Sensitivity of ^{44}Ti production in massive stars to the ^{40}Ca(α,γ)^{44}Ti and ^{44}Ti(α,p)^{47}V reaction rates

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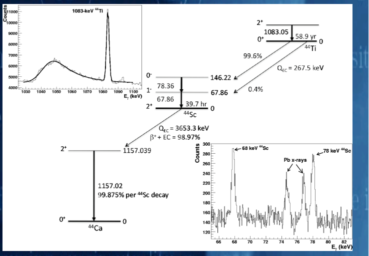
Introduction: The dynamic synergy between observation, theory, and experiment developed over many years around the field of γ-ray astronomy has as its ultimate goal observations of specifc radionuclides informing our understanding of stellar explosions and the theoretical models that predict nucleosynthesis. 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 explosion 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 nickle isotopes, is hoped to one day serve as an even more sensitive diagnostic and a valuable probe of 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.

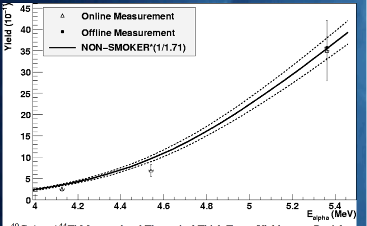
Experimental Methods

We develop 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, then determined the number of ^{44}Ti nuclei produced by counting low-energy γ-rays from the decay of ^{44}Ti in an irradiated target. We have made a similar evaluation of 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 & Thielemann[3].

^{40}Ca(α,γ)^{44}Ti



Partial decay scheme of ^{44}Ti and its daughter ^{44}Sc. Also shown 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.

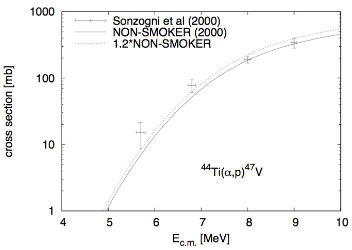


^{40}Ca(α, γ)^{44}Ti Measured and Theoretical Thick Target Yields per α Particle on Target

E_α (MeV)	Y_{1083} (10^{-11})	$Y_{^{44}\mathrm{Ti}}$ (10^{-11})	Y_{theory} (10^{-11})	Y_{offline} (10^{-11})
4.13	2.11 ± 0.40	2.53 ± 0.50	5.96	
4.54	5.72 ± 1.1	6.86 ± 1.4	16.4	
5.36	29.2 ± 5.7	35.0 ± 7.1	61.0	35.7 ± 2.5

Notes. Y_{1083} is the measured yield for the 1083 keV γ-ray, $Y_{^{44}Ti}$ is the total yield for the production of ^{44}Ti, and Y_{theory} is the thick target yield calculated from Equation (2) assuming the theory cross section of Rauscher & Thielemann (2001). Y_{offline} is the yield from our activation measurement of the target irradiated at 5.36 MeV.

^{44}Ti(α,p)^{47}V



Experimental data from Sonzoni[2] et al vs. NON-SMOKER[3] theory cross sections. Within errors, a 20% increase in the theory cross section agrees with experiment. To develop reaction rates we use both the experimental data and its errors along with normalized NON-SMOKER[3] cross sections outside of the measured energy range and integrate the cross section over a Maxwell Boltzmann distribution.

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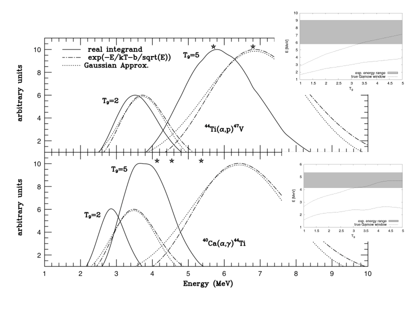
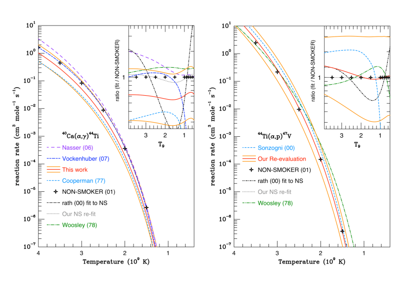
The Gamow Window



