^{40}Ca(α,γ)^{44}Ti and the production of ^{44}Ti in supernovae

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Abstract. The nuclide ^{44}Ti is predicted to be produced in significant quantities in core-collapse supernovae, and indeed it has been observed in the supernova remnant Cassiopeia-A by space-based γ-ray telescopes. The main production of ^{44}Ti takes place in the α-rich freeze-out phase deep inside the supernova. The key reactions governing the ^{44}Ti abundance have been identified in an earlier sensitivity study. Using the recoil mass spectrometer DRAGON at the TRIUMF-ISAC facility in Vancouver, Canada, we measured the main production reaction ^{40}Ca(α,γ)^{44}Ti, resulting in an increased reaction rate compared to the rate derived from previous prompt γ-ray studies, which is commonly used in supernova models. The uncertainty of the ^{44}Ti production is now dominated by the rate of reactions with short-lived nuclides around ^{44}Ti, namely ^{45}V(p,γ)^{46}Cr, ^{44}Ti(α,p)^{47}V and ^{44}Ti(α,γ)^{48}Cr. The sensitivity of these reactions on the ^{44}Ti production has been revisited.

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1. Introduction

^{44}Ti ($t_{1/2} = 58.9 \pm 0.3$ yr [1]) is one of the few short-lived radionuclides which has been detected in space by γ-ray astronomy with COMPTEL [2], BeppoSAX [3] and later with INTEGRAL [4], and thus confirms ongoing nucleosynthesis in our Galaxy. Since it is predicted to be produced predominantly in core-collapse supernovae during the α-rich freeze-out deep inside the supernova near the mass-cut, its measured abundance can be used to constrain supernova models. It has also been attempted to search for previously undiscovered young supernova remnants by γ rays from the decay of ^{44}Ti; however, even with the improved sensitivity of INTEGRAL, only Cassiopeia-A has shown a signal significantly above the background to date [4]. This is in strong contrast with expectations from galactic supernova rates of a few SN per century [5], which indicates large uncertainties in our understanding of supernova explosions and/or the nuclear reactions relevant for ^{44}Ti production.

In a sensitivity study The *et al.* [6] identified several reactions which are important for the understanding of the production of ^{44}Ti. In particular the reactions around the nuclide ^{44}Ti have a large influence, namely ^{40}Ca(α,γ)^{44}Ti, ^{45}V(p,γ)^{46}Cr, ^{44}Ti(α,p)^{47}V and ^{44}Ti(α,γ)^{48}Cr.

The first reaction, ^{40}Ca(α,γ)^{44}Ti, has been studied partly in the past by non-inverse prompt γ-ray measurements [7, 8, 9, 10]. A recent integrated cross-section measurement over a larger temperature regime, by off-line counting of ^{44}Ti nuclei with accelerator mass spectrometry (AMS), showed a significantly larger ^{44}Ti yield compared to the prompt γ-ray data [11]. In order to solve this discrepancy we performed a detailed study in the relevant temperature regime of $T_9 \sim 1-2.8$ at the recoil mass spectrometer DRAGON, located at the TRIUMF-ISAC facility in Vancouver, Canada [12]. Results of this measurement are presented in the first part of the paper.

In the other three reactions unstable nuclides are involved, and thus they can only be studied at radioactive beam facilities. No experiments at the relevant energies are available right now, but plans for measurements at the TRIUMF-ISAC facility are underway. The sensitivity of the ^{44}Ti production in the α-rich freeze-out was revisited, which helps to identify the reactions and energies of interest. This is described in the second part of the paper.

2. Measurement of ^{40}Ca(α,γ)^{44}Ti at DRAGON

A high-purity ^{40}Ca beam (less than 1% ^{40}Ar contamination) was produced in a microwave ion source and accelerated by ISAC accelerators [a radio frequency quadrupole (RFQ) accelerator and a drift-tube linac (DTL)] to the required energies of 600 to 1150 keV/nucleon. Typical currents on target were around $1-2$ pnA.

