Beta-Decay Effects on r-Process Nucleosynthesis in Neutron Star Mergers

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NSF Physics Frontier Award number #2020275

Motivation

The rapid neutron-capture process (r-process) is responsible for creating nearly half of the heavy elements found in the universe. The precise role played by nuclear physics inputs—such as β-decay rates—in shaping the final abundance pattern still remains uncertain. This study aims to investigate the impact of modified β-decay rates on r-process nucleosynthesis during a neutron star merger (NSM) event.

Theory

- The r-process (rapid neutron capture) occurs in high neutron density and temperature.
- Nuclei rapidly absorb neutrons and undergo β-decay to stabilize.
- β-decay rates control how quickly isotopes move toward stability — directly affecting element formation.
- Simulations rely on theoretical β-decay models due to lack of experimental data for neutron-rich nuclei.

Methods and Data

- Used PRISM to simulate 30 tracer particles from a high magnetic field neutron star merger (NES model).
  - Ran two sets of simulations:
    - One with standard Möller et al. (2003) β-decay rates
    - One with modified β-decay rates (reduced half-lives in neutron-rich regions)
  - Analyzed final abundances and β-decay rates
  - Compared results by averaging over all tracers and plotting differences in Y(A), decay rates, and isotope distributions.

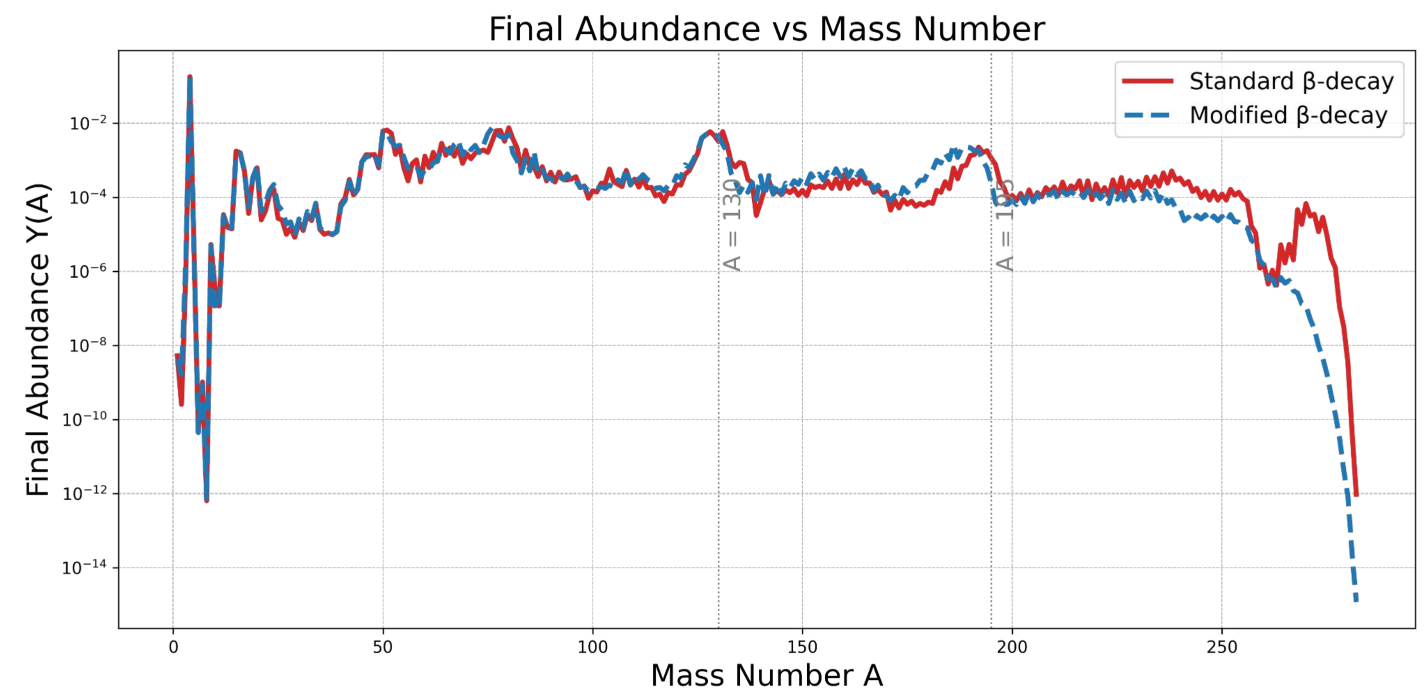

Figure 1: Final abundances (Y(A)) vs mass number A, averaged over 30 tracers. Solid line shows standard β-decay; dashed line shows modified rates. Key features such as the rare-earth peak and third peak are shifted under modified decay rates.

