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Charlène Delacotte, Tatiana Pomelova, Thomas Stephant, Thierry Guizouarn, Stéphane Cordier, et al.. NaGdS₂: A Promising Sulfide for Cryogenic Magnetic Cooling. *Chemistry of Materials*, 2022, 34 (4), pp.1829-1837. 10.1021/acs.chemmater.1c04105 . hal-03622938

HAL Id: hal-03622938

<https://univ-rennes.hal.science/hal-03622938v1>

Submitted on 29 Mar 2022

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NaGdS₂: a promising sulfide for cryogenic magnetic cooling

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KEYWORDS sulfide, powder X-ray diffraction, crystal chemistry, magnetic material, magnetic refrigeration.

ABSTRACT: The development of effective and eco-friendly cooling technology demands an investigation of new magnetocaloric materials. Compounds containing gadolinium are one of the best candidates due to the large spin-only magnetic moment of Gd³⁺ ion. This work reports on the magnetocaloric properties of the AGdS₂ family (A = Li, Na, K, Rb) in relation to crystal chemistry of these compounds. These sulfides crystallize in two different structure-types: NaCl (A = Li) and α -NaFeO₂ (A = Na, K, Rb). Although one would expect the larger magnetocaloric effect to be associated to LiGdS₂ due to its higher magnetic/non-magnetic mass ratio, our study demonstrates that the NaGdS₂ member leads to the best properties among the investigated series. The change of structure from the 3D NaCl structure of LiGdS₂ to the layered α -NaFeO₂ structure of NaGdS₂ drastically improves the magnetocaloric properties. Hence, thanks to its structural features associated to negligible exchange interactions, NaGdS₂ exhibits a magnetic entropy change up to 54 J kg⁻¹ K⁻¹ at 2.5 K for $\mu_0\Delta H = 5$ T, which is comparable to the top ranked inorganic Gd-based materials operating in the cryogenic temperature range. These magnetocaloric figures of merit provide evidence that Gd-based sulfides are promising materials for magnetic refrigeration and, more broadly, this highlights the potential of sulfides in that field.

INTRODUCTION

There is currently an intense research activity for designing magnetocaloric materials for potential magnetic refrigeration either near room temperature for refrigeration and air conditioning, or at cryogenic temperature for gas liquefaction or ultra-low temperature applications.¹⁻¹⁰ Magnetic refrigeration, based on the magnetocaloric effect,² is a known alternative to the scarce helium-3 for sub-Kelvin cooling applications.¹¹ Compared with vapor to liquid cooling technologies, this solid-state alternative has higher cooling performance via adiabatic demagnetization cooling, as first demonstrated with the paramagnetic salt Gd₂(SO₄)₃·8H₂O.¹²

The large spin-only magnetic moment of Gd³⁺ ion ($S = 7/2$) promotes a large magnetic entropy change with negligible magnetic hysteresis. Moreover, gadolinium compounds are usually characterized by low temperature magnetic ordering and by weak exchange interactions that give rise to a large magnetic entropy change. This makes Gd-based materials the most popular magnetocaloric refrigerants for cryogenic applications. The following materials are cited examples of promising Gd-based magnetocalorics: inorganic paramagnetic salts such as Gd₂(SO₄)₃·8H₂O,¹² oxides such as Gd₃Ga₅O₁₂,¹³⁻¹⁵ Gd₂FeCoO₆,¹⁶ GdCrO₄,¹⁷⁻¹⁸ and GdVO₄,¹⁹ intermetallics such as GdPd₂Si,²⁰⁻²⁴ borides, carbides and borocarbides such as GdCo₂B₂,²⁵⁻²⁸ and many molecular organometallic materials, including metal and cluster complexes, metal-organic frameworks and polymers.^{7,29-38} Note that for room-temperature refrigeration, while Gd₅Si₂Ge₂ is still a reference material,³⁹ Mn-based compounds have become best candidates as they are free of “critical” elements.⁴⁰⁻⁴³

Considering that the increase of refrigerant efficiency near liquid helium temperature requires materials with weak exchange interactions,⁴⁴⁻⁴⁵ as well as large magnetic/non-magnetic

mass and volume ratio, recent studies focused on inorganic Gd-based complexes with light and small ligands such as PO₄³⁻, BO₃³⁻, SO₄²⁻, CO₃²⁻, HCO₂⁻, BH₄⁻, HO⁻, or F⁻. This leads to inorganic materials with huge magnetocaloric effect near liquid helium temperature,⁴⁶⁻⁵⁶ such as GdPO₄,⁴⁶ K₃Li₃Gd₇(BO₃)₉,⁴⁷ GdB₃,⁴⁸ Gd₂Cu(SO₄)₂(OH)₄,⁴⁹ Gd(OH)SO₄,⁵⁰ Gd(OH)CO₃,⁵¹ Gd(HCO₂)₃,⁵²⁻⁵³ Gd(BH₄)₃,⁵⁴ K₂Gd(BH₄)₅,⁵⁴ Cs₃Gd(BH₄)₆,⁵⁴ Gd(OH)₃,⁵⁵ Gd₂O(OH)₄(H₂O)₂,⁵⁵ and GdF₃.⁵⁶

