Recent multi-dimensional simulations suggest that high-entropy buoyant plumes help massive stars to explode\textsuperscript{1,2}. Outwardly protruding iron (Fe)-rich fingers of gas in the galactic supernova remnant\textsuperscript{3,4} Cassiopeia A seem to match this picture. Detecting the signatures of specific elements synthesized in the high-entropy nuclear burning regime (that is, α-rich freeze out) would constitute strong substantiating evidence. Here we report observations of such elements—stable titanium (Ti) and chromium (Cr)—at a confidence level greater than 5 standard deviations in the shocked high-velocity Fe-rich ejecta of Cassiopeia A. We found that the observed Ti/Fe and Cr/Fe mass ratios require α-rich freeze out, providing evidence of the existence of the high-entropy ejecta plumes that boosted the shock wave at explosion. The metal composition of the plumes agrees well with predictions for strongly neutrino-processed proton-rich ejecta\textsuperscript{2,3,5}. These results support the operation of the convective supernova engine via neutrino heating in the supernova that produced Cassiopeia A.

Detection of some ‘α-rich freeze-out’ products in the Fe-rich ejecta would allow a direct connection with the predicted high-entropy plumes. α-rich freeze out is a nuclear burning regime that controls explosive nucleosynthesis at high entropy (especially for core-collapse supernovae). In this high-entropy nuclear burning regime, abundant α particles (\(^{4}\)He) are captured by heavy elements. Thus, the coexistence of the main burning product, Fe \(^{56}\)Fe after decay of \(^{56}\)Ni, and other α elements (for example, \(^{44}\)Ti and \(^{64}\)Zn) in the same physical location would be strong evidence for the high-entropy process\textsuperscript{3}. The \(^{44}\)Ti decay line has been detected in Cassiopeia A\textsuperscript{14–16}, but the weak correlation of the spatial distribution between Fe and Ti has complicated the picture\textsuperscript{15} (Fig. I).

In addition to the best-known α-rich freeze-out product—radioactive \(^{44}\)Ti—other rare stable elements synthesized through subsequent captures of α-particles, such as stable Ti, Cr and Zn (see Methods for details of the isotopes), can also be used to characterize the high-entropy nuclear burning regime\textsuperscript{6,17}. X-ray thermal emission lines from these and other elements provide a direct measurement of the relative element compositions within a specific parcel of shocked plasma. This is indeed impossible with the γ-ray lines from \(^{44}\)Ti, since there are no similar detectable lines arising from other species via the same emission mechanism. Here we report the discovery of α-rich freeze-out products, namely stable Ti and Cr, from the Fe-rich ejecta of Cassiopeia A.

We find large residuals from the reference model spectrum around 4.7–4.8 keV and 5.6–5.8 keV in the southeastern Fe-rich ejecta region using the Chandra X-ray Observatory space telescope (Fig. 2), which can be explained only by Kα emission from He-like Ti and Cr ions. Using an ionizing plasma model that includes these lines, we find that the spectrum is well fitted while the residual features are eliminated (see Methods). We compute observed mass ratios of Ti/Fe = 0.09–0.24% and Cr/Fe = 0.39–0.70% (these are 99% confidence level ranges) in this region. These mass ratios must be the yields of Fe-peak elements produced by the α-rich freeze out process (Fig. 3a, Method). There exists some contamination from unrelated Si-rich ejecta within the selected region, but it is negligible in deriving the Ti and Cr abundances.
The lepton fraction, \( \nu_e / (\nu_e + \bar{\nu}_e) \), is key to changing the lepton fraction from the original stellar value (\( \nu_e < 0.5 \)). Both scenarios are the direct consequence of the neutrino-driven convective engine. In fact, some recent simulations predict that strongly neutrino-heated plumes are high-entropy and proton-rich \(^{2,5,6}\).

In Fig. 3b, we show the nucleosynthetic outputs for an extremely hot (\( T_{\text{peak}} = 10 \, \text{GK} \)) burning zone with \( Y_e > 0.5 \) that can be achieved only in such neutrino-heated plumes (Methods). We find that the high-entropy (log([\( T_{\text{peak}} / \rho_{\text{peak}} \) (K cm\(^3\) g\(^{-1}\)] \( \geq 23 \)) and proton-rich (\( Y_e = 0.55 \)) environment can reproduce the observed mass ratios very well. These physical parameters are very similar to those of hot plumes in multi-dimensional simulations\(^{5,6,15}\). In another possible scenario, we can also explain the mass ratios using the material immediately above the hot plumes, which is characterized by lower entropy and higher density (\( T_{\text{peak}} = 6 \, \text{GK}, \rho_{\text{peak}} = 10^6 \, \text{g cm}^{-3}, \log([\ T_{\text{peak}} / \rho_{\text{peak}} \) \( = 22.3 \) ] than the hot plumes themselves. In this case, the lepton fraction needs to be modified to be \( Y_e = 0.5 \) (see curves with square data points in Fig. 3a). Such conditions are found in recent neutrino-driven supernova simulations\(^2\) where the neutrino exposure is key to changing the lepton fraction from the original stellar value (\( Y_e < 0.5 \)). Both scenarios are the direct consequence of the neutrino-driven convective engine. Distinguishing the two scenarios further is not straightforward, but the first scenario, that is, the nucleosynthesis products within the hot plumes, is preferred; a drawback of the second scenario is that the Mn/Fe ratio does not support the \( Y_e \) modification, whereas it does agree well with the proton-rich case (Methods). Other elements such as Ni that are sensitive to the \( Y_e \) value will become useful in the near future with improved X-ray detector technology (Methods).

From the Doppler velocity and proper motion measurements, the total space velocity of the Fe-rich ejecta is estimated to be \( \geq 4,000 \, \text{km s}^{-1} \). In multi-dimensional simulations\(^{10–12}\), Fe-rich clumps produced by the combination of convective overturn and the growth of Rayleigh–Taylor instabilities during the explosion have maximum velocities of about \( 4,000–5,000 \, \text{km s}^{-1} \). Thus, the observed kinematics of the high-entropy Fe-rich ejecta agree well with theoretical predictions.

The high-entropy Fe-rich plumes appear to connect smoothly with the characteristic three-dimensional structures (that is, bubble-like interior and outer ring-like structures) of the ejecta in Cassiopeia \( \Lambda^{10,23}\). Recent multi-dimensional simulations of the remnant formation based on a neutrino-driven supernova explosion model\(^{12,23}\) demonstrated that these observational characteristics of the remnant can be naturally explained by convective overturning in the neutrino-heating layer and the standing accretion shock instability. In particular, the simulated large cavities along the direction of propagation of the Fe-rich plumes bear a remarkable resemblance to the structure around the southeastern Fe-rich region in Cassiopeia \( \Lambda \). Thus our results on the Fe-rich plumes and their proposed formation process agree well with existing evidence from multi-wave band data of the global structure of the remnant interior.
Although $^{44}$Ti (a representative isotope produced in α-rich freeze out) has been detected, the poor spatial correlation between the $^{44}$Ti and Fe-rich X-ray ejecta has been puzzling 1 (Fig. 1). A possible explanation is that most of the Fe processed by the α-rich freeze out has not yet been heated to X-ray-emitting temperatures by the reverse shock. In addition, the sensitivity of the X-ray space telescope NuSTAR (Nuclear Spectroscopic Telescope Array) to blue-shifted $^{44}$Ti lines is worse owing to an instrumental feature of the mirror’s reflectivity (Pt 78.4 keV K-edge), so that only upper limits could be set on the $^{44}$Ti emission in the blue-shifted Fe-rich regions 23,24 (see Methods). Our results show not only that Fe and the α-rich freeze out elements (Ti and Cr) do indeed spatially coexist in the plumes, but also that this region lies at the outermost edge of the remnant in the southeast. Interestingly, the proton-rich ejecta we propose for the Fe-rich plumes typically contains less $^{44}$Ti than neutron-rich ejecta and indeed our estimates of the $^{44}$Ti mass in the Fe-rich plumes falls below the upper limits of NuSTAR (see Methods). The finding here supports the basic picture of the convective supernova explosion mechanism, with also a strong asymmetry requirement, thus shedding light on a long-unresolved problem in astrophysics.

