Ruthenium – Silicon – Uranium

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Introduction

In the recent years, a great deal of interest has been taken in those U based intermetallic compounds which shown a highly correlated state of the electronic system at low temperature. Discovery of URu_2Si_2 as the superconducting heavy fermion system, made the Ru-Si-U system and particularly the URu_2Si_2 compound the subject of intensive experimental and theoretical investigations because of the unusual interplay between superconducting and magnetic interactions at low temperature. The observation of antiferromagnetic order below ~17.5 K and of superconductivity below ~1 K brings the URu_2Si_2 compound to the center of discussions concerning the coexistence of magnetic order and superconductivity. Despite the fact that a large number of articles are devoted to understand the unusual properties of this heavy-fermion superconductor and to determine crystal structure of compounds, information concerning phase relations is very pure. Partial phase diagram of the Ru-Si-U system at 820°C has been constructed by [1994Uga]. Phase compositions of the alloys and crystal structures of the identified intermediate phases were studied by [1977Aks, 1980Bar, 1985Cor, 1985Rau, 1986Vis, 1993Poe, 1994Poe, 1994Uga, 1994Ver, 1995Lej, 1996Che, 2001Hof, 2002Zel]. Data on thermodynamic properties were studied by [1985Pal, 1986Vis, 1987Myd, 1990Fis, 1993Pir, 1994Bri, 1998Tak, 2003Jai]. A summary of physical properties is given below in the section "Notes on Materials Properties and Applications". Information on phase relations, structures and thermodynamics is summarized in Table 1.

Binary Systems

The Si-U and Ru-U binary systems are accepted from [Mas2]. The Ru-Si binary phase diagram has been assessed by [2000Oka] based on the experimental results of [1999Per]. More recently, thermodynamic optimization was carried out by [2001Du] and [2001Liu]. Since then, [2002Oka] assessed this system. The Si rich part of the Ru-Si phase diagram has been updated by [2002Iva]. A new phase, $RuSi_2$, has been observed in the form of inclusions in Ru_2Si_3 single crystals. Ru_2Si_3 single crystals have been grown by the zone melting technique with radiation heating. These crystals contain inclusions, about 500 nm in size, which consist of monocrystalline ruthenium disilicide. Crystal structure has not been determined. Endothermic peaks detected at T = 962°C in the DTA measurement have been interpreted as decomposition of $RuSi_2$ to Ru_2Si_3 and (Si).

Solid Phases

The crystallographic details of all solid phases are listed in Table 2. Eight ternary compounds have been found in the Ru-Si-U system. Heavy fermion superconductor URu_2Si_2 with the $ThCr_2Si_2$ structure type has attracted most attention. Single-crystals of URu_2Si_2 have been determined by [1985Cor]. The temperature dependence of the lattice parameters for URu_2Si_2 was studied by [1986Vis] for the temperature interval between 1.4 and 100 K. [1980Bar] synthesized URu_3Si_2 ternary compound. This compound crystallized in hexagonal $LaRu_3Si_2$ structure and electrical resistivity of this compound has been measured by [1985Rau]. However crystal structure and lattice parameters of URu_3Si_2 are not described by [1980Bar] and [1985Rau]. A new ternary silicide $U_2Ru_{12}Si_7$ has been discovered by [2002Zel]. The crystal structure has been solved on a single crystal. [1995Lej] reports about the crystal structure and physical properties of a new ruthenium-based ternary silicide, neighbor of URu_2Si_2: $U_6Ru_{16}Si_7$. The research of new materials was carried out by cross-checking X-ray diffraction pattern and microprobe analysis. The $U_6Ru_{16}Si_7$ compound has been detected as parasitic phase in as-cast URu_2Si_2 when shifting the composition. Heat treatments (at 1100 and 900°C) led to multiphase samples. No trace of the URu_3Si_2 phase mentioned earlier by [1980Bar] could be detected before and after annealing. The crystal structure has been solved by X-ray and neutron powder refinement using a Rietveld calculation method and according to a $Mg_6Cu_{16}Si_7$ structural model with the cubic space group $Fm\overline{3}m$ (a = 1220.7 ± 0.2 pm). Study of the U_2RuSi_3 compound by electron diffraction reveals that this silicide adopts interesting superstructures of the AlB_2 type [1993Poe, 1994Poe, 1996Che, 2001Hof]. The Ru and Si atoms are perfectly ordered in U_2RuSi_3 which leads to the occurrence of a new hexagonal superstructure having the unit cell parameters a twice as great as that observed for the ideal AlB_2 type. U_2Ru_3Si has been discovered by [1994Ver] and crystal structure has been determined by X-ray single crystal and powder diffraction analysis. Existence of this phase was confirmed by [1995Lej]. $U_2Ru_3Si_5$ has been discovered by [1977Aks]. It crystallizes in the monoclinic $Lu_2Co_3Si_5$ type structure which is a deformation variant of $U_2Co_3Si_5$. The URuSi ternary compound has been identified by [1994Uga]. Arc-melted alloys were heat treated in muffle furnaces at temperatures of 800-1100°C. Alloy specimens were water quenched to room temperature after heating for 3-10 d. Phases present before and after the heat treatments were examined by electron probe microanalysis and X-ray powder diffractometry. Compound crystallized in orthorhombic TiNiSi structure type.

