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Superconductivity

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I. INTRODUCTION

RECENTLY, as a result of the interest in superconductivity there has been a renewed effort in the search for superconductors. The possibility of evaluating current theories, particularly the BCS theory, by observing the systematic occurrence or absence of superconductivity has also contributed greatly to the current interest in superconductivity.

Previous review papers and compilations of superconductors have generally been descriptive in nature and presented very few conclusions. In the present paper, we mention some of the conclusions that we have reached as a result of the occurrence of superconductivity and as a result of recent experiments on the isotope effect in transition metals and compounds.

II. MECHANISMS FOR THE OCCURRENCE OF SUPERCONDUCTIVITY

When the occurrence and behavior of superconductors is systematically investigated, they fall naturally into three different groups—the nontransition elements, the transition elements, and intermetallic compounds. Conclusions drawn from the behavior of one group should not be generalized to include the other two without further consideration.

A. Nontransition Elements

Originally it had been assumed that the electron–phonon interaction described by the theories of Fröhlich,[1] Bardeen[2] and later by the modified BCS[3] theory was the universal cause of superconductivity. One of the most impressive confirmations for this interaction is the isotope effect, according to which the transition temperatures for different isotopes of the same element vary inversely with the square root of the atomic mass:

$$T_c \propto 1/\sqrt{M}$$

The effect was first observed by Reynolds, Serin, and co-workers[4–6] and by Maxwell[7] for the isotopes of Hg. Since then, the isotope shift has been observed for Zn,[8] Cd,[9] Sn,[10–14] Tl,[15,16] and Pb.[14,17–19] This was the first direct proof of a lattice–electron interaction as a mechanism for the occurrence of superconductivity.

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An unnoticed, but important, limitation of the universality of this mechanism was that the isotope effect had been observed only for nontransition elements.

B. Transition Elements

Netzel and Dillinger[20] investigated the superconducting transition temperature of the best available Ti isotopes and found that the temperature varied by a factor of 5. As recognized by the authors, the changes in the transition temperature were probably due to other factors, such as the presence of impurities in the samples, rather than to variations in the isotopic mass.

The next transition elements to be studied for an isotope shift were Ru [21,21a] and Os[8] whose isotopes are readily available and are inert with respect to carbon, oxygen, and nitrogen at elevated temperatures. The latter is an important consideration, since small amounts of these elements dissolved in the isotope could cause shifts in the transition temperature, which would considerably exceed the shift expected from an isotope effect. No isotope effect at all was observed; the accuracy of the experiments is such that any dependence of the transition temperature upon mass would have to be at least an order of magnitude smaller than for the nontransition elements. The absence of an isotope effect in Ru and in Os seems to indicate that the electron–phonon interaction is not the only mechanism for the occurrence of superconductivity.

Several years ago, when the systematic variation of the transition temperature with the number of valence electrons was discovered for the transition elements and compounds, it became clear that there was another mechanism for the occurrence of superconductivity. High transition temperatures always coincided with an odd number of electrons, thus indicating the influence of a net spin and, consequently, a magnetic interaction. This will be discussed later in the paper.

Recent experiments, in which the transition temperature of Ti and of Zr were raised by the addition of magnetic impurities only, point to a spin-exchange interaction mechanism for superconductivity. The experiments of Andres, Olsen, and Rohrer,[22] which show a change in sign for the interaction constant vs volume dependence in going from nontransition elements to transition elements, also indicate the existence of this mechanism. Further evidence that the phonon mechanism is not applicable comes from a consideration of the relationship between the heat capacities and transition temperatures of superconductors in the 3rd, 8th, and 9th columns of the periodic table. For these elements, the transition temperature varies inversely with the electronic heat capacity which is contrary to the behavior expected from the BCS theory.[23] The recent discovery that superconductivity in Mo is suppressed by the presence of few parts per million of Fe may be another indication of this mechanism.

C. Intermetallic Compounds

The results of the isotope effect experiments in intermetallic compounds point to a combination of the two mechanisms mentioned above or possibly to a third mechanism for the occurrence of superconductivity. Devlin and Corenzwit[24] examined the variation of the superconducting transition temperatures of Nb_3Sn, containing different isotopes of Sn, and found that the effect was almost an order of magnitude less than the calculated value based on the $1/\sqrt{M}$ relationship. It was not obvious whether these results obtained by varying the Sn mass were significant, since it could be argued that the superconducting wave functions were associated primarily with the Nb. Therefore, an investigation of the isotope effect in the compound Mo_3Ir was undertaken substituting the various isotopes of Mo.[25] In this way the mass was varied at the sites, where the superconducting wave functions should be at a maximum. The effect observed is intermediate between that of the nontransition elements and that of the Ru and Os. Strangely enough, the isotope effect in the element Mo has the same value namely, $T_c \propto M^{-1/3}$. It seems reasonable, therefore, to assume that there is a mechanism causing superconductivity in compounds and in Mo, which may be intermediate between the electron–phonon interaction for nontransition elements and the spin-exchange mechanism for Ru and Os.

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III. OCCURRENCE OF SUPERCONDUCTIVITY

A. Empirical Rules

While it does not seem possible at present to encompass all superconductors with a unified description or theory, it has been possible to establish empirically the necessary conditions for the occurrence of superconductivity and a criterion for the transition temperatures.[26,27]

If N is defined as the number of valence electrons per atom, counting as such *all* the electrons outside of a filled shell, then superconductivity is found only when N is appreciably greater than 1 or less than 10.[28] Almost all the superconductors known to date follow this rule. In the superconducting range the transition temperature is usually an oscillatory function of N. This applies only to the transition elements. N can be changed continuously by forming solid solutions or intermediate phases of elements within the same group. In contrast to this, solid solutions of nontransition elements in transition elements or vice versa destroy superconductivity rather rapidly. This again is a clear indication of the difference in mechanisms leading to superconductivity.

B. Elements

Elements which have less than two or more than nine valence electrons per atom are not superconducting at the lowest temperatures measured to date. Elements with two valence electrons are borderline cases. The transition temperatures of the transition elements may be represented by an oscillatory function of N:

$$T_c \propto V^x f(N)$$

where T_c varies for the different crystal systems, for the atomic volume, and for the atomic mass. The limitations of this formulation have been discussed previously.[26]

The transition temperatures of the elements have been reviewed by Shoenberg,[29] by Eisenstein,[30] and by Roberts.[31] Recently, Goodman[32] discussed the possible existence of superconducting elements with extremely low transition temperatures.

The transition temperatures of the superconducting elements arranged according to crystal-structure types are given in Table I (references 33 to 78). The

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[26] B. T. Matthias, "Superconductivity in the Periodic System," *Progress in Low-Temperature Physics,* Vol. II, edited by C. J. Gorter (North-Holland Publishing Co., Amsterdam, 1957), p. 138.

[27] B. T. Matthias, Phys. Rev. **97**, 74 (1955).

[28] The earlier formulation of this rule, which stated that superconductivity above 1°K occurs only for $2 \leq N \leq 8$ is essentially correct but must be extended somewhat when temperatures below 1°K are considered.

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TABLE I. Transition temperatures and crystal-structure data of superconducting elements.

	Superconductivity data		Crystal-structure data					
Element	Transition temperature[a] °K	References	Structure type	System	Lattice a, Å	Constants b, Å	c, Å	References
Al	1.171-1.196	33, 34, 35, 36	*A*1–Cu	Cubic	4.0496			37
β-La	5.4-*6.3*	38, 39, 40, 41, c	*A1*–Cu	Cubic	5.296			38
Ir	0.14	42	*A1*–Cu	Cubic	3.8389			37
Pb	7.175-*7.193*-7.23	33, 43, 44	*A1*–Cu	Cubic	4.9502			37
α-Th	1.37	45, 46	*A1*–Cu	Cubic	5.0843			37
V	*5.03*-5.13	33, 47	*A2–W*	Cubic	3.0282			37
Nb	*9.09*-9.465	33, 48, 49	*A2–W*	Cubic	3.3007			37
Mo	0.92	25, 50	*A2–W*	Cubic	3.1468			37
Ta	4.39-*4.482*	33, 51, 52, 53, 54	*A2–W*	Cubic	3.298 3.8389			37
Ti	*0.387*-0.49	55, 56, 57	*A3*–Mg	Hexagonal	2.9504		4.6833	37
Zn	0.825-*0.855*-0.875	8, 33, 58, 59	*A3*–Mg	Hexagonal	2.6649		4.9468	37
Zr	0.546-0.565	57	*A3*–Mg	Hexagonal	3.2312		5.1477	37
Tc	8.22-9.3-11.2	60, 61, b	*A3*–Mg	Hexagonal	2.735		4.388	37
Ru	0.47-*0.493*	21, 62, 63, 64	*A3*–Mg	Hexagonal	2.7058		4.2816	37
Cd	*0.52*-0.602	33, 57, 65	*A3*–Mg	Hexagonal	2.9788		5.6167	37
Hf	0.165	78	*A3*–Mg	Hexagonal	3.1946		5.0511	37
Re	*1.699*-2.42	63, 66, 67	*A3*–Mg	Hexagonal	2.760		4.458	37
Os	0.58-*0.655*-0.71	8, 62, 63, 64	*A3*–Mg	Hexagonal	2.7353		4.3191	37
Tl	2.36-2.39	33, 68	*A3*–Mg	Hexagonal	3.4566		5.5248	37
α-La	4.8-*4.9*-5.0	39, 40, 41, c	*A3′*–La	Hexagonal	3.770		12.159	37
Sn	3.701-*3.722*	33, 52, 69	*A5*–White Sn	Tetragonal	5.8314		3.1814	37
In	3.396-*3.408*	33, 52, 70, 71	*A6*–In	Tetragonal	4.5979		4.9467	37
α-Hg	4.153	68, 72, 73	*A10*–Hg	Rhombohedral	2.9863	$\alpha = 70°44.6'$		37
Ga	*1.087*-1.103	33, 58	*A11*–Ga	Orthorhombic	4.5198	7.6602	4.5258	37
α-U	0.68-0.7	74, 75	*A20*–α–U	Orthorhombic	2.8536	5.8698	4.9555	76
β-Hg	3.949	72, 73		Tetragonal	3.995		2.825	77

[a] In our opinion the italic values of *Tc* appear to be the most reliable.
[b] *Note added in proof.* M. L. Picklesimer and S. T. Sekula [Phys. Rev. Letters **9**, 254 (1962).] recently reported the transition temperature of 99.995% Tc as 8.22°K.
[c] *Note added in proof.* K. Schwidtal, Z. Physik **169**, 564 (1962).

occurrence of superconductivity seems to be most favorable in structure types *A*1, *A*2 and *A*3.

A1–Cu type, face-centered cubic

The fact that Mo became superconducting after purification in an arc furnace[25,50] prompted an investigation of the superconducting properties of Ir treated in a similar manner. Pure Ir is superconducting at the relatively low temperature of 0.14°K,[42] and this indicates that superconducting transition temperatures cannot be predicted from the value of the electronic specific heat. For example, the electronic specific heat[79] γ of Ir is 3.1 mj/mole-deg,[2] and the transition

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temperature[42] is 0.14°K; for Os γ is 2.35,[79] and the transition temperature[8] is 0.655°K; and for Mo γ is 1.91,[80] and the transition temperature is 0.92°K.[25,50]

The superconducting properties of the two forms of La indicate that the cubic close-packed structure is more favorable for the occurrence of superconductivity than the hexagonal close-packed structure. The face-centered cubic form of La has a transition temperature of 6.3°K, whereas that of the hexagonal close-packed form is 4.9°K.[41] Results of an investigation of superconductivity in Os–Ir solid solutions also show that for the same valence-electron concentration the cubic close-packed structure is more favorable than the hexagonal close-packed structure.[81] In both structures, however, the transition temperature is proportional to $1/\gamma$.

