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Reaction Rate Sensitivity of ^{44}Ti Production in Massive Stars and Implications for a Thick Target Yield for ^{40}Ca(α,γ)^{44}Ti

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The dynamic synergy between observation, theory, and experiment developed over many years around the field of γ-ray astronomy has as its ultimate goal observations of specific radionuclides informing our understanding of stellar explosions and the theoretical models that predict nucleosynthesis. Observations of ^{56,57}Ni and their decay products ^{56,57}Co are used in many ways to constrain our current models of the core collapse mechanism. The radionuclide ^{44}Ti ($\tau_{1/2}$ = 58.9 +- 0.3 yr), made in the same explosive environment but in much lower amounts compared to the very abundant nickel isotopes, is hoped to one day serve as an even more sensitive diagnostic and a valuable probe to the conditions extant in some of the deepest layers to be ejected. We [1] investigate ^{44}Ti nucleosynthesis in adiabatic expansions from peak conditions drawn from a model for Cassiopia A and determine variations due to experimental uncertainties in two key reaction rates. We find that the current uncertainty in these two rates could lead to as large a variation in ^{44}Ti synthesis as that produced by different treatments of stellar physics in historical models of SNII.

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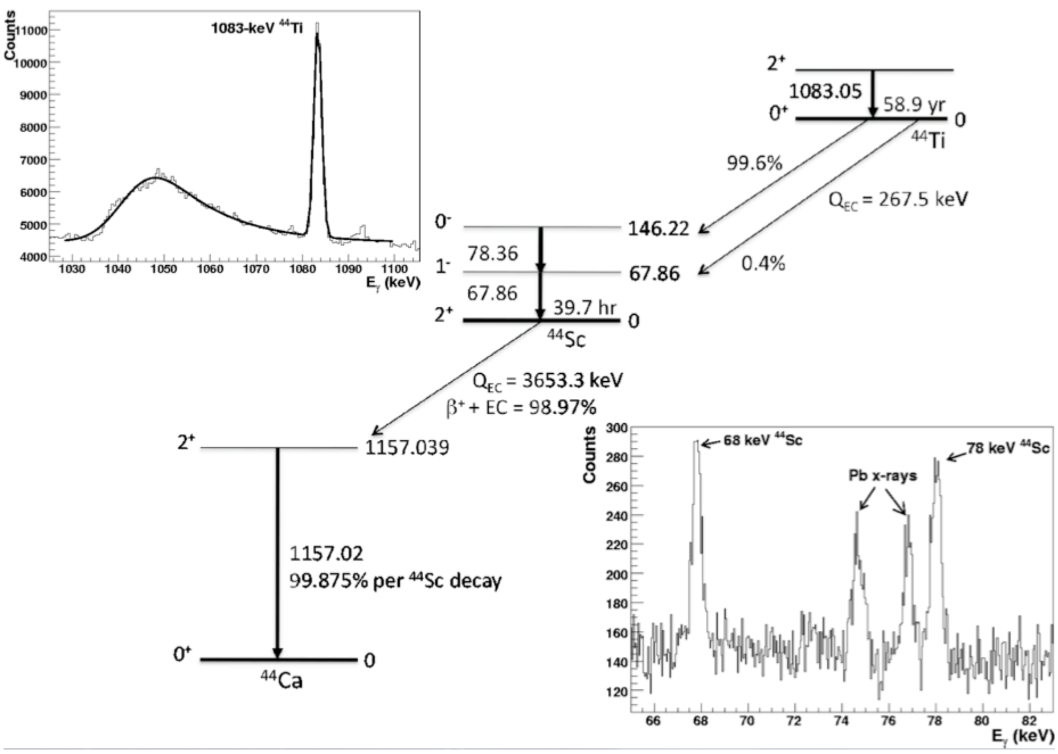
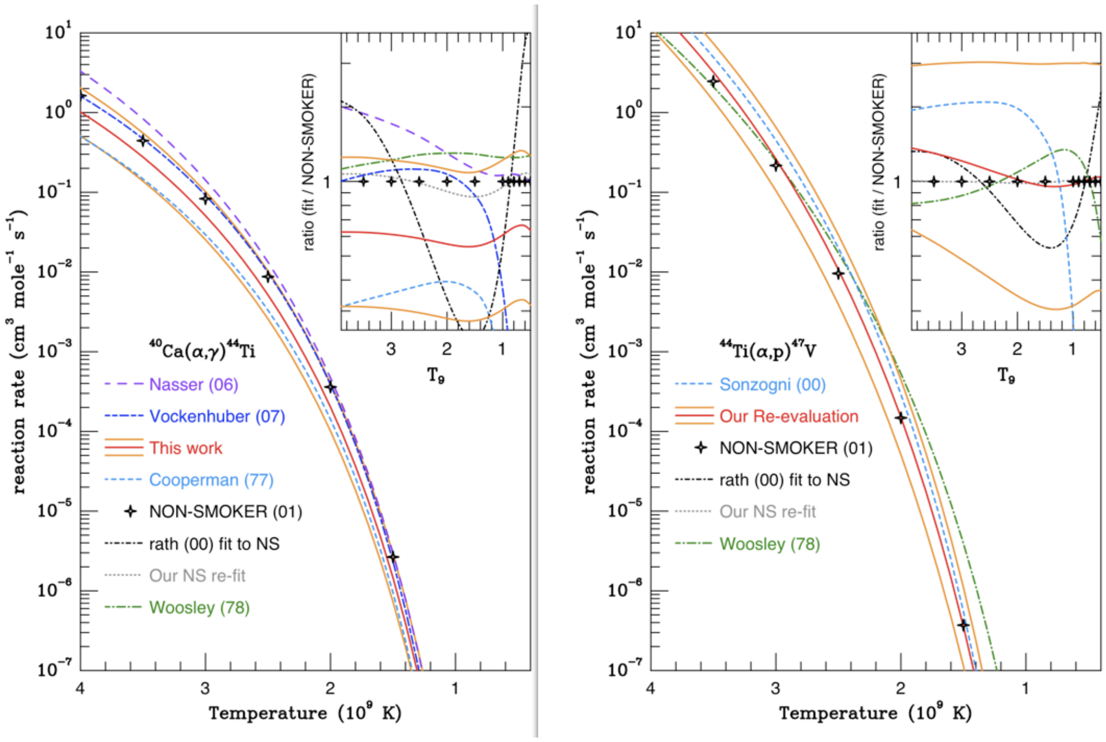
1. Experimental Methods

