Eu$_{1-x}$Sr$_x$Au$_4$Cd$_2$: a ferromagnetic solid solution with adjustable Curie temperature

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Abstract

Samples of the solid solution Eu$_{1-x}$Sr$_x$Au$_4$Cd$_2$ (YbAl$_4$Mo$_2$ type, space group I$4/mmm$) with $x = 0.2$, 0.4, 0.6, and 0.8 were synthesized from the elements by annealing in sealed tantalum ampoules. The structures of Eu$_{0.66}$Sr$_{0.34}$Au$_{4.12}$Cd$_{1.88}$ and Eu$_{0.22}$Sr$_{0.78}$Au$_{4.10}$Cd$_{1.90}$ were refined from X-ray single crystal diffractometer data. Besides the expected Eu/Sr mixing on the 2$a$ sites the diffraction data revealed also a small degree of Cd/Au mixing on the 4$d$ sites of the cadmium chains. Temperature dependent magnetic susceptibility data show divalent europium and ferromagnetic ground states for all samples and a linear decrease of the Curie temperature from 16.3 K for EuAu$_4$Cd$_2$ to 2.9 K for Eu$_{0.2}$Sr$_{0.8}$Au$_4$Cd$_2$. Magnetization isotherms characterize the Eu$_{1-x}$Sr$_x$Au$_4$Cd$_2$ samples as soft ferromagnets. The divalent nature of europium is underpinned by $^{151}$Eu Mössbauer spectra. The decreasing Curie temperature goes along with a decreasing magnetic hyperfine field at 6 K.

Graphic abstract

Keywords Crystal structure · Lanthanoids · Metals · Solid state

Introduction

Strontium and europium have almost similar radii. To give an example, Shannon [1] lists values of 118 (Sr$^{2+}$) and 117 (Eu$^{2+}$) pm for coordination number 6. Thus, it is not surprising that one observes a large crystal chemical similarity between divalent europium and strontium compounds. The simplest example concerns the rocksalt-type phases SrO and EuO. Another prominent example concerns the structure of Eu$_3$O$_4$, where a complete substitution of the divalent europium by Sr$^{2+}$ leads to SrEu$_2$O$_4$ [2].

This isovalent substitution is interesting with respect to the magnetic properties. Sr$^{2+}$ is a diamagnetic cation while Eu$^{2+}$ with its [Xe]4f$^7$ configuration is strongly paramagnetic. To keep the example of the rocksalt phases, SrO is a simple diamagnet, whereas EuO is a strong Curie–Weiss paramagnet which orders ferromagnetically below $T_C = 70$ K [3, 4]. These magnetic characteristics offer the possibility to study solid solutions. Due to the close size of the cations, these solid solutions are mostly strain free and one can investigate the force of the magnetic coupling as a function of the europium-strontium substitution.

Interesting results have been obtained for solid solutions of metal hydrides. Eu$_2$IrH$_5$ orders ferromagnetically at $T_C = 20$ K and the Curie temperature decreases with
increasing strontium content: 11 K for Eu$_{1.0}$Sr$_{1.0}$IrH$_5$, <7 K for Eu$_{1.0}$Sr$_{1.0}$IrH$_5$ and <5 K for Eu$_{0.5}$Sr$_{1.5}$IrH$_5$ [5]. Similar behavior was reported for the solid solutions Eu$_{2-x}$Sr$_x$RuH$_6$ [6] and Eu$_{1-x}$Sr$_x$Mg$_2$H$_6$ ($T_C=21$ K for $x=0.2$ and 15 K for $x=0.4$) [7]. In the three series, $T_C$ decreases with decreasing number of neighboring europium cations, i.e. a decrease of the strength of the Eu–Eu nearest neighbor exchange interactions. A different behavior was observed for the fullerides Eu$_{1−x}$SrxAu$_4$Cd$_2$. As an example, we therefore concentrate only on the structural peculiarities of the solid solution Eu$_{1−x}$SrxAu$_4$Cd$_2$. This was monitored in parallel by $^{151}$Eu Mössbauer spectroscopy.

