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Phase Transition Temperatures of the Solid Elements at Atmospheric Pressure

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Abstract

In this work, we compiled and evaluated phase transition temperatures for the solid elements that can exist in two or more crystalline forms (allotropes). For reference purposes, we also include other elements where only melting points (solid→liquid) exist. We provide both solid-solid transitions (e.g., $\alpha\rightarrow\beta$, $\beta\rightarrow\gamma$) and solid-liquid melting point transitions (e.g., $\alpha\rightarrow\text{liq}$, $\gamma\rightarrow\text{liq}$). The crystal phases are labeled by Greek letters using the most common conventions. The crystal structures of the allotropes are also provided (e.g., $mP\rightarrow aP$, $bcc\rightarrow hcp$, $A\rightarrow oP$, $R\rightarrow fcc$). We also include magnetic phase transitions for the elements where they exist, e.g., $\alpha(T_C)$ and $\alpha(T_N)$ for Curie and Néel transitions, respectively.

Keywords

Solid phase transition temperatures; Melting point transitions; Magnetic transitions; Curie transitions; Néel transitions; Elements; Critical evaluation.

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1. Introduction

In this work, we compiled and evaluated phase transition temperatures for the solid elements that can exist in two or more crystalline forms (allotropes). For reference purposes, we also include other elements where only melting points (solid→liquid) exist. In addition, we include some melting points at atmospheric pressure derived from triple point temperatures using triple point pressures and dP/dT . The crystal phases are labeled by Greek letters using the most common conventions (*e.g.*, $\alpha \rightarrow \beta$, $\beta \rightarrow \gamma$, $\gamma \rightarrow \text{liq}$ – the latter referring to a melting point). The crystal structures of the allotropes are also provided (*e.g.*, $mP \rightarrow aP$, $bcc \rightarrow hcp$, $A \rightarrow oP$, $R \rightarrow fcc$). We include solid-solid transitions (*e.g.*, $\alpha \rightarrow \beta$, $\beta \rightarrow \gamma$) and solid-liquid melting point transitions (*e.g.*, $\alpha \rightarrow \text{liq}$, $\gamma \rightarrow \text{liq}$). We also include magnetic transitions for the elements where they exist, *e.g.*, $\alpha(T_C)$, $\alpha(T_N)$, and $\alpha(T_{\text{mag}})$ for Curie transitions, Néel transitions, and unspecified magnetic transitions, respectively.

All temperatures have been converted to the International Scale of 1990 (ITS-90)[1] from the IPTS-27, IPTS-48, and IPTS-68 temperature scales.[2] [3] In all cases, the corrections were less than the uncertainties in the value. Uncertainties (generally standard uncertainties: u , 1σ , 67 % confidence level) as reported in the original sources are given, except those uncertainties provided in square brackets “[]” are our estimates. Where uncertainties are not available, they were left blank in the tables.

We provide tables of notations used with definitions. All the data refer to normal atmospheric pressure. Solid-solid phase transitions at high pressures and liquid-liquid phase transitions are not given here. Similarly, the melting points of helium (He) and carbon (C) are not provided since they do not exist at normal atmosphere pressure.

Note that because different researchers report phases differently (or maybe mischaracterized), there is some uncertainty in the notation for some of the phases for phosphorus and possibly some other elements, and some uncertainty in the crystal structures. We have done our best to provide consistent phase notation and structures.

Note that there is generally a hysteresis in the transition temperatures where the transitions are higher (*e.g.*, 1 K to 50 K) on heating (*e.g.*, $\alpha \rightarrow \beta$) than on cooling (*e.g.*, $\beta \rightarrow \alpha$) and that transitions occur over a range of temperatures (*e.g.*, 1 K to 50 K) from their onset to their ending. The hysteresis in solid-solid phase transitions are due to various factors during the nucleation and growth of a new phase/structure such as from strain energies, impurity content, grain sizes, diffusion, and kinetic barriers. Also note that transition temperatures can depend upon whether the form is crystalline, polycrystalline, or amorphous and upon the rate of heating. There are also polymeric and glassy (vitreous) forms. Note that at atmospheric pressure that phosphorus (P) and sulfur (S) have many allotropes and that there are other allotropes that are only formed at high pressures, formed in the presence of a catalyst, or under ultraviolet radiation.

Some of the elements have a single phase/structure, while many of the elements have two allotropes/structures. About a dozen elements have three or more phases/structures. Sulfur, phosphorus, and selenium are complex substances that have many crystalline and non-crystalline phases at atmospheric pressure and many more at high pressures. Sulfur (S) has

three crystalline allotropic structures (α , β , γ) and at least three non-crystalline phases (amorphous, fibrous/polymer, glass). Phosphorus (P) has at least nine different allotropic structures: crystalline black, amorphous red, four crystalline red phases, and three white allotropes. Selenium (Se) has one crystalline structure (gray), two amorphous structures (black, red) and a glassy form. Calcium (Ca), iron (Fe), cobalt (Co), samarium (Sm), lanthanum (La), uranium (U), neptunium (Np), and americium (Am) each have three different phases. Manganese (Mg), gallium (Ga) and cerium (Ce) each have four allotropic structures. Plutonium (Pu) has six different phases.