Invariant Equilibria

According with [1994Uga], in the Ru-Si-U system, the URuSi ternary compound melts congruently. The following ternary transition reaction (U type) U_3Si + URuSi $\rightleftharpoons$ U_3Si_2 + L has been proposed by [1994Uga]. The invariant reaction temperature was found to be at a temperature between 820 and 850°C. Invariant plane corresponding to this reaction is shown in the isothermal section at 820°C in Fig. 1. The peritectic liquid may undergo the transformation on rapid cooling from the liquid state of the alloy: L $\rightleftharpoons$ URuSi + (U). It was found that the U_3Si compound does not have tie lines with (Ru) but forms those with the URuSi ternary compound.

Isothermal Sections

The partial isothermal section of the Ru-Si-U system at 820°C, as shown in Fig. 1, based on the investigation by [1994Uga].

Thermodynamics

The low temperature specific heat for URu_2Si_2 has been studied by [1985Pal, 1986Vis, 1987Myd, 1990Fis, 1994Bri, 2003Jai], for U_2RuSi_3 ternary compound by [1998Tak] and for $U_2Ru_3Si_5$ - by [1993Pir].

Notes on Materials Properties and Applications

Physical properties data known for URu_2Si_2, $U_2Ru_3Si_5$, U_2Ru_3Si and U_2RuSi_3 are discussed below.

URu_2Si_2:
Information concerned investigations of the Ru-Si-U materials properties, particularly URu_2Si_2 compound, are generalized in Table 3. The intermetallic compound URu_2Si_2 has been classified as a heavy-fermion system because of its large linear specific-heat coefficient g = 180 $mJ\cdot mol^{-1}\cdot K^{-2}$. Susceptibility, magnetization, and specific-heat measurements on single-crystal samples indicate both a magnetic phase transition at ~17.5 K and a superconducting transition at ~1 K. Ordered moment is unusually small (0.03 ± 0.01) μB. The magnetic and superconducting properties are highly anisotropic. The thermoelectric properties of URu_2Si_2 were studied by [2001Ari]. The Seebeck coefficient of URu_2Si_2 was obtained to be –48.9 $\mu V\, K^{-1}$ at 1100 K and the compound showed poor thermoelectric properties above room temperature. Correlation between superconductivity and magnetism in the URu_2Si_2 heavy fermion compound has been reviewed by [2003Sat]. High magnetic field studies of the hidden order transition in URu_2Si_2 have been investigated by [2002Jai, 2002Cha1, 2002Cha2, 2002Ami, 2003Ami1, 2003Ami2, 2003Mot1, 2003Mot2, 2003Myd, 2004Bel, 2004Jai, 2004Har, 2004Bou, 2005Min, 2005Ten, 2005Bou, 2005Ber]. Thermal transport in the hidden-order state of URu_2Si_2 has been studied by [2005Beh]. A narrow selection of the important experimental observations of inhomogeneous magnetism and hidden order in URu_2Si_2 has been reviewed by [2002Ami, 2002Cha1, 2002Cha2, 2003Ami1, 2003Ami2]. The theoretical implications of two recent NMR experiments on the hidden order have been discussed by [2003Cha]. Crystal field model of the