Recent observations from the Soft X-ray Spectrometer (SXS) on the space telescope Hitomi have demonstrated that high-resolution X-ray spectroscopy with X-ray calorimeters is a powerful tool with which to measure the abundances of rare elemental species 25. Upcoming X-ray calorimeter missions (such as XRISM 26 and Athena 27) will provide a great opportunity to investigate the role of high-entropy nuclear burning in the Universe using stable Ti (and also zinc).

**Online content**

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41586-021-03391-9.

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1. Janka, H.-T., Melson, T. & Summa, A. Physics of core-collapse supernovae in three dimensions: a sneak preview. *Annu. Rev. Nucl. Part. Sci.* **66**, 341–375 (2016).
2. Burrows, A. et al. The overarching framework of core-collapse supernova explosions as revealed by 3D FORNAX simulations. *Mon. Not. R. Astron. Soc.* **491**, 2715–2735 (2020).
3. Hughes, J. P., Rakowski, C. E., Burrows, D. N. & Slane, P. O. Nucleosynthesis and mixing in Cassiopeia A. *Astrophys. J. Lett.* **528**, L109–L113 (2000).
4. Hwang, U. & Laming, J. M. Where was the iron synthesized in Cassiopeia A? *Astrophys. J.* **597**, 362–373 (2003).
5. Buras, R., Ramp, M., Janka, H. T. & Kifonidis, K. Two-dimensional hydrodynamic core-collapse supernova simulations with spectral neutrino transport. I. Numerical method and results for a 15 M$_\odot$ star. *Astron. Astrophys.* **447**, 1049–1092 (2006).
6. Wantong, C., Müller, B., Janka, H.-T. & Heger, A. Nucleosynthesis in the innermost ejecta of neutrino-driven supernova explosions in two dimensions. *Astrophys. J.* **852**, 40 (2018).
7. Bethe, H. A. & Wilson, J. R. Revival of a stalled supernova shock by neutrino heating. *Astrophys. J.* **295**, 14–23 (1985).
8. Burrows, A., Hayes, J. J. & Fryxell, B. A. On the nature of core-collapse supernova explosions. *Astrophys. J.* **450**, 830 (1995).
9. Janka, H.-T. et al. Core-collapse supernovae: reflections and directions. *Prog. Theor. Exp. Phys.* **2012**, 01A309 (2012).
10. Kifonidis, K., Plewa, T., Janka, H.-T. & Müller, E. Non-spherical core collapse supernovae. I. Neutrino-driven convection, Rayleigh-Taylor instabilities, and the formation and propagation of metal clumps. *Astron. Astrophys.* **408**, 621–649 (2003).
11. Hammer, N. J., Janka, H.-T. & Müller, E. Three-dimensional simulations of mixing instabilities in supernova explosions. *Astrophys. J.* **714**, 1371–1385 (2010).
12. Wonpueanant, A., Janka, H.-T.; Müller, E., Piumbii, E. & Wantong, C. Production and distribution of $^{44}$Ti and $^{56}$Ni in a three-dimensional supernova model resembling Cassiopeia A. *Astrophys. J.* **842**, 13 (2017).
13. Nagataki, S., Hashimoto, M.-a., Sato, K., Yamada, S. & Mochizuki, Y.S. The high ratio of \(^{44}\text{Ti}/^{56}\text{Ni}\) in Cassiopeia A and the axisymmetric collapse-driven supernova explosion. Astrophys. J. Lett. 492, L45–L48 (1998).
14. Iyudin, A. F. et al. COMPTEL observations of \(^{44}\text{Ti}\) gamma-ray line emission form CAS A. Astron. Astrophys. 284, L1–L4 (1994).
15. Grefenstette, B. W. et al. Asymmetries in core-collapse supernovae from maps of radioactive \(^{44}\text{Ti}\) in Cassiopeia A. Nature 506, 339–342 (2014).
16. Grefenstette, B. W. et al. The distribution of radioactive \(^{44}\text{Ti}\) in Cassiopeia A. Astrophys. J. 834, 19 (2017).
17. Nakamura, T. et al. Explosive nucleosynthesis in hypernovae. Astrophys. J. 555, 880–899 (2000).
18. Woosley, S. E., Arnett, W. D. & Clayton, D. D. The explosive burning of oxygen and silicon. Astrophys. J. Suppl. 26, 231 (1973).
19. Vance, G. S., Young, P. A., Fryer, C. L. & Ellinger, C. I. Titanium and iron in the Cassiopeia A supernova remnant. Astrophys. J. 895, 82 (2020).
20. Milisavljevic, D. & Fesen, R. A. A detailed kinematic map of Cassiopeia A’s optical main shell and outer high-velocity ejecta. Astrophys. J. 772, 134 (2013).
21. Milisavljevic, D. & Fesen, R. A. The bubble-like interior of the core-collapse supernova remnant Cassiopeia A. Science 347, 526–530 (2015).
22. Orlando, S. et al. The fully developed remnant of a neutrino-driven supernova. Evolution of ejecta structure and asymmetries in SNR Cassiopeia A. Astron. Astrophys. 646, A66 (2021).
23. Willingale, R., Bleeker, J. A. M., van der Heyden, K. J., Kaastra, J. S. & Vink, J. X-ray spectral imaging and Doppler mapping of Cassiopeia A. Astron. Astrophys. 381, 1039–1048 (2002).
24. DeLaney, T. et al. The three-dimensional structure of Cassiopeia A. Astrophys. J. 725, 2038–2058 (2010).
25. Hitomi Collaboration. Solar abundance ratios of the iron-peak elements in the Perseus cluster. Nature 551, 478–480 (2017).
26. Tashiro, M. et al. Status of X-ray imaging and spectroscopy mission (XRISM). In Proc. SPIE Conf. Ser. Vol. 11444, 1144422, https://www.spedigitallibrary.org/conference-proceedings-of-spie/11444/2565812/Status-of-x-ray-imaging-and-spectroscopy-mission-XRISM/10.1117/12.2565812.short?SSO=1 (Society of Photo-Optical Instrumentation Engineers, 2020).
27. Barret, D. et al. The ATHENA X-ray Integral Field Unit (X-IFU). In Proc. SPIE Conf. Ser. Vol. 10699, 106991G, https://www.spedigitallibrary.org/conference-proceedings-of-spie/10699/2312409/The-ATHENA-x-ray-integral-field-unit-X-IFU/10.1117/12.2312409.short (Society of Photo-Optical Instrumentation Engineers, 2018).
28. Gotthelf, E. V. et al. Chandra detection of the forward and reverse shocks in Cassiopeia A. Astrophys. J. Lett. 552, L39–L43 (2001).
29. Anders, E. & Grevesse, N. Abundances of the elements: meteoritic and solar. Geochim. Cosmochim. Acta 53, 197–214 (1989).
30. Sato, T. et al. A subsolar metallicity progenitor for Cassiopeia A, the remnant of a type IIb supernova. Astrophys. J. 893, 49 (2020).