Surprisingly, only few articles focused on the magnetocaloric properties of inorganic sulfides and oxysulfides.⁵⁷⁻⁶³ EuS is characterized by a significant magnetocaloric effect at $T_C = 16.5$ K, with a maximum magnetic entropy change from bulk of 16.8 J kg⁻¹ K⁻¹ and 28.4 J kg⁻¹ K⁻¹ for magnetic field changes of 2 T and 5 T, respectively.⁵⁸ Orthorhombic α -Ln₂S₃ (Ln = Tb, Dy) compounds are characterized by two successive antiferromagnetic transitions ($T_N < 15$ K), which can be shifted to either lower or higher temperature (depending of the crystal orientation) by a magnetic field change, reflecting a strong magnetic anisotropy of the materials.⁶² Consequently, their magnetocaloric effect is reported to be controllable by changing the magnitude and orientation of the magnetic field. FeCr₂S₄, CoCr₂S₄ and CdCr₂S₄ compounds are characterized by a second order magnetic transition at 166 K, 225 K and 87 K,^{59,60,63} leading to significant magnetic entropy changes of 3.72 J kg⁻¹ K⁻¹ ($\mu_0\Delta H = 5$ T), 3.99 J kg⁻¹ K⁻¹ ($\mu_0\Delta H = 5$ T)⁶³ and 3.95 J kg⁻¹ K⁻¹ ($\mu_0\Delta H = 2$ T),⁶⁰ respectively. Zheng et al. showed that the magnetic transition of CoCr₂S₄ can be shifted to higher temperature by Cu for Co substitution, allowing to reach a $-\Delta S_M$ value of 2.57 J kg⁻¹ K⁻¹ for $\mu_0\Delta H = 5$ T at room temperature for the Co_{0.4}Cu_{0.6}Cr₂S₄ compound.⁵⁹ These studies demonstrate the potential of inorganic sulfides as magnetic refrigerants either near room temperature with transition metals as magnetic elements or at low temperature with lanthanides as magnetic centers.

However, for potential applications near liquid helium temperature, it appears necessary to find sulfide materials having weaker magnetic interactions.

ALnS₂ alkali lanthanide sulfides have been previously investigated from the structural point of view,⁶⁴⁻⁶⁹ but only few reports are available about their physical properties.^{66,67,70} In this study, we focus on the Gd-based sulfide series, i.e. the AGdS₂ compounds with A = Li, Na, K, and Rb. Their magnetic and magnetocaloric properties are assessed and discussed in relation with their structural features. To support our discussion, a comparison with structures and properties of some binary and ternary Gd-based sulfides, oxide and oxysulfide is addressed. While the design of phases with large magnetic/non-magnetic mass and volume ratio will allow to make more competitive materials for potential refrigerant applications, the magnetocaloric effect reported for the NaGdS₂ member reminds that crystal structure still governs the magnetic exchange interactions and open the route to consider Gd-based sulfides as new promising magnetorefrigerants near liquid helium temperature.

EXPERIMENTAL SECTION

Synthesis. AGdS₂ (A = Li-Rb) phases were prepared starting from A₂CO₃ (A = Li-Rb) and Gd₂S₃ with the 30:1 molar ratio (note that Gd₂S₃ was prepared by the chemical reaction of high-purity Gd₂O₃ as described by Ohta et al.⁷¹). The mixture was loaded into glassy carbon boat and placed in a quartz reactor. A flow of Ar with products of NH₄SCN thermal decomposition (mainly, H₂S+CS₂) were applied through the reactor and temperature was slowly raised to 700-1000°C. After annealing for 2 hours, the reactor was cooled to room temperature, and the resulting product washed by water and dried by ethanol. Note that the sulfidizing gas mixture contains highly toxic CS₂, H₂S and NH₃. This procedure controlled risk by bubbling the gaseous sulfidation products through ZnSO₄ solution. All operations should be held in a fume hood.

CsGdS₂ was prepared starting from Gd₂S₃ and Cs₂S_x. First, mixture of cesium polysulfides Cs₂S_x (mainly, Cs₂S₆) was prepared at 300°C from Cs₂CO₃.⁷² Then S, Gd₂S₃ and Cs₂S_x (15:1: ~2.5 molar ratio) were loaded in glassy carbon boat and placed in a quartz reactor. The mixture was heated to 1000°C under Ar flow, maintained at this temperature during 30 min and cooled to room temperature. The resulting product was rapidly washed by water and dried by ethanol, and thoroughly ground afterwards.

Sulfides Gd₁₀S₁₉ and Gd₂S₃, and oxysulfide Gd₂O₂S were synthesized using Gd (99.9 at.%, Alfa Aesar), S (99.9 at.%, Strem Chemicals) and Gd₂O₃ (99.99 at.%, Alfa Aesar) commercial powders as starting materials. For each compound, powders were weighed in stoichiometric ratios and ground together in an agate mortar. The mixture was then put into a silica tube and sealed under vacuum ($\approx 10^{-2}$ mbar). The ampule was finally placed in a tubular furnace and heated for 96h at 500°C (Gd₂S₃) or 750°C (Gd₁₀S₁₉ and Gd₂O₂S).

These synthesis protocols allowed us to prepare high quality AGdS₂ (A = Li, Na, K, Rb), Gd₁₀S₁₉, Gd₂S₃ and Gd₂O₂S powder samples with purity suitable for magnetocaloric characterizations. Only a small amount of Gd₂O₂S oxysulfide was detected by powder X-ray diffraction analysis in the AGdS₂ (A = Na, K, Rb) samples, as well as, minor extra peaks corresponding to an unknown phase in the RbGdS₂ sample.

Powder X-ray diffraction. Powder X-ray diffraction analyses were carried out to determine the sample purity and crystal structure of the constituting phases (Figures S1-S7) using a Bruker D8 advance diffractometer equipped with a Cu X-ray tube (K α 1), a Ge [111] monochromator, and a LynxEye detector. Refinements of the

powder X-ray diffraction patterns were performed using the Fullprof software included in the WinPlotr package.⁷³⁻⁷⁴

Magnetic measurements. Magnetic and magnetocaloric measurements were performed on polycrystalline samples using a SQUID magnetometer (MPMS XL5, Quantum Design). Zero field cooled (ZFC) measurement was carried out from 1.8 to 300 K at a constant applied magnetic field of 0.1 T. The magnetocaloric properties were determined from magnetic entropy change, $-\Delta S_M$, evaluated using one of the Maxwell relations:

$$\Delta S_M(T)_{\Delta H} = \int_0^{H_f} \left(\frac{\partial M(T, H)}{\partial T} \right)_H dH \quad (1)$$

The numerical integration of Eq. (1) was carried out using the method proposed by Pecharsky and Gschneidner Jr.,⁷⁵ from magnetization isotherms recorded on heating from 2 K to 20 K in applied magnetic fields up to 5 T, with field steps of 0.2 T and temperature increments of 1 K.

