Trans-Fe elements from Type la Supernovae

Umberto Battino (University of Naples "Federico II", INAF, NuGrid Collaboration)

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Type Ia Supernova and (Astro)physics

- 2/3 of the iron content in the Milky Way was produced by the explosion of white dwarfs in binary systems as type la supernovae.
- And maybe also a fraction of the p-nuclei! (see e.g. Howard & Meyer 1993, Travaglio et al. 2011, Battino et al. 2020)
- Iron is a crucial ingredient for planetary magnetic-field generation, the formation of proteins and enzyme systems (Wade et al. 2021) → central role played in the emergence of life as we know it on Earth.
- Additionally, due to their characteristic lightcurves, SNe Ia are standardizable candles for cosmic-distance measurements → evidence for the accelerated expansion of the Universe (Nobel Prize Physics, 2011)



NASA/ESA, The Hubble Key Project Team The High-Z Supernova Search Team

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...and yet the nature of SNIa progenitors is still a matter of debate!



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SNe la progenitors



Near-Chandrasekhar mass events

Deflagration of Deflagration+Detonation

<u>H-accretor</u> → But only ~6% of SN Ia from there (see e.g. Johansson et al. (2016))

Slow WD merger → Accretion disk formation → Final outcome depends on accretion rate and WD mass ratio (see e.g. Piersanti+2003)



Sub-Chandrasekhar mass events

 $\frac{\text{He-accretor}}{(\text{see Fink+2010; Magee+2021})}$

Major channel (~70%), but we still need ~30% near-Ch (Lach+2020, Collins+2022)

<u>Violent merger</u> → Prompt detonation during the merger process (if mass ratio q > \sim 0.8 or at least \sim 0.01 M_{sun} He present; see Pakmor et al. 2010, 2011, 2012, 2013)

Slow WD mergers



Trans-Fe element nucleosynthesis



¹²C(¹²C,a) ²⁰Ne ²²Ne(a,n) ²⁵Mg

4

Impact of the ²²Ne(a,n)²⁵Mg

Mass Coordinate [M_☉]



