

Melting Temperature of Bismuth to 55 GPa Using Synchrotron X-Ray Phase Contrast Imaging

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The melting temperature of elemental bismuth under high pressure has been measured to 55 GPa using synchrotron x-ray phase-contrast imaging in the laser-heated diamond anvil cell. Imaging of solid-liquid interface formation, combined with radiometric temperature and x-ray diffraction measurements, reveals a pronounced reduction in melting boundary slope in Bi-V with pressure. The unusually steep initial slope is attributed to low configurational entropy of melting, arising from structural ordering and coordination matching in the cool liquid, while slope reduction is driven by entropy increase correlated with significant liquid structure changes with rising pressure and temperature. The data rule out kinetic effects on melting in shock compression experiments and demonstrate the need for improved theoretical phase diagrams.

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Bismuth is among the most heavily studied phase-transforming metals at high pressure and temperature conditions. Complex phase transformation behavior at relatively low pressures, low melting temperature, a minimum in the melting line, and liquid structural complexity including liquid-liquid phase transitions—all below 10 GPa—have made Bi an ideal material for case studies in metals at extremes [1–15].

Under quasistatic compression at room temperature, Bi-I ($R\bar{3}m$) undergoes successive phase transitions to Bi-II ($C2/m$) at 2.5 GPa, Bi-III (incommensurate host-guest, $I4/mcm$ and $I4/mmm$) at 2.8 GPa, and bcc Bi-V ($Im\bar{3}m$) at 8.7 GPa with Bi-IV ($Cmca$) appearing at elevated temperatures between 2.5 and 5.3 GPa [1–9,13]. Above 8.7 GPa [13], Bi-V remains stable to at least 300 GPa at room temperature [14,15] and is the stable solid at melting above the 3.8 GPa IV-V-liquid triple point [2,16–18]. The melting behavior of Bi is poorly constrained beyond this, with the measured melting temperature of Bi-V ranging

from 700 to 950 K at just 7 GPa [2,16,17,27] and limited experimental data on solid phase stability at higher pressure and temperature near the melting line [10].

Additionally, melting temperatures of Bi measured under quasistatic conditions [2,27] tend to be less than those estimated in dynamic shock experiments from calculated temperatures [16,17,28], at similar pressures. Dynamic compression-and-release measurements on Bi suggest that timescales of a few nanoseconds can produce complete melting [17]. This is sufficient to identify the equilibrium melting points in dynamic experiments; however, recent studies suggest dynamic melting can require longer timescales at incipient melting [28,29]. Kinetic effects in the phase transformations of solid bismuth under dynamic compression, including changes in phase stability ranges and disappearance (or appearance) of certain structures, have been widely reported [10,12,13,28,30]. These observations raise the possibility that equilibrium melting is not achieved in dynamic experiments [10,17,28]. Measurements of equilibrium melting using quasistatic compression are limited to 8.5 GPa [2,27], leaving untested the measurements of shock-wave melting along the Hugoniot, beginning at 19 ± 1 GPa [10], or theoretical predictions for high-pressure equilibrium melting, which vary considerably [31–34].

This study determines the melting temperature of Bi at high pressures using the laser-heated diamond anvil cell (LH-DAC) with partially coherent propagation-based x-ray

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phase contrast imaging (XPCI) as a diagnostic of melting and simultaneous x-ray diffraction (XRD) to constrain pressure and phase [18,35]; this approach has been shown to produce melting data compatible with other measurements [35]. These studies include direct spatially resolved temperature measurements and unambiguous melting criteria, supported by finite element modeling (FEM).

Samples were prepared in diamond anvil cells, using a layer of bismuth foil or powder placed between a variety of transparent insulating media to ensure robust media-independent results. The experiments were performed at the Extreme Conditions Beamline (ECB, P02.2) at the PETRA-III synchrotron light source [36], using simultaneous XPCI and XRD [35,37] during infrared laser heating (LH) with spectroradiometry to determine temperature [35,38]. The partially coherent 25.4–25.6 keV synchrotron x-rays were focused with compound refractive lenses before the sample, with the diverging beam forming a circular beam spot 65–165 μm in diameter at the sample position (with a much larger field of view of 85 and 200 μm , respectively, for the two extremes). Laser heating was performed on one or both sides of the samples with flattop laser spots of 10–70 μm diameter ($\lambda = 1070$ nm). XPCI and XRD were recorded with an exposure time of 100–200 ms at 5–10 Hz; thermal emission data were recorded with an acquisition time of 0.1–5 s at up to 1 Hz [38].