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Previous studies of the ejecta distribution in Cassiopeia A
Cassiopeia A, as a young, nearby and bright remnant of a core-collapse supernova, is a unique object with which to probe the explosion mechanism of massive stars. In particular, the asymmetric ejecta distribution and kinematics in the remnant that have been deduced from various observations help us to understand the asymmetry in the explosion itself. Here we summarize the characteristic ejecta distribution in the remnant as investigated in previous studies in order to clarify the novelty of this research.

The high-velocity optical knots clearly show the asymmetric explosion in Cassiopeia A\textsuperscript{31–34}. In particular, the S-rich optical knots in the northeastern jet and southwestern counterjet regions have high velocities of $>$10,000 km s\textsuperscript{-1}, which is a unique feature connected to the explosion mechanism. These jet-like structures are kinematically and chemically distinct from the rest of the remnant. Motivated by this structure, there have been some previous papers\textsuperscript{3} proposing a jet-induced explosion scenario to explain the northeastern/southwestern jet-like structures and the southeastern Fe-rich ejecta. However, the distribution of 44Ti (refs. 34, 36, 38, 41) does not support highly asymmetric bipolar explosions resulting from a fast-rotating progenitor\textsuperscript{3}, even though it implies a (mildly) asymmetric explosion in Cassiopeia A indirectly.

Neutrino-driven convection is a mechanism by which stars explode by neutrino-driven explosion. In particular, a recent simulation succeeded in reproducing the observed supernova properties well, even the explosion energy\textsuperscript{38}, so observational verification of this mechanism would be timely and relevant. To probe this, the Fe-rich ejecta would be a suitable target. The formation process of the southeast Fe-rich ejecta\textsuperscript{3,4,23,39,40} has been much debated. Hughes et al.\textsuperscript{3} proposed that the Fe-rich ejecta could originate from the rising bubbles in the neutrino-driven convection layer\textsuperscript{3,4,23,39,40} during the supernova explosion. Also, Hwang et al.\textsuperscript{3} proposed that the Fe-rich ejecta were produced by an α-rich freeze out, through the same nucleosynthesis process as for the formation of the Fe-rich region, based on the physical properties investigated by X-rays. However, the mismatch of the Ti-rich and Fe-rich ejecta regions did not support the α-rich freeze-out origin well\textsuperscript{3,4,23,39,40}. Our results solve this apparent contradiction, and observationally verify the existence of the neutrino-driven convection based on the discovery of the high-entropy plumes.

The origin of the Fe-rich ejecta should be closely connected to its kinematic structure. DeLaney et al.\textsuperscript{34} argued that the Fe-rich ejecta occupies a hole in the Si-group emission and does not represent ‘overturning’, as previously thought. Instead of overturning, the authors proposed interaction with the circumstellar medium to reproduce the protruding Fe-rich ejecta. If this is the case and there is no inversion of the ejecta layers, the outermost tip of the Fe-rich ejecta should be produced by QSE (and we would see an oxygen (O)-burning layer on the outside of it). It is not expected that all the outer layers (for example, QSE, O-burning and so on) around the Fe-rich ejecta are hidden only by the cross-section effect. That would contrast with the nucleosynthetic origin of the Fe-rich ejecta we constrained in this work. However, the structure of the Fe-rich ejecta can be well reproduced also by multi-dimensional simulations\textsuperscript{12,44,45} even without interaction with the circumstellar medium. Especially, a recent supernova remnant simulation\textsuperscript{3} based on a neutrino-driven explosion have succeeded to reproduce naturally the characteristic ejecta structures in Cassiopeia A without any special interaction with the circumstellar medium. The picture here is consistent with our conclusion that the outermost tip of the southeast Fe-rich ejecta was produced by α-rich freeze out. In summary, we conclude that the formation scenario of the Fe-rich ejecta with the inversion of ejecta layers during the supernova explosion for Cassiopeia A is supported by all the available observational data.

The bubble-like interior observed in Cassiopeia A\textsuperscript{31} also provides strong evidence of turbulent mixing processes during the explosion. At optical and infrared wavelengths, arc- and ring-like structures of shocked ejecta have been observed\textsuperscript{41,44–46}. The bubble-like morphology revealed by near-infrared observations of unshocked ejecta smoothly connects to these structures. This internal structure indirectly supports the existence of a ‘Ni-bubble’ effect during the explosion\textsuperscript{3,4,23,39,40}.

The Ni-bubble effect has been used to explain observations of supernova SN1987A, indicating extensive mixing of chemical species in the envelope of the progenitor star during the explosion. Early simulations of the effect were started by artificially seeding Rayleigh–Taylor instabilities in the mantle and envelope of the progenitor and following their evolution until shock breakout from the stellar surface\textsuperscript{49,50,53–56}. More recent simulations consistently connect the seed asymmetries arising from convective flow in the neutrino-heated bubble and by the standing accretion shock instability during the explosion\textsuperscript{39–41,42,43}. This is the same scenario as the one explaining the formation of the Fe-rich ejecta\textsuperscript{3}. Thus, the origin of the bubble-like interior in the remnant could smoothly connect with the formation process of the protruding Fe-rich ejecta and the recent simulation study supports this picture\textsuperscript{32}.

As summarized above, the previous studies focused on the ejecta distribution in Cassiopeia A to tackle the explosion mechanism. Here, we introduce the nucleosynthetic perspective of the high-entropy bubbles as a key ingredient of the neutrino-driven explosion. We have demonstrated that the X-ray observation of the Fe-rich ejecta can provide the mass fractions of the key elements, which allow us to probe local physical parameters (that is, lepton fraction, peak temperature, peak density and so on) around the convective supernova engine. At present, this is the only way to measure these parameters in a supernova explosion.

Chandra observations and data reduction
Cassiopeia A has been observed with Chandra X-ray imager ACIS-S (Advanced CCD Imaging Spectrometer) several times since the launch\textsuperscript{3,58–61}. We used all ACIS-S observations from 2000 to 2018, with a total exposure of around 1.57 Ms. We reprocessed the event files (from level 1 to level 2) to remove pixel randomization and to correct for charge-coupled device (CCD) charge transfer efficiencies using CIAO\textsuperscript{62} version 4.6 and CalDB 4.6.3. The bad grades were filtered out, and good time intervals were reserved.

Extended Data Figure 1a shows a Fe−K/Si−K ratio map where the white contour outlines the region from which we extracted the spectrum. To extract a Fe-rich spectrum, only bright regions were selected from this image. The position of the Fe-rich ejecta we focused on is shifting from year to year owing to the bulk expansion of the material. Therefore, we carefully considered the shift when we chose the regions for each epoch to ensure that we tracked the same material. The proper motions of the Fe-rich structures were estimated to be around 0.2″ per year. With a similar shift applied to that measurement, we were able to correct the position of the regions well. As shown in Extended Data Fig. 4b, we could track the entire Fe-rich structure well from epoch to epoch although the shape of the structure is changing slightly.

The shape of small structures at the off-axis angle is distorted by the aberrations of Wolter type I optics. This may increase uncertainty for the region selection from epoch to epoch. On the other hand, the radii of energy circles enclosing 90% of the power at 6.4 keV around the Fe-rich region (the off-axis angle of about 3 arcmin) is about 2 arcsec (see figures 4.12 and 4.13 in https://cxc.harvard.edu/proposer/POG/html/chap4.html), which is much smaller than the regions we used (see Extended Data Fig. 1a). Therefore, the difference in the image distortion that is due to the off-axis effect from epoch to epoch can be ignored. In fact, a comparison between single epoch and multiple epoch measurements shows that the results are consistent, indicating that the region selection itself does not have a large impact on the Ti measurements (see following sections and Extended Data Fig. 1d, e).
We also analysed the X-ray spectrum taken from a smaller region shown in Extended Data Fig. 1a (white dashed contour). We found that changing the region boundaries does not change the Ti/Fe ratio (Extended Data Fig. 1e). On the other hand, the Ca/Fe mass ratio decreases from 1.50–1.54% to 1.07–1.20% when we use the smaller region. The decrease of Ca/Fe is interpreted as a decrease of the contamination from the Si-rich component (see also Methods section ‘The origin of the lighter elements in the Fe-rich ejecta’). The unchanged Ti/Fe ratio implies that the Si-rich component is not the main component providing Ti. From these, we are confident that the region selection does not change our conclusion substantially.