We have recently started a systematic investigation of europium-strontium substitution in the field of intermetallic compounds. The first complete solid solution was Eu$_{1−x}$SrxPtIn$_2$ with MgCuAl$_2$ type structure [9]. The course of the cell parameters showed Vegard type behavior. EuPtIn$_2$ shows a comparatively high Curie temperature of 32.5 K and it is remarkable that the ferromagnetic ground state even remains in the Eu$_{0.0}$Sr$_{0.9}$PtIn$_2$ sample with $T_C=3.1$ K and a gradual decrease of the Curie temperature within the complete solid solution. This was monitored in parallel by $^{151}$Eu Mössbauer spectroscopy.

In continuation of these studies we have now investigated the solid solution Eu$_{1−x}$SrxAu$_4$Cd$_2$ with YbAl$_4$Mo$_2$ type structure which also shows adjustable Curie temperatures. The crystal chemistry and the magnetic behavior of this solid solution are reported herein.

**Results and discussion**

**Crystal chemistry**

EuAu$_4$C$_2$ and SrAu$_4$C$_2$ [10] crystallize with the YbAl$_4$Mo$_2$ type structure [11], space group $I4/mmm$. The slightly larger radius of strontium (see “Introduction”) leads to a small increase of the $a$ and $c$ lattice parameters (Table 1) and consequently a larger cell volume for SrAu$_4$C$_2$. We have studied the complete solid solution Eu$_{1−x}$SrxAu$_4$Cd$_2$ for samples with $x=0.2, 0.4, 0.6$, and 0.8. Within the standard deviations, we do not strictly observe Vegard-type behavior. The small differences observed for the two single crystals and the Eu$_{0.2}$Sr$_{0.8}$Au$_4$Cd$_2$ sample can be ascribed to the Cd/Au mixing (formation of small homogeneity ranges) on the $4d$ sites (vide infra).

The prototype YbAl$_4$Mo$_2$ [11] has more than 40 isotypic representatives [12]. The crystal chemistry and chemical bonding of YbAl$_4$Mo$_2$ type phases has repeatedly been discussed in the original contributions [13–20]. Herein we therefore concentrate only on the structural peculiarities of the solid solution Eu$_{1−x}$SrxAu$_4$Cd$_2$. As an example, we present the unit cell of Eu$_{0.66}$Sr$_{0.34}$Au$_{4.12}$Cd$_{1.88}$ in Fig. 1. The projection onto the $ab$ plane (Fig. 1, top) shows the Au$_4$ squares with 279 pm Au–Au. These squares condense with adjacent squares that are shifted by half the translation period $c$ and form the Au$_{12}$ clusters that surround the europium/strontium atoms. The Au–Au distances between the clusters of 299 pm are slightly longer. In average, these Au–Au distances compare well with fcc gold ($12 \times 288$ pm) [21].

The second striking motif concerns the linear cadmium chains that extend in $c$ direction. The Cd–Cd distances of 276 pm are indicative of substantial Cd–Cd bonding given that they are shorter than in $hcp$ cadmium ($6 \times 298$ and $6 \times 329$ pm) [21]. Each cadmium atom is surrounded by eight gold atoms in strongly distorted square prismatic coordination. These polyhedra are capped by cadmium atoms on the rectangular faces in $c$ direction.

The refinements of the occupancy parameters of the $2a$ sites (vide infra) clearly revealed the Eu/Sr mixing, in approximate agreement with the nominal starting compositions of the samples. These deviations indicate that all samples from the solid solution definitely contain quantities of domains with compositions that slightly deviate from the starting ones. The mixed Eu/Sr occupancy for Eu$_{0.66}$Sr$_{0.34}$Au$_{4.12}$Cd$_{1.88}$ is presented by light and dark green segments.