PRE-SUPERNOVA TRANS-FE ABUNDANCES

¹⁹ O 7.62e-03 7.96e-02 2.54e-01 4.95e-01 4.89e-01 3.63e-02 ²⁰ Ne 1.02e-07 1.87e-06 6.21e-02 3.84e-01 3.87e-01 5.88e-07 ²¹ Ne 5.04e-09 8.75e-08 1.59e-04 5.00e-06 2.81e-05 2.29e-09 ²¹ Ma 8.65e-08 1.26e-07 3.12e-03 8.12e-03 8.01e-03 1.52e-07 ²² Mg 1.71e-06 6.89e-06 5.46e-03 1.39e-02 1.34e-02 5.75e-07 ²² Mg 4.73e-01 2.45e-01 1.34e-06 1.38e-06 3.57e-07 ²² Ma 3.52e-01 2.46e-01 1.34e-06 1.38e-06 3.52e-01 ²³ Cr 3.51e-08 8.02e-08 1.23e-06 5.07e-07 3.94e-07 1.70e-08 ²⁵ Cr 5.04e-06 1.65e-06 1.61e-05 2.02e-06 1.77e-06 3.72e-07 ²⁵ Cr 2.04e-07 1.29e-07 3.07e-05 5.37e-05 3.34e-04 ²⁶ Fe 2.10e-06 1.78e-05 1.05e-06 1.05e-06 </th <th>Isotope</th> <th>Model A</th> <th>Model B</th> <th>Model C</th> <th>Model D</th> <th>Model D</th> <th>Model E</th>	Isotope	Model A	Model B	Model C	Model D	Model D	Model E
Wiescher et al. (2023) ²⁰ Ne 1.02e-07 1.87e-06 6.21e-02 3.84e-01 3.87e-01 5.88e-07 ²⁰ Ne 5.04e-09 8.75e-08 1.59e-04 5.060-06 2.28e-02 6.81e-03 5.22e-07 ²⁰ Mg 1.1e-06 6.82e-07 3.12e-03 8.12e-03 8.01e-03 1.52e-07 ²⁰ Mg 1.1e-06 6.82e-06 3.46e-01 2.93e-02 6.86e-05 ²⁰ Mg 1.76e-05 2.65e-04 2.94e-02 2.97e-02 5.69e-02 ²⁷ A1 3.12e-03 1.28e-02 2.74e-02 5.00e-03 3.86e-03 4.83e-01 ²⁸ Si 4.43e-01 2.89e-06 5.47e-07 3.94e-07 7.08e-08 3.38e-06 3.38e-03 3.82e-01 ²⁹ Cr 5.01e-08 1.58e-07 2.12e-07 1.54e-07 7.08e-08 3.38e-06 1.02e-06 7.88e-07 3.94e-07 7.08e-08 ⁵⁹ Cr 5.04e-06 1.61e-06 2.20e-06 7.88e-07 1.02e-06 7.8ee-07 3.94e-07 1.02e-06 7.8ee-07 <td>-</td> <td></td> <td></td> <td></td> <td></td> <td>$^{22}Ne+\alpha$</td> <td></td>	-					$^{22}Ne+\alpha$	
¹⁰ O 7.62e-03 7.96e-02 2.54e-01 4.89e-01 3.63e-02 ²¹ Ne 5.04e-09 8.75e-06 6.12e-02 3.84e-01 3.87e-01 5.88e-07 ²² Ne 5.04e-09 8.75e-08 1.59e-04 5.60e-06 2.81e-05 2.29e-09 ²³ Mg 1.75e-05 2.62e-04 2.22e-02 6.10e-02 6.22e-02 5.66e-05 ²³ Mg 1.71e-05 5.62e-04 2.22e-02 5.69e-02 7.52e-07 ²⁴ Mg 1.11e-06 6.89e-02 2.74e-02 5.90e-03 5.11e-03 5.76e-03 ²³ S 3.96e-01 3.22e-01 2.48e-01 1.34e-06 1.38e-06 3.52e-01 ²³ Cr 3.51e-08 8.02e-08 1.23e-06 5.37e-07 3.94e-07 7.08e-08 ²⁴ Cr 5.04e-06 1.66e-05 7.46e-05 3.07e-05 2.17e-05 7.10e-06 ²⁵ Fe 2.04e-07 2.99e-07 2.80e-05 1.02e-06 1.32e-07 2.96e-07 ²⁶ Fe 3.32e-04 2.39e-07 2.80e-05 </td <td></td> <td></td> <td></td> <td></td> <td></td> <td>Wiescher et al. (2023)</td> <td></td>						Wiescher et al. (2023)	
²⁰ Ne 1.02e-07 1.87e-06 6.21e-02 3.84e-01 3.87e-01 5.88e-07 ²¹ Na 8.65e-08 1.26e-07 3.12e-03 8.12e-03 8.01e-03 1.52e-07 ²¹ Mg 1.11e-06 6.80e-05 3.40e-02 1.34e-02 7.52e-07 ²⁰ Mg 4.11e-06 6.25e-02 2.94e-02 2.97e-02 5.69e-02 ²⁷ A1 3.12e-03 1.28e-02 2.94e-02 2.97e-02 5.69e-02 ²⁷ A1 3.12e-03 1.28e-01 3.80e-03 3.86e-03 4.83e-01 ²⁸ Si 4.34e-01 2.45e-01 1.34e-06 1.38e-06 3.52e-01 5.77e-07 3.94e-07 7.08e-08 ²⁹ Cr 5.10e-08 1.52e-07 2.12e-07 1.54e-07 1.07e-08 - ³⁰ Mn 2.37e-07 2.98e-07 2.08e-06 1.02e-06 7.89e-07 2.04e-07 7.08e-08 ³⁰ Mn 2.37e-07 2.98e-07 2.08e-05 5.07e-05 3.79e-05 5.77e-05 7.10e-06 ³⁰ Fe 2.10e-06	¹⁶ O	7.62e-03	7.96e-02	2.54e-01	4.95e-01	4.89e-01	3.63e-02
2 ¹ Ne 5.04e-09 8.75e-08 1.59e-04 5.60e-06 2.22e-07 ²⁴ Mg 1.76e-05 2.62e-04 2.22e-02 6.10e-02 6.23e-02 6.86e-05 ²⁴ Mg 1.11e-06 6.89e-06 5.46e-03 1.39e-02 2.94e-02 2.97e-02 5.69e-02 ²⁷ Al 3.12e-03 1.28e-02 2.94e-02 2.97e-02 5.69e-03 5.76e-03 ²⁸ Si 4.43e-01 4.24e-01 2.89e-01 3.84e-03 3.86e-03 4.83e-01 ²⁸ C 7.51e-08 8.02e-08 1.23e-06 5.37e-07 3.94e-07 7.08e-08 ³⁵ Cr 2.20e-08 3.25e-07 2.12e-07 1.54e-07 1.77e-06 3.26e-06 ³⁵ Mr 2.37e-07 2.98e-07 2.80e-05 1.49e-05 1.02e-05 6.77e-07 ³⁵ Fe 3.35e-40 2.99e-07 1.79e-05 5.37e-05 3.34e-04 ⁶⁰ Ni 5.32e-08 7.02e-07 3.77e-05 5.46e-07 1.05e-06 ⁶⁰ Ni 5.82e-08 7.08e-07 1.58e-05<	²⁰ Ne	1.02e-07	1.87e-06	6.21e-02	3.84e-01	3.87e-01	5.88e-07
²¹ Na 8.65e-08 1.26e-07 3.12e-03 8.12e-03 8.01e-03 1.52e-07 ²⁴ Mg 1.76e-05 2.62e-04 2.22e-02 6.10e-02 6.23e-02 5.66e-05 ²⁵ Mg 1.11e-06 6.89e-06 5.46e-03 1.39e-02 2.97e-02 5.69e-02 ²⁷ Al 3.12e-03 1.28e-02 2.74e-02 5.00e-03 5.11e-03 5.76e-03 ²⁸ S 3.96e-01 3.52e-01 2.46e-01 1.34e-06 1.38e-06 3.52e-01 ³⁷ Cr 3.51e-08 8.02e-08 1.32e-06 5.77e-07 3.94e-07 1.77e.08 ³⁴ Cr 5.04e-06 1.65e-06 1.61e-06 2.20e-06 1.72e-06 3.22e-08 ³⁵ Cr 2.09e-06 2.78e-05 1.49e-05 1.02e-05 7.70e-05 ³⁶ Cr 3.35e-07 3.29e-04 1.10e-04 7.54e-05 3.37e-05 3.34e-04 ³⁶ Fe 2.10e-06 1.36e-05 3.68e-05 3.26e-05 2.20e-07 ³⁷ Fe 3.33e-04 2.93e-04 1.10e-04<	²² Ne	5.04e-09	8.75e-08	1.59e-04	5.60e-06	2.81e-05	2.29e-09
