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Peculiarities of the Electric Resistivity Behavior of $R_3(\text{Ce, Nd, Sm})\text{Cu}_4\text{Sn}_4$, $R(\text{Gd, Tb, Ho})\text{NiSn}_2$, DyNiSi , and DyNiSi_3 Compounds in Magnetic Fields

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The resistance of ternary intermetallic compounds, namely $RE(\text{Ce, Nd, Sm})_3\text{Cu}_4\text{Sn}_4$ (space group $Immm$), $RE(\text{Gd, Tb, Ho})\text{NiSn}_2$ and DyNiSi (space group $Pnma$) and DyNiSi_3 (space group $Cmmm$), has been studied in the temperature range up to 0.3 K and magnetic field up to 12 Tl. The temperature dependencies of electrical resistivity evidently show the anomalies at low temperatures. The anomalies of resistance temperature dependencies observed at the absence of an external magnetic field, agree well with magnetic phase transitions.

In the majority of the investigated compounds, an increase of the external magnetic field leads to an erosion of the peculiarities on the temperature dependency of resistivity, right up to complete disappearance. Such effect is caused by the corresponding magnetic order phase transitions.

Magnetic field influence on the temperature dependency of resistance is treated as an influence on the magnitude of hybridization between ($s-d$) conductivity electrons and localized f -electrons including influence on change on the charge carries mobility due to a possible spin-compensated interaction. Electron transport properties expose peculiarities in dependency of different chemical environment vicinity in elementary cell of crystal lattice and of magnetic state of the compound.

Keywords: rare-earth elements alloys and compounds, electronic transport, magnetoresistance.

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Introduction

The rare earth intermetallic compounds with transition and p -metals fairly often demonstrated interesting magnetic behavior, which affects other physical properties, including electrical. Thus, the $RE_3T_4X_4$ intermetallics (RE = rare earth elements; T = Cu, Pd, Ag; X = Si, Ge, Sn) crystallize into an orthorhombic $\text{Gd}_3\text{Cu}_4\text{Ge}_4$ structure type (space group $Immm$). In these compounds the rare earth atoms occupy two inequivalent positions $2d$ (1/2, 0, 1/2) and $4e$ (z , 0, 0). In this case, as the results of the magnetism and neutron diffraction experiments testify, the magnetic properties of the compounds may have a complex nature. Particularly, the magnetic moments of the rare earth elements frequently differ one from other and may be less than the values of free ions. The magnetic moments in different positions form different magnetic structures. The good example is $RE_3\text{Cu}_4X_4$ (RE = Tb, Dy, Ho, Er; X = Si, Ge, Sn)

compounds. The results of the magnetization and magnetic susceptibility investigations of polycrystalline samples of these compounds are presented in [1]. All investigated compounds are antiferromagnetic and reveal a complex magnetic behavior. For some of them, the additional peculiarities below the Neel's temperature can be observed.

The works [2-5] are also devoted to the magnetic characteristics of the $RE_3T_4X_4$ compounds, among which the the cerium compounds $\text{Ce}_3\text{Cu}_4\text{Sn}_4$ and $\text{Ce}_3\text{Cu}_4\text{Ge}_4$ [5] are probably the most interesting. The high values of the resistivity coefficient in these compounds classify them as the strong electron-electron correlation systems (heavy fermions). In these compounds cerium also occupies two inequivalent positions. The magnetization curve obtained on $\text{Ce}_3\text{Cu}_4\text{Sn}_4$ at low temperatures points to different magnetic interactions, particularly the complex magnetic transformations are observed below the magnetic ordering temperature T_N . It is assumed that the magnetic ordering

happens due the long-range exchange interaction mechanism *RKKY* (Ruderman-Kittel-Kasuya-Yosida exchange interactions). The obtained resulting magnetic moment relates to the cerium atom: $\mu_{\text{eff}} = 2.37 \mu_{\text{B}}$, at the theoretical value for Ce^{3+} ion of $2.54 \mu_{\text{B}}$.

The electron transport properties of the $RE_3\text{Cu}_4\text{Sn}_4$ ($RE = \text{Ce}, \text{Nd}, \text{Sm}, \text{Gd}, \text{Dy}$) compounds have been described in Refs. [3, 6]. The correlation of peculiarities in the magnetic and electron transport studies has been observed.

The *RETX*₂ compounds crystalize in different orthorhombic structures. In particular, the ternary compounds of the rare earth compounds with Gd, Tb, Ho crystalize in the LuNiSn_2 structure type (space group *Pnma*). Rare earth atoms occupy three inequivalent sites in these compounds. The neutron diffraction data indicate that in the $RE\text{NiSn}_2$ compounds magnetic moments are localized only on atoms of rare earth elements. No magnetic moment has been observed in the nickel atoms. In TbNiSn_2 the rare earth element form a non-collinear magnetic structure while in HoNiSn_2 antiferromagnetic structure is collinear with different magnitude of the magnetic order in each sublattice. From the magnetization experiments have been observed two anomalies for TbNiSn_2 at 5.2 K and 2.8 K and in HoNiSn_2 an explicitly seen maximum at 2.2 K [7].

Electron transport properties of the $RE\text{NiSn}_2$ ($R = \text{Y}, \text{Gd}, \text{Tb}, \text{Dy}, \text{Er}, \text{Tm}$) compounds have been studied by L. Romaka and co-authors [8].

The next two compounds with unique physical properties are DyNiSi with TiNiSi structure type (space group *Pnma*), DyNiSi_3 with ScNiGe_3 structure type (space group *Cmmm*). In the case of DyNiSi compound the peculiarity on the temperature dependency of resistivity at 9K have been observed. Magnetic studies reveal a magnetic transition in DyNiSi at 3 K and the Néel's temperature $T_{\text{N}} = 8.8$ K [9]. The two peculiarities on the temperature dependency of resistivity of the DyNiSi_3 compound at 6.5 K and 21 K have been observed [10].

As a unifying factor of all listed compounds is an existence of some peculiarities on the temperature dependencies of resistivity, which correlated by the evidence temperature with magnetic phase transitions.

Therefore, in this work we presents the results of the electric resistivity studies of $RE_3\text{Cu}_4\text{Sn}_4$ ($RE = \text{Ce}, \text{Nd}, \text{Sm}$), $RE\text{NiSn}_2$ ($RE = \text{Gd}, \text{Tb}, \text{Ho}$), DyNiSi , DyNiSi_3 , partially presented earlier in [6, 8, 10]. In comparison with the mentioned works the low limit of the studies temperature has been lowered, the temperatures of the specific points (phase transitions) have been adjusted, as well as the resistivity studies have been conducted in the circumstances of an applied external magnetic field.

I. Materials and methods

Samples of nominal compositions were synthesized from high-purity metals: rare earths - 99.9 wt.%, Cu, Ni ≥ 99.999 wt.%, and Sn, Si ≥ 99.999 wt.%) by arc-melting under a purified argon atmosphere, using Ti as a getter and a tungsten electrode. To achieve high efficiency of the interaction between the components, the samples were

melted twice.

The ingots were annealed at appropriate for each composition temperatures under vacuum in evacuated quartz ampoules for a corresponding duration of time and subsequently quenched in cold water.

The phase and structural analyses were performed based on X-ray powder diffraction data collected on diffractometers DRON-2.0M (Fe $K\alpha$ radiation). Crystallographic parameters were calculated using WinCSD program package [11]. The elemental composition of some samples was confirmed using a registering scanning electron microscope REMMA-102-2.

The electrical resistivity was measured by the standard the two-probe method using well-shaped pieces cut by spark erosion from the polycrystalline samples (parallelepiped form, optimal proportions and sizes). Soldered contacts were used. Studies of the electrical resistivity to the temperature of liquid helium were conducted in the Scientific-technical and Educational Center of Low Temperature Studies, I. Franko National University of Lviv, and studies below the temperature of liquid helium and in a magnetic field at the Institute of Solid State Physics, Vienna University of Technology.

II. Results and discussion

The influence of magnetic field on resistivity of the ternary intermetallics $RE_3\text{Cu}_4\text{Sn}_4$ ($RE = \text{Ce}, \text{Nd}, \text{Sm}$), $RE\text{NiSn}_2$ ($RE = \text{Gd}, \text{Tb}, \text{Ho}$), DyNiSi and DyNiSi_3 has been studied. All listed compounds exhibit peculiarities of temperature dependencies at the low temperature range. Since the temperature of appearance of these peculiarities correlate with the observed phase transition temperatures, it can be assumed that in most cases these peculiarities on the temperature dependencies of resistance are caused by a magnetic ordering and magnetic transitions

Therefore, the temperature of explosion of peculiarities correspond with the Néel's temperatures or magnetic transitions, which are components of multiple magnetic transitions observed in these compounds. Thus, several phase transitions or the transition of phases, which in itself can have a complex, step by step nature, effect on changes of resistivity. The existence of multiple phase transitions consequences in presence not in one but two and more peculiarities in the low temperature range of the temperature dependency of resistivity.

