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Thermodynamic and elastic data of Cs at high pressure

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General properties

Table 4.1 Atomic properties of the alkali metals

Property	Li	Na	K	Rb	Cs	Fr
Atomic number	3	11	19	37	55	87
Number of naturally occurring isotopes	2	1	$2 + 1^{(a)}$	$1 + 1^{(a)}$	1	$1^{(a)}$
Atomic weight	6.941(2)	22.989 768(6)	39.0983(1)	85.4678(3)	132.90543(5)	(223)
Electronic configuration	$[He]2s^1$	$[Ne]3s^1$	$[Ar]4s^1$	$[Kr]5s^1$	$[Xe]6s^1$	$[Rn]7s^1$
Ionization energy/kJ mol^{-1}	520.2	495.8	418.8	403.0	375.7	~375
Electron affinity/kJ mol^{-1}	59.8	52.9	46.36	46.88	45.5	(44.0)
ΔH_{dissoc}/kJ mol^{-1} (M_2)	106.5	73.6	57.3	45.6	44.77	—
Metal radius/pm	152	186	227	248	265	—
Ionic radius (6-coordinate)/pm	76	102	138	152	167	(180)
E°/V for $M^+(aq) + e^- \longrightarrow M(s)$	−3.045	−2.714	−2.925	−2.925	−2.923	—

[a] Radioactive: ^{40}K $t_{1/2}$ 1.277×10^9 y; ^{87}Rb $t_{1/2}$ 4.75×10^{10} y; ^{223}Fr $t_{1/2}$ 21.8 min.

Table 4.2 Physical properties of the alkali metals

Property	Li	Na	K	Rb	Cs
MP/°C	180.6	97.8	63.7	39.5	28.4
BP/°C	1342	883	759	688	671
Density (20°C)/g cm^{-3}	0.534	0.968	0.856	1.532	1.90
ΔH_{fus}/kJ mol^{-1}	2.93	2.64	2.39	2.20	2.09
ΔH_{vap}/kJ mol^{-1}	148	99	79	76	67
ΔH_f (monatomic gas)/kJ mol^{-1}	162	108	89.6	82.0	78.2
Electrical resistivity (25°C)/μohm cm	9.47	4.89	7.39	13.1	20.8

Chemistry of the Elements
N. N. Greenwood, A. Earnshaw

TABLE II. Elastic constants at fusion and T_M, ρ, α, and M for eleven cubic elements.

Element	T_M (°K)	$c_{11}(T_M)$	$c_{12}(T_M)$ (10^{12} dyn/cm^2)	$c_{44}(T_M)$	$\rho(300)$ (g/cm^3)	α (10^{-4}°K^{-1})	M
fcc							
Li	459	0.1266[a]	0.1064[a]	0.0739[a]	0.534[b]	...	6.94
Na	370.7	0.0709[c]	0.0599[c]	0.0370[c]	0.971[d]	2.75[e]	23.00
K	335.2	0.0363[f]	0.0310[f]	0.0172[f]	0.851[f]	2.5[e]	39.10
Rb	311.7	0.0269[g]	0.0230[g]	0.0130[g]	1.53[b]	...	85.48
Cs	301.7	0.0218[h]	0.0186[h]	0.0107[h]	1.873[b]	...	132.91
bcc							
Al	932.7	0.683[i]	0.403[i]	0.188[i]	2.699[d]	0.99[e]	26.97
I		1.315[i]	1.053[i]	0.4833[i]			
Cu	1356				8.937[j]	0.70[e]	63.54
II		1.269[j]	1.018[j]	0.470[j]			
I		0.958[i]	0.791[i]	0.279[i]			
Ag	1233.8				10.50[j]	0.81[e]	107.88
II		0.916[j]	0.764[j]	0.287[j]			
I		1.538[i]	1.343[i]	0.294[i]			
Au	1336				19.30[j]	0.58[e]	197.00
II		1.572[j]	1.380[j]	0.281[j]			
Pb	600.4	0.419[i]	0.374[i]	0.100[i]	11.34[b]	1.2[e]	207.21
Ni	1728	1.52[i]	1.42[i]	0.66[i]	8.90[b]	0.57[e]	58.69

[a] T. Slotwinski and J. Trivisonno, J. Phys. Chem. Solids **30**, 1276 (1969).
[b] See Ref. 17.
[c] M. E. Diederich and J. Trivisonno, J. Phys. Chem. Solids **27**, 637 (1966).
[d] O. L. Anderson, in *Physical Acoustics* (Academic Press Inc., New York, 1965), Vol. III, Part B.
[e] O. Kubaschewski, Trans. Faraday Soc. **45**, 931 (1949).
[f] W. R. Marquardt and J. Trivisonno, J. Phys. Chem. Solids **26**, 273 (1965).
[g] See Ref. 18.
[h] F. J. Kollarits and J. Trivisonno, J. Phys. Chem. Solids **29**, 2133 (1968).
[i] See Ref. 10.
[j] See Ref. 11.

$$Cs: C_{11} = 2.18\,\text{GPa}; C_{12} = 1.86\,\text{GPa}; C_{44} = 1.07\,\text{GPa}; \rho = 1873\,\text{kg/m}^3$$

Lindemann and lattice dynamics
Shapiro (1970)

Reactivity

• Cesium is extremely reactive, and hence the sample container was filled and the furnace parts assembled in an argon dry box [Kennedy 1962]

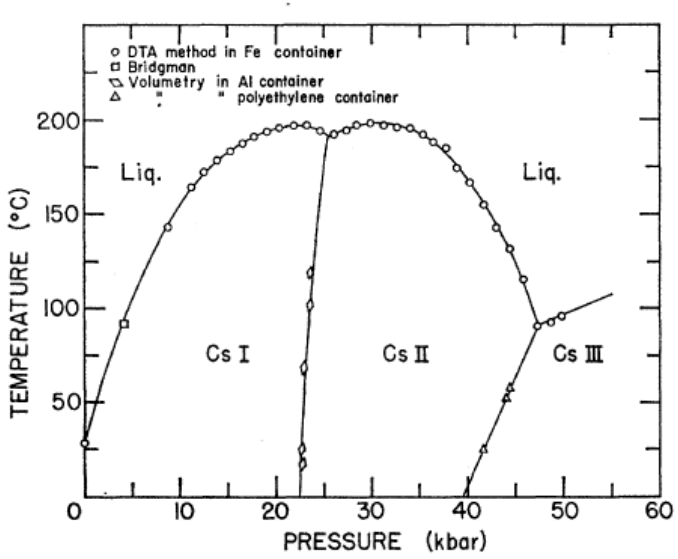
• Iron was chosen because it is known to be completely inert to the presence of alkali metals even at their boiling temperatures [Kennedy 1962]

• The Cs was loaded without a pressure-transmitting medium, in an oxygen- and water-free atmosphere to prevent contamination. A small ruby sphere was enclosed with the sample for pressure measurement [McMahon 2001]

Phase diagram

• Kennedy (1962)	up to 5 GPa
• Kennedy (1962b)	
• Jayaraman (1967)	up to 5 GPa
• Rapoport (1968)	
• Wittig (1970)	superconducting Cs
• Makarenko (1973)	up to 2.2 GPa
• Cannon (1974)	
• Boehler (1986)	up to 9 GPa
• Young (1991)	
• Tonkov (2005)	
• Falconi (2005)	up to 10.5 GPa

Kennedy (1962)



G. C. Kennedy, A. Jayaraman, and R. C. Newton
Fusion Curve and Polymorphic Transitions of Cesium at High Pressures
Phys. Rev. **126**, 1363 (1962)

Kennedy (1962b)

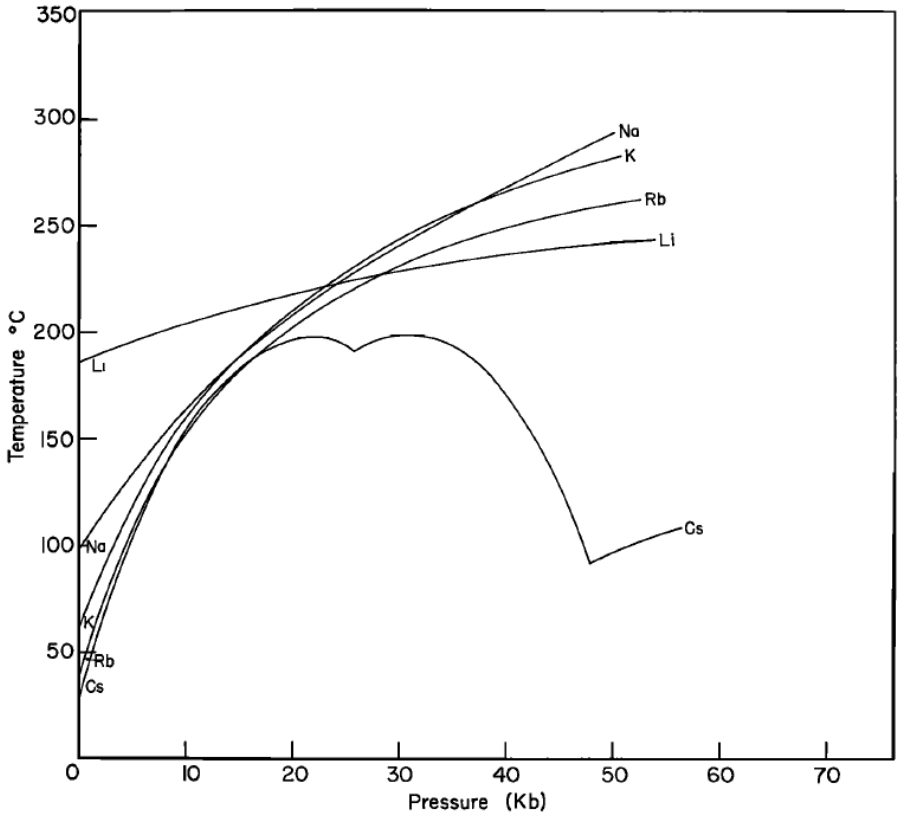


Fig. 6. Fusion curves of the alkali metals.

The fusion curve for cesium displays a double maximum. At a temperature of 195°, four different melting-freezing points for cesium exist, and a fifth point probably occurs at pressures of the order of 100 kb where Cs III melts. The two minima shown in the melting curve of cesium represent the points where the boundaries of Cs I ⇄ Cs II and Cs II ⇄ III intersect the melting curve. The features of the cesium melting curve are discussed in detail by *Kennedy, Jayaraman, and Newton* [1961].

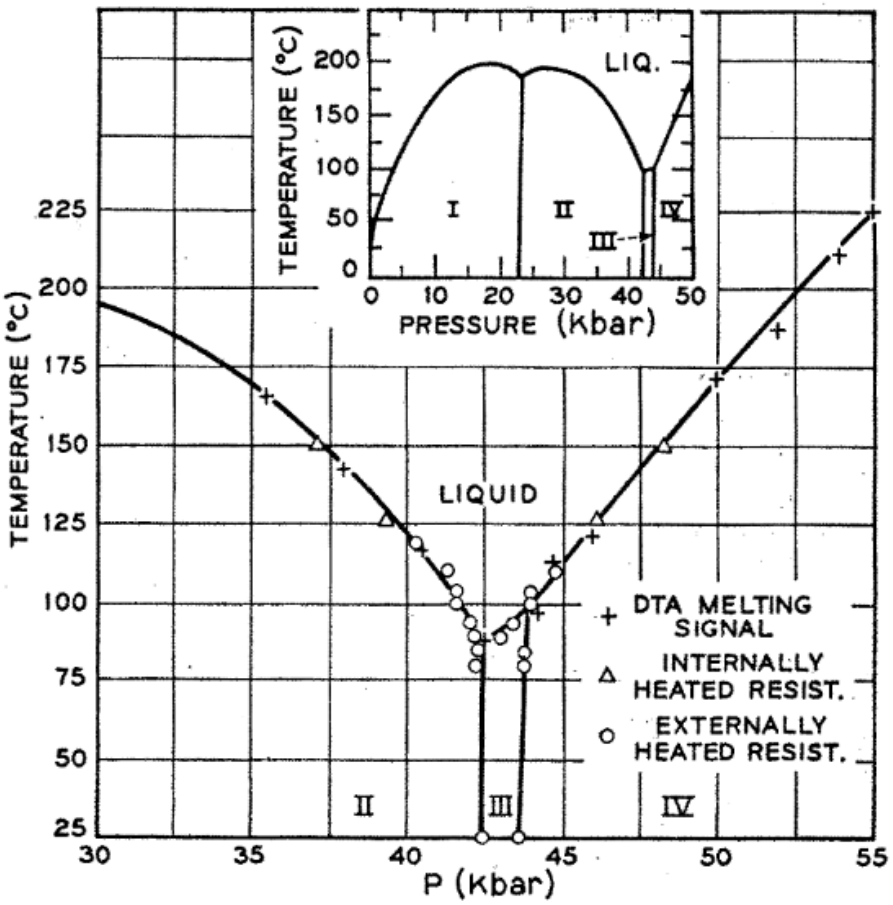
Kennedy G. C., A. Jayaraman, and R. Newton, Melting of cesium at high pressures, *Phys. Rev.*, in press, 1962.

TABLE 1. Melting Points of Alkali Metals

	Temperature, deg. C					
Pressure, kb	Li	Na	K	Rb	Cs	Na-K eutectic
5	195	134	120	109	104	07
10	203	164	111	103	106	22
15	211	189	189	183	184	34
20	218	209	211	203	196	44
25	223	226	229	218	193	53
30	229	241	244	231	198	60
35	233	255	256	241	193	—
40	236	268	266	249	169	—
45	239	281	274	255	124	—
50	242	294	281	260	97	—

R.C. Newton, A. Jayaraman, and G.C. Kennedy, *The fusion curves of the alkali metals up to 50 kilobars*, *J. Geophys. Res.*, **67(6)**, 2559–2566 (1962), doi: 10.1029/JZ067i006p02559.

Jayaraman (1967)



A. Jayaraman, R. C. Newton and J.M. McDonough
Phase Relations, Resistivity, and Electronic Structure of Cesium at High Pressures
Phys. Rev. **159,** 315 (1967)

Rapoport (1968)

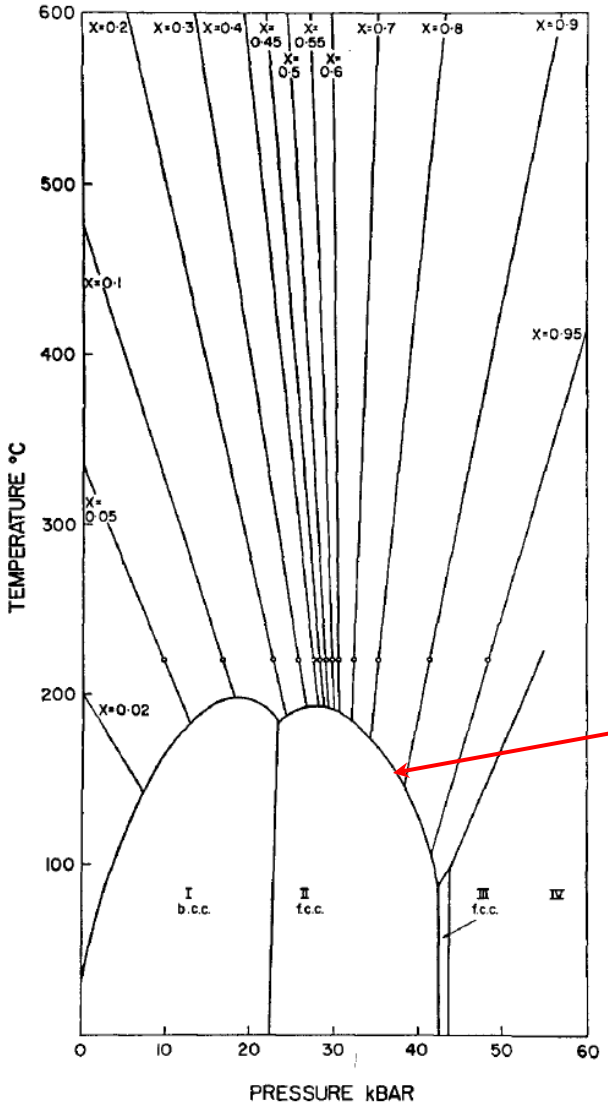


FIG. 1. Iso-concentration lines in liquid cesium.

data from Jayaraman (1967)

E. Rapoport , *Melting-Curve Maxima at High Pressure. II. Liquid Cesium. Resistivity, Hall Effect, and Composition of Molten Tellurium*, The Journal of Chemical Physics **48**, 1433 (1968)
doi: 10.1063/1.1668858

Wittig (1970)

Superconducting Cs

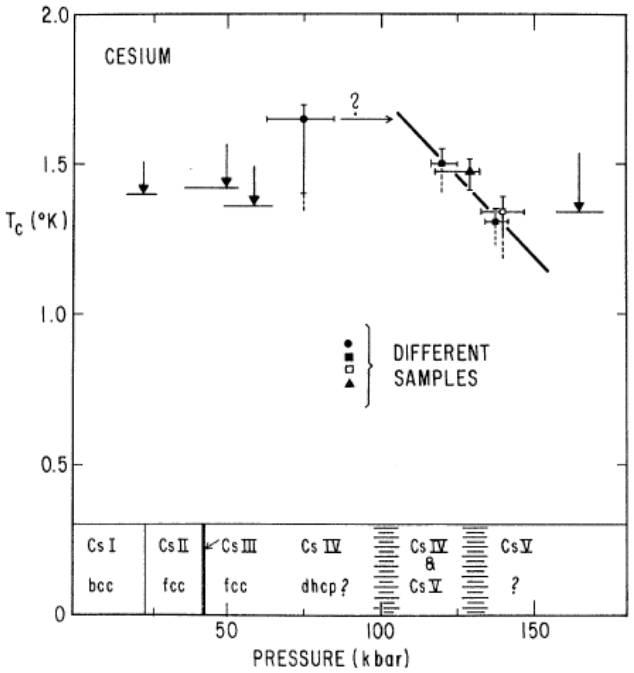


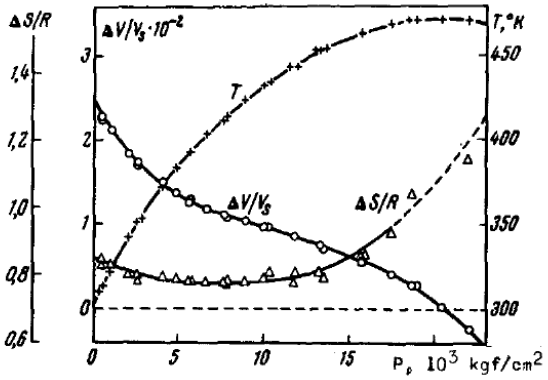
FIG. 1. T_c versus pressure for the phase Cs(V). Arrows indicate the absence of superconductivity. Horizontal bars represent the pressure inhomogeneity along the sample. The inset delineates the regions of stability for the various phases at room temperature.

Makarenko (1973)

Thermodynamics of the melting of cesium [3)]

T, °K	P, kg/cm²	ΔV cm³/mole	ΔV/V_s	ΔS/R	ΔH cal/mole	ΔU cal/mole
301.52	1	1.691	0.0243	0.8477	507.7	507.7
323.23	1000	1.408	0,0210	0.8272	531.1	498.1
341.85	2000	1.188	0,0184	0,8104	550.3	494.7
372.08	4000	0,888	0,0148	0.7904	584.2	501.0
395.75	6000	0,707	0,0124	0.7852	617.3	517.9
415.08	8000	0,587	0,0108	0.7854	647.6	537.6
431.25	10000	0,493	0,0096	0,7853	672.8	557.3
444.76	12000	0.410	0,0083	0.7895	697.5	582.4
455.70	14000	0.331	0,0069	0.8103	733.5	625.0
463.95	16000	0.250	0,0054	0.8618	794.2	700.5
469.34	18000	0.158	0,0036	0.9525	888.0	821.4
471.76	20000	0.042	0,0012	1.0746	1007.0	987.3
471.20	22000	- 0.101	-0,0023	1.1864	1110.4	1162.7

T, P. — melting temperature and melting pressure, ΔV — discontinuity of the volume upon melting, V_S — volume of solid phase at the melting point, ΔS — melting entropy, R — gas constant, ΔH — melting heat, ΔU — change of internal energy upon melting.



Pressure dependence of melting temperature T, relative jump of volume upon melting $\Delta V/V_S$ and melting entropy ΔS/R of cesium.

Makarenko, I. N., V. A. Ivanov, and S. M. Stishov. "Thermodynamics of the melting of cesium at high pressures." *Soviet Journal of Experimental and Theoretical Physics Letters* **18** 187 (1973)

Cannon (1974)

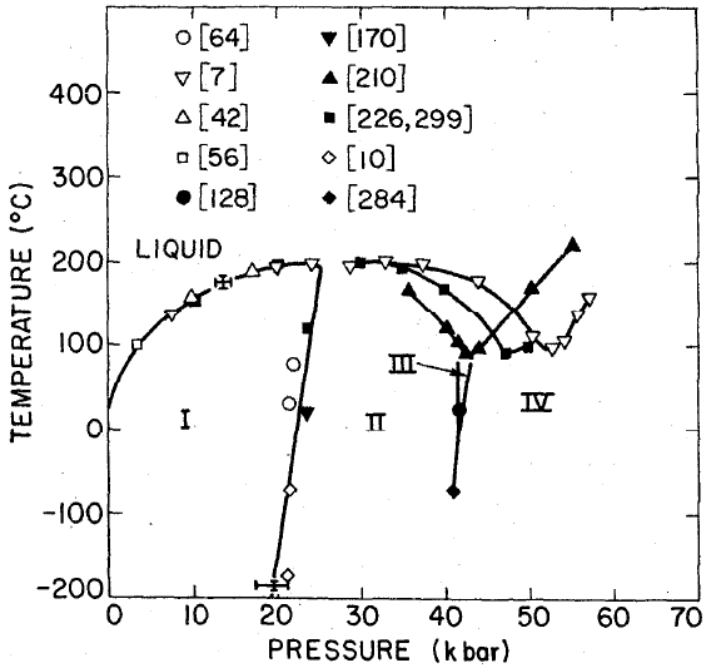


FIGURE 6. Phase diagram for cesium.