We provide about 210 recommended phase transitions for the elements hydrogen (H_2 , $Z=1$) to fermium (Fm, $Z=100$). We provide about 50 recommended magnetic transitions for about 20 different elements. In this work, we only present recommended values taken from just over 100 different references. Our full compilation from the literature consists of just over 1000 values taken from about almost 400 different references. This full set of data will be published later.

2. Notations Used

2.1. Table 1. Column Headings

Column Heading	Definition
Z	Atomic number for element
Element	Atomic symbol for element or molecule (<i>e.g.</i> , O ₂) when the form is a molecule at room temperature and atmospheric pressure.
Transition	Allotropic phase transitions using most common allotropic nomenclature, <i>e.g.</i> , $\alpha \rightarrow \beta$, $\beta \rightarrow \gamma$ or magnetic transition, <i>e.g.</i> , $\alpha(T_{FC})$, $\alpha(T_N)$. Melting points are also provided, <i>e.g.</i> , $\beta \rightarrow \text{liq}$. See “Table 2. Notation Used” for definitions.
Structure	Crystal structures of allotropes in phase transition using standard notation, <i>e.g.</i> , mP \rightarrow aP, dfcc \rightarrow fcc, oC \rightarrow tP). See “Table 2. Notation Used” for definitions.
T/K	Temperature of phase transition in K on the International Scale of 1990 (ITS-90).[1]
u/K	Uncertainty (generally standard uncertainties <i>u</i>) of phase transition in K. Uncertainties given in square brackets “[]” are our estimates, others are as reported in the literature. Where uncertainties are not provided in the tables, they were not available in the literature.
M	Method used. EC (critically evaluated data), ER (evaluated data, but based on a limited review of the literature), RV (review value with a very limited review of the literature). No method given in the column is generally the best experimental value.

2.2. Table 2. Notation Used.

Notation	Definition
α	Alpha phase
A	Amorphous
aP	Triclinic
β	Beta phase
bcc	Body-centered cubic
bct	Body-centered tetragonal
br	Brown red phosphorus
cP	Cubic
δ	Delta phase
δ'	Delta phase (different structure)
dfcc	Distorted face-centered cubic
dhcp	Double hexagonal close-packed
EC	Critically evaluated data
ER	Evaluated data, but based on a limited review of the literature
ϵ	Epsilon phase
fcc	Face-centered cubic
fib	Fibrous red
FP	Normal freezing point – temperature where solid and liquid phases are in equilibrium at 101.325 kPa (1 atm). Determined upon cooling (liquid→solid).
γ	Gamma phase
hcp	Hexagonal close-packed
hP	Hexagonal
liq	Liquid phase
mP	Monoclinic
MP	Normal melting point – temperature where solid and liquid phases are in equilibrium at 101.325 kPa (1 atm).
oC	Base-centered orthorhombic
oP	Orthorhombic
P3	Trigonal
PC	Paramagnetic Curie temperature
PCL	Paramagnetic Curie temperature (perpendicular)
PCP	Paramagnetic Curie temperature (parallel)
R	Rhombohedral
RV	Review value with a very limited review of the literature
R(br)	Red-brown phosphorus
R(fib)	Fibrous red phosphorus
R(II)	Red phosphorus phase identified as II
R(III)	Red phosphorus phase identified as III
R(viol)	Violet red phosphorus
Red	Amorphous red phosphorus

sc	Loose-packed cubic crystal structure
SFT	Spin-flip transition
SP	Normal sublimation point – temperature where solid and gas phases are in equilibrium at 101.325 kPa (1 atm)
T_{FC}	Curie temperature (ferromagnetic to paramagnetic transition)
T_{mag}	Temperature of unspecified magnetic transition
T_N	Néel temperature (antiferromagnetic to paramagnetic transition)
tP	Tetragonal
TP	Triple point – temperature where solid, liquid, and gas phases are in equilibrium. The triple point pressure is given in parenthesis.
unk	Unknown
α -white-spc	Supercooled α -white phosphorus

3. Solid Phase Transitions for the Elements

Table 3 provides recommended solid phase transitions for the elements from hydrogen ($Z=1$) to fermium ($Z=100$). This includes both solid-solid and solid-liquid (melting points) phase transitions. The table is ordered by atomic number (Z). For convenience, the melting points for each element are listed first with solid-solid transitions listed subsequently. The solid-solid transitions provided here are generally upon heating (e.g., $\alpha \rightarrow \beta$), while transitions upon cooling (e.g., $\beta \rightarrow \alpha$) are not provided.