RESULTS AND DISCUSSION

Structural features. According to powder X-ray diffraction data, the AGdS₂ (A = Li, Na, K, Rb) sulfides are characterized by either the cubic NaCl structure type or the rhombohedral α -NaFeO₂ structure type. LiGdS₂ forms with the NaCl cubic structure (Figure S1) while other members crystallize with the rhombohedral α -NaFeO₂ structure (Figures S2-S4). Crystallographic parameters refined from powder X-ray diffraction data recorded at room temperature are given in Table 1 and the corresponding structural models are shown in Figure 1.

Table 1. Refined crystallographic data of the AGdS₂ (A = Li, Na, K, Rb) compounds.

| Compound | LiGdS ₂ | NaGdS ₂ | KGdS ₂ | RbGdS ₂ |
|---------------------|--------------------|------------------------------|-------------------|--------------------|
| Structure type | NaCl | α -NaFeO ₂ | | |
| Crystal system | Cubic | trigonal | | |
| Space group | $Fm\bar{3}m$ | $R\bar{3}m$ | | |
| a (Å) | 5.5299(1) | 4.0134(1) | 4.0771(1) | 4.1172(1) |
| c (Å) | -- | 19.9187(4) | 21.9170(8) | 24.0408(5) |
| V (Å ³) | 169.10(1) | 277.86(1) | 315.51(2) | 352.93(1) |
| Z | 2 | 3 | 3 | 3 |

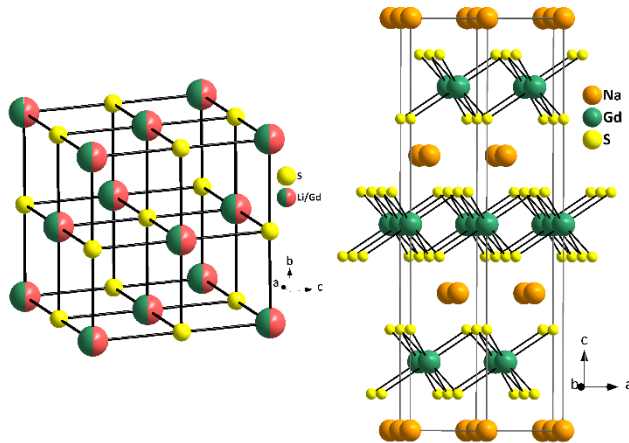


Figure 1. Representation of the crystal structures encountered in the AGdS₂ family: (left) NaCl-type with A = Li and (right) α -NaFeO₂-type with A = Na, K and Rb.

Magnetic and magnetocaloric properties. In order to shed light on the structure-properties relationships of the AGdS₂ (A = Li, Na, K, Rb) series, magnetic and magnetocaloric properties will be presented by drawing a parallel between LiGdS₂ (NaCl structure type) and NaGdS₂ (α -NaFeO₂ structure type) compounds. For the other members, the results are shown in Supporting Information (Figures S8-S10).

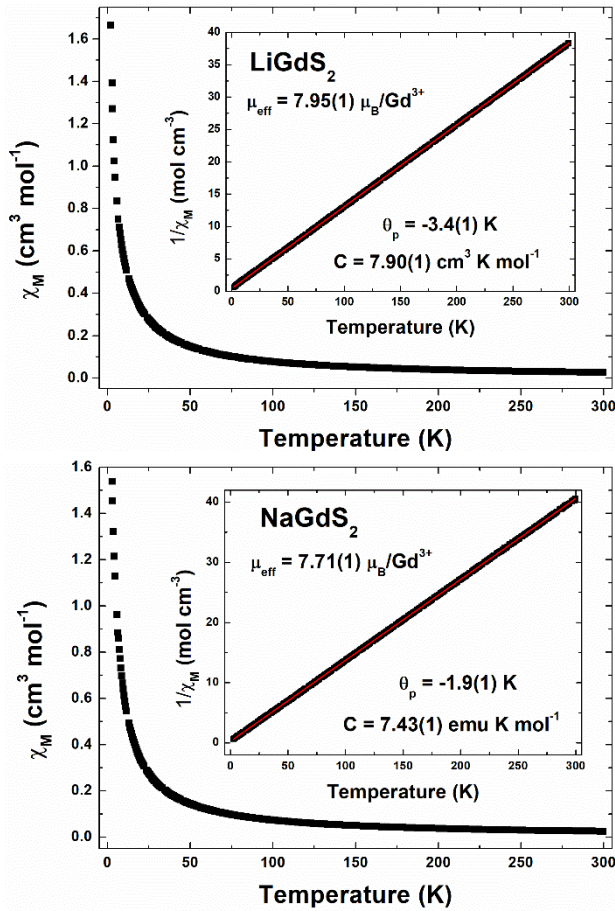


Figure 2. Temperature dependence of the molar magnetic susceptibility (χ_M) of (top) LiGdS₂ and (bottom) NaGdS₂ recorded from 1.8 K to 300 K under an applied magnetic field of 0.1 T. Corresponding inverse of magnetic susceptibility ($1/\chi_M$) curves fitted from 1.8 K to 300 K with the Curie-Weiss law are shown in insets.