[64] Bridgman, P. W . Proc. Amer. Acad. Arts Sci., **72**, 157-205 (1938).
[7] Anderson, D. R., Unpublished Dissertation, Brigham Young University, Provo, Utah, 156 pp., 1969.
[42] Bogdanov, V. S., JETP Lett., 3, 26-28 (1966); Engl. Transl. Of Zh. Eksp. Teor. Fiz. Pis'ma Red., 3 ,44-47. (19(:i6).
[56] Bridgman, P. W., Proc. Amer. Acad. Arts Sci., 60, 385-421 (1925).
[128] Decker, D. L., Bassett, W. A., Merrill, L., Hall, H. T., Barnett, J. D., J. Phys. Chem. Ref. Data, 1, 773-836 (1972).
[170] Hall, H. T., Merrill, L., Barnett, J. D., Science, 146, 1297-1299 (1964).
[210] Jayaraman, A., Newton, R. C., McDonough, J. M., Phys. Rev., **159**,527-533 (1967).
[226] Kennedy, G. C., Jayaraman, Newton, Phys. Rev., **126**, 1363-1366 (1962).
[299] Newton, R. C., Jayaraman, A., Kennedy, G. C., J. Geophys. Res., **67**,2559 (1962)
[10] Anderson, M. S., Gutman, E. J., Packard, J. R., Swenson, C. A., J. Phys. Chern. Solids, 30, 1587-1601 (1969).
[284J] McWhan, D. B.. Stevens, A. L., Solid State Commun., 7,301-304 (1969).

Behavior of the Elements at High Pressures
John Francis Cannon, J. Phys. Chem. Ref. Data 3, 781 (1974)

Boehler (1986)

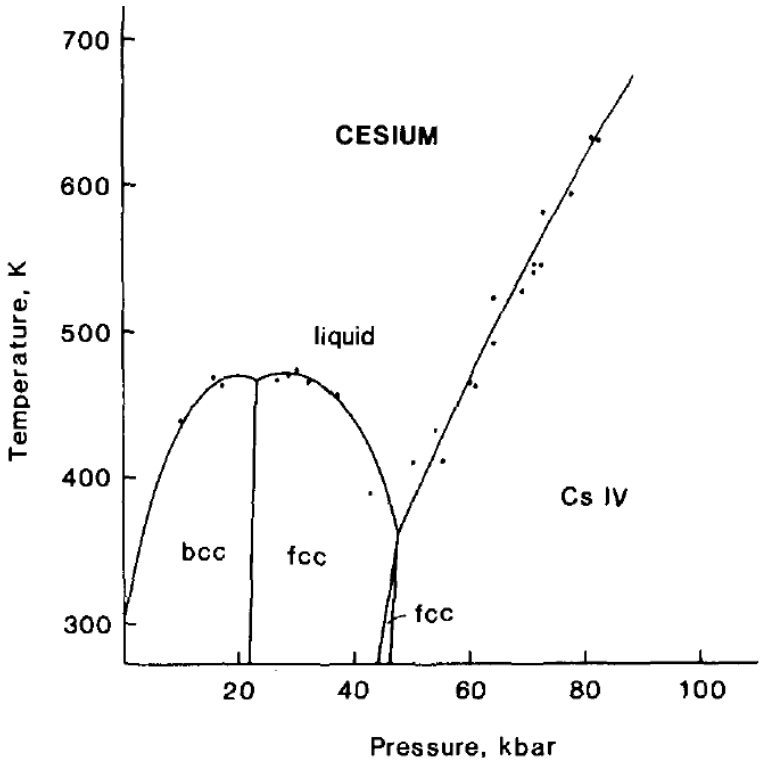


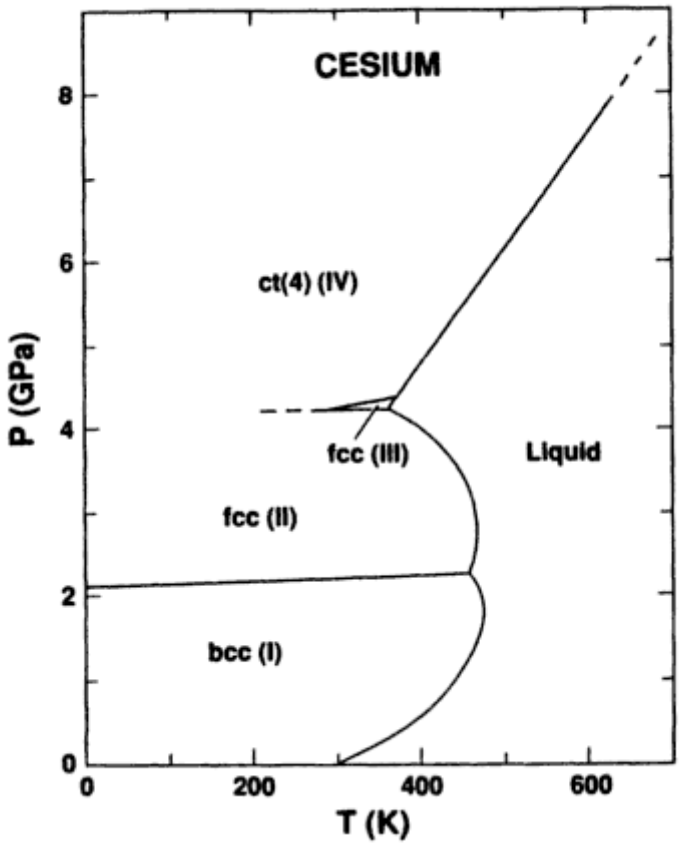
Fig. 4. Phase diagram of cesium. The phase boundaries below 50 kbar are taken from piston–cylinder work. The dots are melting points from the present DAC work.

Systematics in the melting behavior of the alkali metals from DAC measurements
R. Boehler and C.-S. Zha
Physica B+C **139–140** 233–236 (1986)

Melting line (data points)

P(GPa)	T(K)
0.98684	438.7
1.5526	467.79
1.7105	462.6
2.6579	466.23
2.8553	469.87
3	473.51
3.1974	464.68
3.7105	456.36
4.2763	388.31
5.0263	410.13
5.3947	431.95
5.5526	410.65
6	464.68
6.1053	462.6
6.4079	491.17
6.4211	522.34
6.9079	527.01
7.1053	540
7.1184	545.19
7.2368	545.19
7.2763	580.52
7.7632	594.03
8.1053	631.95
8.2237	630.39

Young (1991)



David A. Young, *Phase diagrams of the elements,*
University of California Press (1991)

Tonkov (2005)

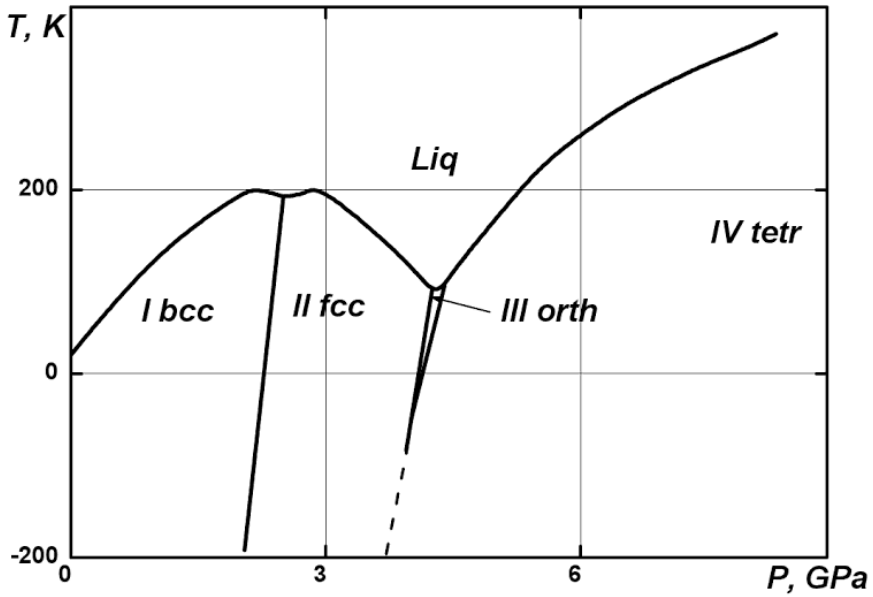


Figure 9. The phase diagram of cesium.

Phase Transformations of Elements Under High Pressure, E. Yu Tonkov,E.G. Ponyatovsky (2005) (p.36)

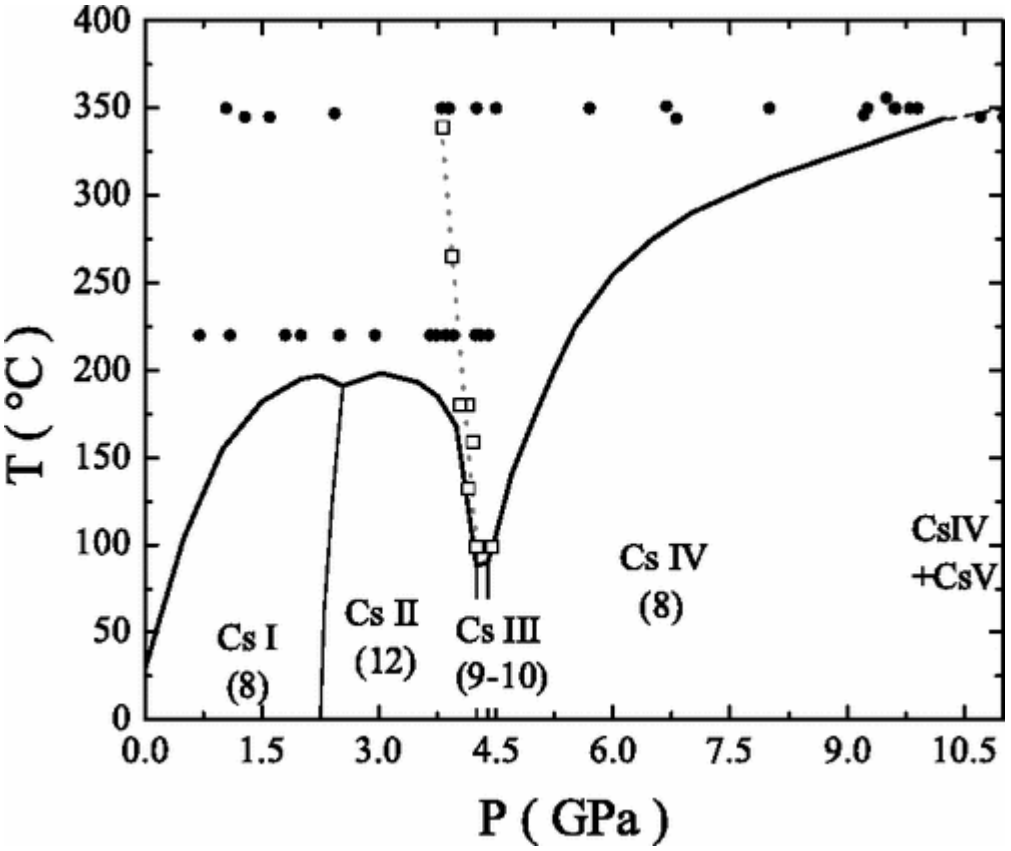
Cesium

At 0.1 MPa, cesium has a bcc structure with a = 0.6141 nm at 25°C and melts at 28°C. The fusion curve was accurately determined by the volumetric method up to 0.4 GPa [1], up to 1.65 GPa [55] up to 2.14 GPa [12,13], by DTA up to 5 GPa [6,7,68], up to 5.5 GPa [57], up to 8 GPa [59], and in [26]. The melting curve is unique: it shows two temperature maxima. The first maximum for phase I was observed at 200°C and 2.015 GPa and the second maximum for phase II at 198°C and 3 GPa. The structural changes in liquid state were determined up to 4.5 GPa [47,48,63]. The fusion curve was calculated in [14,25,32,37–39,44,45,52,61,62,66]. The melting curve of Cs IV was observed at 225°C and 5.5 GPa [57], and at 357°C and 8.3 GPa with dT/dP = 70 K/GPa at 4.4–5.5 GPa [26]. Two changes in liquid state were determined at about 2 GPa and 3–4 GPa [47,48,63]. The liquid can become more dense than the solid in the region of the transformation II–III at about 3–4 GPa. The high-temperature phase diagram was studied in [57]. The following triple points were detected: I–II–Liquid at 2.5 GPa and 191°C, II–III–Liquid at 4.25 GPa and 88°C, and III–IV–Liquid at 4.39 GPa and 98°C.

Phase transitions in Cs at room temperature are used as calibrants of pressure scale [2–9,11,43,51,54,56,58,59,65,67]. The I–II phase transformation was determined at 2.26 GPa and 25°C and at 2.08 GPa and –196°C [59], by calculation [74]. Phase transitions near 4.3 GPa were investigated by volumetric, electroresistance, and structural studies [17–21,43,46,56–58].

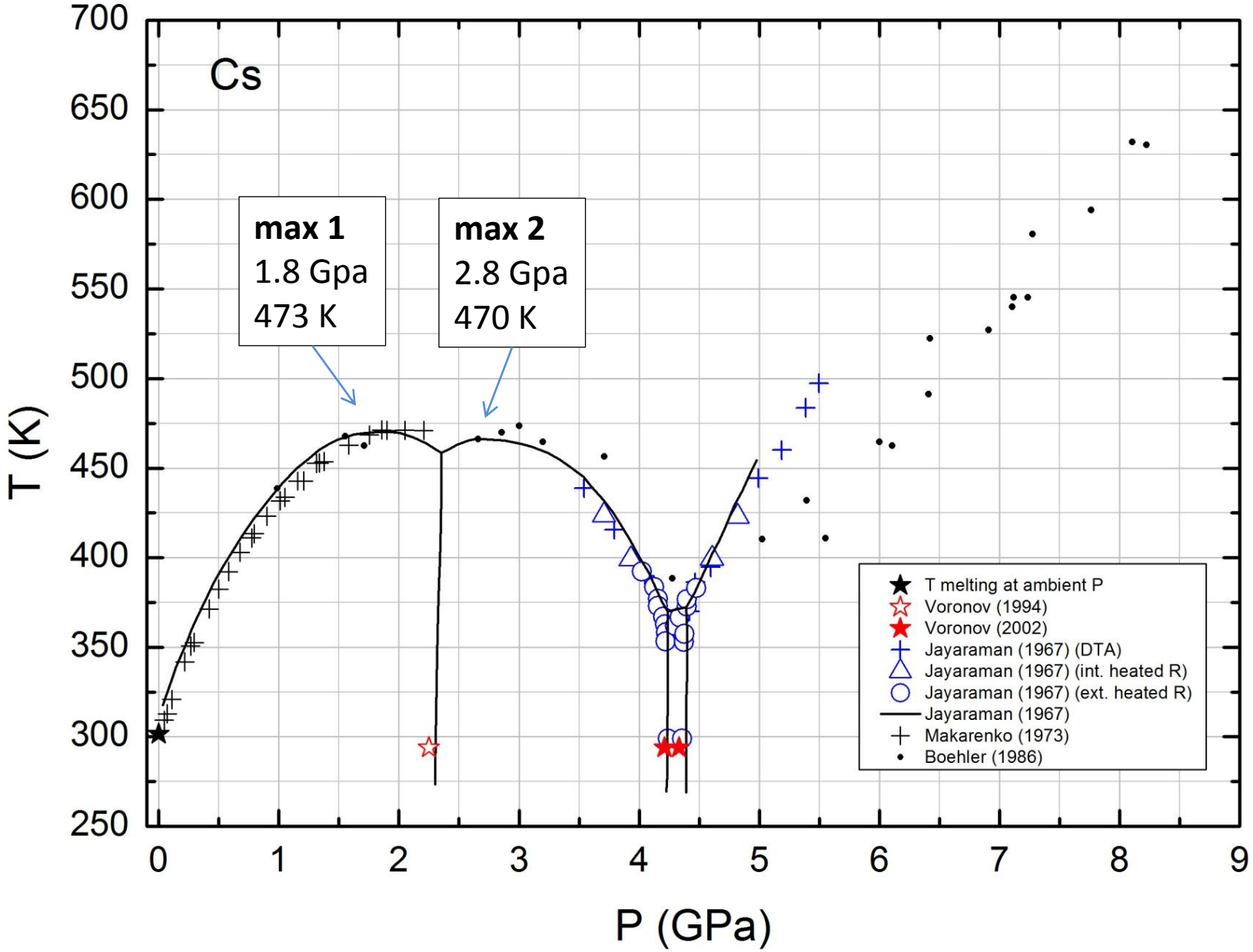
At room temperature, the II–III phase transition was observed at 4.15 GPa and the III–IV phase transition at 4.2 GPa. Slopes within the temperature range between the triple points II–III–Liquid, III–IV–Liquid, and II–III–IV exceed at

Falconi (2005)



X-ray Diffraction Study of Liquid Cs up to 9.8 GPa
S. Falconi, L. F. Lundegaard, C. Hejny, and M. I. McMahon
Phys. Rev. Lett. **94**, 125507 (2005)

Cs, phase diagram



Cs-II

TABLE II. Parameters of the bcc–fcc phase transition in cesium.

T, K	p, GPa	V/V_0^*	$-\Delta(V/V_0)$,%	Year	Source
294	2.25 ± 0.02	0.6006	0.70 ± 0.03	1993	
298	2.25	0.602	0.6	1938	[21]
298	2.28	0.628	0.6	1948	[10]
298	2.26 ± 0.06	-	-	1962	[22]
295	2.24	0.589	0.6	1969	[11]
295	2.22	0.6024	0.63	1985	[14]

(from Voronov 1994)

Cs-III

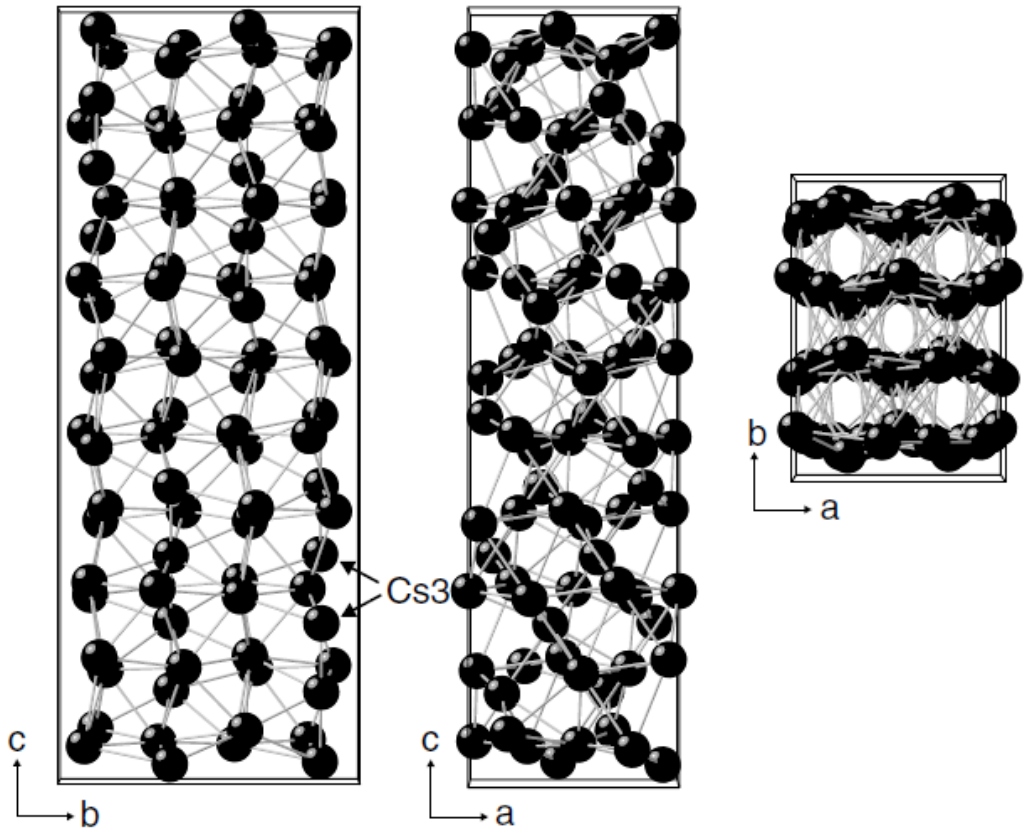


FIG. 3. Crystal structure of Cs-III as viewed down the a, b, and c axes of the orthorhombic $C222_1$ unit cell. Bonds are shown between atoms whose interatomic spacing is between 3.6 and 4.4 Å. The labeled Cs3 atoms are discussed in the text.

Complex Crystal Structure of Cesium-III

M. I. McMahon, R. J. Nelmes, and S. Rekhi

Cs-IV

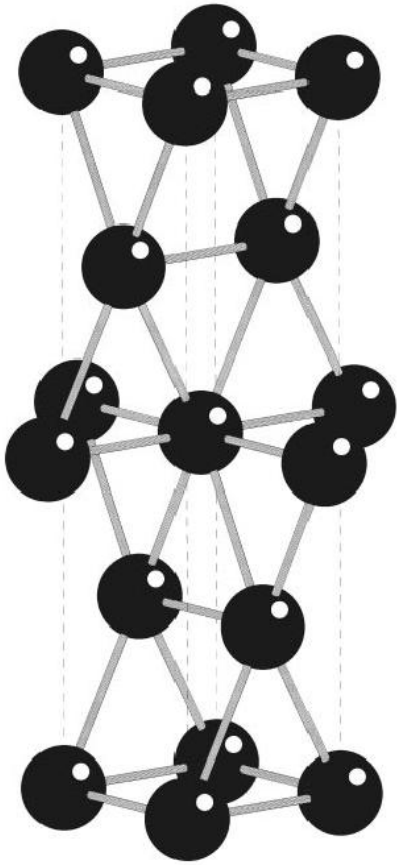


FIG. 3. Crystal structure of Cs(IV) at 13.3 GPa. The tetragonal *c* axis is vertical. Some of the cesium atoms have been removed for clarity. The structure can be constructed from trigonal prisms of cesiums. The eight-coordination about a single cesium can be seen for the central body-centered atom. The nearest neighbor bonds (four) that are in the *a*–*b* plane are 3.37 Å long. All of the other nearest neighbor bonds (four) that are not in the *a*–*b* plane are 3.52 Å long.

