Solar abundance ratios of the iron–peak elements in the Perseus cluster

Hitomi Collaboration*

The metal abundance of the hot plasma that permeates galaxy clusters represents the accumulation of heavy elements produced by billions of supernovae. Therefore, X-ray spectroscopy of the intracluster medium provides an opportunity to investigate the nature of supernova explosions integrated over cosmic time. In particular, the abundance of the iron–peak elements (chromium, manganese, iron and nickel) is key to understanding how the progenitors of typical type Ia supernovae evolve and explode. Recent X-ray studies of the intracluster medium found that the abundance ratios of these elements differ substantially from those seen in the Sun, suggesting differences between the nature of type Ia supernovae in the clusters and in the Milky Way. However, because the K-shell transition lines of chromium and manganese are weak and those of iron and nickel are very close in photon energy, high-resolution spectroscopy is required for an accurate determination of the abundances of these elements. Here we report observations of the Perseus cluster, with statistically significant detections of the resonance emission from chromium, manganese and nickel. Our measurements, combined with the latest atomic models, reveal that these elements have near-solar abundance ratios with respect to iron, in contrast to previous claims. Comparison between our results and modern nucleosynthesis calculations disfavours the hypothesis that type Ia supernova progenitors are exclusively white dwarfs with masses well below the Chandrasekhar limit (about 1.4 times the mass of the Sun). The observed abundance pattern of the iron–peak elements can be explained by taking into account a combination of near- and sub-Chandrasekhar-mass type Ia supernova systems, adding to the mounting evidence that both progenitor types make a substantial contribution to cosmic chemical enrichment.

The Soft X-ray Spectrometer (SXS) on board the Hitomi observatory has achieved unprecedented spectral resolution in orbit (∆E ≈ 5 eV in the 2–10 keV band). Figure 1 shows the SXS spectrum of the core of the Perseus cluster (radius r smaller than about 2′, approximately 40 kpc) in the 1.8–9.0 keV band. This was obtained from the same series of observations as that used in our previous work, which constrained turbulent velocities in the intracluster medium (ICM) but, with 25% longer exposure times, which totalled 290 ks. The refined calibration of the effective area of the telescope and the aperture window transmission of the SXS allow the flux measurement of each individual line in the 1.8–9.0 keV band, which encompasses the H- and He-like transitions from Si to Ni.

The excellent performance of the SXS also makes possible the detection of weak He-like resonance lines from Cr, Mn and Ni, with statistical significance of 6σ, 4σ and 12σ, respectively (Fig. 1b, c). Flux measurements of these lines in celestial sources have been extremely challenging with traditional non-dispersive X-ray detectors (such as charge-coupled devices, or CCDs) because such weak features blend into the bremsstrahlung continuum under lower spectral resolution and the Ni xxvii Heα and Fe xxv Heβ lines cannot be resolved (see Fig. 1c).

The hot ICM, confined in the deep gravitational potential well of the cluster, contains the largest fraction (about 80%) of metals in the cluster. Among these, the Fe–peak elements (Cr, Mn, Fe and Ni) are thought to be created predominantly by type Ia supernovae over a cosmological time period. Therefore, the abundance of these elements provides crucial information about the integrated nucleosynthesis in type Ia supernova and its physics.

Despite the importance of type Ia supernovae as distance indicators in cosmology, many of their basic features remain elusive. One important open question is whether the mass of an exploding white dwarf is close to the Chandrasekhar limit (Mc = 1.4M⊙, where M⊙ is the mass of the Sun), regardless of whether it originates from a single white dwarf accreting mass from a non-degenerate companion or a violent merger of two white dwarfs. Recent hydrodynamical simulations show that both delayed-detonation explosions of near-Mc white dwarfs and full detonations of sub-Mc white dwarfs can reproduce the observed properties (such as optical light curves and spectra) of type Ia supernovae. Therefore, it is difficult to distinguish the two scenarios from optical observations of individual explosions alone.

From the point of view of type Ia supernova nucleosynthesis, the main difference between near-Mc and sub-Mc explosions is whether the core of the white dwarf is dense enough for electron capture (p + e− → n + νe) to take place during the initial phase of the explosion. The threshold density for this reaction (ρ ≈ 10^9 g cm^-3) is achieved only when the white dwarf mass is close to Mc. A distinguishing characteristic of the two models is therefore the production efficiency of neutron-rich species, such as Ni and Mn, which is higher in the near-Mc scenario. We can use this distinction to identify the dominant system of type Ia supernova progenitor in galaxy clusters by measuring the abundance of the Fe–peak elements in the ICM. The results may apply globally because the large scale of rich galaxy clusters makes them representative of the Universe as a whole.