For the whole AGdS₂ family, the magnetic susceptibility curves do not indicate a magnetic phase transition within the investigated temperature range (1.8K-300K) as illustrated on Figures 2 and S8. This indicates that all members of the family are paramagnets. The inverse of magnetic susceptibility data were analyzed using the Curie-Weiss law $\chi_M = C/(T - \theta_p)$ where χ_M is the magnetic susceptibility, C is the Curie constant, T is the absolute temperature and θ_p is the paramagnetic Curie-Weiss temperature. All compounds obey to the Curie-Weiss law over the entire temperature range as shown in insets of Figures 2 and S8. Outcomes of the inverse of magnetic susceptibility fits are summarized in Table 2. Resulting effective magnetic moment $\mu_{\text{eff}}/\text{Gd}^{3+}$ values agree with the theoretical one expected for Gd³⁺ free ion (i.e. 7.94 μ_B). The Curie-Weiss fitting parameters indicate small and negative paramagnetic temperatures θ_p for the whole series (ranging from -1.9 K for NaGdS₂ to -3.7 K for KGdS₂) suggesting the existence of very weak local antiferromagnetic interactions whatever the crystal structure.

From magnetic susceptibility curves, LiGdS₂ and NaGdS₂ exhibit similar profiles, but in contrast, magnetization data recorded at 2 K evidence two distinct behaviors (Figure 3). Near and below liquid helium temperature, the NaGdS₂ magnetization curves tend to follow a Brillouin function, while those of the LiGdS₂ compound are still almost linearly field dependent leading to a magnetization far from saturation even under an applied magnetic field of 5 T. This latter feature indicates the existence of local magnetic frustrations suggesting a spin glass behavior for LiGdS₂. Moreover, this means that the nature and the strength of the local magnetic coupling characterizing LiGdS₂ and NaGdS₂ are likely to be different and influenced by the crystal structure.

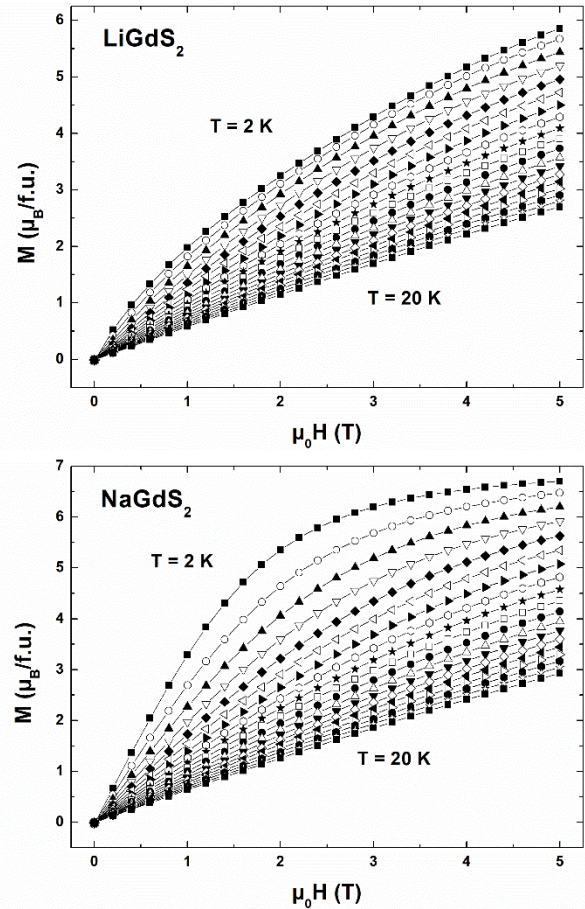


Figure 3. Magnetization isotherms of (top) LiGdS₂ and (bottom) NaGdS₂ recorded from 2 K to 20 K in applied magnetic fields up to 5 T, with field steps of 0.2 T and temperature increments of 1 K.

The absence of magnetic ordering down to 1.8 K and the very weak local magnetic interactions constitute encouraging experimental features for an interesting magnetocaloric effect near liquid helium temperature. These two points added to (i) the large spin-only magnetic moment of Gd³⁺ ion ($S = 7/2$) favoring a large magnetic entropy change with negligible magnetic hysteresis and (ii) the high magnetic/non-magnetic mass ratio of the AGdS₂ family, led us to investigate their magnetocaloric properties. The magnetic entropy change was then determined for the whole series from isothermal magnetization curves recorded on heating from 2 K to 20 K in applied magnetic fields up to 5 T (Figures 3 and S9).

Table 2. Magnetic properties (fitted effective magnetic moments μ_{eff} and paramagnetic Curie-Weiss temperatures θ_p) and magnetocaloric properties (mass and volume magnetic entropy change) of the AGdS₂ series (A = Li, Na, K, Rb).

| Compound | Structure type | Magnetic properties | | Magnetocaloric properties | | | | | |
|--------------------|------------------------------|------------------------------------|----------------|---------------------------|--|-------|---|-------|--|
| | | μ_{eff} (μ_B/Gd^{3+}) | θ_p (K) | T (K) | $-\Delta S_M^{max}$ (J kg ⁻¹ K ⁻¹) | | $-\Delta S_M^{max}$ (mJ cm ⁻³ K ⁻¹) | | ρ_{calc} (g cm ⁻³) |
| | | | | | 0-2 T | 0-5 T | 0-2 T | 0-5 T | |
| LiGdS ₂ | NaCl | 7.95(1) | -3.4(1) | 4.5 | 6.8 | 23.3 | 30.2 | 104.2 | 4.48 |
| NaGdS ₂ | α -NaFeO ₂ | 7.71(1) | -1.9(1) | 2.5 | 23.5 | 54.0 | 102.8 | 236.7 | 4.38 |
| KGdS ₂ | α -NaFeO ₂ | 7.32(1) | -3.7(1) | 2.5 | 14.6 | 43.6 | 60.3 | 179.5 | 4.11 |
| RbGdS ₂ | α -NaFeO ₂ | 7.23(1) | -3.3(1) | 2.5 | 10.0 | 32.6 | 46.1 | 149.9 | 4.60 |