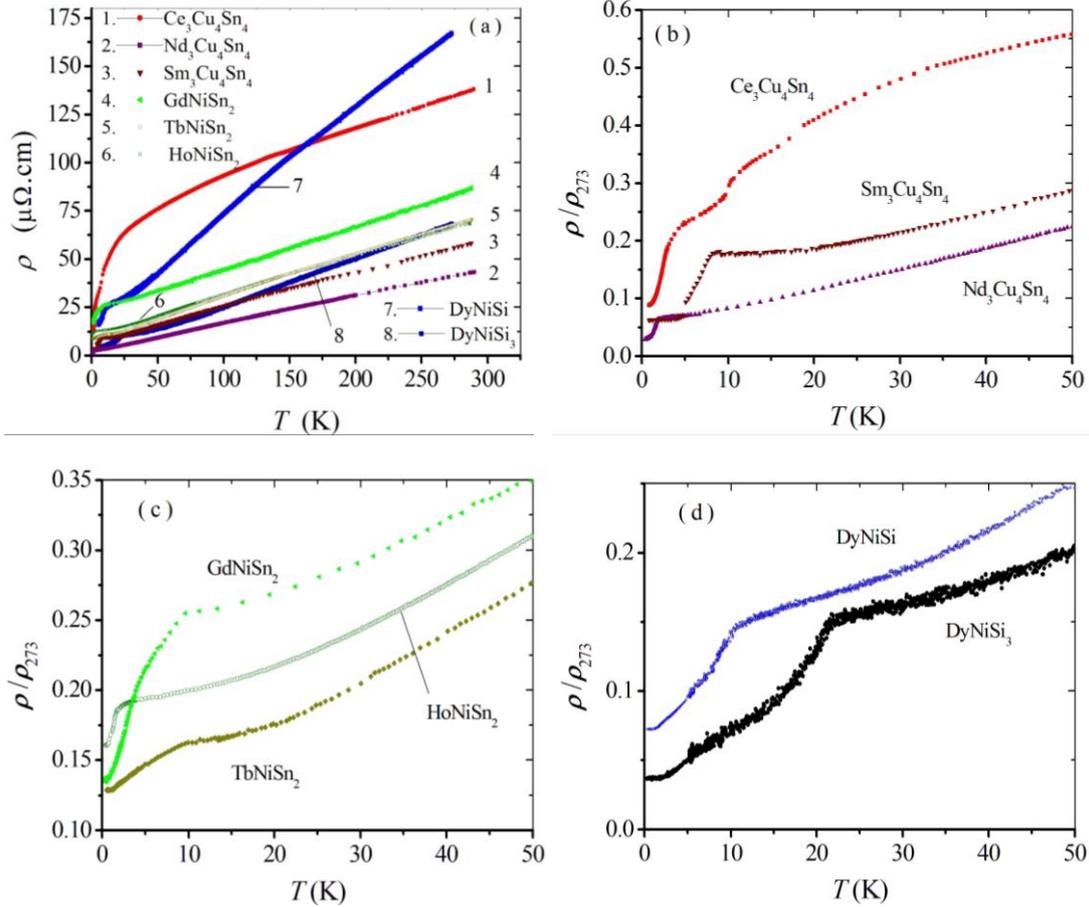
The intermetallics with different crystal structures and therefore with different crystallographic parameters have been selected for the studies. Crystal lattices for some compounds have asymmetric nonequivalent rare earth location sites. The basic crystallographic parameters of the studied compounds are represented in the **Table 1**. Let us note a significant difference of the lattice parameters of the studied compounds of different structural types. More precisely crystallographic studies can be found in [6, 8, 10].

Before proceeding to the actual description of the experimental resistance data, several remarks need to be made. First, even though the resistivity absolute value is

Table 1

Crystallographic data for the studied compounds.

Compound	Structure type	Space group	Lattice parameters, nm		
			<i>a</i>	<i>b</i>	<i>c</i>
Ce ₃ Cu ₄ Sn ₄	Gd ₃ Cu ₄ Ge ₄	<i>Immm</i>	0.4594(2)	0.7023(2)	1.5094(4)
Nd ₃ Cu ₄ Sn ₄	Gd ₃ Cu ₄ Ge ₄	<i>Immm</i>	0.4542(1)	0.6984(2)	1.4953(3)
Sm ₃ Cu ₄ Sn ₄	Gd ₃ Cu ₄ Ge ₄	<i>Immm</i>	0.4503(2)	0.6956(3)	1.4825(3)
GdNiSn ₂	LuNiSn ₂	<i>Pnma</i>	1.6129(3)	0.4436(3)	1.4668(4)
TbNiSn ₂	LuNiSn ₂	<i>Pnma</i>	1.6064(4)	0.4427(3)	1.4611(5)
HoNiSn ₂	LuNiSn ₂	<i>Pnma</i>	1.6002(5)	0.4400(3)	1.4509(4)
DyNiSi	TiNiSi	<i>Pnma</i>	0.68625(6)	0.41568(5)	0.71686(6)
DyNiSi ₃	SmNiGe ₃	<i>Cmmm</i>	0.39225(3)	2.0955(1)	0.39465(3)

**Fig. 1.** RE-M(Cu,Ni)-X(Sn,Si). Resistivity temperature dependency (a), low temperature range of the reduced resistivity temperature dependency (b, c, d).

an important parameter but considering that, the samples were obtained using the arc-melting method we would not concentrate our attention on the absolute value of resistivity treating it as a qualitative feature. Due to the considerations mentioned above, resistivity temperature dependencies that will be presented below on Fig. 1, will be also presented in the normalized form.

Secondly, presenting temperatures obtained from resistance temperature dependencies peculiarities (phase transitions) measurements, we would like to state a restriction regarding the method of obtaining one. There is a practice to take the maximum temperature on the heat capacity dependency of temperature as the transition point for magnetic phase transitions. However, the reflection of the corresponding phase transition on the resistance temperature dependency always has, more or less,

continuous temperature range. That explains difficulties of exact establishing of phase transition temperature using resistance measurements.

More important is the fact of observing the phase transition itself on temperature dependency curve of resistivity $\rho = f(T)$.

The phase transition temperature was established as the temperature of the beginning of the sharp change of resistance and by the curve maximums dp/dT . Comparing the manifestation temperatures of phase transitions obtained from the magnetic studies, heat capacity studies and from resistance temperature dependencies analysis, we must consider the restrictions mentioned above.

The resistivity temperature dependencies of the studied compounds have been presented on Fig. 1(a) and additionally low temperature parts of these dependencies

in normalized form on Fig. 1(b, c, d).

As seen from the figure, resistance temperature dependencies of all studied compounds have the metallic nature. Peculiarities in the form of resistance sharp drop in the low temperature range we, considering the restrictions mentioned above, identify as a manifestation of phase transitions related to magnetic ordering in rare earth element sublattice.

Resistance temperature dependencies above the mentioned phase transition temperature in the studied compounds have a similar to each other metallic temperature behavior with a slight nonlinearity. As the exception of such a resistance temperature dependency is the resistivity temperature dependency of $\text{Ce}_3\text{Cu}_4\text{Sn}_4$. The properties of $\text{Ce}_3\text{Cu}_4\text{Sn}_4$ compound will be discussed separately a little later.

A slight deviation of the temperature dependency from the linear one allows describing resistance temperature dependency above the phase transition temperature with the Bloch-Grüneisen-Mott formula [12], which takes into account the residual resistance, phonon component and an interzone scattering contribution. The last one can cause a deviation of the dependency from the linear one.

Note that nonlinearity of resistance temperature dependency can also be a consequence of some other reasons. Particularly, it can be demonstrated with simple calculus that in case of presence of more than two or more phases in an alloy in the form of inclusions, even if each of them reveals linear nature of resistance temperature dependency separately, the total resistance temperature dependency will be nonlinear. In the absence of significant evidence of presence of a significant presence of second phase in the compounds studied by us we wrap up to a conclusion that the resistance temperature dependency nonlinearity observed by us is caused by the interzone scattering contribution.

The $\text{Ce}_3\text{Cu}_4\text{Sn}_4$ differs significantly from other samples by its temperature dependency nature (see Fig. 1(a)). Firstly, the resistivity of this sample (same as the DyNiSi sample), though not drastically but is bigger by its absolute value than the resistivity of other samples. Secondly, resistivity temperature dependency of this compound is characterized by a significant deviation from the linear nature and is more alike to the temperature dependencies in systems with strong electron-electron correlations. The big value of the resulting electronic specific heat coefficient) $\gamma = 330 \text{ mJ/mol}_{\text{Ce}}\text{K}^2$ [5] is a direct evidence that the $\text{Ce}_3\text{Cu}_4\text{Sn}_4$ can be classified as a strong electron- electron correlation system.

The fact that many cerium compounds are classified as strong electron- electron interaction system (intermediate valence state, Kondo lattice and concentrated Kondo lattices, heavy fermions systems) has been known for a quite long time. Regarding the $\text{Ce}_3\text{Cu}_4\text{Sn}_4$ compound in particular we should note its heavy fermion state and absence of direct evidences of a Kondo behavior of resistance temperature dependency [3, 5]. At the same time we omit the discussion regarding intermediate valence state as state of a Kondo system with strong connection and high Kondo temperature T_K [13].