NuSTAR observations and data reduction
In Fig. 1, the same 44Ti image as in ref. 16 was used. Cassiopeia A was observed by NuSTAR during the first 18 months of the NuSTAR mission with a total exposure time of 2.4 Ms. We reduced the NuSTAR data with NuSTAR Data Analysis Software (NuSTARDAS) version 1.4.1 and NuSTAR calibration database (CALDB) version 20150316 to produce images, exposure maps, and response files for each telescope.

Modelling of X-ray spectrum
We extract the X-ray spectrum from the southeastern Fe-rich structure (Fig. 2). To model it, we use an absorbed thermal plasma model with a gsMOOTH model that is used for modelling the lines broadened by thermal broadening and/or multiple velocity components (− phabs × gsMOOTH × vvpshock in Xspec using AtomDB version 3.0.9). We assumed that the plasma parameters (for example, ionization state, temperature and redshift) for each element are identical. Although the column density $n_{\text{H}}$ is not sensitive to this energy band (3.7–7.1 keV), we fixed it to the typical value around this region. The best-fit parameters are summarized in Extended Data Fig. 1d.

The residuals around 4.7–4.8 keV in Fig. 2 are very well explained by the Ti emissions of the thermal model (Extended Data Fig. 1). The main difference in the models shown in these two figures is whether Ti is included (Extended Data Fig. 1) or not (Fig. 2). The significance of the Ti detection in the thermal fitting is about $5.6\sigma$ ($\Delta \chi^2 = 33.044$). Even if we used only the data in 2004 (the net exposure time is around 980 ks), the significance level is still above $5\sigma$ ($\Delta \chi^2 = 25.422$). Even if we use an ionizing plasma model with a single ionization state (the non-equilibrium ionization collisional plasma (NEI) model), the significance level of the line detection is almost the same ($\Delta \chi^2 = 25.219$). We also analysed all the data except for 2004 (the net exposure time is around 590 ks) to check the consistency and again detected the Ti emissions at a 2.7σ confidence level. All the Ti/Fe ratios in the different datasets are consistent with each other (Extended Data Fig. 1d, e), which indicates the robustness of our Ti measurements.

We also performed a simple Gaussian fitting for the residual line. Here we used a gsmOllus model in Xspec to express the blue-shifted line. Assuming the same blue-shift velocity as in the vvpshock model (about $-2.860$ km s$^{-1}$), the centroid energy of the residual line is estimated to be $4.74\pm0.03$ keV (90% confidence level, $\Delta \chi^2 = 2.706$) in the rest frame, which is consistent with the Ka emission from the He-like Ti ion (Extended Data Fig. 2a). We note that there is almost no bright X-ray line around this energy band in the AtomDB database, except for Ti. For the Gaussian fitting, the significance of the line detection is almost the same as that in the thermal fitting ($\Delta \chi^2 = 26.997$).

We note that the energy of the Heα lines of Sc are 4.295 keV (resonance line) and 4.316 keV (intercombination line). This is close to the H-like Ca Kα line energy (4.1 keV), but it would not be a source of confusion for the detection of stable Ti. On the other hand, we note that the uncertainty on the line emissivities (that is, the uncertainty of the atomic database) could change the estimations of mass ratios.

The narrow fitting range from 3.7 keV to 7.1 keV does not affect our conclusion. Even if we expanded the fitting range, we could obtain good spectral fits ($\chi^2 < 2$) and the Ti/Fe mass ratios are consistent with each other (Extended Data Fig. 1e). In Extended Data Fig. 2c–e, we show the entire X-ray spectra fitted with different fitting ranges. In all the fittings, the entire spectra are roughly explained by the best-fit models. Here, elements in areas outside the fitting range are fitted by eye and fixed. In Extended Data Fig. 2d, we fit the spectrum up to 9.5 keV, where the Ni emissions are included. The current modelling around 8.0–8.5 keV is not accurate enough (see Methods section ‘Additional evidence of a rich freeze-out’). This is due to the uncertainties of the emissivities of the Fe Kβ, γ, δ, ..., emissions. To model a lack of these emissions, we added a Gaussian model in this fitting. In Extended Data Fig. 2e, we fit the spectrum from 2.2 keV to 9.5 keV where the emissions from S to Ni are included (a complete spectral modelling for the entire energy band from 0.7 to 9.5 keV is too complicated to realize here). Even in the wide range fitting, we could obtain a good fit (reduced $\chi^2 = 1.71$). The best-fit parameters are summarized in Extended Data Fig. 2f. In this case, we added the bremsstrahlung model in Xspec because a low-temperature component cannot be ignored owing to the expansion to the lower energy band. Considering the uncertainties of handling the multi-temperature modelling and also the uncertainties of modelling around the Ni emission line, we presented only the result for the 3.7–7.1 keV band in the main text.
models are the same as Set L in ref. 67. Nucleosynthesis of 300 isotopic species is also calculated with the stellar evolution code. The metallicity dependence of the mass-loss rate is $Z_{\odot}$ as for main-sequence stars and $Z_{\odot}/5$ for yellow and red supergiants.

The simulation of the supernova explosion is performed with a PPM hydrodynamics code69,70, assuming a spherically symmetric explosion. The explosion energy $E_{\text{exp}}$ is set to be $3 \times 10^{51}$ erg. The location of the mass cut is determined so that the ejected $^{56}$Ni mass is $0.07M_\odot$. After the supernova explosion simulations, the explosive nucleosynthesis calculations are performed in a postprocessing step. Radioactive decays in the supernova ejecta after 350 yr are also taken into account.

As shown in Extended Data Fig. 4, the region where Fe (after decay of $^{56}$Ni) is abundantly produced is divided into two layers; the $\alpha$-rich freeze out as characterized by the higher temperature (or entropy), producing mainly Fe-peak elements, and the incomplete QSE burning as characterized by the lower temperature, producing intermediate-mass elements abundantly. In the one-dimensional model, the $\alpha$-rich freeze-out region is located in the deepest layer because a higher entropy is realized in the inner layer in the one-dimensional model. However, this is not necessarily the case in realistic three-dimensional simulations since the penetration of the high-entropy bubbles into the outer layers is essential to initiate the explosion.

$\alpha$-rich elements are stable isotopes, of which $^{44}$Ti is the most abundant, comprising 74% of the Ti atoms in terrestrial samples. In our supernova model with $Y_e \lesssim 0.5$, around 90% of all Ti is $^{48}$Ti. The isotope of Ti most well known to supernova researchers is $^{44}$Ti, which has a half-life of 60 years, decaying to $^{44}$Sc by electron capture (and then to $^{44}$Ca by $\beta$ decay). In our models, all Ti isotopes are contained within $^{56}$Ti. The radioactive element $^{44}$Ti is also included, but stable Ti is dominant after the 350-yr decay. We summarized the stable isotopes of Ti, Cr and Ni for neutron-rich and proton-rich ejecta in Extended Data Fig. 5. The mass fractions among isotopes are different between them. In the case of Ti, the synthesized amount of $^{46,47,48}$Ti drastically increases in the proton-rich ejecta. The $Y_e$ dependence of each isotope can be checked in figure 10 of ref. 4.