magnetic properties of the URu_2Si_2 compound have been proposed by [1987Nie, 1987Fra, 1992Rad, 1994San, 2005Nag]. Theoretical model for magnetic ordering in the heavy-fermion metal URu_2Si_2 has been suggested by [2005Min]. High field magnetic (B,T) phase diagram of URu_2Si_2 with superconducting and magnetically ordered phases was constructed basically combining experimental and literature data by [2003Kim]. Quantum criticality and multiple phase transitions in URu_2Si_2 are evidenced in Fig. 2. Region I refers to the hidden order phase, while II, III, and V constitute newly discovered phases. Region IV was proposed to be a field-induced recovery of the normal metallic phase. The p–T phase diagram has been investigated by [2003Mot1, 2003Mot2, 2003Sus, 2004Bou, 2005Bou,]. The p–T phase diagram (Fig. 3) deduced by [2005Bou] from the resistivity measurements by [1993Sch] and neutron-scattering measurements under pressure by [2004Bou, 2005Bou] shows two distinct phases for $p > p_M$, where $p_M \approx$ 4.9 kbar. The small-moment antiferromagnetic phase (SMAF), observed below the second-order phase transition at T_m = 17.5 K, is the same as that observed at p = 0 and is characterized by a small moment ~ 0.03 μB. The transition between the paramagnetic phase and the SMAF phase at T_m is second order and is accompanied by large anomalies in bulk properties. The low temperature antiferromagnetic phase (LMAF), observed below the transition T_M, which seems to be a first-order transition, is characterized by a large moment ~ 0.33 μB and small anomalies in the macroscopic properties. [2005Bou] found that the absence of magnetic scattering at the (0, 0, 21 + 1) reflections shows that the ordered moments are along the c-axis at all pressures, *i.e.* the SMAF and LMAF phases have the same AFM structure. A first-order transition line between the SMAF and the LMAF phases is also found in the thermal expansion measurements by Motoyama *et al.* [2003Mot1, 2003Mot2] under pressure along the a and the c axis. Their p-T phase diagram is similar, but not identical with [2005Bou]. The position of the line $T_m(p)$ is quite sensitive to the sample quality, and the onset pressure p_M for the LMAF phase varies from 4 to 8 kbar. They conclude that transition temperatures join at a critical point. This is in contrast to neutron- scattering measurements of [2005Bou], where the first-order character is preserved all the way up to 11.8 kbar.

$U_2Ru_3Si_5$:
Electrical resistivity, thermoelectric power, thermal conductivity, specific heat and magnetic susceptibility of the polycrystalline $U_2Ru_3Si_5$ silicide have been measured by [1988Ali, 1993Pir]. $U_2Ru_3Si_5$ behaves like a nonmagnetic compound and displays distinct anomalies in the low-temperature domains of resistivity and thermoelectric power. The thermoelectric properties of this compound also have been studied by [2001Ari]. The Seebeck coefficient of $U_2Ru_3Si_5$ was obtained to be –32.8 $\mu V \cdot K^{-1}$ at 1100 K and compound showed poor thermoelectric properties above room temperature.

U_2RuSi_3:
Magnetic susceptibility, low-temperature electrical resistivity and specific heat of the polycrystalline U_2RuSi_3 have been measured by [1998Tak]. The Weiss temperature for U_2RuSi_3 is 139 K and is very close to the values reported by [1996Che]. The reciprocal magnetic susceptibility of this compound follows a Curie-Weiss law above 60 K and effective magnetic moment for uranium 3.02 $\mu B \cdot (U\ atom)^{-1}$ [1994Poe, 1996Che].

U_2Ru_3Si:
Magnetization and resistivity of U_2Ru_3Si compound on a single crystal along the {001} direction of the hexagonal cell have been measured by [1994Ver]. U_2Ru_3Si exhibits an enhanced Pauli paramagnetic behavior and no anomalies in the magnetization and in the resistivity curves occur in this material. The resistivity of the single crystal decreases from 153 μΩ at room temperature to a saturated value of 7.6 μΩ at 4.2 K. The high residual resistivity measured at low temperature reflects the disorder between ruthenium and silicon.