We developed the cross section for ^{40}Ca(α,γ)^{44}Ti by two separate methods as a check on systematic uncertainties. First we used in-beam γ-ray spectroscopy to measure a thick target yield. We then determined the number of ^{44}Ti nuclei produced by counting low-energy γ-ray's from the decay of an irradiated target. We have also re-evaluated the stellar reaction rate for the dominant destruction reaction, ^{44}Ti(α,p)^{47}V, based on the original experimental work of Sonzoni [2] and the theoretical cross section work of Rauscher and Theilemann [3].



Shown above is the partial decay scheme of ^{44}Ti and its daughter ^{44}Sc. Also shown (upper left) is the partial HPGe γ-ray spectra at E_α = 5.36 MeV with a simultaneous fit to the 1039 keV ^{70}Ge and 1083 kev ^{44}Ti γ-rays, and the γ-ray spectra observed in a two week low background count of the activated target bombarded at E_α = 5.36 MeV (lower right).

At this energy both the on-line and off-line results indicated that a factor of 1.71 reduction in the NON-SMOKER [3] theory cross section for ^{40}Ca(α,γ)^{44}Ti would reproduce our thick target yield. We also determined that a 20% increase in the NON-SMOKER theory cross section for ^{44}Ti(α,p)^{47}V would agree within errors with the experimental data measured by Sonzoni [2]. Since both experimental efforts only measured data outside the relevant Gamow windows for the stellar temperature range important for ^{44}Ti production ($2 < T_9 < 4$), our derived reaction rates exhibited large error bars which were dominated by the uncertainty on the theory cross sections in this important energy range ($2 < E_\alpha < 5$ MeV).