Rietveld Refinement of the Crystal Structure of Cs(IV), ad-Electron Metal
J.L. Delattre, J.V. Badding
Journal of Solid State Chemistry, **144**, 16 (1999)

Cs-V

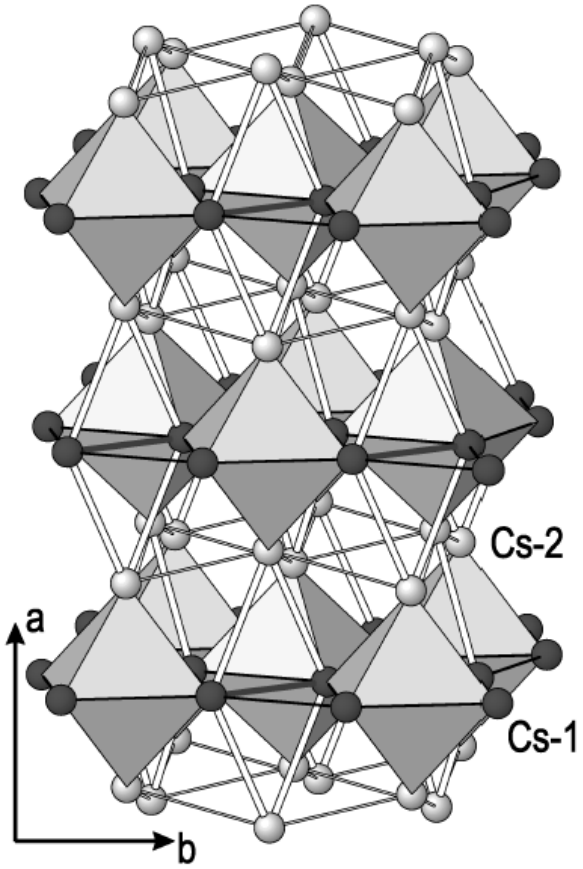


FIG. 2. Perspective view of the *Cmca* crystal structure of Cs-V. Atoms occupy two different Wyckoff positions. The thick solid and open lines between atoms indicate the shortest and longest bond lengths, respectively, in the first coordination sphere. The octahedra mark nearly close-packed units. Note that there are no central atoms inside the octahedra.

Crystal Structure of Cesium-V
U. Schwarz, K. Takemura, M. Hanfland and K. Syassen
Phys. Rev. Lett. **28** (1998)

Cs-VI

TABLE I. Fitted equation-of-state parameters [Vinet relation, Eq. (1)] for the phases Cs-V and Cs-VI. V_0, B_0, and B' are the atomic volume, bulk modulus, and pressure derivative of the bulk modulus at the reference pressure P_0. Errors refer to 95% confidence limits. The last row lists corresponding parameters for the calculated PV relation of rhenium (see the Appendix).

	P_0 (GPa)	V_0 (Å^3)	B_0 (GPa)	B'
Cs-V (expt.)	12	30.60	65(12)	4.7(10)
Cs-V (theor.)	11.4	31.12	51	5.06
Cs-VI (expt.)	74	19.92(10)	330(40)	4 (fixed)
Cs-VI (theor.)	72.1	19.99	279.6	3.49
Re (theor.)	−3.9	14.686	371	4.19

Phase stability of highly compressed cesium
K. Takemura, N. E. Christensen, D. L. Novikov, K. Syassen, U. Schwarz, and M. Hanfland
Phys. Rev. B **61**, 14399 (2000)

Comparison with other alkali metals

Li	bcc $\xrightarrow{7.5}$ fcc $\xrightarrow{39}$ *hR*1 $\xrightarrow{42}$ *cI*16 $\xrightarrow{60}$ *oC*88 $\xrightarrow{70}$ *oC*40 $\xrightarrow{95}$ *oC*24 < 125
Na	bcc $\xrightarrow{65}$ fcc $\xrightarrow{104}$ *cI*16 $\xrightarrow{117}$ *oP*8 $\xrightarrow{125}$ h-g (*tI*19*) $\xrightarrow{180}$ *hP*4 < 200 GPa
K	bcc $\xrightarrow{11.6}$ fcc $\xrightarrow{20}$ h-g (*tI*19*) $\xrightarrow{54}$ *oP*8 $\xrightarrow{90}$ *tI*4 $\xrightarrow{96}$ *oC*16 < 112 GPa fcc $\xrightarrow{25}$ *hP*4 $\xrightarrow{35}$
Rb	bcc $\xrightarrow{7}$ fcc $\xrightarrow{13}$ *oC*52 $\xrightarrow{17}$ h-g (*tI*19*) $\xrightarrow{20}$ *tI*4 $\xrightarrow{48}$ *oC*16 < 70 GPa
Cs	bcc $\xrightarrow{2.4}$ fcc $\xrightarrow{4.2}$ *oC*84 $\xrightarrow{4.3}$ *tI*4 $\xrightarrow{12}$ *oC*16 $\xrightarrow{72}$ dhcp < 223 GPa

V.F. Degtyareva. Solid State Sciences **36** 62 (2014)

Katzke PRB 2005

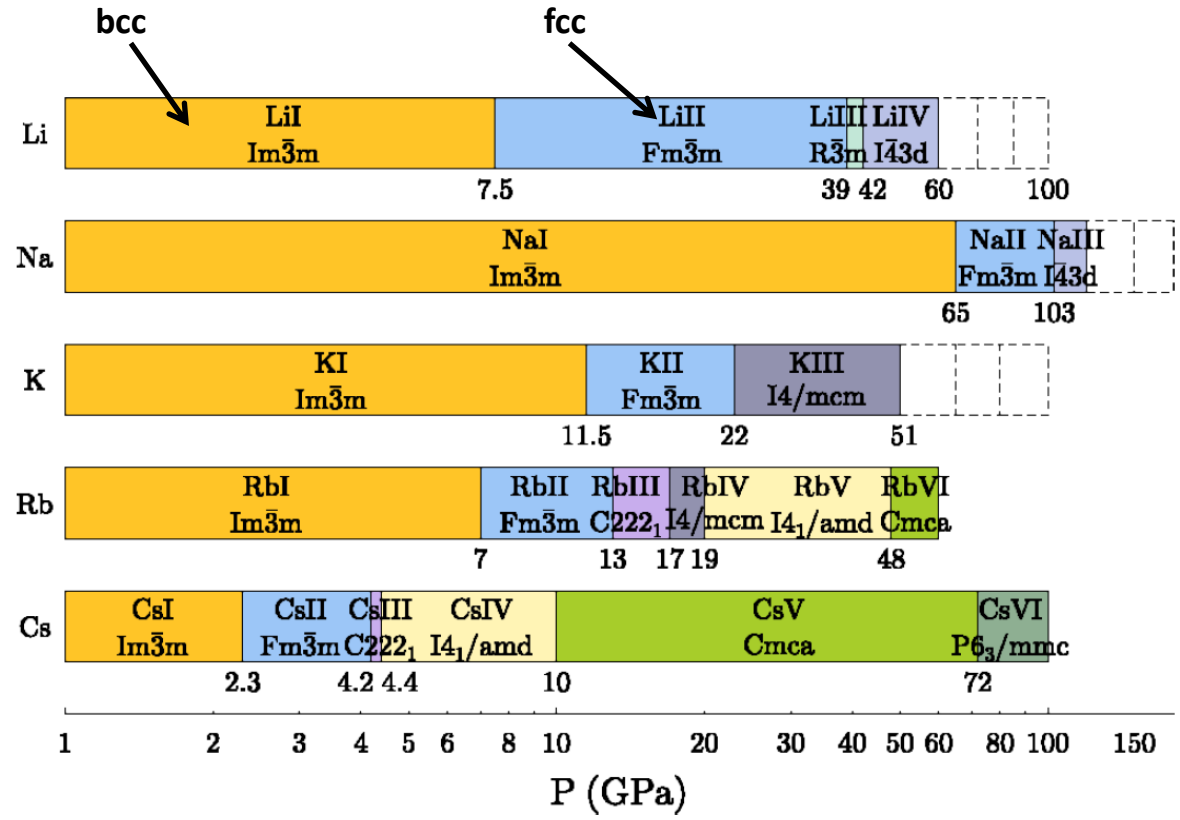


FIG. 1. (Color online) Phase sequences for the alkali metals as a function of pressure (Refs. 2–7, 11, and 13–15).

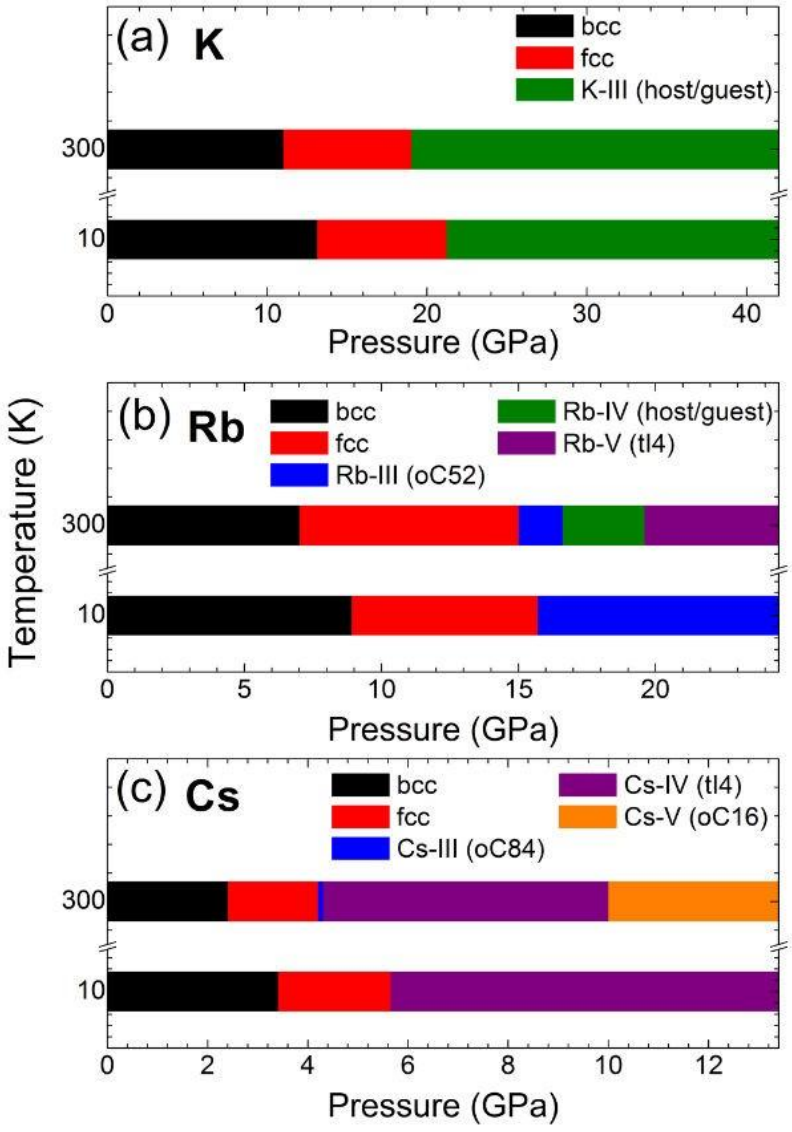


FIG. 7. (Color online) Phases of K, Rb, and Cs at 10 K and room temperature [4,19].

Electronic and structural ground state of heavy alkali metals at high pressure

G. Fabbris. J. Lim. L. S. I. Veiga. D. Haskel. and J. S. Schilling

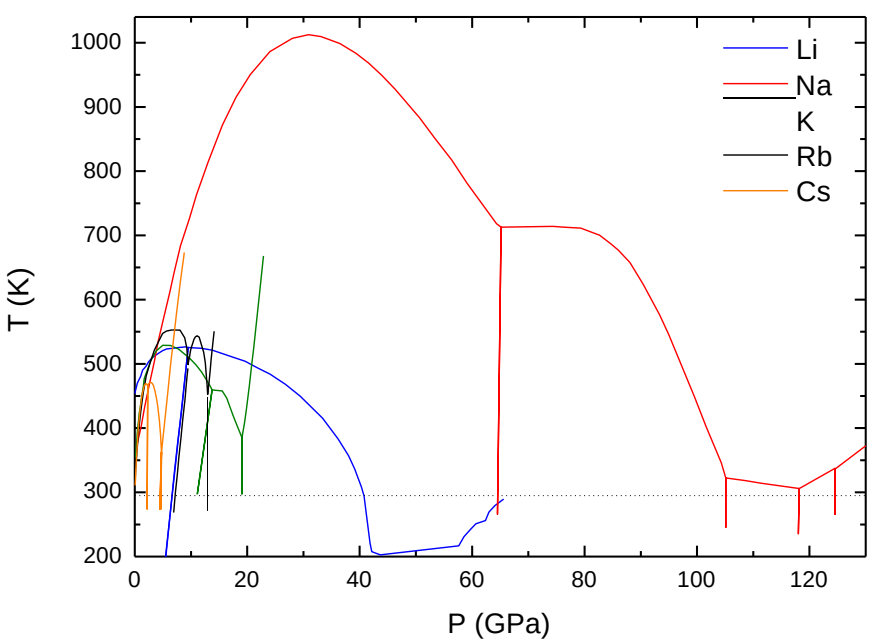
PRB **91** 085111 (2015)

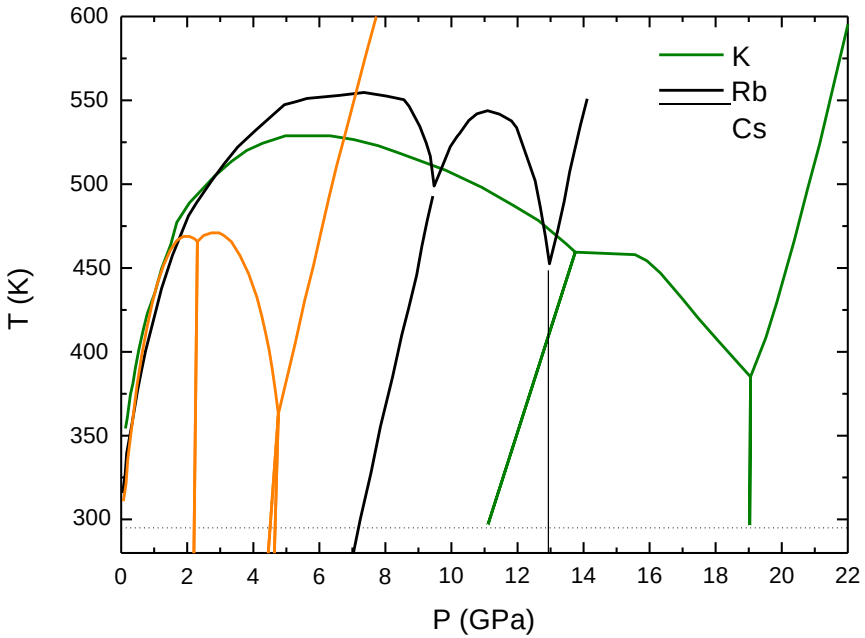
Melting line

TABLE I. Input data and melting maximum.

Solid	Cs	Rb	K	Na	Li
Pressure range (kbar)	0–25	0–80	0–80	0–80	0–80
Temp. range (K)	301.85–464.15	312.05–557.15	336.85–553.15	370.95–608.15	453.65–527.15
T_0 (K)	301.85	312.05	336.85	370.95	453.65
$B_T(0,T_0)$ (kbar)	24.315	23.031	28.52	53.42	98.15
		(22.2)	(27.8)	(54.5)	
$B'_T(0,T_0)$	1.792	4.704	5.018	5.696	6.248
		(4.63)	(4.74)	(4.94)	
$\gamma(0,T_0)$	1.050	1.020	1.017	1.006	0.7214
		(1.0639)	(1.0412)	(1.071)	
$\gamma'(0,T_0)$ ($\times 10^{-3}$ kbar^{-1})	33.366	8.997	9.506	1.784	4.506
RMSD (in T_m)	0.59	1.15	1.18	0.86	0.55
$(P)_{max}$ (kbar)	21.5	76.5	72	377	86
bcc-fcc transition at room temp. (kbar)	22	70	110		

N. Dass
Melting maximum in alkali metals
Phys. Rev. B **52**, 3023 (1995)


T (K)
P (GPa)
Li
Na
K
Rb
Cs
1000
900
800
700
600
500
400
300
200
0
20
40
60
80
100
120


T (K)
P (GPa)
K
Rb
Cs
600
550
500
450
400
350
300
0
2
4
6
8
10
12
14
16
18
20
22

Critical point

Table 1. The results of theoretical calculations and experimental measurements of T_c (K).

Me	Li	Na	K	Rb	Cs	Fr
[11]	3293	—	—	—	—	—
[12]	—	2800	2440	2190	2150	—
[13]	—	2880	2440	—	—	—
[14]	3223 ± 600	2573 ± 350	2223 ± 600	2093 ± 25	2057 ± 40	—
[15]	2938	—	—	—	—	—
[16]	3286	2573 ± 60	2173 ± 50	—	—	—
[5]	—	2136	1790	—	—	—
[17]	—	—	—	—	—	1550
[18]	3831	2635	2185	2061	1942	—
[19]	3223	2573	2223	2093	2057 ± 40	1810
[20]	—	2504	2281 ± 5	2106	2048 ± 4	—
[2]	—	2326	1924	—	—	—
[21, 22]	3680 ± 300	2503 ± 50	2281	2106 ± 15	2043 ± 15	1980 ± 50
[23]	—	2504 ± 50	2240 ± 40	2097 ± 10	2043 ± 6	—
[24]	—	—	2280	2090	2010	—
[25]	—	—	—	—	1924	—
[26]	3503 ± 10	2497 ± 18	2239 ± 49	2100 ± 15	2035 ± 23	—
[26]	3344 ± 42	—	—	—	—	—
[27]	3741	2429	2195	1995	2018	—
[28]	3474	2590	2195	—	—	—
[7]	3407	—	2050	—	—	—
[8]	3232	—	—	—	—	—
[29]	—	—	—	—	1938 ± 10	—
[30]	—	2485	2280	2017	1924	—
[4]	3285	2421	2106	1796	1736	—
[31]	3214	2908	2152	1912	1770	—
[32]	3350	2263	2111	1946	1884	—
[6]	3225	—	—	—	—	—
[33, 34]	3503 ± 10	2497 ± 18	2239	—	2035 ± 23	—
[35]	3210	2480	2230	2120	2020	—
[36]	—	—	—	—	—	1400
[37]	—	—	1987	1822	—	—
[38]	3940	2489	—	—	—	—
[39]	—	—	—	—	—	1690
[40]	2797	2180	2233	1836	1786	—
This work	3190	2420	2106	1930	1830	1690

Estimation of the critical temperatures of alkaline metals on the basis of specified data on surface tension polytherms
B B Alchagirov, B S Karamurzov, Kh Kh Kalazhokov, Z A Kokov and O Kh Kyasova
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Journal of Physics: Conference Series, Volume 1147, conference 1

Adiabatic sound velocity

• Kleppa (1950)	liquid Cs, up to 130°C
• Kemp & Letcher (1968)	liquid Cs*, reported in Kim (1971)*
• Kim (1971)	liquid Cs, 50-250°C
• Chan (1972)	liquid Cs
• Shaw (1985)	liquid Cs, up to 0.7 GPa
• Vargaftik (1986)	liquid Cs, 400-1400 K
• Kozhevnikov (1990)	liquid and vapor , up to 2200 K to 60 Mpa
• Voronov (1994)	solid Cs, up to 2.5 GPa
• Voronov (2002)	solid Cs, up to 5.5 Gpa
• Decremps (2018)	liquid Cs, T=493 K, up to 4.8 GPa

Kleppa (1950)

TABLE II. Sound velocities and temperature gradients.

Metal	m.p. t°C	u (m/sec.)	$\frac{du}{dt}$ (m sec.$^{-1}$ deg.$^{-1}$, approx.)	Temp. Range m.p. to °C
Zn	420	2790±60	—	480
Ga	30	2740±50	—	50
Cd	321	2200±20	−0.5	360
In	156	2215±20	−0.5	260
Sn	232	2270±20	−0.7	380
Tl	302	1625±15	—	310
Pb	327	1790±15	−0.5	380
Bi	271	1635±15	−0.5	365
Na	98	2395±25	−0.3	235
K	64	1820±20	−0.5	160
Rb	39	1260±10	−0.4	160
Cs	29	967±10	−0.3	130

[7] T. W. Richards and S. Boyer, J. Am. Chem. Soc. **43**, 294 (1921).

O. J. Kleppa, *Ultrasonic Velocities of Sound in Some Metallic Liquids. Adiabatic and Isothermal Compressibilities of Liquid Metals at Their Melting Points,* The Journal of Chemical Physics **18,** 1331 (1950)
doi: 10.1063/1.1747472

Kim (1971)

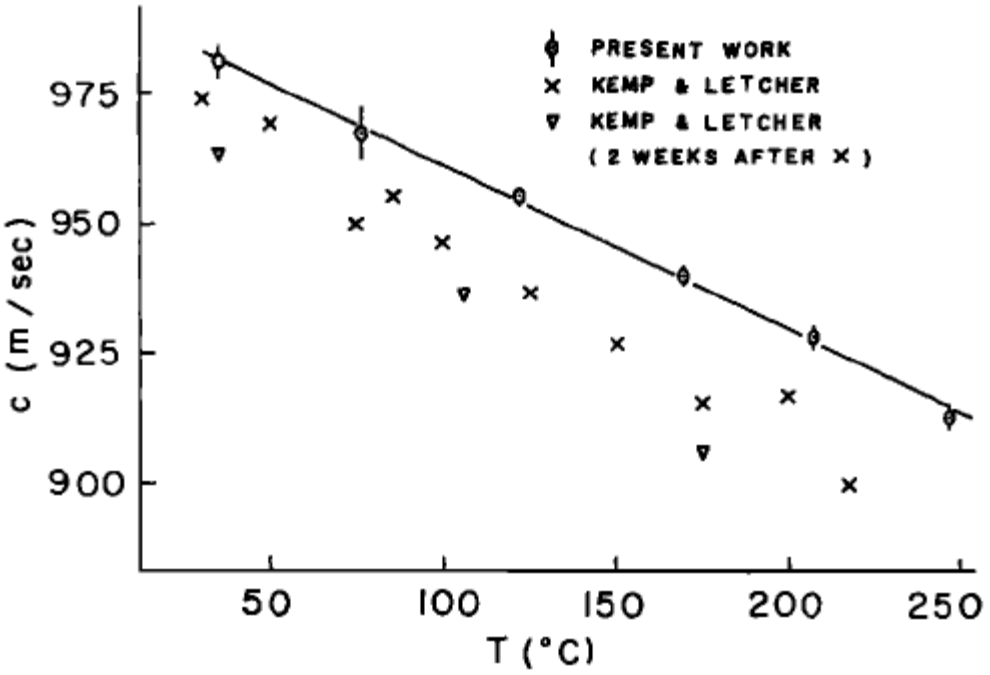


FIG. 4. Sound velocity versus temperature in liquid Cs.