 ²¹Mg 1.76e-05 2.62e-04 2.22e-02 6.80e-05 2.42e-02 7.52e-07 ²⁶Mg 4.78e-02 4.55e-02 3.04e-02 2.94e-02 2.97e-02 5.69e-02 ²⁷A1 3.12e-03 1.28e-02 2.74e-02 5.00e-03 5.11e-03 5.76e-03 ²⁸Si 4.32e-01 3.28e-01 3.28e-03 3.86e-03 4.83e-01 3.28e-01 3.28e-01 3.28e-01 3.28e-01 3.28e-03 3.86e-03 4.83e-01 3.28e-06 5.37e-07 3.94e-07 7.84e-07 7.78e-08 3.22e-08 3.52e-07 2.12e-07 1.54e-07 1.77e-08 7.20e-06 2.32e-08 3.25e-07 2.12e-07 1.54e-07 1.24e-07 2.46e-07 ²⁸Fe 2.00e-06 1.36e-05 9.74e-05 3.07e-05 2.17e-05 7.10e-06 ³⁵Fe 6.92e-07 2.09e-04 1.0e-04 7.54e-05 3.36e-03 3.34e-04 ⁶⁹Fe 2.0e-07 1.51e-06 9.88e-05 1.02e-04 7.37e-05 1.02e-05 2.20e-07 ⁶⁹Ni 4.52e-08 7.45e-05 1.25e-07 ⁶⁰Ni 4.52e-08 7.45e-05 7.16e-05 4.42e-08 ⁶⁴Ni 1.86e-04 1.09e-05 7.3ee-05 4.46e-04 3.76e-05 2.26e-07 1.58e-05 1.62e-05 3.66e-07 4.42e-08 6.42e-06	²³ Na	8.65e-08	1.26e-07	3.12e-03	8.12e-03	8.01e-03	1.52e-07
²³ Mg 1.11e-06 6.89e-06 5.46e-02 2.94e-02 2.97e-02 5.69e-02 ²⁷ Al 3.12e-03 1.28e-02 2.74e-02 5.00e-03 5.11e-03 5.76e-03 ²³ S 3.96e-01 3.28e-01 2.89e-01 3.8e-06 3.88e-03 4.83e-01 ²³ Cr 3.51e-08 8.02e-08 1.23e-06 5.37e-07 3.94e-07 7.08e-08 ³³ Cr 2.04e-06 1.52e-06 1.72e-06 3.26e-06 3.26e-06 ⁵⁴ Cr 5.04e-06 1.56e-06 1.01e-06 7.17e-05 7.10e-06 ⁵⁴ Fe 2.04e-06 1.36e-05 9.74e-05 3.07e-05 3.78e-07 2.46e-07 ⁵⁸ Fe 3.25e-04 1.10e-04 7.54e-05 5.37e-05 3.34e-04 ⁶⁹ Fe 1.47e-06 1.92e-07 3.27e-05 5.63e-05 3.96e-05 2.20e-07 ⁶⁹ Ko 3.58e-08 7.02e-04 7.37e-05 3.04e-04 1.05e-06 ⁶⁰ Ni 5.82e-08 7.03e-07 1.99e-05 5.73e-05 4.07e-05 </td <td>²⁴Mg</td> <td>1.76e-05</td> <td>2.62e-04</td> <td>2.22e-02</td> <td>6.10e-02</td> <td>6.23e-02</td> <td>6.86e-05</td>	²⁴ Mg	1.76e-05	2.62e-04	2.22e-02	6.10e-02	6.23e-02	6.86e-05
²⁹ Mg 4.78e-02 4.55e-02 2.94e-02 2.97e-02 5.66e-03 ²⁷ AI 3.12e-03 1.28e-02 2.74e-02 5.00e-03 5.11e-03 5.76e-03 ²⁸ Si 4.43e-01 4.24e-01 2.89e-01 3.80e-03 3.86e-03 4.83e-01 ²⁸ Cr 3.51e-08 8.002-08 1.22e-06 5.37e-07 3.94e-07 7.708e-08 ⁵³ Cr 5.04e-06 1.65e-06 1.61e-06 2.20e-06 3.72e-07 2.96e-06 ⁵⁴ Cr 5.37e-07 2.98e-07 2.40e-06 1.02e-06 7.89e-07 2.46e-07 ⁵⁴ Fe 2.10e-06 1.36e-05 9.74e-05 3.76e-05 3.74e-04 3.74e-04 ⁶⁴ Fe 1.47e-06 1.92e-07 1.574e-05 3.76e-05 2.20e-07 ⁶⁹ Co 4.98e-07 1.58e-05 1.02e-05 6.77e-07 ⁵⁹ Fe 3.35e-04 2.93e-04 1.10e-04 7.35e-05 3.07e-05 1.05e-06 ⁶⁰ Ni 5.22e-07 1.68e-05 1.05e-06 ⁶⁰ Ni 5.28e-07 1.58e-06 1.52e-07	²⁵ Mg	1.11e-06	6.89e-06	5.46e-03	1.39e-02	1.34e-02	7.52e-07
2 ¹ Al 3.12e-03 1.28e-02 2.74e-02 5.00e-03 5.11e-03 5.76e-03 2 ⁸ Si 4.43e-01 4.24e-01 2.89e-01 3.80e-03 3.86e-03 4.83e-01 3 ² S 3.96e-01 3.52e-01 2.44e-01 1.34e-06 1.38e-06 3.52e-01 5 ³ Cr 2.20e-08 2.32e-08 3.55e-07 2.12e-07 1.54e-07 1.72e-06 5 ⁴ Cr 5.04e-06 1.61e-06 2.20e-06 1.72e-06 3.26e-06 5 ⁴ Mn 2.37e-07 2.98e-07 2.80e-05 1.49e-05 1.02e-06 7.70e-05 5 ⁴ Fe 2.10e-06 1.36e-05 9.74e-05 5.37e-05 3.34e-04 6 ¹⁰ Fe 1.47e-06 1.92e-07 3.27e-05 5.63e-05 3.96e-05 2.20e-07 ¹⁰⁰ Fe 1.02e-04 1.02e-04 7.37e-05 1.05e-06 6 ¹⁰ Ni 5.26e-07 1.05e-06 6 ¹⁰ Ni 5.26e-07 1.54e-05 1.25e-07 1.54e-05 1.25e-07 1.54e-05 1.25e-07 1.54e-05 1.26e-07 1.25e-07 1.54e-05 1.26e-07 1.25e-05 2.66e-05 3.02e-05 3.65e-07 6 ¹⁰ Ni	²⁶ Mg	4.78e-02	4.55e-02	3.04e-02	2.94e-02	2.97e-02	5.69e-02
 ²³Si 4.43c-01 4.24c-01 2.89c-01 3.80c-03 3.86c-03 4.83c-01 ²³S 3.96c-01 3.52c-01 2.46c-01 1.34c-06 1.38c-06 3.52c-01 ²³Cr 3.51c-08 8.02c-08 1.23c-06 5.37c-07 3.94c-07 7.08c-08 ⁵³Cr 2.20c-08 2.32c-08 3.55c-07 2.12c-07 1.54c-07 1.77c-08 - ⁵⁴Cr 5.04c-06 1.65c-06 1.61c-06 2.20c-06 1.72c-06 3.26c-06 ⁵⁵Fe 2.10c-06 1.36c-05 9.74c-05 3.07c-05 2.17c-05 7.10c-06 ⁵⁶Fe 2.10c-06 1.36c-05 9.74c-05 3.07c-05 2.17c-05 7.10c-06 ⁵⁷Fe 6.92c-07 2.09c-06 2.78c-05 1.49c-05 1.02c-05 6.77c-07 ⁵⁸Fe 3.35c-04 2.93c-04 1.10c-04 7.54c-05 3.36c-05 2.20c-07 ⁵⁹Co 4.98c-07 1.51c-06 9.88c-05 1.02c-04 7.37c-05 1.05c-06 ⁶⁰Ni 4.52c-08 2.45c-07 1.58c-05 1.91c-05 4.07c-05 5.66c-07 ⁶¹Ni 4.52c-08 2.45c-07 1.58c-05 1.91c-05 1.45c-05 1.25c-07 ⁶²Ni 2.96c-04 4.14c-04 1.49c-04 1.00c-04 8.87c-05 4.42c-08 ⁶⁴Ni 1.86c-04 1.76c-05 7.45c-05 1.22c-04 1.28c-04 7.23c-05 ⁶⁴Ni 1.86c-04 3.76c-05 7.45c-05 1.22c-04 1.28c-04 7.23c-05 ⁶⁶Cu 2.49c-07 1.96c-07 1.25c-05 2.63c-05 2.85c-05 3.02c-05 2.60c-07 ⁶⁶Zn 3.12c-08 2.02c-08 1.21c-06 1.27c-05 1.68c-05 2.86c-07 ⁶⁶Zn 1.31c-08 2.02c-08 1.21c-06 1.27c-05 1.68c-05 2.86c-07 ⁷⁶Ge 4.59c-10 9.12c-08 5.86c-06 7.01c-06 9.32c-05 2.60c-07 ⁶⁶Zn 1.12c-08 2.02c-08 1.21c-06 1.27c-05 1.68c-05 2.86c-06 ⁷⁰Ge 4.59c-10 9.12c-08 5.86c-06 7.01c-06 9.32c-05 4.22c-09 ⁷³Ge 1.24c-08 1.20c-07 4.75c-06 8.36c-06 1.12c-05 3.67c-07 ⁷⁴Ge 5.63c-06 1.91c-05 1.77c-06 8.38c-06 4.69c-10 ⁷⁹Se 1.32c-09 2.07c-08 1.72c-05 1.78c-05 1.68c-05 2.86c-06 ⁷⁴Ge 5.63c-06 1.91c-05 1.78c-05 1.79c-05 3.67c-06 ⁷⁶Ge 4.59c-10 9.12c-08 8.78c-06 1.20c-05 5.53c-08 ⁷⁶Ge 4.59c-10 9.12c-08 8.78c-06 1.27c-05 1.79c-05 3.67c-06 ⁷⁶Ge 4.59c-10 9.12c-08 8.78c-06 1.27c-05 1.79c-05	27A1	3.12e-03	1.28e-02	2.74e-02	5.00e-03	5.11e-03	5.76e-03