XPCI measurements are sensitive to phase variations in the coherent component of x-ray illumination, which are, in turn, sensitive to the refractive index and density variations at, and the shape of, material interfaces [37,39,40], making the approach especially suited to detecting phase boundaries [35,37]. A dynamic flat-field correction is performed with principal component analysis, based on singular value decomposition of image stacks where principal components describe the directions of the largest variances in the dataset. The components describe contributions of object changes, beam fluctuations, and static features [37,41,42], allowing the former to be separated out for analysis [18]. XRD patterns were processed in DIOPTAS [43], and batch structural analysis employing the *le Bail* method was used [18].

Samples were observed for 80–400 s (depending on exposure time, 800–2000 frames in XPCI and XRD). We used ramp heating, where the laser power was gradually and continuously increased in a single run from zero, and step heating, where the laser was flashed on the sample at a fixed power during a run. Laser power was increased until thermal emission became measurable and was further increased until melting had clearly occurred in XPCI.

The melting temperature T_{melt} was established from the emission temperature at the time of first melting onset in XPCI. From the spatially dependent emission temperature across the hot spot [35], resolved along the spectrometer slit on both sides of the sample [38], the maximal sample temperature T_{max} at the time of melting was, thus, obtained and taken to represent the melting point; this could

be slightly larger than temperatures averaged over the whole hot spot at the same time [35] by ~ 200 K at the maximum pressure. Uncertainties were established as $\Delta T = |T_{\text{melt}} - T_{\text{solid}}|$, with T_{solid} being the temperature of the last condition where only a solid was observed in XPCI (i.e., just before melting in ramp heating or in a lower power run in step heating), plus fitting uncertainty [18].

Figure 1 shows XPCI results obtained at initial pressures of 17.6 and 54.9 GPa. In both cases, melting was observed in XPCI as a distinct new (dynamically changing) feature, forming at the laser-heated spot. As this feature is difficult to visualize in raw images [Figs. 1(b) and 1(f)], respective principal component analysis-processed images are displayed. If only the components of the fluctuation of the x-ray beam are removed, the solid-liquid boundary becomes more visible, while some static contributions are still kept in the processed image [Figs. 1(c) and 1(g)]. If both the beam fluctuations and the static features are removed, only the sample changes (i.e., the phase change) remains in the processed image [Figs. 1(d) and 1(h)]. While solid-solid phase transition interfaces were also detectable and observed at lower pressures in addition to the solid-liquid interface [18], at high pressures only a single solid phase (Bi-V) was observed in XRD and a single boundary in XPCI attributed to the melt-solid interface. Moreover, the growth of the melt area with temperature closely matches predictions of finite element models of sample melting [Fig. 1(i) [18]].

In our experiments, a large sample volume is probed by the x-rays: For XPCI to work as a melt diagnostic, the x-ray beam has to illuminate an area larger than the laser spot, to clearly observe phase boundaries. XRD, thus, samples the pressure and temperature distribution across the entire laser spot and area surrounding it. This leads to the bulk of the detected sample still being in a cold state, a scenario that is the opposite of conventional LH-DAC experiments with XRD detection [38,44,45]. This leads to a broad, split, or multiple peak profile in observed reflections (Figs. 2 and S4 [18]), resulting from the time-dependent pressure and temperature gradients in the sample. For the extreme case, use of a 165 μm FWHM x-ray spot [experiment 5; Figs. 1(a)–1(d) and 2] and a 10 μm laser spot implies the probed area is ~ 270 times larger than the heated area; for a 65 μm x-ray spot [experiment 17; Figs. 1(e)–1(i)], the probed area is ~ 36 times larger. Thus, XRD signal tends to predominantly originate from cold material, though the relative contribution from hot material is also controlled by the Bi layer geometry [Figs. 1(a)–1(d), 2, and S4 [18]]. However, signal from hot material, separated from main peaks, remains detectable [e.g., Figs. 2, S4(c), and S4(d)] and is uniformly consistent with high temperature solid Bi-V grains near the melting point, appearing at lower angles than the cold Bi-V signal. No evidence for new phases appearing at high temperature were detected, confirming that bcc Bi-V is the stable phase at melting at all pressures studied here.