The recoil mass spectrometer DRAGON was specially designed to reach high enough suppression of beam particles in order to detect the few recoils from radiative capture reactions at astrophysical energies [13]. It consists of a windowless gas target followed by a two-stage spectrometer based on magnetic and electrostatic dipoles with magnetic quadrupole and sextupole elements for focusing. Beam suppression factors depends on many parameters and ranges from 10^7 to 10^{13} [14]. The recoils are finally detected in an ionization chamber equipped with a thin entrance window and a segmented anode for isobaric identification. The gas target is surrounded by a high-efficiency γ-ray detector array consisting of 30 BGO scintillators. In order to improve the identification of the ^{44}Ti recoils, we use a coincidence between γ-ray detection at the BGO array and heavy-ion detection at the ionization chamber. Additionally, a narrow time-of-flight window and cuts on energy-loss signals allow a clear identification of the ^{44}Ti recoils (see Fig. 3 of Ref. [12]). Because of the higher masses involved in this reaction, we had to add a thin 100 nm silicon nitride foil after the gas target [called the charge-state booster (CSB) foil] in order to reach high enough charge states to be bent by the spectrometer [15].

The yield of ^{44}Ti, which is the number of recoils per incoming projectile, is measured as a function of initial beam energy and gas-target thickness:

$$Y = \frac{N_{44\mathrm{Ti}}}{N_{40\mathrm{Ca}}\ F_q\ \epsilon}\ . \tag{1}$$

$N_{44\mathrm{Ti}}$ denotes the detected recoils in a particular charge state and in most cases in coincidence with a high-energy γ ray detected at the BGO array (called here "coincidences" as opposed to "singles" which means recoil detection only). The number of incoming beam particles $N_{40\mathrm{Ca}}$ is calculated based on detection of elastically-scattered He atoms in a solid-state detector placed at 57° and normalization to an upstream Faraday cup. The charge-state fraction of the ^{44}Ti recoils, F_q, have been measured with a stable ^{48}Ti beam at four energies which cover the same velocity (or energy-per-nucleon) range. The detection efficiency ϵ includes the transmission through the spectrometer and the efficiency of the end detector; both are close to 100%. For coincidences, ϵ also includes the efficiency of the BGO-detector array determined from singles to coincidence ratios of high-yield runs and GEANT3 simulations.

Depending on the pressure in the gas target, the beam loses between 2.8 keV/nucleon at 1 Torr (corresponding to a target thickness of 2.9 μg/cm^2) and 22.8 keV/nucleon at 8 Torr. In order to cover the large energy range with a reasonable resolution, we decided to measure most of the time with a pressure of 4 Torr. The energy steps were chosen to overlap slightly in order not to miss any narrow resonances. At lower energies (below 850 keV/nucleon) we decided to measure at 8 Torr and without the CSB foil. This was motivated because at the lower energies the most probable charge states with the CSB foil are close to 11^+, where beam suppression in the spectrometer is strongly reduced because of A/q ambiguities [15]; without the CSB foil we could measure at 9^+ and 10^+. However, more overlap was necessary because a target thickness of $3-4$ μg/cm^2 is necessary to reach charge-state equilibrium. This is important, otherwise the charge-state distribution would depend on the position of the reaction along the path in the gas target; ^{44}Ti recoils which originate from a reaction at the first section of the gas target (i.e. at the higher section of the covered energy range) are likely