³³ S 3.96c-01 3.52c-01 2.46c-01 1.34c-06 1.38c-06 3.52c-01 ⁵² Cr 3.51c-08 8.02c-08 1.23c-06 5.37c-07 3.94c-07 7.08c-08 ⁵³ Cr 2.02c-08 2.32c-08 3.55c-07 2.12c-07 1.54c-07 1.77c-08 ⁵⁴ Cr 5.04c-06 1.65c-06 1.01c-06 7.89c-07 2.46c-07 ⁵⁴ Fe 2.10c-06 1.56c-05 9.74c-05 3.07c-05 2.17c-05 7.10c-06 ⁵⁴ Fe 3.35c-04 2.93c-04 1.10c-04 7.54c-05 5.37c-05 3.34c-04 ⁶⁷ Fe 6.32c-07 2.90c-06 2.78c-05 1.49c-05 1.02c-05 6.67c-07 ⁶⁹ Fe 1.47c-06 1.98c-05 1.02c-04 7.37c-05 1.05c-06 ⁶⁰ Ni 5.82c-08 7.03c-07 1.98c-05 1.91c-05 1.45c-05 1.25c-07 ⁶⁰ Ni 5.82c-07 1.05c-06 ⁶⁰ Ni 1.86c-04 1.49c-04 1.00c-04 8.87c-05 1.12c-07 1.25c-07 ⁶⁶ Ni 1.86c-04 7.16c-05	28Si	4.43e-01	4.24e-01	2.89e-01	3.80e-03	3.86e-03	4.83e-01
⁵³ Cr 3.51e-08 8.02e-08 1.23e-06 5.37e-07 3.94e-07 7.08e-08 ⁵³ Cr 2.20e-08 2.32e-08 3.55e-07 2.12e-07 1.54e-07 1.77e-08 - ⁵⁴ Cr 5.04e-06 1.65e-06 1.61e-06 2.20e-06 7.72e-05 7.10e-06 ⁵⁵ Fe 2.92e-07 2.80e-06 1.02e-06 7.89e-07 2.46e-07 ⁵⁸ Fe 3.35e-04 2.93e-04 1.10e-04 7.54e-05 5.37e-05 3.34e-04 ⁶⁹ Fe 9.29e-07 7.32re-05 5.63e-05 3.96e-05 2.20e-07 ⁵⁹ Co 4.98e-07 1.58e-05 1.91e-05 1.45e-05 1.55e-06 ⁶⁰ Ni 5.82e-08 7.03e-07 1.99e-05 7.73e-05 4.14e-04 ⁶³ Ni 1.86e-04 1.10e-06 4.16e-05 7.85e-05 7.16e-05 4.42e-08 ⁶⁴ Ni 1.86e-04 3.76e-05 2.63e-05 2.85e-05 3.65e-07 ⁶⁶ Cu 2.49e-07 1.52e-05 2.669e-05 3.02e-05 2.66e-07	32S	3.96e-01	3.52e-01	2.46e-01	1.34e-06	1.38e-06	3.52e-01
5 ³ Cr 2.20e-08 2.32e-08 3.55e-07 2.12e-07 1.54e-07 1.77e-08 ⁵⁴ Cr 5.04e-06 1.65e-06 1.61e-06 2.02e-06 1.72e-06 3.26e-06 ⁵⁵ Fe 2.10e-06 1.36e-05 9.74e-05 3.07e-05 2.17e-05 7.10e-06 ⁵⁵ Fe 6.92e-07 2.09e-04 1.10e-04 7.54e-05 5.37e-05 3.34e-04 ⁶⁰ Fe 1.47e-06 1.92e-07 3.27e-05 5.63e-05 3.96e-05 2.20e-07 ⁵⁹ Co 4.98e-07 1.51e-06 9.88e-05 1.02e-04 7.37e-05 1.05e-06 ⁶⁰ Ni 5.82e-08 7.03e-07 1.98e-05 1.91e-05 1.45e-05 1.25e-07 ⁶⁴ Ni 1.86e-04 3.07e-05 7.16e-05 4.14e-04 4.9e-04 1.00e-04 8.87e-05 7.16e-05 4.42e-08 ⁶⁴ Ni 1.86e-06 1.0e-06 7.25e-05 2.63e-05 3.02e-05 3.65e-07 ⁶⁴ Ni 1.86e-04 1.9e-07 1.25e-05 2.63e-05 3.02e-05 4.	⁵² Cr	3.51e-08	8.02e-08	1.23e-06	5.37e-07	3.94e-07	7.08e-08
⁵⁴ Cr 5.04e-06 1.65e-06 1.61e-06 2.20e-06 1.72e-06 3.26e-06 ⁵⁵ Fe 2.10e-06 1.56e-05 9.74e-05 3.07e-05 2.17e-05 7.10e-06 ⁵⁷ Fe 6.92e-07 2.09e-06 2.78e-05 1.49e-05 1.02e-05 6.77e-07 ⁵⁸ Fe 3.35e-04 2.93e-04 1.10e-04 7.54e-05 5.37e-05 3.34e-04 ⁶⁹ Fe 4.74e-06 1.92e-07 3.7e-05 5.63e-05 2.00e-07 2.00e-07 ⁵⁹ Co 4.98e-07 1.51e-06 9.88e-05 1.02e-04 7.37e-05 1.05e-06 ⁶⁴ Ni 5.82e-08 7.03e-07 1.99e-05 5.73e-05 4.07e-05 1.22e-07 ⁶⁴ Ni 4.86e-04 1.49e-04 1.00e-04 8.87e-05 7.14e-04 638i ⁶⁴ Ni 1.86e-04 3.76e-05 7.22e-04 2.28e-04 7.23e-05 3.66e-07 ⁶⁴ Cu 2.49e-07 1.48e-06 1.02e-08 2.66e-05 3.02e-05 2.60e-07 ⁶⁴ Cu 3.99e-07	⁵³ Cr	2.20e-08	2.32e-08	3.55e-07	2.12e-07	1.54e-07	1.77e-08 -
⁵⁵ Min 2.37e-07 2.98e-07 2.80e-06 1.02e-06 7.89e-07 2.46e-07 ⁵⁶ Fe 2.10e-06 1.36e-05 9.74e-05 3.07e-05 2.17e-05 6.77e-07 ⁵⁸ Fe 3.35e-04 2.99e-06 2.78e-05 1.49e-05 5.37e-05 3.34e-04 ⁶⁹ Fe 1.47e-06 1.92e-07 3.27e-05 5.63e-05 3.96e-05 2.20e-07 ⁵⁹ Co 4.98e-07 1.51e-06 9.88e-05 1.02e-04 7.37e-05 1.05e-06 ⁶⁰ Ni 5.82e-08 7.03e-07 1.99e-05 7.45e-05 1.25e-07 5.66e-07 ⁶¹ Ni 4.52e-08 2.45e-07 1.58e-05 1.91e-05 1.45e-05 1.22e-04 ⁶² Ni 1.86e-04 1.06e-07 1.25e-05 2.63e-05 2.85e-05 3.65e-07 ⁶⁴ Xi 1.86e-04 1.02e-06 2.63e-05 2.85e-05 3.65e-07 ⁶⁴ Zn 3.12e-08 2.02e-08 1.21e-06 1.27e-05 1.68e-05 2.28e-09 ⁷¹ Ga 4.11e-10 2.71e-0	⁵⁴ Cr	5.04e-06	1.65e-06	1.61e-06	2.20e-06	1.72e-06	3.26e-06
⁵⁶ Fe 2.10e.06 1.36e.05 9.74e.05 3.07e.05 2.17e.05 7.10e.06 ⁵⁷ Fe 6.92e.07 2.09e.06 2.78e.05 1.49e.05 1.02e.05 6.77e.07 ⁵⁸ Fe 3.35e.04 2.93e.04 1.10e.04 7.54e.05 3.37e.05 3.34e.04 ⁶⁰ Fe 1.47e.06 1.92e.07 3.27e.05 5.63e.05 3.96e.05 2.20e.07 ⁵⁹ Co 4.98e.07 1.51e.06 9.88e.05 1.02e.04 7.37e.05 1.05e.06 ⁶⁰ Ni 5.82e.08 7.03e.07 1.99e.05 5.73e.05 4.07e.05 5.66e.07 ⁶¹ Ni 4.52e.08 2.45e.07 1.58e.05 1.16e.05 1.45e.05 1.25e.07 ⁶² Ni 2.96e.04 4.14e.04 1.49e.04 1.00e.04 8.87e.05 4.14e.04 ⁶⁴ Ni 1.86e.04 3.76e.05 7.45e.05 7.16e.05 2.85e.05 3.65e.07 ⁶⁴ Cu 2.49e.07 1.96e.07 1.25e.05 2.69e.05 3.02e.05 2.60e.07 ⁷⁰ Zn 1.12e.08<	⁵⁵ Mn	2.37e-07	2.98e-07	2.80e-06	1.02e-06	7.89e-07	2.46e-07
5 ³ Fe 6.92e-07 2.09e-06 2.78e-05 1.49e-05 1.02e-05 6.77e-07 ⁵⁸ Fe 3.35e-04 2.93e-04 1.10e-04 7.54e-05 5.37e-05 3.34e-04 ⁶⁹ Fe 1.47e-06 1.92e-07 3.7e-05 5.63e-05 2.00e-07 5.05e-06 ⁵⁹ Co 4.98e-07 1.51e-06 9.88e-05 1.02e-04 7.37e-05 1.05e-06 ⁶⁰ Ni 4.52e-08 2.45e-07 1.58e-05 1.91e-05 1.45e-05 1.25e-07 ⁶¹ Ni 4.52e-08 2.45e-07 1.58e-05 7.16e-05 4.42e-08 ⁶⁴ Ni 1.86e-06 1.10e-06 4.16e-05 7.85e-05 7.16e-05 4.42e-08 ⁶⁴ Ni 1.86e-04 3.76e-05 2.63e-05 3.02e-05 3.02e-06 5.26e-07 ⁷⁰ Zn 1.12e-08 2.02e-08 1.21e-06 5.32e-05 3.02e-05 3.02e-07 1.32e-07 1.	⁵⁶ Fe	2.10e-06	1.36e-05	9.74e-05	3.07e-05	2.17e-05	7.10e-06
	⁵⁷ Fe	6.92e-07	2.09e-06	2.78e-05	1.49e-05	1.02e-05	6.77e-07
	⁵⁸ Fe	3.35e-04	2.93e-04	1.10e-04	7.54e-05	5.37e-05	3.34e-04