Here we model the SXS spectrum of the Perseus cluster in the 1.8–9.0 keV band (Fig. 1a) with an optically thin thermal plasma in collisional ionization equilibrium using the latest atomic databases (AtomDB v.3.0.8 and SPEX v.3.03). The emission from the active galactic nucleus (AGN) of the cD galaxy NGC 1275 is taken into account by adding a power law and redshifted Fe xii Kα and Kβ lines. Details about the analysis and systematic uncertainty assessment are provided in Methods. Our constraints on the elemental abundances with respect to Fe are shown in Fig. 2 (red circles). These are fully consistent with the latest measured solar abundance ratios.

Figure 2 also displays previously measured ICM abundances of the core of the Perseus cluster as well as the average abundance of 44 objects, including galaxy clusters, groups and elliptical galaxies, from XMM-Newton (X-ray Multi Mirror Mission) observations (blue triangles and squares). This plot highlights some important differences between the measurements. First, the SXS-measured abundances have statistical uncertainties comparable to those of the XMM-Newton results from the combined data of the 44 objects, despite a 15-times-shorter exposure time and a much smaller field of view. Second, while the abundances of Si, Ar and Ca obtained in the two studies are consistent, the earlier measurements systematically obtained supersolar abundances of the Fe–peak elements from both the Perseus cluster and the 44-object average.

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Previous X-ray studies of clusters and elliptical galaxies often obtained a supersolar Ni/Fe abundance ratio, leading to a debate about differences in the nature of type Ia supernovae in early-type galaxies and the Milky Way\cite{ref1, ref2, ref3, ref4, ref5}. By contrast, optical spectra of old stars in early-type galaxies indicate that the relative abundances of the Fe-peak elements are consistent with the solar values (see yellow stars in Fig. 2)\textsuperscript{26}. Our X-ray measurement resolves this discrepancy and strongly suggests that the average nature of type Ia supernovae is independent of the star-formation history of their host galaxies. This robust result, which is unaffected by complicated radiative-transfer processes that may lend uncertainty to optical studies, is obtained by accurately determining the Ni abundance using the intensity of its resonance emission line, which is easily resolved from the Fe He\textsubscript{β} line and other weak emissions of Fe xxiv and Fe xxv in the SXS spectrum.

Because Cr and Mn abundances of individual objects were not constrained by the previous XMM-Newton observations\textsuperscript{11,14}, we cannot exclude the possibility that sample variance leads, at least in part, to the discrepancy between our results and those of ref. 11. Nevertheless, we demonstrate in Methods that high-resolution spectroscopy is essential for robust measurements of these abundances. In short, only the SXS can clearly separate the weak resonance lines from the continuum component, allowing abundance measurements that are much less subject to systematic uncertainties in spectral modelling. The high-resolution SXS data have also stimulated the development of atomic models, reducing the uncertainties in the modelled line emissivities and improving the accuracy of the abundances with respect to previous work.

Figure 3 compares the SXS-measured abundances of the Fe-peak elements (black data points) with theoretical results from the latest three-dimensional calculations of the near-\textit{M}\textsubscript{Ch} type Ia supernova\textsuperscript{12} (blue region) and sub-\textit{M}\textsubscript{Ch} merger\textsuperscript{13} (green region). We also consider a one-dimensional explosion of a single 1.0\textsubscript{M}\textsubscript{☉} white dwarf\textsuperscript{14} (grey region) as an alternative example of a sub-\textit{M}\textsubscript{Ch} type Ia supernova model. All of these models predict typical type Ia supernova brightness (absolute magnitude \textasciitilde-19.5 at the maximum brightness) and a synthesized \textsuperscript{56}Ni mass of approximately 0.6\textsubscript{M}\textsubscript{☉}. In addition, they account for contributions of core-collapse supernovae using mass-dependent yields\textsuperscript{37} averaged over the Salpeter initial mass function (IMF). We allow a conservatively wide range for the fraction of core-collapse supernovae, \textit{f}_{\text{CC}} \equiv \text{N}_{\text{CC}} / (\text{N}_{\text{CC}} + \text{N}_{\text{Ia}}) = 0.6-0.9 (typical for cluster cores\textsuperscript{19,28,29}), instead of constraining an actual value from our