In any case, we investigate a strong correlated system, in which while lowering temperature, we transit to

magnetic ordered state of a complex nature or in a state with strong electron-electron correlations, which coexist with a magnetic ordering at low temperatures.

Allow us proceed to the influence of an external magnetic field on resistivity of the compounds listed above. Studies of sign and nature of the rare earth element magnetoresistance behavior are a way to understand the $f(d)$ -s interaction mechanism in various metallic systems featuring localized magnetic moments.

Two temperatures on the resistivity temperature dependency of studied compounds were selected to estimate quantitatively the external magnetic field influence on resistance. The first temperature was selected slightly above the magnetic ordering temperature (first peculiarity manifestation temperature on resistance temperature dependency while cooling the sample). The second temperature is 0.4 - 0.5 K (i.e., at the lowest temperatures acquired at $T \rightarrow 0$). Such approach to selecting control temperatures will be kept in future for all studied compounds. At control temperature we will evaluate a quantitative change of resistivity under an applied external magnetic field $\Delta\rho_{\text{mag}}$, as well as at the highest values of magnetic field tension applied for a particular compound.

$$\Delta\rho_{\text{max}} = \frac{\rho(T, H \neq 0) - \rho(T, H = 0)}{\rho(T, H = 0)} \cdot 100\% \quad - \text{percentage}$$

difference between resistivity at a fixed temperature, zero magnetic field and resistivity at the same temperature in presence of maximal magnetic field, applied during studies of a particular compound.

2.1. Influence of external magnetic field on the nature of resistivity temperature dependency

$\text{RE}_3\text{Cu}_4\text{Sn}_4$ ($\text{RE} = \text{Ce, Nd, Sm}$)

$\text{Ce}_3\text{Cu}_4\text{Sn}_4$. The $\text{Ce}_3\text{Cu}_4\text{Sn}_4$ compound sample, in the absence of external magnetic field, exhibits a temperature behavior similar to the behavior the Ce metallic compounds resistance, in which Ce is in the state with strong electron-electron correlations (Fig. 1). The imposition of an external magnetic field leads to transformation of resistivity temperature dependency of $\text{Ce}_3\text{Cu}_4\text{Sn}_4$, significantly bigger in the low temperature part of the dependency. Therefore, only the low temperature part of resistivity temperature dependency is presented (Fig. 2).

Resistance temperature dependency of $\text{Ce}_3\text{Cu}_4\text{Sn}_4$ in the low temperature region explicitly indicates the presence of at least two peculiarities at $\sim 3.5 \text{ K}$, $\sim 7.7 \text{ K}$. The presence of a higher temperature (above 10 K) peculiarity can be assumed, which does not get revealed due to a peculiar nature of this temperature dependency.

Evidently the presence of two peculiarities on the resistivity temperature dependency of $\text{Ce}_3\text{Cu}_4\text{Sn}_4$ is directly caused by cerium atom location in two inequivalent sites of crystal lattice $4e$ and $2d$, and therefore by a complex nature of magnetic ordering at low temperatures. It will be recalled that the rare earth elements atoms can occupy two inequivalent positions $2d$ ($1/2, 0, 1/2$) and $4e$ ($z, 0, 0$) in the compounds, which crystalize in the orthorhombic structure of the $\text{Gd}_3\text{Cu}_4\text{Ge}_4$ type ($Immm$ space group).

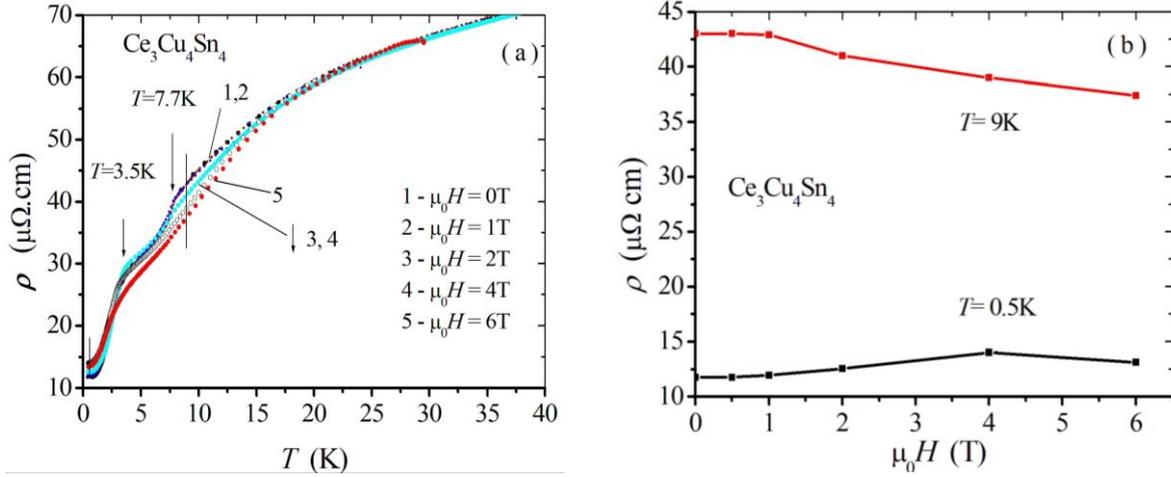


Fig. 2. $\text{Ce}_3\text{Cu}_4\text{Sn}_4$. Temperature dependences of electrical resistivity in magnetic fields of different magnitudes (a); the dependence of the resistivity on the magnitude of the external magnetic field (b).

At extremely low temperature transition to constant value of resistance (residual resistance) is observed, which is expected to be observed at $T \rightarrow 0$ in a classic case.

The magnetic ordering data in the $\text{Ce}_3\text{Cu}_4\text{Sn}_4$ compound is known, magnetic ordering temperature is given $T_N = \sim 10.3 \text{ K}$, and complex step by step nature of the magnetic ordering evolution on temperature decrease is presented [5]. The peculiarities manifestation temperatures $T^p_{\text{mag(Ord)}}$ 7.7 K and 3.5 K can be related with the magnetic ordering evolution temperatures T_N : $T_2 = 7.3 \text{ K}$ and $T_3 = 2.6 \text{ K}$ [5]. As it can be see, considering the restrictions mentioned above, regarding evaluating phase transition temperatures using magnetic measurements and resistance temperature dependency measurements, the correlation is quite accurate.

Now let's look at a qualitative transformation of resistivity temperature dependency of $\text{Ce}_3\text{Cu}_4\text{Sn}_4$ and evaluate quantitative indicators of magnetic field influence at the control temperatures (Fig. 2, b). The first temperature of 9 K was selected slightly above the peculiarity temperature of $\sim 7.7 \text{ K}$ and the second of 0.5 K, at the lowest obtained temperatures, below the second peculiarity temperature of $\sim 3.5 \text{ K}$. As mentioned above, this approach to the choice of control temperatures will be maintained in the future for other test compounds.

As the external magnetic field strength increases, the resistivity in the temperature environment above the magnetic ordering temperature (i.e., above the manifestation of the first feature) generally decreases. This can be explained by partial ordering of thermally disoriented magnetic moments of rare earth metals atoms (at least in one sublattice of a rare earth element). With the further increase in the magnetic field strength, the electrical resistivity decreases monotonically until the complete disappearance of the peculiarity (in the form of a sharp decrease in electrical resistance at $\sim 7.7 \text{ K}$) under the magnetic already at 6 T. At the temperature of the second peculiarity on the curve of resistivity ($\sim 3.5 \text{ K}$) the resistance at first increases and with a further increase in the magnetic field decreases. At the magnetic field tension of $\mu_0 H = 6 \text{ T}$ this peculiarity on the temperature dependence of the electrical resistance is still observed. Therefore, in this case it would have been necessary to use stronger magnetic fields, for unambiguous conclusions.

Approximately the second control temperature $T = 0.5 \text{ K}$, the resistance ("residual resistance") increases monotonically on increasing magnetic field strength. (see Fig. 2).

$\text{Nd}_3\text{Cu}_4\text{Sn}_4$. The compound with crystal structure isostructural to the structure of $\text{Ce}_3\text{Cu}_4\text{Sn}_4$ compound, exhibits a generally normal metallic type of conductivity in the absence of an external magnetic field (Fig. 3(a)). There is a peculiarity at 3.5 K in the form of an almost imperceptible fracture of the $\rho(T)$ curve and a clear peculiarity in the form of a sharp drop in the value of the resistivity on the temperature dependence of the resistivity at temperatures below 1.9 K.

According to the *Refs.* [4], no anomalies of the temperature dependence of the resistivity in the 1.6–300 K temperature range have been observed. At the same time, their measurements of magnetic susceptibility and heat capacity display an occurrence of antiferromagnetic transition at the temperature of 1.8 K. This temperature coincides with the phase transition temperature determined from our measurements of electrical resistivity at the reachable maximum on the $(d\rho/dT) = f(T)$ curve.