The following elements have been investigated for superconductivity and have been found normal at the temperatures given: α-Ca–0.35°K,[82] Co–1.36°K,[83] Ni–0.35°K,[82] Cu–0.05°K,[83] α-Sr–0.35°K,[82] Rh–0.086°K,[85] Pd–0.10°K,[62] Ag–0.35°K,[82] Ce–0.25°K,[62] Yb–0.35°K,[82] Pt–0.10°K,[62] and Au–0.05°K.[83]

A2-W type, body-centered cubic

Most of the nonferromagnetic elements with this structure and with a favorable number of valence electrons are superconducting. Cr, Mo, and W each with six valence electrons are located in a minimum in a plot of the number of valence electrons vs. transition temperature.[27] The superconducting properties of very dilute solutions of Re in Mo suggested that pure Mo would be superconducting and in fact, pure Mo becomes superconducting at about 0.92°K.[25,50] Wolfram can become superconducting if its N is slightly changed; for example a few percent of Rh[27] or of Pt[81] dissolved in it will render the metal superconducting. However, strictly speaking, the superconducting property is associated with the solid solution and not with the element.

The following elements have been investigated for superconductivity and have been found normal at the temperatures given: Na–0.09°K,[62] K–0.08°K,[62] Cr–0.082°K,[85] Fe–0.75°K,[84] Rb–0.8°K,[86] Cs–0.35°K,[82] Ba–0.15°K,[62] and W–0.035°K.[87]

A3-Mg type, close-packed hexagonal

This structure is particularly favorable for the occurrence of superconductivity among the transition elements with $N < 6$. Technetium ($N = 7$) has the highest known transition temperature for an element, namely 11.2°K.[61,87a] For $N < 6$, Ti, Zr and Hf are superconductors. Recently, Hein[78] has determined that various samples of highly purified Hf become superconducting at 0.165°K.

These elements have been investigated for superconductivity and have been found normal at the temperatures given: Li–0.08°K,[62] Be–0.064°K,[85] Mg–0.05°K,[83] Sc–0.08°K,[64] Co–1.36°K,[83] Y–0.07°K,[87] Er–0.8°K,[86] Tm–0.35°K,[82] and Lu–0.35°K.[82]

The occurrence of superconductivity in the elements with $A3'$-, $A4$-, $A7$-, $A8$- and $A12$-type structures has been investigated. Alpha-Pr and α-Nd which crystallize in the hexagonal La-type structure ($A3'$) are not superconducting above 0.25°K.[62] The semiconducting elements Si, Ge, and Sn (grey) have the diamond-type $A4$ structure and are not superconducting above 0.073,[85] 0.05,[83] and 1.32°K,[88] respectively. For the semimetals the rhombohedral As-type structure ($A7$) seems to be unfavorable for the occurrence of superconductivity. Arsenic is normal down to 0.8°K,[86] Sb to 0.152°K[85] and Bi to 0.05°K.[83] Selenium and Te have the trigonal Se-type structure ($A8$) and are normal above 1.26°K.[89] Although cubic α-Mn ($A12$-type structure) is not superconducting above 0.15°K,[62] this structure is a favorable one for the occurrence of superconductivity in transition metal compounds. This is the first example of superconductivity occurring in a structure which lacks a center of symmetry.

The absence of superconductivity in many of the elements investigated may be due to the presence of extremely small amounts of impurities as illustrated by the behavior of Mo. For this reason it is important that further investigations work in the direction of higher purity as well as lower temperatures.

Several elements occur in two modifications, one of which is superconducting. The first one to be dis-

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Conférence de Physique des Basses Températures (Centre de la Recherche Scientifique and UNESCO, Paris, 1956), p. 286.

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[87a] *Note added in proof.* The transition temperature has recently been determined as 8.22°K (see Table I).

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covered was tin. Grey tin, which has the cubic $A4$ diamond-type structure is a semiconductor and does not become superconducting above 1.32°K[88]; whereas white tin with a tetragonal $A5$-type structure is a superconductor. Beryllium and Bi, which are normally nonsuperconductors, become superconducting when condensed as thin films at about 4°K. The transition temperature for Be in this form is 8.0°K,[90,91] and for Bi, 6.0°K.[92,93] It is possible that Mg and Sc might show similar behavior. The transition temperature of thin films of Ga condensed at about 4°K is 8.4°K[94,95] compared with 1.09°K for the usual form of Ga. Two high-pressure superconducting modifications of Bi have been observed. One formed at 25 000 atm has a transition temperature of 3.93°K and the other formed at 25 000 to 29 000 atm has a transition temperature of 7.25°K.[96]

C. Alloys

1. Solid Solutions

Nontransition elements. Representative examples of complete solid solutions between nontransition elements are somewhat limited by the lack of any extended solid solubility between them. For this reason it has not been possible to follow the relationship between the valence–electron concentration and the transition temperature through any maxima or minima, if present, without a change in crystal structure. However, in the systems investigated to date, the transition temperature never changes appreciably with composition.

Superconductivity in the Hg–In system has been investigated by Reeber[71] and by Merriam and Jensen.[97] Reeber restricted the study to solid solutions containing up to 7 at. % In and found that the transition temperature did not vary appreciably with composition. Merriam and Jensen studied superconductivity in the system up to 85 at. % In. The transition temperature ranged from less than 3.2°K for a 20 at. % In alloy to 4.5°K for a 80 at. % In alloy. However, the solid-solution range is not appreciable, and the relative insensitivity of the transition temperature to changes in crystal structure seems remarkable.

Stout and Guttman[98] have investigated the superconducting properties of solid solutions containing up to 50 at. % Tl in the In–Tl system. The transition temperature decreases with increasing amounts of Tl and the transition temperature of the 50 at. % alloy is 2.652°K. The transition temperatures of solid solutions in the Sn–Sb and in the Sn–Bi systems have been studied in the composition range 0 to 8 at. % Sb and 0 to 10 at. % Bi.[99] In both systems the transition temperature increases with increasing values of N and for an alloy containing 10 at. % Bi the transition temperature is 4.18°K.

Shoenberg[100] has summarized much of the data for solid solutions of nontransition elements.

Transition elements. The superconducting properties of solid solutions of transition elements have received considerable attention which is due to the very extensive range of solid solutions formed between these elements. In addition, the transition temperatures of these solid solutions changes appreciably with variations in the valence-electron concentration which is in marked contrast to the effect in nontransition element solid solutions.

Hulm and Blaugher[101] have investigated the superconducting solid solutions of the transition elements. Plots of transition temperature vs composition are given for binary alloys of neighboring elements in a row, for binary alloys of diagonal neighbors, and for alloys of neighbors in columns.

The transition temperature of all superconducting elements may be raised or lowered by solid-solution formation in accordance with the described empirical rules. The transition temperature of Ti is raised by the addition of any transition element to the right of it in the periodic table. Solid solutions of Ti with V,[101,102] Zr,[101] Nb,[101,102] and Mo[103,104] have been investigated. The depression of the transition tempera-

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ture of V by solid-solution formation with Cr,[105] Mn,[105] Fe,[105] Co,[105] Ni,[105] Nb,[101] and Mo[106] is also due to changes in the valence-electron concentration. The addition of almost every transition element to the right of Zr in the periodic table will increase its transition temperature. This has been observed in solid solutions of Zr with Ru,[107] Rh,[27] Pd,[107] Os,[107] Ir,[107] Pt,[107] and even with Au[107] which is a borderline element. The largest increase in the transition temperature occurs in a Zr alloy containing 15 at. % Rh which has a transition temperature of about 9°K.

The transition temperature of Nb is increased by additions of Ti,[101] Zr,[101,108] or Hf.[101] In Nb–Zr solid solutions the maximum transition temperature occurs near 11°K for an alloy containing 20 to 30 at. % Zr.[108] The transition temperature of Nb is lowered by solid-solution formation with any transition element to the right of it in the periodic table. This effect has been reported for solid solutions of Nb with Cr,[101] Mo,[101,109,110] Ta,[101] and W.[101]

The variation of transition temperature with composition for Nb–Mo solid solutions has been investigated to temperatures below 0.25°K. Blaugher and Hulm[101] describe the superconducting behavior down to 1°K; Hulm, Blaugher, Geballe, and Matthias[109] for the temperature range 0.3 to 1.0°K; Hein and co-workers[110] for temperatures below 0.25°K. The depression of the transition temperature for solid solutions containing up to about 42 at. % Mo is roughly proportional to the concentration. The transition temperature vs composition data for alloys containing more than 42 at. % Mo (temperatures below 0.25°K) seemed to indicate that the transition temperature vs composition curve was no longer linear and suggested that the temperature was approaching zero in an asymptotic manner. However, we do not believe that this is valid, since the deviation from linearity begins only at temperatures of the order of the width of the transition itself (< 0.1°K). Inhomogeneities or any deviation from a perfect solid solution would give such an effect. In addition, the effect of magnetic impurities will be appreciable in this temperature range and therefore, the present data should be considered with some caution.

The transition temperature of Mo is raised when any of the elements listed below are dissolved in it:

$$\begin{array}{cccc} \underline{\mathrm{Tc}} & \underline{\mathrm{Ru}} & \mathrm{Rh} & \mathrm{Pd} \\ \underline{\mathrm{Re}} & \underline{\mathrm{Os}} & \underline{\mathrm{Ir}} & \mathrm{Pt}\,. \end{array}$$

The underlined elements are superconducting. The variation of the transition temperature with composition and therefore with N has been studied for the solid solutions Mo–Tc,[60] Mo–Ru,[27,111] Mo–Rh,[112] and Mo–Re.[113] Rather high transition temperatures have been observed for Mo–Re solid solutions; the maximum transition temperature is somewhat above 12°K for an alloy containing 40 at. % Re. In solid solutions of Mo and Rh, in which the maximum solubility is 16 at. % Rh, the transition temperature is 8°K for this concentration.

The transition temperatures of solid solutions of Ru containing 50 at. % Mo or W have been reported as 9.5 to 10.5 and 7.5°K, respectively.[27]

Anderson, Legvold, and Spedding[40] studied the superconducting properties of solid solutions in the La–Y and in the La–Lu systems. In both systems the transition temperature decreases with decreasing amounts of La in the alloys.

Blaugher, Taylor, and Hulm[113] report that the β-Hf region in both the Mo–Hf and Re–Hf systems is superconducting. For Mo–Hf alloys the maximum transition temperature is 2.5°K and in the Re–Hf system an alloy containing 87.5 at. % Hf has a transition temperature of 1.70°K. The variation in the valence-electron concentration accounts for the increase in the transition temperature of Ta by the addition of Hf[101] and for its decrease by the addition of W.[101]

It has been possible to induce superconductivity in an element which is normal in the observable temperature range by the formation of a solid solution. For example, W which is normal down to 0.035°K[87] becomes superconducting when a few percent Pt is dissolved in it.[81] Similarly 30 at. % of W dissolved in Pt will render this element superconducting at 0.40°K. The same elements which raise the transition temperature of Mo should also form superconducting solid solutions with W. The transition temperatures of solid solutions of W–Re,[113] W–Os,[113] and W–Pt[81] have been investigated as a function of composition. The transition temperature of a W solid solution containing 25 at. % Re is about 4.6°K; for a 10 at. % Os

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solid solution it is about 1.5°K; and for 5 at. % Pt it is about 2.2°K.