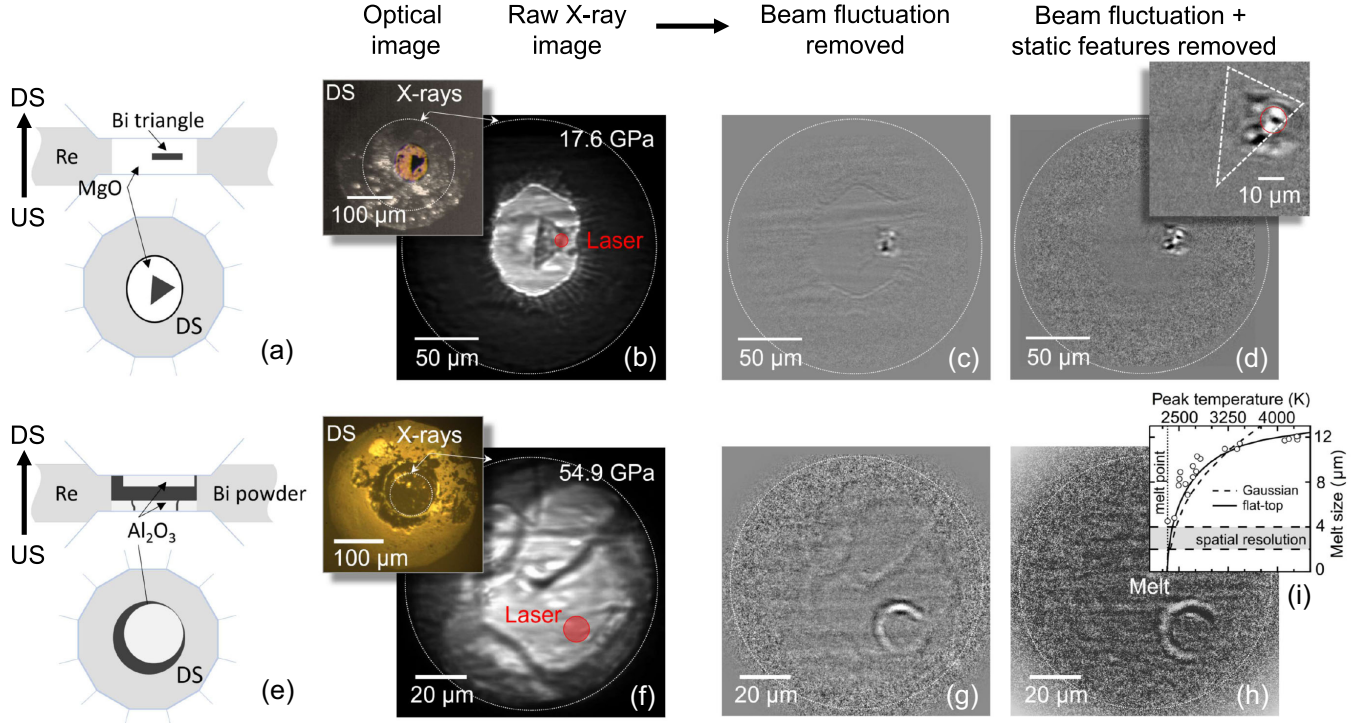


FIG. 1. Melting data on bismuth at initial pressures of 17.6 and 54.9 GPa under ramp heating. The sample comprised a triangular Bi foil in MgO in (a)–(d), experiment 5 [18], and Bi powder between two amorphous Al_2O_3 plates in (e)–(i), experiment 17 [18] (the insulating plates fractured and the resulting features can be seen in XPCI images). Panels show sample sketches (a),(e); selected frames of direct x-ray imaging with a corresponding optical image (b),(f), with FWHM of IR-laser (red line) and x-ray field of view (white line); the same frame after removing all principal components originating from the beam fluctuation (c),(g); and the frame after removing all beam components and static features (d),(h). Panel (i) shows the measured scaling of melted area with temperature (symbols) for the run in (f)–(h), and finite element model (FEM) for these data with Gaussian and flattop spot laser intensity profiles [18]. Videos of the XPCI for these experiments can be found in Supplemental Material [18].

To obtain the time-dependent pressure of the heated sample, a thermodynamic thermal equation of state was used. We take at each time $P(T, V) = P_{\text{BM}}(300, V) + fP_{\text{th}}$ [46], where $P_{\text{BM}}(300, V)$ represents the cold compression response, given by a third-order Birch-Murnaghan equation of state fitted to experimental literature data [15,18], and the thermodynamic thermal pressure $P_{\text{th}} = \bar{\alpha}K(T - 300)$ [44,46] is calculated assuming the product of thermal expansivity α and bulk modulus K is a constant [44] ($\bar{\alpha}K = 0.00228 \text{ GPa/K}$ [18]). Referenced to the values in the cold sample, a thermal pressure correction of $f = 0.3$ [46] is used. At each time, temperature T is determined from the spectroradiometric temperature, while volume V is determined from the cold average Bi unit cell [Fig. 2(b)]; assuming V corresponds to near room temperature Bi, this tracks the average pressure in the sample cavity and allows correction for the pressure at melting, P_{melt} , including thermal pressure in the hot spot. The uncertainty in our melting point pressures is obtained considering any pressure gradient within the cell, and the thermal pressure estimated due to heating, leading to maximum errors of 1–2 GPa; assessed uncertainties are comparable to equation of state uncertainty for Bi-V [14,15,18,47,48].

Measurements of melting with laser heating were successful from 8.2 to 54.9 GPa, due to emission temperature being measurable only above 1200 K. For this reason, two data points below $\sim 8 \text{ GPa}$ were obtained with resistive heating with diffraction only, following previously described techniques [49]. The melting criterion was the first appearance of liquid diffuse scattering, and the melting point and uncertainty were obtained from the average T and P of the last solid and first liquid data points around melting [18].