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**Figure 1** The Hitomi SXS spectra of the Perseus cluster. a, Measured (black) and modelled (red) spectra in the 1.8–9.0 keV band. The modelled spectrum was obtained using an optically thin thermal plasma and the atomic database AtomDB. The error bars represent a 1\sigma confidence level. The emission from NGC 1275 (AGN) is indicated by the grey curve. The spectrum is rebinned into 4-eV bins for clarity, although 1-eV bins were used for fitting. b, Magnified spectrum in the 5.3–6.4 keV band, where the He-like emission from Cr and Mn are detected. The redshifted Fe i resonance line, which originates from leakage from the on-board \textsuperscript{55}Fe calibration source (instrumental origin). c, Magnified spectrum in the 7.4–8.0 keV band showing the Ni xxvii resonance (w) line clearly separated from the stronger Fe xxiv He\textsubscript{β} line and other emissions, allowing an accurate measurement of the Ni abundance in a galaxy cluster. For comparison, an XMM-Newton CCD spectrum extracted from the same spatial region is shown (blue data points).

**Figure 2** Elemental abundances of the Perseus cluster. Relative abundances with respect to Fe (X/Fe, X = Si, S, Ar, Ca, Cr, Mn, Ni) normalized to the corresponding solar abundances\textsuperscript{25} (dashed line). The red circles represent the SXS measurements, with error bars of typical statistical uncertainty at a 1\sigma confidence level (thick magenta) and systematic uncertainty due to the model selection (thin black; see Methods section 'Spectral analysis' for details). The blue triangles and squares represent the XMM-Newton results\textsuperscript{11} from the core of the Perseus cluster and the integrated data of 44 objects, respectively, with the error bars including both statistical and systematic uncertainties at a 1\sigma confidence level. The yellow stars show optical measurements of stellar abundances in early-type galaxies from the Sloan Digital Sky Survey\textsuperscript{26}; the error bars include the velocity-dispersion dependence and systematic errors of 0.05 dex. Si is not shown because its abundance is highly sensitive to the velocity dispersion. S and Ar abundances are unavailable in the optical study.
observation (see Methods for more details). As expected, the near-\(\text{M}_{\odot}\)
model predicts higher abundances of Mn and Ni due to the efficient
electron capture in exploding white dwarfs. The observed abundance
pattern disfavours the hypothesis that all type Ia supernovae involve
\(\text{sub-M}_{\odot}\) white dwarfs and supports the combination of near-\(\text{M}_{\odot}\) and
\(\text{sub-M}_{\odot}\) type Ia supernovae with roughly equal numbers (red region in the Fig. 3). We also find that our result starkly contrasts previous
claims that the introduction of rather non-standard full-deflagration
type Ia supernova models is required to explain a Ni/Fe ratio that was
estimated to be much higher\(^{13}\) than our measurement. In Methods, we
investigate other type Ia and core-collapse supernova models and find
that our main conclusion remains valid, although the exact ratio of
near-\(\text{M}_{\odot}\) to \(\text{sub-M}_{\odot}\) contributions may depend on the model details.

The Hitomi SXS observation has demonstrated the power of high-resolution X-ray spectroscopy: measurement of the chemical enrichment of a single object has provided new insight into funda-
mental phenomena that shape the present-day Universe. A common abundance pattern between the solar neighbourhood and the Perseus
cluster suggests that the chemical composition of the Sun is probably
a good indicator of the nature of the average type Ia supernova in the
Universe. To confirm this conclusion, it is extremely important to scrutinize other environments, such as the outskirts of galaxy clusters\(^{30}\), at high spectral resolution in future X-ray observatories.