Another important feature concerns the cadmium chains. For both crystals, we observed small degrees of Cd/Au mixing on the $4d$ position, similar to the original work on EuAu$_4.80$Cd$_{1.20}$ [10]. This is a general feature of the YbAl$_4$Mo$_2$ type. We have recently studied the solid solution CeAu$_{4+x}$Cd$_{2−x}$ towards CeAu$_4$Cd [20]. Other examples are SrAu$_4.76$In$_{1.24}$ [13], CaAu$_4.88$Zn$_{1.11}$ [17], EuAu$_4.73$In$_{1.25}$ [19], LaAg$_{2.4}$Mg$_{1.6}$ [14], or CaAu$_{4.08}$Zn$_{1.92}$ [15]. The driving force for these mixed occupancies is

| Compound               | $a$/pm  | $c$/pm  | $V$/nm$^3$ | References |
|------------------------|---------|---------|------------|------------|
| EuAu$_4$C$_2$           | 717.0(1)| 553.2(2)| 0.2844     | [10]       |
| Eu$_{0.2}$Sr$_{0.8}$Au$_4$Cd$_2$ | 717.6(1)| 553.6(1)| 0.2851     | This work  |
| Eu$_{0.4}$Sr$_{0.6}$Au$_4$Cd$_2$ | 718.4(1)| 554.1(1)| 0.2860     | This work  |
| Eu$_{0.6}$Sr$_{0.4}$Au$_4$Cd$_2$ | 718.48(10)| 552.88(7)| 0.2854     | This work  |
| Eu$_{0.8}$Sr$_{0.2}$Au$_4$Cd$_2$ | 719.0(2)| 554.7(2)| 0.2866     | This work  |
| Eu$_{0.66}$Sr$_{0.34}$Au$_{4.12}$Cd$_{1.88}$ | 719.24(9)| 553.66(7)| 0.2864     | This work  |
| Eu$_{0.66}$Sr$_{0.34}$Au$_{4.12}$Cd$_{1.88}$ | 719.4(1)| 554.0(2)| 0.2867     | This work  |
| Eu$_{0.66}$Sr$_{0.34}$Au$_{4.12}$Cd$_{1.88}$ | 721.4(1)| 556.8(3)| 0.2898     | [10]       |
| Eu$_{0.66}$Sr$_{0.34}$Au$_{4.12}$Cd$_{1.88}$ | 720.03(8)| 555.5(1)| 0.2880     | This work  |

Standard deviations are given in parentheses

*Single crystal data
the covalent bonding Au–Cd, Au–In, Au–Zn, and Ag–Mg within the chains.

Summing up, the present X-ray powder and single crystal data clearly manifest the solid solution Eu₁₋ₓSrxAu₄Cd₂ with Vegard type behavior, but also show Cd/Au mixing on the chains, underpinning that the bulk samples all have distributions of domains with slightly varying compositions, most likely occurring for all YbAl₄Mo₂ type phases.

**Magnetic properties**

Results of the magnetic property measurements of the solid solution Eu₁₋ₓSrxAu₄Cd₂ are summarized in Table 2. Measurements of $M(T,H)$ of Eu₀.₄Sr₀.₆Au₄Cd₂ are shown as an example in Fig. 2.

Measurements of $M(T)$ performed on the samples of the solid solution in zero-field-cooled/field-cooled (ZFC/FC) mode from 2.5 to 100 K, with an applied field of 100 Oe, show ferromagnetic ordering for all members of the solid solution at low temperatures, which is in accordance with the properties of EuAu₄Cd₂. As expected, the Curie-temperature $T_C$ decreases (Fig. 3) with decreasing europium content (increasing Eu/Sr disorder). Similar behavior has been observed in other solid solutions of europium and strontium such as Eu₁₋ₓSrₓPtxIn₂.

The effective magnetic moments determined from zero-field-cooled (ZFC) measurements with an applied field of 10 kOe in a temperature range of 3–300 K are in good accordance with the theoretical value of 7.94 $\mu_B$ per Eu²⁺ ion for Eu₀.₈Sr₀.₂Au₄Cd₂ and Eu₀.₄Sr₀.₆Au₄Cd₂. The slight deviations observed for Eu₀.₂Sr₀.₈Au₄Cd₂ and Eu₀.₆Sr₀.₄Au₄Cd₂ most likely result from minor impurity phases. In the case of the Eu₀.₂Sr₀.₈Au₄Cd₂ sample this might by a Eu(III) impurity phase which lowers the experimental moment. All compounds exhibit Curie–Weiss behaviour at high temperatures. The Weiss-constants of all compounds are positive, indicating ferromagnetic interactions in the paramagnetic regime.