Reaction Rates

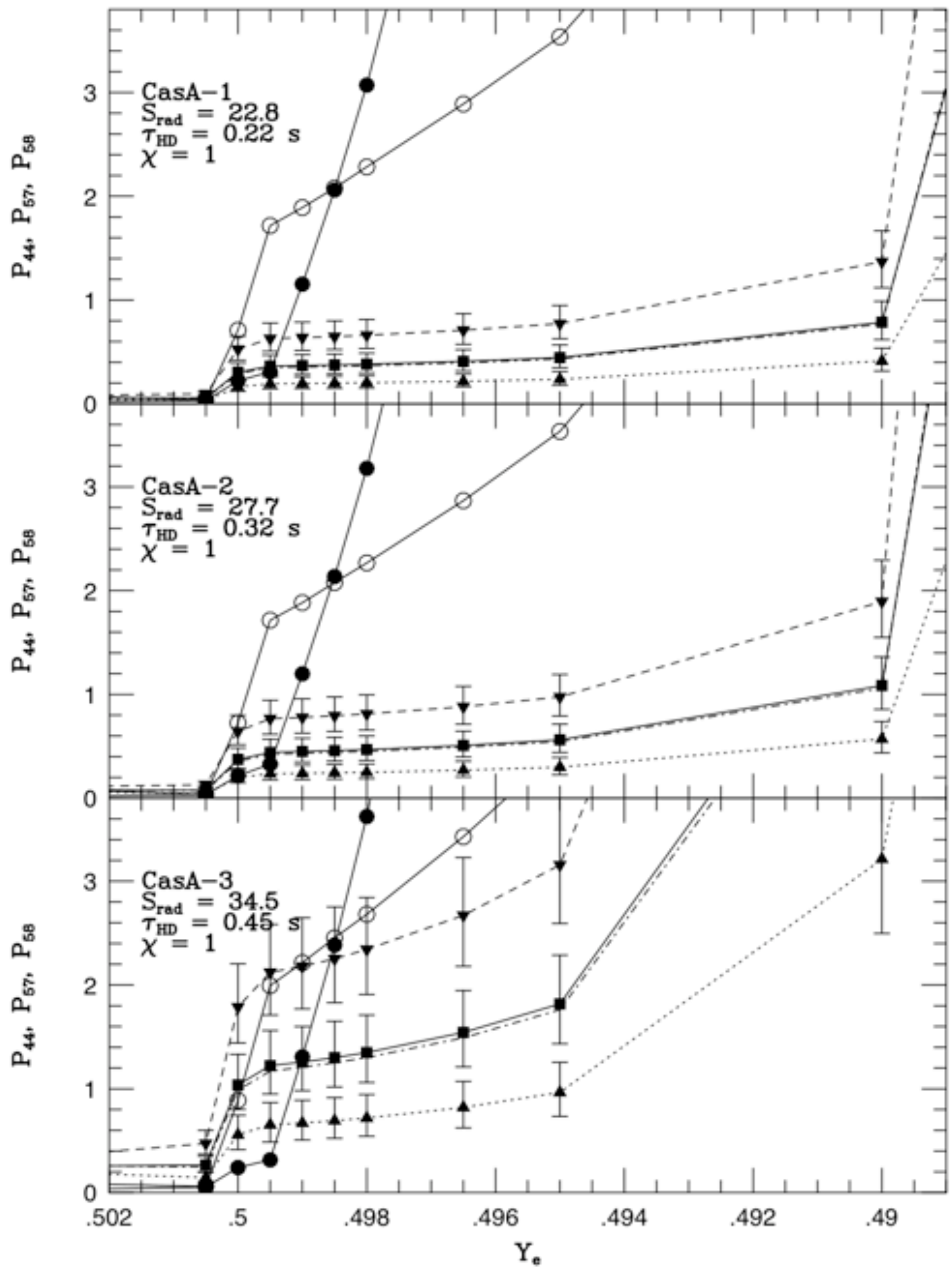
Shown above are fits to reaction rates used in this study. Solid lines denote experimental rates from various authors, dashed and dot-dashed lines represent various theory efforts. The tabulated NON-SMOKER [3] rates are denoted by crosses. The insets illustrate the ratio of each rate to the NON-SMOKER theory rate.