⁵⁹ Co 4.98e-07 1.51e-06 9.88e-05 1.02e-04 7.37e-05 1.05e-06 ⁶⁰ Ni 5.82e-08 7.03e-07 1.99e-05 5.73e-05 4.07e-05 5.66e-07 ⁶¹ Ni 4.52e-08 2.45e-07 1.58e-05 1.91e-05 1.45e-05 1.14e-04 ⁶³ Ni 1.86e-06 1.10e-06 4.16e-05 7.85e-05 7.16e-05 4.42e-08 ⁶⁴ Ni 1.86e-04 3.76e-05 7.45e-05 2.22e-04 1.22e-04 7.23e-05 ⁶⁵ Cu 2.49e-07 1.96e-07 1.25e-05 2.63e-05 3.02e-05 2.60e-07 ⁶⁶ Zn 5.99e-07 7.48e-06 2.82e-05 4.14e-05 5.23e-05 4.87e-07 ⁷⁰ Zn 1.12e-08 2.02e-08 1.21e-06 1.27e-05 1.68e-05 2.28e-09 ⁷¹ Ga 4.11e-10 2.71e-09 2.25e-06 6.30e-06 8.38e-06 4.69e-10 ⁷⁰ Ge 4.59e-10 9.12e-08 8.86e-06 6.12e-05 5.53e-08 ⁷³ Ge 1.24e-08 1.20e-07<	⁶⁰ Fe	1.47e-06	1.92e-07	3.27e-05	5.63e-05	3.96e-05	2.20e-07
	59Co	4.98e-07	1.51e-06	9.88e-05	1.02e-04	7.37e-05	1.05e-06
61 Ni 4.52e-08 2.45e-07 1.58e-05 1.91e-05 1.45e-05 1.25e-07 62 Ni 2.96e-04 4.14e-04 1.00e-04 8.87e-05 4.14e-04 63 Ni 1.86e-06 1.10e-06 4.16e-05 7.85e-05 7.16e-05 4.42e-08 64 Ni 1.86e-04 3.76e-05 2.63e-05 2.85e-05 3.65e-07 65 Cu 2.49e-07 1.96e-07 1.25e-05 2.63e-05 2.85e-05 3.65e-07 66 Zn 3.12e-08 2.42e-06 1.62e-05 2.69e-05 3.02e-05 2.60e-07 70 Zn 1.12e-08 2.02e-08 1.21e-06 1.27e-05 1.68e-05 2.28e-09 71 Ga 4.11e-10 2.71e-09 2.25e-06 6.30e-06 8.38e-06 4.69e-10 70 Ge 4.59e-10 9.12e-08 8.86e-06 6.26e-05 3.32e-06 5.26e-09 74 Ge 5.63e-06 1.91e-05 1.72e-05 1.79e-05 3.67e-06 74 Ge 5.63e-06 1.91e-05 1.27e-05 1.79e-05	60Ni	5.82e-08	7.03e-07	1.99e-05	5.73e-05	4.07e-05	5.66e-07
⁶² Ni 2.96e-04 4.14e-04 1.49e-04 1.00e-04 8.87e-05 4.14e-04 ⁶³ Ni 1.86e-06 1.10e-06 4.16e-05 7.85e-05 7.16e-05 4.42e-08 ⁶⁴ Ni 1.86e-04 3.76e-05 7.45e-05 1.22e-04 1.28e-04 7.23e-05 ⁶⁵ Cu 2.49e-07 1.96e-07 1.25e-05 2.63e-05 2.85e-05 3.65e-07 ⁶⁶ Zn 3.12e-08 2.42e-06 1.62e-05 2.69e-05 3.02e-05 2.60e-07 ⁶⁶ Zn 5.99e-07 7.48e-06 2.82e-05 4.14e-05 5.23e-05 4.87e-07 ⁷⁰ Ga 4.11e-10 2.71e-09 2.25e-06 6.30e-06 8.38e-06 4.69e-10 ⁷¹ Ga 4.11e-10 2.71e-08 5.86e-06 7.01e-06 9.32e-06 5.26e-09 ⁷² Ge 8.60e-07 1.98e-05 8.68e-06 6.12e-05 3.16e-10 ⁷⁴ Ge 5.63e-06 1.91e-05 1.72e-05 1.79e-05 3.67e-06 ⁷⁶ Ge 2.97e-07 1.46e-07 9.65e-06<	⁶¹ Ni	4.52e-08	2.45e-07	1.58e-05	1.91e-05	1.45e-05	1.25e-07
⁶³ Ni 1.86e-06 1.10e-06 4.16e-05 7.85e-05 7.16e-05 4.42e-08 ⁶⁴ Ni 1.86e-04 3.76e-05 7.45e-05 1.22e-04 1.28e-04 7.23e-05 ⁶⁵ Cu 2.49e-07 1.96e-07 1.25e-05 2.63e-05 2.85e-05 3.65e-07 ⁶⁶ Zn 3.12e-08 2.42e-06 1.62e-05 2.69e-05 3.02e-05 2.60e-07 ⁷⁰ Zn 5.99e-07 7.48e-06 2.82e-05 4.14e-05 5.23e-05 4.87e-07 ⁷⁰ Zn 1.12e-08 2.02e-08 1.21e-06 1.27e-05 1.68e-05 2.28e-09 ⁷¹ Ga 4.11e-10 2.71e-09 2.25e-06 6.30e-06 8.38e-06 4.69e-10 ⁷⁰ Ge 4.59e-10 9.12e-08 5.86e-06 7.01e-06 9.32e-06 5.26e-09 ⁷¹ Ge 8.60e-07 1.98e-05 8.68e-06 6.62e-06 9.01e-06 1.99e-06 ⁷³ Ge 5.32e-06 1.21e-05 1.75e-06 8.36e-06 1.12e-05 3.16e-10 ⁷⁴ Ge 5.63e-06 1.91e-05 1.57e-06 8.25e-06 1.26e-05 5.53e-08	62Ni	2.96e-04	4.14e-04	1.49e-04	1.00e-04	8.87e-05	4.14e-04
⁶⁴ Ni 1.86e-04 3.76e-05 7.45e-05 1.22e-04 1.28e-04 7.23e-05 ⁶⁵ Cu 2.49e-07 1.96e-07 1.25e-05 2.63e-05 2.85e-05 3.65e-07 ⁶⁶ Zn 3.12e-08 2.42e-06 1.62e-05 2.69e-05 3.02e-05 2.60e-07 ⁶⁶ Zn 5.99e-07 7.48e-06 2.82e-05 4.14e-05 5.23e-05 4.87e-07 ⁷⁰ Zn 1.12e-08 2.02e-08 1.21e-06 1.27e-05 1.68e-05 2.28e-09 ⁷¹ Ga 4.11e-10 2.71e-09 2.25e-06 6.30e-06 8.38e-06 5.26e-09 ⁷² Ge 8.60e-07 1.98e-05 8.68e-06 6.12e-05 3.16e-10 ⁷⁴ Ge 5.63e-06 1.91e-05 1.75e-05 3.67e-06 3.66e-06 ⁷⁴ Ge 2.66e-09 2.53e-07 8.74e-07 2.01e-06 2.96e-06 4.85e-08 ⁷⁵ Se 1.32e-09 2.07e-08 1.72e-06 8.94e-06 1.34e-05 5.28e-06 ⁷⁸ Se 3.12e-06 1.37e-05 8.77e-06<	63Ni	1.86e-06	1.10e-06	4.16e-05	7.85e-05	7.16e-05	4.42e-08
⁶⁵ Cu 2.49e-07 1.96e-07 1.25e-05 2.63e-05 2.85e-05 3.65e-07 ⁶⁶ Zn 3.12e-08 2.42e-06 1.62e-05 2.69e-05 3.02e-05 2.60e-07 ⁶⁸ Zn 5.99e-07 7.48e-06 2.82e-05 4.14e-05 5.22e-05 4.87e-07 ⁷⁰ Zn 1.12e-08 2.02e-08 1.21e-06 1.27e-05 1.68e-05 2.28e-09 ⁷¹ Ga 4.11e-10 2.71e-09 2.25e-06 6.30e-06 8.38e-06 4.69e-10 ⁷⁰ Ge 4.59e-10 9.12e-08 5.86e-06 7.01e-06 9.32e-06 5.26e-09 ⁷² Ge 8.60e-07 1.98e-05 8.68e-06 6.62e-06 9.01e-06 1.99e-06 ⁷³ Ge 1.24e-08 1.20e-07 4.75e-06 8.36e-06 1.12e-05 3.16e-10 ⁷⁴ Ge 5.63e-06 1.27e-05 1.79e-05 3.67e-06 1.62e-05 5.53e-08 ⁷⁵ As 1.44e-09 1.67e-08 1.81e-06 3.03e-06 4.22e-06 7.70e-08 ⁷⁶ Se 6.96e-09 2.53e-07 8.74e-07 2.01e-06 1.94e-05 5.62e-06	⁶⁴ Ni	1.86e-04	3.76e-05	7.45e-05	1.22e-04	1.28e-04	7.23e-05
⁶⁶ Zn 3.12e-08 2.42e-06 1.62e-05 2.69e-05 3.02e-05 2.60e-07 ⁶⁸ Zn 5.99e-07 7.48e-06 2.82e-05 4.14e-05 5.23e-05 4.87e-07 ⁷⁰ Zn 1.12e-08 2.02e-08 1.21e-06 1.27e-05 1.68e-05 2.28e-09 ⁷¹ Ga 4.11e-10 2.71e-09 2.25e-06 6.30e-06 8.38e-06 4.69e-10 ⁷⁰ Ge 4.59e-10 9.12e-08 5.86e-06 7.01e-06 9.32e-06 5.26e-09 ⁷² Ge 8.60e-07 1.98e-05 8.68e-06 6.62e-06 9.01e-06 1.99e-06 ⁷³ Ge 1.24e-08 1.20e-07 4.75e-06 8.36e-06 1.12e-05 3.16e-10 ⁷⁴ Ge 5.63e-06 1.91e-05 1.15e-05 1.27e-05 1.79e-05 3.67e-06 ⁷⁵ As 1.44e-09 1.67e-08 1.81e-06 3.03e-06 4.22e-06 7.70e-08 ⁷⁶ Se 6.96e-09 2.53e-07 8.74e-07 2.01e-06 1.34e-05 6.28e-10 ⁷⁸ Se 3.12e-06<	⁶⁵ Cu	2.49e-07	1.96e-07	1.25e-05	2.63e-05	2.85e-05	3.65e-07