Effective Gamow windows at T_9 = 2 & 5 for ^{40}Ca(α,γ)^{44}Ti and ^{44}Ti(α,p)^{47}V as given by the real integrand of the reaction rate formula, the product of the high-energy tail of the Maxwell-Boltzmann distribution with the simple Coulomb barrier penetration factor and the usual Gaussian approximation to the latter. The insets show the windows vs. T_9 and the energy ranges over which experimental data were measured in our effort[1] and Sonzoni[2]. Neither experiment fully samples the relevant energy range (E_α = 2-5 MeV) for ^{44}Ti synthesis (T_9 = 2-4). The Gaussian approximation is widely used to estimate the Gamow window but often predicts it at too high an energy, especially for the α-capture reaction[4]. Consequently, reaction rate uncertainties will be dominated by the theory cross sections that supplement the experiments outside the measured energy range.

Reaction Rates



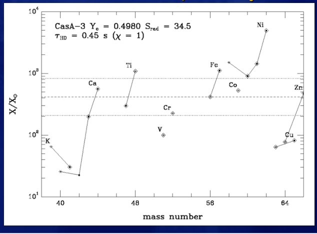
Fits to reaction rates for ^{40}Ca(α,γ)^{44}Ti and ^{44}Ti(α,p)^{47}V considered in this study. Solid and dashed line types denote experimental rates from various authors[6-8], dotted and dot-dash line types are from various theory efforts. The tabulated NON-SMOKER theory rate[5] is denoted by crosses. Our recommended rates[1] (and their errors) are shown as solid lines. The inset illustrates the ratio of each reaction rate to the NON-SMOKER theory rate[5].

Nucleosynthesis

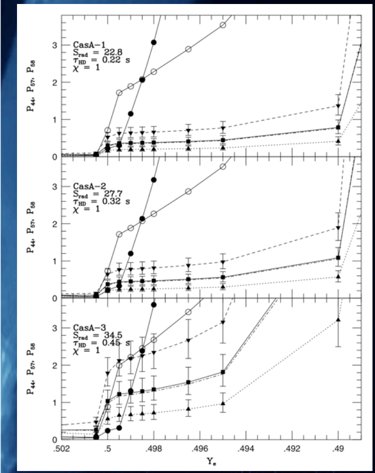
Nucleosynthesis Survey: Peak Initial Conditions

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)	$\tau_{\mathrm{HD}} \times 5$ (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

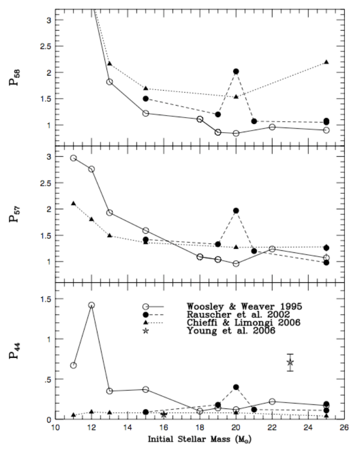
From each set of peak conditions above we calculate the hydrodynamic time scale τ_{HD} = 446$\chi/\rho_p^{1/2}$ and the radiation entropy S_{rad}=3.33T_{9p}/ρ_{5p}. We then assume an initial composition composed of nucleons and α–particles and expand the material adiabatically until the temperature declines to T9 < 0.25. Production factors for the CasA-3 expansion at Y_e=0.498 are below.



Sensitivity Survey



Normalized production factors (the ratio of the usual production factor to that of ^{56}Fe) versus electron mole number Y_e for adiabatic freeze outs from peak conditions defined for points CasA 1-3. Each central point represents a calculation that utilizes our recommended[1] ^{40}Ca(α,γ)^{44}Ti (production) rate 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 for all three surveys reflect the minimum and maximum deviations of P_{44} due to the six other choices[6-9] of ^{40}Ca(α,γ)^{44}Ti reaction rate considered. The variations in normalized production factors due to ^{40}Ca(α,γ)^{44}Ti (x1.5) and ^{44}Ti(α,p)^{47}V (x3.2) are as large as those between historical SNII models[10-13] which utilized very different stellar physics.



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