Solid solutions of V in Re raise the transition temperature of Re rather sharply. For an alloy containing 10 at. % V the transition temperature is 9.4°K.[82] Solid solutions of Hf in Re also show this very remarkable behavior and for a Re solid solution containing 2.5 at. % Hf the transition temperature is 7.3°K.[113] The superconducting properties of Os–Ir solid solutions have been described earlier in the paper.

The superconducting properties of Th–Y solid solutions in the composition range of 0–55 at. % Y have been investigated.[41] There is a maximum in the transition temperature at 1.76°K for an alloy containing 25 at. % Y. At the present time, it is not clear whether this maximum is due to the variation in electron concentration or to the onset of a depression in the transition temperature by a magnetic interaction introduced by Y.

The variation of the transition temperature with composition has been investigated for U–Mo and U–Nb solid solutions.[114–116] Chandrasekhar and Hulm[114] obtained a hypothetical transition temperature of 1.8°K for γ-body-centered cubic U by extrapolating their U–Nb solid solution data. An extrapolation of the data in the orthorhombic α–U region yields a transition temperature of 0.7°K for α–U which agrees reasonably well with the measured value of 0.68°K.[74]

Solid solutions of the ferromagnetic and of the antiferromagnetic elements in Ti,[117] and also to some extent in Zr,[107] raise the transition temperature of Ti and of Zr, respectively. The increase in the transition temperature of Ti by adding small amounts of Cr, Mn, Fe, or Co is larger than that expected solely from a change in the valence–electron concentration. This is seen by comparing the transition temperatures of solid solutions of Ti with elements having a magnetic moment with those of the corresponding solid solutions containing nonmagnetic elements but having the same valence; for example, Ti–Fe vs. Ti–Ru or Ti–Co vs Ti–Rh. The transition temperature vs composition curve for Ti–Fe and for Ti–Ru solid solutions is given in Fig. 1. This is also illustrated by the effect of identical amounts of Fe and of Ru on the transition temperature of a $Ti_{0.60}V_{0.40}$ alloy.[118] The temperature is lowered much less for additions of Fe than for Ru. Therefore, it would seem that the superconductivity of dilute Ti and Zr solid solutions with the magnetic elements is enhanced by some kind of a magnetic interaction.

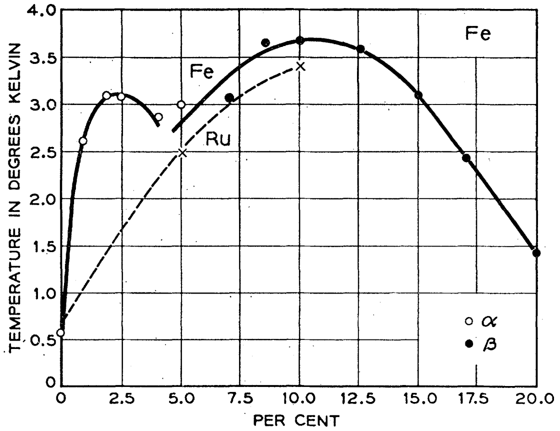

Fig. 1. Superconducting transition temperatures of Fe or Ru solid solutions in Ti.[117]

On the other hand, the transition temperature of a $Mo_{0.80}Re_{0.20}$ solid solution is lowered drastically by the addition of small amounts of metals belonging to the first row of the transition series.[119] For example, the temperature decreases linearly with the concentration of Fe at a rate of 22° per at. % Fe. This lowering of the transition temperature of $Mo_{0.80}Re_{0.20}$ by a $3d$ element is due to a localized magnetic moment and is analogous to the effects produced by the magnetic rare-earth ions in La, which will be described later in the paper. The addition of small amounts of Fe to Nb–Mo solid solutions (containing up to 40 at. % Mo) does not, however, result in any appreciable reduction in the transition temperature indicating that Fe does not exhibit a localized moment in these alloys. However, as the amount of Mo is increased a localized moment appears. Clogston and co-workers[120] have investigated the occurrence of a local magnetic moment of an Fe atom dissolved in transition metal alloys of the entire second-row transition metals. The appearance and disappearance of a localized moment resembles somewhat the variation

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of the transition temperature with valence-electron concentration. However, the maxima for the magnetic-moment plot coincide with the minima for the transition-temperature plot.

An interesting case is the depression of the transition temperature of Ru by the addition of small amounts of Cr, up to 20 at. % Cr, which also seems to be due to a magnetic interaction. For higher concentrations of Cr the magnetic interaction disappears, as had been observed in the Cr–Ir system, and for Ru solid solutions containing more than 30 at. % Cr the variation in transition temperature with composition is in accord with the empirical rules.[111]

The effect of magnetic rare-earth elements on the superconducting transition temperature of La has been investigated in detail.[121,122] The lowering of the transition temperature by the rare-earth element seems to be correlated chiefly with the projection of the spin on the orbit of the solute atoms and not with an increase of the effective moment.[121] The effective magnetic moments and spins of the rare-earth elements follow Van Vleck's[123] well-known curve, given in Fig. 2. The superconducting transition temperatures of solid solutions of La containing 1 at. % of rare-earth element are shown in Fig. 3. It was also concluded from these studies that the depression was essentially symmetrical with respect to Gd. The results of additional studies indicate that a deviation from the symmetrical behavior occurs in La–Nd and in La–Er solid solutions.[122] The transition temperature of La is lowered much more rapidly by Nd than by Er. Both elements have the same spin but the effective magnetic moment of Er is much larger than that of Nd. Here again a larger effective moment increases the transition temperature rather than decreasing it. Theoretical calculations[124–126] which attribute the lowering of the transition temperature by the rare-earth solute to the lowering of the free energy of the normal state by the polarized spins give a reasonable interpretation of the data.

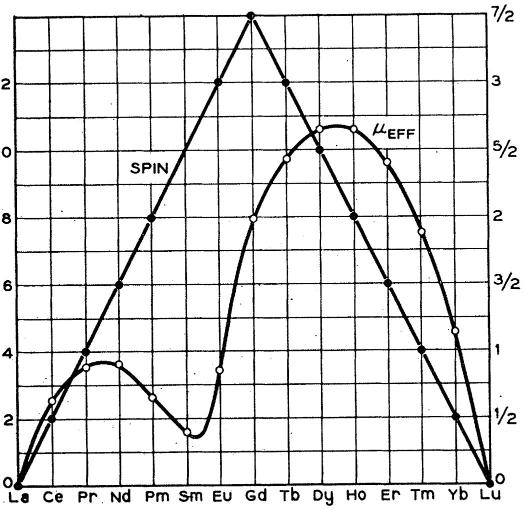

FIG. 2. Effective magnetic moments and spins of the rare earth elements[123].

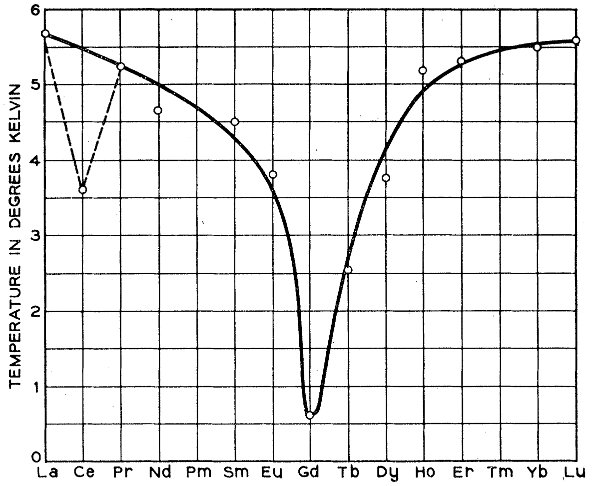

FIG. 3. Superconducting transition temperatures of 1 at. % rare earth solid solutions in La[121].

Transition–nontransition elements. The superconducting transition temperature is always lowered by the formation of solid solutions between transition and nontransition elements, regardless of how N varies. For example, the transition temperature of Nb is increased by solid-solution formation with any transition element with $N < 5$. The addition of Zr ($N = 4$) raises the transition temperature to about 11°K for a solid solution containing 20 to 30 at. % Zr,[108] whereas the addition of Sn ($N = 4$) lowers the transition temperature to 5.6°K for a solid solution containing 8 at. % Sn.[82]

2. Intermediate Phases

Nontransition elements. The variation of transition temperature with composition has been studied for

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alloys in the In–Sn system.[127] The system contains two intermediate phases, β and γ. The β phase has an ideal composition of In_3Sn and exists over a wide range of composition from about 14 to 28 at. % Sn. The hexagonal γ phase, $InSn_4$, has a homogeneity range from about 78–90 at. % Sn. According to the literature the structure of the β phase is still somewhat uncertain. A maximum in the transition temperature occurs at 7.30°K for the β alloy $In_{0.70}Sn_{0.30}$. This composition corresponds to a valence-electron-per-atom ratio of 3.3. Meissner[128] reports that $In_{0.75}Sn_{0.25}$ has a transition temperature of 5.5°K.

According to the results of Merriam and Jensen,[97] it would seem that the valence-electron concentration is relatively unimportant in determining the occurrence of superconductivity in alloys of nontransition elements. Superconductivity will always occur, regardless of crystal structure and composition, whenever the valence-electron concentration is considerably greater than one.

Transition elements. The occurrence of superconductivity in intermediate phases between transition elements is in accordance with the empirical rules stated previously. Superconducting intermediate phases of Cr with Rh and with Ir have been reported.[111] In both systems the two cubic elements form a superconducting hexagonal close-packed alloy which has a homogeneity range. The maximum transition temperature for the Cr–Rh intermediate phase is 1.1°K for a $Cr_{0.70}Rh_{0.30}$ alloy (6.9 valence electrons) and also for a $Cr_{0.75}Rh_{0.25}$ alloy (6.75 valence electrons); for the Cr–Ir phase, it is 0.83°K for a $Cr_{0.72}Ir_{0.28}$ alloy (6.84 valence electrons).

The hexagonal close-packed intermediate phases in the Mo–Rh,[27] Mo–Pd,[82] Mo–Ir,[25] and W–Rh[27] systems are superconducting. The transition temperature for a $Mo_{0.50}Rh_{0.50}$ alloy is 1.97°K; for a $Mo_{0.50}Pd_{0.50}$, 3.52°K; $Mo_{0.60}Ir_{0.40}$, 8.4°K and for $W_{0.50}Rh_{0.50}$, 2.64°–3.37°K.

Blaugher, Taylor, and Hulm[113] report that a Re alloy containing 33 at. % Hf, which is in the hexagonal region of the phase diagram, has a transition temperature of 5.61°K.