URu_3Si_2:
The resistivity of URu_3Si_2 has been studied by [1985Rau]. Resistivity is very high and has a negative slope between 70 K and room temperature.

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Table 1: Investigations of the Ru-Si-U Phase Relations, Structures and Thermodynamics

Reference	Method/Experimental Technique	Temperature/Composition/Phase Range Studied
[1977Aks]	XRD, crystal structure investigations	Formation, structure of $U_2Ru_3Si_5$
[1985Cor]	X-ray single crystal four-circle data	Formation, structure of URu_2Si_2
[1985Rau]	XRD, EPMA, electrical resistivity	Formation, structure of URu_3Si_2
[1987Myd]	Menovsky single-crystal growth, XRD, metallography, electron microprobe	Formation, structure of URu_2Si_2
[1987Hie]	Arc melting, XRD	Formation, structure of Ru_2Si_2U
[1993Poe]	X-ray diffraction (XPD), crystal structure investigations	Formation, structure of U_2RuSi_3
[1994Poe]	XPD, X-ray single-crystal four-circle data	Formation, structure of U_2RuSi_3, physical properties
[1994Uga]	XPD	Formation, structure of URuSi, partial isothermal section at 820°C

Reference	Method/Experimental Technique	Temperature/Composition/Phase Range Studied
[1994Ver]	Czochralski single-crystal growth, X-ray single-crystal four-circle data, XPD,	Formation, structure of U_2Ru_3Si, physical properties
[1995Lej]	Czochralski single-crystal growth, Rietveld refinement method, microprobe analysis	Formation, structure of U_2Ru_3Si and $U_6Ru_{16}Si_7$, magnetic properties
[1996Che]	XPD, TEM,SEM	Formation, structure of U_2RuSi_3
[2002Zel]	XPD, Rietveld refinement method, crystal structure investigations	Formation, structure of $U_2Ru_{12}Si_7$

Table 2: Crystallographic Data of Solid Phases

Phase/ Temperature Range [°C]	Pearson Symbol/ Space Group/ Prototype	Lattice Parameters [pm]	Comments/References
(Ru) < 2334	*hP*2 *P*6$_3$/*mmc* Mg	*a* = 270.58 *c* = 428.16	at 25°C [Mas2]
(δSi)	*hP*4 *P*6$_3$/*mmc* αLa	*a* = 380 *c* = 628	at 25°C, 16 GPa ~ 1 atm [Mas2]
(γSi)	*cI*16 *Im*$\overline{3}$*m* γSi	*a* = 663.6	at 25°C, 16 GPa [Mas2]
(βSi)	*tI*4 *I*4$_1$/*amd* βSn	*a* = 468.6 *c* = 258.5	at 25°C, 9.5 GPa [Mas2]
(αSi) < 1414	*cF*8 *Fd*$\overline{3}$*m* C (diamond)	*a* = 543.06	at 25°C [Mas2]
(γU) 1135 - 776	*cI*2 *Im*$\overline{3}$*m* W	*a* = 352.4	[Mas2]
(βU) 776 - 668	*tP*30 *P*4$_2$/*mnm* βU	*a* = 1075.9 *c* = 565.6	[Mas2]
(αU) < 668	*oC*4 *Cmcm* αU	*a* = 285.37 *b* = 586.95 *c* = 495.48	at 25°C [Mas2]
Ru_2Si 1544 - 1240	*oP*12 *Pnma* Co_2Si	*a* = 528.35 *b* = 400.44 *c* = 741.86	[V-C2]
		a = 528.7 ± 0.2 *b* = 400.5 ± 0.1 *c* = 741.3 ± 0.1	[1999Per]

