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Study of the ^{40}Ca(α,γ)^{44}Ti reaction at stellar temperatures with DRAGON

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The short-lived radionuclide ^{44}Ti, which has been observed in space by γ-ray astronomy, is believed to be produced in supernovae during the α-rich freeze-out by α capture on ^{40}Ca. This reaction has been studied in inverse kinematics using the recoil mass spectrometer DRAGON at the ISAC facility at TRIUMF in Vancouver, Canada. A large energy range was covered corresponding to the temperature range of $T_9 \sim 1-2.8$ for freeze-out conditions. A preliminary analysis shows additional contribution to the total ^{44}Ti yield between the resonances measured by prompt γ-ray studies.

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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] and later with INTEGRAL [3] and thus confirms ongoing nucleosynthesis in our Galaxy. Since it is conjectured to be produced predominantly in supernovae during the α-rich freeze-out, its measured abundance can be used to constrain supernova models. It has also 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 showed 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.

The ^{40}Ca(α,γ)^{44}Ti reaction plays a key role in ^{44}Ti production and was identified as one of the most critical reactions in network calculations [6]. It has been studied partly in the past by non-inverse prompt γ-ray measurements [7 – 10]. A recent integral 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].

We have measured this reaction in inverse kinematics using the recoil mass spectrometer DRAGON located at the ISAC facility at TRIUMF (Vancouver, Canada). The advantage of direct detection of ^{44}Ti recoils and prompt γ rays is that it allows a detailed study of this reaction over a large energy range with sufficient resolution to resolve individual resonances. In this paper we report on the status of our investigations and present preliminary results.

2. Measurement at DRAGON

The goal of this experiment was to measure directly the ^{44}Ti production by α capture on ^{40}Ca over a wide temperature regime which is relevant for nucleosynthesis in the α-rich freeze-out, i.e. $T_9 \sim 1 - 2.8$. The measurement has been performed in inverse kinematics with a ^{40}Ca beam with energies of 600 to 1200 keV/u.

High-purity ^{40}Ca beam (less than 0.5% ^{40}Ar contamination) was produced in a micro-wave ion source by sputtering from a Ca target. In order to meet the requirements of the ISAC accelerators ($A/q < 30$), the 2+ charge state was employed. Up to $\sim$ 100 enA of ^{40}Ca^{2+} were extracted and first accelerated to 150 keV/u with a room-temperature radio frequency quadrupole (RFQ) accelerator. After the beam passed through a thin carbon stripper foil, charge state 7+ was selected to accelerate the ^{40}Ca beam with a drift tube linac (DTL) to the required energies. An overview of the ISAC accelerators is described by Laxdal *et al.* [12]. Typical currents on target were around 10 enA.

The recoil mass spectrometer DRAGON 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. The recoils are finally detected in an ion 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 coincidence between γ-ray detection at the BGO array and heavy-ion detection at the ion chamber. Additionally, a narrow time-of-flight win-

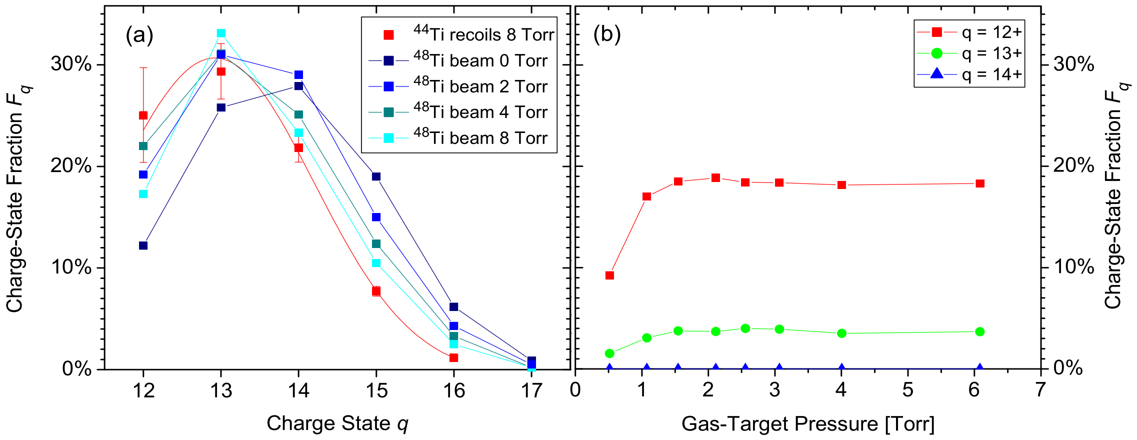

Figure 1: Charge states of Ti at 920 keV/u. (a) Charge-state distribution after the CSB foil measured with ^{44}Ti recoils (red) at 8 Torr and ^{48}Ti beam (blue shades) at different gas pressures. (b) Charge-state fractions without the CSB foil as a function of gas target pressure measured with a ^{48}Ti beam.

dow and cuts on energy-loss signals allow a clear identification of the ^{44}Ti recoils. Details of the DRAGON setup are described by Hutcheon *et al.* [13]; however, for 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. Details about the modification for this reaction are covered by Vockenhuber *et al.* [14].

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:

$$Y = \frac{N_{44\mathrm{Ti}}}{N_{40\mathrm{Ca}}\, F_q\, \varepsilon}\ . \tag{2.1}$$

$N_{44\mathrm{Ti}}$ 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. Corrections for the charge-state fraction of the recoils F_q and the detection efficiency ε have to be considered as well. The quantity 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.