3. Compounds

The influence of crystal structure on superconductivity is more pronounced in compounds than in solid solutions or in intermediate phases, particularly if the compound contains at least one transition element. The crystal structures which are particularly favorable for superconductivity include the cubic β–W type structure ($A15$), the cubic NaCl type ($B1$) and the cubic $MgCu_2$ type ($C15$). With the exception of NbC and NbN, which have the $B1$ type structure, most of the high-temperature superconductors have the β–W type structure. However, not all cubic crystal structures are favorable; for example, the CsCl-type structure ($B2$) has been shown to be one of the least favorable.

To date only one superconductor has been found in the trigonal system, $PdTe_2$,[129] and only one in the monoclinic system, α-Bi_2Pd.[130–134] The occurrence of superconductivity in orthorhombic compounds is not too common—only thirteen have been reported to date.

In order to facilitate the discussion of the superconducting behavior of compounds, they have been arranged and tabulated according to their crystal-structure types. Both superconductors and nonsuperconductors whose crystal structures have been identified are included. In addition to the compounds reported in the literature, the results of our recent investigations of the occurrence of superconductivity in compounds particularly in the temperature range of 0.35 to 1.0°K are also given. The crystal structures of these compounds were identified from x-ray diffraction powder photographs and the observed intensities were compared with those published or with those calculated from the published structural data.

Several new compounds were discovered in the course of our studies. These include $ScAl_2$, VZn_3, ZrCuAl,[135] Zr_3Au, Zr_3Pb, and NbVCo. $ScAl_2$, ZrCuAl, and Zr_3Au were prepared by reacting appropriate amounts of the elements in an arc furnace; Zr_3Pb and NbVCo by reacting the elements in an arc furnace followed by annealing at about 900°C; and VZn_3 by reacting the elements in a quartz tube at 900°C. Both $ScAl_2$ and ZrCuAl have the cubic $MgCu_2$-type structure ($C15$) and neither is superconducting above 1.02°K; VZn_3 has the cubic Cu_3Au-type structure (Ll_2) and is not superconducting above 1.02°K; Zr_3Au has the tetragonal sigma phase-type structure ($D8_b$) and is not superconducting above 1.02°K; and Zr_3Pb

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[135] E. A. Wood suggested the preparation of this compound and correctly predicted that it would have the C15 type structure.

has the cubic β–W type structure (A15) and is superconducting at 0.76°K. The sigma phase Zr_3Au compound has the cubic β–W type structure (A15), as reported[136,137] after an anneal at 900°C and has a transition temperature of 0.91°K. NbVCo has the hexagonal $MgZn_2$-type structure (C14) and is not superconducting above 1.02°K.

TABLE II. Superconductivity and crystal-structure data for compounds with the A2-type structure.

	Superconductivity data			Crystal-structure data	
Compound	T_c^a °K	T_n^b °K	References	Lattice constants a,Å	References
TiFe		0.30	82	2.973	37,82,138
TiCo	0.71		82	2.99	37,82,138
TiNi		1.02	82	3.02	37,82,138

[a] Superconducting transition temperature.
[b] The compound exhibited no superconductivity above this temperature.

A2, W-type, body-centered cubic. The superconductivity and crystal structure data for TiFe, TiCo and TiNi which have a disordered body-centered cubic, W type, structure are given in Table II (references 37, 82, and 138). Of these only TiCo is superconducting and has a transition temperature of 0.71°K.

A12, α–Mn-type, body-centered cubic. This is considered a favorable structure for the occurrence of superconductivity in transition metal compounds since all the A12-type binary compounds with suitable valence-electron concentrations, investigated to date, are superconducting. These include compounds of Tc with Zr and with Nb, compounds of Pd with Nb, compounds of Re with Ti, Zr, Nb, Mo, Hf, Ta, and W, and compounds of Os with Nb and with Ta. The transition temperatures of compounds in this structure type range from 1.58°K for $Ta_{0.35}Re_{0.65}$ to 10.5°K for $NbTc_3$. The superconductivity and crystal structure data are given in Table III (references 60, 82, 113, and 139–143).

A15, β–W type, cubic. This is by far the most favorable crystal structure for the occurrence of superconductivity not only because of the large number of A15 type superconducting compounds, but also because the transition temperatures of many of the compounds are above 10°K. The compound Nb_3Sn which has the highest transition temperature known, 18.05°K, crystallizes in this structure.

The formation of solid solutions between superconducting compounds with this structure always results in a lowering of the transition temperature of the compound with the higher temperature. For example, V_3Si and V_3Ga are superconducting at 17.1 and 16.5°K, respectively, and yet the transition temperature of $V_3(Si_{.5}Ga_{0.5})$ is 8.6 to 11.9°K.[82] This effect also occurs in solid solutions of Nb_3Al and Nb_3Sn whose transition temperatures are 17.5 and 18.05°K, respectively. A solid solution with the composition $Nb_3(Al_{0.5}Sn_{0.5})$ has a transition temperature of 16.3°K.[82] The transition temperature of Nb_3Sn is lowered by the formation of solid solutions with V_3Sn,[144] with V_3Sn–Ta_3Sn,[144] with Nb_3Ga,[82] and with

TABLE III. Superconductivity and crystal-structure data for compounds with A 12-type structure.

	Superconductivity data			Crystal-structure data	
Compound	T_c °K	T_n °K	References	Lattice constants a,Å	References
Mg_3Al_2		0.35	82	10.55	82,139
Ti_5Re_{24}	6.6		140	9.587	140
$Ti_{0.17}Re_{0.83}$	5.1		141	9.595	141
$V_3Fe_5Si_2$		0.37	82	8.851	82,142
$V_{2.8}Co_{5.2}Si_2$		1.02	82	8.774	82,142
$V_3Ni_5Ge_2$		0.35	82	8.928	82,142
$ZrTc_6$	9.7		60	9.636	60
$ZrRe_6$	7.4		140	9.698	140
$NbTc_3$	10.5		60	9.625	60
$Nb_{0.60}Pd_{0.40}$	2.04-2.47		141	9.77	141
$Nb_{0.40}Re_{0.60}$	2.36		141	9.781	141
$Nb_{0.18}Re_{0.82}$	9.7; 8.89		140; 143	9.641	140; 143
NbOs	2.86		141	9.760	141
$NbOs_2$	2.52		140	9.655	140
$MoRe_3$	9.26		143		143
$Hf_{0.50}Re_{0.50}$		1.02	113		113
$Hf_{0.14}Re_{0.86}$	5.86		113		113
$Ta_{0.36}Re_{0.64}$	1.46		140	9.765	140
$Ta_{0.35}Re_{0.65}$	1.58		141	9.762	141
$TaRe_3$	6.78		143		143
TaOs	1.95		140	9.773	140
WRe_3	9.00		143		143

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Ta_3Sn.[144–146] Recently, the superconducting behavior of the binary systems Nb_3Al–Nb_3Sb[147] and Nb_3Sn–Nb_3Sb[148] has been studied as a function of composition.

In addition, it has not been possible to raise the transition temperature of an *A*15-type superconductor by the addition of other elements. For example, Hardy and Hulm[149] found that the transition temperature of V_3Si was always lowered when part of the V or Si was replaced by other elements.[149a]

The superconductivity and crystal-structure data for *A*15 structure-type compounds are given in Table IV (references 25, 27, 82, 111, 112, 136, 137, 140, 141, 144, and 149–163).

B1, NaCl type, face-centered cubic. The only superconducting compounds with this type structure are the interstitial carbides and nitrides. Giorgi and coworkers[164] studied the transition temperatures of NbC and TaC as a function of composition and found that the highest temperature is reached for the stoichiometric compositions. In the case of NbC the composition ranged from $NbC_{0.977}$ which has a transition temperature of 11.1°K to $NbC_{0.70}$ which is not superconducting above 1.05°K. For TaC the composition ranged from $TaC_{0.987}$ with a transition temperature of 9.7°K to $TaC_{0.754}$ which is not superconducting above 1.05°K. Rögener[165] investigated the transition temperature of NbN as a function of composition and reported that $NbN_{0.96}$ has a transition temperature of 15.63°K.

The face-centered cubic carbides of Ti, V, and Zr, which are normal down to 1.20°K, will form superconducting solid solutions with hexagonal MoC. The transition temperature of NbC is also raised to 12.50°K by solid-solution formation with MoC.[112] The transition temperatures of the *B*1-type solid solutions are:

$(TiC)_{0.17}(MoC)_{0.83}$	10.20°K
$(VC)_{0.20}(MoC)_{0.80}$	9.30
$(ZrC)_{0.17}(MoC)_{0.83}$	9.50

TABLE IV. Superconductivity and crystal-structure data for compounds with *A*15-type structure.

	Superconductivity data			Crystal-structure data	
Compound	T_c °K	T_n °K	References	Lattice constants *a*,Å	References
Ti_3Sb	5.8		140	5.217	140
Ti_3Ir	5.4		140	5.009	140
Ti_3Pt	0.58		82	5.032	82,150
Ti_3Au		1.20	149		149
V_3Si	17.1		149	4.722	149
V_3Co		0.35	82	4.684	82,151
V_3Ga	16.5		112,152	4.816	152
V_3Ge	6.01		149		149
V_3As		1.02	112	4.74	112
V_3Rh	0.38		82	4.784	82,153
V_3Sn	7.0		154	4.94	154
	3.8		144	4.96	144
V_3Sb	0.80		82	4.941	82,136,152
V_3Ir		0.35	82	4.786	82,136,163
$(V_{2.67}Ir_{0.33})Ir$	1.39		140	4.794	140
V_3Pt	2.83		140	4.814	140
V_3Au	0.74		82	4.883	82,155
Cr_3Si		1.20	149		149
Cr_3Ga		0.35	82	4.645	82,152
Cr_3Ge		1.20	149		149
Cr_3Ru	3.3		111		111
Cr_3Rh		0.30	111		111
$Cr_{0.85}Ir_{0.15}$	0.77		111		111
Cr_3Pt		0.30	111		111
Zr_3Au	0.92		82	5.483	82,136,137
Zr_3Pb	0.76		82	5.656	82
Nb_3Al	17.5		152	5.187	152
	16.8–18.0		156, a		156, a
Nb_3Ga	14.5		152	5.171	152
Nb_3Ge	6.90		82	5.166	82,136,157
Nb_3Rh	2.50		112	5.115	112
Nb_3In	9.2		158	5.303	158
Nb_3Sn	18.05		159,160	5.289	154
Nb_3Sb		1.02	112,152	5.262	152
Nb_3Os	1.05		112	5.121	154
Nb_3Pt	9.2		154	5.153	154
Nb_3Ir	1.7		154	5.131	154
Nb_3Au	11.5		155	5.21	155
Mo_3Al	0.58		82	4.950	82,152
Mo_3Si	1.30		149		149
Mo_3Ga	0.76		82	4.943	82,152
Mo_3Ge	1.43		149		149
Mo_3Os	7.2		27		27
Mo_3Ir	8.35; 8.8		25; 27	4.974	82,161,162
$Mo_{0.74}Ir_{0.26}$	9.05		141	4.972	141
Ta_3Sn	6.0		154,159	5.276	154
	6.4		144	5.278	144

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The transition temperature of NbN is raised by the formation of a solid solution with NbC and a transition temperature of 17.8°K is reported for NbN containing 25 to 30 at. % NbC.[108]

Hardy and Hulm[149] studied the effect of oxygen on the transition temperatures of Ti, V, and Zr nitrides and found that the transition of TiN and VN are affected by the presence of oxygen in the sample, whereas that of ZrN is not. Schröder[166] also found that oxygen lowered the transition temperature of NbN and reported that Nb(N + O)$_{0.97}$ has a transition temperature of 7.66°K.