Ultrasonic Measurement in Liquid Alkali Metals
M. G. Kim, K. A. Kemp and S. V. Letcher
J. Acoust. Soc. Am. **49**, 706 (1971)
http://dx.doi.org/10.1121/1.1912406

Chan (1972)

Chan, J. P., *The velocity of sound in liquid cesium from its melting point to 655 K*, Physics and Chemistry of Liquids, **3(1),** 55-58 (1972)
http://dx.doi.org/10.1080/00319107208084088

Shaw (1985)

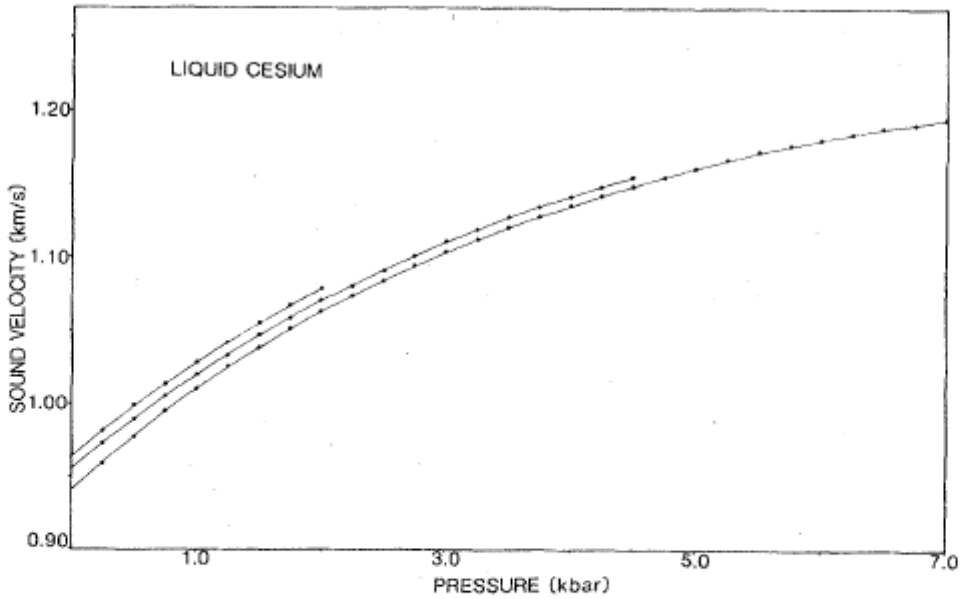


FIG. 5. Thermodynamic sound velocity in cesium as a function of pressure. The dots are individual data points, and the curves are sketched in. The upper curve is for 49.7 °C, the middle curve is for 108.3 °C, and the lower curve is for 150.1 °C.

G.H. Shaw and D. A. Caldwell, *Sound-wave velocities in liquid alkali metals studied at temperatures up to 150°C and pressures up to 0.7 GPa*, Phys. Rev. B **32**, 7937 (1985)

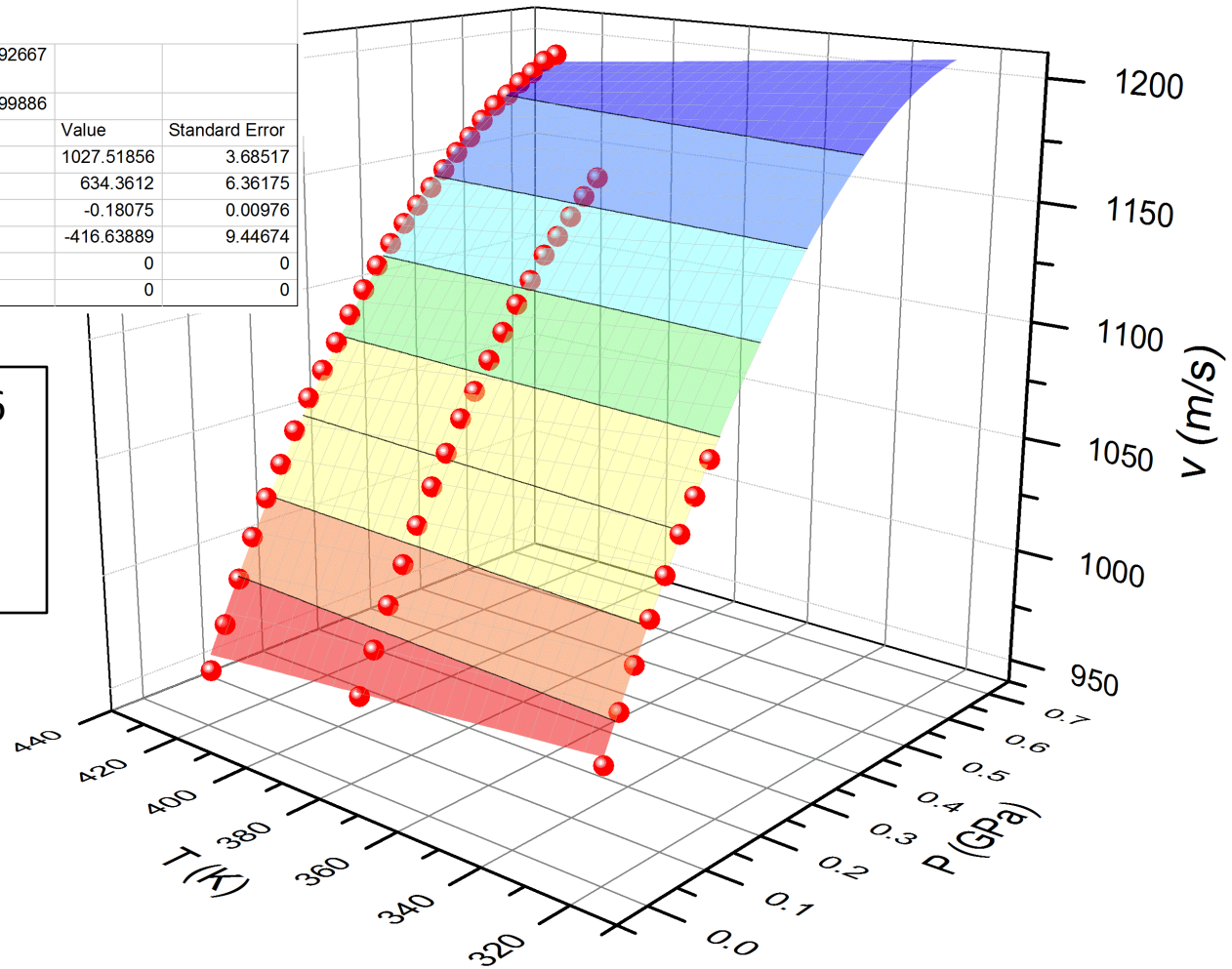
Shaw & Caldwell (1985) –
thermodynamic (or true) adiabatic sound velocities (in km/s)
in liquid Cs
(scan data of Fig. 2 p. 7938)

P (GPa)	T=49.7°C	T=108.3°C	T=150.1°C
0.025	0.98172	0.97285	0.95956
0.05	0.99889	0.98947	0.97729
0.075	1.0139	1.0055	0.99501
0.1	1.0288	1.0199	1.0111
0.125	1.0427	1.0338	1.026
0.15	1.056	1.0476	1.0388
0.175	1.0681	1.0593	1.0515
0.2	1.0798	1.0715	1.0637
0.225	--	1.0809	1.0742
0.25	--	1.092	1.0848
0.275	--	1.1019	1.0953
0.3	--	1.1119	1.1047
0.325	--	1.1202	1.1136
0.35	--	1.1291	1.1219
0.375	--	1.1357	1.1296
0.4	--	1.1424	1.1363
0.425	--	1.1496	1.1429
0.45	--	1.1562	1.1496
0.475	--	--	1.1562
0.5	--	--	1.1618
0.525	--	--	1.1684
0.55	--	--	1.174
0.575	--	--	1.1778
0.6	--	--	1.1823
0.625	--	--	1.1861
0.65	--	--	1.1906
0.675	--	--	1.1928

Sound velocity polynomial fit

Model	Poly2D		
Equation	z=z0+a*x+b*y+c*x^2+d*y^2+f*x*y;		
Reduced Chi-Sqr	4.92667		
Adj. R-Square	0.99886		
		Value	Standard Error
C	z0	1027.51856	3.68517
	a	634.3612	6.36175
	b	-0.18075	0.00976
	c	-416.63889	9.44674
	d	0	0
	f	0	0

z0	1027.51856
a	634.3612
b	-0.18075
c	-416.63889



Vargaftik (1986)

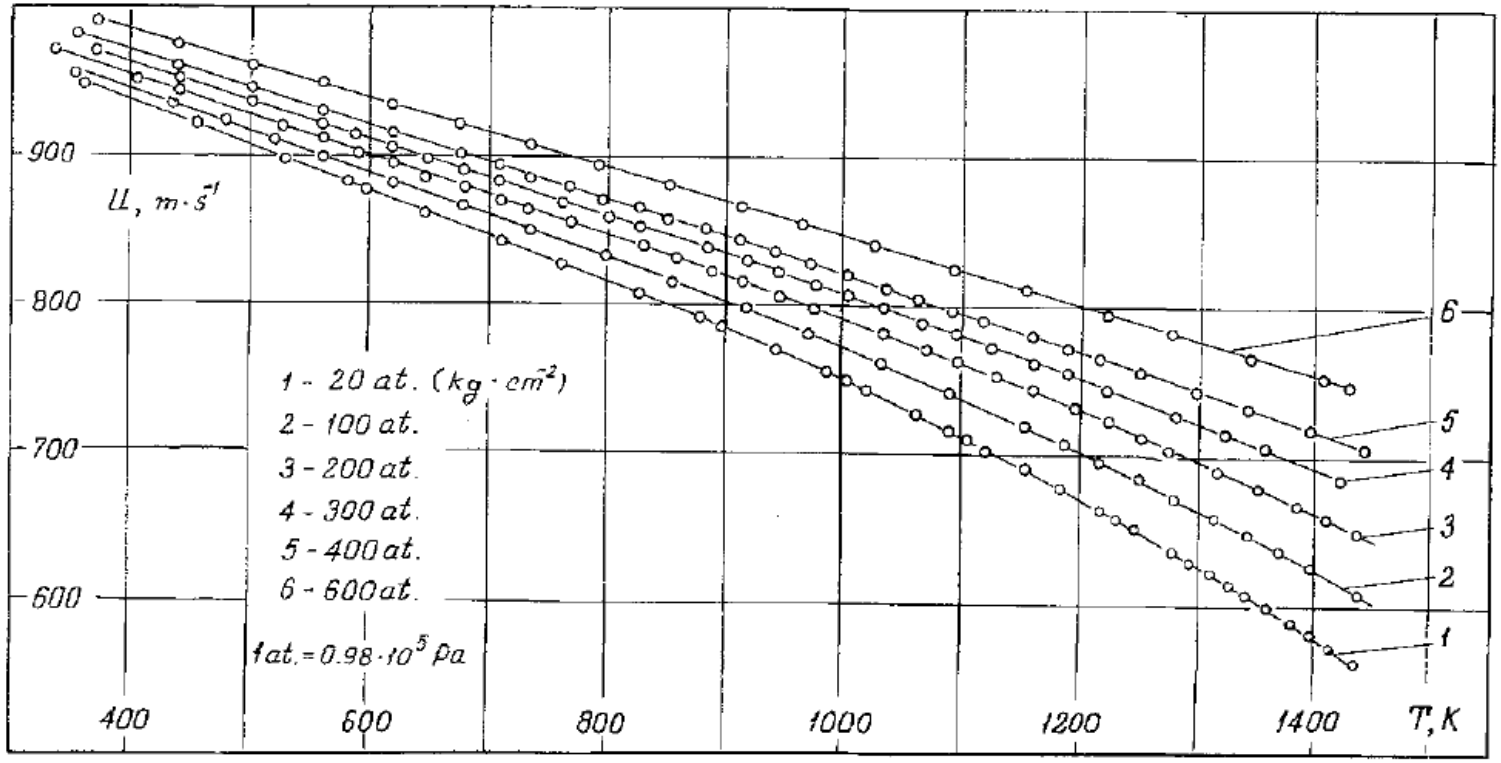


Fig. 4. Sound velocity isobars in liquid cesium as a function of temperature.

N.B. Vargaftik, V.F. Kozhevnikov, A.M. Gordeenko *et al.*, Int. J. Thermophys. **7** 821 (1986)

Kozhevnikov (1990)

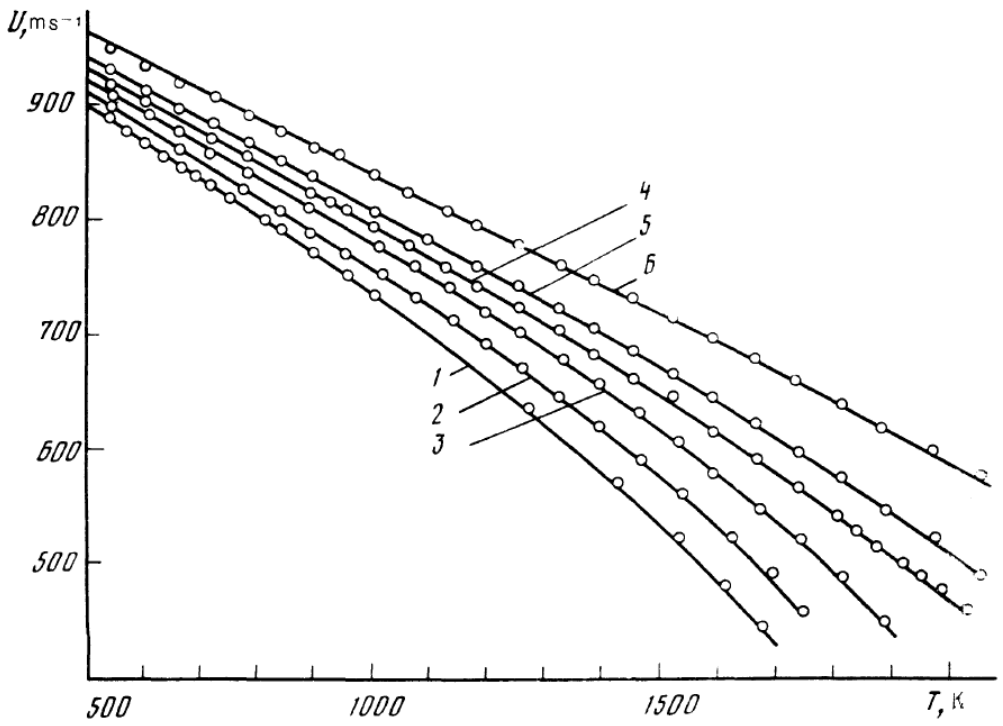
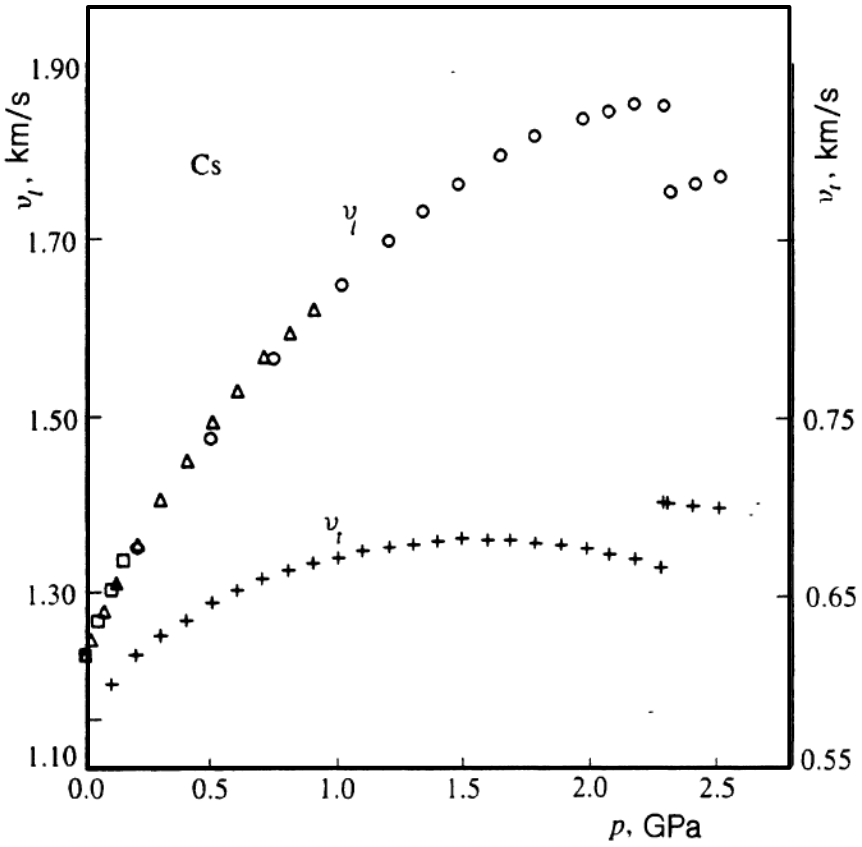


FIG. 3. Speed of sound in liquid cesium: 1—on the saturation curve; 2—for $P = 9.9$ MPa; 3—for $P = 19.7$ MPa; 4—for $P = 29.5$ MPa; 5—for $P = 39.3$ MPa; 6—for $P = 58.9$ MPa.

Kozhevnikov, V. F., *Equation of State and Sound Speed of Cesium at Temperatures up to 2200 K and Pressures up to 60 Mpa,* Journal of Experimental and Theoretical Physics, ***70*(2)**, 298-310 (1990).

Voronov (1994)



F. F. Voronov, O.V. Stal'gorova, and E. L. Gromnitskaya, *Anomalous elastic properties and bcc-fcc transition of cesium at high pressures up to 2.5 GPa,* Zh. Eksp. Teor. Fiz. **105**, 1456-1469 (1994)

Voronov (2002)

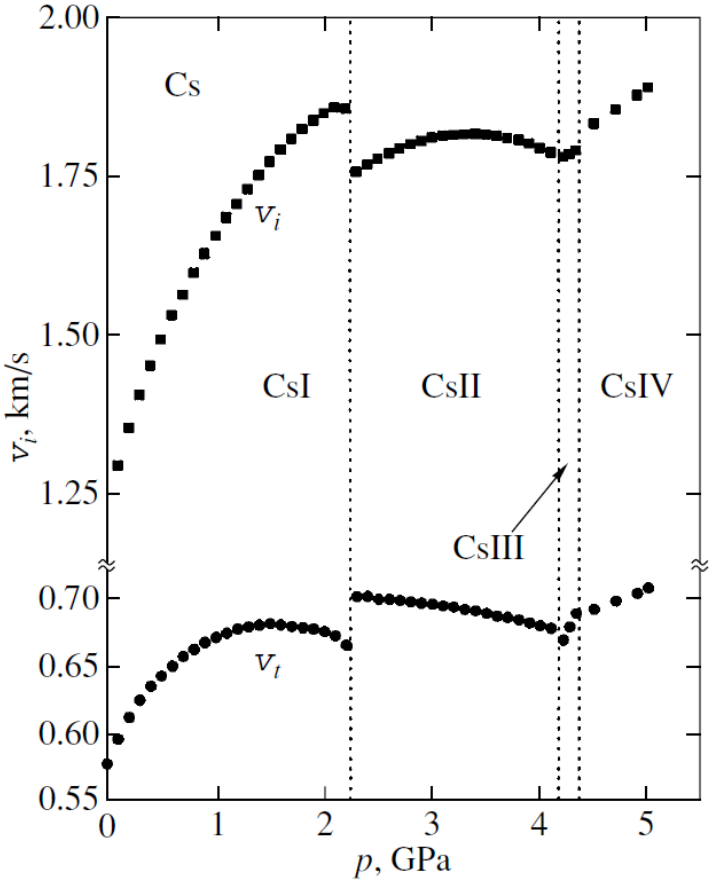
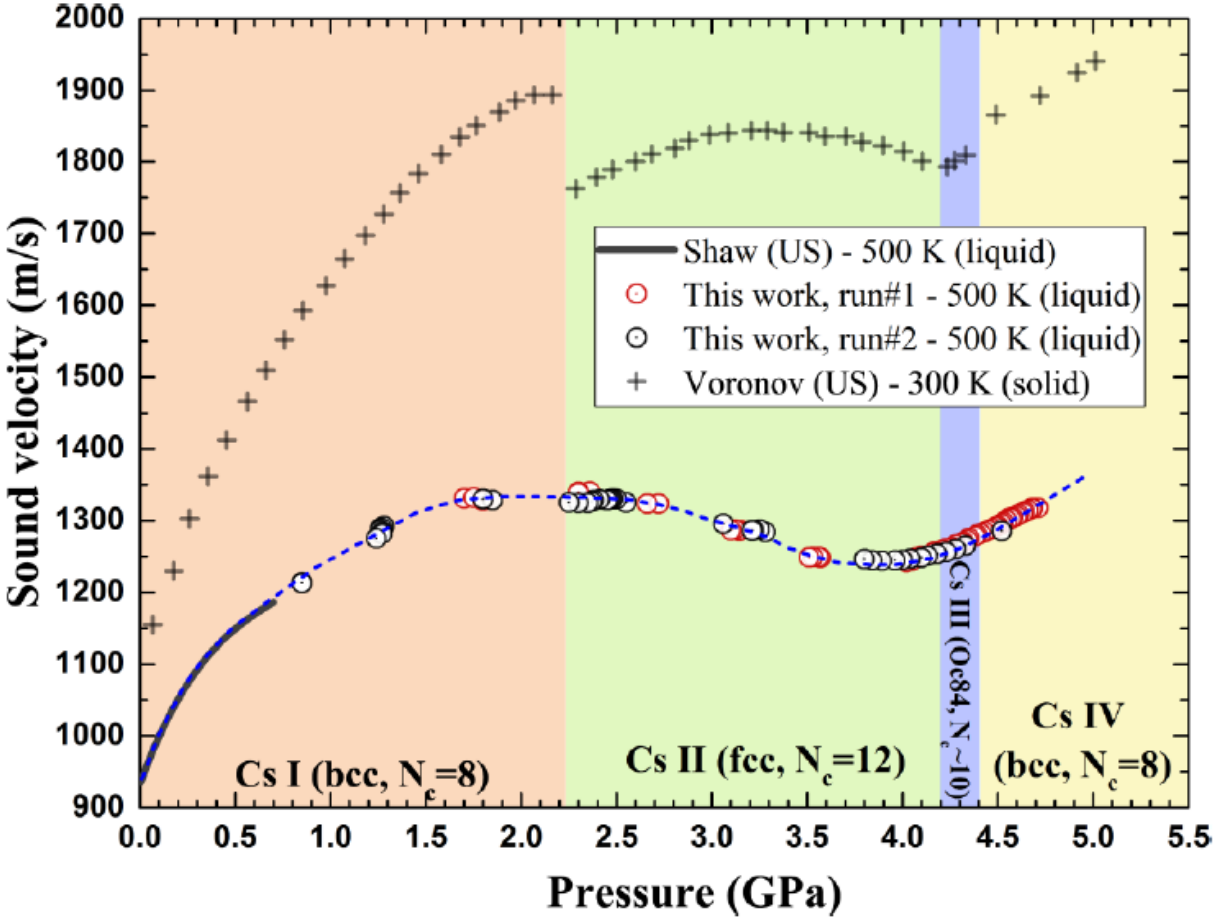


Fig. 1. Pressure dependences of the velocities of longitudinal, v_l, and transverse, v_t, ultrasonic waves in cesium.