In the presence of an external magnetic field, with a gradual increase in the magnetic field strength, the resistivity (control point $T = 1.9 \text{ K}$) increases at first in absolute value (Fig. 3, b) and the temperature of the peculiarity is shifted slightly towards lower temperatures. Subsequently, the growth of magnetic field leads to decrease in resistivity and temperature shift of the peculiarity towards higher temperatures at $\mu_0 H = 2 \text{ T}$, up to a complete erosion of characteristic abrupt change in resistance at $\mu_0 H = 4 \text{ T}$. At the lowest temperatures reached ($T \rightarrow 0$) on magnetic field tension increasing up to $\mu_0 H = 6 \text{ T}$ resistivity increases and decreases slightly at $\mu_0 H = 8 \text{ T}$.

$\text{Sm}_3\text{Cu}_4\text{Sn}_4$. The results of resistivity investigation, magnetic susceptibility, magnetization and heat capacity of the $\text{Sm}_3\text{Cu}_4\text{Sn}_4$ compound are described in [4]. It is important to report that although Sm ions are in the trivalent state and occupy two symmetrically non-equivalent crystallographic sites, similar to the Ce ions in the $\text{Ce}_3\text{Cu}_4\text{Sn}_4$. As in $\text{Ce}_3\text{Cu}_4\text{Sn}_4$ a multiple magnetic transition is observed at low temperatures.

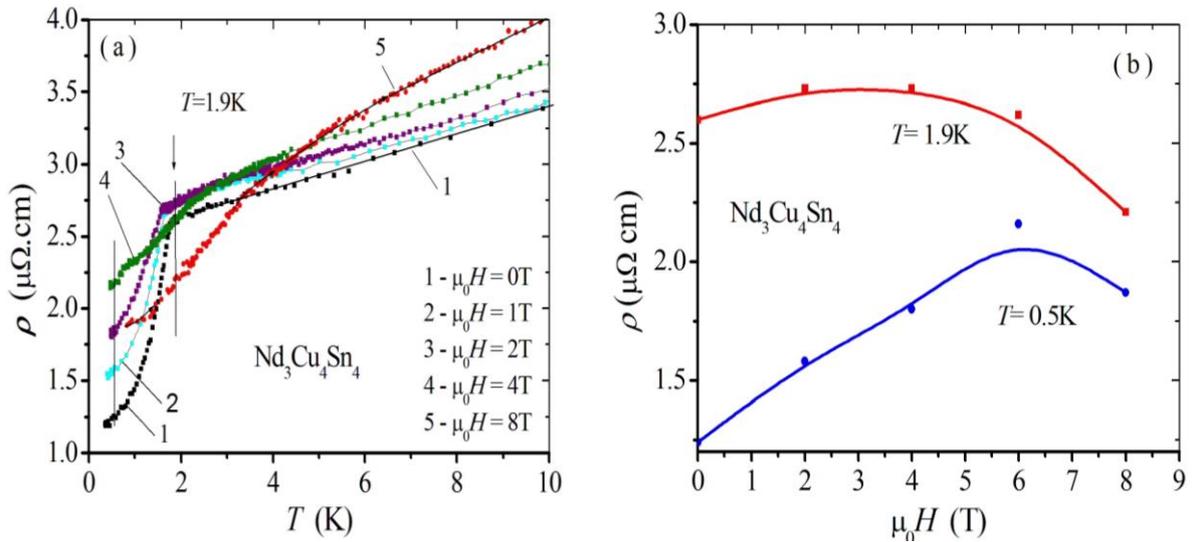


Fig. 3. $\text{Nd}_3\text{Cu}_4\text{Sn}_4$. Temperature dependences of electrical resistivity in magnetic fields of different magnitudes (a); the dependence of the resistivity on the magnitude of the external magnetic field (b).

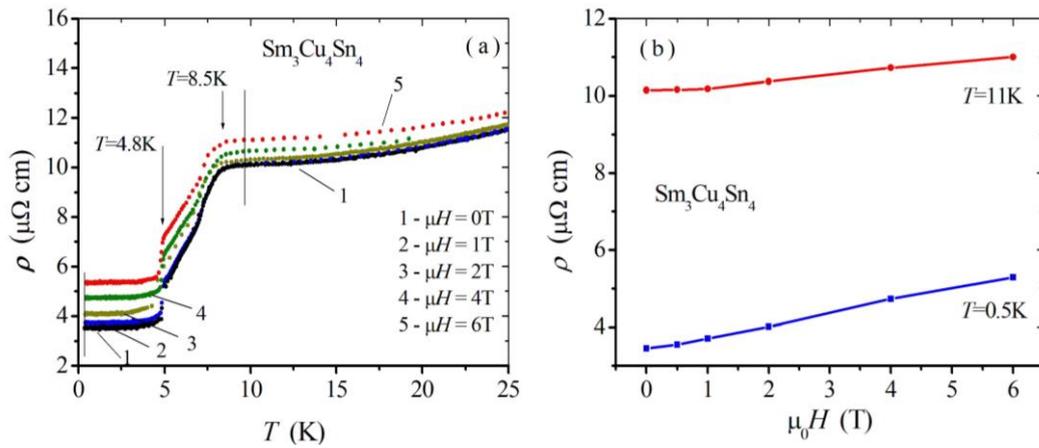


Fig. 4. $\text{Sm}_3\text{Cu}_4\text{Sn}_4$. Temperature dependences of electrical resistivity in magnetic fields of different magnitudes (a); the dependence of the resistivity on the magnitude of the external magnetic field (b).

Our studies of electrical resistance confirm multiple magnetic transformations, showing peculiarities on the temperature dependences of electrical resistance at temperatures of 4.8 K, 6.9 K and 8.5 K (in zero external magnetic field) Fig. 4, a.

First, the nature of the temperature dependency of $\text{Sm}_3\text{Cu}_4\text{Sn}_4$ in the field of magnetic phase transitions qualitatively (visually) differs from the temperature dependence of the electrical resistance of the previous $\text{Nd}_3\text{Cu}_4\text{Sn}_4$ compound. The difference lies in the extremely sharp drop in the value of resistivity (type of step) at each temperature of the detected peculiarities with the same sharp transition to a region with a constant value of resistivity (residual resistance) at $T \rightarrow 0$. We think that the observed, atypical nature of the temperature dependence of the resistivity of $\text{Sm}_3\text{Cu}_4\text{Sn}_4$ is solely because the magnetic phase transformations in $\text{Sm}_3\text{Cu}_4\text{Sn}_4$ occur when the temperature drops in a relatively small temperature range. They begin at that point of temperature dependence on which the resistivity has almost reached the limit value of the residual resistance and end also in the same range (~ 4.5 K, far before superlow temperatures). In this segment of the temperature dependence, the phonon fraction in the resistivity tends to

zero and the sharp decline in resistivity is determined mainly by nature of the magnetic ordering.

The external magnetic field leads to changes in resistivity (Fig. 4, b) in a slightly different way than in the case of $\text{Ce}_3\text{Cu}_4\text{Sn}_4$ and $\text{Nd}_3\text{Cu}_4\text{Sn}_4$. Within the applied values of the external magnetic field, the resistivity only exhibit growth. Probably the studies of the electrical resistance of this compound ($\text{Sm}_3\text{Cu}_4\text{Sn}_4$) had better be continued in larger magnetic fields, because, in contrast to the previous two isostructural compounds, a decrease in the resistivity in the external magnetic field has not been observed.

***RENiSn₂* (*RE* = Gd, Tb, Ho).**

Temperature dependences of resistivity in the external magnetic field of the GdNiSn_2 , TbNiSn_2 , HoNiSn_2 compounds are presented on Fig. 5, Fig. 6 and Fig. 7 respectively.

In all three compounds, there are two peculiarities on temperature dependencies of the resistance at temperatures 3.7 K and 10.5 K for GdNiSn₂, 4.0 K and 9.5 K for TbNiSn₂ and 2.1 K and 3.6 K for HoNiSn₂. Considering that in compounds of this type, the magnetic moments are localized only on atoms of rare earth elements, and the atoms of rare earth elements occupy three non-equivalent positions in these compounds, a complex nature of magnetic phase transformations in these compounds' resistivity can be assumed.

From the magnetization experiments, two anomalies have been observed for TbNiSn₂ at 5.2 K and 2.8 K, and for the HoNiSn₂ compounds an explicitly maximum at 2.2 K [7] has been observed. For the TbNiSn₂ compound the match of the temperatures of the manifestation of the peculiarities obtained from magnetic studies and from our measurements of the resistivity is not the best. The authors [7] present only one peculiarity for HoNiSn₂ at the 2.2 K temperature, which matches well with one of two peculiarities observed by us (Fig. 7, a).