The superconductivity and crystal-structure data for $B1$-type compounds are listed in Table V (references 82, 149, 164, 165, and 167–176).

Table V. Superconductivity and crystal-structure data for compounds with $B1$-type structure.

	Superconductivity data			Crystal-structure data	
Compound	T_c °K	T_n °K	References	Lattice constants a,Å	References
ScN		1.40	167	4.45	167
TiC		1.20	149		149
TiN	5.6; 4.86		149; 168		149;168
TiO		1.20	149		149
VC		1.20	149		149
VN	8.2; 7.5		149;168		149;168
VO		1.20	149		149
CrN		1.28	168		168
YSb		1.02	82	6.161	82,169
YTe		1.02	82	6.120	82,169
ZrC		1.20	149		149
ZrN	8.9; 9.05		149;168		168
	10.7		176		[a]
NbC$_{0.977}$	11.1		164		164
NbC	6.0; 10.3		149;170	4.40	170
NbN$_{0.96}$	15.63		165	4.377-4.381	165
NbN	14.7; 16.0		168;171	4.38	171
NbO		1.20	149		149
LaN$_{0.99}$		1.8	172	5.295	172
LaSb		1.02	82	6.498	82,173
CeBi		1.28	168	6.487	174
PrBi		[b]	174	6.448	174
HfN	6.2		176		[a]
TaC$_{0.987}$	9.7		164		164
TaC	2.40-3.55		175	4.455	175
UC		1.20	149	4.952	149
UN		1.20	149		149

[a] See section on superconducting compounds of unknown structure.
[b] Not stated.

B2, CsCl type, cubic. Superconductivity and crystal structure data for compounds with this type structure are given in Table VI (references 37, 82, 140, and 177–181). Only TiRu and TiOs are superconducting at 1.07 and 0.46°K, respectively.[181a] This structure is considered to be one of the least favorable for the occurrence of superconductivity.

Table VI. Superconductivity and crystal-structure data for compounds with $B2$-type structure.

	Superconductivity data			Crystal-structure data	
Compound	T_c °K	T_n °K	References	Lattice constants a,Å	References
MgRh		1.02	177	3.099	178
MgAg		1.02	82	3.31	37,82,179
MgAu		0.35	82	3.252	37,82
AlOs	0.39		82		140
ScRh		1.02	177	3.206	178
ScPt		1.02	140		140
TiRu	1.07		82	3.067	82,180
TiOs	0.46		82	3.077	82,180
VOs$_{0.40}$		0.37	82		140
HfRu		1.02	82	3.22	82,181

$B8_1$, NiAs type, hexagonal. Most NiAs type compounds that have favorable valence-electron concentrations and are not ferromagnetic are superconducting. The data for $B8_1$-type compounds are given in Table VII (references 37, 82, 108, 130, 168, 174, and 182–189).

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[181a] *Note added in proof.* Recently, we have found that AlOs is superconducting at 0.39°K.

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B10,PbO type, tetragonal. Jones and Ittner[190] report that BiIn which has this type structure is not superconducting above 1.55°K.

B11,γ-CuTi type, tetragonal. γ CuTi is not superconducting above 1.02°K.[82]

TABLE VII. Superconductivity and crystal-structure data for compounds with $B8_1$-type structure.

	Superconductivity data			Crystal-structure data		
				Lattice constants		
Compound	T_c °K	T_n °K	References	a,Å	c,Å	References
CrSb		1.00	108			108
MnSb		1.00	108			108
MnBi		1.28	168			168
CoTe		1.00	108			108
NiSb		0.35	82	3.942[a]	5.155[a]	37,82
NiTe		1.00	108			108
NiBi	4.25		130	4.070	5.35	174
RhTe		1.06	182	3.99	5.66	183
RhBi	2.06		130,184	4.094	5.663	184
$(Pd_{0\ 75}Ni_{0.25})As$	1.6		185	3.66	5.03	186
PdSb	1.5		108,187			108,187
PdTe	2.3		108,187			108,187
IrTe		0.35	82	3.930[a]	5.386[a]	82,188
PtSb	2.1		108,187			108,187
PtBi	1.21		187,189	4.315	5.49	174
	2.4		174	4.20	5.55	174

[a] Powder patterns in present investigation were indexed based on these reported lattice constants.

B18,CuS type, hexagonal. The compounds CuS and CuSe crystallize in this structure type, and their superconducting properties have been investigated. CuS is superconducting at 1.66°K,[191] and CuSe is not superconducting above 1.28°K.[168]

B20,FeSi type, cubic. The only superconducting compound with this type structure is AuBe. A number of other compounds with favorable valence-electron concentrations are not superconducting in the temperature range measured. The data for $B20$-type compounds are given in Table VIII (references 82, 149, and 192–195).

B31,MnP type, orthorhombic. This structure is a distortion of the NiAs-type structure ($B8_1$) and seems to be favorable for the occurrence of superconductivity. The superconductivity and crystal-structure data for $B31$-type compounds are listed in Table IX (references 82, 108, 187, 194, 197, and 198). Three superconducting compounds are known, namely, PdSi, IrGe, and PtSi.[198a] Since both RhGe and IrGe have the same number of valence electrons, the difference in their superconducting behavior is somewhat surprising; RhGe is not superconducting above 1.00°K,[196] and IrGe is superconducting at 4.7°K. This was another indication that the assignment of the same number of valence electrons to all the elements in the same column of the periodic system was an oversimplification. In general, the number of valence electrons for the 5*d* elements seems to be shifted somewhat to the right with respect to the corresponding 4*d* elements.

TABLE VIII. Superconductivity and crystal-structure data for compounds with $B20$-type structure.

	Superconductivity data			Crystal-structure data	
Compound	T_c °K	T_n °K	References	Lattice constants a,Å	References
CrGe		1.20	149		149
RhSi		0.35	82	4.673	82,192
Pd_4Al_3Si		1.02	82	4.840	82,193
OsSi		0.60	82	4.728	82,194
AuBe	2.64		195		195

TABLE IX. Superconductivity and crystal-structure data for compounds with $B31$-type structure.

	Superconductivity data			Crystal-structure data			
				Lattice constants			
Compound	T_c °K	T_n °K	References	a,Å	b,Å	c,Å	References
RhGe		0.96	82	5.70[a]	6.48[a]	3.25[a]	82,197
RhSb		0.35	82	6.340[a]	5.955[a]	3.876[a]	82,198
PdSi	0.93		82	6.133[a]	5.599[a]	3.381[a]	82,198
PdGe		0.35	82	6.259[a]	5.782[a]	3.481[a]	82,198
IrSi		1.02	82	5.558[a]	3.211[a]	6.273[a]	82,194
IrGe	4.7		108,187				108,187
PtSi	0.88		82	5.932[a]	5.595[a]	3.603[a]	82,198
PtGe	0.40		82	6.088[a]	5.733[a]	3.701[a]	82,198
AuGa		1.02	82	6.397[a]	6.266[a]	3.421[a]	82,198

[a] Powder patterns in present investigation were indexed based on these reported lattice constants.

B_f, ζ-CrB type, orthorhombic. The B_f-type compound NbB is the only reported superconductor with this structure. The data are given in Table X (references 149 and 168).

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[197] S. Geller, Acta Cryst. **8**, 15 (1955).

[198] H. Pfisterer and K. Schubert, Z. Metallk. **41**, 358 (1950).

[198a] *Note added in proof.* RhGe and PtGe are also superconducting at 0.96 and 0.40k, respectively.

B_g, MoB type, tetragonal. MoB and WB crystallize in this type structure and are not superconducting above 1.28°K.[168]

B_h, WC type, hexagonal. MoP and WC are not superconducting above 1.03[185] and 1.28°K,[168] respectively.

Table X. Superconductivity and crystal-structure data for compounds with B_f-type structure.

	Superconductivity data			Crystal-structure data			
Compound	T_c °K	T_n °K	References	Lattice constants a,Å	b,Å	c,Å	References
VB		1.20	149	3.058	8.026	2.971	149
CrB		1.28	168				168
NbB	8.25		168				168
MoB		1.28	168				168
TaB		1.28	168				168

B_i, γ′-MoC type, hexagonal. Schröder[166] found that NbN remained normal down to 1.94°K. The lattice constants of the sample were $a = 2.950$ Å and $c = 11.252$ Å.

C1, CaF_2 type, face-centered cubic. $CoSi_2$ is the only superconductor reported and has a transition temperature of 1.22°K. The data for C1-type compounds investigated for superconductivity are given in Table XI (references 108, 185, and 199).

$C1_b$, MgAgAs *type, face-centered cubic.* Matthias and Hulm[168] report that CuMgBi which crystallizes in this structure is not superconducting above 1.28°K.

Table XI. Superconductivity and crystal-structure data for compounds with C1-type structure.

	Superconductivity data			Crystal-structure data	
Compound	T_c °K	T_n °K	References	Lattice constants a,Å	References
$CoSi_2$	1.22		199		199
$NiSi_2$		1.00	108		108
Rh_2P		1.03	185		185
$PtAl_2$		1.00	108		108
$AuAl_2$		1.00	108		108

C2, FeS_2 type, cubic. The superconductivity and crystal structure data for C2-type compounds are given in Table XII (references 27, 82, 174, 183, 185, 186, 188, 189, and 200–202). A number of the compounds have a wide homogeneity range. Superconductivity occurs both in compounds with the ideal composition and also in those which deviate from the ideal 1:2 stoichiometry.

Table XII. Superconductivity and crystal-structure data for compounds with C2-type structure.

	Superconductivity data			Crystal-structure data	
Compound	T_c °K	T_n °K	References	Lattice constants a,Å	References
$RhSe_{1.75}$	6.0		27,185	6.015	27,200
α-$RhTe_2$	1.51		27,185	6.441	183
$(Pd_{0.88}Ni_{0.12})As$	1.39		186		186
$(Pd_{0.75}Ni_{0.25})As$	1.34		186		186
$PdSb_2$	1.25		82	6.459	82,201
$IrTe_{2.67}$		0.35	82	6.410	82,188
α-$PtBi_2$		a	174,189	6.683	174
$AuSb_2$	0.58		82	6.658	82,202

[a] Not stated.

C6, CdI_2 type, trigonal. Recently, Guggenheim, Hulliger and Müller[129] investigated the superconducting properties of some C6-type compounds and reported that $PdTe_2$ is superconducting. This is the only superconductor with this type structure reported to date. The compound has a homogeneity range from $PdTe_2$ to $Pd_{1.75}Te_2$ and the corresponding transition temperatures are 1.53 and 2.25°K, respectively. Mixed crystals of $PdTe_2$ containing small amounts of Ni or Rh or Pt are also superconducting. The compound PdSeTe which crystallizes in this structure is not superconducting above 1.2°K.

The data for C6-type compounds are given in Table XIII (references 129, 182, and 183).

Table XIII. Superconductivity and crystal-structure data for compounds with C6-type structure.