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**Author Information**

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**Supplementary Information**

is available in the online version of the paper.
adding a Gaussian at the energy of the Fe xxv resonance line with a negative flux. The data reduction was made with tools from the Hitomi software package, which is publicly available from NASA's HEASARC archive (https://heasarc.gsfc.nasa.gov/docs/software/heasoft/download.html). We used cleaned event data of the latest release version with the standard screening for the post-pipeline processes. The spectral analysis was performed using only high-resolution primary events, which have the best energy resolution. The redistribution matrix file was generated with the extra-large size option, which accounts for all components of the line spread function, including the main peak, low-energy exponential tail, escape peaks and electron-lens continuum (10.13). The full-width at half-maximum of the main-peak component was measured to be 4.9 eV for the Fe calibration source (10.35). Additional gain correction. Because of the short life of the mission (launched on 17 February 2017, lost on 26 March 2017), opportunities for on-board calibration were limited. This caused some uncertainty in the detectorgain (pulse height–energy conversion factors), particularly at energies far from the Mn Kα lines (5.9 keV) from the on-board Fe calibration source. We thus applied the following gain calibration and correction using the Perseus data, in addition to the original calibration, which is described in ref. 17.

First, we modelled the Fe Heα complex with an ionization equilibrium plasma for each pixel in each sequence listed in Extended Data Table 1 (sequences 100040030–100040050) and measured the X-ray energies of the detected lines. The redistribution matrix file was generated with the extra-large size option, which accounts for all components of the line spread function, including the main peak, low-energy exponential tail, escape peaks and electron-lens continuum (10.13). The full-width at half-maximum of the main-peak component was measured to be 4.9 eV for the Fe calibration source (10.35). Additional gain correction. Because of the short life of the mission (launched on 17 February 2017, lost on 26 March 2017), opportunities for on-board calibration were limited. This caused some uncertainty in the detectorgain (pulse height–energy conversion factors), particularly at energies far from the Mn Kα lines (5.9 keV) from the on-board Fe calibration source. We thus applied the following gain calibration and correction using the Perseus data, in addition to the original calibration, which is described in ref. 17.

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for these weak emission lines in this high-resolution spectrum. Extended Data Fig. 5b shows a similar plot, but the spectrum is convolved to the resolution of CCDs using a representative XMM-Newton response function. Unlike the SXS spectrum, the peak-to-continuum level ratios for the Cr and Mn emissions are extremely low (only a few per cent above unity). Moreover, the emission lines no longer have a sharp profile, making it difficult to separate them from the continuum. In fact, if we fitted this simulated CCD spectrum with a model with 1% higher (or lower) continuum normalization, the line components with their broad profiles would ‘compensate’ for the excess (or lack) of continuum flux by requiring about 50% lower (or higher) values of the Cr/Fe and Mn/Fe abundance ratios. The high-resolution SXS spectrum is much less subject to such systematic uncertainties because the line and continuum intensities are measured almost independently; hence, a slight over- or under-estimation of the continuum level has little effect on the abundance measurement. This point is illustrated quantitatively in Extended Data Fig. 6, which shows the result of our test analysis.

Comparison with supernova nucleosynthesis models. The measured abundances of the Fe-peak elements are compared with theoretical predictions to determine the nature of type Ia supernovae that may have contributed to the chemical enrichment in the Perseus cluster. As prototype type Ia supernova models, we select those used in the latest three-dimensional calculations of refs 12 and 13. The former (model M100) assumes a delayed–detonation explosion of a near-M3 ⊙ white dwarf with 100 deflagration ignition sites. The latter (model 1.1.0.9 in Extended Data Tables 5.) assumes the violent merger of two sub-M3 ⊙ white dwarfs with masses of 1.1M⊙ and 0.9M⊙ and the subsequent full detonation of the primary (more massive) white dwarf. Both models successfully replicate the typical observables of type Ia supernovae, including the average maximum brightness and synthesized 56Fe mass of approximately 0.6M⊙. The pre-explosion white dwarf is composed of 47.5% 12C, 50% 16O and 2.5% 22Ne by mass, which corresponds to nearly solar metallicity for the progenitor. As another example of a sub-M3 ⊙ explosion, we choose the 10HC model from ref. 14, which assumes an explosion of a single carbon–oxygen white dwarf with a mass of 1.0M⊙ accreting helium at a rate of M=4.0×10−3M⊙yr−1. An initial detonation ignited in the helium layer triggers a second detonation in the C–O core, resulting in a complete explosion of the white dwarf with a kinetic energy of 1.2×1051 erg and 56Ni mass of about 0.64M⊙, as typically inferred for type Ia supernovae.