For each AGdS₂ member, the highest values of mass and volume magnetic entropy change $-\Delta S_M^{max}$ are reported in Table 2 for an applied magnetic field variation of 2 T and 5 T. The best magnetocaloric effect, with values reaching 54 J kg⁻¹ K⁻¹ (or 236.7 mJ cm⁻³ K⁻¹) at 2.5 K for $\mu_0\Delta H = 5$ T, is obtained for the NaGdS₂ compound while LiGdS₂ exhibits moderate magnetocaloric properties at low temperature (23.3 J kg⁻¹ K⁻¹ (or 104.2 mJ cm⁻³ K⁻¹) at 4.5 K for $\mu_0\Delta H = 5$ T). As it was suspected from the magnetization data profiles at low temperature (Figure 3), the two structure types induce different local magnetic interactions and consequently sharply affect the magnetocaloric properties. This is illustrated by the effect intensity of LiGdS₂ which is about 2 times weaker than that of NaGdS₂. Moreover, even when the magnetic/non-magnetic mass ratio decreases (i.e. for A = K and Rb), the magnetocaloric effect of the α -NaFeO₂ structure type materials is still higher than that of the NaCl structure type compound.

Figure 4 shows the evolution of the mass magnetic entropy change versus temperature for the two prototypical compounds of the AGdS₂ family. The magnetocaloric effect of NaGdS₂ continuously increases upon cooling (as well as that of KGdS₂ and RbGdS₂, Figure S10) while LiGdS₂ reaches a maximum at 4.5 K for $\mu_0\Delta H = 5$ T. This maximum decreases to lower temperatures for lower magnetic field variations. The decrease of the magnetic entropy change of LiGdS₂ at very low temperature can be related to the existence of local magnetic frustrations, likely leading to a spin glass behavior, as already discussed from its magnetic susceptibility data. Once again, this is an evidence of the impact of the crystal structure on the magnetocaloric properties of the AGdS₂ series.

Discussion. This study shows that the two different crystal structures (i.e. NaCl and α -NaFeO₂) encountered in the AGdS₂ (A = Li, Na, K, Rb) family strongly affect their physical properties. Based on magnetic measurements, and in particular on the magnetization curve profiles at 2 K, one can observe that the NaCl structure type of LiGdS₂ is associated to stronger magnetic couplings compared to the α -NaFeO₂ structure type of NaGdS₂, KGdS₂ or RbGdS₂. The strength of the magnetic exchanges can also be assessed by calculating the theoretical maximum of the magnetic entropy change for isolated Gd³⁺ ions. Indeed, the experimental values for $\mu_0\Delta H = 5$ T, of 23.3 J kg⁻¹ K⁻¹ (at 4.5 K) and 54.0 J kg⁻¹ K⁻¹ (at 2.5 K) for LiGdS₂ and NaGdS₂ respectively, correspond to 31% and 76% of the theoretical maximum values (i.e. 75.7 J kg⁻¹ K⁻¹ and 70.7 J kg⁻¹ K⁻¹, calculated from $R \ln(2S+1)/M_w$ with $S = 7/2$ and $M_w(\text{LiGdS}_2) = 228.32$ g mol⁻¹ and $M_w(\text{NaGdS}_2) = 244.37$ g mol⁻¹). The magnetocaloric effect is indeed more dramatically hindered by the magnetic interactions occurring in LiGdS₂ than in NaGdS₂.

Hence, the α -NaFeO₂ structure type leads to weaker local magnetic interactions and thus to the most significant magnetocaloric properties.

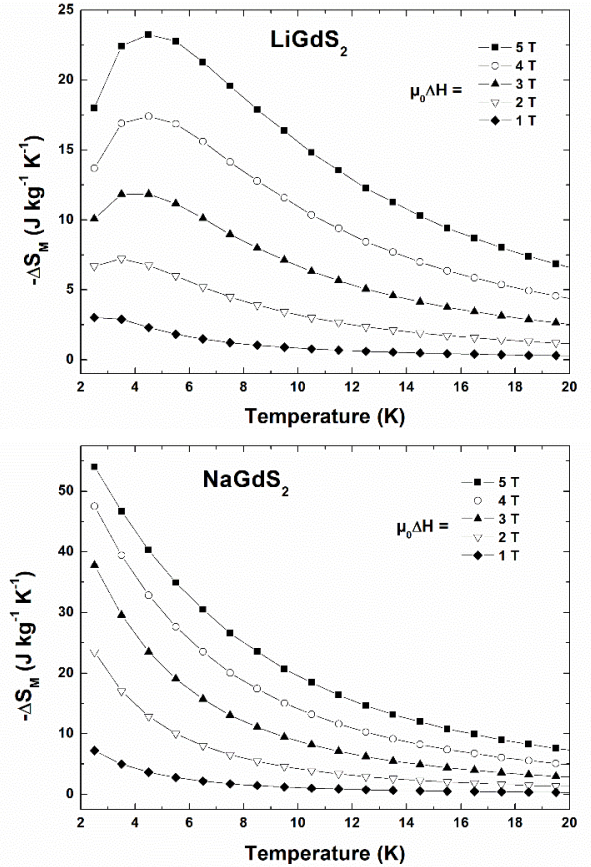


Figure 4. Temperature dependence of the mass magnetic entropy change ($-\Delta S_M$) in (top) LiGdS₂ and (bottom) NaGdS₂ for different magnetic field variations.