	Superconductivity data			Crystal-structure data		
Compound	T_c °K	T_n °K	References	Lattice constants a,Å	c,Å	References
$NiTe_2$		1.2	129			129
β-$RhTe_2$		1.06	182	3.92	5.41	183
$PdTe_2$	1.53		129			129
$PtTe_2$		1.2	129			129

C11b, $MoSi_2$ type, body-centered tetragonal. Hardy and Hulm[149] report that β–$MoGe_2$ is not superconducting above 1.20°K.

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[199] B. T. Matthias and J. K. Hulm, Phys. Rev. **89**, 439 (1953).

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[201] L. Thomassen, Z. Phys. Chem. **135**, 383 (1928).

[202] O. Nial, A. Almin, and A. Westgren, Z. Phys. Chem. **B14**, 81 (1931).

C14, $MgZn_2$ type, hexagonal (Laves Phase). This structure is favorable for the occurrence of superconductivity. In addition, ferromagnetism also occurs in the $C14$ rare-earth Laves phases in which the rare-earth atom contains $4f$ electrons.[203] Solid solutions between $C14$-type rare-earth compounds with $4f$ electrons and those without $4f$ electrons are both superconducting and ferromagnetic simultaneously. Superconductivity and ferromagnetism have been studied in the YOs_2–$GdOs_2$ system for compositions containing up to 14 at. % $GdOs_2$ in YOs_2.[118]

The superconductivity and crystal structure data are given in Table XIV (references 82, 121, 140, and 203–208).

C15, $MgCu_2$ type, cubic (Laves Phase). Since many compounds with this type structure are superconducting, it is considered a very favorable one. The data for $C15$-type compounds are given in Table XV (references 37, 82, 113, 114, 121, 140, 174, 203, 207, and 212–229).

TABLE XIV. Superconductivity and crystal-structure data for compounds with $C14$-type structure.

	Superconductivity data			Crystal-structure data		
				Lattice constants		
Compound	T_c °K	T_n °K	References	a,Å	c,Å	References
$CaMg_2$		1.02	82	6.23[a]	10.12[a]	82,204
$ScRu_2$	1.67		121,203	5.119	8.542	203
$ScOs_2$	4.6		203	5.179	8.484	203
$TiZn_2$		1.02	82	5.064[a]	8.210[a]	82,205
YRu_2	1.52		203	5.256	8.792	203
YRe_2	1.83		203	5.396	8.819	203
YOs_2	4.7		203	5.307	8.786	203
$ZrAl_2$	0.30[b]		82	5.282[a]	8.748[a]	82,206
$ZrCr_2$		0.35	82	5.102[a]	8.239[a]	82,207
Zr_2VCo_3		0.35	82	4.982	8.114	82,207
$ZrRu_2$	1.84		140	5.144	8.504	140
$ZrRe_2$	6.8		82	5.262[a]	8.593[a]	82,208
$ZrOs_2$	3.00		140	5.219	8.538	140
NbVCo		1.02	82	4.928	8.008	82
$LuRu_2$	0.86		82	5.204	8.725	203
$LuOs_2$	3.49		203	5.254	8.661	203
$HfRe_2$	4.8		203	5.239	8.584	203
$HfOs_2$	2.69		203	5.184	8.468	203

[a] Powder patterns in present investigation were indexed based on these reported lattice constants.
[b] Beginning of transition.

The simultaneous occurrence of superconductivity and ferromagnetism was investigated by solid-solution formation between a superconducting Laves phase and a ferromagnetic one. The rare-earth systems which have been studied in this respect include the $CeRu_2$–$PrRu_2$ and $CeRu_2$–$GdRu_2$ $C15$-type solid solutions[209,210] and the $C15$–$C14$-type $LaOs_2$–$GdOs_2$ solid solutions.[210] These phenomena have also been investigated in the $ThRu_2$–$GdRu_2$ solid solutions.[211]

$CeRu_2$ is the only known superconductor which contains a rare-earth element that usually has $4f$ electrons. However, based on the lattice constant of this compound, it was concluded that most of the $4f$ electrons have been squeezed into the outer s and d shells.[121]

C15$_b$, $AuBe_5$ type, face-centered cubic. No superconducting compounds with this type structure have been reported. The compounds which have been investigated are listed in Table XVI (references 82, 230–232).

C16, $CuAl_2$ type, body-centered tetragonal. The transition temperatures of the isomorphous series of Th compounds with Cu, Ag, and Au indicated, as stated earlier, that the assignment of the same number of valence electrons to all the elements in the same column should be considered as a rough approximation. Since $AgTh_2$ has the optimum volume/mass ratio, it should have the highest transition

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temperature. Actually its transition temperature is lower than that of $CuTh_2$ and that of $AuTh_2$, and this would seem to indicate that the number of valence electrons in Ag is either more or less than that in Cu or Au. Copper, Ag, and Au nominally contribute one electron/atom when the *d* band is full.

TABLE XV. Superconductivity and crystal-structure data for compounds with *C*15-type structure.

	Superconductivity data			Crystal-structure data	
Compound	T_c °K	T_n °K	References	Lattice constants a,Å	References
$NaAu_2$		1.02	82	7.814	82,212,213
$MgCu_2$		1.02	82	7.034	37,82,214
KBi_2	3.57		215	9.501	174,216
$CaAl_2$		1.02	82	8.035	82,217
$CaRh_2$	6.4		218	7.525	219
$CaPd_2$		1.02	218	7.665	219
$CaIr_2$	4.0-6.15		218	7.545	219
$CaPt_2$		1.02	218	7.629	219
$ScAl_2$		1.02	82	7.579	82
$ScIr_2$	1.03		203	7.348	203
$TiBe_2$		1.02	82	6.451	82,220
$RbBi_2$	4.25		221	9.609	221
$SrRh_2$	6.2		218	7.706	219
$SrPd_2$		1.02	218	7.826	219
$SrIr_2$	5.7		218	7.700	219
$SrPt_2$		1.02	218	7.777	219
YAl_2		1.00	203	7.860	203
YRh_2		0.35	82	7.459	203
YIr_2	2.18		203	7.500-7.520	203
YPt_2	1.57		203	7.590	203
$ZrCuAl$[a]		1.02	82	7.322	82
ZrV_2	8.8		140	7.439	140
$ZrCo_2$		1.02	82	6.935	37,82,207
$ZrV_{0.5}Ni_{1.5}$	0.43		82	7.068	82,222
$ZrMnNi$		0.35	82	7.070	82,222
ZrW_2	2.16		140	7.621	140
$ZrIr_2$	4.10		140	7.359	140
$CsBi_2$	4.75		223	9.746	223
$BaRh_2$	6.0		218	7.852	219
$BaPd_2$		1.02	218	7.953	219
$BaPt_2$		1.02	218	7.920	219
$LaMg_2$		1.02	82	8.763	82,224
$LaRu_2$	1.63		121,203	7.702	203
$LaRh_2$		1.00	203	7.646	203
$LaOs_2$	6.5		203	7.737	203
$LaIr_2$		1.00	203	7.686	203
$LaPt_2$		1.00	203	7.763–7.774	203
$CeRu_2$	4.9		203	7.535	203
$CeRh_2$		0.35	82	7.538	203
$CeOs_2$		0.62	82	7.593	203
$CeIr_2$		0.37	82	7.571	203
$LuAl_2$		1.02	82	7.744	82,225
$HfMo_2$		1.02	113		113
HfW_2		1.02	82	7.594	37,82
$BiAu_2$	1.84		226	7.958	227
$ThRu_2$	3.56		140	7.651	140
$ThOs_2$		1.02	82	7.704	81,228
$ThIr_2$	6.5		140	7.664	140
UAl_2		1.12	114		114
UFe_2		1.06	114		114
Uos_2		0.37	82	7.509	82,229
UIr_2		0.35	82	7.496	82,229

[a] E. A. Wood suggested the preparation of this compound and correctly predicted that it would have the *C*15-type structure.

The superconductivity and crystal-structure data for *C*16-type compounds are given in Table XVII (references 82, 140, 149, 168, and 233–237).

C32, AlB_2 type, hexagonal. The only known superconductor with this type structure is β–$ThSi_2$. The data for *C*32 compounds are given in Table XVIII (references 82, 114, 149, 168, 171, 233, and 238–240).

TABLE XVI. Superconductivity and crystal-structure data for compounds with $C15_b$-type structure.

	Superconductivity data			Crystal-structure data	
Compound	T_c °K	T_n °K	References	Lattice constants a,Å	References
$PdBe_5$		0.35	82	5.995	82,230
$AuBe_5$		1.02	82	6.097	82,230,231
UCu_5		1.02	82	7.037	82,232

C36, $MgNi_2$ type, hexagonal (*Laves Phase*). $HfMo_2$ is not superconducting above 1.02°K.[113]

C49, $ZrSi_2$ type, orthorhombic. The *C*49-type compounds investigated for superconducting properties include $ZrSi_2$ and $ZrGe_2$. $ZrSi_2$ is not superconducting above 1.02°K and $ZrGe_2$ is not superconducting above 0.35°K.[82]

TABLE XVII. Superconductivity and crystal-structure data for compounds with *C*16-type structure.

			Lattice Constants			
Compound	T_c °K	T_n °K	References	a,Å	c,Å	References
BCr_2		1.20	149			149
BMo_2	4.74		168,234			168,234
BW_2	3.10		149			149
$AlTh_2$		0.35	82	7.614[a]	5.857[a]	82,233
$MnSn_2$		1.12	234			234
$FeGe_2$		1.02	82	5.911[a]	4.951[a]	82,235
$CoSn_2$		1.02;1.12	82;234	6.361[a]	5.452[a]	82,236
$CuAl_2$		1.02;1.066	82;234	6.066[a]	4.874[a]	82,237
$CuTh_2$	3.49		140	7.28	5.75	140
$RhPb_2$	2.66		234			234
$PdPb_2$	2.95		234			234
$AgIn_2$	2.30–2.46		234			234
$AgTh_2$	2.26		140	7.56	5.84	140
$AuPb_2$	4.42		234			234
$AuTh_2$	3.08		140	7.42	5.95	140

[a] Powder patterns in present investigation were indexed based on these reported lattice constants.

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C54, $TiSi_2$ type, orthorhombic. $TiGe_2$ is not superconducting above 1.20°K.[149]

C_c, $ThSi_2$ type, body-centered tetragonal. The data for compounds with this type structure are given in Table XIX (references 82, 149, 241, 242). To date only two superconductors have been reported, YGe_2 and α–$ThSi_2$.

TABLE XVIII. Superconductivity and crystal-structure data for compounds with *C*32-type structure.

	Superconductivity data			Crystal-structure data		
Compound	T_c °K	T_n °K	References	Lattice constants a,Å	c,Å	References
$CaGa_2$		1.02	82	4.323[a]	4.323[a]	82,238
TiB_2		1.28	168			168
TiU_2		1.06	114			114
YSi_2		0.35	82	3.85[a]	4.14[a]	82,239
ZrB_2		1.8	171			171
NbB_2		1.28	168			168
TaB_2		1.28	168			168
OsB_2		1.02	82	2.876[a]	2.871[a]	82,240
$ThAl_2$		0.35	82	4.388[a]	4.162[a]	82,233
β-$ThSi_2$	2.41		149			149

[a] Powder patterns in present investigation were indexed based on these reported lattice constants.