Magnetization isotherms were measured for every member of the solid solution at 3, 10, and 50 K with applied fields of up to 80 kOe. All magnetization isotherms at 50 K show a linear course as expected for paramagnetic compounds. The isotherms at 3 K, which are below or close to the ordering temperatures of the compounds, show typical behaviour for soft ferromagnetic compounds as the magnetization rises rapidly at low fields. The saturation magnetization of Eu₀.₈Sr₀.₂Au₄Cd₂ and Eu₀.₆Sr₀.₄Au₄Cd₂ at 3 K and 80 kOe is in good accordance with the theoretical

| Compound          | $T_C$/K | $\mu_{eff}$/μB per Eu-atom | $\mu_{sat}$/μB per Eu-atom | $\theta$/K | $\chi$ (300 K)/emu mol⁻¹ |
|-------------------|---------|---------------------------|---------------------------|------------|--------------------------|
| Eu₁.₀Sr₀.₄Au₄Cd₂   | –       | –                         | –                         | –          | 7.9(2) × 10⁻⁴            |
| Eu₀.₄Sr₀.₆Au₄Cd₂   | 2.9 (2) | 6.93 (1)                  | 4.88 (5)                  | 2.0 (1)    | –                        |
| Eu₀.₆Sr₀.₄Au₄Cd₂   | 5.6 (5) | 7.95 (1)                  | 6.76 (5)                  | 5.3 (1)    | –                        |
| Eu₀.₄Sr₀.₂Au₄Cd₂   | 7.7 (1) | 8.56 (1)                  | 7.49 (5)                  | 5.9 (1)    | –                        |
| Eu₀.₂Sr₀.₄Au₄Cd₂   | 12.3 (1)| 7.98 (1)                  | 6.63 (5)                  | 2.8 (1)    | –                        |
| Eu₀.₄Au₄Cd₂ [10]   | 16.3 (5)| 7.86 (1)                  | 6.8 (1)                   | 16.7 (5)   | –                        |
The magnetic susceptibility data (vide ultra) showed a decreasing $T_C$ with increasing strontium content. The Mössbauer spectrometer allowed data collections only above a temperature of 6 K. Thus, in Fig. 4 we only

$^{151}$Eu Mössbauer spectroscopy

The europium valence and the magnetic ordering within the solid solution Eu$_{1-x}$Sr$_x$Au$_4$Cd$_2$ were further studied through temperature dependent $^{151}$Eu Mössbauer spectra. Figure 4 presents the $^{151}$Eu Mössbauer spectra of these samples at 78 and 6 K, respectively. The corresponding fitting parameters are listed in Table 3. The extremely high absorption caused by the high content of highly absorbing heavy elements leads to a low resolution of the experimental spectra. The 78 K $^{151}$Eu Mössbauer spectroscopic investigations confirm divalent europium in the Eu$_{1-x}$Sr$_x$Au$_4$Cd$_2$ samples. Only the Eu$_{0.6}$Sr$_{0.4}$Au$_4$Cd$_2$ sample revealed a small degree of an additional Eu(III) component, most likely resulting from surface oxidation/surface hydrolys of the polycrystalline material, frequently observed for intermetallic europium compounds (even if samples are handled under inert conditions, small amounts of Eu(III) deterioration products occur; this is decomposition, not intrinsic trivalent europium of the main sample) [25, 26]. The isomer shifts values are in the usual range observed for structurally related intermetallics [25, 26]. The small quadrupole splitting parameters account for the non-cubic site symmetry of the europium atoms.