Phase/ Temperature Range [°C]	Pearson Symbol/ Space Group/ Prototype	Lattice Parameters [pm]	Comments/References
Ru_5Si_3 1550 - 1330	*oP*16 *Pbam* Rh_5Ge_3	*a* = 524.57 *b* = 981.90 *c* = 402.36	[V-C2]
Ru_4Si_3 < 1560	*oP*28 *Pnma* Rh_4Si_3	*a* = 1713.43 ± 0.31 *b* = 402.16 ± 0.05 *c* = 519.36 ± 0.09 *a* = 518.7 ± 0.1 *b* = 402.1 ± 0.1 *c* = 1712.8 ± 0.1	[V-C2] [1999Per]
RuSi < 1850	*cP*8 $P2_13$ FeSi or *cP*2 $Pm\overline{3}m$ CsCl	*a* = 470.75 *a* = 470.0 ± 0.1 *a* = 290.73 *a* = 291.0 ± 0.1 *a* = 290.2 ± 0.1	[V-C2] [1999Per] [V-C2] 47.1 at.% Si [1999Per] 48.2 at.% Si [1999Per]
Ru_2Si_3 < 1703	*oP*40 *Pbcn* Ru_2Si_3	*a* = 1106.0 ± 0.2 *b* = 895.2 ± 0.2 *c* = 553.0 ± 0.1 *a* = 1105.2 ± 0.4 *b* = 893.7 ± 0.1 *c* = 552.5 ± 0.1	[V-C2] [1999Per]
$RuSi_2$ < 962	-	-	[2002Iva]
U_2Ru < 937	*mP*12 $P2/m$ or $P2_1/m$	*a* = 1310.6 ± 0.2 *b* = 334.3 ± 0.1 *c* = 520.2 ± 0.1 β = 96.17 ± 0.05	[V-C2]
αURu < 1158	-	-	[Mas2]
βURu < 795	-	-	[Mas2]
U_3Ru_4 < 1148	-	-	[Mas2]
U_3Ru_5 < 1163	-	-	[Mas2]
U_2Ru_3	*cF*120 $Fd\overline{3}m$	*a* = 1289.5 ± 0.1	[V-C2]

Phase/ Temperature Range [°C]	Pearson Symbol/ Space Group/ Prototype	Lattice Parameters [pm]	Comments/References
URu_3 < 1850	*cP*4 $Pm\overline{3}m$ $AuCu_3$	*a* = 398.0	[V-C2]
USi_3 < 1510	*cP*4 $Pm\overline{3}m$ $AuCu_3$	*a* = 403.6 *a* = 403.53	[V-C2] at 78 at.% Si [1992Rem] as cast
USi_2 < 450	*hP*3 *P*6/*mmm* AlB_2	*a* = 402.8 ± 0.1 *c* = 385.2 ± 0.1	[V-C2]
USi_2 metastable	*tI*12 $I4_1/amd$ defect $ThSi_2$	*a* = 399.0 *c* = 1315.0 *a* = 394.06 *c* = 1377.8	[V-C2] [1992Rem] heat treatment 1400°C
$USi_{1.88}$ < 1710	*tI*12 $I4_1/amd$ defect $ThSi_2$	*a* = 394.57 *c* = 1373.9 *a* = 393.78 *c* = 1372.9 *a* = 394.23 *c* = 1371.2	[1992Rem] heat treatment 1400°C [1992Rem] heat treatment 1000°C at 64 at.% Si [1992Rem] heat treatment 1000°C
U_3Si_5 < 1770	*hP*3 *P*6/*mmm* defect AlB_2 distortion AlB_2	*a* = 384.75 *c* = 407.4 *a* = 384.2 *c* = 403.6 *a* = 389.3 *b* = 671.8 *c* = 403.5 *a* = 389.7 *b* = 673.5 *c* = 403.5 *a* = 389.3 *b* = 671.7 *c* = 404.2	at 62.5 at.% Si [1992Rem] heat treatment 1400°C at 62.5 at.% Si [1992Rem] heat treatment 1400°C at 62.5 at.% Si [1992Rem] heat treatment 1000°C at 63.2 at.% Si [1992Rem] heat treatment 1000°C at 63.2 at.% Si [1992Rem] heat treatment 1400°C
USi < 1580	*tI*138 *I*4/*mmm* USi	*a* = 1058.7 *c* = 2431.0	[1992Rem, 1996Bih]
USi (metastable)	*oP*8 *Pnma* FeB	*a* = 758.5 *b* = 390.3 *c* = 566.3	probably impurity (O) stabilized [1992Rem, 1993LeB]