**Parameter studies of nucleosynthetic outputs in the peak temperature-density plane**

In the case of one-dimensional supernova calculations, it is difficult to express an extreme environment in the hot bubbles produced by neutrino heating. The one-dimensional supernova calculations as described above deal only with the regions above the hot plumes, which are heated by the shock wave produced by the action of the hot plumes. To express the high-entropy environment within the hot plumes seen in multi-dimensional models, another approach is necessary. To discuss the element composition in the hot bubbles, a parameter study beyond the parameter range in one-dimensional supernova models would be suitable. Magkotsios et al.71 have investigated the sensitivity of $^{44}$Ti and $^{56}$Ni synthesis for both dependencies over an extended parameter space. Here, we use a similar approach to investigate the stability of $^{44}$Ti and $^{56}$Ni, which would be useful for discussing the nucleosynthesis that cannot be expressed with the one-dimensional supernova models. The data in Fig. 3b were taken from the nucleosynthesis calculations we introduce here.

Extended Data Figure 5 shows the Ti/Fe and Cr/Fe mass ratios in the peak temperature–density plane. We can clearly see that both the mass ratios increase as the peak radiation entropy increases. This trend is the same as for $^{44}$Ti (ref. 67), and so these elements could be an alternative tool for probing the high-entropy process. In computing this, we need to specify the thermodynamic trajectory for the hot bubbles. Since the timescale for the expansion and cooling in the bubbles (that is, the rate of change in the temperature and density) should be similar to the innermost zone seen in the one-dimensional simulation, we first extrapolate the thermodynamic trajectory from the innermost zones of the one-dimensional model to match the peak temperature to a given peak temperature for the hot plumes. Then, we multiply a constant value to the density trajectory to match it to the density condition for the hot plumes. Radioactive decays in the supernova ejecta after 350 yr are also taken into account.

In Extended Data Fig. 6, we show the Ti/Fe and Cr/Fe mass ratios that are calculated with some situations that are not considered in Extended Data Fig. 5. Extended Data Fig. 6a shows the mass ratios calculated with $Y_e = 0.53$–0.58 and $T_{\text{peak}} \approx 10$ GK. In multi-dimensional simulations, the lepton fraction in the innermost proton-rich ejecta whose progenitor mass is in 15–20 $M_\odot$ has a wide range from $Y_e = 0.5$ to 0.6 (refs. 46,75). As shown in Fig. 3b, slightly proton-rich ejecta could not reproduce the observed mass ratios. On the other hand, we found that the proton-rich ejecta with $Y_e \geq 0.51$ can reproduce the observed mass ratios. When the $Y_e$ increases to a certain extent, we can no longer use these mass ratios to distinguish the $Y_e$ differences (Extended Data Fig. 6a).

The yields of the $\alpha$-rich freeze out are very sensitive to the thermodynamic evolution of the material, especially for intermediate mass elements like Ti and Cr. Therefore, we also investigated nucleosynthetic outputs using different thermodynamic evolutions. In Extended Data Fig. 6b, we show the Ti/Fe and Cr/Fe mass ratios produced by power-law thermodynamic trajectories. Here we calculate the evolution of temperature and density using equation 5 in ref. 47. As a result, we found that the yields of intermediate-mass elements by the power-law thermodynamic trajectories need higher entropy to reproduce the observation. Thus, we note that the current estimation of the radiation entropy (that is, peak temperature and density) has a certain uncertainty. Special thermodynamic evolutions, such as those realized in multidimensional simulations, may further alter the synthesis of these intermediate mass elements, a topic for future investigation.

**The origin of the lighter elements in the Fe-rich ejecta**

We found X-ray lines not only from the $\alpha$-rich freeze-out products, but also from the intermediate-mass elements (for example, Si, S, Ar, Ca) in the spectrum of the Fe-rich ejecta. In our analysis, the region we chose is relatively large, so that we can obtain enough photon statistics, which could produce contamination from some ejecta that are not Fe-rich. Therefore, if the Ti and Cr we found were not the origin of the Fe-rich ejecta, our conclusion could change. We confirm here that the effect of this contamination is not relevant to our conclusion.

In Extended Data Fig. 8a, we defined a Si-rich ejecta region to compare with the Fe-rich ejecta. The Si-rich region is adjacent to the Fe-rich ejecta. Extended Data Fig. 8b shows the X-ray spectrum extracted from the Si-rich region, which is well explained by a thermal plasma model (phabs + xspec). The best-fit parameters are summarized in Extended Data Fig. 8e. Using the plasma model, we attempted to model the X-rays from the lighter elements in the Fe-rich region (Extended Data Fig. 8c). As a result, we found that the Si-rich region reproduces the intermediate-mass element lines up to Ca, while the lines from Fe-peak elements and continuum are dominated by the Fe-rich region. Thus, it was confirmed that the lighter elements probably originate in the contamination from faint Si-rich emissions along the same line of sight.

The nucleosynthetic origin for the Si-rich ejecta can be determined from their relative mass fractions. Extended Data Fig. 8d shows the relation between the Ca/Si and Fe/Si mass ratios. The observed Ca/Si and Fe/Si mass ratios in the Si-rich ejecta are consistent with those at $T_{\text{peak}} = 4.5$ GK. Therefore, we conclude that the Si-rich ejecta have been reprocessed through the QSE (incomplete Si burning) layer (see Extended Data Fig. 4). Around this peak temperature, a large amount of Ti and Fe cannot be produced. This means that the contamination from the Si-rich ejecta to the Ti and Fe emissions in the Fe-rich ejecta is negligible. Given that this contamination would not affect the fluxes of the Ti, Cr and Fe lines, Ti/Fe and Cr/Fe are hardly affected. In fact, we confirmed that the derived ratios of Ti/Fe and Cr/Fe are nearly unchanged even if we subtract the Si-rich model from the Fe-rich spectrum.
Additional evidence of α-rich freeze out

A strong line feature around 7.8 keV in the spectrum of the Fe-rich structure (see Extended Data Fig. 2c–e and Extended Data Figs. 8 and 10) implies a large abundance of Ni. The stable Ni isotopes ($^{56}$Ni and $^{60}$Ni) make Ni the second-most abundant element in the α-rich freeze out (Extended Data Fig. 4). The existence of Ni in the Fe-rich ejecta strongly supports the α-rich freeze-out origin.

Extended Data Figure 9 shows a relation between the Ni/Fe and Cr/Fe mass ratios in the core-collapse supernova ejecta. We found that the best-fit Ni/Fe mass ratios estimated in the Fe-rich ejecta are above a few per cent, which can be archived only at high peak temperature, above 5.5 GK. On the other hand, we note that there are large uncertainties of the current modellings. In particular, both the Ni Kα emissions and Fe Kβ emissions contribute to the feature of the 7.8 keV line. The emissivities of these emissions vary from atomic code to atomic code, and thus the derived value of Ni/Fe has a large uncertainty (see blue and red dashed lines in Extended Data Fig. 9). We plan to undertake further investigations for Ni, taking these uncertainties into account. For example, high-X-ray-resolution spectroscopy will help us to measure the element abundances accurately even for such rare metals. Extended Data Fig. 10c, d shows a comparison of spectra between XRISM and Chandra. As in Extended Data Fig. 10, we will soon be able to separate fine structures in the X-ray spectrum, which will provide robust element abundance measurements.