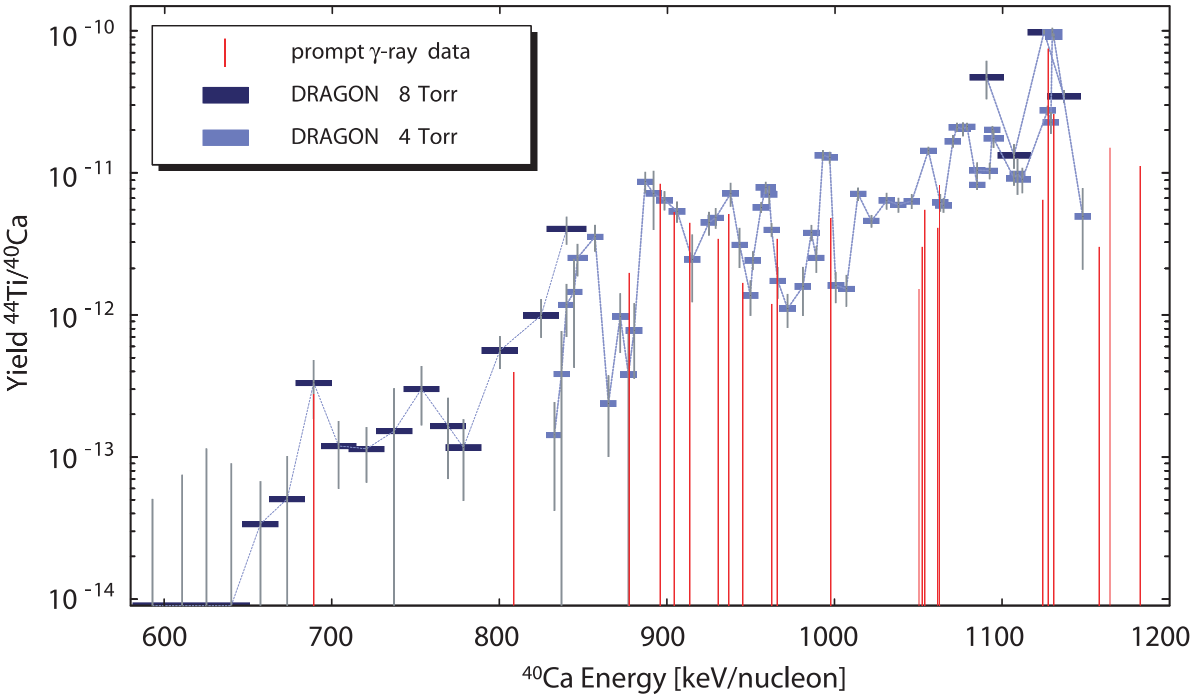

Figure 1. (Color online) Excitation function of the ^{40}Ca(α,γ)^{44}Ti reaction measured at DRAGON. Data sets at 4 Torr and 8 Torr are indicated in different shades, and the connecting lines are only to guide the eye. The yield at each measurement point depends on how many narrow resonances are hit, and thus overlapping bars at different pressures agree with each other only if the same resonances are hit in both cases. At the four lowest energies we observed only upper limits. For comparison, vertical lines indicate known resonance strengths from prompt γ-ray studies. Figure taken from Ref. [12].

to reach charge-state equilibrium, whereas ^{44}Ti recoils from reactions near the end of the path in the gas target (i.e. at the lower section of the energy range) pass through less gas and thus result in a different CSD. This effect is not present if the CSB foil is used since the CSB foil ”resets” the CSD independent of the incoming charge states.

Based on the measured yield, a resonance strength $\omega\gamma$ can be calculated at each energy:

$$\omega\gamma = \frac{2}{\lambda^2}\frac{m_t}{m_p + m_t}\left(\frac{dE}{dx}\right)Y \tag{2}$$

with λ as the de Broglie wavelength of the reduced mass of the compound system, m_p and m_t are the masses of projectile and target, and dE/dx is the stopping power per atom/cm^2 of the projectile in the target. From the resonance strength and the energy the astrophysical reaction rate for the ^{40}Ca(α,γ)^{44}Ti reaction was calculated and its implications studied with the model described in Ref. [6]. Our results (Fig. 1) show a significantly increased ^{44}Ti yield compared to previous prompt γ-ray studies – mainly resulting from yield between resonances known from previous studies. This suggests that the level density in ^{44}Ti is higher than previously thought or deduced from other reactions populating states in ^{44}Ti (see [12] for details). With our reaction rate the