DO_3, BiF_3 type, face-centered cubic. Alekseevskii, Brandt, and Kostina[130] report that $BiLi_3$ is normal down to 1.43°K. The reported lattice for the compound is 6.708 Å.[130]

TABLE XIX. Superconductivity and crystal-structure data for compounds with C_c-type structure.

	Superconductivity data			Crystal-structure data		
Compound	T_c °K	T_n °K	References	Lattice constants a,Å	c,Å	References
YGe_2	3.8		241			241
$LaSi_2$		1.20;1.00	149;241			149;241
$CeSi_2$		1.20;1.00	149;241			149;241
$NdSi_2$		1.00	241			241
α-$ThSi_2$	3.16		149			149
USi_2		0.35	82	3.98[a]	13.74[a]	82,242

[a] Powder patterns in present investigation were indexed based on these reported lattice constants.

DO_{18}, Na_3As type, hexagonal. The data for DO_{18}-type compounds are given in Table XX (references 82, 130, and 243). No superconductors have been reported.

DO_{19}, Ni_3Sn type, hexagonal. The data for DO_{19}-type compounds are given in Table XXI (references 82, 233, 244, and 245). The only superconducting compound is Al_3Th which has a transition temperature of 0.75°K.

TABLE XX. Superconductivity and crystal-structure data for compounds with DO_{18}-type structure.

	Superconductivity data			Crystal-structure data		
Compound	T_c °K	T_n °K	References	Lattice constants a,Å	c,Å	References
Na_3Bi		1.39	130	5.448	9.655	130
Si_3Ir		1.02	82	4.350[a]	6.630[a]	82,243
α-K_3Bi		1.40	130	6.178	10.933	130

[a] Powder patterns in present investigation were indexed based on these reported lattice constants.

DO_{22}, $TiAl_3$ type, tetragonal. No superconductors have been reported with this type structure. The data for the compounds investigated are given in Table XXII (references 82, 246, and 247).

TABLE XXI. Superconductivity and crystal-structure data for compounds with DO_{19}-type structure.

	Superconductivity data			Crystal-structure data		
Compound	T_c °K	T_n °K	References	Lattice constants a,Å	c,Å	References
Al_3Th	0.75		82	6.500[a]	4.626[a]	82,233
Ti_3Ga		0.35	82	5.76[a]	4.64[a]	82,244
Ti_3Sn		1.02	82	5.916[a]	4.764[a]	82,245

[a] Powder patterns in present investigation were indexed based on these reported lattice constants.

TABLE XXII. Superconductivity and crystal-structure data for compounds with DO_{22}-type structure.

	Superconductivity data			Crystal-structure data		
Compound	T_c °K	T_n °K	References	Lattice constants a,Å	c,Å	References
$TiAl_3$		1.02	82	5.436[a]	8.596[a]	82,246
$TiGa_3$		1.02	82	5.558[a]	8.109[a]	82,247
$ZrGa_3$		1.02	82	5.616[a]	8.730[a]	82,247

[a] Powder patterns in present investigation were indexed based on these reported lattice constants.

DO_{23}, $ZrAl_3$ type, body-centered tetragonal. $ZrAl_3$ is not superconducting above 1.02°K.[82]

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DO_e, Ni_3P type, body-centered tetragonal. Mo_3P has a transition temperature of 7.0°K.[185]

$D1_3$, $BaAl_4$ type, body-centered tetragonal. $CaAl_4$ is not superconducting above 1.02°K.[82]

$D1_c$, $PtSn_4$ type, orthorhombic. Recently Gendron and Jones[234] investigated the occurrence of superconductivity in $D1_c$-type compounds and reported that $PtPb_4$ and $AuSn_4$ are superconducting at 2.80 and 2.38°K, respectively. $PdSn_4$ and $PtSn_4$ are not superconducting above 1.30°K.

$D2_c$, U_6Mn type, body-centered tetragonal. The superconducting properties of $D2_c$-type U compounds with Mn, Fe, Co, and Ni were investigated by Chandrasekhar and Hulm.[114] The transition temperature of U_6Mn is 2.32°K, of U_6Fe, 3.86°K, of U_6Co, 2.29°K and U_6Ni is not superconducting above 1.12°K.

$D5_2$, La_2O_3 type, trigonal. The compound α–Bi_2Mg_3 is not superconducting above 1.5°K.[130] The lattice constants for the compound are $a = 4.666$ Å and $c = 7.401$ Å.

$D5_8$, Sb_2S_3 type, orthorhombic. Alekseevskii, Brandt, and Kostina[130] report that Bi_2S_3 is not superconducting above 1.3°K. The lattice constants are $a = 11.13$ Å, $b = 11.27$ Å and $c = 3.97$ Å.

$D7_b$, Ta_3B_4 type, orthorhombic. Nb_3B_4 and Ta_3B_4 are not superconducting above 1.28°K.[168]

$D8_8$, Mn_5Si_3 type, hexagonal. The data for $D8_8$ compounds are given in Table XXIII (references 82, 149, and 248–251). The only superconductor is Zr_5Pb_3 which has a transition temperature of 4.60°K.

TABLE XXIII. Superconductivity and crystal-structure data for compounds with $D8_8$-type structure.

	Superconductivity data			Crystal-structure data		
				Lattice constants		
Compound	T_c °K	T_n °K	References	a,Å	c,Å	References
Ti_5Ge_3		1.20	149			149
V_5Si_3[b]		0.35	82	7.135[a]	4.842[a]	82,248
V_5Ge_3[b]		1.02	82	7.295[a]	4.970[a]	82,249
Zr_5Ge_3		0.35	82	7.993[a]	5.597[a]	82,250
Zr_5Pb_3	4.60		82	8.529[a]	5.864[a]	82,251
Nb_5Si_3[b]		1.02	82	7.536[a]	5.249[a]	82,248

[a] Powder patterns in present investigation were indexed based on these reported lattice constants.
[b] Stabilized by the addition of 5 at. % C to the melt.

$D8_b$, CrFe type, tetragonal (Sigma phase). This structure seems to be favorable for the occurrence of superconductivity. Blaugher and Hulm[143] and Bucher, Heiniger and Müller[141] have plotted the transition temperatures against the average number of valence electrons per atom for σ-type phases and for α–Mn type ($A12$) phases of transition metal compounds. The maximum in the transition temperature occurs at about 6.5 valence electrons in the former's and at

TABLE XXIV. Superconductivity and crystal-structure data for compounds with $D8_b$-type structure.

	Superconductivity data			Crystal-structure data		
				Lattice constants		
Compound	T_c °K	T_n °K	References	a,Å	c,Å	References
Cr_2Ru	2.0		111			111
CrRe		1.02	82	9.20	4.78	82,153
MnRe		1.02	82	9.23	4.79	82,252
Zr_3Au		1.02	82	10.58	5.53	82
Nb–Al	7.0–12.0		156			156
$Nb_{0.60}Rh_{0.40}$	4.04		141	9.80	5.07	141
Nb–Rh	4.1		143			143
Nb–Pd	2.0		143			143
NbRe	2.0–3.8		141	9.79	5.10	141
Nb–Re	2.0		143			143
Nb_3Os_2	1.78		140	9.844	5.056	140
Nb_3Os_2	1.85		141	9.85	5.06	141
Nb–Os	1.4		143			143
$Nb_{0.63}Ir_{0.37}$	2.40		141	9.86	5.06	141
Nb_3Ir_2	9.8		140	9.834	5.052	140
Nb–Ir	7.9		143			143
Nb_5Pt_3	3.73		140	9.91	5.12	140
$Nb_{0.62}Pt_{0.38}$	4.01		141	9.91	5.13	141
Nb–Pt	2.4		143			143
$Mo_{0.60}Ru_{0.40}$	7.0		141	9.55	4.95	141
Mo–Ru	6.9		143			143
$Mo_{0.50}Re_{0.50}$	7.3/6.4		141	9.61	4.98	141
$Mo_{0.42}Re_{0.58}$	8.4		141	9.59	4.97	141
$Mo_{0.35}Re_{0.65}$	8.6		141	9.57	4.97	141
Mo–Re	6.0		143			143
$Mo_{0.62}Os_{0.38}$	5.65		141	9.60	4.93	141
Mo–Os	5.2		143			143
Mo_3Ir	6.8		25	9.631	4.956	25,82,162
$Mo_{0.74}Ir_{0.26}$	6.7		141	9.63	4.96	141
Ta_3Al		1.02	82	9.97	5.19	82,253,254
$Ta_{0.60}Rh_{0.40}$	2.35		141	9.80	5.09	141
Ta–Rh	2.0		143			143
$Ta_{0.40}Re_{0.60}$	1.4		141	9.77	5.09	141
Ta–Re	1.3		143			143
$Ta_{0.70}Os_{0.30}$		1.2	141	9.88	5.14	141
Ta–Os		1.0	143			143
$Ta_{0.65}Ir_{0.35}$		1.2	141	9.86	5.09	141
Ta–Ir		1.0	143			143
$Ta_{0.80}Pt_{0.20}$		1.2	141	10.02	5.20	141
$Ta_{0.70}Pt_{0.30}$	$\begin{Bmatrix}1.45\\1.5\end{Bmatrix}$ –	<1.2	141	9.93	5.16	141
Ta–Pt	1.0		143			143
$Ta_{0.67}Au_{0.33}$		1.2	141			141
$W_{0.60}Ru_{0.40}$	4.67		141	9.57	4.96	141
W–Ru	5.2		143			143
$W_{0.50}Re_{0.50}$	5.03		141	9.63	5.01	141
W–Re	5.2		143			143
$W_{0.80}Os_{0.20}$	2.5		113			113
$W_{0.66}Os_{0.34}$	3.81		141	9.63	4.98	141
$W_{0.64}Os_{0.36}$	3.8		113			113
W–Os	4.4		143			143
$W_{0.72}Ir_{0.28}$	4.46		141	9.67	5.00	141

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6.65 in the latter's plot. These values are in agreement with the empirical rules derived for the occurrence of superconductivity and the criteria for the maximum transition temperature.

TABLE XXV. Superconductivity and crystal-structure data for compounds with $D10_2$-type structure.

	Superconductivity data			Crystal-structure data		
				Lattice constants		
Compound	T_c °K	T_n °K	References	a,Å	c,Å	References
Ru_7B_3	2.58		140	7.465	4.715	140
Rh_7B_3		0.35	82	7.47	4.78	82,255
Th_7Fe_3	1.86		140	9.823	6.211	140
Th_7Co_3	1.83		140	9.833	6.200	140
Th_7Ni_3	1.98		140	9.885	6.225	140
Th_7Rh_3	2.15		82	10.031[a]	6.287[a]	82,256
Th_7Os_3	1.51		140	10.02	6.285	140
Th_7Ir_3	1.52		140	10.06	6.290	140
Th_7Pt_3		1.02	82	10.126[a]	6.346[a]	82,256

[a] Powder patterns in present investigation were indexed based on these reported lattice constants.

The superconductivity and crystal-structure data are given in Table XXIV (references 25, 82, 111, 113, 140, 141, 143, 153, 156, 162, and 252–254).

D8ᵢ, Mo_2B_5 type, rhombohedral. Mo_2B_5 is not superconducting above 1.28°K.[168]

$D10_2$, Th_7Fe_3, hexagonal. Superconductivity has been observed in several compounds with this type structure. The data are given in Table XXV (references 82, 140, 255, 256).