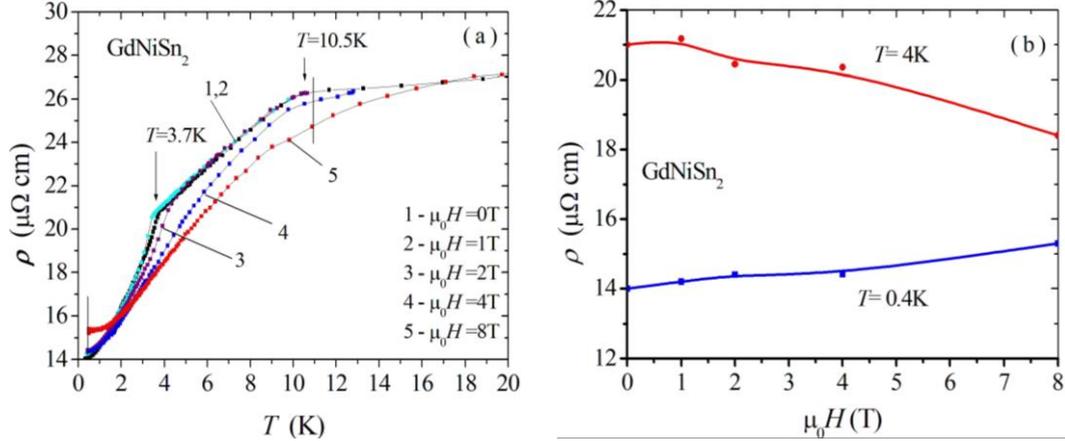


Fig. 5. GdNiSn₂. Temperature dependences of electrical resistivity in magnetic fields of different magnitudes (a); the dependence of the resistivity on the magnitude of the external magnetic field (b).

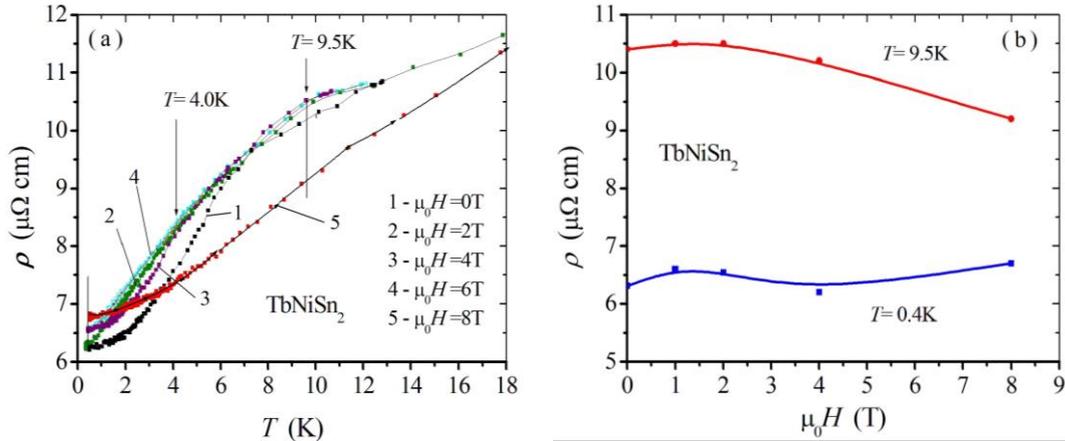


Fig. 6. TbNiSn₂. Temperature dependences of electrical resistivity in magnetic fields of different magnitudes (a); the dependence of the resistivity on the magnitude of the external magnetic field (b).

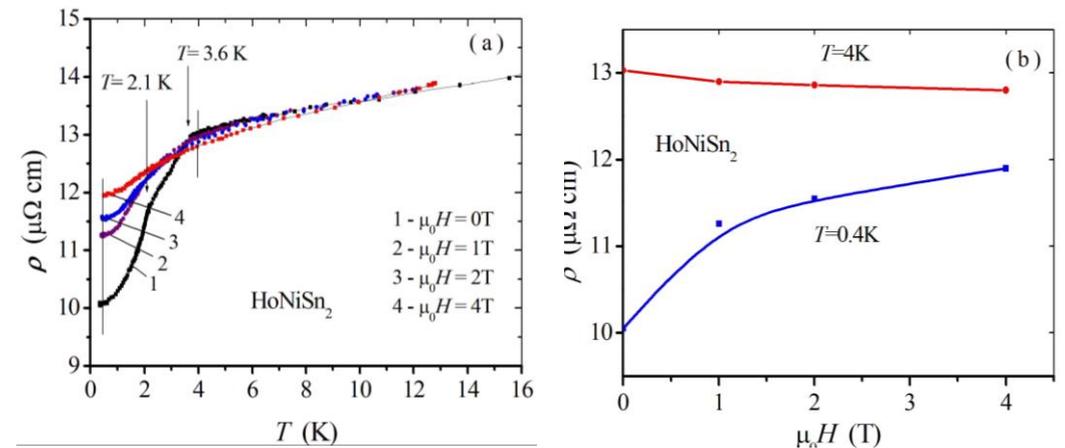


Fig. 7. HoNiSn₂. Temperature dependences of electrical resistivity in magnetic fields of different magnitudes (a); the dependence of the resistivity on the magnitude of the external magnetic field (b).

Similarly to $\text{Ce}_3\text{Cu}_4\text{Sn}_4$ and $\text{Nd}_3\text{Cu}_4\text{Sn}_4$, the peculiarities on the temperature dependencies of the resistivity erode with the increase of external magnetic field until they completely disappear after reaching an appropriate value of the external magnetic field. In quantitative terms, the effect of an external magnetic field on the resistivity of this series of isostructural compounds is shown graphically in Fig. 5, b; 6, b; 7, b for two control temperatures. The second control temperature (slightly above the Néel temperature) differs for all these three compounds. At the control temperature of $T = 0.4$ K, together with the increase of the external magnetic field, the resistivity increases monotonically. Above the second control temperature, the resistivity may initially increase slightly with the imposition and gradual growth of the external magnetic field and then monotonically decreases in absolute value. In the HoNiSn_2 sample, the reduction of the resistivity at the second control temperature on increasing external magnetic field occurs without a prior growth.

DyNiSi, DyNiSi₃

Resistivity temperature dependences in the low-temperature range up to 40 K for DyNiSi and DyNiSi₃ and their transformation in the external magnetic field, is shown in Fig. 8, and Fig. 9. Peculiarities have been observed on these temperature dependencies: for DyNiSi they are a hardly observable one at 2.2 K and 4.6 K and an

explicit one at 9 K, for DyNiSi₃ – at 6.5 K and 21 K.

One of the described peculiarities as vaguely exhibited, on the temperature dependence of the resistivity of DyNiSi at $T = 4.6$ K in magnetic field of $\mu_0 H = 2$ T manifests itself quite clearly. In other higher fields this peculiarity is not evidenced on the temperature dependence of the resistivity. Besides at the same magnitude of a magnetic field one more peculiarity in the form of Condo-like growth of resistance manifests itself starting from the $T = 1.5$ K temperature and down to the lowest reached temperatures. This peculiarity was also observed only under the field of $\mu_0 H = 2$ T.

A visible effect of an external magnetic field on magnetic transformations is observed in DyNiSi₃. As the magnitude of the external magnetic field increases, the peculiarities detected in the zero external magnetic field on the temperature dependence of the electrical resistance at 6.5 K and 21 K erode (decreases until complete disappearance). On contrary in the magnetic field of $\mu_0 H = 10$ T a peculiarity clearly manifests itself at $T = 15$ K. Thus, the reason-consequence relationship between the external magnetic field and the existence (or absence) of peculiarities on the temperature dependence of the resistivity can be tracked within the temperature range of the phase transition.

The obtained values of the temperatures of the manifestation of the peculiarities on the temperature dependences of the resistivity in the absence of an external

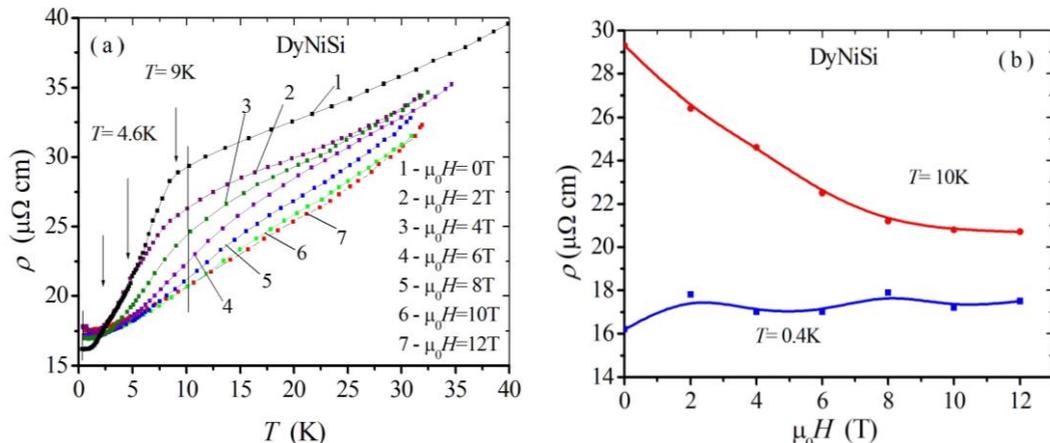


Fig. 8. DyNiSi. Temperature dependences of electrical resistivity in magnetic fields of different magnitudes (a); the dependence of the resistivity on the magnitude of the external magnetic field (b).