The strength of the magnetic coupling between Gd³⁺ ions can be related to the crystal structure. On the one hand, the NaCl structure type of LiGdS₂ corresponds to a semi-ordered three-dimensional structure where Gd atoms are coordinated to six S atoms in regular octahedral environments ($6 \times d_{Gd-S} = 2.76$ Å). These octahedra interact with each other by sharing edges. By considering that Gd³⁺ and Li⁺ are randomly distributed on the same crystallographic site, each Gd atom is surrounded by 12/2 other Gd atoms that are at a mean distance of 3.91 Å. These six Gd neighbours are statistically located in three perpendicular squared planes as illustrated on the left side of Figure 5. Hence, in this semi-ordered structure the Gd...Gd interactions may exist

in the three space directions, favouring local magnetic frustrations and, most likely, leading to spin-glass behaviors. On the other hand, the α -NaFeO₂ structure of NaGdS₂ consists of two-dimensional [GdS₂]⁻ layers stacked perpendicularly to the *c* axis and separated by Na⁺ cations. Within these layers, each Gd atom is coordinated to six S atoms in a regular octahedral arrangement ($6 \times d_{\text{Gd-S}} = 2.79 \text{ \AA}$) and connected to a neighbouring Gd atom by sharing edges of its octahedron. Hence, each Gd atom is surrounded by six other Gd atoms that are at a distance of 4.01 \AA as shown on the right side of Figure 5. These six Gd neighbours form a hexagon and are all located in the *ab* plane, making that in the α -NaFeO₂ structure, the Gd...Gd interactions mainly take place in the two-dimensional [GdS₂]⁻ layers. This perfect triangular 2D Gd lattice should favour magnetic frustrations and, consequently, should suppress or at least significantly lower the antiferromagnetic ordering temperature if any.

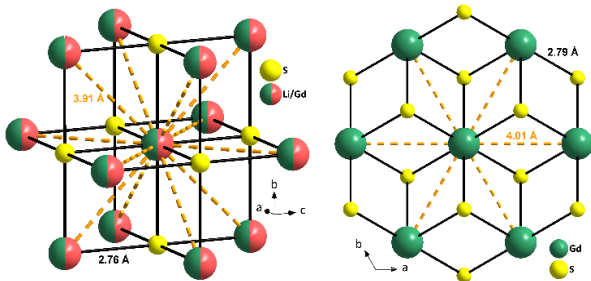


Figure 5. Representation of the gadolinium atoms environments in (left) the NaCl structure type of LiGdS₂ and (right) the α -NaFeO₂ structure type of NaGdS₂. The Gd-S distances are mentioned in black and the Gd...Gd distances in orange. The distances are calculated from refined crystallographic data (Table 1).

From these crystal structure descriptions, one can note that the geometry of the Gd polyhedra are similar in both structures but differ by their connectivities. This results in 3D versus 2D structures for LiGdS₂ and NaGdS₂ respectively. Moreover, the distances between a Gd atom and its closest Gd neighbours differ from one structure to another, the NaCl structure exhibiting the shortest Gd...Gd interaction distances. Finally, the Li/Gd mixed site occupancy encountered in the NaCl structure type of LiGdS₂ probably also affects the magnetic interactions. All of these structural features appear to limit the magnetic decoupling of Gd³⁺ ions in the NaCl structure type and therefore lead to a worsened magnetocaloric effect in LiGdS₂. On the contrary, in the α -NaFeO₂ structure type, the separation between each [GdS₂]⁻ layers seems to favor a magnetic decoupling of the Gd³⁺ ions along the *c* axis, and consequently, generates better magnetocaloric properties near liquid helium temperature. Hence, in the AGdS₂ series, the reduction of the structure dimensionality together with different Gd environments lead to better magnetocaloric properties for the ordered α -NaFeO₂ structure type materials compared to the cationic disordered NaCl structure type one.

Based on the significant magnetocaloric effect observed for NaGdS₂, we also decided to assess the magnetocaloric properties of the GdS₂ binary sulfide. This phase can be considered as the “starting point” of the AGdS₂ series (i.e. “□GdS₂”, the symbol □ corresponding to the alkaline element deficiency) and its large magnetic/non-magnetic mass ratio (wt% Gd = 72%) can lead to a promising magnetocaloric effect.

However, attempts to synthesize the nominal GdS₂ phase failed and it appears that high-pressure is mandatory for its syn-

thesis.⁷⁶ Following our synthesis protocol, the Gd₁₀S₁₉ compound forms preferentially. Gd₁₀S₁₉ crystallizes in the Ce₁₀Se₁₉ structure type, a three-dimensional tetragonal structure (space group $P4_2/n$) where Gd atoms sit in bicapped and tricapped trigonal prisms that are connected by faces and edges. These structural features clearly differ from those of the AGdS₂ members. The magnetic behaviour also deviates from that of the AGdS₂ (A = Li, Na, K, Rb) compounds as the existence of an antiferromagnetic ordering at $T_N = 5.8 \text{ K}$ is detected on the temperature dependant magnetic susceptibility curve (Figure S11). Note that there are structural and physical similarities between Gd₁₀S₁₉ and the nominal GdS₂ material; regarding the latter it is reported that (i) Gd coordination polyhedrons are tricapped trigonal prisms sharing faces and edges in a three-dimensional structure and (ii) an antiferromagnetic ordering is observed at $T_N = 7.7 \text{ K}$.⁷⁶ Using the Gd₁₀S₁₉ binary sulfide as a comparison material thus makes sense. The evaluation of its magnetocaloric properties was carried out: the maximum mass magnetic entropy change is reached at 6.5 K with a value of $14.2 \text{ J kg}^{-1} \text{ K}^{-1}$ for $\mu_0\Delta H = 5 \text{ T}$ which is about four times less than that of NaGdS₂ at the same temperature (Figure 4).

The evolution of the maximum mass magnetic entropy change in the AGdS₂ (A = Li, Na, K, Rb) family is represented in Figure 6. In addition, as the starting point, Gd₁₀S₁₉ is also plotted and denominated as “□GdS₂”. This illustrates the benefit of the alkaline element presence and the impact of the structural modification from NaCl to α -NaFeO₂. Indeed, the best magnetocaloric effects are obtained for the “layered” α -NaFeO₂ structure type materials whatever the alkaline element. Note that the structural modification also influences the temperature for which the effect is maximum.