Phase/ Temperature Range [°C]	Pearson Symbol/ Space Group/ Prototype	Lattice Parameters [pm]	Comments/References
U_5Si_4 < 1100	*hP*18 *P6/mmm* U_5Si_4	*a* = 1046.7 *c* = 391.2	Single crystal study [2006Noe]
U_3Si_2 < 1665	*tP*10 *P*4/*mbm* U_3Si_2	*a* = 732.99 *c* = 390.04	[V-C2, Mas2]
γU_3Si 930 - 759	*cP*4 $Pm\bar{3}m$ Cu_3Au	*a* = 434.6	[V-C2, 1965Str]
βU_3Si 762 - –153	*tI*16 *I*4/*mcm* βU_3Si	*a* = 603.28 *c* = 869.07	[V-C2, 1965Str]
αU_3Si < –153°C, at –193°C	*oF*32 *Fmmm* αU_3Si	*a* = 865.4 *b* = 854.9 *c* = 852.3	[V-C2, 1965Str]
* URu_2Si_2	*tI*10 *I*4/*mmm* $ThCr_2Si_2$	*a* = 412.6 ± 0.2 *c* = 956.8 ± 0.4 *a* = 412.6 *c* = 956.8	[V-C2] [1985Cor]
* $U_2Ru_{12}Si_7$	*oP*84 *Pnma* $Mg_2Co_{12}As_7$	*a* = 1116.9 *b* = 398.9 *c* = 2618.5	[2002Zel]
* $U_6Ru_{16}Si_7$	*cF*116 $Fm\bar{3}m$ Th_6Mn_{23}	*a* = 1220.7	[1995Lej]
* U_2RuSi_3	*hP*3 *P*6/*mmm* AlB_2 *hP*3 *P*6/*mmm* U_2RuSi_3	*a* = 407.5 *c* = 383.8 *a* = 814.8 *c* = 385.5	[1993Poe] [1994Poe]
* U_2Ru_3Si	*hR*6 $R\bar{3}m$ $MgCu_2$	*a* = 550.1 *c* = 1136.7	[1994Ver], [1995Lej]
* $U_2Ru_3Si_5$	*mC*40 *C*2/*c* $Lu_2Co_3Si_5$	*a* = 1109.2 *b* = 1176.2 *c* = 570.7	[1977Aks]
* URuSi	*oP*12 *Pnma* TiNiSi	*a* = 637.0 *b* = 399.0 *c* = 725.0	[1994Uga]

Table 3: Investigations of the Ru-Si-U Materials Properties

Reference	Method/Experimental Technique	Type of Property
[2005Ten]	Magnetic measurements under high pressures	Magnetization
[2005Bou]	Magnetic measurements	Neutron-scattering and specific-heat
[2005Ber]	Magnetic measurements	^{29}Si NMR in powdered URu_2Si_2
[2005Beh]	Electrical measurements	Thermal conductivity
[2004Bel]	Electrical measurements	Thermoelectricity
[2004Jai]	Magnetic and electrical measurements	Magnetization and resistivity in continuous and pulsed magnetic fields up to 45 T
[2004Har]	Magnetic and electrical measurements	Magnetization, electrical transport, specific heat
[2003Jai]	Magnetic measurements	Specific heat, magnetocaloric effect
[2003Ami1]	Zero-field μSR technique under hydrostatic pressures	static magnetic order under high pressure
[2003Yok]	Magnetic measurements, elastic neutron scattering	Effects of uniaxial stress on the AF state
[2003Mat]	Magnetic measurements	^{29}Si NMR under pressure.
[2003Sus]	Magnetic measurements	Ultrasonic properties
[2002Jai]	Magnetic measurements	Specific heat, magnetocaloric effect, and magnetoresistance
[2002Tsu]	Magnetic measurements	^{29}Si NMR in powdered URu_2Si_2
[2002Par]	High energy inelastic neutron scattering	Magnetic excitations
[2002Sou]	Magnetic measurements	Ultrasonic properties
[1999Sug]	Magnetic measurements	Magnetization
[1999Ina]	Magnetic and electrical measurements	Electrical resistivity, magnetic susceptibility
[1999Ami]	Elastic neutron-scattering experiments, magnetic measurements	Neutron-scattering at high pressure
[1997Dij]	Elastic and inelastic neutron-scattering measurements	Ordered moment and the magnetic gap
[1996Sak]	Electrical measurements, transport Phenomena	Thermoelectric power
[1995Nai]	Electrical measurements	Electrical resistivity
[1994Bri]	Magnetic and electrical measurements	Specific heat, superconductivity
[1994Esc]	Electrical measurements, point-contact spectroscopy	Spin-density wave behavior
[1994Kin]	Magnetic measurements	Electron spin resonance
[1993Ido]	Electrical measurements	Resistivity at high pressure
[1992Rad]	Magnetic measurements	Magnetic susceptibility