A ZFC measurement characterizes SrAu$_4$Cd$_2$ as a Pauli paramagnetic compound. The magnetic susceptibility stays nearly constant until ca. 100 K and a weak Curie tail, caused by a trace of paramagnetic impurities is evident at low temperature. The room temperature values of $7.9(2) \times 10^{-4}$ emu/mol is in the typical range for Pauli paramagnetic intermetallics [23, 24].

value of 7 μB per Eu-atom, calculated by $g_J \times J$. The higher saturation magnetization of Eu$_{0.8}$Sr$_{0.2}$Au$_4$Cd$_2$ could again be caused by a ferromagnetic impurity. The smaller value for the Eu$_{0.2}$Sr$_{0.8}$Au$_4$Cd$_2$ sample, in line with the reduced moment in the paramagnetic range is indicative of a Eu(III) impurity contribution.
Fig. 4 Experimental and simulated $^{151}$Eu Mössbauer spectra of samples from the solid solution $\text{Eu}_{1-x}\text{Sr}_x\text{Au}_4\text{Cd}_2$ with $x=0.2$–0.8 at 78 (left) and $x=0.2$–0.4 at 6 K (right).

Table 3 Fitting parameters of $^{151}$Eu Mössbauer spectroscopic measurements of the compounds $\text{Eu}_{1-x}\text{Sr}_x\text{Au}_4\text{Cd}_2$ ($x=0.2$–0.8) at 78, 15, and 6 K. $\delta$ = isomer shift (mm s$^{-1}$)

| Compound                  | $T$ | $\delta$ | $\Delta E_Q$ | $\Gamma$ | $B_{hf}$ | Area |
|---------------------------|-----|----------|--------------|----------|----------|------|
| $\text{Eu}_0.8\text{Sr}_0.2\text{Au}_4\text{Cd}_2$ | 78  | $-10.14(4)$ | 1.9(3)  | 2.3*        | –         | 100% |
| 6                         | $-10.05(6)$ | 1.5(3)  | 2.3*        | 26.2(2)   | 100%    |
| $\text{Eu}_0.6\text{Sr}_0.4\text{Au}_4\text{Cd}_2$ | 78  | $-10.18(2)$ | 1.8(2)  | 2.3*        | –         | 89 (1)% |
| 6                         | $-10.20(9)$ | 2.9(5)  | 2.3*        | 21.9(3)   | 89 (1)% |
| 15                        | $-10.01(5)$ | 1.6(3)  | 2.3*        | –         | 100%    |

Parameters assigned with an asterisk where kept fixed during the fitting procedure

$\Delta E_Q$ electric quadrupole splitting (mm s$^{-1}$), $\Gamma$ experimental line width (mm s$^{-1}$), $B_{hf}$ hyperfine field (T)

present spectra for the $x=0.2$ and 0.4 samples. The increasing strontium content leads to a dilution of the magnetic centers and this is expressed in the $^{151}$Eu spectra in a decrease of the magnetic hyperfine field: 26.2 T for the $x=0.2$ vs. 21.9 T for the $x=0.4$ sample. The Mössbauer spectroscopic data thus fully support the magnetic ones.
Conclusion

EuAu₄Cd₂ and SrAu₄Cd₂, both crystallizing with the tetragonal YbAl₃Mo₄ type structure, space group I4/mmm form a complete solid solution EuₓSr₁-xAu₄Cd₂. The dilution of the europium substructure with diamagnetic Sr²⁺ reduces the Eu–Eu magnetic exchange and leads to a drastic decrease of the Curie temperature, although ferromagnetic ordering is still present in the x = 0.8 sample with Tₚ = 2.9(2) K.

Experimental

Synthesis

Starting materials for the synthesis of samples of the solid solution Eu₁−xSrₓAu₄Cd₂ (in x = 0.2 steps) were europium ingots (American Elements, 99.99%), dendritic pieces of strontium (Onyxmet, 99.95%), pieces of gold droplets (Agosi, 99.9%), and a cadmium rod (Sigma Aldrich, 99.999%). First, the europium pieces were cleaned from surface contamination under dry cyclohexane (over sodium) and cut into small pieces. Also, strontium pieces were cut into smaller pieces. The tantalum ampoules were then sealed in quartz tubes for protection against oxidation and were subsequently heated and arc-welded [27] in small tantalum tubes under an argon atmosphere of ca. 800 mbar. The argon (Westfalen, 99.998%) was purified over titanium sponge (870 K), silica gel, and molecular sieves. A slight excess of europium and strontium was necessary to minimize the amount of by-products.