The present data together with literature data and theory [2,10,16,17,27,31–34] are plotted in Fig. 3. The triple point Bi-IV/Bi-V/melt has been established as $P_{\text{TP}} = 3.8 \text{ GPa}$ and $T_{\text{TP}} = 567 \text{ K}$ from the literature [2]; based on this reference point, a Simon-Glatzel-type melt line [50] of the form $T_m = T_{\text{TP}}(1 + [P - P_{\text{TP}}]a^{-1})^b$ ([GPa] vs [K]) was fitted to our data (including uncertainties) and literature data in the low- P regime [2] resulting in the parameters $a = 1.53(36)$ and $b = 0.407(26)$. A Kechin fit [51] of the form $T_m = T_{\text{TP}}(1 + [P - P_{\text{TP}}]a^{-1})^b \exp(c[P - P_{\text{TP}}])$ was fitted as well to better take into account the rapidly changing melt slope. The respective fitting parameters are $a = 0.82(47)$, $b = 0.306(69)$, and $c = 0.0038(26)$.

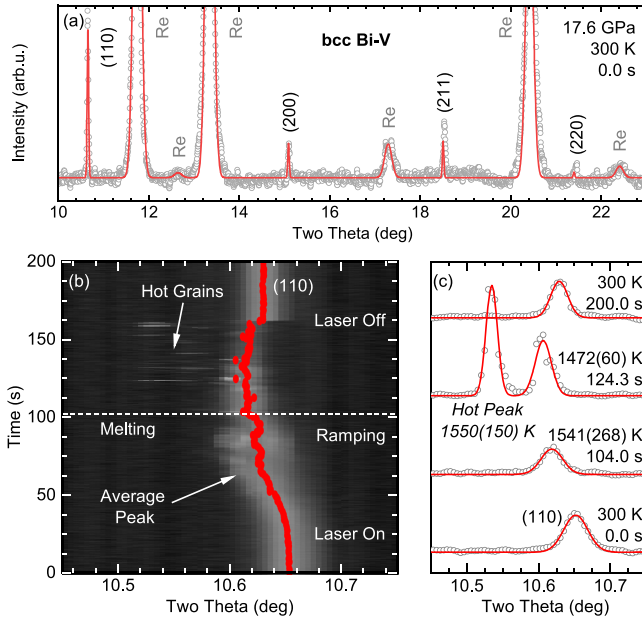


FIG. 2. Diffraction data for Bi sample in MgO initially at 17.6 GPa during ramp heating [Figs. 1(a)–1(d), experiment 5 [18]]. Patterns were collected at 10 Hz with 100 ms collection time. (a) Initial diffraction pattern (points) with representative Le Bail fit (red) including bcc Bi-V and hcp Re gasket also targeted with the imaging beam [Fig. 1(b)]. (b) Intensity of the (110) reflection signal as function of time and Bragg angle. Red circles show the maximum of the main peak, representing the sample average. Peaks appearing intermittently to lower angle ($\approx 10.55^\circ$) are large Bi-V crystallites, with apparent temperatures of 1000–1550 K according to our thermal equation of state, suggesting recrystallization near melting. (c) Selected (110) reflection data with Le Bail fit including a high-temperature component and corresponding temperature determined from radiometry (right) and EOS analysis (left). The melting temperature from our global fits is 1450 K at similar pressures. Pressure was estimated assuming the main peak primarily measures cold material [18]; pressure varies by about 1.7 GPa over the whole run including cold pressure changes and thermal pressure contributions; the sample quenches at 16.8 GPa.

The present static melting data suggest a steeper melt line than prior static measurements [2,27] (Figs. 3 and S9 [18]). The data are consistent with the melting points from shock-and-release experiments [16,17] up to 7 GPa. For melting on the principal shock Hugoniot, measured to occur between 19 and 27 GPa [10], we conclude that shock melting should initiate at 1500 K (and complete at 1750 K) at equilibrium. This compares well with the predicted shock temperature of 1460(130) K [32] at 19(1) GPa (Fig. 3). These findings are consistent with limited kinetic effects upon melting in dynamic experiments [16,17] and high atomic mobility near melting points [52], though this conclusion rests on the accuracy of calculated shock temperatures [32].