Reference	Method/Experimental Technique	Type of Property
[1992Iki]	Electrical measurements	Electrical resistivity measured up 80 kbar
[1992Bak]	Magnetic measurements, superconductivity	Effect of uniaxial stress on the superconducting and magnetic transition
[1992Has]	Electrical measurements, point-contact measurements	Interplay of superconductivity, magnetic order and magnetic excitations
[1992Uwa]	Magnetic and electrical measurements	Effect of pressure and magnetic field on the electrical resistivity
[1991Ali]	Electrical measurements	Thermal conductivity, electrical resistivity
[1991Roz]	Electronic structure	Positron-Annihilation study of the electronic structure of URu_2Si_2, measurements of the two-dimensional angular correlation of annihilation radiation
[1990Fis]	Magnetic and electrical measurements	Effect of pressure and magnetic field on the magnetic and superconducting transition
[1991Bro]	Neutron scattering measurements	Antiferromagnetic order and fluctuations
[1990Sug]	Magnetic measurements	High-field magnetization, magnetoresistance
[1990Mas]	Magnetic and electrical measurements, neutron scattering measurements	Temperature and magnetic field dependence of the antiferromagnetic Bragg peak
[1989Daw]	Magnetic and electrical measurements	Magnetic susceptibility, transport properties
[1987Myd]	Magnetic and electrical measurements	Magnetization susceptibility, high-field magnetization, thermal expansion, resistivity
[1987Nie]	Magnetic measurements	Crystal-fields calculation
[1987Fra]	Magnetic measurements	Crystal-fields calculation
[1987Hie]	Magnetic measurements	Magnetization
[1987Bro]	Magnetic measurements, neutron scattering experiment	Magnetic excitation, superconductivity
[1987Kay]	Magnetic measurements	Magnetostriction
[1987Onu]	Magnetic and electrical measurements	Electrical resistivity, thermoelectric power, magnetic susceptibility, magnetoresistance under hydrostatic pressure, magnetization
[1986Vis]	Electrical measurements	Thermal expansion
[1986Koh]	Magnetic measurements	Magnetic susceptibility
[1980Bar]	Electrical measurements	Superconductivity