As discussed above, sulfur (S), phosphorus (P), and selenium (Se) are complex substances that have many crystalline and non-crystalline phases. There are some differences in the literature pertaining to identification of phases and crystal structures for these elements. We have done our best to resolve these differences and refer the reader to the literature for more information.

Some uncertainties contained in the table are exactly zero since these temperatures are exactly defined temperatures on the International Temperature Scale of 1990 (ITS-90).[1]

Some melting points provided in the table were derived from triple point temperatures that are defined exactly on the ITS-90 scale[1] using the triple point pressures (P_{TP}) and dP/dT found in the literature (provided as the reference in the derived quantity) and the equation:

$$T_{MP} = T_{TP} + (1 - P_{TP}) * (dT/dP).$$

The triple point pressures are given in parenthesis in the TP entries. Similarly, for reference purposes, some triple point temperatures were derived from melting points that are defined exactly on the ITS-90 scale. We provide our estimates of the uncertainties in the derived values. The triple points (solid-liquid-gas) are displayed in italics in the table to distinguish them from solid phase transitions.

Note that on the ITS-90 scale, some of the solid-liquid transitions are defined (and measured) as freezing points (upon cooling, liquid \rightarrow solid), rather than as melting points (upon heating, solid \rightarrow liquid). These are indicated in the table as FP and MP, respectively.

Note that the first listing is equilibrium hydrogen (e- H_2) which contains an equilibrium distribution of ortho and para states of hydrogen.

Please note that the literature usually gives the melting point of arsenic (As) as 1090 K. However, this is the triple point temperature at a pressure of 37 atm. Arsenic sublimates at a much lower temperature (887 K). These data are provided in the table for reference purposes.

3.1. Table 3. Solid Phase Transitions

Z	Element	Transition	Structure	T/K	u/K	M	Reference
1	e-H ₂	<i>TP (0.0694 atm)</i>	sol-liq-gas	13.8033	0	EC	1990PRE[1]
1	e-H ₂	MP	hP→liq	13.835	[0.005]	EC	2018CCT[4]
3	Li	MP	bcc→liq	453.61	0.14	EC	2024NAR[5]
3	Li	$\alpha \rightarrow \beta$	R→bcc	70.7	0.1		1968HOV[6]
4	Be	MP	bcc→liq	1556	2		2000KLE[7]
4	Be	$\alpha \rightarrow \beta$	hP→bcc	1542	1		2000KLE[7]
5	B	MP	R→liq	2365	[10]	EC	2000OKA1[8]
5	B	$\alpha \rightarrow \beta$	R→R	933	20		2011PAR[9]
5	B(amorph)	A→ α	A→R	1443	10		2000SHA[10]
7	N ₂	<i>TP (0.123 atm)</i>	sol-liq-gas	63.1526	0.0015		2008LIP[11]
7	N ₂	MP	hP→liq	63.172	[0.003]		2000SPA[12]
7	N ₂	$\alpha \rightarrow \beta$	cP→hP	35.620	0.004		2007LIP[11]
8	O ₂	<i>TP (0.0014 atm)</i>	<i>sol-liq-gas</i>	53.3584	0	EC	<i>1990PRE[1]</i>
8	O ₂	MP	cP→liq	54.3705	[0.0017]	EC	2018CCT[4]
8	O ₂	$\alpha \rightarrow \beta$	mP→R	23.89485	0.00005		2022STE[13]
8	O ₂	($\alpha \rightarrow \beta$)'	mP→R	23.814	0.008		2022STE[13]
8	O ₂	$\beta \rightarrow \gamma$	R→cP	43.7991	0.0015		2020STE[14]
9	F ₂	MP	cP→liq	53.54	0.02		1953HU[15]
9	F ₂	$\alpha \rightarrow \beta$	mP→cP	45.55	0.02		1953HU[15]
10	Ne	<i>TP (0.428 atm)</i>	<i>sol-liq-gas</i>	24.5561	0	EC	<i>1990PRE[1]</i>
10	Ne	MP	fcc→liq	24.5653	[0.0007]	EC	2018CCT[4]
11	Na	MP	bcc→liq	370.93	0.06	EC	2024NAR[5]
11	Na	$\alpha \rightarrow \beta$	hP→bcc	45	5	EC	1993ALC[16]
12	Mg	MP	hP→liq	923	[2]		2005GRO[17]
13	Al	<i>TP (<1 Pa)</i>	<i>sol-liq-gas</i>	933.466	[0.001]	EC	<i>1990PRE[1]</i>
13	Al	FP	fcc→liq	933.473	0	EC	1990PRE[1]
14	Si	MP	cP→liq	1688	3		2010SEV[18]
15	P(red)	MP	A→liq	873	[5]		1969STE[19]
15	P(red)	red→R(II)	A→aP	723			1969STE[19]
15	P(red)	R(II)→R(III)	aP→hP	793			1947ROT[20]
15	P(red)	R(III)→R(viol)	hP→mP	833	[10]		1969STE[19]
15	P(red)	red→R(fib)	A→aP	823		RV	1997GRE[21]
15	P(red)	R(fib)→R(viol)	aP→mP	848			1969STE[19]
15	P(black)	MP	oP→liq	880	15		2024MUH[22]
15	P(black)	black→red	oP→A	870			1992BRA[23]
15	P(α -white)	MP	bcc→liq	317.28	0.1		1969STE[19]
15	P(α -white)	$\alpha \rightarrow$ red	bcc→A	553			1947ROT[20]
15	P(α -white)	$\alpha \rightarrow \beta$	bcc→aP	193.2			1997SIM[24]
15	P(α -white-spc)	$\alpha \rightarrow \gamma$	bcc→mP	108			1974SPI[25]
15	P(β -white)	$\beta \rightarrow$ R(br)	aP→A	83	R		1997GRE[21]
15	P(β -white)	$\beta \rightarrow \alpha$	aP→bcc	196.7	2		1997SIM[24]
15	P(γ -white)	$\gamma \rightarrow \beta$	mP→aP	153	2		1997SIM[24]
16	S(amorph)	MP	A→liq	451.5	11		1971MIL[26]
16	S(fibrous)	MP	fibrous→liq	377			1982THE[27]
16	S(glass)	MP	glass→liq	350			1971MIL[26]
16	S(α)	MP	oP→liq	386.0	[6]		1964MEY[28]