Voronov, F.F., Stal'gorova, O.V. & Gromnitskaya, E.L. J. Exp. Theor. Phys. **95**, 77 (2002) doi:10.1134/1.1499904

Decremps (2018)



Frédéric Decremps, Simon Ayrinhac, Michel Gauthier, Daniele Antonangeli, Marc Morand, Yiuri Garino, and Paraskevas Parisiades, *Sound velocity and equation of state in liquid cesium at high pressure and high temperature,* Phys. Rev. B **98**, 184103 (2018)
DOI:https://doi.org/10.1103/PhysRevB.98.184103

Sound attenuation

Table 1
Acoustical data for liquid metals.

Metal	T (K)	c_ℓ [a] (m/s)	ρ_ℓ [a] (g/cm^3)	$\Delta V/V$	ΔF (kcal mole^{-1}) present theory	ΔF (kcal mole^{-1}) ref. [16]	η_s [a] (CP)	τ (10^{-12} s)	α/f^2 (10^{-17} cm^{-1} s^2) expt. α/f^2	classical α_{cl}/f^2	excess α_B/f^2	present theory α_B/f^2
Na	373	2526	0.9269	0.27	1.47	1.25	0.705	0.68	11.40 [b]	9.20	2.20	1.93
K	348	1890	0.8237	0.27	1.21	1.20	0.503	1.22	31.90 [b]	27.20	4.70	5.58
Rb	316	1260	1.4750	0.27	1.06	1.23	0.670 [c]	2.29	75.50 [b]	58.40	17.10	17.35
Cs	308	967	1.8400	0.27	1.07	1.15	0.690 [c]	2.87	110.30 [b]	87.07	23.23	26.81
Cd	633	2166	8.0310	0.29	3.20	2.60	1.440	0.28	14.50 [a]	11.28	3.22	1.43
Sn	513	2464	6.9690	0.29	3.41	1.30	2.100	0.28	5.63 [a]	4.29	1.34	1.04
Pb	613	1776	10.6800	0.29	4.03	2.06	2.560	0.34	9.40 [a]	7.57	1.83	1.37
Bi	553	1645	10.0600	0.29	3.31	1.54	1.830	0.39	8.05 [a]	5.73	2.32	2.13

[a] Ref. [2]. [b] Ref. [1]. [c] Ref. [16].

O. N. Awasthi, & B.V.S. Murthy, *Bulk viscosity and ultrasonic attenuation in liquid metals*, *Physics Letters A*, **108,** 119 (1985)

Elastic constants

TABLE II. The calculated elastic constants for bcc and fcc Cs. The available experimental data from Ref. 22 are indicated in parentheses.

		V_0	$0.84V_0$	$0.74V_0$	$0.66V_0$
bcc	C_{11} (GPa)	2.27 (2.46)	3.78	3.76	2.74
	C_{12} (GPa)	1.88 (2.06)	1.94	2.44	3.67
	C_{44} (GPa)	1.94 (1.48)	3.18	3.13	2.46
	$C' = \frac{1}{2}(C_{11} - C_{12})$ (GPa)	0.18 (0.20)	0.92	0.66	−0.46
fcc	C_{11} (GPa)	2.28	3.98	3.90	3.86
	C_{12} (GPa)	1.88	3.24	2.87	3.18
	C_{44} (GPa)	1.90	2.42	2.68	3.07
	$C' = \frac{1}{2}(C_{11} - C_{12})$ (GPa)	0.20	0.37	0.52	0.34
	$\Delta H^{\mathrm{fcc/bcc}}$ (meV/atom)	17.6	23.6	31.3	−16.9

Xie, J., Chen, S. P., John, S. T., Klug, D. D., Li, Z., Uehara, K., & Wang, L. G. *Phonon instabilities in high-pressure bcc-fcc and the isostructural fcc-fcc phase transitions of Cs, Phys. Rev. B,* **62(6)** 3624 (2000)

Voronov (1994)

TABLE I. Elastic properties and propagation velocities of ultrasonic waves in cesium at $T=294$ K and $p=0$.

	Longitudinal wave		Transverse wave	
Single crystal				
[hkl],[mnp]*	[100],[100]	[111],[111]	[100],[010]	[110],[1$\bar{1}$0]
c_{ij},	c_{11}	$(c_{11}+2c_{12}+4c_{44})/3$	c_{44}	$(c_{11}-c_{12})/2$
c_{ij}, GPa**	2.190	3.430	1.090	0.162
$v_{ij}=\sqrt{c_{ij}/\rho}$, км/с	1.076	1.347	0.759	0.293
Polycrystalline sample				
v, km/s***	1.185		0.518	
data of present study;				
Variable-length method	1.240 ± 0.040		-	
Piezometer measurements	1.220 ± 0.040		0.578 ± 0.090****	
Average value	1.230 ± 0.040		0.578 ± 0.090****	

*Wave propagation direction, polarization of wave

**extrapolation of data of Ref. 15 to $T=294$ K (the largest and smallest values are shown)

***Found by the method of Ref. 20 through the use of c_ij

****the average scatter from sample to sample is shown.

Density

• Bridgman (1925)	l-Cs, T=75°C (348 K)
• Bridgman (1947-1948)	solid Cs
• Kennedy (1962)	specific V, along the melting line
• Hall (1964)	solid Cs, up to 5.5 GPa
• Stishov (1966)	ΔV, along the melting line
• Kim (1971)	liquid, $\rho(T)$, up to 1000°C
• Vargaftik (1979)	liquid, 360 K – 1000 K
• Takemura (1982)	V/V_0, solid Cs, up to 10 GPa
• Takemura (1985)	solid Cs, up to 30 GPa
• Anderson (1985)	V/V_0, solid, low T
• Vargaftik (1985)	review, density, up to 300 atm
• Shaw (1985)	V/V_0, liquid, from ultrasonics
• Takemura (1991)	solid Cs, up to 100 GPa
• Voronov (1994)	solid Cs, up to 2.5 GPa
• Voronov (2002)	solid Cs, up to 5 GPa
• Falconi (2005)	l-Cs, T=220°C, T=350°C
• Belashchenko (2014)	l-Cs, molecular dynamics, up to 10 Gpa
• Hattori (2018)	l-Cs, 232°C & 350°C, 0.5-5 Gpa
• Decremps (2018)	l-Cs, T=493 K, from vS by picosecond acoustics

Bridgman (1925)

P. W. Bridgman, Proc. Am. Acad. Sci. **60**, 385 (1925).

Bridgman (1947-1948)

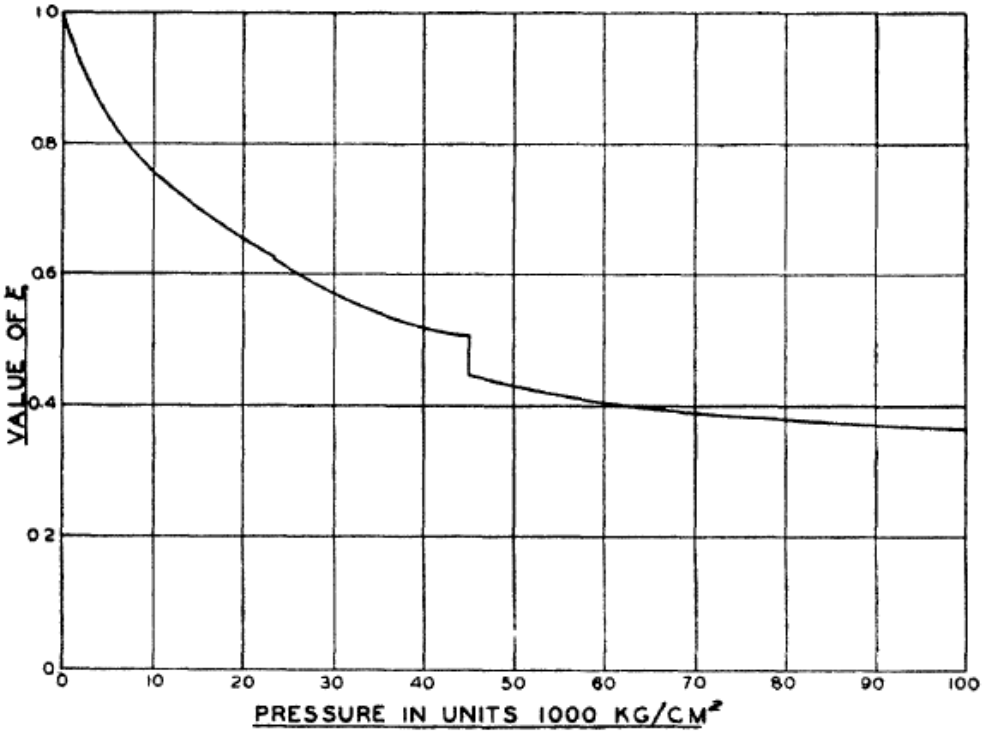


FIG. 1. Volume of cesium as a function of the pressure. The ordinate ξ is the ratio of the volume to the volume at normal pressure. (From Bridgman, reference 1.)

P. Bridgman, Phys. Rev. **72**, 533 (1947);
P. Bridgman, Proc. Am. Acad. **76**, 55 (1948).

Kennedy (1962)

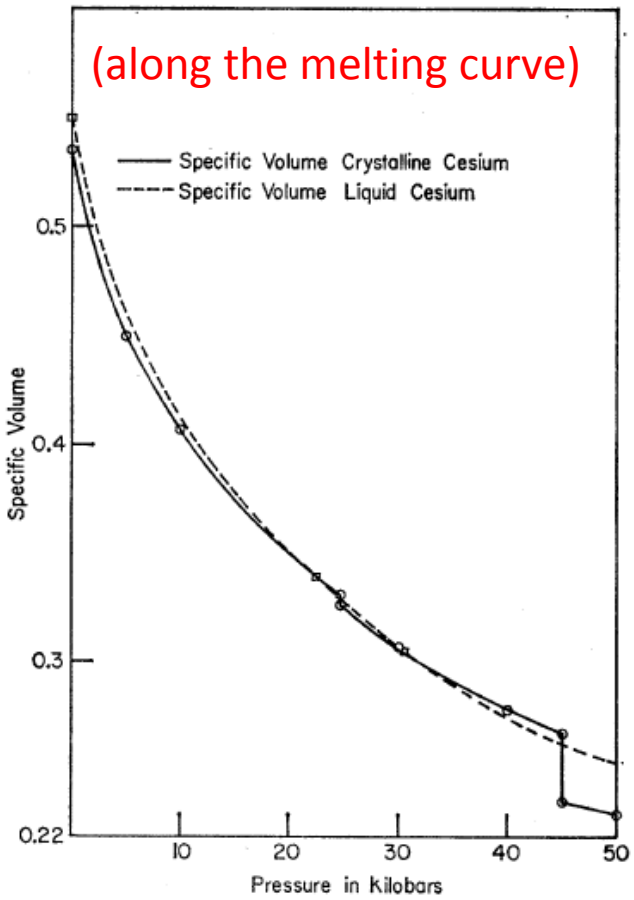
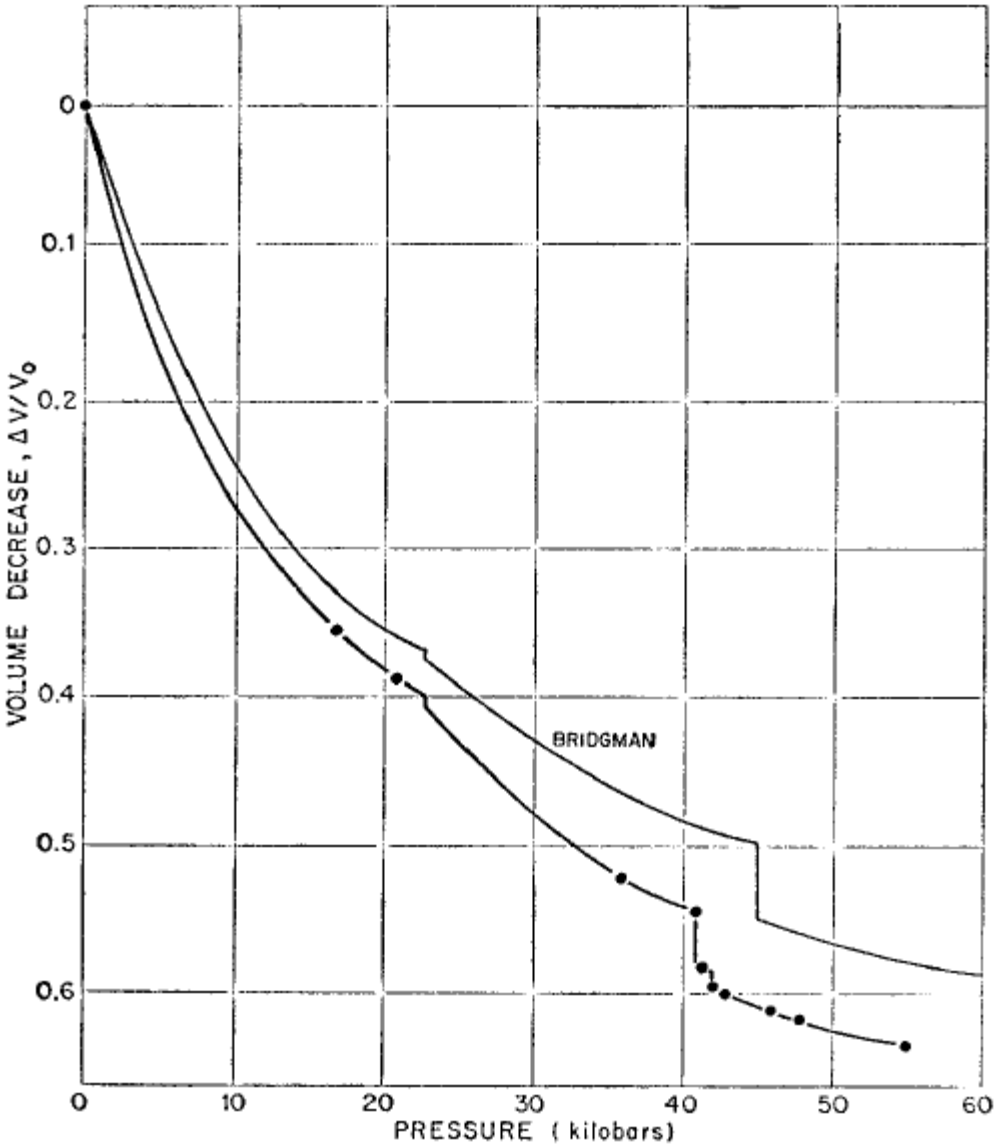


FIG. 3. Specific volume of coexisting solid and liquid cesium.

"Bridgman has published data on the density of solid cesium as a function of pressure at room temperature. The density change of cesium on melting at one atmosphere is known. Further, the value of dT/dP at the two maxima in the melting point curve is zero indicating that the liquids and solids have identical densities at these points, thus providing two points for the density of liquid cesium at these two pressures. From these data we have prepared a plot (see Fig. 3) of specific volume, which is the reciprocal of density, as a function of pressure for solid and liquid cesium along the melting curve. We have, however, ignored the effect of thermal expansion. To obtain the compressibility curve of liquid cesium we have drawn a smooth curve connecting the three points mentioned."

G. C. Kennedy, A. Jayaraman, and R. C. Newton
Fusion Curve and Polymorphic Transitions of Cesium at High Pressures
Phys. Rev. **126**, 1363 (1962)

Hall (1964)


VOLUME DECREASE, $\Delta V/V_o$
0
0.1
0.2
0.3
0.4
0.5
0.6
0
10
20
30
40
50
60
PRESSURE (kilobars)
BRIDGMAN

Stishov (1966)

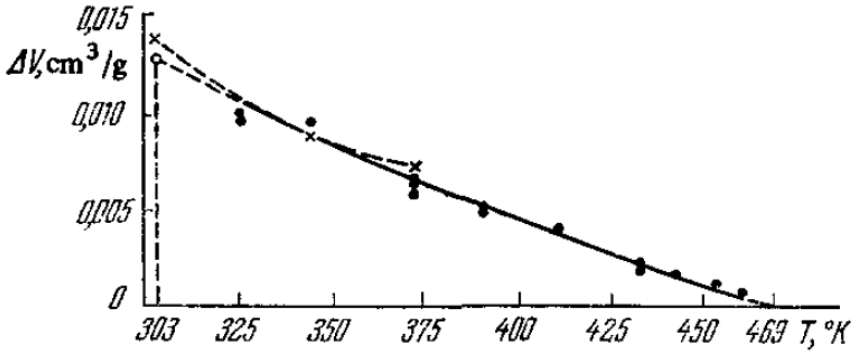


FIG. 23. Unit volume discontinuity during melting of cesium as a function of temperature [95].

V. S. Bogdanov, ZhETF Pis. Red. 3, 44 (1966) [JETP Lett. 3, 26 (1966)], *in Stishov (1968)*

Kim (1971)

(in liquid state)

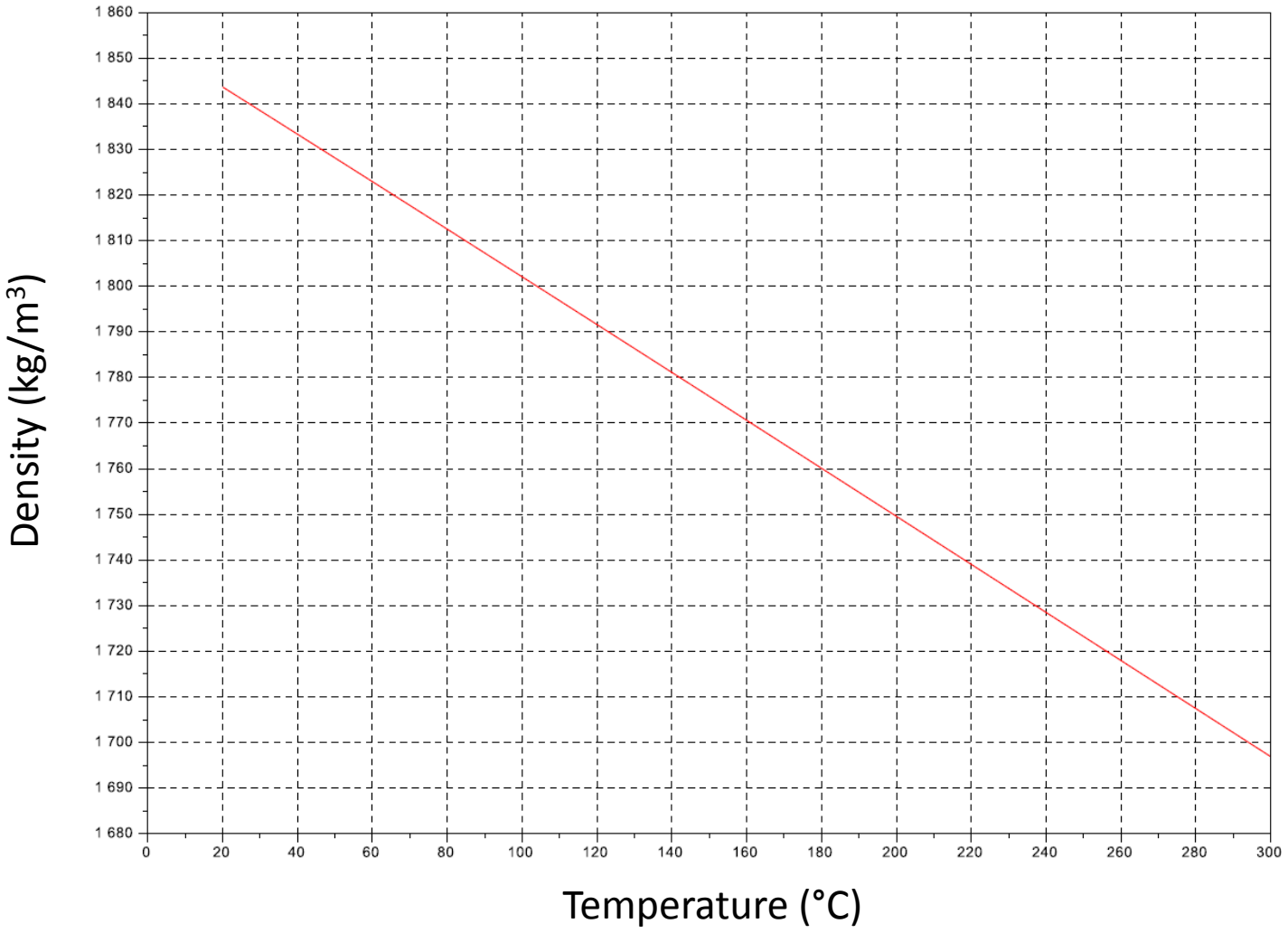
Using the cesium density data reported in the literature by Cochran,[21] Achener,[23] Shpil'rain *et al.*,[24] Tepper *et al.*,[25] and Basin *et al.*,[26] the following equation was derived as a best-fit curve from the melting point up to 1000°C:

$$\rho(\mathrm{Cs}) = 1.854 - 5.15\times10^{-4}T - 4.9\times10^{-8}T^2 + 6.7\times10^{-11}T^3. \quad (19)$$

In Eqs. 16–19 the densities are expressed in grams per cubic centimeter and temperature in degrees Celsius.