Theoretical calculations using perturbation theory [31] give an accurate representation of the high-pressure melting line up to 40 GPa, especially when corrected for the

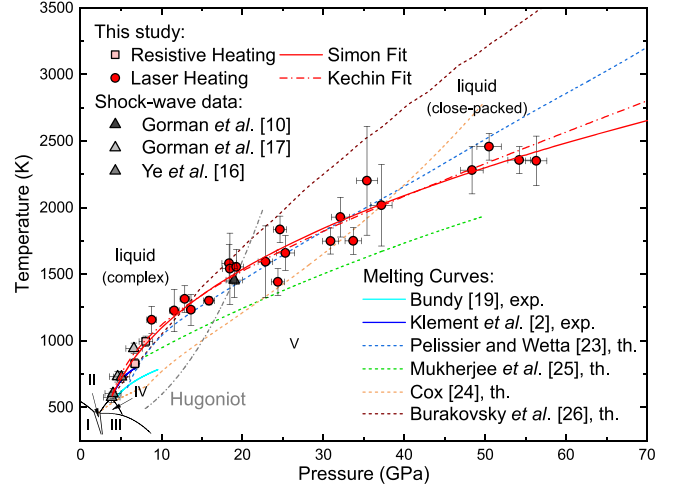


FIG. 3. Phase diagram of bismuth. Red data points were measured in this study (circle for LH, square for RH) with fits (red lines) to Simon-Glatzel (solid) and Kechin (dashed) models. Black curves represent the established phase diagram at low pressure [2,13,18]; solid blue lines refer to prior static experimental melt measurements in Bi-V [2,27]. Dotted lines are computational predictions of melting under pressure [31–34]. The dashed gray line is the shock Hugoniot [16,17,32], and triangles are melting points on shock loading [17] (black) and on release isentropes [10,16].

+2 GPa error in modeled IV-V-liquid triple point. Melting predictions based on indirect estimates from ground state density functional theory in combination with thermodynamic modeling [33], and quantum molecular dynamics simulations [34], show significant deviations from our results.

The initial melting slope of Bi-V, determined as 163(20) K/GPa (error from difference between Simon and Kechin fit) at the triple point (3.8 GPa), is among the largest known for melting of elemental systems [53,54]. Up to 15 GPa, there is a dramatic reduction in melting line slope to a nearly fixed value of 28(5) K/GPa at 20–50 GPa in the Kechin model. In the context of the Clapeyron relation, $(dT/dP)_{\text{melt}} = \Delta V/\Delta S$, the initially steep slope can be attributed to large volume or small entropy change above the triple point.

We constructed thermal equations of state for the liquid and solid state utilizing the solid-liquid coexistence zone of shock-wave experiments [10], pinned to our determined melting curve (Fig. 3), and existing equation of state data for liquid Bi [55] and solid Bi-V [15]. Volume contrast ΔV varies only weakly under pressure (4.8%–3.4% [18]) and cannot account for the large slope changes observed. Instead, the trend corresponds to initially low entropy of melting in Bi-V, significantly lower than the ambient value, which rises rapidly with pressure [Fig. 4(a)]. This analysis self-consistently describes the estimated entropy of melting indicated by the coexistence domain observed under shock loading.

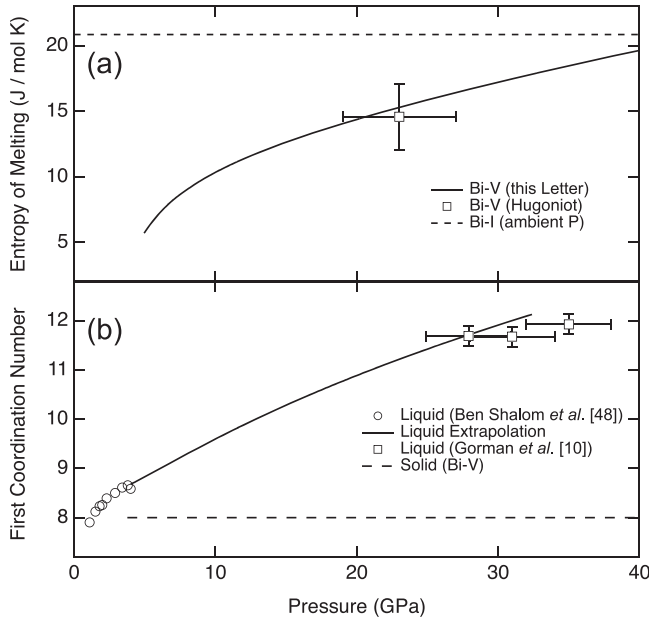


FIG. 4. Properties of bismuth along the melt curve. (a) Entropy of melting for Bi-V. Present values are calculated from equations of state for liquid and solid bismuth [18] and the measured Clapeyron slope (solid line); value on the principal Hugoniot (square) is estimated from the temperature reduction ΔT from the extrapolated Bi-V Hugoniot [32] in the coexistence region, where $L/C_p = \Delta T$, with latent heat $L = T\Delta S$ and heat capacity $C_p = 25.52 \text{ J mol}^{-1} \text{ K}^{-1}$. (b) First coordination number of Bi close to the melting curve. Liquid bismuth data are from recent static-pressure measurements [56] (circles), with the solid line a linear extrapolation in liquid density, and values determined upon melting on the shock Hugoniot (squares) [10]. The value for solid Bi-V is the dashed line.