Nucleosynthesis

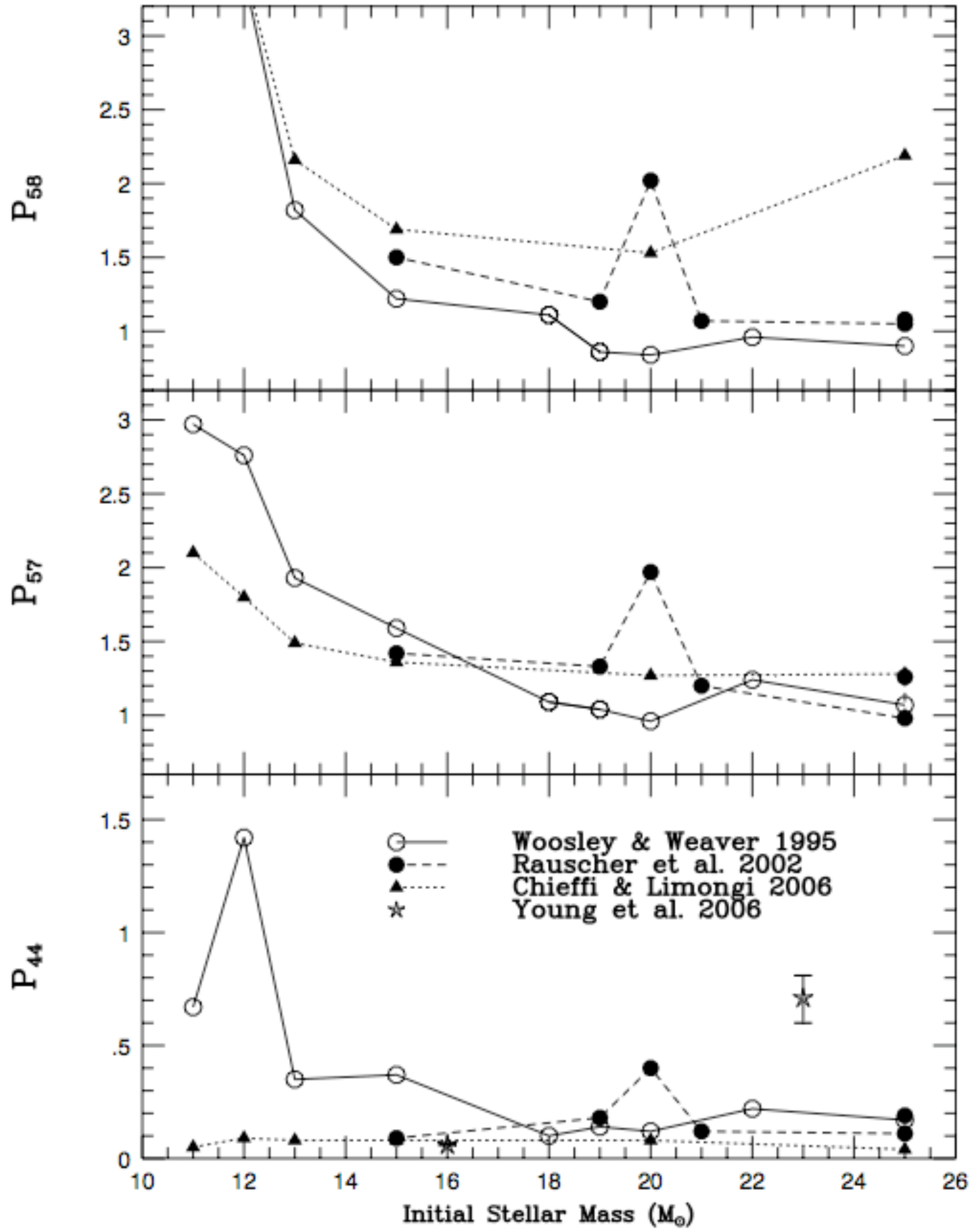
From a model for CasA [4] we study expansions from peak conditions shown in the Table below. For each (T_{9p},ρ_p) we calculate the hydrodynamic time scale $\tau_{HD} = 446\chi\rho^{-1/2}$ and the radiation entropy $S_{rad} = 3.33 T_{9p}^3/\rho_p$. For a given electron mole number (Y_e) we then calculate an initial composition composed of nucleons and α-particles and expand the material adiabatically until the temperature declines to $T_9 < 0.25$. Our results will be presented as "Normalized Production Factors", i.e. ratios of traditional production factors for ^{57,58}Ni and ^{44}Ti (e.g. $X(^{44}Ti)/X(^{44}Ca)_{sun}$) divided by that for the dominant species of iron ($X(^{56}Ni)/X(^{56}Fe)_{sun}$).

Nucleosynthesis Survey: Peak Initial Conditions

Point	Model	T_{9p} (10^9 K)	ρ_{7p} (10^7 g cm^{-3})	S_{rad} (k^{-1})	τ_{HD} (s)	$t_{\chi=1}$ (s)	$\tau_{HD} \times 5$ (s)	$t_{\chi=5}$ (s)
1	CasA	6.5	0.4	22.8	0.22	2.1	1.10	10.8
2	CasA	5.5	0.2	27.7	0.32	2.9	1.60	14.3
3	CasA	4.7	0.1	34.5	0.45	3.9	2.25	18.0



Shown above are normalized production factors vs. electron mole number for the three points in Table 1. Each central point represents a calculation that utilizes our recommended (production) rate for ^{40}Ca(α,γ)^{44}Ti for three choices of ^{44}Ti(α,p)^{47}V (destruction) rate. Solid line type and filled squares represent our recommended destruction rate, filled triangles represent its upper (dotted) and lower (dashed) bound. The error bars on each central point reflect the minimum and maximum deviations of P_{44} due to the six other production rates used. Taken together, the uncertainties due to production and destruction rates translate into variations in ^{44}Ti nucleosynthesis that are as large as those calculated in historical models of SNII that used very different treatments of stellar physics (see below).



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