Ultrasonic Measurement in Liquid Alkali Metals
M. G. Kim, K. A. Kemp, and S. V. Letcher
49, 706 (1971); doi: 10.1121/1.1912406

(liquid Cs, Kim 1971)



$\rho_{MP=28.5°C}$=1839.3 kg/m^3

$\rho_{220°C}$ =1739.0 kg/m^3

Vargaftik (1979)

Liquid Cs

TABLE 3. Experimental Data on the Density of Liquid Cesium

P, kgf/cm²	ρ, g/cm³	T, °K	P, kgf/cm²	ρ, g/cm³	T, °K	P, kgf/cm²	ρ, g/cm³	T, °K
10	1,801	367,3	155	1,697	586,5	300	1,707	607,8
10	1,782	397,6	155	1,686	606,4	301	1,687	645,3
10	1,764	430,8	155	1,668	639,1	300	1,666	687,3
10	1,745	461,8	155	1,655	662,3	300	1,651	712,4
10	1,731	489,0	155	1,640	690,2	300	1,637	740,1
10	1,716	516,6	155	1,627	711,0	300	1,616	776,7
10	1,697	548,1	155	1,609	745,2	300	1,600	805,9
10	1,680	576,5	155	1,568	820,1	300	1,580	846,6
10	1,663	609,6	155	1,629	710,6	302	1,563	877,0
10	1,643	644,3	155	1,613	739,1	300	1,546	912,0
10	1,624	676,9	155	1,596	769,9	300	1,494	1007,3
10	1,607	705,0	157	1,577	803,5			
10	1,572	766,8	155	1,523	902,4	735	1,779	582,0
10	1,556	796,3	155	1,501	942,4	735	1,768	603,8
10	1,515	870,5	156	1,484	973,6	734	1,750	639,3
10	1,503	891,5	155	1,470	988,5	736	1,709	727,5
10	1,480	929,7	155	1,460	1016,6	735	1,669	805,4
10	1,455	975,3	157	1,434	1064,1	735	1,614	918,6
10	1,438	1003,0				735	1,596	960,5
			300	1,765	496,1	735	1,580	991,7
155	1,775	444,5	301	1,749	529,2			
156	1,756	478,1	300	1,724	575,0			

EQUATION OF STATE OF THE LIQUID ALKALI METALS. I.
N. B. Vargaftik, V. A. Alekseev, V. F. Kozhevnikov, Yu. F. Ryzhkov

Takemura (1982)

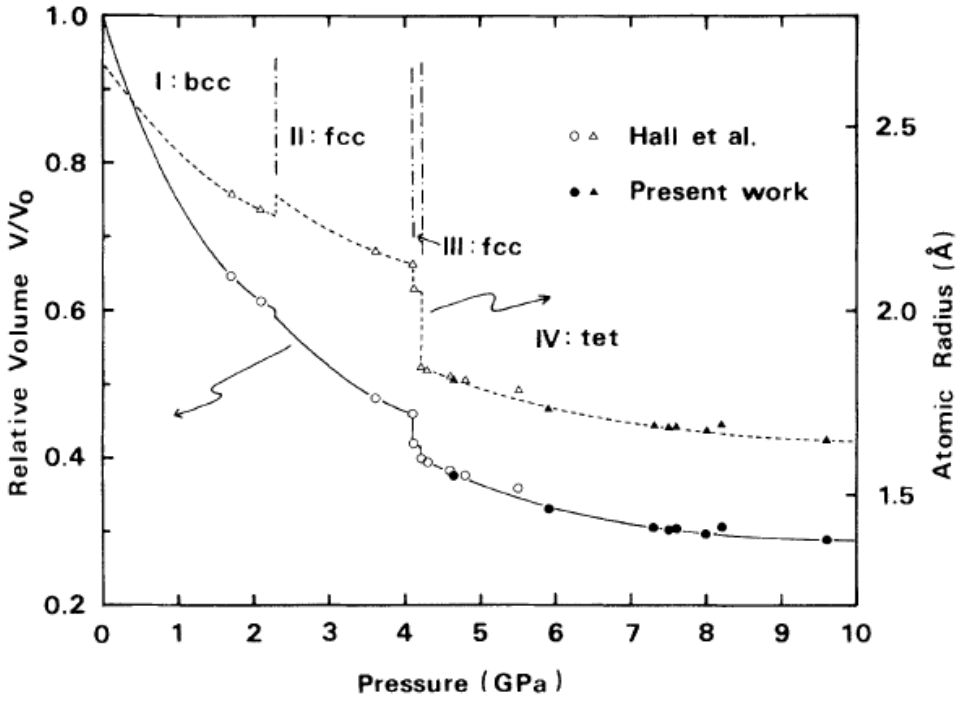


FIG. 3. Variation of relative volume (circles) and atomic radius (triangles) of Cs with pressure. Closed symbols are the present results and open symbols are those by Hall, Merrill, and Barnett (Ref. 1).

X-Ray Diffraction Study of Electronic Transitions in Cesium under High Pressure
K. Takemura, S. Minomura, and O. Shimomura
Phys. Rev. Lett. 49, 1772 (1982)

Takemura (1985)

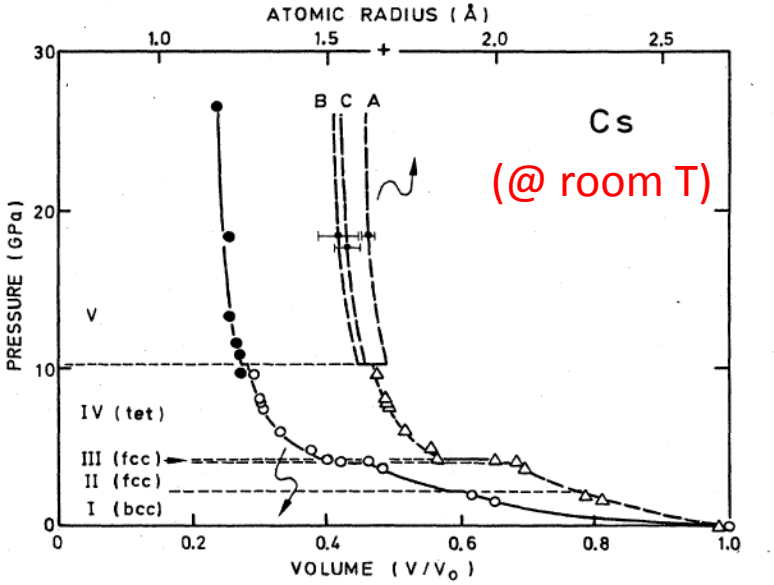


FIG. 4. Pressure as a function of relative volume (solid curve) and pressure-atomic radius relation (dashed curves). Data for phases I, II, III, and IV (open circles and open triangles) are from Refs. 3 and 4. Solid circles are from present work. The pressure-volume relation is common to the three proposed structures *A*, *B*, and *C*. Curves are a guide for the eye. The ionic radius of Cs at normal conditions is indicated by a cross on the abscissa for atomic radii.

P (GPa)	V/V0	rho (kg/m3)
-0.10304	1.0011	1897.9123
1.4731	0.65054	2920.65054
1.8869	0.61613	3083.76479
3.6336	0.48387	3926.67452
4.0925	0.46237	4109.26314
4.0492	0.42043	4519.18274
4.1876	0.4	4750
4.784	0.37634	5048.62624
5.9308	0.33011	5755.65721
7.3967	0.30538	6221.7565
7.8089	0.30108	6310.61512
8.0835	0.3	6333.33333
9.5943	0.2914	6520.24708
9.687	0.27097	7011.84633
10.877	0.26989	7039.90515
11.61	0.26559	7153.88381
13.303	0.25484	7455.65845
18.338	0.25376	7487.38966
26.623	0.23548	8068.62579

High-pressure structural investigation of cesium above 10 GPa
K. Takemura and K. Syassen, Phys. Rev. B **32** (1985)

Anderson (1985)

TABLE II. Room-temperature and 4 K compressions for cesium and lithium. See the text for details.

	Cs		Li	
V/V_0[a]	295 K	4 K	294 K	4 K
1.000	0	−1.083	0	−3.10
0.975	0.445	−0.645	3.06	−0.10
0.9742			3.16	0
0.950	0.950	−0.148	6.49	3.29
0.9432	1.110	0		
0.925	1.525	0.421	10.33	7.12
0.900	2.179	1.071	14.66	11.46
0.875	2.924	1.812	19.52	16.39
0.850	3.772	2.660	(25.0)	(21.98)
0.825	4.741	3.630	(31.1)	
0.800	5.846	4.741	(38.0)	
0.775	7.108	6.010	(45.8)	
0.750	8.548	7.459	(54.6)	
0.725	10.19	9.110	(64.3)	
0.700	12.06	11.00		
0.675	14.20	13.14		
0.650	16.63	15.58		
0.625	19.39	18.34		
0.6024	22.20	21.15		
0.5961	22.20			

[a] V_0 is 70.42 cm^3/mole at 295 K for cesium, and 13.02 cm^3/mole at 294 K for lithium.

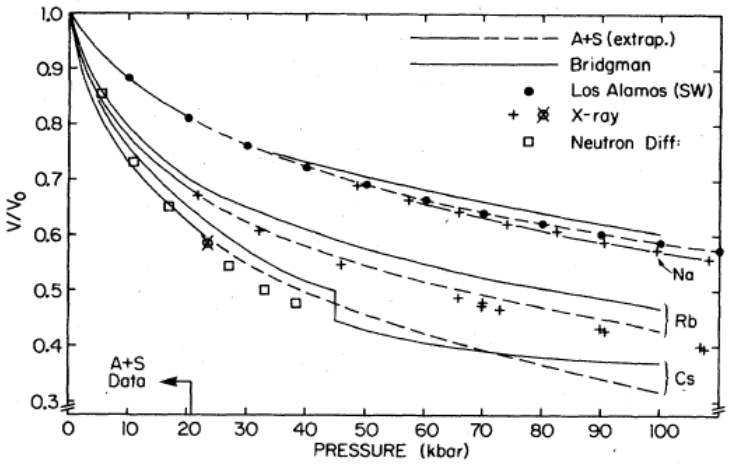


FIG. 8. Room-temperature compressions of sodium, rubidium, and cesium metals. The dashed lines refer to extrapolations above 20 kbar of the present work and that of Ref. 14. The neutron diffraction and x-ray data for cesium are from Refs. 12 and 22, respectively. Bridgman's data are from Refs. 5 and 6. See the text for a discussion of the sodium and rubidium comparisons.

Experimental equations of state for cesium and lithium metals to 20 kbar and the high-pressure behavior of the alkali metals

M. S. Anderson and C. A. Swenson

Phys. Rev. B **31**, 668 (1985)

Anderson (1985)

Solid Cs

TABLE I. Summary of the isotherm results for cesium. The data points for the isotherms are indicated in Figs. 2 and 3. (RMSD denotes root-mean-square deviation.)

T (K)	P^* (kbar)	$(V/V_0)_{P=0}$[a]	B_0[a]	B_0[b] (kbar)	B_0'[b]	B_0''[b] (kbar^{-1})	RMSD (10^{-4} in V/V_0)
290	+0.085	1.0050	16.90[d]	16.98±0.06	3.79∓0.02	−0.077±0.001	0.8
270	(0)	(1.0000)[c]	(17.23)	17.23±0.05[c]	3.87∓0.03[c]	−0.103±0.005[c]	2.8
				[17.13±0.03][f]	[3.98∓0.03][f]	[−0.150±0.004][f]	2.7
248	−0.09	0.9948	17.58	17.60±0.10	3.87∓0.06	−0.112±0.011	3.7
200	−0.275	0.9838	18.29	18.32±0.12	3.82∓0.07	−0.105±0.014	4.6
146	−0.505	0.9726	19.17	19.05±0.12	3.89∓0.01	−0.113±0.012	7.7
99.5	−0.69	0.9634	19.88	19.86±0.14	3.79∓0.06	−0.099±0.018	8.1
82	−0.765	0.9598	20.16	20.26±0.08	3.73∓0.04	−0.098±0.008	8.8
43	−0.915	0.9528	20.73	20.94±0.06	3.67∓0.02	−0.087±0.005	6.7
34	−0.96	0.9508	20.90[e]	20.50±0.15	3.95∓0.06	−0.125±0.012	6.1
20	−0.975	0.9501	20.95	21.09±0.06	3.69∓0.02	−0.087±0.006	7.1
4	−1.00	0.9489	21.05	21.03±0.06	3.76∓0.02	−0.096±0.006	6.8
				[20.79±0.09][f]	[3.98∓0.04][f]	[−0.168±0.009][f]	6.6

[a]Derived from the 270-K isotherm and P^*.
[b]Parameters derived from nonlinear least-squares fits of the ME-2 relation, Eq. (6), to the data for each isotherm. The 3σ uncertainties are those associated with the fitting procedure and do not include an allowance for systematic effects. A more qualitative estimate gives minimum uncertainties of ±0.3 kbar for B_0, ∓0.1 for B_0' and ±0.01 kbar^{-1} for B_0''.
[c]These parameters define the reference isotherm with V_0 (270 K, $P=0$)=70.00 cm^3/mole.
[d]0.354-in. sample-holder data only.
[e]0.250-in. sample-holder data only.
[f]Alternative representations of the data usng the MME relation, Eq. (9).

Anderson, M. S., & Swenson, C. A., *Experimental equations of state for cesium and lithium metals to 20 kbar and the high-pressure behavior of the alkali metals,* Physical Review B, ***31*(2)**, 668 (1985).

Vargaftik (1985)

CHAPTER 6.3.4

DENSITY OF LIQUID CESIUM AND SODIUM

N. B. Vargaftik†, V. F. Kozhevnikov†, V. A. Alekseev*

†Moscow Aviation Institute, Moscow, USSR

*Kurchatov Institute of Atomic Energy, Moscow, USSR

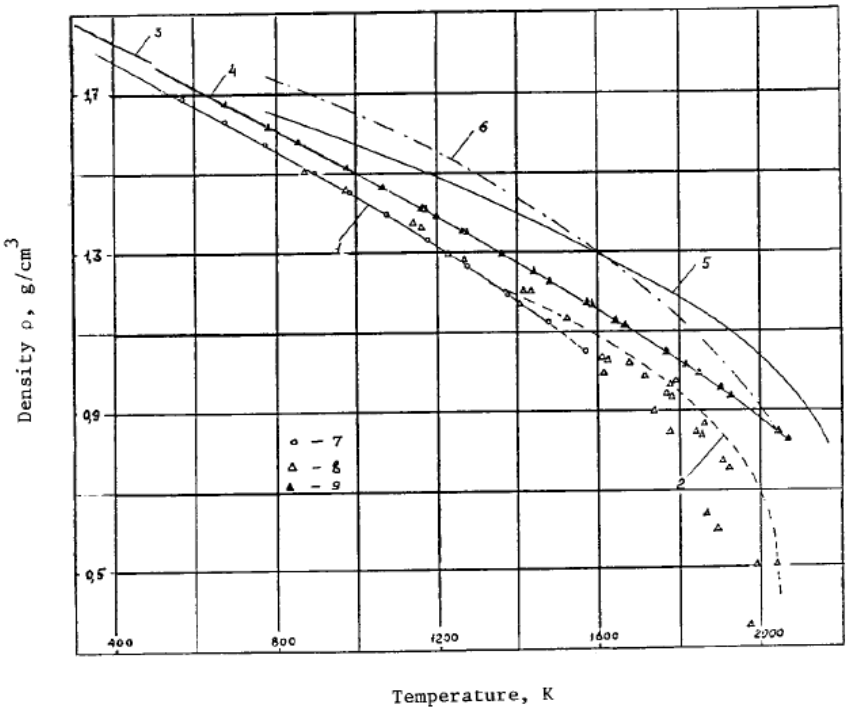


Fig. 10. Density of liquid cesium as reported by various scholars:
1 - Shpil'rain et al. (Ref. 20); 2 - Das Gupta et al. (Ref. 22); 3 - Makarenko et al. (Ref. 4); 4 - Vargaftik, Kozhevnikov et al. (Ref. 10); 5 - Korshunov et al. (Ref. 15); 6 - Alekseev et al. (Ref. 14); 7 - Basin (Ref. 19); 8 - Dillon et al. (Ref. 21); 9 - Vargaftik, Kozhevnikov et al. (Ref. 16);
1, 2, 7, 8 - data on density in the vicinity of the coexistence curve;
3, 4, 5, 6, 9 - data on density under the pressure of 300 at.

Shaw (1985)

Liquid Cs
(T=150.1°C)

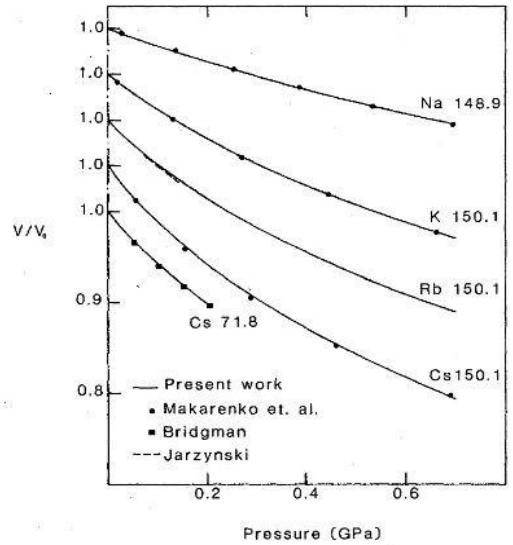


FIG. 11. Compression curves for the liquid-alkali metals. Compressions calculated from the present data using the second-order Murnaghan equation. Comparisons are made with piezometer determinations of Makarenko *et al.* (Ref. 18) for sodium, potassium, and cesium for the highest temperature runs, where the pressure range is the greatest. The data of Makarenko *et al.* were interpolated to the comparison temperatures. Their data were also extrapolated to get the data point at the highest pressure in each case. A comparison is also shown with the rubidium data of Jarzynski (Ref. 19) as calculated from his equation at 150.1 °C. A separate curve is also given for cesium at 71.8 °C and comparison made with Bridgman's (Ref. 17) data for cesium at 75 °C.

[Ref.18] I. N. Makarenko, H. M. Nikolaenko, and S. M. Stishov, in *Liquid Metals—1976*, edited by R. Evans and D. A. Greenwood, (IOP, London, 1977), pp. 79–89

[Ref.17] P. W. Bridgman, Proc. Am. Acad. Sci. **60**, 385 (1925).

Sound-wave velocities in liquid alkali metals studied at temperatures up to 150 °C and pressures up to 0.7 GPa
Phys. Rev. B **32**. 7937 (1985)
George H. Shaw and D. A. Caldwell

Takemura (1991)

Solid Cs
(T ambient)

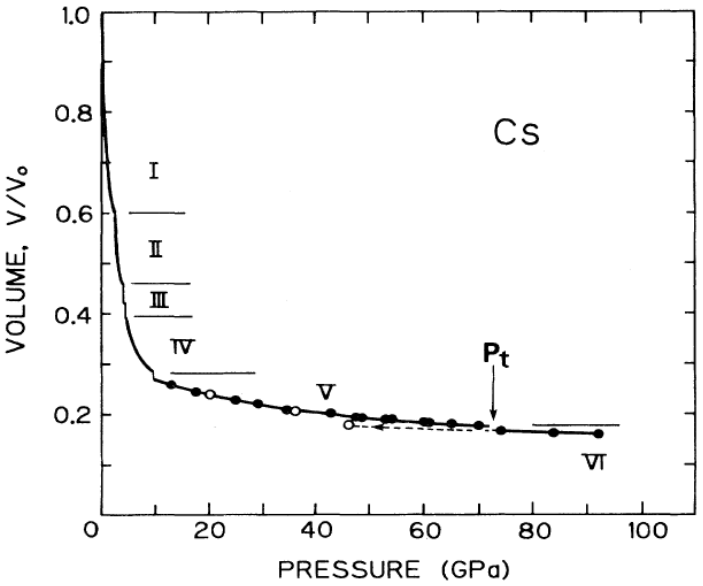
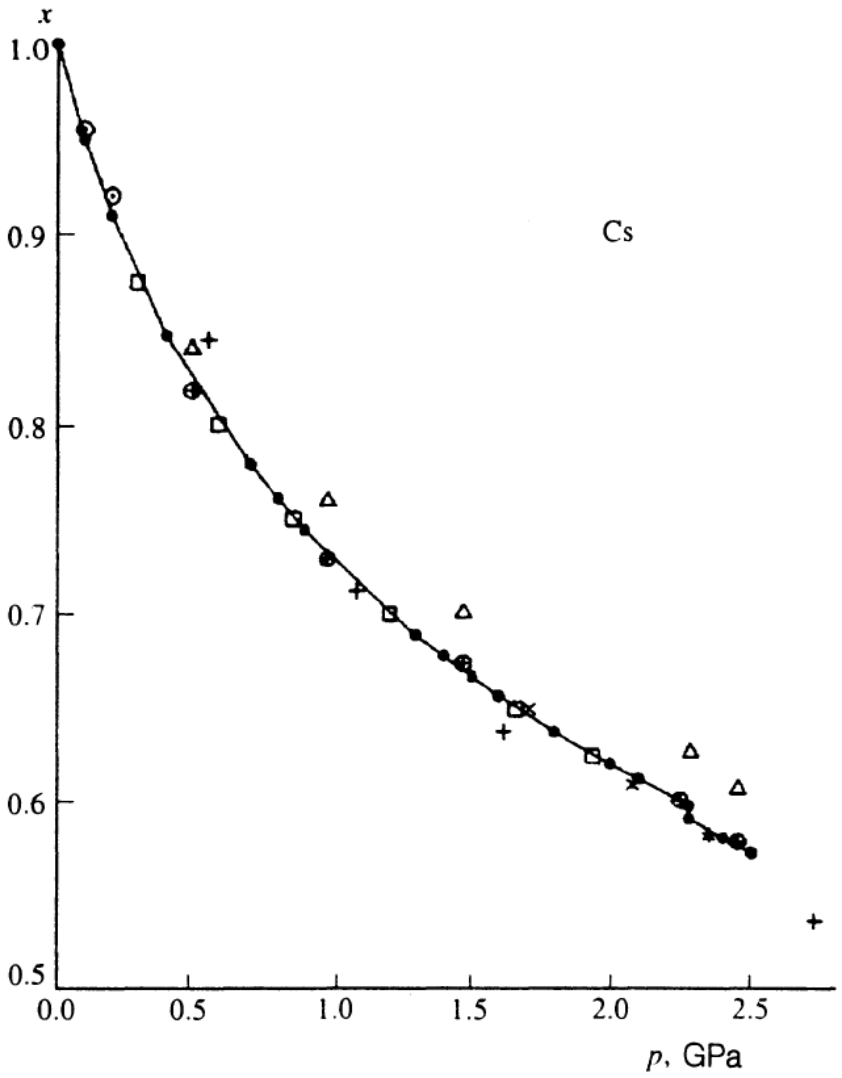


FIG. 2. The equation of state of cesium to 92 GPa. The present results are shown by solid circles (on increasing pressure) and open circles (on decreasing pressure). The other data are from Refs. 1, 4, and 5. The curves are fits by the Birch equation of state, except that for Cs(VI), which is a guide to the eye. The horizontal bars indicate the approximate boundaries between each phase.