To account for the core–collapse supernova contributions, we consider mass-dependent yields weighted by the Salpeter IMF (slope α = 2.35), with the assumption that 50% of stars with masses of at least 25M⊙ explode as hypernovae. Because type Ia supernovae produce Fe efficiently, whereas core-collapse supernovae dominate α-element production, the SXS spectra that we extracted could be used to constrain the type Ia supernova/core-collapse ratio in the Perseus cluster. However, instead of determining the actual fCC value, we allow a conservatively wide range for the core-collapse supernova fraction, fCC = NCC/NCC + NIA = 0.6–0.9 (refs 2, 19, 28, 29, 46, 47). This choice was made because (1) the lighter elements that are most sensitive to fCC (that is, O, Ne and Mg) were not detected owing to the attenuation of soft-X-rays by the closed aperture window; (2) the measured abundances of the intermediate-mass α-burning elements, unlike those of the Fe-peak elements, are dominated by systematic, rather than statistical, uncertainties (Extended Data Fig. 5); and (3) the primary origins of Ar and Ca are currently under debate.48 Future high-resolution X-ray spectroscopy with sensitivity to softer X-rays will improve the accuracy of the abundances of the lighter elements, as well as that of the ICM spectral model, hence allowing better constraints on the type Ia/core-collapse supernova ratio. We emphasize that, in contrast to the intermediate-mass α-burning elements, the abundances of the Fe-peak elements are robustly determined with little model dependency (Extended Data Fig. 3). As a result, the main conclusions of this paper are not affected by any of the issues described above.

The abundance ratios predicted by the model calculations are given in Fig. 3. Because of the efficient electron capture and the low-entropy freeze-out from nuclear statistical equilibrium,49 higher abundances of Mn and Ni are expected in the near-M3 ⊙ type Ia supernovae. We also tested other combinations of supernova models and different IMF slopes (for core-collapse supernovae). Extended Data Table 3 summarizes the mass ratios of the Fe-peak elements and Fe yields (in M⊙) predicted by the various type Ia supernova models that we investigated46,12–14,49–53. Because this paper discusses exclusively the products of electron capture, we consider only recent calculations that were based on up-to-date weak interaction rates4. For core-collapse supernova models, we use different IMF slopes (α = 2.0 and 2.7) and assume that all 10M⊙ – 50M⊙ stars explode as normal supernovae, without any hypernova contribution. These results are summarized in Extended Data Table 4. We reach essentially the same conclusion as that described in the main text; higher mass ratios of Mn/Fe and Ni/Fe are always expected for near-M3 ⊙ type Ia supernovae (Extended Data Table 3), and a combination of near-M3 ⊙ and sub-M3 ⊙ type Ia supernovae explains the observed abundance pattern of the Fe-peak elements independently of contributions from core-collapse supernova (Extended Data Table 4).
Extended Data Figure 1 | The SXS field of view overlaid on a Chandra image in the 1.8–9.0 keV band. The corresponding sequence IDs of the Hitomi observations are given. Each side of the SXS field of view has an angular size of 3′ (about 64 kpc).
Extended Data Figure 2 | Additional gain correction. a–c, The data points indicate the difference $\Delta E = E' - E_0$ between the measured ($E'$) and theoretical ($E_0$) energies of each detected line at the given X-ray energy. The best-fitting parabolic functions are given as solid curves. The error bars correspond to the 1σ confidence level. a, b and c show the results from sequence 100040020, 100040030–50 (combined) and 100040060, respectively.
Extended Data Figure 3 | Elemental abundances calculated with different model assumptions. ‘A’ and ‘S’ indicate the results obtained using the atomic databases AtomDB v.3.0.8 and SPEX v.3.03, respectively, and ‘S’ represents an old atomic model (SPEX v.2.05, which does not contain Cr and Mn line data). Numerical designations are as follows: ‘1’, one-temperature fit with the Fe xxv resonance-scattering effect; ‘2’, one-temperature fit without the resonance-scattering effect; ‘3’, two-temperature fit with the resonance-scattering effect; ‘4’, two-temperature fit without the resonance-scattering effect. The error bars correspond to the 1σ confidence level.
Extended Data Figure 4 | Elemental abundances of the Perseus cluster core from different X-ray measurements. Relative abundances with respect to Fe (X/Fe, X = Si, S, Ar, Ca, Cr, Mn, Ni) normalized to the corresponding solar abundances\textsuperscript{25} (dashed line). The red circles are identical to those in Fig. 2 and represent the SXS measurements, with error bars that include both the 1\(\sigma\) statistical uncertainty and systematic uncertainty. The red diamonds show the same SXS measurements analysed with an outdated atomic model that was used in the XMM-Newton study. The blue triangles represent the XMM-Newton results\textsuperscript{11}, as in Fig. 2. The green squares are abundances obtained from Suzaku observations of the innermost 2\textquoteright region of the Perseus cluster\textsuperscript{39}, converted using the updated solar abundance table\textsuperscript{25} for direct comparison with the other measurements. The error bars are also converted to represent the statistical uncertainty at a 1\(\sigma\) confidence level.
Extended Data Figure 5 | Weak emission lines at different energy resolutions. a, SXS spectrum of the Perseus cluster around the Cr and Mn emission. The red line is the best-fitting model (model A1) with the Cr and Mn abundances set to zero. The bottom panel shows the ratio between the data and the model results. The error bars correspond to the 1σ confidence level. b, Simulated spectrum at the typical energy resolution of the XMM-Newton CCD data (MOS1 detector), assuming the best-fitting model for the SXS data and sufficiently long exposure time (4 Ms). This comparison demonstrates the robustness of our measurements of weak emission lines with high-resolution spectroscopy (see Methods for details).
Extended Data Figure 6 | Effect of potential bias in the continuum-level estimate on the abundance measurement using weak emission lines. a, Abundances of Cr (red), Mn (blue) and Fe (black) determined by intentionally adding a small offset to the continuum normalization (within ±3% of the measured value). The solid and dashed lines are obtained from our test analysis of the simulated CCD spectrum (Extended Data Fig. 5b) and the Hitomi spectrum, respectively. This illustrates that the CCD measurement of Cr and Mn abundances is sensitive to the accuracy of the continuum-level determination because of the weakness of the emission and the low spectral resolution. The Fe abundance is less subject to such uncertainty, even in the CCD measurement, owing to the much larger equivalent width of the emission. b, Abundance ratios of Cr/Fe (red) and Mn/Fe (blue), calculated using the values in a as a function of offset in the continuum level.
Extended Data Table 1 | Summary of the observations