The tantalum ampoules were then sealed in quartz tubes for protection against oxidation and were subsequently heated within one hour to 1273 K. This temperature was held for five minutes before the samples were cooled to 1073 K within 20 min, kept at that temperature for another three hours and finally cooled to room temperature at a rate of 10 K h⁻¹. The polycrystalline samples were powdered in an agate mortar under dry cyclohexane, cold pressed into pellets (⌀ 6 mm) and thermally post-treated in a muffle furnace (680 K for four days, followed by slow cooling to room temperature at a rate of 5 K h⁻¹) to increase the phase purity and crystallinity. The samples were mechanically separated from the ampoules. No reactions with the ampoule material were evident. All samples are stable in air over several weeks and have metallic luster, ground powders are dark grey.

X-ray diffraction on powders and single crystals

The polycrystalline Eu₁−xSrₓAu₄Cd₂ samples were ground to fine powders and studied by X-ray powder diffraction using the Guinier technique (Enraf–Nonius FR 552 camera) with CuKα₁ radiation and α-quartz (a = 491.30 and c = 540.46 pm) as an internal standard. The diffraction patterns were collected through imaging plate technique (Fuji film, BAS-READER 1800). The lattice parameters (Table 1) were obtained from least-squares refinements. Intensity calculations (Lazy-Pulverix routine [28]) facilitated the correct indexing of the diffraction lines.

Conchoidally fractured crystal splinters were selected from the crushed samples with the nominal compositions Eu₀.₆₆Sr₀.₃₄Au₄.₁₂Cd₁.₈₈ and Eu₀.₃₂Sr₀.₈₈Au₄.₁₀Cd₁.₉₀ and glued to glass fibers with bees wax. The crystals were first investigated on a Bruker precession camera (white Mo radiation, Fuji-film imaging plate) in order to check their quality for intensity data collection. Complete data sets were collected at room temperature by using a Stoe IPDS-II image plate system (graphite monochromatized Mo radiation; λ = 71.073 pm) in oscillation mode. Numerical absorption corrections were applied to the data sets. Details on the crystallographic data are given in Table 4.

EDX data

The Eu₀.₆₆Sr₀.₃₄Au₄.₁₂Cd₁.₈₈ and Eu₀.₃₂Sr₀.₈₈Au₄.₁₀Cd₁.₉₀ single crystals were semiquantitatively analyzed by EDX in a Zeiss EVO® MA10 scanning electron microscope (variable pressure mode (60 Pa) and LaB₆ cathode) using EuF₃, SrF₂, Au and Cd as standards. The measurements (8 ± 1 at.% Eu: 3 ± 1 at.% Sr: 62 ± 1 at.% Au: 27 ± 1 at.% Cd, for the Eu₀.₆₆Sr₀.₃₄Au₄.₁₂Cd₁.₈₈ and 3 ± 1 at.% Eu: 7 ± 1 at.% Sr: 62 ± 1 at.% Au: 28 ± 1 at.% Cd, for the Eu₀.₃₂Sr₀.₈₈Au₄.₁₀Cd₁.₉₀) confirmed the compositions refined from the single crystal X-ray data of 9.4:4.9:58.9:26.9 for the Eu₀.₆₆Sr₀.₃₄Au₄.₁₂Cd₁.₈₈ and 3.1:11.1:58.6:27.1 for the Eu₀.₃₂Sr₀.₈₈Au₄.₁₀Cd₁.₉₀ crystal. Slight deviations as well as the standard deviations result from the irregular crystal surface (conchoidal fracture) and the coating with beeswax. No impurity elements (especially with respect to the tantalum tubes) were detected.

Structure refinements

Both data sets showed tetragonal body-centered lattices with high Laue symmetry and no further extinctions. Similar to Eu₂Au₁₄Cd₂ and Sr₂Au₄Cd₂ [10], the centrosymmetric space group I4/mmm was found to be correct. The positional parameters of Sr₂Au₄Cd₂ [10] were taken as starting values and the structures were refined on F² with the JANA2006 [29] software package using anisotropic displacement parameters for all atoms. Both data sets showed mixed occupancies. Besides the Eu/Sr mixing on the 2a sites we observed small degrees of Cd/Au mixing on the 4d sites, similar to Eu₂Au₁₄Cd₂₁₂ reported earlier [10]. These site occupancies were refined as least-squares
variables. The final difference Fourier syntheses were flat. The final atomic coordinates, displacement parameters and interatomic distances of both structures are listed in Tables 5, 6.