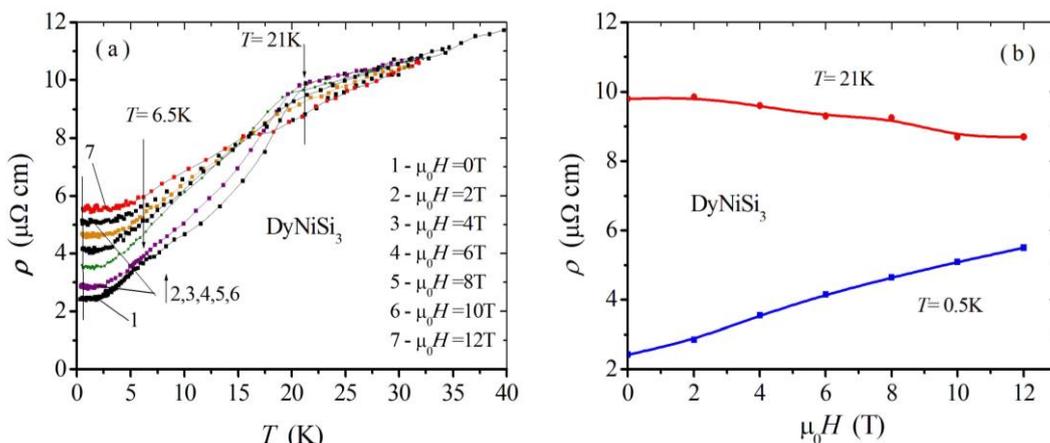


Fig. 9. DyNiSi₃. Temperature dependences of electrical resistivity in magnetic fields of different magnitudes (a); the dependence of the resistivity on the magnitude of the external magnetic field (b).

magnetic field can be matched with the temperatures of the magnetic phase transitions at 3 K and 8.8 K for DyNiSi [9] and at 21 K for metamagnetic DyNiSi₃ [14]. While there is a complete match on the peculiarity manifestation temperature for DyNiSi₃, at the same time the absolute value of resistivity at this temperature is described as significantly smaller in the mentioned work (It should be reminded about our reservations regarding absolute values).

On applying an external magnetic field, the resistivity (again at this temperature) in our investigations initially increases slightly, and the peculiarity shifts toward lower temperatures. At higher magnetic fields, the resistivity decreases and the peculiarity at 21 K erodes. Only increase in the resistivity at magnetic field slightly smaller than used by us, and shift of the peculiarity toward lower temperatures have been observed in *Refs.* [14]. Unfortunately, it is impossible to match the results of the influence of large external magnetic fields.

From the temperature dependence of heat capacity and magnetic susceptibility it is impossible to conclude if there is a peculiarity at temperature lower than the peculiarity at $T = 21$ K. On the temperature dependence of the resistivity the second peculiarity are observed at $T \sim 6.5$ K (see Fig. 9).

The above-described peculiarities of the electrical resistance of the investigated compounds, the nature of the temperature dependences of the resistance, some parameters of these temperature dependences without a magnetic field and in a magnetic field are summarized in Table 2.

Let's supplement Table 2 with more interesting, in our opinion, values. If we apply the Bloch-Grüneisen-Mott fitting formula (BGM model) BGM [12] to describe temperature dependency of resistivity then we can evaluate ρ_0 and Θ_D :

$$\rho(T) = \rho_0 + 4RT \left(\frac{T}{\theta_D} \right)^4 \int_0^{\theta_D/T} \frac{x^5 dx}{(e^x - 1)(1 - e^{-x})} - AT^3$$

where ρ_0 - temperature-independent component of resistance, which includes two components - scattering of conduction electrons on the defects of the crystal lattice ("residual" resistance) and scattering associated with spin

disposition in the presence of disordered magnetic moments $\Delta\rho_{mag}$, Θ_D – the Debye temperature. The ρ_0 will correspond with the value of the residual resistance only if the magnetic ordering does not occur in presence of disordered magnetic moments. The genuine residual resistance in the presence of magnetic ordering will be equal to the value of $\rho_{residual} = \rho_0 - \Delta\rho_{mag}$.

The second term of the formula describes scattering of carriers on the phonons of the crystal lattice, where R is the temperature-independent electron-phonon interaction constant, the third term of the formula describes the processes of interband scattering of the Mott type.

Having value of ρ_0 , we can approximately estimate the contribution of scattering on magnetically disordered ions of rare earth metals in the crystal lattice of the test compound. Fig.10 show an example of determining of approximate value of the scattering contribution at disordered magnetic moments for the GdNiSn₂ compound.

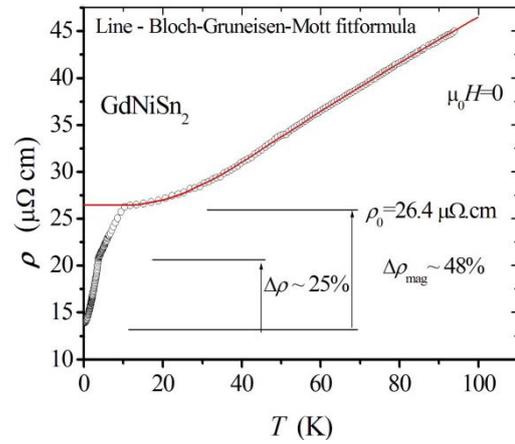


Fig. 10. Fragment of temperature dependence of GdNiSn₂ resistivity in the absence of external magnetic field. Example of an approximation using Bloch-Grüneisen-Mott-fit formula (solid line).

In this case, the $\Delta\rho_{mag}$ is presented as a percentage:

$$\Delta\rho_{mag}(\%) = \frac{\rho_0 - \rho(T \rightarrow 0, H = 0)}{\rho_0} \cdot 100\%$$

From this value, the part of the “residual” resistance (in percent) which is caused by magnetic interactions at low temperatures (in the absence of an external magnetic

Table 2

Parameters of temperature dependences of resistivity, temperature of manifestation of peculiarities on temperature dependence of resistance, temperature of magnetic phase transitions, influence of magnetic field on behavior of temperature dependence of resistivity.

Compound	$\rho_{T=273K}$	$T^p_{mag(ord)}$ (resistivity)	$T^{*mag}_{mag(ord)}$ (magnetism)		$\Delta\rho_{max}$
	$\mu\Omega cm$	K	K		
Ce ₃ Cu ₄ Sn ₄	128.6	~ 3.5, ~7.7	2.6, 7.3, 10.4	[3, 5]	6T; +21 (0.5K); -11 (9K)
Nd ₃ Cu ₄ Sn ₄	41.1	~1.9	1.8	[2, 4]	8T; +75 (0.5K); -17 (1.9K)
Sm ₃ Cu ₄ Sn ₄	55.4	~ 4.8, ~ 6.9, ~ 8.5	5.0, 7.5, 8.5	[4]	6T; +57 (0.4K); +11 (11K)
GdNiSn ₂	76.3	~3.7, ~10.5			8T; +8.6 (0.4K); -5.9 (11K)
TbNiSn ₂	65.1	~4.0, ~9.5	2.8, 5.2	[7]	8T; +8.0 (0.4K); -12 (10K)
HoNiSn ₂	66.1	~2.1, ~3.6,	2.2	[7]	4T; +20 (0.4K); -7.3 (4K)
DyNiSi	168.0	~2.2, ~4.6, ~9.0	3.0, 8.8	[9]	12T; +8 (0.4K); -29 (10K)
DyNiSi ₃	68.0	~6.5, 21.0	21	[14]	12T; +128 (0.5K); -11 (21K)

$T^p_{mag(ord)}$ - temperature of manifestation of peculiarities on temperature dependences of resistivity;

$T^{*mag}_{mag(ord)}$ - temperature of manifestation of peculiarities in magnetic researches [1-5, 7, 9, 14];

$\Delta\rho_{max}$ – magnetoresistance (as a percentage at the specified value of the magnetic field and temperature).

field) can be estimated.

The approximation parameters using the formula Bloch-Grüneisen-Mott-fit formula to temperature dependences of the studied intermetallic compounds (except $\text{Ce}_3\text{Cu}_4\text{Sn}_4$) are shown in Table 3.

The different, at first glance, nature of the temperature dependence of the resistivity of $\text{Sm}_3\text{Cu}_4\text{Sn}_4$ can be explained taking into account the results of studies of all compounds and match probability. All the investigated compounds, regardless of whether they have normal phase transitions or multiple, show temperature dependences of resistance more similar to the temperature dependence of $\text{Nd}_3\text{Cu}_4\text{Sn}_4$. A sharp decrease in the value of the resistivity (with or without the following other peculiarities) and a gradual transition to a constant value at $T \rightarrow 0$ K are observed.

Magnetic transitions in $\text{Nd}_3\text{Cu}_4\text{Sn}_4$ occur in the temperature range of 1.4 K and can be considered complete below 0.5 K. After a sharp drop in resistance at the beginning of the phase transition there is a more or less gradual transition to the values of the residual resistance. The similar situation is in HoNiSn_2 – an interval of 3.1 K ending below 0.5 K. These two compounds have the smallest temperature intervals of magnetic transformations. In other of the investigated compounds, the temperature intervals of magnetic transformations are much larger up to 19 K in DyNiSi_3 and end at the lowest temperatures.

These quantitative parameters are presented to confirm the assumption that the special nature of the temperature dependence of $\text{Sm}_3\text{Cu}_4\text{Sn}_4$ is determined exclusively by the relatively short interval of magnetic transformations. It is important that the beginning of magnetic transformations resides already in the area of residual resistance and the end at a relatively high temperature. For $\text{Sm}_3\text{Cu}_4\text{Sn}_4$ the highest end temperature of magnetic transitions is 3.8 K and the length is 4.7 K. In total, this determines the characteristic step-shaped form of the temperature dependence of the resistivity.