This behavior correlates with rapid structural evolution of liquid bismuth under pressure [Fig. 4(b)]. At low pressures, near the triple point, the coordination number of the liquid is low (~ 8.5) [56], close to the value for bcc Bi-V (8). The trend of increasing liquid coordination number with pressure up to the triple point [56] is consistent with achieving close packed values (~ 12) above 27 GPa as observed upon shock melting [10], with our melting data consistent with a continuous variation.

The entropy increase on melting is primarily due to configurational entropy [57]. The low initial entropy of melting, near the IV-V-liquid triple point, hence originates in a low configurational entropy change. This correlates with similarity in local liquid and solid structures near the triple point and the ordered nature of the liquid at these conditions with multiple distinct coordination shells [56,58]. Though the liquid evolves to a close packed structure further along the melting curve, it nonetheless exhibits higher entropy. Thus, while conventional packing efficiency is enhanced, presumably as a result of compression, liquid disorder is increased likely driven by the higher temperatures at melting. Consequently, accurate theoretical

treatment of the melting curve of Bi requires careful assessment of liquid structure validated against its complex evolution [10,11,53,56,58]. The nearly invariant Clapeyron slope above 15 GPa seen in the present data, also observed in previous theoretical calculations [31–33] (Fig. 3), is consistent with nearly constant density, entropy and structure contrast along the melt line at higher pressures, in stark contrast to low-pressure behavior where both solid [2,10,12,28] and liquid [11,58,59] bismuth exhibits structural complexity.

In summary, we established the melting line for bismuth to ~ 55 GPa using static high-pressure measurements and a robust melt criterion of partially coherent, propagation-based x-ray phase contrast imaging to resolve solid-melt boundary formation in laser-heated samples. Our study exposes remarkable variability in the melt line slope, correlated to entropy and structure variations in the liquid evolving from a cold, dense ordered state to high-temperature disorder. The melting behavior of Bi under shock compression is consistent with equilibrium melting and, hence, a rapid melting timescale.

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Data availability—The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

- [1] P. Cucka and C. Barrett, *Acta Crystallogr.* **15**, 865 (1962).
- [2] W. Klement, A. Jayaraman, and G. C. Kennedy, *Phys. Rev.* **131**, 632 (1963).
- [3] R. Brugger, R. Bennion, and T. Worlton, *Phys. Lett.* **A24**, 714 (1967).
- [4] P. Schaufelberger, H. Merx, and M. Contre, *High Temp. High Press.* **5**, 221 (1973).
- [5] M. I. McMahon, O. Degtyareva, and R. J. Nelmes, *Phys. Rev. Lett.* **85**, 4896 (2000).