	⁶⁶ Zn	3.12e-08	2.42e-06	1.62e-05	2.69e-05	3.02e-05	2.60e-07
	⁶⁸ Zn	5.99e-07	7.48e-06	2.82e-05	4.14e-05	5.23e-05	4.87e-07
	⁷⁰ Zn	1.12e-08	2.02e-08	1.21e-06	1.27e-05	1.68e-05	2.28e-09
	71Ga	4.11e-10	2.71e-09	2.25e-06	6.30e-06	8.38e-06	4.69e-10
	⁷⁰ Ge	4.59e-10	9.12e-08	5.86e-06	7.01e-06	9.32e-06	5.26e-09
	⁷² Ge	8.60e-07	1.98e-05	8.68e-06	6.62e-06	9.01e-06	1.99e-06
	⁷³ Ge	1.24e-08	1.20e-07	4.75e-06	8.36e-06	1.12e-05	3.16e-10
	⁷⁴ Ge	5.63e-06	1.91e-05	1.15e-05	1.27e-05	1.79e-05	3.67e-06
	⁷⁶ Ge	2.97e-07	1.46e-07	9.65e-06	8.25e-06	1.26e-05	5.53e-08
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	75As	1.44e-09	1.67e-08	1.81e-06	3.03e-06	4.22e-06	7.70e-08
	⁷⁶ Se	6.96e-09	2.53e-07	8.74e-07	2.01e-06	2.96e-06	4.85e-08
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	⁷⁷ Se	1.32e-09	2.07e-08	1.72e-06	8.94e-06	1.34e-05	6.28e-10
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	⁷⁸ Se	3.12e-06	1.37e-05	8.77e-06	6.10e-06	1.00e-05	5.62e-06
	⁷⁹ Se	6.86e-08	1.29e-07	3.16e-06	2.95e-06	4.65e-06	2.63e-09
	⁸⁰ Se	1.05e-05	6.72e-06	1.01e-05	1.04e-05	1.74e-05	4.59e-06
	⁸² Se	6.25e-07	5.96e-08	7.97e-06	6.54e-06	1.43e-05	1.82e-07
	⁸¹ Br	1.82e-08	5.90e-08	1.53e-06	1.78e-06	2.98e-06	5.64e-07
$ \begin{array}{rrrrrrrrrrrrrrrrrrrrrrrrrrrrrrr$	⁸² Kr	6.83e-09	4.42e-07	6.68e-07	7.91e-07	1.38e-06	2.35e-07
84 Kr 5.37e-06 3.57e-05 1.31e-05 1.03e-05 2.00e-05 1.31e-05 ⁸⁶ Kr 2.59e-05 2.61e-05 1.90e-05 2.52e-05 6.22e-05 1.86e-05 ⁸⁵ Rb 3.71e-10 3.05e-09 6.30e-07 6.08e-06 1.21e-05 2.61e-08 ⁸⁷ Rb 3.44e-06 2.44e-06 3.32e-06 2.74e-06 7.67e-06 3.02e-06 ⁸⁸ Sr 2.27e-06 3.52e-06 3.62e-06 3.82e-06 1.40e-05 1.68e-06 ⁸⁹ Y 4.20e-10 5.03e-09 2.15e-07 1.46e-06 5.48e-06 4.79e-10 ⁹⁰ Zr 7.06e-09 3.35e-07 7.59e-08 6.65e-07 2.51e-06 2.01e-08 ¹¹⁰ Cd 4.44e-09 7.05e-09 7.34e-10 1.29e-09 1.12e-08 5.59e-09 ¹¹⁶ Sn 4.91e-08 4.18e-08 9.94e-10 4.80e-10 4.93e-09 5.50e-08 ¹¹⁸ Sn 1.13e-08 1.44e-09 5.04e-09 9.15e-09 7.84e-08 3.43e-09	⁸³ Kr	2.30e-09	6.35e-08	2.05e-06	3.37e-06	5.99e-06	1.06e-08
	⁸⁴ Kr	5.37e-06	3.57e-05	1.31e-05	1.03e-05	2.00e-05	1.31e-05
⁸⁵ Rb 3.71e-10 3.05e-09 6.30e-07 6.08e-06 1.21e-05 2.61e-08 ⁸⁷ Rb 3.44e-06 2.44e-06 3.32e-06 2.74e-06 7.67e-06 3.02e-06 ⁸⁸ Sr 2.27e-06 3.52e-06 3.62e-06 3.82e-06 1.40e-05 1.68e-06 ⁸⁹ Y 4.20e-10 5.03e-09 2.15e-07 1.46e-06 5.48e-06 4.79e-10 ⁹⁰ Zr 7.06e-09 3.35e-07 7.59e-08 6.65e-07 2.51e-06 2.01e-08 ¹¹⁰ Cd 4.44e-09 7.05e-09 7.34e-10 1.29e-09 1.12e-08 5.59e-09 ¹¹⁰ Sn 4.91e-08 4.18e-08 9.94e-10 4.80e-10 4.93e-09 5.50e-08 ¹¹⁸ Sn 1.13e-08 1.44e-09 5.04e-09 9.15e-09 7.84e-08 3.43e-09	⁸⁶ Kr	2.59e-05	2.61e-05	1.90e-05	2.52e-05	6.22e-05	1.86e-05
$ \begin{array}{rrrrrrrrrrrrrrrrrrrrrrrrrrrrrrr$	⁸⁵ Rb	3.71e-10	3.05e-09	6.30e-07	6.08e-06	1.21e-05	2.61e-08
⁸⁸ Sr 2.27e-06 3.52e-06 3.82e-06 1.40e-05 1.68e-06 ⁸⁹ Y 4.20e-10 5.03e-09 2.15e-07 1.46e-06 5.48e-06 4.79e-10 ⁹⁰ Zr 7.06e-09 3.35e-07 7.59e-08 6.65e-07 2.51e-06 2.01e-08 ¹¹⁰ Cd 4.44e-09 7.05e-09 7.34e-10 1.29e-09 1.12e-08 5.59e-09 ¹¹⁶ Sn 4.91e-08 4.18e-08 9.94e-10 4.80e-10 4.93e-09 5.50e-08 ¹¹⁸ Sn 1.13e-08 1.44e-09 5.04e-09 9.15e-09 7.84e-08 3.43e-09	87Rb	3.44e-06	2.44e-06	3.32e-06	2.74e-06	7.67e-06	3.02e-06
⁸⁹ Y 4.20e-10 5.03e-09 2.15e-07 1.46e-06 5.48e-06 4.79e-10 ⁹⁰ Zr 7.06e-09 3.35e-07 7.59e-08 6.65e-07 2.51e-06 2.01e-08 ¹¹⁰ Cd 4.44e-09 7.05e-09 7.34e-10 1.29e-09 1.12e-08 5.59e-09 ¹¹⁶ Sn 4.91e-08 4.18e-08 9.94e-10 4.80e-10 4.93e-09 5.50e-08 ¹¹⁸ Sn 1.13e-08 1.44e-09 5.04e-09 9.15e-09 7.84e-08 3.43e-09	88Sr	2.27e-06	3.52e-06	3.62e-06	3.82e-06	1.40e-05	1.68e-06
90Zr 7.06e-09 3.35e-07 7.59e-08 6.65e-07 2.51e-06 2.01e-08 ¹¹⁰ Cd 4.44e-09 7.05e-09 7.34e-10 1.29e-09 1.12e-08 5.59e-09 ¹¹⁶ Sn 4.91e-08 4.18e-08 9.94e-10 4.80e-10 4.93e-09 5.50e-08 ¹¹⁸ Sn 1.13e-08 1.44e-09 5.04e-09 9.15e-09 7.84e-08 3.43e-09	89Y	4.20e-10	5.03e-09	2.15e-07	1.46e-06	5.48e-06	4.79e-10
110Cd 4.44e-09 7.05e-09 7.34e-10 1.29e-09 1.12e-08 5.59e-09 116Sn 4.91e-08 4.18e-08 9.94e-10 4.80e-10 4.93e-09 5.50e-08 118Sn 1.13e-08 1.44e-09 5.04e-09 9.15e-09 7.84e-08 3.43e-09	90Zr	7.06e-09	3.35e-07	7.59e-08	6.65e-07	2.51e-06	2.01e-08
116 Sn 4.91e-08 4.18e-08 9.94e-10 4.80e-10 4.93e-09 5.50e-08 118 Sn 1.13e-08 1.44e-09 5.04e-09 9.15e-09 7.84e-08 3.43e-09	110Cd	4.44e-09	7.05e-09	7.34e-10	1.29e-09	1.12e-08	5.59e-09
¹¹⁸ Sn 1.13e-08 1.44e-09 5.04e-09 9.15e-09 7.84e-08 3.43e-09	116Sn	4.91e-08	4.18e-08	9.94e-10	4.80e-10	4.93e-09	5.50e-08
	118Sn	1.13e-08	1.44e-09	5.04e-09	9.15e-09	7.84e-08	3.43e-09
¹²³ Sb 1.84e-15 1.63e-14 6.81e-10 4.51e-09 4.38e-08 6.83e-16	123Sb	1.84e-15	1.63e-14	6.81e-10	4.51e-09	4.38e-08	6.83e-16