Accurate Ni measurements will help us to estimate the lepton fraction in the ejecta. On the proton-rich side $^{56}$Ni and $^{60}$Ni are the most abundant stable nickel isotopes (Extended Data Fig. 5b) where the Ni/Fe mass ratio is $\geq 10\%$. On the proton-rich side, $^{56}$Ni is the most abundant stable nickel isotope (Extended Data Fig. 5b) where the Ni/Fe mass ratio is around 3–5% (see Extended Data Fig. 6b and Extended Data Fig. 9). In the current spectral fitting, the model in SPEX does a better job of reproducing the spectrum (at least, SPEX does not need the Gaussian line used in Xspec), but still we found some fitting residuals. Here, the best-fit Ni/Fe mass ratio with SPEX is around 7%, which is in between the proton-rich and neutron-rich ejecta (Extended Data Fig. 9b). In addition, the Ni/Fe dependence on $Y_e$ is not as sensitive on the proton-rich side (Extended Data Fig. 9b). Therefore, a tight constraint of Ni/Fe beyond the current measurement will be needed to determine the $Y_e$. At least, some updates of the atomic codes and the spectral resolution as done by Hitomi will be needed for such a measurement. We hope that XRISM will achieve this (Extended Data Fig. 10c, d).

The amount of manganese in the Fe-rich ejecta

In contrast with the Cr production, the Mn is more effectively produced on the proton-rich side. This tendency should help us to discriminate between the proton-rich and neutron-rich ejecta. In Extended Data Fig. 7, we found that the high-entropy proton-rich ejecta could reproduce the observed Mn/Fe ratio very well. On the other hand, the Mn/Fe in the neutron-rich ejecta is out of the observed range. In addition, we needed a modified $Y_e$ of 0.5 to reproduce both Ti/Fe and Cr/Fe as shown in the main text (see Fig. 3). This modification (increase of $Y_e$) suppresses the production of neutron-rich elements like Mn, which provides a further deviation from the observed ratio (see square data symbols in Extended Data Fig. 7). Thus, the high-entropy proton-rich ejecta are more favourable to explain the observation.

We note that the Mn production around the mass-cut region is sensitive to the $\nu$-process. Here, $^{57}$Co ($^{59}$Mn) is produced through $\nu$-process and complete SpI burning. The contribution of the $\nu$-process to the Mn production is substantial, especially on the neutron-rich side because the Mn is rarely synthesized by $\alpha$-rich freeze out with the neutron-rich environment ($Y_e < 0.5$). On the proton-rich side, the $\nu$-process causes almost no change in the amount of Mn. In the $\nu$-process, the amount of Mn depends on the total neutrino energy in the supernovae. The total energy carried away by the neutrinos is determined by the binding energy released during the formation of a neutron star, where the binding energy ($E_{\text{binding}}$) is described as $E_{\text{binding}} = 1.5 \times 10^{53} (M/M_\odot)^2$ erg (ref. 75). In our calculations, we assumed a total neutrino energy of $3 \times 10^{53}$ erg, which corresponds to the binding energy at a typical neutron-star mass of around 1.4$M_\odot$. Even if we assumed a heavy neutron star with around 2$M_\odot$ ($E_{\text{binding}} = 6 \times 10^{53}$ erg), the Mn/Fe mass ratio produced by a supernova model with $Y_e = 0.5$ is out of the 90% error range of the observation. The proton-rich environment for producing the Fe-rich ejecta is thus still preferred by the model.

X-ray spectra in other Fe-rich regions

We investigated X-ray spectra in three Fe-rich regions of Cassiopeia A to search for products by high-entropy burning, where the Fe-rich regions are located at the southeast, north and southwest regions (Extended Data Fig. 10a). We found that the spectrum in the north region has a significant Ti line with a confidence level of 3.3σ (Extended Data Fig. 1e, but we also found that there is a strong Cr line (Extended Data Fig. 10b). The strong Cr line means that the majority of the ejecta were produced at the incomplete SI-burning (QSE) layer (see Fig. 3 and Extended Data Fig. 4). The QSE layer could also produce Ti, so it was difficult to discuss the Ti production at the high-entropy burning using this region. In the case of the southwest region, the non-thermal emissions are substantial, making it difficult to detect the Ti line. Thus, we discussed only the southeast Fe-rich region, for which we discuss only the high-entropy process (in the main text).

The Ti underproduction problem in the classical Galactic chemical evolution models

Interestingly, the observed Ti/Fe ratio is consistent with the solar ratio (Fig. 3), whereas the chemical evolution of our Galaxy requires overproduction of Ti for typical core-collapse supernovae ($Ti/Fe = 0.4$; ref. 76). Whereas the deficiency of Ti in the supernova yield may come from atomic data/nuclear reaction rate uncertainties, another possibility is that it could be related to the yet-unknown explosion mechanism—on which the present result may shed some light. The high Ti yield exceeding the solar ratio, which is necessary to reproduce the abundances of the metal-poor stars, may be realized if the hot and high-entropy bubble could substantially contribute to the Ti production; the Ti is limited to the solar value for the incomplete (QSE) Si burning regime. It can exceed the solar value substantially for the high-entropy bubble (Fig. 3), especially for a higher explosion energy (or higher entropy) and low $Y_e$ below 0.5.

To realize [Ti/Fe] = 0.4 (that is, a Ti/Fe mass ratio of 0.45%) in a core-collapse supernova, most of the Fe-rich ejecta needs to be synthesized in a high-entropy environment. If we assume the Ti/Fe mass ratios of 10$^{-3}$ and 10$^{-2}$ for normal Fe-rich ejecta and extremely high-entropy Fe-rich ejecta, respectively, 40% of the Fe-rich ejecta must be synthesized in the extremely high-entropy environment. In addition, such a high Ti/Fe mass ratio of 10$^{-3}$ is hardly achievable with one-dimensional supernova calculations (Extended Data Fig. 5). In the three-dimensional simulation of ref. 76, the highest ejecta have Ti/Fe = 10$^{-2}$, whereas the thermodynamic trajectories from the three-dimensional supernova explosion model enhanced the Ti production (although this is radioactive $^{44}$Ti). If there is a core-collapse supernova, most of whose Fe-rich ejecta are synthesized in such an environment, the overabundance of Ti in the early phase might be explained by the core-collapse supernova. Thus, future multi-dimensional simulations will also help us to understand the Galactic chemical evolution.

Data availability

All the Chandra and NuSTAR data used in this research are available from the Chandra Data Archive (https://cxc.harvard.edu/cda/) and
the NuSTAR Archive (https://heasarc.gsfc.nasa.gov/docs/nustar/nustar_archive.html) in raw and reduced formats.

**Code availability**

To analyse X-ray data with Chandra, we used public software, Chandra Interactive Analysis of Observations: CIAO (https://cxc.cfa.harvard.edu/ciao/). We used public atomic data in atomDB (http://www.atomdb.org/) and SPEX (https://www.sron.nl/astrophysics-spex). We fitted the X-ray spectra with a public package, Xspec (https://heasarc.gsfc.nasa.gov/xanadu/xspec/). We have not made publicly available codes for the hydrodynamics and nucleosynthesis of supernova explosions because they are not prepared for open use. Instead, the simulated thermodynamic profiles of the supernova explosions and the composition distributions shown in this paper are available on request.