VOLUME 66, NUMBER 15 PHYSICAL REVIEW LETTERS 15 ApRIL 1991
Cs(VD: A New High-Pressure Polymorph of Cesium above 72 GPa
K. Takemura and O. Shimomura
National Institute for Research in Inorganic Materials, Tsukuba, Ibaraki 305, Japan
H. Fujihisa

Voronov (1994)



Voronov (2002)

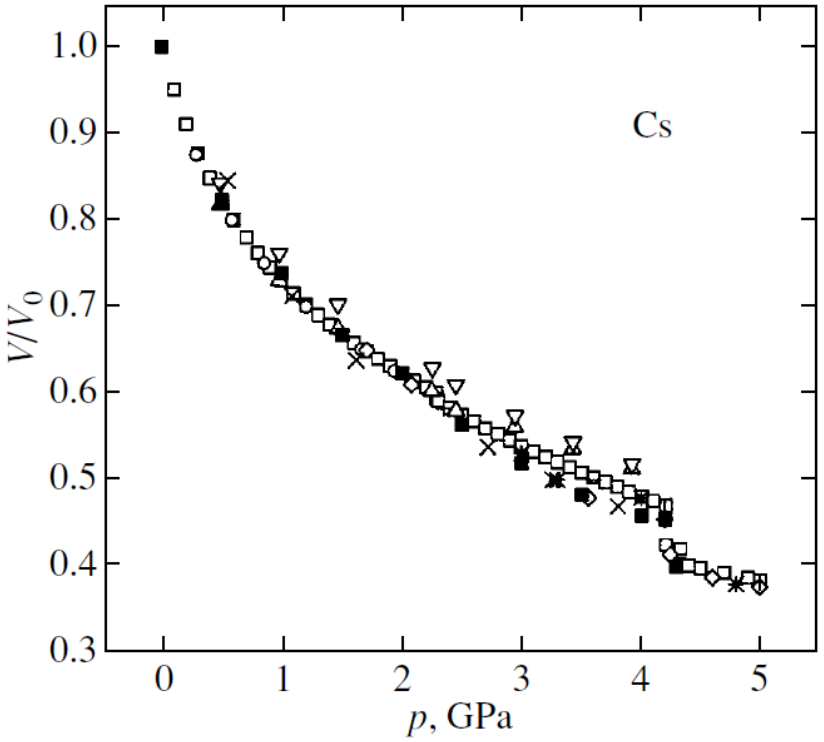


Fig. 2. Dependence of compression of cesium on pressure up to 5.0 GPa: our results (□), results obtained in [20] (○), 21 (△), [1] (▽), [7] (◇), [22] (+), [13] (×), [8] (*), [23] (–), [24] (|), and [25] (■).

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[21] P. W. Bridgman, Proc. Amer. Acad. Arts Sci. **72,** 207 (1938).
[1] P. W. Bridgman, Proc. Amer. Acad. Arts Sci. **76,** 55 (1948).
[7] N. E. Christensen, D. J. Boers, J. L. van Velsen, and D. L. Novikov, Phys. Rev. B **61,** 3764 (2000).
[22] C. E. Weir, G. J. Piermarini, and S. Bloch, J. Chem. Phys. **54,** 2768 (1971).
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[8] K. Takemura, S. Minomura, and O. Shimomura, Phys. Rev. Lett. **49**, 1772 (1982).
[23] D. Glötzel and A. K. McMahan, Phys. Rev. B **20**, 3210 (1979).
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[25] R. Böehler, Mater. Res. Soc. Symp. Proc. **22**, 21 (1984).

Voronov, F.F., Stal'gorova, O.V. & Gromnitskaya, E.L. J. Exp. Theor. Phys., **95** 77 (2002). doi:10.1134/1.1499904

Falconi (2005)

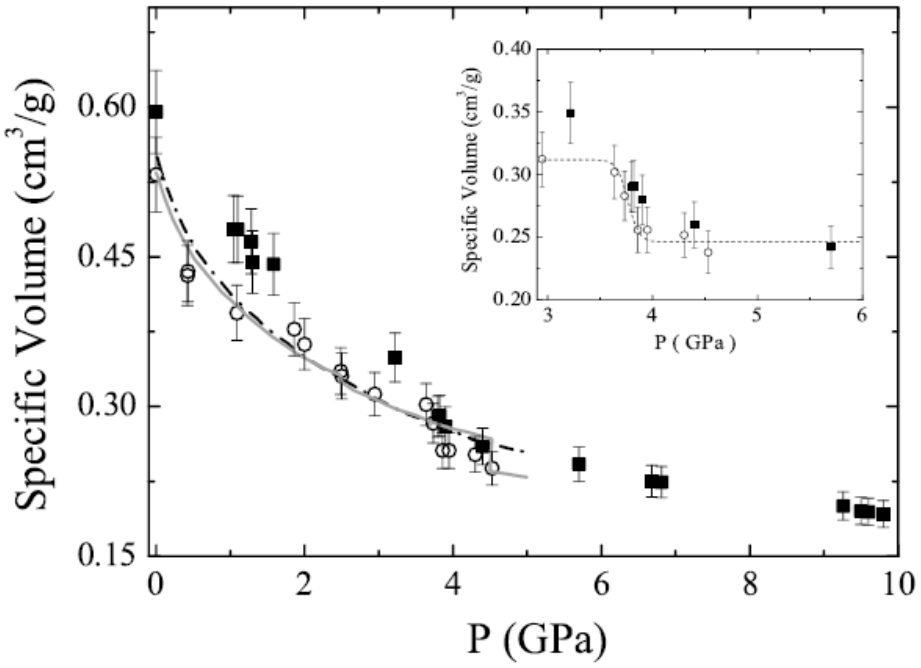


FIG. 3. The specific volume of *l*-Cs at $T = 220\,^{\circ}\mathrm{C}$ (open circles) and $T = 350\,^{\circ}\mathrm{C}$ (filled squares) as a function of pressure. The solid and dot-dashed lines are the specific volume data of the solid at $20\,^{\circ}\mathrm{C}$ and liquid at $198\,^{\circ}\mathrm{C}$, respectively, from Ref. [1]. The inset shows an enlarged view of the data in the region 2.9 and 6 GPa. The dashed line is a guide for the eye.

X-ray Diffraction Study of Liquid Cs up to 9.8 Gpa
S. Falconi, L. F. Lundegaard, C. Hejny, and M. I. McMahon
Phys. Rev. Lett. **94**, 125507 (2005)

Falconi (2005)

T=220°C

P (GPa)	Specific V.	ρ (kg/m^3)
0	0.53281	1900
0.42407	0.43609	2321.39925
0.42409	0.43201	2343.32307
1.0807	0.39434	2567.173
1.8605	0.37805	2677.7913
1.9973	0.36278	2790.50389
2.4897	0.33529	3019.29375
2.5034	0.3302	3065.83586
2.9412	0.3129	3235.34356
3.6389	0.30271	3344.25358
3.7346	0.28337	3572.49885
3.8577	0.25588	3956.30374
3.9535	0.25588	3956.30374
4.2955	0.25181	4020.24939
4.528	0.23857	4243.36254

T=350°C

P (GPa)	Specific V.	ρ (kg/m^3)
0	0.59593	1678.04944
1.0397	0.47885	2088.33664
1.0944	0.47885	2088.33664
1.2859	0.46561	2147.7202
1.2996	0.44525	2245.92925
1.5869	0.44321	2256.26678
3.2148	0.34955	2860.82106
3.8167	0.29152	3430.29638
3.8851	0.28032	3567.3516
4.3912	0.26097	3831.85807
5.6908	0.24265	4121.16217
6.6758	0.22534	4437.73853
6.8126	0.22432	4457.91726
9.2613	0.2009	4977.6008
9.4938	0.19581	5106.99147
9.6033	0.19581	5106.99147
9.7948	0.19276	5187.7983

Belashchenko (2014)

T=493 K

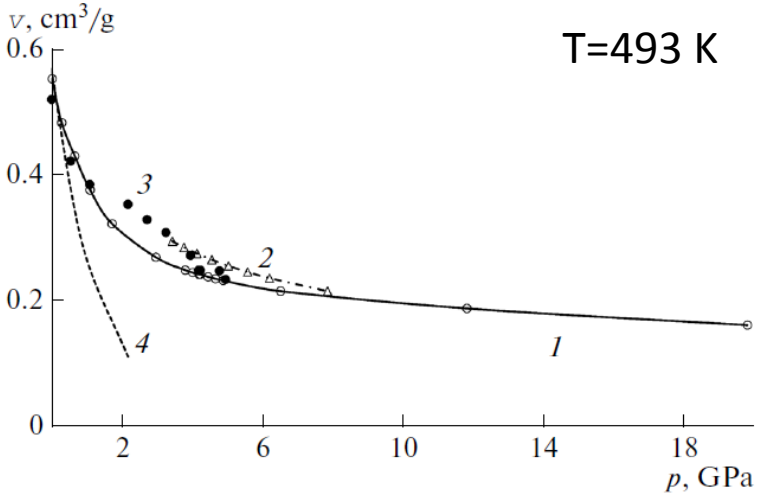


Fig. 2. Specific volume of cesium vs. pressure at 493 K: (*1*) molecular dynamics with the EAM-1 potential, (*2*) molecular dynamics with the EAM-2 potential, (*3*) data from [10], and (*4*) equation $V = 0.579\exp(-0.815p)$.

T=623 K

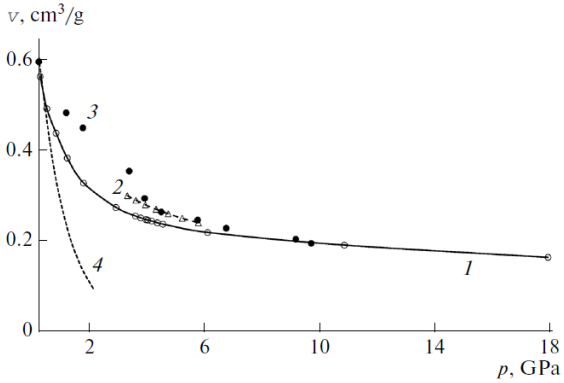
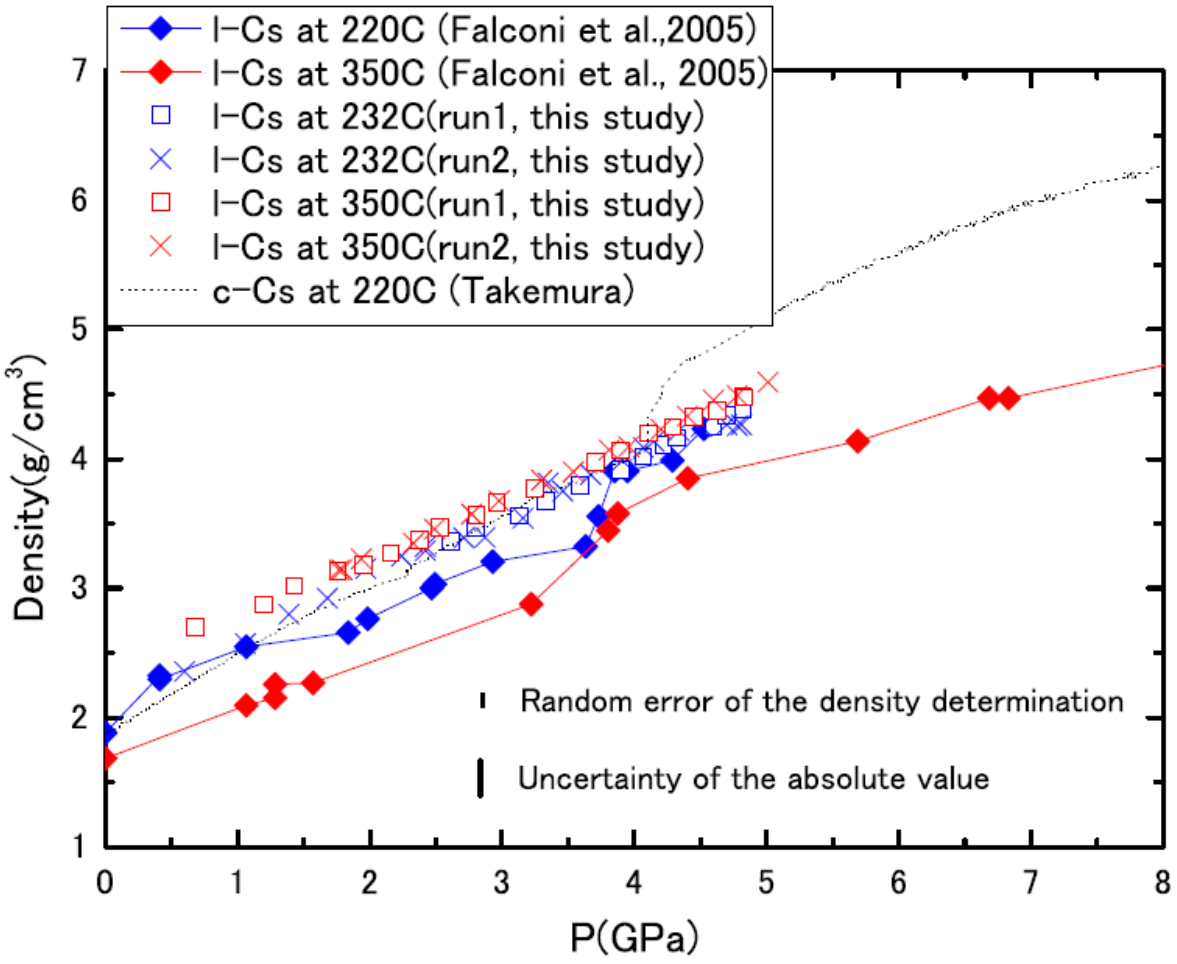


Fig. 3. Specific volume of cesium vs. pressure at 623 K: (*1*) molecular dynamics with the EAM-1 potential, (*2*) molecular dynamics with the EAM-2 potential, (*3*) data from [10], and (*4*) equation $V = 0.605\exp(-0.94p)$.

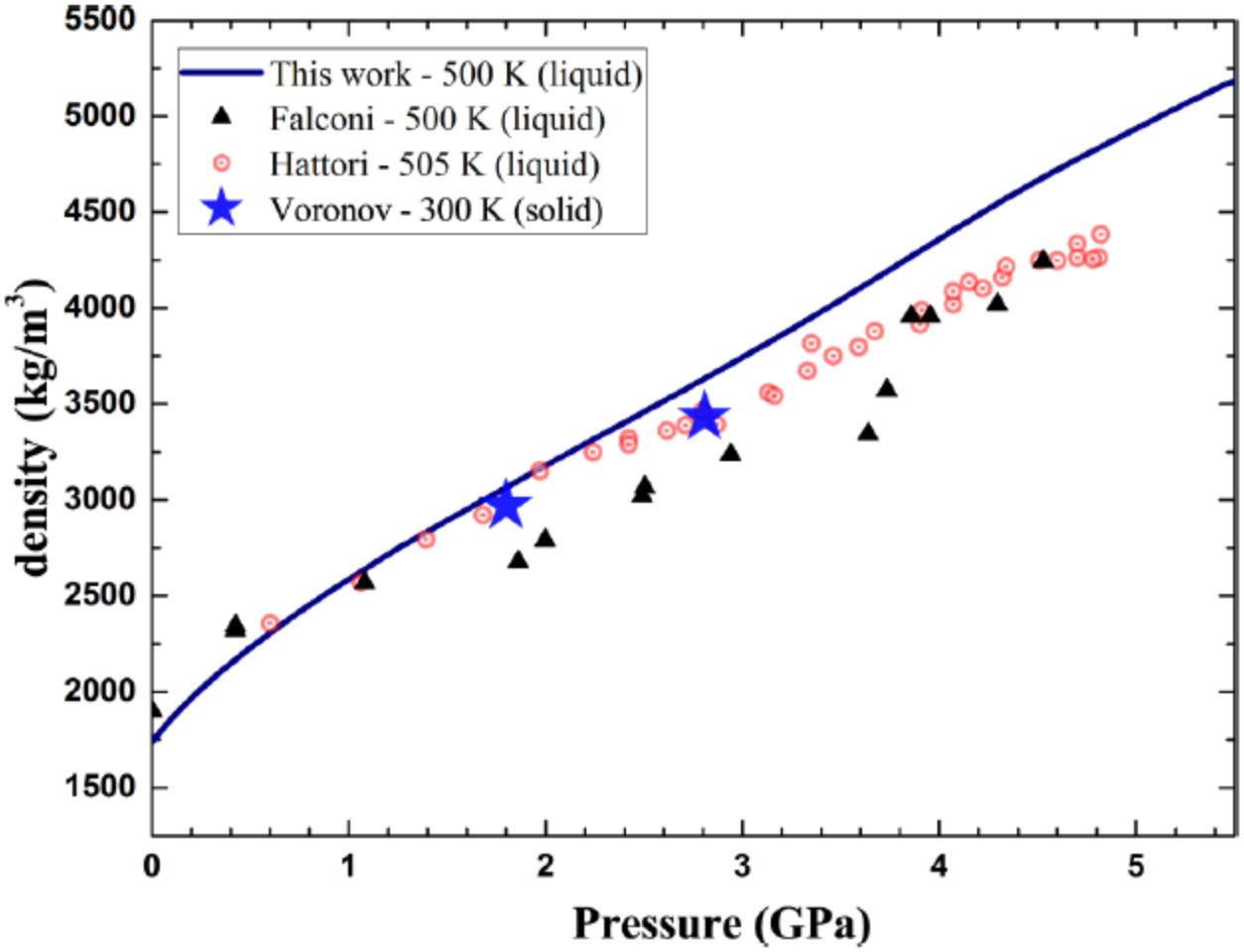
D.K. Belashchenko, *Structural transitions in liquid cesium*, *Russian Journal of Physical Chemistry A*, **88** 1533 (2014)

Hattori (2018)



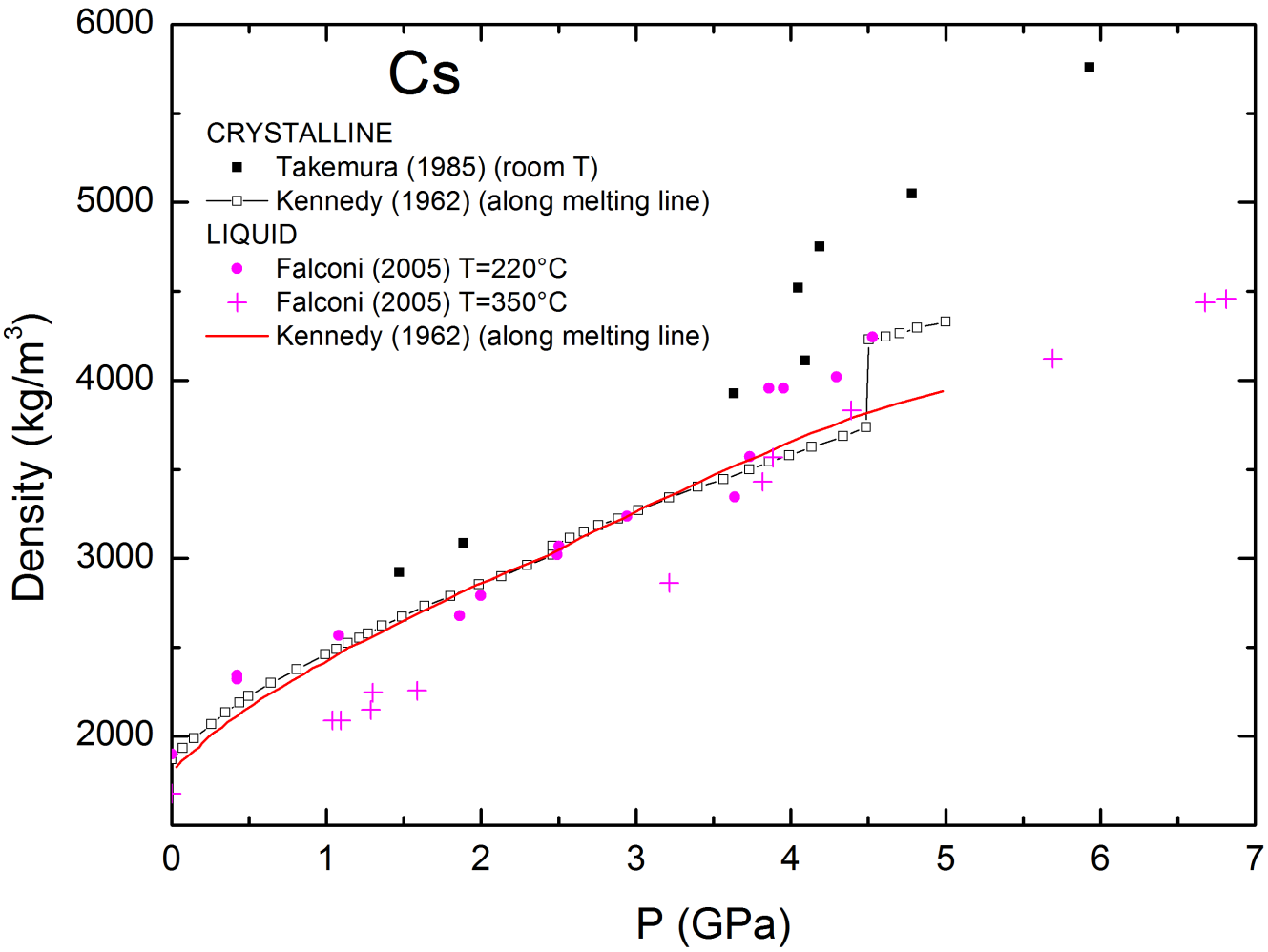
Hattori, Takanori. "Is there a pressure-induced discontinuous volume change in liquid Cs?" *Physical Review B* 97.10 (2018): 100101.