- [6] U. Häussermann, K. Söderberg, and R. Norrestam, *J. Am. Chem. Soc.* **124**, 15359 (2002).
- [7] L. G. Akselrud, M. Hanfland, and U. Schwarz, *Z. Kristallogr.* **218**, 447 (2003).
- [8] O. Degtyareva, M. I. McMahon, and R. J. Nelmes, *High Press. Res.* **24**, 319 (2007).
- [9] W. Chaimayo, L. F. Lundegaard, I. Loa, G. W. Stinton, A. R. Lennie, and M. I. McMahon, *Rev. Mod. Phys.* **11**, 442 (2012).
- [10] M. G. Gorman, A. L. Coleman, R. Briggs, R. S. McWilliams, D. McGonegle, C. A. Bolme, A. E. Gleason, E. Galtier, H. J. Lee, E. Granados, M. Śliwa, C. Sanloup, S. Rothman, D. E. Fratanduono, R. F. Smith, G. W. Collins, J. H. Eggert, J. S. Wark, and M. I. McMahon, *Sci. Rep.* **8**, 16927 (2018).
- [11] M. Emuna, S. Matityahu, E. Yahel, G. Makov, and Y. Greenberg, *J. Chem. Phys.* **148**, 034505 (2018).
- [12] M. G. Gorman, A. L. Coleman, R. Briggs, R. S. McWilliams, A. Hermann, D. McGonegle, C. A. Bolme, A. E. Gleason, E. Galtier, H. J. Lee, E. Granados, E. E. McBride, S. Rothman, D. E. Fratanduono, R. F. Smith, G. W. Collins, J. H. Eggert, J. S. Wark, and M. I. McMahon, *Appl. Phys. Lett.* **114**, 120601 (2019).
- [13] R. Husband, E. O'Bannon, H. Liermann, M. J. Lipp, A. S. J. Méndez, Z. Konôpková, E. McBride, W. J. Evans, and Z. Jenei, *Sci. Rep.* **11**, 14859 (2021).
- [14] C. V. Storm, J. D. McHardy, M. J. Duff, S. G. MacLeod, I. E. F. O'Bannon, and M. I. McMahon, *J. Appl. Phys.* **133**, 245904 (2023).
- [15] D. J. Campbell, D. T. Sneed, E. F. O'Bannon, P. Söderlind, and Z. Jenei, *Phys. Rev. B* **107**, 224104 (2023).
- [16] T. Ye, Y. Yu-Ying, D. Cheng-Da, Y. Ji-Dong, W. Qing-Song, and T. Hua, *Rev. Sci. Instrum.* **62**(3), 036401 (2013).
- [17] M. G. Gorman, R. Briggs, E. E. McBride, A. Higginbotham, B. Arnold, J. H. Eggert, D. E. Fratanduono, E. Galtier, A. E. Lazicki, H. J. Lee, H. P. Liermann, B. Nagler, A. Rothkirch, R. F. Smith, D. C. Swift, G. W. Collins, J. S. Wark, and M. I. McMahon, *Phys. Rev. Lett.* **115**, 095701 (2015).
- [18] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/ldw3-5x6p> for further details on experiments and analysis, which includes Refs. [19–26].
- [19] J. S. Loveday, *High-Pressure Physics* (CRC Press, Boca Raton, FL, 2012), Vol. 1.
- [20] M. Rivers, V. B. Prakapenka, A. Kubo, C. Pullins, C. M. Holl, and S. D. Jacobsen, *High Pressure Res.* **28**, 273 (2008).
- [21] D. Pennicard, S. Smoljanin, F. Pithan, M. Sarajlic, A. Rothkirch, Y. Yu, H. Liermann, W. Morgenroth, B. Winkler, Z. Jenei, H. Stawitz, J. Becker, and H. Graafsma, *J. Instr.* **13**, C01026 (2018).
- [22] E. F. Cave and L. V. Holroyd, *J. Appl. Phys.* **31**, 1357 (1960).
- [23] H. P. Liermann *et al.*, *J. Synchrotron Radiat.* **28**, 688 (2021).
- [24] V. Petricek, M. Dusek, and L. Palatinus, *Z. Kristallogr.* **229**, 345 (2014).
- [25] O. L. Anderson, D. G. Isaak, and S. Yamamoto, *J. Appl. Phys.* **65**, 1534 (1989).
- [26] S. Ono, *High Pressure Res.* **38**, 1 (2018).
- [27] F. Bundy, *Phys. Rev.* **110**, 314 (1958).
- [28] C. M. Pépin, A. Sollier, A. Marizy, F. Occelli, M. Sander, R. Torchio, and P. Loubeyre, *Phys. Rev. B* **100**, 060101(R) (2019).
- [29] P. Renganathan, S. M. Sharma, S. J. Turneaure, and Y. M. Gupta, *Sci. Adv.* **9**, 5745 (2023).
- [30] R. F. Smith, J. H. Eggert, M. D. Saculla, A. F. Jankowski, M. Bastea, D. G. Hicks, and G. W. Collins, *Phys. Rev. Lett.* **101**, 065701 (2008).
- [31] J. Péliissier and N. Wetta, *Physica (Amsterdam)* **289A**, 459 (2001).
- [32] G. A. Cox, *AIP Conf. Proc.* **955**, 1 (2007).
- [33] D. Mukherjee, B. D. Sahoo, K. D. Joshi, and S. C. Gupta, *J. Appl. Phys.* **115**, 053702 (2014).
- [34] L. Burakovsky, D. A. Rehn, S. Anzellini, and D. Errandonea, *J. Appl. Phys.* **135**, 245104 (2024).
- [35] E. Ehrenreich-Petersen, B. Massani, T. Engler, O. S. Pardo, K. Glazyrin, N. Giordano, J. Hagemann, D. Sneed, T. Fedotenko, D. J. Campbell, M. Wendt, S. Wenz, C. G. Schroer, M. Trabs, R. McWilliams, H.-P. Liermann, Z. Jenei, and E. F. O'Bannon, *Results Phys.* **69**, 108132 (2025).
- [36] H.-P. Liermann, Z. Konôpková, W. Morgenroth, K. Glazyrin, J. Bednarčík, E. E. McBride, S. Petitgirard, J. T. Delitz, M. Wendt, Y. Bican, A. Ehnes, I. Schwark, A. Rothkirch, M. Tischer, J. Heuer, H. Schulte-Schrepping, T. Kracht, and H. Franz, *J. Synchrotron Radiat.* **22**, 908 (2015).
- [37] R. J. Husband, J. Hagemann, E. F. O'Bannon, H.-P. Liermann, K. Glazyrin, D. T. Sneed, M. J. Lipp, A. Schropp, W. J. Evans, and Z. Jenei, *Rev. Sci. Instrum.* **93**, 053903 (2022).
- [38] Z. Konôpková, W. Morgenroth, R. Husband, N. Giordano, A. Pakhomova, O. Gutowski, M. Wendt, K. Glazyrin, A. Ehnes, J. T. Delitz, A. Goncharov, V. Prakapenka, and H. Liermann, *J. Synchrotron Radiat.* **28**, 1747 (2021).
- [39] S. W. Wilkins, T. E. Gureyev, D. Gao, A. Pogany, and A. W. Stevenson, *Nature (London)* **384**, 335 (1996).
- [40] F. Wittwer, J. Hagemann, D. Brückner, S. Flenner, and C. Schroer, *Optica* **9**, 295 (2022).
- [41] J. Hagemann, M. Vassholz, H. Hoeppe, M. Osterhoff, J. M. Rosselló, R. Mettin, F. Seiboth, A. Schropp, J. Möller, J. Hallmann, C. Kim, M. Scholz, U. Boesenberg, R. Schaffer, A. Zozulya, W. Lu, R. Shayduk, A. Madsen, C. G. Schroer, and T. Salditt, *J. Synchrotron Radiat.* **28**, 52 (2021).
- [42] S. Flenner, J. Hagemann, M. Storm, A. Kubec, P. Qi, C. David, E. Longo, S. Niese, P. Gawlitza, B. Zeller-Plumhoff, J. Reimers, M. Müller, and I. Greving, *Proc. SPIE Int. Soc. Opt. Eng.* **12242**, 1 (2022).
- [43] C. Prescher and V. B. Prakapenka, *High Press. Res.* **35**, 223 (2015).
- [44] A. Dewaele, A. B. Belonoshko, G. Garbarino, F. Occelli, P. Bouvier, M. Hanfland, and M. Mezouar, *Phys. Rev. B* **85**, 214105 (2012).
- [45] T. Fedotenko, L. Dubrovinsky, G. Aprilis, E. Koemets, A. Snigirev, I. Snigireva, A. Barannikov, P. Ershov, F. Cova, M. Hanfland, and N. Dubrovinskaja, *Rev. Sci. Instrum.* **90**, 104501 (2019).
- [46] A. Dewaele, G. Fiquet, and P. Gillet, *Rev. Sci. Instrum.* **69**, 2421 (1998).
- [47] O. Degtyareva, M. I. McMahon, and R. J. Nelmes, *High Press. Res.* **24**, 319 (2004).