31. Fesen, R. A. An optical survey of outlying ejecta in Cassiopeia A: evidence for a turbulent, asymmetric explosion. Astrophys. J. Suppl. 133, 161–186 (2001).
32. Fesen, R. A. et al. The expansion asymmetry and age of the Cassiopeia A supernova remnant. Astrophys. J. 645, 283–292 (2006).
33. Fesen, R. A. & Milisavljevic, D. An HST survey of the highest-velocity ejecta in Cassiopeia A. Astrophys. J. 818, 17 (2016).
34. Thorstensen, J. R., Fesen, R. A. & van den Bergh, S. The expansion center and dynamical age of the galactic supernova remnant Cassiopeia A. Astron. J. 122, 297–307 (2001).
35. Wheeler, J. C., Maund, J. R. & Couch, S. M. The shape of Cas A. Astrophys. J. 677, 1099–1109 (2008).
36. Vink, J. et al. Detection of the 67.9 and 78.4 keV lines associated with the radioactive decay of 64Ni in Cassiopeia A. Astrophys. J. Lett. 606, L79–L82 (2003).
37. Renaud, M. et al. The signature of 54Ti in Cassiopeia A revealed by BIS/ISGRI on INTEGRAL. Astrophys. J. Lett. 647, L41–L44 (2006).
38. Boillot, R. et al. Self-consistent 3D supernova models from 7 minutes to 7 seconds: a 1-beam explosion of a 18 solar-mass progenitor. Preprint at https://arxiv.org/abs/1010.1506 (2020).
39. Hwang, U., Holt, S. S. & Petre, R. Mapping the X-ray-emitting ejecta in Cassiopeia A with Chandra. Astrophys. J. Lett. 537, L119–L122 (2000).
40. Hwang, U. et al. A million second Chandra view of Cassiopeia A. Astrophys. J. Lett. 615, L117–L120 (2004).
41. Herant, M., Benz, W., Hix, W. R., Fryer, C. L. & Colgate, S. A. Inside the supernova: a powerful convective engine. Astrophys. J. 435, 339 (1994).
42. Janka, H. T., Langanke, K., Marek, A., Martinez-Pinedo, G. & Müller, B. Theory of core-collapse supernovae. Phys. Rep. 442, 38–174 (2007).
43. Burrows, A. & Vartanyan, D. Core-collapse supernova explosion theory. Nature 589, 29–39 (2021).
44. Maeda, K. & Nomoto, K. Bipolar supernova explosions: nucleosynthesis and implications for abundances in extremely metal-poor stars. Astrophys. J. 599, 1163–1200 (2003).
45. Orlando, S., Miceli, M., Pumo, M. L. & Bocchino, F. Modeling SNR Cassiopeia A from the supernova explosion to its current age: the role of post-explosion anisotropies of ejecta. Astrophys. J. 822, 22 (2016).
46. Rees, E. E., Hester, J., Fabian, A. C. & Winkler, P. F. The three-dimensional structure of the Cassiopeia A supernova remnant. I. The spherical shell. Astrophys. J. 440, 706 (1995).
47. Lawrence, S. S. et al. Three-dimensional Fabry-Perot imaging spectroscopy of the Crab nebula, Cassiopeia A, and Nova GK Persei. Astron. J. 109, 2635 (1995).
48. Alarie, A., Blidouea, A. & Drissen, L. A hyper-spectral view of Cassiopeia A. Mon. Not. R. Astron. Soc. 441, 2996–3008 (2014).
49. Arnett, D., Fryxell, B. & Mueller, E. Instabilities and nonradial motion in SN 1987A. Astrophys. J. 341, L63 (1989).
50. Li, H., McCray, R. & Sunyaev, R. A. Iron, cobalt, and nickel in SN 1987A. Astrophys. J. 419, 824 (1993).
51. Blondin, J. M., Borkowski, K. J. & Reynolds, S. P. Dynamics of Fe bubbles in young supernova remnants. Astrophys. J. 437, 782–791 (1993).
52. One, M. et al. Matter mixing in aspherical core-collapse supernovae: a search for possible conditions for conveying 56Ni into high velocity regions. Astrophys. J. 733, 161 (2013).
53. Fryxell, B., Mueller, E. & Arnett, D. Instabilities and clumping in SN 1987A. I. Early evolution in two dimensions. Astrophys. J. 367, 619 (1990).
54. Hachisu, I., Matsuda, T., Nomoto, K. & Shigeyama, T. Nonlinear growth of Rayleigh-Taylor instabilities and mixing in SN 1987A. Astrophys. J. Lett. 358, L57 (1990).
55. Mueller, E., Fryxell, B. & Arnett, D. Instability and clumping in SN 1987A. Astron. Astrophys. 251, 505 (1991).
56. Herant, M. & Benz, W. Hydrodynamical instabilities and mixing in SN 1987A: two-dimensional simulations of the first 3 months. Astrophys. J. Lett. 370, L81 (1991).
57. Gabler, M., Wongwathanarat, A. & Janka, H.-T. The influence of core-collapse supernova remnants. Mon. Not. R. Astron. Soc. 502, 3284–3293 (2021).
58. Patnaude, D. J., Vink, J., Laming, J. M. & Fesen, R. A. A decline in the nonthermal X-ray emission from Cassiopeia A. Astrophys. J. Lett. 729, L28 (2011).
Extended Data Fig. 1 | X-ray analysis for the southeastern Fe-rich region. a, The Fe-K/Si-K ratio map in 2004. The solid white contour shows the region used for the result discussed in the main text. b, The Fe−K image in 2000 (left), 2009 (middle) and 2018 (right). In order to track the proper motions of each structure, we shift the region from epoch to epoch. c, The X-ray spectrum and its best-fit model for the southeastern Fe-rich region. The spectrum (black data) taken is the same as in Fig. 2, but the best-fit thermal model has the Ti and Cr emissions. The residuals around 4.7−4.8 keV and 5.5−5.9 keV in Fig. 2 are well explained by the Ti and Cr emissions. d, The best-fit parameters for the Fe-rich ejecta. The errors show 1σ confidence level (Δχ² = 1.0). The solar abundance in ref. 29 is used. e, The summary of the Ti measurements in the Fe-rich regions of Cassiopeia A. The errors show 1σ confidence level (Δχ² = 1.0). d.o.f., degrees of freedom; n_H, column density. n is density of plasma, t is ionization time and V is the volume of hot plasma.
Extended Data Fig. 2 | X-ray spectral modelling around the Ti line. 

**a**, The red and black show a plasma model (vvshock) with Ti and without Ti, respectively. The Heα emissions from Ti (red) are between Ca Heβ and Ca Heγ. The grey area shows the 90% error range of the centroid energy of the Ti line observed by Chandra. The plasma parameters are the same as in Extended Data Fig. 1e (without the line broadening). 

**b**, Comparison of 4–5 keV model spectra (vnei) that have different ionization states. The grey area shows the 90% error range of the centroid energy of the Ti line by Chandra. The most prominent lines are the Ca Heβ and Ca Heγ lines at 4.584 keV and 4.822 keV, respectively. These two Ca lines become stronger at high ionization states (>5 × 10¹⁰ cm⁻³ s⁻¹). Ly, Lyman. DR, dielectronic recombination. 

**c**, The black data and red curves show the observed spectra and the best-fit models, respectively. The fitting range (grey area) is 3.7–7.1 keV. This result is used in the main text. 

**d**, The fitting range is 3.7–9.5 keV where the emissions up to Ni are included. To express the lack of emissions around 8.3 keV, one Gaussian line is added. 

**e**, The fitting range is 2.2–9.5 keV. Here, we added a thermal bremsstrahlung model to express a low temperature component. The best-fit parameters are summarized in the table in **f**. 