Magnetic ordering in all other compounds studied by us, except $\text{Sm}_3\text{Cu}_4\text{Sn}_4$, begins at temperatures at which the phonon part in scattering can still have a certain

contribution and the resistivity in this region of temperature dependence is determined by influence of both the phonon component and the magnetic one.

Before analyzing results of investigations of the external magnetic field influence on the resistivity of the studied compounds, we recall that there are three groups of compounds with different crystal structure, different parameters of the crystal lattice and based on different rare earth elements. Atoms of rare earth elements in many of these compounds occupy non-equivalent sites in the crystal lattice and, accordingly, have different environments in the unit cell of the crystal lattice. Due to this, the magnetic ordering and magnetic phase transformations in these compounds have a complex, multiple nature, which is clearly reflected in the presence of appropriate peculiarities on the temperature dependences of the resistivity of the studied compounds. As it was already noted, the compound $\text{Ce}_3\text{Cu}_4\text{Sn}_4$, additionally differs by nature of resistivity temperature dependence on other studied compounds (Fig. 2). This difference in the nature of the temperature dependence of the heavy-fermion state in the compound based on Ce is explained.

At first glance, the compound $\text{Sm}_3\text{Cu}_4\text{Sn}_4$ also differs with a slightly unusually sharp drop in the resistivity in the region of magnetic ordering (Fig. 4). Above we tried to find an explanation for this kind of temperature dependence of $\text{Sm}_3\text{Cu}_4\text{Sn}_4$ resistivity.

Some more general remarks can be made. Note that the selection of the maximum value of the external magnetic field used in the study of a particular compound is done using the erosion of peculiarities on the temperature dependences of the resistivity under the influence of an external magnetic field. That is, we unreasonably have not used for research the maximum available value of the external magnetic field. This applies in particular to the compound $\text{Sm}_3\text{Cu}_4\text{Sn}_4$, for the study of which the use of large external magnetic fields would be appropriate. Obviously, it would be good to have a number of compounds for research to compare. It is assumed that in two isostructural series of compounds $RE_3\text{Cu}_4\text{Sn}_4$ and $RENiSn_2$ there should be compounds based on the same

Table 3

Approximation parameters and evaluating the contribution to the resistivity component.

Compound	K1	K2	K3	K4	$\rho_{T \rightarrow 0K}$	$\Delta\rho_{\text{mag}}$	$\rho_{273K} / \rho_{T \rightarrow 0K}$	ρ_{273K} / ρ_0
	ρ_0 ($\mu\Omega\text{cm}$)		Θ_D (K)	A ($\mu\Omega\text{cm}/\text{K}^3$)	$\mu\Omega\text{cm}$	%		
$\text{Ce}_3\text{Cu}_4\text{Sn}_4$					11.4		11.28	
$\text{Nd}_3\text{Cu}_4\text{Sn}_4$	2.7	33.5	58.0	5.0×10^{-8}	1.2	55.5	34.25	15.2
$\text{Sm}_3\text{Cu}_4\text{Sn}_4$	9.9	98.5	140	6.9×10^{-8}	3.5	64.6	15.83	5.6
GdNiSn_2	26.2	94	118.8	-1.7×10^{-7}	14.0	46.5	5.45	2.9
TbNiSn_2	10.8	109.6	125.4	1.1×10^{-7}	6.2	42.6	10.50	6.0
HoNiSn_2	13.0	86.8	109	5.4×10^{-8}	10.0	30.0	6.61	5.1
DyNiSi	27.5	362	168.4	2.5×10^{-7}	16.3	40.7	10.31	6.1
DyNiSi_3	10.4	208.8	267.2	-2.3×10^{-7}	2.4	76.9	28.33	6.5

K1 (ρ_0), K2, K3 (Θ_D), K4 (A) - approximating parameters of resistivity temperature dependence using the Bloch-Grüneisen-Mott-fit formula (model); ρ_0 is obtained from the approximation results; Θ_D – Debye temperature; $\Delta\rho_{\text{mag}}$ - the share in the “residual” resistance ρ_0 caused by spin disorder resistivity (in Table 3 we present this share as a percentage $\Delta\rho_{\text{mag}}$ (%)).

rare earth elements.

Therefore, we will try to draw conclusions from the analysis of the influence of the external magnetic field on the resistivity and, accordingly, on the nature of the temperature dependencies of the resistivity of all studied compounds. The influence of the external magnetic field on the resistivity of the studied compounds is shown in Fig. 2-9. The dependences of the resistivity on the magnitude of the external magnetic field at two control points are given separately. Quantitative indicators of the influence of the external magnetic field are given in Tables 1 and 2.

The value of the electrical resistivity of all tested compounds at temperature $T \rightarrow 0$ K, including heavy fermionic compound $\text{Ce}_3\text{Cu}_4\text{Sn}_4$, with a successive increase in the value of the external magnetic field increases (positive magnetoresistance):

- magnetoresistance increases monotonically with increasing magnetic field for $\text{Sm}_3\text{Cu}_4\text{Sn}_4$, GdNiSn_2 , DyNiSi_3 ;

- Increases insignificantly in $\text{Ce}_3\text{Cu}_4\text{Sn}_4$, TbNiSn_2 , DyNiSi ;

- grows rapidly at first further growth of magnetoresistance slows down in HoNiSn_2 ;

- increases but at the maximum applied magnetic field decreases slightly in $\text{Nd}_3\text{Cu}_4\text{Sn}_4$.

The above division of the nature of changes in the magnetoresistance in external magnetic field shows that belonging to a certain type of crystal structure is not a determining factor in the behavior of the magnetoresistance at this control temperature.

The behavior of magnetoresistance at temperatures above the temperature of magnetic ordering (T_N) can be considered as:

- the magnitude of the resistivity decreases rapidly with increasing external magnetic field in DyNiSi with a gradual decrease in $d\rho/dH$, the peculiarity shifts toward higher temperatures and gradually erodes up to a complete disappearance.

- resistance decreases gradually in $\text{Ce}_3\text{Cu}_4\text{Sn}_4$ and HoNiSn_2 .

Peculiarity gradually erodes up to a complete disappearance:

- the resistivity first increases slightly (the feature shifts toward lower temperatures) and then gradually decreases (the peculiarity shifts toward higher temperatures until the complete disappearance of manifestation of the peculiarity on the curve of temperature dependence of resistance in compounds $\text{Nd}_3\text{Cu}_4\text{Sn}_4$, GdNiSn_2 , TbNiSn_2 , DyNiSi_3);

- the resistivity increases monotonically, the temperature of manifestation of the feature is constant in $\text{Sm}_3\text{Cu}_4\text{Sn}_4$.

Summarizing the above, we state that even at the second control temperature, the nature of changes in the resistivity in the external magnetic field is not determined directly due to belonging to a certain type of crystal structure.

The nature of the temperature dependencies of the resistivity of the studied compounds, the presence of peculiarities at these temperature dependencies, and the transformation of the temperature dependencies of the resistivity under the influence of an external magnetic

field are determined rather by the specific environment of the rare earth element atom, complex (multiple), step-by-step magnetic transitions, possibly strong electron-electron correlations in some cases.

We have investigated compounds of rare earth elements (*REs*), in which magnetic ordering occurs when the temperature decreases. In a number of solid substitution solutions based on *REs* Ce, Eu, Yb by changing composition, you can initiate a transition from the state of the system with a stable *RE*-ion to a system with the Kondo effect and then to the state of intermediate valence of the *RE*-ion. We will be interested in systems with Kondo - effect, concentrated Kondo-lattices, namely systems for which the Kondo temperature (T_K) is higher than the temperature of magnetic ordering (T_{RKKI}). Let us recall that the ratio of T_K and T_{RKKI} determines the exchange parameter J_{sf} , which, in turn, depends on the energy proximity of E_f and E_F . In the case of $T_K > T_{RKKI}$, the system with a decrease in temperature quickly goes to the state of the Kondo lattice and not to the state of magnetic ordering.

In this class of materials, studies of influence of external magnetic field on resistance have been performed [15]. We will select from a large number of such compounds, or solid substitution solutions, those for which studies of influence of the external magnetic field on the resistivity have been carried out and compare them to our studies of compounds with magnetic ordering.

In substitution type solid solutions $\text{Eu}(\text{Cu}_{1-x}\text{Ag}_x)_2\text{Si}_2$, when the temperature decreases, the $\text{Eu}(\text{Cu}_{0.875}\text{Ag}_{0.125})_2\text{Si}_2$ phase exhibits the presence of resistivity growth characteristic for concentrated Kondo systems with a maximum on the temperature dependence of the resistance at $T = 10$ K. Application of external magnetic field leads to decrease in resistivity (negative magnetoresistance) and at magnetic field 13 T completely eliminates the Kondo maximum on the temperature dependence of the electrical resistance.