16	S(α)	SP	oP	368.5			1976MEY[29]
16	S(α)	$\alpha \rightarrow \beta$	oP \rightarrow mP	368.43	0.1		1970THA[30]
16	S(α)	$\alpha \rightarrow \gamma$	oP \rightarrow mP	383	10		1971MIL[26]
16	S(β)	MP	mP \rightarrow liq	392.5	[4]		1964MEY[28]
16	S(β)	SP	mP	368.5			1976MEY[29]
16	S(β)	$\beta \rightarrow \gamma$	mP \rightarrow mP	388.31			1964MEY[28]
16	S(γ)	MP	mP \rightarrow liq	381.8	0.3[1]		1970THA[30]
17	Cl ₂	MP	oP \rightarrow liq	172.20	[0.15]		1939GIA[31]
18	Ar	<i>TP (0.680) atm</i>	<i>sol-liq-gas</i>	83.8058	0	EC	1990PRE[1]
18	Ar	MP	fcc \rightarrow liq	83.8138	[0.0003]	EC	2018CCT[4]
19	K	MP	bcc \rightarrow liq	336.84	0.12	EC	2024NAR[5]
20	Ca	MP	bcc \rightarrow liq	1115	2	EC	1993ALC[16]
20	Ca	$\alpha \rightarrow \beta$	fcc \rightarrow bcc	716		RV	1991DIN[32]
20	Ca	$\alpha \rightarrow \epsilon$	fcc \rightarrow unk	695		ER	2008OKA[33]
21	Sc	MP	bcc \rightarrow liq	1814	[2]	ER	2000OKA2[34]
21	Sc	$\alpha \rightarrow \beta$	hP \rightarrow bcc	1610			2016XU[35]
22	Ti	MP	bcc \rightarrow liq	1943	2	EC	1996BED[36]
22	Ti	$\alpha \rightarrow \beta$	hP \rightarrow bcc	1155	[5]	ER	2002OKA1[12]
23	V	MP	bcc \rightarrow liq	2201	7		1997MCL[37]
24	Cr	MP	bcc \rightarrow liq	2180	[10]		2011WAL[38]
25	Mn	MP	bcc \rightarrow liq	1519	5		1987DES[39]
25	Mn	$\alpha \rightarrow \beta$	bcc \rightarrow cP	980	20		1987DES[39]
25	Mn	$\beta \rightarrow \gamma$	cP \rightarrow fcc	1360	10		1987DES[39]
25	Mn	$\gamma \rightarrow \delta$	fcc \rightarrow bcc	1411	15		1987DES[39]
26	Fe	MP	bcc \rightarrow liq	1811	[3]	ER	2002OKA2[40]
26	Fe	$\alpha \rightarrow \gamma$	bcc \rightarrow fcc	1185		ER	2002OKA2[40]
26	Fe	$\gamma \rightarrow \delta$	fcc \rightarrow bcc	1667	[1]	ER	2002OKA2[40]
27	Co	MP	fcc \rightarrow liq	1768	1		1947DUS[41]
27	Co	$\epsilon \rightarrow \alpha$	hP \rightarrow fcc	695	[1]	ER	2008OKA[33]
28	Ni	MP	fcc \rightarrow liq	1729	4		1984CEZ[42]
29	Cu	MP	fcc \rightarrow liq	1357.77	0	EC	1990PRE[1]
30	Zn	<i>TP (65 Pa)</i>	<i>sol-liq-gas</i>	692.673	[0.001]	EC	1982FUR[43]
30	Zn	MP	hP \rightarrow liq	692.677	0	EC	1990PRE[1]
31	Ga(α)	<i>TP (<1 Pa)</i>	<i>sol-liq-gas</i>	302.9166	[0.0002]	EC	1982FUR[43]
31	Ga(α)	MP	oP \rightarrow liq	302.9146	0	EC	1990PRE[1]
31	Ga(β)	MP	mP \rightarrow liq	256.9			1969BOS[44]
31	Ga(δ)	MP	unk \rightarrow liq	253.8			1969BOS[44]
31	Ga(ϵ)	MP	unk \rightarrow liq	244.6			1969BOS[44]
31	Ga(γ)	MP	unk \rightarrow liq	237.6			1969BOS[44]
32	Ge	MP	fcc \rightarrow liq	1211.40	0.08		2018GAV[45]
33	As	<i>TP (37 atm)</i>	<i>sol-liq-gas</i>	1090			1982ROU[46]
33	As	SP	R \rightarrow gas	887		ER	2010OKA2[47]
34	Se(gray)	MP	R \rightarrow liq	494.2	0.1		1988WUN[48]
34	Se(black)	black \rightarrow black	vitreous \rightarrow A	318	2		1970BEN[49]
34	Se(black)	black \rightarrow gray?	vitreous \rightarrow hP	395	5		1970BEN[49]
34	Se(glass)	glass \rightarrow solid	glass \rightarrow solid	314			2011CER[50]
34	Se(liq)	liq \rightarrow solid	supercool \rightarrow sol	413.2			2011CER[50]
34	Se(red)	red \rightarrow black	mP \rightarrow A	327.2	0.5		1970BEN[49]
34	Se(red)	red \rightarrow glass	mP \rightarrow glass	300	5		1970BEN[49]