| Sequence ID | Observation Start Time | Pointing R.A. (deg) | Pointing Dec. (deg) | Exposure Time (ks) |
|-------------|-------------------------|---------------------|---------------------|--------------------|
| 100040020   | 2016-02-25 02:14:12     | 49.9316             | 41.5194             | 97.44              |
| 100040030   | 2016-03-04 02:17:32     | 49.9324             | 41.5201             | 72.51              |
| 100040040   | 2016-03-05 12:00:15     | 49.9321             | 41.5199             | 68.13              |
| 100040050   | 2016-03-06 19:37:59     | 49.9323             | 41.5215             | 5.45               |
| 100040060   | 2016-03-06 22:56:19     | 49.9510             | 41.5123             | 45.79              |
| **Total**   |                         |                     |                     | **289.32**         |

Sequences 100040030, 100040040 and 100040050 are continuous observations, separated for data processing reasons. R.A., right ascension; dec., declination.
Extended Data Table 2 | Solar abundance table used in this work

| Element | Relative Number |
|---------|-----------------|
| H       | 1.00            |
| He      | $9.71 \times 10^{-2}$ |
| Si      | $3.85 \times 10^{-5}$ |
| S       | $1.62 \times 10^{-5}$ |
| Ar      | $3.57 \times 10^{-6}$ |
| Ca      | $2.33 \times 10^{-6}$ |
| Cr      | $5.05 \times 10^{-6}$ |
| Mn      | $3.56 \times 10^{-6}$ |
| Fe      | $3.27 \times 10^{-5}$ |
| Ni      | $1.89 \times 10^{-6}$ |