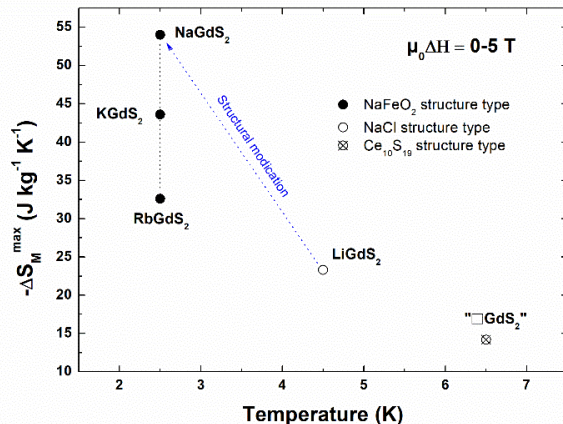


Figure 6. Temperature dependence of the maximum mass magnetic entropy change ($-\Delta S_M^{\text{max}}$) for $\mu_0\Delta H = 5 \text{ T}$ of the AGdS₂ (A = Li, Na, K, Rb) family and the “□GdS₂” binary sulfide.

In order to complete our comparison of the AGdS₂ series with binary or ternary materials with high magnetic/non-magnetic mass ratio, we also synthesized and characterized three additional compounds: α -Gd₂S₃ sulfide (wt% Gd = 77%), Gd₂O₂S (wt% Gd = 83%) and Gd₂O₃ (wt% Gd = 87%). Their crystallographic data and magnetic measurements are gathered in Table S1 and Figures S12-S14. Tables 3 and S2 summarize structural, magnetic and magnetocaloric properties for both binary and ternary compounds reported in this study. The magnetic behaviours of α -Gd₂S₃ (Figure S14) and Gd₂O₂S (Figure S13) are characterized by long-range antiferromagnetic ordering occurring below $T_N = 10.0 \text{ K}$ and 6.4 K respectively.

Table 3. Magnetic and magnetocaloric properties of the AGdS₂ series (A = Li, Na, K, Rb) compared to those of some Gd-based binary or ternary sulfide/oxy sulfide/oxide.

| Compound | wt% Gd | T _N (K) | μ _{eff} (μ _B /Gd ³⁺) | θ _P (K) | T (K) | -ΔS _M ^{max} (J kg ⁻¹ K ⁻¹) 0-5 T | -ΔS _M ^{max} (mJ cm ⁻³ K ⁻¹) 0-5 T | ρ _{calc} (g cm ⁻³) |
|--|--------|--------------------|---|--------------------|-------|---|--|--|
| "□GdS ₂ "= Gd ₁₀ S ₁₉ | 72 | 5.8 | 7.86(1) | -4.9(1) | 6.5 | 14.2 | 82.2 | 5.81 |
| LiGdS ₂ | 69 | -- | 7.95(1) | -3.4(1) | 4.5 | 23.3 | 104.2 | 4.48 |
| NaGdS ₂ | 64 | -- | 7.71(1) | -1.9(1) | 2.5 | 54.0 | 236.7 | 4.38 |
| KGdS ₂ | 60 | -- | 7.32(1) | -3.7(1) | 2.5 | 43.6 | 179.5 | 4.11 |
| RbGdS ₂ | 51 | -- | 7.23(1) | -3.3(1) | 2.5 | 32.6 | 149.9 | 4.60 |
| α-Gd ₂ S ₃ | 77 | 10.0 | 7.78(1) | -9.9(1) | 10.5 | 0.1 | 0.9 | 6.18 |
| Gd ₂ O ₂ S | 83 | 6.4 | 8.12(1) | -21.1(1) | 8.5 | 5.0 | 36.8 | 7.33 |
| Gd ₂ O ₃ | 87 | -- | 7.98(1) | -15.1(1) | 4.5 | 7.9 | 59.9 | 7.62 |

For Gd₂O₃, only local antiferromagnetic couplings are suggested by the negative θ_P value determined from the Curie-Weiss fit (Figure S12). Moreover, despite their high magnetic/non-magnetic mass ratio, none of the binary and ternary additional compounds exhibit better magnetocaloric properties near or below liquid helium temperature than those of the NaGdS₂ compound. For most of them, this is mainly related to their antiferromagnetic ordering.

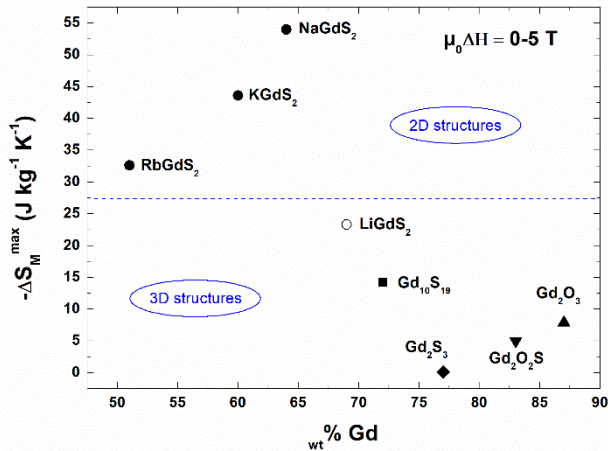


Figure 7. Maximum mass magnetic entropy change ($-\Delta S_M^{max}$) for $\mu_0\Delta H = 5$ T of AGdS₂ (A = Li, Na, K, Rb) members and some binary and ternary Gd-based materials depending on their magnetic/non-magnetic mass ratio (wt% Gd). Each symbol corresponds to one structure type.