34	Se(red)	red→gray	mP→R	407.2			2011CER[50]
35	Br ₂	MP	oP→liq	265.90	0.05		1958HIL[51]
36	Kr	<i>TP (0.720 atm)</i>	<i>sol-liq-gas</i>	<i>115.7755</i>	<i>0.0003</i>		<i>2013HIL[52]</i>
36	Kr	MP	fcc→liq	115.7969	[0.0016]		1952MIC[53]
37	Rb	MP	bcc→liq	312.46	0.09	EC	2024NAR[5]
38	Sr	MP	β→liq	1041	2	EC	1993ALC[16]
38	Sr	α→β	fcc→bcc	820	3	EC	1993ALC[16]
39	Y	MP	bcc→liq	1795		ER	2006OKA[54]
39	Y	α→β	hP→bcc	1751		ER	2006OKA[54]
40	Zr	MP	hP→liq	2128	[3]	ER	2002OKA3[55]
40	Zr	α→β	hP→bcc	1136		ER	2002OKA3[55]
41	Nb	MP	bcc→liq	2745		EC	1996BED[36]
42	Mo	MP	bcc→liq	2895	4	EC	1996BED[36]
43	Tc	MP	hP→liq	2429	30		1989GUI[56]
44	Ru	MP	hP→liq	2606	10	EC	1996BED[36]
45	Rh	MP	hP→liq	2236	3	EC	1996BED[36]
46	Pd	MP	fcc→liq	1828.0	0.1	EC	1996BED[36]
47	Ag	<i>TP (32 Pa)</i>	<i>sol-liq-gas</i>	<i>1234.92</i>	<i>[0.005]</i>	EC	<i>1982FUR[43]</i>
47	Ag	MP	fcc→liq	1234.93	0	EC	1990PRE[1]
48	Cd	<i>TP (<1 Pa)</i>	<i>sol-liq-gas</i>	<i>594.2124</i>	<i>[0.0003]</i>	EC	<i>1982FUR[43]</i>
48	Cd	MP	hP→liq	594.2186	0.0002	EC	1996BED[36]
49	In	<i>TP (0.6 kPa)</i>	<i>sol-liq-gas</i>	<i>429.7436</i>	<i>[0.0003]</i>	EC	<i>1982FUR[43]</i>
49	In	FP	bcc→liq	429.7485	0	EC	1990PRE[1]
50	Sn(β-white)	MP	tP→liq	505.078	0	EC	1990PRE[1]
50	Sn(α-gray)	α→β	fcc→tP	286.4	0.1		1935COH[57]
51	Sb	MP	R→liq	903.77	0.001	EC	1982FUR[43]
52	Te	MP	hP→liq	722.72	[0.02]	ER	2000OKA3[58]
53	I ₂	MP	oP→liq	386.8			1938FRE[59]
54	Xe	<i>TP (0.807 atm)</i>	<i>sol-liq-gas</i>	<i>161.40596</i>	<i>0.00032</i>		<i>2005HIL[60]</i>
54	Xe	MP	fcc→liq	161.4140	[0.0013]		2018STE[61]
55	Cs	MP	bcc→liq	301.66	0.1	EC	2024NAR[5]
56	Ba	MP	bcc→liq	1000	3	EC	1993ALC[16]
57	La	MP	bcc→liq	1192	1	EC	2010KON[62]
57	La	α→β	dhcp→fcc	566	7		1961SPE[63]
57	La	β→γ	fcc→bcc	1140	[3]	EC	2010KON[62]
58	Ce	MP	bcc→liq	1070	3	EC	2010KON[62]
58	Ce	α→β	fcc→dhcp	143	[5]		1962GSC[64]
58	Ce	α→γ	fcc→fcc	174.2	3.8		1962GSC[64]
58	Ce	β→γ	dhcp↔fcc	283	5		1999GSC[65]
58	Ce	γ→δ	fcc→bcc	998	[3]	EC	2010KON[62]
59	Pr	MP	bcc→liq	1208	3	EC	2010KON[62]
59	Pr	α→β	dhcp→bcc	1068	[3]	EC	2010KON[62]
60	Nd	MP	bcc→liq	1289	5	EC	2010KON[62]
60	Nd	α→β	dhcp→bcc	1133	[5]	EC	2010KON[62]
61	Pm	MP	bcc→liq	1315			1995GSC[66]
61	Pm	α→β	dhcp→bcc	1163			1995GSC[66]
62	Sm	MP	bcc→liq	1346	5	EC	2010KON[62]
62	Sm	α→β	R→hP	970	[5]	EC	2010KON[62]
62	Sm	β→γ	hP→bcc	1185	5	EC	2010KON[62]
63	Eu	MP	bcc→liq	1095	5	EC	2010KON[62]