Data are from ref. 25.
## Extended Data Table 3 | Mass ratios of the Fe-peak elements in type Ia supernova models

| Model           | Cr/Fe | Mn/Fe | Ni/Fe | Fe mass $(M_\odot)$ | Reference |
|-----------------|-------|-------|-------|---------------------|-----------|
| **Near-$M_{Ch}$ SN Ia models** |
| N40             | 0.012 | 0.016 | 0.095 | 0.78                | 12        |
| N100            | 0.014 | 0.018 | 0.10  | 0.74                | 12        |
| N150            | 0.015 | 0.020 | 0.11  | 0.71                | 12        |
| N40def          | 0.0092| 0.022 | 0.14  | 0.44                | 49        |
| N100def         | 0.0094| 0.022 | 0.14  | 0.47                | 49        |
| N150def         | 0.0094| 0.022 | 0.14  | 0.50                | 49        |
| W7              | 0.0069| 0.0088| 0.16  | 0.76                | 4         |
| CDEF            | 0.0092| 0.019 | 0.22  | 0.39                | 4         |
| CDDT            | 0.0098| 0.017 | 0.21  | 0.36                | 4         |
| ODDT            | 0.016 | 0.011 | 0.12  | 0.65                | 4         |
| c3_2d_512       | 0.0078| 0.018 | 0.22  | 0.32                | 50        |
| c3_2d_256       | 0.0084| 0.015 | 0.21  | 0.41                | 50        |
| c3_3d_256       | 0.0082| 0.013 | 0.20  | 0.41                | 50        |
| b5_3d_256       | 0.011 | 0.011 | 0.16  | 0.40                | 50        |
| b30_3d_768      | 0.0060| 0.012 | 0.20  | 0.53                | 50        |
| DDTa            | 0.019 | 0.020 | 0.099 | 0.72                | 51        |
| **Sub-$M_{Ch}$ SN Ia models** |
| 1.1_0.9         | 0.011 | 0.0059| 0.050 | 0.65                | 13        |
| 10HC            | 0.012 | 0.0023| 0.032 | 0.63                | 14        |
| 10HCD           | 0.028 | 0.0034| 0.037 | 0.61                | 14        |
| 10HD            | 0.018 | 0.0025| 0.041 | 0.65                | 14        |
| 11HD            | 0.0076| 0.0014| 0.038 | 0.76                | 14        |
| 10B             | 0.017 | 0.0022| 0.039 | 0.73                | 14        |
| 10C             | 0.014 | 0.0021| 0.044 | 0.69                | 14        |
| 10D             | 0.0098| 0.0017| 0.046 | 0.74                | 14        |
| 9B              | 0.026 | 0.0034| 0.050 | 0.61                | 14        |
| 9C              | 0.021 | 0.0028| 0.040 | 0.64                | 14        |
| 9D              | 0.018 | 0.0024| 0.044 | 0.66                | 14        |
| 1.06$M_\odot$   | 0.031 | 0.0059| 0.059 | 0.76                | 6 (52)    |
| 0.97$M_\odot$   | 0.013 | 0.0092| 0.051 | 0.58                | 6 (52)    |
| 0.8$M_\odot$ + 0.6$M_\odot$ | 0.017 | 0.0027| 0.019 | 0.41                | 53        |
## Example calculations of supernova nucleosynthesis models