Explosive Yields

Explosive model: 1.4 M_{sun} def-to-det model (Townsley et al. 2016 T1.4),

Element	Atomic number	Ejecter mas $[M_{\odot}]$				
Ga	31	1.36e-06				
Ge	32	6.03e-06				
As	33	8.10e-07				
Se	34	5.00e-06				
Br	35	4.37e-07				
Kr	36	6.66e-06				
Rb	37	1.41e-06				
Sr	38	1.74e-06				
Y	39	3 70s SI				
Zr	40	7.64e-07				
Nb	41	1.63e-09				
Mo	42	5.10e-08				
Tc	43	5.22e-10				
Ru	44	7.29e-09				
Rh	45	5.20e-10				
Pd	46	1.94e-08				
Ag	47	1.48e-10				
Cd	48	1.95e-08				
In	49	1.03e-10				
Sn	50	5.56e-08				
Sb	51	1.41e-09				
Te	52	2.94e-09				
I	53	6.48e-10				
Xe	54	1.20e-08				
Cs	55	1.16e-09				
Ba	56	1.62e-08				
New observable 'smoking gun' of a						
Chandrasekhar explosion? (~10 ⁻⁵ M _{sun} of Sr						
successfully detected in the AT2017gfo						
kilonova, see Watson et al. 2019)						

6

PRE-SUPERNOVA TRANS-FE ABUNDANCES

	Malate	M. LID	MILLIN	Malac	Malan		
	Model E	Model D	Model D	Model C	Model B	Model A	Isotope
EXDIC		$- Ne + \alpha$ Wieschar at al. (2022)					
<u> </u>	2 63 - 02	4 80a 01	4.05 - 01	2.540.01	7.06 02	7.62 02	160
(Tow)	5.050-02	4.0%-01	4.95e-01	6.210.02	1.900-02	1.02e-05	20 N.o.
(1011)	2 200 00	2.81e.05	5.600.06	0.21e-02	8.75e.08	5.04e.00	22No
	1.520.07	2.01c-03	8 120 03	3 120 03	1.260.07	8.65a.08	23No
	6.862.05	6.010-0.0	6.12e-03	2.22-02	2.62-04	1.76-05	24Ma
	7.520.07	1.240.02	1.200.02	5.460.02	2.02e-04	1.110.06	25Mg
	5.600.02	2.070.02	2.040.02	3.406-03	4.550.02	4.780.02	26Mg
	5.096-02	5.110.02	2.94e-02	2.74-02	4.556-02	4.766-02	27 A 1
	3.70e-05	3.110-03	3.000-03	2.746-02	1.266-02	5.12e-05	28 c;
	3.520.01	1 380 06	1.34e.06	2.69e-01	4.24e-01 3.52e 01	3.06e.01	328
	7.08e.08	3.04e.07	5 37e 07	1.23e.06	8.02e-01	3.51e.08	52Cr
	1 77e 08	1.54e 07	2 12e 07	3 550 07	2 320 08	2 200 08	53Cr
	3.262.06	1.540-07	2.120-07	1.610.06	2.526-06	2.20e-08	54Cr
	2.46e-07	7.80e_07	1.02e-06	2.80e-06	2.98e-07	2 37e-07	55Mn
	7.10= 06	2.17e.05	3.07e.05	0.74e.05	1 36e 05	2.10= 06	56Eo
	6770.07	1.020.05	1.400.05	2.780.05	2.000.06	6.020.07	57Eo
	0.776-07	5.340.05	7.540.05	2.766-03	2.096-00	0.926-07	58Eo
	2 200 07	3.06-05	5.630.05	3 270 05	1.020.07	1.470.06	60Ea
	2.20e-07	7.27-05	1.020.04	0.88-05	1.526-07	4.900-00	59Co
	5.66e-07	4.07e-05	5.73e-05	1.99e-05	7.03e-07	5.82e-08	60Ni
'Fe increased	1.25e-07	1.45e-05	1.91e-05	1.58e-05	2.45e-07	4 52e-08	61 Ni
	4 14e-04	8 87e-05	1.00e-04	1.49e-04	4 14e-04	2.96e-04	62Ni
mes compar	4.42e-08	7.16e-05	7.85e-05	4.16e-05	1.10e-06	1.86e-06	63Ni
	7.23e-05	1.28e-04	1.22e-04	7.45e-05	3.76e-05	1.86e-04	64Ni
ases without	3.65e-07	2.85e-05	2.63e-05	1.25e-05	1.96e-07	2.49e-07	65Cu
_	2.60e-07	3.02e-05	2.69e-05	1.62e-05	2.42e-06	3.12e-08	667n
ans-Fe	4 87e-07	5.02e-05	4 14e-05	2.82e-05	7.48e-06	5 99e-07	68Zn
	2.28e-09	1.68e-05	1.27e-05	1.21e-06	2.02e-08	1.12e-08	⁷⁰ Zn
nrichment.	4.69e-10	8.38e-06	6.30e-06	2.25e-06	2.71e-09	4.11e-10	71Ga
	5.26e-09	9.32e-06	7.01e-06	5.86e-06	9.12e-08	4.59e-10	⁷⁰ Ge
	1.99e-06	9.01e-06	6.62e-06	8.68e-06	1.98e-05	8.60e-07	72Ge
	3.16e-10	1.12e-05	8.36e-06	4.75e-06	1.20e-07	1.24e-08	⁷³ Ge
	3.67e-06	1.79e-05	1.27e-05	1.15e-05	1.91e-05	5.63e-06	⁷⁴ Ge
	5.53e-08	1.26e-05	8.25e-06	9.65e-06	1.46e-07	2.97e-07	⁷⁶ Ge
	7.70e-08	4.22e-06	3.03e-06	1.81e-06	1.67e-08	1.44e-09	75As
	4.85e-08	2.96e-06	2.01e-06	8.74e-07	2.53e-07	6.96e-09	⁷⁶ Se
	6.28e-10	1.34e-05	8.94e-06	1.72e-06	2.07e-08	1.32e-09	⁷⁷ Se
ext-generatio	5.62e-06	1.00e-05	6.10e-06	8.77e-06	1.37e-05	3.12e-06	⁷⁸ Se
	2.63e-09	4.65e-06	2.95e-06	3.16e-06	1.29e-07	6.86e-08	⁷⁹ Se
amma-rav	4.59e-06	1.74e-05	1.04e-05	1.01e-05	6.72e-06	1.05e-05	⁸⁰ Se
<u></u>	1.82e-07	1.43e-05	6.54e-06	7.97e-06	5.96e-08	6.25e-07	⁸² Se
elescones	5.64e-07	2.98e-06	1.78e-06	1.53e-06	5.90e-08	1.82e-08	⁸¹ Br
lescopes	2.35e-07	1.38e-06	7.91e-07	6.68e-07	4.42e-07	6.83e-09	⁸² Kr
ave the note	1.06e-08	5.99e-06	3.37e-06	2.05e-06	6.35e-08	2.30e-09	⁸³ Kr
ave the poter	1.31e-05	2.00e-05	1.03e-05	1.31e-05	3.57e-05	5.37e-06	⁸⁴ Kr
	1.86e-05	6.22e-05	2.52e-05	1.90e-05	2.61e-05	2.59e-05	⁸⁶ Kr
o detect a si	2.61e-08	1.21e-05	6.08e-06	6.30e-07	3.05e-09	3.71e-10	⁸⁵ Rb
	3.02e-06	7.67e-06	2.74e-06	3.32e-06	2.44e-06	3.44e-06	⁸⁷ Rb
NR directly!	1.68e-06	1.40e-05	3.82e-06	3.62e-06	3.52e-06	2.27e-06	⁸⁸ Sr
<u> </u>	4.79e-10	5.48e-06	1.46e-06	2.15e-07	5.03e-09	4.20e-10	⁸⁹ Y
	2.01e-08	2.51e-06	6.65e-07	7.59e-08	3.35e-07	7.06e-09	⁹⁰ Zr
	5.59e-09	1.12e-08	1.29e-09	7.34e-10	7.05e-09	4.44e-09	110Cd
	5.50e-08	4.93e-09	4.80e-10	9.94e-10	4.18e-08	4.91e-08	¹¹⁶ Sn
	3.43e-09	7.84e-08	9.15e-09	5.04e-09	1.44e-09	1.13e-08	118Sn
	6.83e-16	4.38e-08	4.51e-09	6.81e-10	1.63e-14	1.84e-15	123Sb