64	Gd	MP	bcc→liq	1591	10	EC	2010KON[62]
64	Gd	$\alpha\rightarrow\beta$	hP→bcc	1534	[3]	EC	2010KON[62]
65	Tb	MP	bcc→liq	1624	5	EC	2010KON[62]
65	Tb	$\alpha\rightarrow\beta$	hP→bcc	1560	5	EC	2010KON[62]
66	Dy	MP	bcc→liq	1683	4	EC	2010KON[62]
66	Dy	$\alpha\rightarrow\beta$	hP→bcc	1653	4		2000STA1[67]
67	Ho	MP	hP→liq	1742	5		2000STA2[68]
68	Er	MP	hP→liq	1795	10	EC	2010KON[62]
69	Tm	MP	hP→liq	1822	10	EC	2010KON[62]
70	Yb	MP	bcc→liq	1091	10	EC	2010KON[62]
70	Yb	$\alpha\rightarrow\beta$	hP→fcc	270			1971KAY[69]
70	Yb	$\beta\rightarrow\alpha$	fcc→hP	260			1971KAY[69]
70	Yb	$\beta\rightarrow\gamma$	fcc→bcc	1033	20	EC	2010KON[62]
71	Lu	MP	hP→liq	1950	15	EC	2010KON[62]
72	Hf	MP	bcc→liq	2504	[20]	ER	1997OKA[70]
72	Hf	$\alpha\rightarrow\beta$	hP→bcc	2016	[20]	ER	1997OKA[70]
73	Ta	MP	bcc→liq	3280	[20]	ER	2013OKA[71]
74	W	MP	bcc→liq	3687	7	EC	1996BED[36]
75	Rh	MP	fcc→liq	3463	[15]		1955SIM[72]
76	Os	MP	hP→liq	3328	30		1960KNA[73]
77	Ir	MP	fcc→liq	2719	4[6]		1933HEN[74]
78	Pt	MP	fcc→liq	2041.9	0.5	EC	1996BED[36]
79	Au	<i>TP (<1 Pa)</i>	<i>sol-liq-gas</i>	<i>1337.32</i>	<i>[0.005]</i>	EC	<i>1982FUR[43]</i>
79	Au	MP	fcc→liq	1337.33	0	EC	1990PRE[1]
80	Hg	<i>TP (<1 Pa)</i>	<i>sol-liq-gas</i>	<i>234.3156</i>	<i>[0.0006]</i>	EC	<i>1982FUR[43]</i>
80	Hg	MP	R→liq	234.3210	0.0005	EC	1996BED[36]
81	Tl	MP	bcc→liq	577		ER	2015OKA[75]
81	Tl	$\alpha\rightarrow\beta$	hP→bcc	503		ER	2015OKA[75]
82	Pb	MP	fcc→liq	600.612	0.001		1960MCL[76]
83	Bi	MP	R→liq	544.556	0.003		2004ARC[77]
84	Po	MP	cP→liq	527			1949MAX[78]
84	Po	$\alpha\rightarrow\beta$	cP→R	327	1.5		1957GOO[79]
85	At ₂	MP	unk→liq	575			1985VAS[80]
86	Rn	MP	fcc→liq	202			1909GRA[81]
87	Fr	MP	unk→liq	300	3	EC	2024NAR[5]
88	Ra	MP	bcc→liq	200.0	0.1		2007FER[82]
89	Ac	MP	fcc→liq	1324	50		1955STI[83]
90	Th	MP	bcc→liq	2020	10	EC	2010KON[62]
90	Th	$\alpha\rightarrow\beta$	fcc→bcc	1650	15	EC	2010KON[62]
91	Pa	MP	fcc→liq	1843	50	EC	2010KON[62]
91	Pa	$\alpha\rightarrow\beta$	bct→fcc	1443	50	EC	2010KON[62]
91	Pa	$\alpha\rightarrow\beta$	bct→fcc	1443		RV	1991DIN[32]
91	Pa	$\alpha\rightarrow\beta$	bct→fcc	1441	20		1965MAR[84]
92	U	MP	bcc→liq	1407	2	EC	2010KON[62]
92	U	$\alpha\rightarrow\beta$	oC→tP	941	2	EC	2010KON[62]
92	U	$\beta\rightarrow\gamma$	tP→bcc	1049	2	EC	2010KON[62]
93	Np	MP	bcc→liq	913	4		1992GIB[85]
93	Np	$\alpha\rightarrow\beta$	oP→tP	555	4		1992GIB[85]
93	Np	$\beta\rightarrow\gamma$	tP→bcc	851	4		1992GIB[85]
94	Pu	MP	bcc→liq	913	2[1]	EC	2010KON[62]

