials.
209 *Fundam. Res.* in press. <https://doi.org/10.1016/j.fmre.2022.09.020>
- 210 [25] N.H. Dung, L. Zhang, Z. Q. Ou, E. Brück, Magnetoelastic coupling and magnetocaloric
211 effect in hexagonal $Mn-Fe-P-Si$ compounds, *Scripta Mater.* 67 (2012) 975-978.
212 <https://doi.org/10.1016/j.scriptamat.2012.08.036>
- 213 [26] F. Guillou, H. Yibole, N.H. van Dijk, L. Zhang, V. Hardy, E. Brück, About the mechanical
214 stability of $MnFe(P,Si,B)$ giant-magnetocaloric materials. *J. Alloys and Compd.* 617 (2014)
215 569–574. <http://dx.doi.org/10.1016/j.jallcom.2014.08.061>
- 216 [27] Z. Gercsi, E. K. Delczeg-Czirjak, L. Vitos, A. S. Wills, A. Daoud-Aladine, K. G. Sandeman,
217 Magnetoelastic effects in doped Fe_2P , *Phys. Rev. B* 88 (2013) 024417.
218 <http://dx.doi.org/10.1103/PhysRevB.88.024417>
- 219 [28] M. Yue, D. Liu, Q. Huang, T. Wang, F.X. Hu, J. Li, G. Rao, B.G. Shen, J. W. Lynn, J.
220 Zhang, Structure evolution and entropy change of temperature and magnetic field induced
221 magneto-structural transition in $Mn_{1.1}Fe_{0.9}P_{0.76}Ge_{0.24}$. *J. Appl. Phys.* 113 (2013) 043925.
222 <https://doi.org/10.1063/1.4788803>
- 223 [29] Xinmin You, M. Maschek, N.H. van Dijk, E. Brück, Magnetic Phase Diagram of the
224 $MnxFe_{2-x}P_{1-y}Si_y$ System. *Entropy* 24 (2022) 2. <https://doi.org/10.3390/e24010002>
- 225 [30] Fengqi Zhang, I. Batashev, Qi Shen, Ziyang Wu, R. I. Smith, G. A. de Wijs, N. van Dijk, E.
226 Brück, Impact of F and S doping on $(Mn,Fe)_2(P,Si)$ giant magnetocaloric materials. *Acta Mater.*
227 234 (2022) 118057. <https://doi.org/10.1016/j.actamat.2022.118057>
- 228 [31] Y. Nishihara and Y. Yamaguchi, Magnetic Properties of the $(Sc_{1-x}Ti_x)Fe_2$ System Having
229 Two Magnetic States with Different Degrees of Localization. *J. Phys. Soc. Jpn.* 55 (1986) 920-
230 935. <https://doi.org/10.1143/JPSJ.55.920>

- 231 [32] Y. Nishihara and Y. Yamaguchi, Magnetic Phase Transitions in Itinerant Electron Magnets
232 $\text{Hf}_{1-x}\text{Ta}_x\text{Fe}_2$. J. Phys. Soc. Jpn. 52 (1983) 3630-3636. <https://doi.org/10.1143/JPSJ.52.3630>