Decremps (2018)

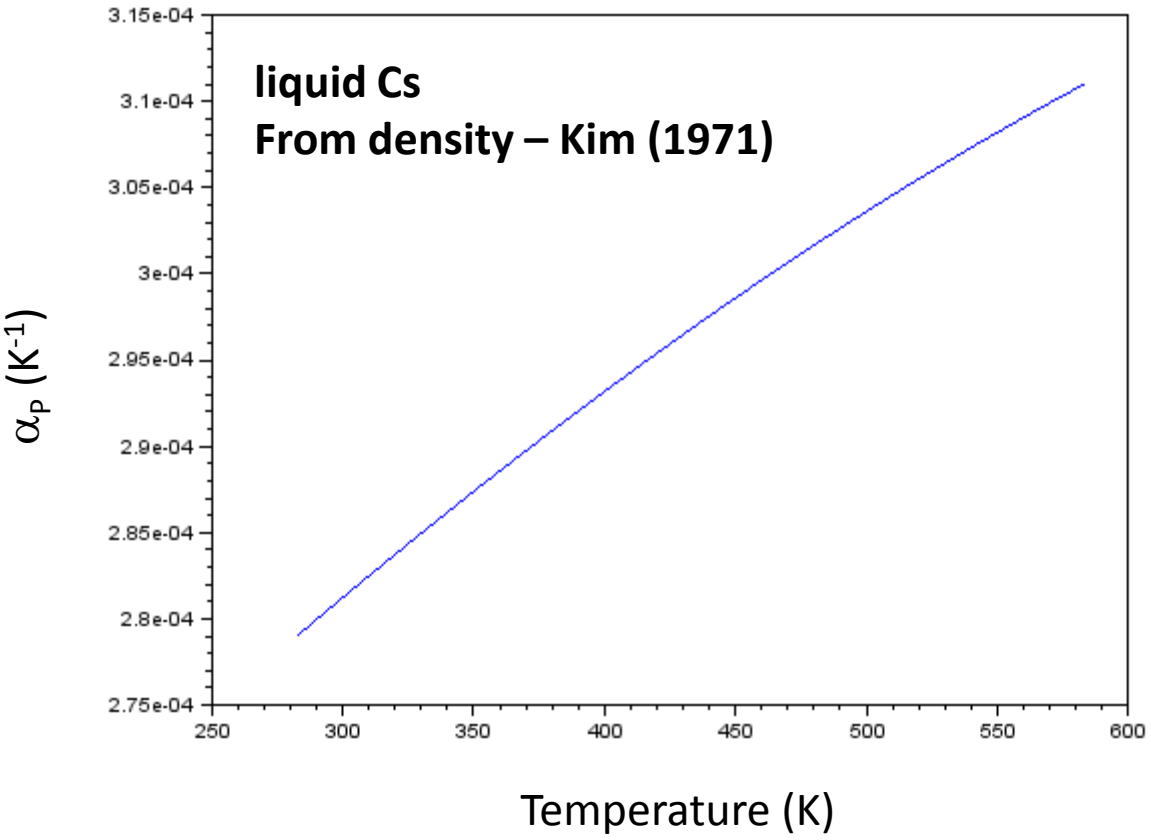


Frédéric Decremps, Simon Ayrinhac, Michel Gauthier, Daniele Antonangeli, Marc Morand, Yiuri Garino, and Paraskevas Parisiades, *Sound velocity and equation of state in liquid cesium at high pressure and high temperature,* Phys. Rev. B **98**, 184103 (2018)
DOI:https://doi.org/10.1103/PhysRevB.98.184103

Density overview



Thermal expansion coefficient



Bulk modulus

Solid Cs

TABLE I. Summary of the isotherm results for cesium. The data points for the isotherms are indicated in Figs. 2 and 3. (RMSD denotes root-mean-square deviation.)

T (K)	P^* (kbar)	$(V/V_0)_{P=0}$[a]	B_0[a]	B_0[b] (kbar)	B_0'[b]	B_0''[b] (kbar^{-1})	RMSD (10^{-4} in V/V_0)
290	+0.085	1.0050	16.90[d]	16.98±0.06	3.79∓0.02	−0.077±0.001	0.8
270	(0)	(1.0000)[c]	(17.23)	17.23±0.05[c]	3.87∓0.03[c]	−0.103±0.005[c]	2.8
				[17.13±0.03][f]	[3.98∓0.03][f]	[−0.150±0.004][f]	2.7
248	−0.09	0.9948	17.58	17.60±0.10	3.87∓0.06	−0.112±0.011	3.7
200	−0.275	0.9838	18.29	18.32±0.12	3.82∓0.07	−0.105±0.014	4.6
146	−0.505	0.9726	19.17	19.05±0.12	3.89∓0.01	−0.113±0.012	7.7
99.5	−0.69	0.9634	19.88	19.86±0.14	3.79∓0.06	−0.099±0.018	8.1
82	−0.765	0.9598	20.16	20.26±0.08	3.73∓0.04	−0.098±0.008	8.8
43	−0.915	0.9528	20.73	20.94±0.06	3.67∓0.02	−0.087±0.005	6.7
34	−0.96	0.9508	20.90[e]	20.50±0.15	3.95∓0.06	−0.125±0.012	6.1
20	−0.975	0.9501	20.95	21.09±0.06	3.69∓0.02	−0.087±0.006	7.1
4	−1.00	0.9489	21.05	21.03±0.06	3.76∓0.02	−0.096±0.006	6.8
				[20.79±0.09][f]	[3.98∓0.04][f]	[−0.168±0.009][f]	6.6

[a]Derived from the 270-K isotherm and P^*.
[b]Parameters derived from nonlinear least-squares fits of the ME-2 relation, Eq. (6), to the data for each isotherm. The 3σ uncertainties are those associated with the fitting procedure and do not include an allowance for systematic effects. A more qualitative estimate gives minimum uncertainties of ±0.3 kbar for B_0, ∓0.1 for B_0' and ±0.01 kbar^{-1} for B_0''.
[c]These parameters define the reference isotherm with V_0 (270 K, $P=0$)=70.00 cm^3/mole.
[d]0.354-in. sample-holder data only.
[e]0.250-in. sample-holder data only.
[f]Alternative representations of the data usng the MME relation, Eq. (9).

Anderson, M. S., & Swenson, C. A., *Experimental equations of state for cesium and lithium metals to 20 kbar and the high-pressure behavior of the alkali metals,* Physical Review B, ***31*(2)**, 668 (1985).

Isobaric heat capacity C_P

Solid Cs

Solid Phase Heat Capacity (Shomate Equation)

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$C_p^\circ = A + B*t + C*t^2 + D*t^3 + E/t^2$

$H^\circ - H^\circ_{298.15} = A*t + B*t^2/2 + C*t^3/3 + D*t^4/4 - E/t + F - H$

$S^\circ = A*\ln(t) + B*t + C*t^2/2 + D*t^3/3 - E/(2*t^2) + G$

C_p = heat capacity (J/mol*K)
H° = standard enthalpy (kJ/mol)
S° = standard entropy (J/mol*K)
t = temperature (K) / 1000.

View plot Requires a JavaScript / HTML 5 canvas capable browser.

Temperature (K)	298. - 301.55
A	57.04424
B	-50.00340
C	48.55950
D	-16.72822
E	-1.223804
F	-19.28397
G	160.2012
H	0.000000
Reference	Chase, 1998
Comment	Data last reviewed in June, 1968

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Liquid Phase Heat Capacity (Shomate Equation)

$C_p° = A + B*t + C*t^2 + D*t^3 + E/t^2$

$H° - H°_{298.15} = A*t + B*t^2/2 + C*t^3/3 + D*t^4/4 - E/t + F - H$

$S° = A*\ln(t) + B*t + C*t^2/2 + D*t^3/3 - E/(2*t^2) + G$

C_p = heat capacity (cal/mol*K)

H° = standard enthalpy (kcal/mol)

S° = standard entropy (cal/mol*K)

t = temperature (K) / 1000.

View plot Requires a JavaScript / HTML 5 canvas capable browser.

View table.

Liquid Cs

Temperature (K)	301.55 - 947.967
A	7.181250
B	0.121007
C	0.083068
D	-0.023772
E	0.047110
F	-1.490001
G	30.92180
H	0.498805
Reference	Chase, 1998
Comment	Data last reviewed in June, 1968

http://webbook.nist.gov/cgi/cbook.cgi?ID=C7440462&Units=CAL&Mask=FFFFFF

Liquid Cs

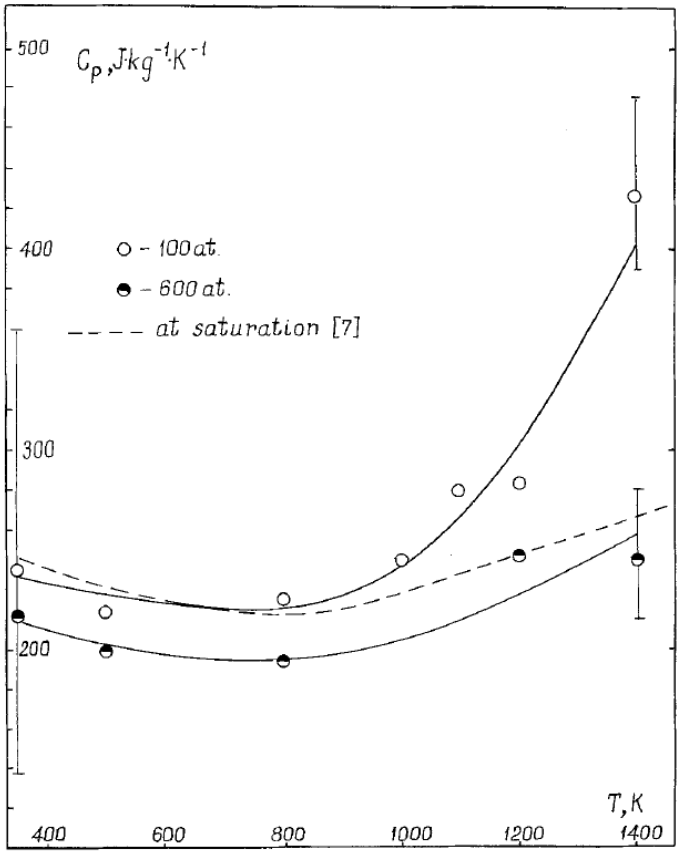
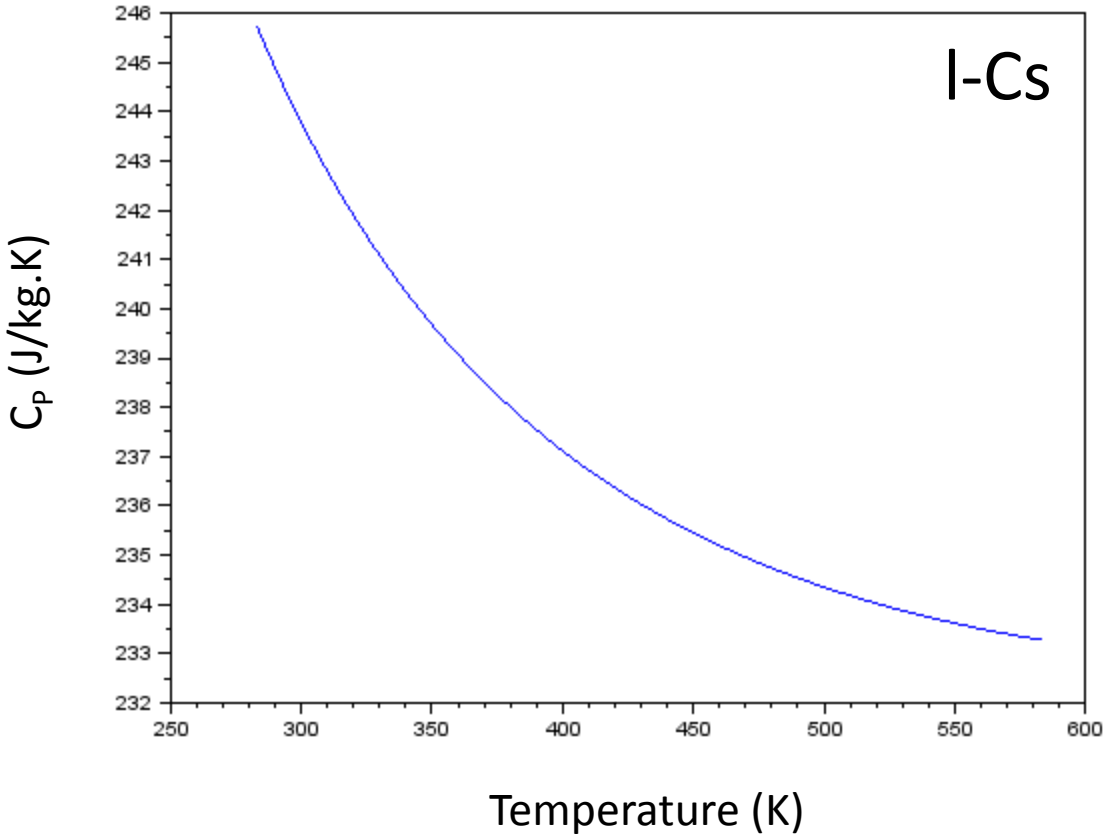


Fig. 5. Heat capacity at constant pressure of liquid cesium as a function of temperature.

N.B. Vargaftik, V.F. Kozhevnikov, A.M. Gordeenko *et al.*, Int. J. Thermophys. **7** 821 (1986)

Liquid heat capacity



Temperature ranges for experimental specific-heat data for alkali metals

Metal	Temperature range (K)	Source
Lithium	15–300	a
	20–300	b
	3–30	c
	1.5–20	d
Sodium	20–300	e
	16–120	f
	3–30	c
	1.5–20	d
	1.5–20	g
Potassium	15–275	f
	12–320	h
	1.5–20	d
	0.4–26	i
	0.2–4.2	j
Rubidium	1.3–12	k
	0.4–320	i
	0.2–4.2	j
	1.2–4.2	k
Cesium	1.3–12	l
	0.4–320	i
	0.2–4.2	j

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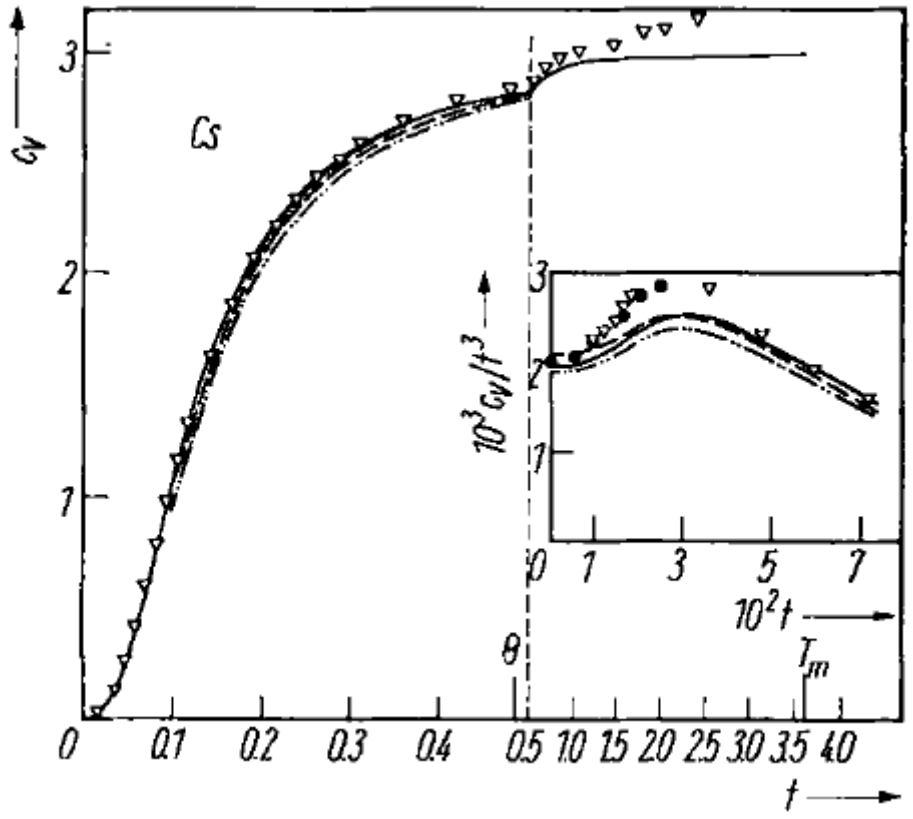
Solid Cs



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Comparison with Na, K

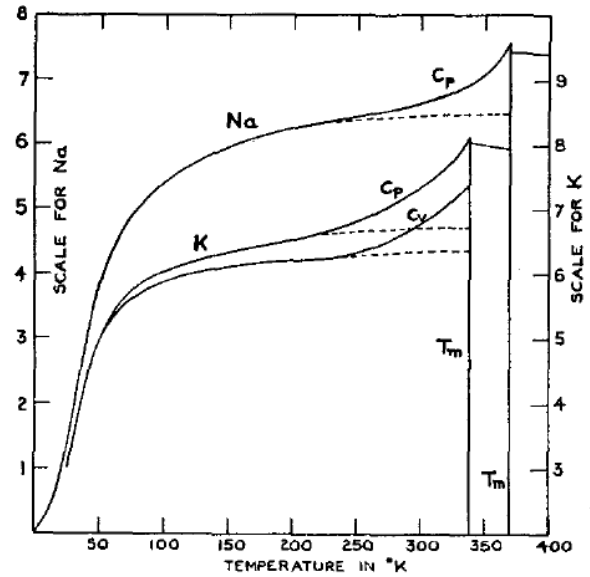

FIG. 1. The atomic heats of K and Na in cal deg^{-1} mole^{-1}.

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Heat capacity ratio $\gamma=C_P/C_V$

Liquid Cs

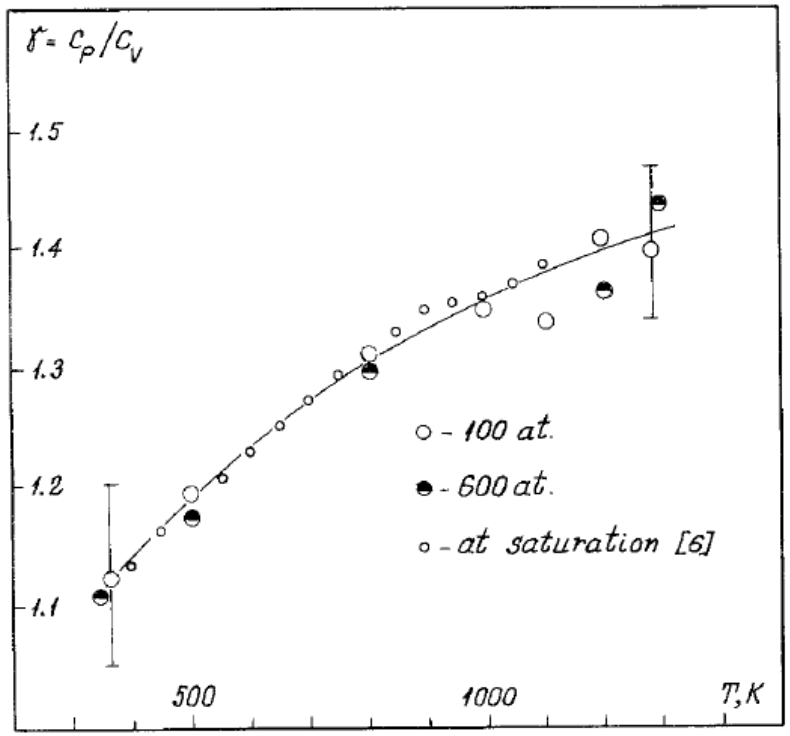


Fig. 6. Heat capacity ratio of liquid cesium as a function of temperature.

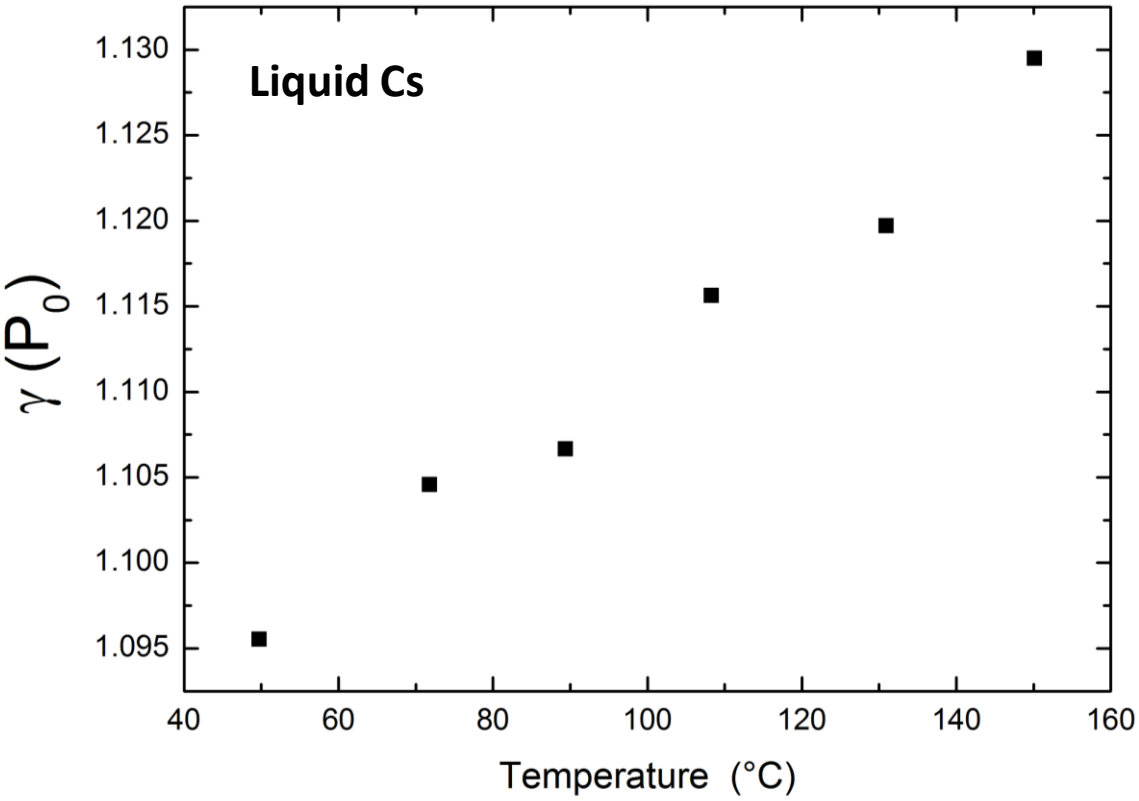
$$\gamma \equiv \frac{C_P}{C_V} = \frac{\beta_T}{\beta_S} = \frac{B_S}{B_T} = \frac{c_S^2}{c_T^2}$$

(line data points)
Vargaftik (1986), liquid Cs

T (K)	γ
380.11	1.1306
397.86	1.1402
415.59	1.1489
431.37	1.1576
456.96	1.1691
472.74	1.1778
490.45	1.1855
521.93	1.1989
555.4	1.2143
586.88	1.2278
622.29	1.2422
677.31	1.2624
728.42	1.2816
789.3	1.3018
848.16	1.3181
908.95	1.3335
957.99	1.3469
1010.9	1.3603
1059.9	1.3709
1128.5	1.3853
1189.2	1.3967
1244	1.4054
1300.8	1.4149
1322.3	1.4178

N.B. Vargaftik, V.F. Kozhevnikov, A.M. Gordeenko *et al.*, Int. J. Thermophys. **7** 821 (1986)

Shaw (1985)



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