94	Pu	$\alpha \rightarrow \beta$	mP \rightarrow mP	399.39	0.05[0.3]		2006ZOC[86]
94	Pu	$\beta \rightarrow \gamma$	mP \rightarrow dfcc	487.1	0.5[0.8]		2006ZOC[86]
94	Pu	$\gamma \rightarrow \delta$	dfcc \rightarrow fcc	596.6	0.04[0.8]		2006ZOC[86]
94	Pu	$\delta \rightarrow \delta'$	fcc \rightarrow bct	740.8	0.44[1.2]		2006ZOC[86]
94	Pu	$\delta' \rightarrow \epsilon$	bct \rightarrow bcc	759.1	0.13[0.3]		2006ZOC[86]
95	Am	MP	oP \rightarrow liq	1449	5	EC	2010KON[62]
95	Am	$\alpha \rightarrow \beta$	hP \rightarrow supercool	1042	10	EC	2010KON[62]
95	Am	$\beta \rightarrow \gamma$	supercool \rightarrow oP	1350	5	EC	2010KON[62]
96	Cm	MP	hP \rightarrow liq	1619	50	EC	2010KON[62]
96	Cm	$\alpha \rightarrow \beta$	hP \rightarrow fcc	1313	50	ER	2000OKA4[87]
96	Cm	$\beta \rightarrow \gamma$	fcc \rightarrow oP	1583	50	ER	2000OKA4[87]
97	Bk	MP	fcc \rightarrow liq	1323	50		1982WAR[88]
97	Bk	$\alpha \rightarrow \beta$	hP \rightarrow fcc	1250	50		1982WAR[88]
98	Cf	MP	fcc \rightarrow liq	1173	30		1979HAI[89]
98	Cf	$\alpha \rightarrow \beta$	hP \rightarrow fcc	873		EC	2010KON[62]
99	Es	MP	fcc \rightarrow liq	1133	50		1979HAI[89]
100	Fm	MP	fcc \rightarrow liq	1125	50		1989HAI[90]

4. Magnetic Phase Transitions for the Elements

Table 4 provides magnetic transitions for the elements. We have found 19 elements with magnetic transitions. The elements in the table are ordered by atomic number. Most of the transitions are Curie (T_{FC}) and Néel (T_N) temperatures. We also include various other type of magnetic transitions. Curie and Néel temperatures are ferromagnetic (FM) to paramagnetic (PM) transitions and antiferromagnetic (AFM) to paramagnetic transitions (PM), respectively. These are often second-order phase transitions where there is a discontinuous change in magnetic susceptibility without a change in the heat content. In contrast, solid-solid and solid-liquid phase transitions are first-order phase transitions where there is a release of heat (*i.e.*, latent heat of transition). The Curie temperature is lower than the Néel temperature. Note that gadolinium (Gd) is the only heavy rare earth metal (Pr, Gd, Tb, Dy, Ho, Er, Tm) that does not have a Néel temperature. There are several elements where there is some uncertainty in the literature of the structure at the magnetic transitions: cerium (Ce), praseodymium (Pr), neodymium (Nd), samarium (Sm), and curium (Cm). It is beyond the scope of this work to resolve the differences, and we refer the reader to the literature for these transitions.