CCDC-1995352 (Eu0.66Sr0.34Au4.12Cd1.88) and CCDC-1995314 (Eu0.22Sr0.78Au4.10Cd1.90) contain the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

### Magnetic characterization

The samples of the solid solution Eu1−xSrxAu4Cd2 (x = 0.2, 0.4, 0.6, and 0.8) were investigated using the vibrating sample magnetometer (VSM) option of a physical property measurement system (PPMS) by Quantum Design. The samples were ground to a fine powder and each was filled into a polypropylene capsule, which was then inserted into a brass sample holder, which was attached to the sample holder rod of the VSM. The samples of the solid solution with

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**Table 4** Crystal data and structure refinement parameters for the compounds Eu0.66Sr0.34Au4.12Cd1.88 and Eu0.22Sr0.78Au4.10Cd1.90 of the solid solution Eu1−xSrxAu4Cd2 (YbAl4Mo2 type, space group I4/mmm, Z = 2)

| Crystal data | Eu0.66Sr0.34Au4.12Cd1.88 | Eu0.22Sr0.78Au4.10Cd1.90 |
|--------------|--------------------------|--------------------------|
| Empirical formula | Eu0.66Sr0.34Au4.12Cd1.88 | Eu0.22Sr0.78Au4.10Cd1.90 |
| Formula weight/g mol⁻¹ | 1152.9 | 1123.2 |
| Lattice parameters/pm | a = 718.48(10) | a = 719.24(9) |
| c = 552.88(7) | c = 553.66(7) |
| Cell volume/nm³ | 0.2854 | 0.2864 |
| Calculated density/g cm⁻³ | 13.42 | 13.02 |
| Crystal size/µm | 30 × 40 × 100 | 20 × 30 × 80 |
| Transmission (min/max) | 0.286/0.583 | 0.132/0.162 |
| Absorption coefficient/mm⁻¹ | 122.4 | 121.0 |
| Detector distance/mm | 70 | 70 |
| Exposure time/min | 6 | 12 |
| ω range; increment/° | 0–180/1 | 0–180/1 |
| Integration param. (A, B, EMS) | 14.0; − 1.0; 0 | 14.0; − 1.0; 0 |
| F(000)/e | 940 | 917 |
| θ range/° | 4.0–33.4 | 4.0–33.4 |
| R1/wR2 for I ≥ 3σ(I) | 0.0174/0.0361 | 0.0128/0.0285 |
| R1/wR2 for all data | 0.0128/0.0291 |
| Goodness-of-fit on F² | 1.31 | 1.04 |
| Largest diff. peak/hole/e Å⁻³ | + 1.23/− 1.21 | + 0.97/− 1.29 |

**Table 5** Atomic coordinates, anisotropic and equivalent isotropic displacement parameters (pm²) for Eu0.66Sr0.34Au4.12Cd1.88 and Eu0.22Sr0.78Au4.10Cd1.90 of the solid solution Eu1−xSrxAu4Cd2 (YbAl4Mo2 type, I4/mmm)

| Atom | Wyck | x | y | z | U₁₁ | U₂₂ | U₃₃ | U₁₂ | U₁₃ | U₂₃ |
|------|------|----|----|----|-----|-----|-----|-----|-----|-----|
| Eu₀.₆₆Sr₀.₃₄Au₄.₁₂Cd₁.₈₈ | 0.66(2)Eu/0.34(2)Sr | 2a | 0 | 0 | 0 | 172(5) | 201(6) | 0 | 182(3) |
| Au1 | 8h | 0.30609(4) | x | 0 | 172(2) | 221(2) | 2(1) | 188(1) |
| 0.94(1)Cd/0.06(1)Au2 | 4d | 0 | 1/2 | 1/4 | 208(5) | 156(5) | 0 | 190(3) |
| Eu₀.₂₂Sr₀.₇₈Au₄.₁₀Cd₁.₉₀ | 0.22(2)Eu/0.78(2)Sr | 2a | 0 | 0 | 0 | 188(5) | 130(6) | 0 | 122(3) |
| Au1 | 8h | 0.30630(3) | x | 0 | 188(1) | 157(2) | 2(1) | 131(1) |
| 0.95(1)Cd/0.05(1)Au2 | 4d | 0 | 1/2 | 1/4 | 148(3) | 93(4) | 0 | 129(2) |

Uₑₑ is defined as one third of the trace of the orthogonalized Uₑ tensor.