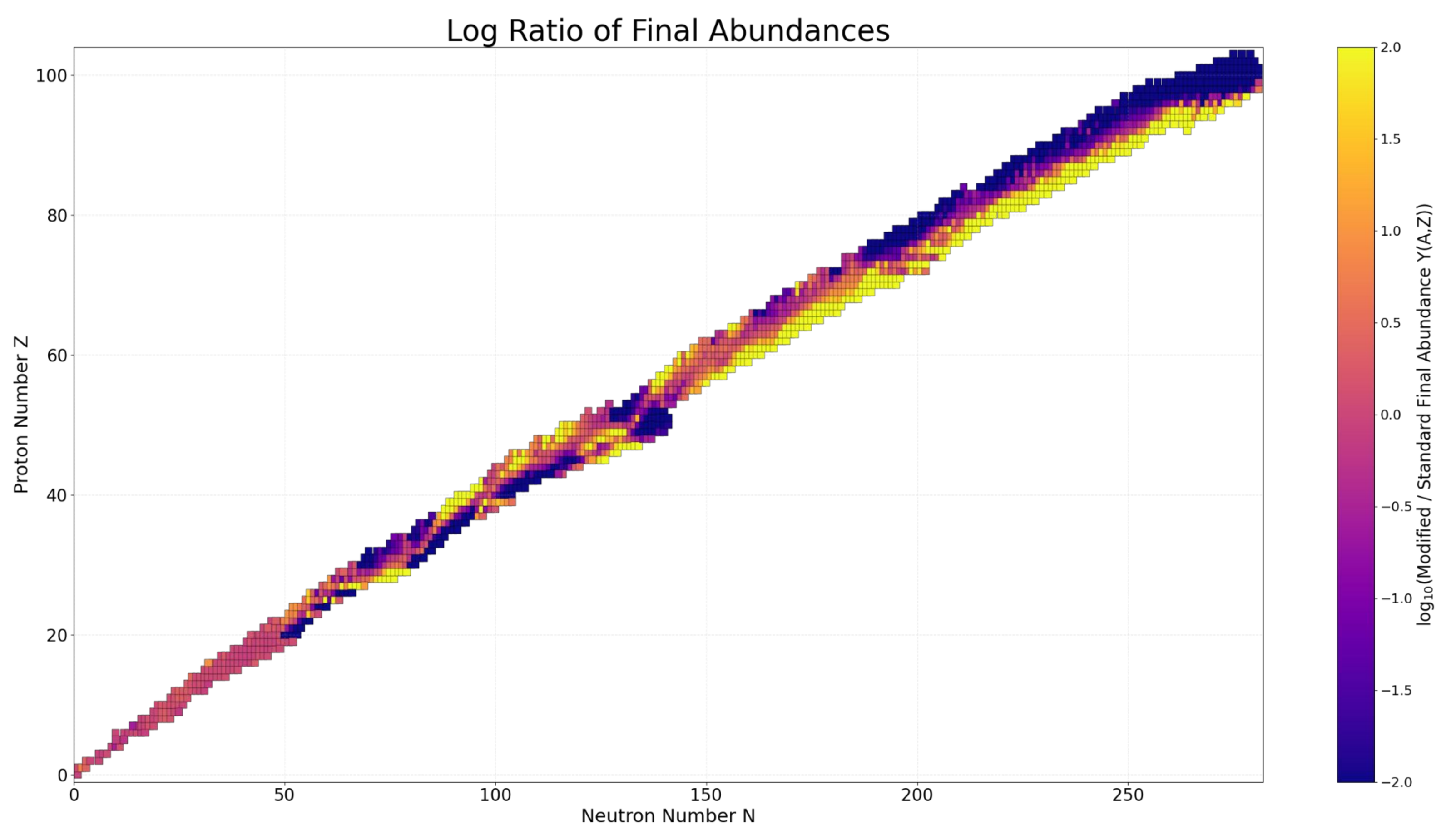

Figure 2: Logarithmic ratio of final abundances between modified and standard datasets from a high magnetic field neutron star merger simulation (NES model). Yellow regions reflect significantly more production under modified β-decay rates based on the methodology of Lund et al. (2023).

Results

- Modified β-decay rates produced notable differences in the heavy-mass region (A > 200).
- The final abundance peak near A ≈ 195 is broadened and shifted.
- Logarithmic comparison of β-decay rates (Z, N) shows a systematic speed-up in decay times across neutron-rich nuclei.
- Modified rates increase the speed of matter flow back to stability, shortening the freeze-out period.

Conclusion

- β-decay physics has a measurable impact on r-process abundance patterns.
- This effect is most pronounced in heavy nuclei beyond the second r-process peak.
- Future models should explore broader nuclear datasets and uncertainty quantification.

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References:

Lund, K., et al. "Impact of nuclear data on r-process nucleosynthesis." *Astrophysical Journal*, 2023.

Möller, P., et al. "Nuclear Ground-State Masses and Deformations." *At. Data Nucl. Data Tables*, 2003.

Eichler, M., et al. "Impact of β-decay rates on r-process nucleosynthesis." *Astrophysical Journal*, 2015.

Vassh, N., et al. "Using nuclear theory for r-process simulations." *Journal of Physics* G, 2019.