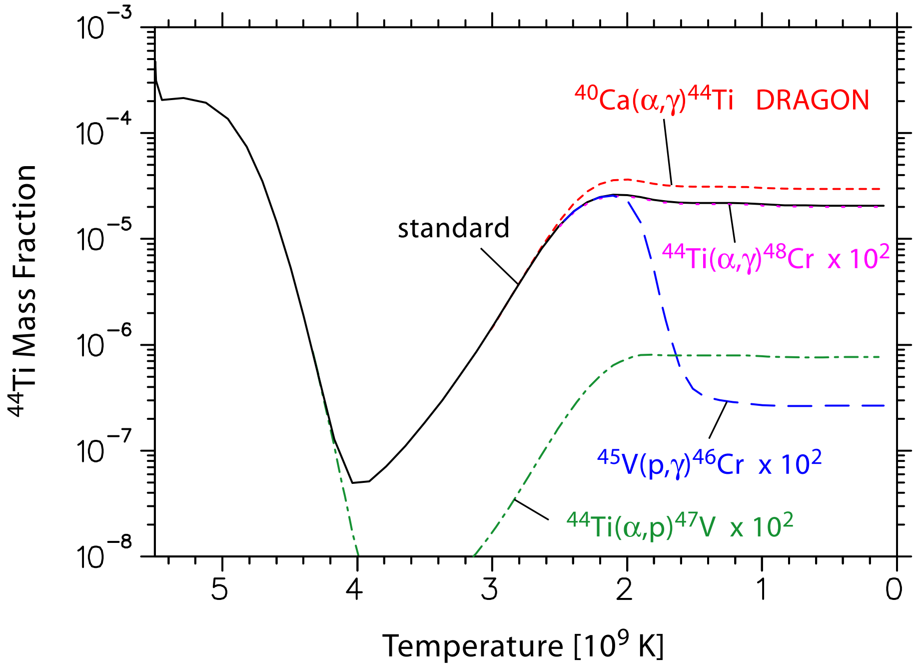

Figure 2. (Color online) The ^{44}Ti mass fraction as a function of temperature in the α-rich freeze-out (peak temperature $T_9 = 5.5$, peak density $\rho = 10^7$ g cm^3, neutron excess $\eta = 0$) calculated for several sets of reaction rates: the standard rate (solid line) uses the NON-SMOKER rates, the short-dashed line is with the ^{40}Ca(α,γ)^{44}Ti rate measured at DRAGON showing the increased production of ^{44}Ti; the other lines indicate the influence of the other key reactions if multiplied by a factor of 100: ^{45}V(p,γ)^{46}Cr (long-dashed line), ^{44}Ti(α,p)^{47}V (dot-dashed line), and ^{44}Ti(α,γ)^{48}Cr (dotted line – very close to the solid line).

final ^{44}Ti mass fraction in a simulation of the α-rich freeze-out is about 40% higher [12] compared to the semi-empirical rate from Ref. [16] commonly used in supernova models (Fig. 2). The uncertainty of our measurement results in a small 1σ uncertainty of ±3% in the final calculated mass fraction of ^{44}Ti. This brings the predicted ^{44}Ti amount from core-collapse supernova models closer to the one inferred from observation in Cas A.

3. Reactions with radioactive beam

With the improved rate of ^{40}Ca(α,γ)^{44}Ti the uncertainty of the ^{44}Ti production is now dominated by reactions with short-lived nuclides identified in a large sensitivity study by The *et al.* [6], namely ^{44}Ti(α,p)^{47}V, ^{44}Ti(α,γ)^{48}Cr and ^{45}V(p,γ)^{46}Cr. The first two reactions are responsible for the destruction of ^{44}Ti, while the third one controls the breaking of the (p,γ)–(γ,p) equilibrium among the $N = 22$ isotones in the quasi-statistical equilibrium [6]. The original study was based on reaction rates from the SMOKER code [17]. We reinvestigated the sensitivity of these three reactions with the improved NON-SMOKER code [18]. The results are plotted in Fig. 2. We found a similar importance for the ^{45}V(p,γ)^{46}Cr and the ^{44}Ti(α,p)^{47}V reactions.

However, the importance of ^{44}Ti(α,γ)^{48}Cr reaction has dropped significantly.

As pointed out in the original study [6] the ^{44}Ti(α,γ)^{48}Cr reaction competes with ^{44}Ti(α,p)^{47}V reaction for the destruction of ^{44}Ti and is only important if its rate is increased over the standard rate. We found that the NON-SMOKER rate of ^{44}Ti(α,γ)^{48}Cr is reduced by a factor of about 100 compared to the SMOKER rate in the relevant temperature range of $T_9 \sim 1 - 2$, probably due to the inclusion of isospin suppression for α-capture reactions on $N = Z$ in the NON-SMOKER code; the ^{44}Ti(α,p)^{47}V reaction increased a little. An increase of about a factor of 1000 of the ^{44}Ti(α,γ)^{48}Cr rate over the NON-SMOKER rate is required to reduce the ^{44}Ti mass fraction significantly. This is highly unlikely.

Thus, future experiments should focus on ^{45}V(p,γ)^{46}Cr and ^{44}Ti(α,p)^{47}V which both requires radioactive beams. The first one is particulary challenging because of the 0.5 s half-life of ^{45}V and the refractory nature of Vanadium. This requires high power targets and a high efficiency ion source to produce the required intensities (at least 10^7 ^{45}V per second on target) for a direct measurement.

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