Samples of another solid substitution solution $\text{EuCu}_2(\text{Si}_x\text{Ge}_{1-x})_2$ ($0.5 \geq x \geq 0.8$) also display properties characteristic for Kondo scattering in concentrated Kondo systems. At the $T = 15$ K there is a characteristic Kondo maximum, the amplitude of which decreases with increasing of magnetic field (up to its complete erosion at the field of 8 Tl) [16]. In the $\text{EuCu}_2(\text{Si}_{0.7}\text{Ge}_{0.3})_2$ sample, the decrease in the amplitude of the Kondo maximum of the electrical resistance with an increase in the magnetic field is accompanied by a shift in its temperature. A sample of this composition at a temperature of 4.2 K has a positive magnetoresistance, while at 10 K the magnetoresistance is already negative.

Qualitatively similar behavior of the resistivity in the magnetic field is also observed in a solid substitution solution of $\text{YbNi}_2(\text{Si}_{0.7}\text{Ge}_{0.3})_2$, which has Kondo properties [17].

Thus, we observe a certain similarity of influence of the external magnetic field on the resistivity of the samples of the above representatives of Kondo systems with influence of the magnetic field on the resistivity of studied systems with magnetic ordering.

The possible main components of the factors that cause electrical resistance are next: scattering by phonons; scattering due to interband interaction; scattering at

disordered magnetic moments of atoms; magnetic phase transformations and ordering; classical magnetoresistance due to the curvature of the trajectories of charge carriers under the action of a magnetic field; anomalous magnetoresistance, quantum effects in the motion of electrons, taking into account the ratio of de Broglie wavelength and free run length; scattering on lattice defects, etc.

All these factors determine the resistivity and its behavior depending on the temperature and the external magnetic field. Those factors that are present in a particular case may have more or less contribution, depending on the type of crystal structure, type of atoms forming the compound, magnetic interactions, from temperature, etc.

The phenomenological explanation of the behavior of electrical resistance under the action of the magnetic field of the studied intermetallic compounds REM can be given. At higher temperatures, the main factors in the formation of the resistivity are scattering by phonons of the crystal lattice, scattering due to interband interactions, scattering at disordered magnetic moments.

In the presence of an external magnetic field and its gradual increase, on decreasing temperature, there is a gradual collinearization of magnetic moments along the external magnetic field. This leads to decrease in the magnetic component of the scattering of carriers in the total resistance. At the same time, as the temperature decreases, the phonon component of the electrical resistance decreases, the exchange interaction between the magnetic moments of the atoms increases up to the magnetic ordering at a certain temperature (in many cases by the RKKY mechanism). In this case, the electrical resistivity at the onset of magnetic ordering decreases sharply due to the reduction of the magnetic component in scattering of carriers. The resistivity has a reason consequence connection to the nature of magnetic transitions and transformations. At low temperatures, the

influence of other factors at resistivity increases. Classical magnetoresistance is determined as due to the distortion of the trajectory of electrons in an external magnetic field due to the action of the Lorentz force (can be considered as a decrease in mobility). On the other hand, an application of magnetic field leads to a decrease in the spin-compensation interaction between (*s-d*)-electrons of conductivity and localized *f*-electrons and an increase in mobility. Thus, the presence of many factors and the predominant influence of one or other at one or other temperature form the nature of the temperature dependences of the resistivity of the compounds have been studied by us.

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- [1] A. Szytula, E. Wawrzynska, A. Zarzycki, J. Alloys Compd. 442, 200 (2007); <https://doi.org/10.1016/j.jallcom.2006.10.171>.
- [2] B. Pens, D. Kaczorowski, A.Szytula, A. Winiarski, A. Zarzycki, Intermetallics 15, 1489 (2007); <https://doi.org/10.1016/j.intermet.2007.05.010>.
- [3] S. Singh, S.K. Dhar, P. Manfrinetti, A. Palenzona, J. Alloys Compd. 298, 68 (2000); [https://doi.org/10.1016/S0925-8388\(99\)00661-1](https://doi.org/10.1016/S0925-8388(99)00661-1).
- [4] S. Singh, S.K. Dhar, P. Manfrinetti, A. Palenzona, J. Magn. Magn. Mater. 250, 190 (2002); [https://doi.org/10.1016/S0304-8853\(02\)00380-3](https://doi.org/10.1016/S0304-8853(02)00380-3).
- [5] O. Zaharko, E. Keller, C. Ritter, J. Magn. Magn. Mater. 253, 130 (2002); [https://doi.org/10.1016/S0304-8853\(02\)00440-7](https://doi.org/10.1016/S0304-8853(02)00440-7).
- [6] L. Romaka, V. Romaka, B. Kuzhel, Yu. Stadnyk, Visnyk Lviv Univ. Ser. Chem. 54(1), 136 (2013).
- [7] L. Romaka, B. Penc, S. Baran, J. Leciewicz, A. Szytula, N. Stusser, J. Hernandez-Velasco, A. Zygmunt, J. Alloys Compd. 343, 66 (2002); [https://doi.org/10.1016/S0925-8388\(02\)00283-9](https://doi.org/10.1016/S0925-8388(02)00283-9).
- [8] L. Romaka, B. Kuzhel, Yu. Stadnyk, Visnyk Lviv Univ. Ser. Chem. 51, 122 (2010).
- [9] A. Szytuła, M. Bałanda, M. Hofmann, J. Leciejewicz, A. Zygmunt, J. Magn. Magn. Mater. 191, 122 (1999); [https://doi.org/10.1016/S0304-8853\(98\)00330-8](https://doi.org/10.1016/S0304-8853(98)00330-8).
- [10] O. Bardin, B. Belan, S. Pukas, B. Kuzhel, Ya. Tokaychuk, M. Manyako, R. Gladyshevskii, Chem. Met. Alloys. 7, 194 (2014).
- [11] L. Akselrud, Yu. Grin, J. Appl. Crystallogr, WinCSD: software package for crystallographic calculations (Version 4) 47, 803 (2014); <https://doi.org/10.1107/S1600576714001058>.
- [12] N.F. Mott, H. Jones, The Theory of the Properties of Metals and Alloys (Oxford University Press, 1958).
- [13] D.I. Khomskiy, Uspekhi fizicheskikh nauk 129(3), 442 (1979).

- [14] A.V. Morozkin, V.O. Yapaskurt, J. Yao, R. Nirmala, S. Quezado, S.K. Malik, *Intermetallics* 107, 81 (2019); <https://doi.org/10.1016/j.intermet.2019.01.016>.
- [15] U. Rauchschwalbe, F. Steglich, A. de Visser, J.J.M. Franse, J. Magn. Magn. Mater. 63-64, 347 (1987); [https://doi.org/10.1016/0304-8853\(87\)90607-X](https://doi.org/10.1016/0304-8853(87)90607-X).
- [16] E.M. Levin, T. Palewski, B.S. Kuzhel, *Physica B* 294-295, 267 (2001); [https://doi.org/10.1016/S0921-4526\(00\)00656-6](https://doi.org/10.1016/S0921-4526(00)00656-6).
- [17] E.M. Levin, T. Palewski, B.S. Kuzhel, *Physica B* 259-261, 142 (1999); [https://doi.org/10.1016/S0921-4526\(98\)00607-3](https://doi.org/10.1016/S0921-4526(98)00607-3).

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Особливості поведінки електричного опору сполук $R_3(\text{Ce}, \text{Nd}, \text{Sm})\text{Cu}_4\text{Sn}_4$, $R(\text{Gd}, \text{Tb}, \text{Ho})\text{NiSn}_2$, DyNiSi , та DyNiSi_3 у магнітних полях

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Досліджено температурну залежність електричного опору тернарних інтерметалідних сполук складу $RE(\text{Ce}, \text{Nd}, \text{Sm})_3\text{Cu}_4\text{Sn}_4$ (структурний тип $\text{Gd}_3\text{Cu}_4\text{Ge}_4$, просторова група $Immm$), $RE(\text{Gd}, \text{Tb}, \text{Ho})\text{NiSn}_2$ (структурний тип LuNiSn_2 , просторова група $Pnma$), DyNiSi (структурний тип TiNiSi , просторова група $Pnma$), DyNiSi_3 (структурний тип SmNiGe_3 , просторова група $Cmmm$) в діапазоні температур до 0,3 К та магнітних полях до 12 Тл. На кривих цих залежностей за низьких температур спостерігали певні аномалії, які за відсутності зовнішнього магнітного поля добре узгоджуються з магнітними фазовими переходами.

У більшості випадків у досліджуваних сполуках збільшення зовнішнього магнітного поля призводило до нівелювання на кривих температурної залежності опору особливостей, які спричинені відповідними переходами магнітного упорядкування, аж до їх повного зникнення.

Вплив магнітного поля на температурну залежність електричного опору можна трактувати як вплив на величину гібридизації між ($s-d$) електронами провідності та локалізованими f -електронами, включаючи вплив на зміну рухливості носіїв заряду внаслідок можливої спин-компенсованої взаємодії. Кожна сполука демонструє свої електронно-транспортні властивості особливості, що залежать від їхнього хімічного складу та кристалічної будови, а також від магнітного стану сполуки.

Ключові слова: сплави та сполуки рідкісноземельних елементів, електронно-транспортні властивості, магнітоопір.