**f**, The best-fit parameters for the Fe-rich ejecta in the spectrum shown in **e**. The errors show 1σ confidence level (Δχ² = 1.0). The solar abundance in ref. 29 is used. Some other lighter elements that are not shown here are also included in the model. D is the distance to the source and k is the Boltzmann constant.
Extended Data Fig. 3 | The Fe distribution (image) and the $^{44}$Ti upper limit map (coloured boxes) around the southeastern region. We use the $^{44}$Ti upper limits estimated in ref. 14. The box size is $45'' \times 45''$. The box IDs are the same as those in the paper. The white contour regions are the same as in Fig. 1. Almost all of the areas from which we extracted spectra are included in three boxed regions: 31, 39 and 47. $M_{44}$ is the mass of $^{44}$Ti.
Extended Data Fig. 4 | The one-dimensional core-collapse supernova nucleosynthesis model used in this study. The model assumed a high-energy explosion of $3 \times 10^{51}$ erg for a 15$M_\odot$ progenitor. The $\alpha$-rich freeze out produces some $\alpha$ elements (for example, Fe, Ni, Cr, Ti, Zn) at the deepest layer with high peak temperatures (>5.5 GK). At the QSE (that is, incomplete Si burning) layer, the intermediate mass elements (such as Si, S, Ar, Ca, Cr, Mn) are abundant. Mr is the Lagrangian mass coordinate.
Extended Data Fig. 5 | Nucleosynthesis calculations in the peak temperature–density plane. a, Ti/Fe (top row) and Cr/Fe (bottom row) mass ratios in the peak temperature–density plane. From left to right, the lepton fraction corresponds to \( Y_e = 0.499, 0.5, \text{ and } 0.55 \). Here, we used the thermodynamic trajectories taken from our one-dimensional supernova model. All the stable isotopes are included. The production of Ti and Cr is sensitive to the high-entropy environment (toward the bottom right), which is the same as radioactive \( ^{44}\text{Ti} \) (ref. 1). The dashed lines show the boundary between incomplete and complete Si burning. The black boxes show typical parameter spaces for the complete Si burning (r-rich freeze out) in our one-dimensional supernova model and the three-dimensional supernova model in ref. 19. In the proton-rich environment, \( \alpha \)- and p-rich (ap-rich) freezeout occurs (ref. 17). b, Mass fractions of Ti, Cr and Ni isotopes in the nucleosynthesis calculations. n-rich, neutron-rich; p-rich, proton-rich.
Extended Data Fig. 6 | The observed Ti/Fe and Cr/Fe mass ratios and nucleosynthesis models. The pink-shaded areas show the observed mass ratios. a, The coloured points show parameter studies for hot ($T_{\text{peak}} = 10$ GK) and proton-rich environment while changing the peak density from $10^{5.5}$ g cm$^{-3}$ to $10^{7.5}$ g cm$^{-3}$. The circle, star and square symbols show $Y_e = 0.53$, 0.55 and 0.58, respectively. Here, we used the thermodynamic trajectories taken from our one-dimensional supernova model. b, Parameter studies with power-law thermodynamic evolution. The star and square symbol data show the Ti/Fe and Cr/Fe mass ratios produced by $T_{\text{peak}} = 8$ GK and $T_{\text{peak}} = 10$ GK, respectively. To reproduce the observed mass ratios, a higher radiation entropy is needed than that in the model with the thermodynamic trajectories taken from the one-dimensional supernova model.
Extended Data Fig. 7 | The observed Ti/Fe and Mn/Fe mass ratios and nucleosynthesis models. The Mn/Fe mass ratio is derived from the best-fit model in the left column of Extended Data Fig. 1d. The shaded areas show the observed mass ratios with 90% and 99% error range. The coloured circles show the mass ratios in our one-dimensional supernova model (a 15 M\(_{\odot}\) progenitor, \(E_{\text{exp}} = 3 \times 10^{51}\) erg, \(Z = 0.5 Z_{\odot}\)). For the square data symbols, the same one-dimensional supernova model was used, but the lepton fraction at the \(\alpha\)-rich freeze out is modified to \(Y_e = 0.5\). The modification from circle to square symbols (increase of \(Y_e\)) suppresses the synthesized amount of neutron-rich elements like Mn. The coloured stars show a parameter study for hot (\(T_{\text{peak}} = 10\) GK) and proton-rich (\(Y_e = 0.55\)) environment while changing the peak density from \(10^{5.5}\) g cm\(^{-3}\) to \(10^{7.5}\) g cm\(^{-3}\). SN, supernova.
Extended Data Fig. 8 | Comparison between the Fe-rich and Si-rich regions.

a, Two-colour image around the southeastern Fe-rich region. The red and green show the Fe and Si images, respectively. The green box is defined as the Si-rich ejecta region. b, The X-ray spectrum extracted from the Si-rich region. The blue curve (Si-rich component) shows the best-fit thermal model. c, The X-ray spectrum at the Fe-rich region. The Si-rich component has the same plasma parameters as in the model of b. The red model shows the Fe-rich component that has emissions from H, He, Ti, Cr, Mn, Fe and Ni. d, Comparisons of the observed Ca/Si and Fe/Si mass ratios in the Si-rich ejecta region with those by theoretical calculations. The faint orange shading shows the observed mass ratios (99% confidence level, \( \Delta \chi^2 = 6.64 \)). The coloured points show the mass ratios of the nucleosynthesis calculations in Fig. 3. e, The best-fit parameters for the Si-rich ejecta in the spectrum of b. The spectrum is extracted from the 2004 data. The errors show 1σ confidence level (\( \Delta \chi^2 = 1.0 \)). The solar abundance in ref. 29 is used.
Extended Data Fig. 9 | Comparisons of the observed Ni/Fe and Cr/Fe mass ratios in the Fe-rich ejecta region with those by theoretical calculations. a, The blue and red dashed lines show the best-fit Ni/Fe mass ratios with Xspec (AtomDB, version 3.0.9) and SPEX (version 3.0.5), respectively. The best-fit Ni/Fe mass ratios are different from each other because the emissivities of the Fe Kβ, γ, δ, ... emissions are different depending on the atomic code. The faint orange shading indicates the observed Cr/Fe mass ratios in Fig. 3. The coloured points show the mass ratios of the nucleosynthesis calculations in Fig. 3. b, The Ni/Fe dependence on the lepton (electron) fraction, $Y_e$. The blue and red dashed lines show the best-fit Ni/Fe mass ratios with Xspec and SPEX, respectively. Here, we assumed an explosion energy of $3 \times 10^{51}$ erg, and a region with the peak temperature of $T_{\text{peak}} = 6.5$ GK is analysed. On the neutron-rich side, the Ni/Fe ratio changes more dramatically because the neutron-rich element, $^{56}$Ni, is efficiently synthesized. On the other hand, on the proton-rich side, the Ni is not as sensitive to the lepton fraction. Here, $^{60}$Ni is dominantly synthesized (see Extended Data Fig. 5b).
Extended Data Fig. 10 | Comparison of three Fe-rich regions in Cassiopeia A. (a) Three-colour image of Cassiopeia A. The red, green and blue colours show the Fe–K, Si–K and the continuum (approximately non-thermal) emissions, respectively. (b) X-ray spectra in the southeast (red), north (black) and southwest (green) regions. (c) Comparison of spectra between XRISM and Chandra. We assumed an energy resolution of 7 eV (FWHM) and exposure time of 1 Ms for the XRISM simulation. In the simulated XRISM spectrum, we do not consider the line broadening effects (either thermal and Doppler). (d) Zoom of area around the Ti emissions in c. Here we simulated a spectrum with the thermal broadening assuming $kT_{\text{ion}} = 125$ keV (data with error bars). The black and red lines show the thermal models with $kT_{\text{ion}} = 125$ keV and $kT_{\text{ion}} = 780$ keV, respectively.