| Near-$M_{\text{Ch}}$ | Sub-$M_{\text{Ch}}$ | CC | IMF | $f_{\text{CC}}$ | $f_{\text{M}}$ | $f_{\text{Fe, Ia}}$ | Cr/Fe | Mn/Fe | Ni/Fe |
|----------------------|---------------------|----|-----|-------------|-------------|----------------|-------|-------|-------|
| **Near-$M_{\text{Ch}}$ SNe Ia only** | | | | | | | | | |
| N100 | – | SN+HN | 2.35 | 0.60 | 1.0 | 0.85 | 0.98 | 1.51 | 1.54 |
| N100 | – | SN+HN | 2.35 | 0.90 | 1.0 | 0.49 | 1.00 | 1.08 | 1.23 |
| N100 | – | SN+HN | 2.0 | 0.60 | 1.0 | 0.84 | 0.99 | 1.50 | 1.54 |
| N100 | – | SN+HN | 2.0 | 0.90 | 1.0 | 0.47 | 1.04 | 1.07 | 1.23 |
| N100 | – | SN+HN | 2.7 | 0.60 | 1.0 | 0.86 | 0.97 | 1.52 | 1.55 |
| N100 | – | SN+HN | 2.7 | 0.90 | 1.0 | 0.50 | 0.98 | 1.0 | 1.24 |
| N100 | – | SN only | 2.35 | 0.60 | 1.0 | 0.87 | 1.01 | 1.54 | 1.54 |
| N100 | – | SN only | 2.35 | 0.90 | 1.0 | 0.52 | 1.14 | 1.17 | 1.21 |
| **Sub-$M_{\text{Ch}}$ SNe Ia only** | | | | | | | | | |
| – | 1.1_0.9 | SN+HN | 2.35 | 0.60 | 0.0 | 0.83 | 0.81 | 0.55 | 0.83 |
| – | 1.1_0.9 | SN+HN | 2.35 | 0.90 | 0.0 | 0.45 | 0.92 | 0.53 | 0.83 |
| – | 1.1_0.9 | SN+HN | 2.0 | 0.60 | 0.0 | 0.82 | 0.82 | 0.55 | 0.84 |
| – | 1.1_0.9 | SN+HN | 2.0 | 0.90 | 0.0 | 0.44 | 0.95 | 0.54 | 0.84 |
| – | 1.1_0.9 | SN+HN | 2.7 | 0.60 | 0.0 | 0.84 | 0.80 | 0.54 | 0.83 |
| – | 1.1_0.9 | SN+HN | 2.7 | 0.90 | 0.0 | 0.47 | 0.89 | 0.53 | 0.82 |
| – | 1.1_0.9 | SN only | 2.35 | 0.60 | 0.0 | 0.85 | 0.85 | 0.56 | 0.82 |
| – | 1.1_0.9 | SN only | 2.35 | 0.90 | 0.0 | 0.48 | 1.05 | 0.59 | 0.77 |
| – | 10HC | SN+HN | 2.35 | 0.60 | 0.0 | 0.83 | 0.86 | 0.27 | 0.59 |
| – | 10HC | SN+HN | 2.35 | 0.90 | 0.0 | 0.45 | 0.95 | 0.38 | 0.69 |
| – | 10HC | SN+HN | 2.0 | 0.60 | 0.0 | 0.82 | 0.88 | 0.27 | 0.59 |
| – | 10HC | SN+HN | 2.0 | 0.90 | 0.0 | 0.43 | 0.98 | 0.39 | 0.71 |
| – | 10HC | SN+HN | 2.7 | 0.60 | 0.0 | 0.84 | 0.85 | 0.26 | 0.58 |
| – | 10HC | SN only | 2.35 | 0.60 | 0.0 | 0.85 | 0.90 | 0.28 | 0.57 |
| – | 10HC | SN only | 2.35 | 0.90 | 0.0 | 0.48 | 1.09 | 0.43 | 0.63 |
| **Both contributions of near- and sub-$M_{\text{Ch}}$ SNe Ia** | | | | | | | | | |
| N100 | 1.1_0.9 | SN+HN | 2.35 | 0.60 | 0.5 | 0.84 | 0.90 | 1.05 | 1.21 |
| N100 | 1.1_0.9 | SN+HN | 2.35 | 0.90 | 0.5 | 0.47 | 0.96 | 0.81 | 1.04 |
| N100 | 1.1_0.9 | SN only | 2.35 | 0.60 | 0.5 | 0.86 | 0.94 | 1.08 | 1.20 |
| N100 | 1.1_0.9 | SN only | 2.35 | 0.90 | 0.5 | 0.50 | 1.10 | 0.89 | 1.00 |
| N100 | 10HC | SN+HN | 2.35 | 0.60 | 0.5 | 0.84 | 0.92 | 0.93 | 1.10 |
| N100 | 10HC | SN+HN | 2.35 | 0.90 | 0.5 | 0.47 | 0.98 | 0.74 | 0.97 |
| N100 | 10HC | SN only | 2.35 | 0.60 | 0.5 | 0.86 | 0.96 | 0.95 | 1.09 |
| N100 | 10HC | SN only | 2.35 | 0.90 | 0.5 | 0.50 | 1.11 | 0.81 | 0.93 |

The first three columns indicate the name and combination of supernova models and the fourth column presents the assumed index of the IMF. $f_{\text{CC}}=N_{\text{CC}}/(N_{\text{CC}}+N_{\text{M}})$. $f_{\text{Fe, Ia}}=N_{\text{Fe, Ia}}/N_{\text{Ia}}$ and $f_{\text{M}}$ are the number fraction of core-collapse supernovae, the number fraction of near-$M_{\text{Ch}}$ type Ia supernovae and the mass fraction of Fe originating from type Ia supernovae, respectively. The remaining columns indicate abundance ratios relative to the solar values²⁶. SN, supernova; HN, hypernova.