Explosive Yields

Explosive model: 1.4 M_{sun} def-to-det model (Townsley et al. 2016 T1.4),

	Element	Atomic number	Ejecte I_{max} $[M_{\odot}]$
-	Ga	31	1.36e-06
	Ge	32	6.03e-06
	As	33	8.10e-07
	Se	34	5.00e-06
	Br	35	4.37e-07
	Kr	36	6.66e-06
	Rb	37	1.41e-06
	Sr	38	1.74e-06
	Y	39	3.70p 51
reased by ~20	Zr	40	7.64e-07
compared to	Nb	41	1.63e-09
without pro SN	Mo	42	5.10e-08
vitilout pre-si	Tc	43	5.22e-10
elemen	Ru	44	7.29e-09
ent.	Rh	45	5.20e-10
	Pd	46	1.94e-08
	Ag	47	1.48e-10
JL	Cd	48	1.95e-08
	In	49	1.03e-10
neration	Sn	50	5.56e-08
	Sb	51	1.41e-09
<u>-ray</u>	Te	52	2.94e-09
pes will	I	53	6.48e-10
o notontial	Xe	54	1.20e-08
epotential	Cs	55	1.16e-09
<u>ect a single</u>	Ba	56	1.62e-08
ectly!	New ob	oservable 'smo	king gun' of a
	Chandras	ekhar explosion	1? (~10⁻⁵ M_{sun} of Sr
	successfu	illy detected i	n the AT2017gfo
	kilonova.	see Watson et al	. 2019)

6

PRE-SUPERNOVA TRANS-FE ABUNDANCES



Explosive Yields

<u>model</u>: 1.4 M_{sun} def-to-det model et al. 2016 T1.4),

Element	Atomic num	ber Ejected mass $[M_{\odot}]$			
Ga	31	1.36e-06			
Ge	32	6.03e-06			
As	33	8.10e-07			
Se	34	5.00e-06			
Br	35	4.37e-07			
Kr	36	6.66e-06			
Rb	37	1.41e-06			
Sr	38	1.74e-06			
Y	39	3.705 51			
Zr	40	7.64e-07			
Nb	41	1.63e-09			
Mo	42	5.10e-08			
Tc	43	5.22e-10			
Ru	44	7.29e-09			
Rh	45	5.20e-10			
Pd	46	1.94e-08			
Ag	47	1.48e-10			
Cď	48	1.95e-08			
In	49	1.03e-10			
Sn	50	5.56e-08			
Sb	51	1.41e-09			
Te	52	2.94e-09			
I	53	6.48e-10			
Xe	54	1.20e-08			
Cs	55	1.16e-09			
Ba	56	1.62e-08			
New ol	oservable '	smoking gun' of a			
Chandrasekhar explosion? (~10 ⁻⁵ M of Sr					
successfully detected in the Al 2017gfo					
kilonova see Watson et al 2010)					

Summary and future perspectives

- As our slowly merging CO WDs models approach the Chandrasekhar mass, C-burning ignites on the surface before it does in the center → ¹²C(¹²C, α)²⁰Ne → ²²Ne(α, n)²⁵Mg.
- Large production of trans-Fe elements in the outermost $\sim 0.04 M_{\odot}$ to $\sim 0.11 M_{\odot}$. Something similar happens also in the case of in near-Ch WD from H-accreting systems (see Battino+2020).
- Kr, Rb and Sr overproduced by up to ~1000 times compared to solar, Ga, Ge, Se, Kr, Rb, and Sr are all ejected in high amounts (>10⁻⁶ M_{\odot}) during the explosion.
- A new observable 'smoking gun' of a Chandrasekhar explosion? It's highly possible trans-Fe elements from SNIa can only be produced by near-Chandrasekhar events → New way to constrain the progenitors? (Synthetic spectra from radiative transfer needed)
- Can we see this? Great deep and all-sky surveys are about to start! (LSST, 4MOST-TiDES)
- ⁶⁰Fe increased by a factor of ~20 compared to what is obtained from models without the inclusion of pre-SN trans-Fe element enrichment → Potential good case for nextgeneration gamma-ray telescopes

Summary and future perspectives

• As our slowly merging CO WDs models approach the Chandrasekhar mass, C-burning ignites on the surface before it does in the center $\rightarrow {}^{12}C({}^{12}C, \alpha){}^{20}Ne \rightarrow {}^{22}Ne(\alpha, n){}^{25}Mg$.

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Trans-Fe elements from Type la Supernovae

I. Heavy element nucleosynthesis during the formation of near-Chandrasekhar white dwarfs

U. Battino,^{1,2,3} J. D. Keegans,^{4,3} M. Allen,^{4,5} F. K. Röpke,^{6,7,8} F. Herwig,^{9,10,3} A. Best,^{1,11} R. Hirschi,^{12,3} L. Piersanti,^{2,13} O. Straniero,^{2,13} S. A. Sim,¹⁴ C. Travaglio,¹⁵ and P. A. Denissenkov^{9,10,3}

 ⁶⁰Fe increased by a factor of ~20 compared to what is obtained from models without the inclusion of pre-SN trans-Fe element enrichment → Potential good case for nextgeneration gamma-ray telescopes

7 Full results in Battino et al. 2025 (Submitted to A&A)



Thank you!!



C-burning flame propagation





8.5