- [48] Y. Akahama, H. Kawamura, and A. K. Singh, *J. Phys. Condens. Matter* **14**, 11495 (2002).
- [49] H. Hwang, Y. Bang, J. Choi, H. Cynn, Z. Jenei, W. J. Evans, A. Ehnes, I. Schwark, K. Glazyrin, G. Diego Gatta, P. Lotti, C. Sanloup, Y. Lee, and H.-P. Liermann, *Rev. Sci. Instrum.* **94**, 083903 (2023).
- [50] F. E. Simon and G. Z. Glatzel, *Z. Anorg. Allg. Chem.* **178**, 309 (1929).
- [51] V. V. Kechin, *Phys. Rev. B* **65**, 052102 (2001).
- [52] Z. Yang, Y. Zhu, J. Shi, S. Pan, S. Yu, Y. Pan, Z. Liang, J. Wang, and J. Sun, *J. Chem. Phys.* **164**, 114503 (2026).
- [53] J. W. E. Drewitt, *J. Phys. Condens. Matter* **33**, 1 (2021).
- [54] D. A. Young, *Phase Diagrams of the Elements* (University of California Press, Berkeley, CA, 1991).
- [55] C. Su, Y. Liu, Z. Wang, W. Song, P. Asimow, H. Tang, and H. Xie, *Physica (Amsterdam)* **524B**, 154 (2017).
- [56] S. Ben Shalom, N. Ellert, L. Henry, M. Emuna, Y. Kirshon, P. Pault, A. King, N. Guignot, Y. Greenberg, E. Yahel, and G. Makov, *Commun. Mater.* **6**, 246 (2025).
- [57] C. M. Bernal-Choban, V. Ladygin, G. E. Granroth, C. N. Saunders, S. H. Lohaus, D. L. Abernathy, J. Y. Y. Lin, and B. Fultz, *Commun. Mater.* **5**, 271 (2024).
- [58] K. Yaoita, K. Tsuji, Y. Katayama, M. Imai, J.-Q. Chen, T. Kikegawa, and O. Shimomura, *J. Non-Cryst. Solids* **150**, 25 (1992).
- [59] C. Lin, J. S. Smith, S. V. Sinogeikin, Y. Kono, C. Park, C. Kenney-Benson, and G. Shen, *Nat. Commun.* **8**, 14260 (2017).