4.1. Table 4. Magnetic Phase Transitions

Z	Element	TRS	Structure	T/K	u/K	Reference
8	O ₂	$\beta(T_N)$	R	30		1985UYE[91]
22	Ti	$\alpha(T_N)$	hP	276	4	1985POP[92]
24	Cr	$\alpha(T_{SFT})$	tP	123		1984DUB[93]
24	Cr	$\alpha(T_N)$	oP	311.4	0.2	1979WIL[94]
25	Mn	$\alpha(T_N)$	bcc	101.4	2	2015WHI[95]
26	Fe	$\alpha(T_N)$	bcc	230		2023YAN[96]
26	Fe	$\gamma(T_{FC})$	bcc	1044.6	1.5	2018WAN[97]
27	Co	$\varepsilon(T_{FC})$	hP	1249		2017LIZ[98]
27	Co	$\alpha(T_{FC})$	fcc	1388		1965COL[99]
28	Ni	$\alpha(T_{FC})$	fcc	631.43	0.04	2011LEG[100]
58	Ce	$\gamma(T_{mag})$	fcc	8		1971MEA[101]
58	Ce	$\beta(T_N)$	dhcp	14.5		1971MEA[101]
58	Ce	$\alpha(T_{mag})$	fcc	23		1971MEA[101]
59	Pr	$\beta(T_{FC})$	fcc	9.2		1971MEA[101]
59	Pr	$\beta(T_N)$	fcc	18.3		2010KON[62]
59	Pr	$\gamma(T_N)$	bcc	18.5		1971MEA[101]
59	Pr	$\alpha(T_{FC})$	dhcp	20		1971MEA[101]
59	Pr	$\alpha(T_N)$	dhcp	22.3		1971MEA[101]
59	Pr	$\alpha(T_{mag})$	dhcp	25		1972MEA[101]
60	Nd	$\alpha(T_N)$	dhcp/oP	7.5		1971JOH[102]
60	Nd	$\alpha(T_N)$	dhcp/hP	19.9		1971MEA[101]
60	Nd	$\beta(T_{FC})$	bcc	29		1971MEA[101]
61	Pm	$\alpha(T_{FC})$	dhcp	98		1973KOE[103]
62	Sm	$\beta(T_N)$	hP	13.8		2017JOH[104]
62	Sm	$\alpha(T_N)$	R	106		2010KON[62]
63	Eu	$\alpha(T_N)$	bcc	88.3	0.1	1972SZE[105]
64	Gd	$\alpha(T_{mag})$	hP	232		2021GIM[106]
64	Gd	$\alpha(T_{FC})$	hP	293		2021GIM[106]
64	Gd	$\alpha(T_{PC})$	hP	317		1965KOE[107]
65	Tb	$\alpha(T_{PCL})$	hP	195		1965KOE[107]
65	Tb	$\alpha(T_{FC})$	hP	220.5		2021GIM[106]
65	Tb	$\alpha(T_N)$	hP	229.0		2021GIM[106]
65	Tb	$\alpha(T_{PCP})$	hP	239		1965KOE[107]
66	Dy	$\alpha(T_{FC})$	hP	89		2021GIM[106]
66	Dy	$\alpha(T_{PCL})$	hP	121		1965KOE[107]
66	Dy	$\alpha(T_{PCP})$	hP	169		1965KOE[107]
66	Dy	$\alpha(T_{mag})$	hP	174		1965KOE[107]
66	Dy	$\alpha(T_N)$	hP	178.5	4	2021GIM[106]
67	Ho	$\alpha(T_{FC})$	hP	20		2021GIM[106]
67	Ho	$\alpha(T_{PCL})$	hP	73		1965KOE[107]
67	Ho	$\alpha(T_{PCP})$	hP	88		1965KOE[107]
67	Ho	$\alpha(T_N)$	hP	131.7		2021GIM[106]
68	Er	$\alpha(T_{FC})$	hP	17		2021GIM[106]
68	Er	$\alpha(T_{PCP})$	hP	33		1965KOE[107]
68	Er	$\alpha(T_{mag})$	hP	54		1965KOE[107]
68	Er	$\alpha(T_{PCL})$	hP	62		1965KOE[107]

68	Er	$\alpha(T_N)$	hP	86	2021GIM[106]
69	Tm	$\alpha(T_{FC})$	hP	32	2021GIM[106]
69	Tm	$\alpha(T_N)$	hP	56	2021GIM[106]
96	Cm	$\beta(T_N)$	dhcp/oP	13.7	1974KOS[108]
96	Cm	$\alpha(T_N)$	dhcp	65	2019LAN[109]
96	Cm	$\beta(T_{FC})$	fcc	205	2019LAN[109]

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