From a structural point of view, the Gd polyhedra of the binary and ternary sulfide/oxy sulfide/oxide are less symmetric compared to those of the AGdS₂ members and are all connected within a three-dimensional framework. Regarding the Gd...Gd interaction distances, no obvious correlation with the coordination environment can be made. This is not surprising given that all compounds crystallize in different structure types. Nevertheless, as illustrated in the Figure 7, the structure dimensionality of the studied compounds seems to be an important feature, since the best magnetocaloric properties are observed in the two-dimensional α-NaFeO₂ structure type materials. However,

on a broader scale, this feature is not the only one that matters. For example, the GdF₃ compound is characterized by a three-dimensional structure and yet is the top ranked inorganic Gd-based magnetic refrigerant near liquid helium temperature.⁵⁶ This reflects that magnetocaloric properties depend on several chemical and structural parameters: structure dimensionality, Gd polyhedron symmetry, number of Gd neighbours and their arrangement, Gd...Gd interaction distances, magnetic/non-magnetic mass ratio, etc. All of these influence the nature and the strength of the local magnetic interactions and thus the magnetocaloric effect of Gd-based materials.

Finally, the magnetocaloric properties of some inorganic Gd-based compounds belonging to different material classes (oxides, intermetallics, borides, carbides, borocarbides, inorganic complexes and now sulfides and oxy sulfide — details are gathered in Table S3) are illustrated by the Figure 8, where each class is depicted by one symbol. From this figure, one can see that NaGdS₂ is well ranked compared to other inorganic Gd-based materials, and especially compared to complexes with light and small ligands represented here by the stars. Moreover, despite their lower wt.% Gd, the AGdS₂ (A = K, Rb) sulfides crystallizing in the α-NaFeO₂ structure type are also in good position. These results indicate that α-NaFeO₂ structural type must be a good starting point for further investigations of magnetic cooling materials.

CONCLUSION

We have synthesized and characterized structurally and magnetically the AGdS₂ family (A = Li, Na, K and Rb). Powder X-ray diffraction data evidenced two typical crystal structures within the series: NaCl (for A = Li) and α-NaFeO₂ (for A = Na, K, Rb). While the former structure type leads to a moderate magnetocaloric effect near liquid helium temperature, the lower dimensionality of the latter allows to reach the best magnetocaloric properties among the series due to limited magnetic exchange interactions between Gd³⁺ ions. Consequently, NaGdS₂ exhibits a magnetocaloric effect comparable to the top ranked inorganic Gd-based materials operating in the cryogenic temperature range, revealing that sulfides can be considered as a new class of promising magnetocaloric materials.

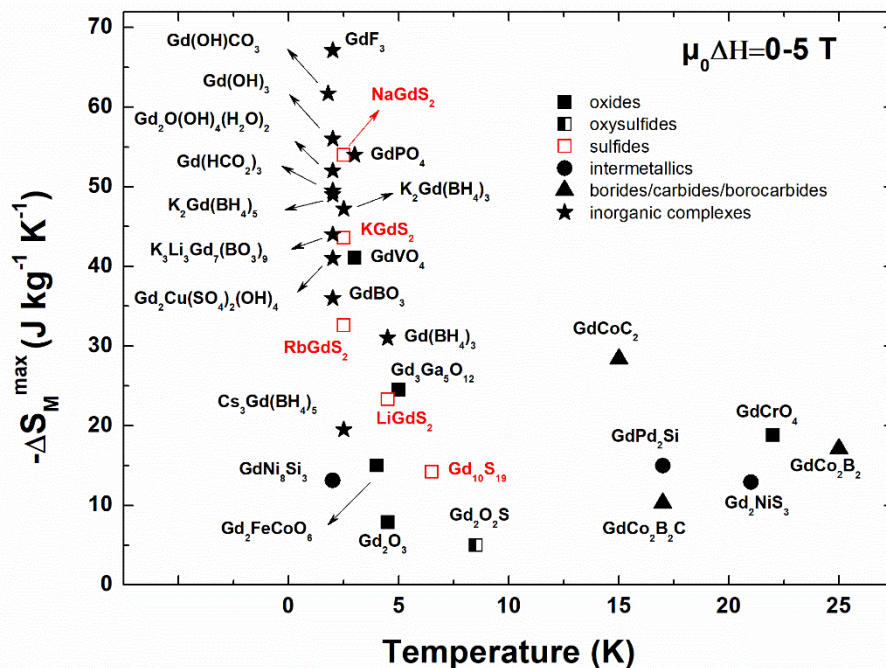


Figure 8. Overview of the maximum mass magnetic entropy change for some Gd-based inorganic materials at cryogenic temperatures ($T \leq 25$ K).^{15-16,18-19,21-28,46-56}

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Author Contributions

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

Note

The authors declare no competing financial interest.

SUPPORTING INFORMATION

Additional figures and tables are available in the supporting information, including PXRD patterns and Rietveld refinements of AGdS_2 ($A = \text{Li, Na, K, Rb}$), $\text{Gd}_{10}\text{S}_{19}$, $\alpha\text{-Gd}_2\text{S}_3$ and $\text{Gd}_2\text{O}_2\text{S}$ compounds, crystallographic data of $\text{Gd}_{10}\text{S}_{19}$, $\alpha\text{-Gd}_2\text{S}_3$, $\text{Gd}_2\text{O}_2\text{S}$, Gd_2O_3 and AGdS_2 ($A = \text{Li, Na, K, Rb}$), magnetic and magnetocaloric data of KGdS_2 and RbGdS_2 , magnetic data of $\text{Gd}_{10}\text{S}_{19}$, Gd_2O_3 , $\text{Gd}_2\text{O}_2\text{S}$ and $\alpha\text{-Gd}_2\text{S}_3$, and review table on the magnetocaloric properties of inorganic Gd-based materials presented in Figure 8.

ACKNOWLEDGMENTS

Authors are grateful to Thomas Mazet for scientific discussion. The research was supported by the Ministry of Science and Education of the Russian Federation and CNRS through the EMERGENCE@INC 2021 NCIS project.

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