Coefficients Uᵢⱼ of the anisotropic displacement factor tensor of the atoms are defined by:

\[-2\pi^2[(ha*)² U₁₁ + ... + 2hka*b*U₁₂]. U₄₄ = U₁₁, U₄₃ = U₁₃ = 0\]
x ranging between 0.2 and 0.8 were investigated through measurements of \( M(T,H) \) in a temperature range from 2.5 to 300 K and fields up to 80 kOe. Measurements of \( M(T) \) were performed for the end member of the solid solution, SrAu4Cd2, in the temperature range from 3 to 300 K and a field of 10 kOe.

Mössbauer spectroscopy

The samples of the solid solution \( \text{Eu}_{1-x}\text{Sr}_{x}\text{Au}_{4}\text{Cd}_{2} \) (\( x = 0.2, 0.4, 0.6, \) and 0.8) were investigated via \(^{151}\text{Eu} \) Mössbauer spectroscopic investigations. For the measurements a \(^{151}\text{Sm:EuF}_3 \) source (the 21.53 keV transition was utilized, 55 MBq, 1% of the total activity) was used in either a continuous flow helium cryostat system (Janis Research Co LLC) equipped with a resistance thermometer (accuracy ± 0.5 K) or a commercial liquid nitrogen bath cryostat in the usual transmission geometry. The source was kept at room temperature while the samples were cooled to the respective temperature (Table 3). The sample amounts were adjusted to the ideal absorber thickness [30] and mixing with \( \alpha \)-glucose assured homogeneous coverage. The samples were then placed in thin-walled PMMA containers. The high gold and europium content (see also the high absorption coefficients in Table 4) caused long measuring times between one and two weeks with a barely satisfactory resolution of the spectra especially for the spectra that were recorded below the magnetic ordering temperature. Fitting of the spectra was done with the WinNormos for Igor6 program package [31].

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### Table 6 Interatomic distances (pm) for \( \text{Eu}_{0.66}\text{Sr}_{0.34}\text{Au}_{4.12}\text{Cd}_{1.88} \) and \( \text{Eu}_{0.22}\text{Sr}_{0.78}\text{Au}_{4.10}\text{Cd}_{1.90} \)

|                | \( \text{Eu}_{0.66}\text{Sr}_{0.34}\text{Au}_{4.12}\text{Cd}_{1.88} \) | \( \text{Eu}_{0.22}\text{Sr}_{0.78}\text{Au}_{4.10}\text{Cd}_{1.90} \) |
|----------------|-------------------------------------------------|-------------------------------------------------|
| \( \text{Sr/Eu} \) | 4 Au 311.0 | 4 Au 311.6 |
| 8 Au           | 339.5     | 8 Au 339.8 |
| 8 Cd/Au        | 384.9     | 8 Cd/Au 385.3 |
| \( \text{Au} \) | 2 Au 278.6 | 2 Au 278.6 |
| 4 Cd/Au        | 294.8     | 4 Cd/Au 295.1 |
| 2 Au           | 299.0     | 2 Au 299.6 |
| 1 Sr/Eu        | 311.0     | 1 Sr/Eu 311.6 |
| 2 Sr/Eu        | 339.5     | 2 Sr/Eu 339.8 |
| \( \text{Cd/Au} \) | 2 Cd/Au 276.4 | 2 Cd/Au 276.8 |
| 8 Au           | 294.8     | 8 Au 295.1 |
| 4 Sr/Eu        | 384.9     | 4 Sr/Eu 385.3 |

Standard deviations are equal or smaller than 0.1 pm

All distances of the first coordination spheres are listed. Note the Sr/Eu and Cd/Au mixed occupancies (Table 5)

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