Fig. 1: Ru-Si-U.
Partial isothermal section at 820°C

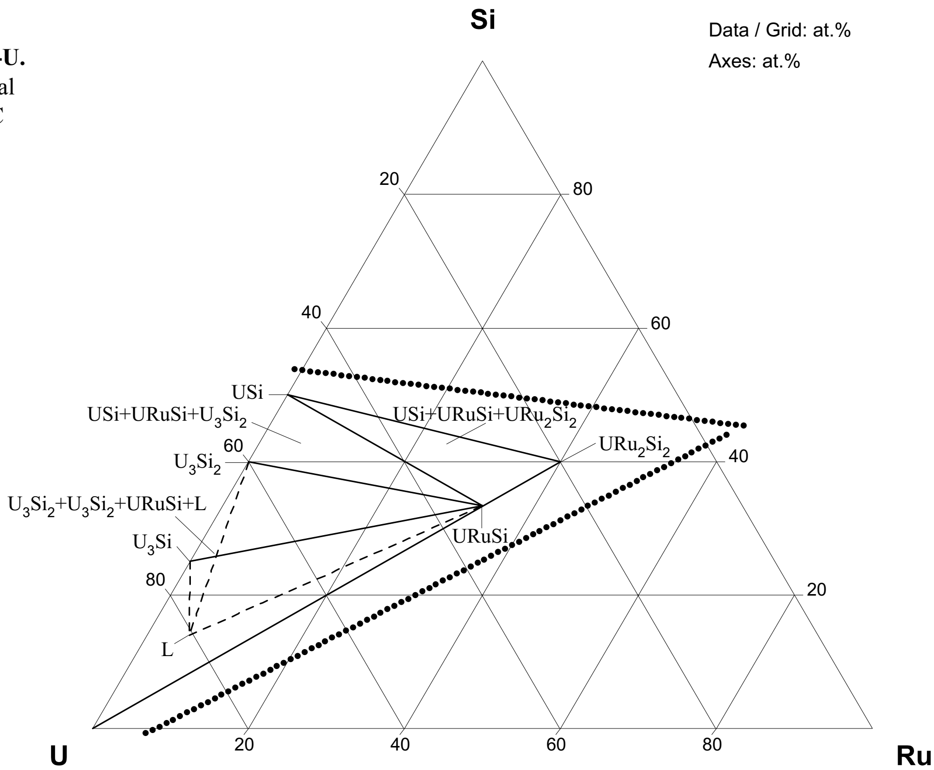

Fig. 2: Ru-Si-U.
Schematic magnetic (B,T) phase diagram of URu_2Si_2 with different magnetically ordered phases. Region I refers to the hidden order phase, while II, III, and V constitute newly discovered phases. Region IV was proposed to be a field-induced recovery of the normal metallic phase

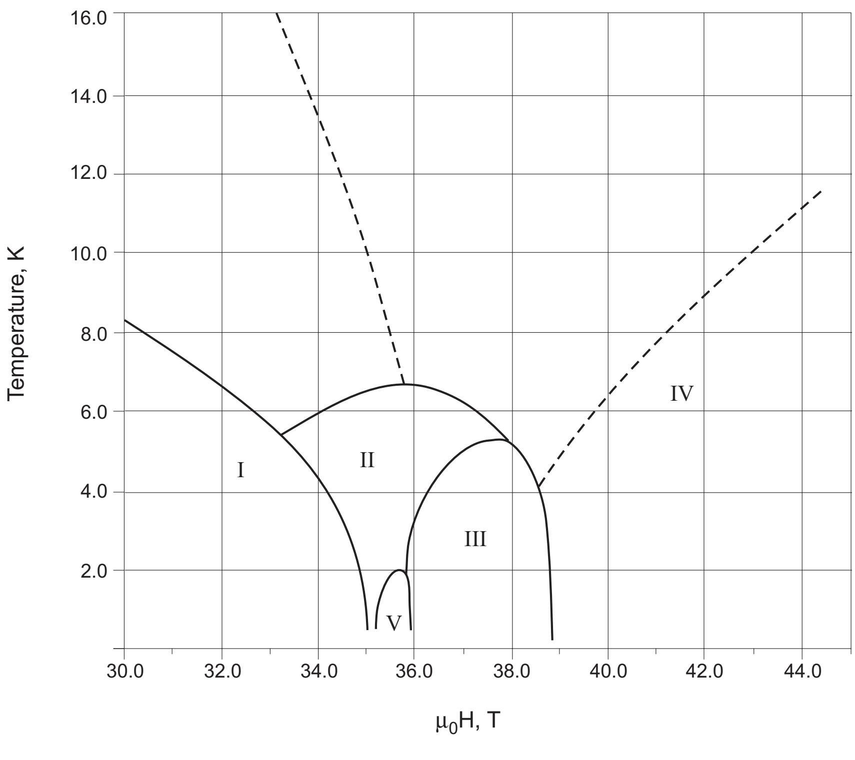

Fig. 3: Ru-Si-U.
p-*T* phase diagram of URu_2Si_2 with magnetic ordered phases:
small-moment antiferromagnetic phase (SMAF) and low temperature antiferromagnetic phase (LMAF)