Impact of electron-captures on nuclei near N=50 on core-collapse supernovae

Rachel Titus
Nuclei in the Cosmos XV
Outline

• Introduction
• Weak rate library
• Sensitivity study of N=50 region
• Experimental program
• Conclusions
Introduction

• Weak rates – important nuclear physics inputs to astrophysical simulations
  • Stellar nucleosynthesis
  • Core-collapse and thermonuclear supernovae
  • Neutron star mergers
  • Neutron star crust processes
  • …

• Electron capture rates are of particular interest

**Introduction**

- Electron-capture rates on nuclei
  - Depend on stellar temperature and density
  - Include transitions from excited states due to finite temperature in stars (green)
- Dominated by Gamow-Teller transitions
  - Characterized by a $Q$-value and a strength, $B(GT)$
  - Only a fraction, if any, of the transitions can be measured directly – low-lying excited states
  - Rely on theoretical models for additional transitions
- Charge-exchange experiments
  - No limitations due to the $Q$-value window, compared to $\beta$-decay

\[
\lambda_{EC} = \ln 2 \sum_{ij} f_{ij}(T, \rho, U_F) B(GT)_{ij}
\]
Weak rate library

• Initially published in 2016; continually updated with new rate tables

• Electron capture rates from a variety of sources
  • Theoretical calculations
    • Shell model, Monte Carlo shell model, independent particle model
  • Approximation
  • Experimental data
    • Charge-exchange experiments

• Good coverage of the chart of nuclides for the valley of stability and low-mass nuclei

• Available as part of NuLib or as plain ASCII tables

• First application of the library is in the sensitivity study of core-collapse supernovae

[1] https://groups.nscl.msu.edu/charge_exchange/weakrates.html
Sensitivity study

• High-impact region of electron-capture rates, centered on the N=50 shell closure, cause the largest change in electron fraction

• Goal: to determine the effect of nuclei in this high-sensitivity region on the late stages of core-collapse

• Method: scale electron capture rates by different factors to determine the magnitude of such a change on parameters from the simulation
  • Scaling factors based on the systematic uncertainty in the rates in this region

Weak rate library

- For nuclei without calculated electron capture rates, an approximate method is used

- Single B(GT) and excitation energy
  - Based on fits to middle-mass, mid-shell, stable nuclei (LMP table)

- Often extrapolating to high-mass nuclei, highly unstable nuclei, and those nuclei lying on a shell closure
  - Does not account for Pauli blocking
  - Overestimate electron-capture rates by an order of magnitude or more

---

Sensitivity study

- Scaling factors x10, x0.1, x0.01
  - Scale rates of all nuclei participating in the simulation (blue lines)
  - Scale rates of 74 nuclei in the high-sensitivity region (red lines)

- Lepton fraction as a function of core density (=time)
  - Electron capture rates affect the speed of the deleptonization of the core
  - Lower EC rates yield a higher lepton fraction

- Nuclei in the high-sensitivity region account for 50% of the difference in the final lepton fraction

Sensitivity study

• Conclusion: electron capture rates for 74 nuclei in the high-sensitivity region have a high impact on the dynamical evolution of the core-collapse supernova simulation
  • Lepton fraction, electron fraction, entropy, density, in-fall velocity, neutrino luminosity
  • Using an inaccurate rate approximation can have a noticeable effect on the simulation
  • Calculating/measuring these rates accurately is imperative to understanding the late stages of core collapse
• Further experimental analysis of this region is required
  • Validate and benchmark current theoretical models
  • Guide future theoretical development

Experimental program

• Charge exchange reactions are effective for extracting Gamow-Teller strength
  • Probes: (t,^3He), (n,p), (d,^2He)
• (t, ^3He) experiments performed at the National Superconducting Cyclotron Laboratory
  • ^86Kr (R. Titus), ^88Sr (J. Zamora)
  • ^93Nb (B. Gao), ^100Mo (K. Miki)

[Image of reaction diagrams]

Experimental program

- $^{88}\text{Sr}(t,^3\text{He}+\gamma)$ experimental results
  - Very little Gamow-Teller strength measured (L=0 in red)
  - Calculated electron-capture rates smaller than the approximate method by 2 orders of magnitude
  - Indicate strong overestimation of EC rates in the current simulation

- Tentatively, similar results from the $^{86}\text{Kr}$ analysis
Experimental program

- Many of the nuclei of interest for nuclear astrophysics are unstable
- \((d,^2\text{He})\) charge-exchange reaction in inverse kinematics: probe for electron-capture rates on unstable isotopes
  - Active Target Time Projection Chamber (AT-TPC) in conjunction with the S800 magnetic spectrometer
  - Measure Gamow-Teller strength for nuclei pertinent to astrophysics

AT-TPC and the S800 at the NSCL
Conclusions

- Electron-capture rates are used as inputs in simulations of many astrophysical phenomena.
- Electron-captures on nuclei near the N=50 shell closure have a large effect on the behavior of core-collapse supernova simulations.
  - Nuclei predominately have their EC rates approximated.
  - Likely overestimating rates and introducing large uncertainties into the simulation.
- Necessary to obtain accurate rates for nuclei in the high-sensitivity region.
  - Development of new theoretical models and rate sets.
  - Charge-exchange experiments to benchmark current theories.
- Good nuclear physics inputs yield more accurate representation of core-collapse supernovae and other phenomena.
Acknowledgements

• This work was supported in part by the National Science Foundation
  • Grant No. PHY-1565546 (National Superconducting Cyclotron Laboratory)
  • Grant No. PHY-1430152 (JINA Center for the Evolution of the Elements)
• GRETINA was funded by the US DOE Office of Science. Operation of the array at NSCL is supported by NSF under Cooperative Agreement PHY-11-02511 (NSCL) and DOE under grant DE-AC02-05CH11231 (LBNL)
• Experimental Collaboration
  • R. G. T. Zegers
  • J. Zamora
  • B. Gao
  • J. Schmitt
  • S. Lipschutz
  • C. Sullivan
  • B. A. Brown
  • D. Bazin
  • S. Noji
  • J. Pereira
  • A. Gade
  • D. Weisshaar
  • B. Elman
  • B. Longfellow
  • E. Lunderberg
  • J. Belarge
  • P. Bender
  • T. Mijatovic
Extras
• Rate tables
Red = krypton isotopes
Blue = N=50 nuclei
Black = B(GT) for the approximation, 4.6
Credit to Juan Zamora