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

$$\omega\gamma = \frac{2}{\lambda^2}\frac{m_t}{m_p+m_t}\left(\frac{dE}{dx}\right)Y \tag{2.2}$$

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.

Charge-state distributions (CSD) have been measured with a stable ^{48}Ti beam at four energies which cover the same velocity (or energy-per-nucleon) range. Due to limitations of the bending magnet, only the high charge states of the CSD were accessible. Fig. 1a shows the CSD of the ^{44}Ti recoils at the strong resonances near 1130 keV/u and compared with the CSD measured with stable beam at different gas pressures (both with the CSB foil). The slight change between the different pressures is caused by a small fraction of gas leaking behind the foil, enough to shift the CSD a little bit towards lower values. Fig. 1b shows the charge-state fraction as function of gas-target pressure. At this energy, charge-state equilibrium is reached around 1.5 Torr which corresponds to $\sim 4\ \mu$g/cm^2.

Depending on the pressure in the gas target, the beam loses between 2.8 keV/u at 1 Torr (corresponding to a target thickness of 2.9 μg/cm^2) and 22.8 keV/u 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/u) 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 (see [14] for discussion) whereas without the CSB foil we could measure at 9+ and 10+. However, more overlap was necessary because a target thickness of $3-4\ \mu$g/cm^2 is necessary to reach charge-state equilibrium (see Fig. 1b). 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 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.

3. Preliminary results

First tests were performed at strong resonances (an isospin triplet at $E_x = 9.2$ MeV) at a beam energy of 1130 keV/u, which were measured in the past several times by prompt γ-ray spectrometry [9, 10] and off-line counting using AMS [15]. The high yield allowed measurements at several charge states (12+ to 16+) and a clear signal in the singles spectrum was observed. Thus, a direct determination of the resonance strength was possible. With a measured summed resonance strength for the isospin triplet of $\sum \omega\gamma = 7.7 \pm 0.7$ eV [14], a good agreement with the previous measurements were found.

Fig. 2 shows the preliminary excitation function of the entire energy range. Each horizontal box (blue) indicates the covered energy range in the x direction and the yield in the y direction with the error as vertical line at the center energy. Previously known resonances (with a known resonance strength) are shown as vertical bars (red). Not included in our data for this plot are the full analyses of the CSD and BGO efficiencies based on γ-ray data. However, the DRAGON data clearly show ^{44}Ti yields at energies between known resonances. Note, excitation functions shown in the literature of the prompt γ-ray spectrometry [7 – 9] indicate some yield between these resonances, but it is not clear if this yield originates from instrumental background or reactions

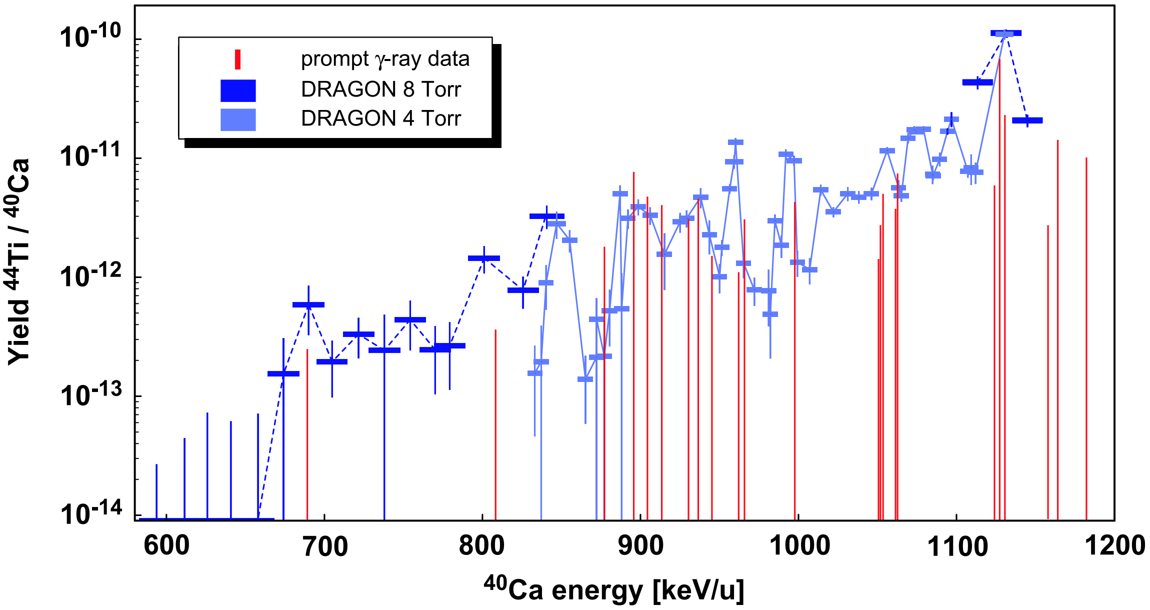

Figure 2: Preliminary excitation function of the ^{40}Ca(α,γ)^{44}Ti reaction measured at DRAGON. Data sets at 4 Torr and 8 Torr are indicated in different blue shades, the connecting lines are only to guide the eye. The yield at each measurement point depends how many narrow resonances are hit, thus overlapping bars at different pressures agree with each other only if the same resonances are hit in both cases. For comparison, vertical red lines indicate known resonance strengths from prompt γ-ray studies.

with contaminants; commonly used reaction rates are based on adaption of statistical model codes to these known resonances [16].

Our study results in a higher summed yield compared to the summed yield of known resonances from the prompt γ-ray measurements and confirms – at least to some extent – the finding of the integral measurement using AMS. A detailed analysis including the γ-ray data is under way.

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