$E9_3$, Fe_3W_3C type, face-centered cubic. The superconducting properties of some recently reported Ti_2Ni type phases (isomorphous with Fe_3W_3C type) are given in Table XXVI (references 82, 140, 257, and 258). This is the only structure known in which the presence of oxygen, required for the stabilization of some of these compounds, is not detrimental to the superconducting behavior.

$L1_0$, CuAu type, tetragonal. The compounds α–LiBi and NaBi crystallize in this structure and are superconducting at 2.47°K[130] and 2.25°K,[174] respectively. The reported lattice constants for α–LiBi are a = 3.361 Å and c = 4.247 Å[130] and for NaBi, a = 3.46 Å and c = 4.80 Å.[130,132]

$L1_2$, Cu_3Au type, cubic. The data for $L1_2$ compounds that have been investigated for superconductivity are given in Table XXVII (references 82, 140, 168, 216, and 259–264). The superconductors are $SrBi_3$, Zr_3Al, and La_3In.

TABLE XXVI. Superconductivity and crystal-structure data for compounds with $E9_3$-type structure.

	Superconductivity data			Crystal-structure data	
Compound	T_c °K	T_n °K	References	Lattice constants a,Å	References
Ti_2Co	3.44		140	11.30	140
$Ti_{0.573}Cu_{0.287}O_{0.14}$		1.02	82	11.446	82,257
$Ti_{0.573}Rh_{0.287}O_{0.14}$	3.37		82	11.588	82,257
$Ti_{0.573}Ir_{0.287}O_{0.14}$	5.5		82	11.620	82,257
Zr_3V_3O	7.5		82	12.160	82,258
$Zr_{0.61}Rh_{0.285}O_{0.105}$	11.8		82	12.408	82,257
$Zr_{0.61}Pd_{0.285}O_{0.105}$	2.09		82	12.470	82,257
$Zr_{0.65}Ir_{0.265}O_{0.085}$	2.30		82	12.430	82,257
Hf_2Fe		0.35	82	12.043–12.065	82,257
Hf_2Co		0.56	82	12.067	82,257
$Hf_{0.67}Ni_{0.233}Ru_{0.10}$		1.02	82	12.183	82,257
$Hf_{0.63}Ni_{0.25}Re_{0.12}$		1.02	82	12.173	82,257

L'_{2b}, ThH_2 type, body-centered tetragonal. ZrH_2 which crystallizes in the L'_{2b}-type structure is not superconducting above 1.02°K.[37,82]

L'_3, W_2C type, hexagonal. Mo_2C, Ta_2C, and W_2C have been reported superconducting at 2.78,[168]

TABLE XXVII. Superconductivity and crystal-structure data for compounds with $L1_2$-type structure

	Superconductivity data			Crystal-structure data	
Compound	T_c °K	T_n °K	References	Lattice constants a,Å	References
VZn_3		1.02	82	3.846	82
$SrBi_3$	5.62		168	5.042	216
Zr_3Al	0.73		82	4.37	82,259
Zr_3In		1.02	82	4.46	82,260,261
$NbZn_3$		1.02	82	3.932	82,262
La_3In	10.4		140	5.07	140
$LaIn_3$		1.02	82	4.734	82,263
UGe_3		0.35	82	4.206	82,264

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3.26,[149,265] and 2.74°K,[168] respectively. However, recently Giorgi and Szklarz[266] report that Ta_2C is not superconducting down to 2.0°K, and in our opinion this is the more reliable value.

Cubic compounds. The superconductivity and crystal-structure data for various cubic compounds which have been investigated are given in Table XXVIII (references 82, 114, 168, 171, 174, 191, 265, and 267–277).

TABLE XXVIII. Superconductivity and crystal-structure data for cubic compounds.

	Superconductivity data			Crystal-structure data		
Compound	T_c °K	T_n °K	References	Lattice constants a,Å	Lattice type[a]	References
Mg_2Al_3	0.84		82	28.28	fcc	82,267
TiH_2		1.02	82	4.444	fcc	37,82
$CrGa_4$		1.02	82	5.648	bcc	82,268
$Cu_{1.8}S$		1.3	191		fcc	191
$Cu_{18}As_4Sb_3$		0.35	82	7.540	p	82,269
Mo_2N	5.0		168		fcc	168
$MoAl_{12}$		1.02	82	7.580	bcc	82,270,271
$Pd_{17}Se_{15}$		1.00	272	10.606	p	273
Cs_3Bi		b	174	9.305	fcc	174
$LaH_{2.45}$		1.8	171	5.636	fcc	171
$LaCd_{11}$		0.35	82	9.331	p	82,274
W_2C	5.2		265	4.25	fcc	265
W_2N		1.28	168		fcc	168
$ReN_{0.34}$	4.0		275		fcc	275
$AuZn_3$	1.21		82	7.893	p	82,269
α-Bi_4Rh		0.10	276	14.928	bcc	277
UCo	1.70		114		bcc	114

[a] fcc–face-centered cubic; bcc–body-centered cubic; p–primitive.
[b] Not stated.

Tetragonal compounds. The superconductivity and crystal-structure data for tetragonal compounds are given in Table XXIX (references 82, 114, 132, 133, 149, 165, 168, 216, and 278 to 284). Rögener[165] determined the transition temperature of the face-centered tetragonal Nb–N compounds as a function of composition and found that the maximum transition temperature, 11.8°K, occurred in $NbN_{0.79}$. Lautz and Schröder[278] reported that $NbN_{0.8}$ had a transition temperature of 8.9°K. Hardly and Hulm[149] found that Nb_4N_3 was superconducting at 7.2°K and Schröder[166] reported that face-centered tetragonal $Nb\ (N + 0)_{0.77}$ had a transition temperature of 6.80°K.

TABLE XXIX. Superconductivity and crystal-structure data for tetragonal compounds

	Superconductivity data			Crystal-structure data			
Compound	T_c °K	T_n °K	References	Lattice constants a,Å	c,Å	Lattice type[a]	References
V_5Si_3		0.30	82	9.429[b]	4.757[b]	bc	82,279
Cr_3Ge_2		1.20	149			bc	149
$CuGa_2$		1.27	82	2.836[b]	5.847[b]	p	82,280
Nb–N	8.90/11.8		165,278			fc	165,278
Nb_5Si_3		1.02	82	10.018[b]	5.072[b]	bc	82,279
Nb_5Ge_3		1.02	82	10.148[b]	5.152[b]	bc	82,281
Nb_3Sn_2	16.6		c	6.90	9.53		c
$RhIn_3$		1.02	82	7.01[b]	7.15[b]	p	82,282
β-$PdBi_2$	4.25		133	3.362	12.983	bc	132,133
$BaBi_3$	5.69		168	5.188	5.157		216
HgCd	1.77		82	3.940[b]	2.916[b]	bc	82,283,284
Th_3Si_2		1.20	149			p	149
U_3Si		1.10	114			bc	114

[a] bc–body-centered; fc–face-centered; p–primitive.
[b] Powder patterns in present investigation were indexed based on these reported lattice constants.
[c] *Note added in proof.* T. B. Reed and H. C. Gatos, J. Appl. Phys. **33**, 2657 (1962).

Hexagonal compounds. The data for hexagonal compounds are given in Table XXX (references 149, 166, 168, 174, 190, 266, 276, 285, and 286).

Orthorhombic compounds. The superconductivity and crystal-structure data for orthorhombic compounds are given in Table XXXI (references 82, 108, 130, 131, 133, 134, 149, 196, 197, 241, 276, and 287–290).

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Table XXX. Superconductivity and crystal-structure data for hexagonal compounds.

	Superconductivity data			Crystal-structure data		
				Lattice constants		
Compound	T_c °K	T_n °K	References	a,Å	c,Å	References
V_2C		1.20	149	2.944	4.608	149
V_5N_2		1.20	149			149
Nb_2C	9.18		149	3.105	4.970	149
		2.0[a]	266			266
Nb_2N		1.20;1.94	149;166	3.050	4.954	166
MoN	12.0		168			168
Ta_2N		1.20	149			149
γ-Bi_4Rh	2.7		276			285
$BiIn_2$	5.6		190			190
β-Bi_2Pt	0.155		286	6.44	6.25	174

[a] In our opinion this is a more reliable value.

Table XXXI. Superconductivity and crystal-structure data for orthorhombic compounds.

	Superconductivity data			Crystal-structure data			
				Lattice constants			
Compound	T_c °K	T_n °K	References	a,Å	b,Å	c,Å	References
$CoGe_3$		0.35	82	5.66[a]	5.66[a]	10.82[a]	82,287
$NiBi_3$	4.06		130	8.875	4.112	11.477	288
Ge_3Rh_5	2.12		108	5.42	10.32	3.96	197
YSi_2		1.0	149,241				241
Rh_2B		1.0	196				197
$LaGe_2$	1.49		241				241
β-Bi_3Rh	3.2		276	9.027	4.24	11.522	289
BiPd	3.7		131,133	7.203	8.707	10.662	134
URe_2		1.02	82	5.600[a]	9.178[a]	8.463[a]	82,290

[a] Powder patterns in present investigation were indexed based on these reported lattice constants.

Table XXXII. Superconductivity and crystal-structure data for monoclinic compounds.

	Superconductivity data			Crystal-structure data				
				Lattice constants				
Compound	T_c °K	T_n °K	References	a,Å	b,Å	c,Å	β	References
α-Bi_2Rh		1.34	276,285	6.96	6.83	7.01	118.2°	291
β-Bi_2Rh		1.27	276	16.2	7.0	10.5	92°30′	292
α-Bi_2Pd	1.70–1.75		130–134	12.74	4.25	5.665	102°35′	133,134

Monoclinic compounds. The data for monoclinic compounds which have been investigated for superconducting properties are given in Table XXXII (references 130–134, 276, 285, 291, and 292).

Superconducting compounds of unknown crystal structure. Many superconducting compounds whose crystal structures were not specifically stated or were not determined have been reported. Data for these are given in Roberts' compilation.[31]

Recently we have found that Zr_3Sb_2 is superconducting at 1.74°K and $Zr_{0.7}Bi_{0.3}$ at 1.51°K.[82] The patterns for these substances have not been interpreted as yet. Raub and co-workers[293] report that superconductivity occurs in the Pd–As system for alloys with the approximate composition of Pd_2As and also in alloys containing Co or Ni additions. The superconducting transition temperature of $LaSi_2$ begins at about 2.5°K.[294] Previous measurements of tetragonal $LaSi_2$ (C_c type) indicated that the compound was not superconducting above 1.00°K.[149,241] However, the structure of the superconducting $LaSi_2$ compound is not stated. Szklarz and Giorgi[176] have recently reported superconductivity data for HfN and for HfN–ZrN solid solutions. The transition temperature for HfN is 6.2°K and for the solid solutions the transition temperatures range from 6.2 to 10.7°K. The structure of these phases was not stated but they are probably the cubic NaCl type (*Bl*). Compounds of Li, Na, or Pt with Hg have been reported superconducting.[295] The transition temperature for Hg_3Li is 1.8°K; for Hg_4Na, 3.0°K; for Hg_2Na, 1.6°K; and for Hg_4Pt, 3.5°K. *Note added in proof.* W. E. Henry [Bull. Am. Phys. Soc. **7**, 621 (1962)] reports that La_5Si_3 is superconducting at 1.6°K.

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