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The supernova-nucleosynthesis ^{40}Ca $(\alpha,\gamma)^{44}$Ti reaction

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The ^{44}Ti ($t_{1/2}$ = 59 y) nuclide is considered an important signature of core-collapse supernova (SN) nucleosynthesis and has recently been observed as live radioactivity by γ-ray astronomy from the Cas A SN remnant. We investigated in the laboratory the major ^{44}Ti production reaction ^{40}Ca$(\alpha,\gamma)^{44}$Ti ($E_{cm} \sim 0.6$-1.2 MeV/u) by off-line counting of ^{44}Ti nuclei using accelerator mass spectrometry. The observed yield is significantly higher than inferred from previous prompt γ-spectroscopy experiments. The present data are interpreted in terms of the BRUSLIB statistical model which incorporates a microscopic model of nuclear level densities and of the γ-ray strength function, and a global α-nucleus optical-model potential and confirm the strong suppression in yield expected for (α,γ) reactions on self-conjugate (N =Z) nuclei. The derived astrophysical rate of the ^{40}Ca$(\alpha,\gamma)^{44}$Ti reaction is a factor 5-10 higher than calculated in current models. We will present results of stellar calculations in spherical hydrodynamics using this reaction rate, showing an increase of the calculated SN ^{44}Ti yield by a factor ~ 2 over current estimates. An increase by a factor of ~ 2 in ^{44}Ti is found also in the calculated fall back material. The yields calculated by multi-dimensional SN explosion calculations proposed to explain the observed ^{44}Ti yield of Cas A, in which parts of deeper layers can be ejected while some of the outer layers fall back, are expected to be enhanced in ^{44}Ti as well.

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1. Introduction

The radionuclide ^{44}Ti ($t_{1/2}$ = 59 y) is considered an important signature of explosive nucleosynthesis in core collapse supernovae (SN) [1]. ^{44}Ti is believed to be produced during an α-rich freeze-out phase occurring during the expansion through the ^{28}Si pre-supernova shell. Two important physical observables of ^{44}Ti nucleosynthesis have been established at this point. Live ^{44}Ti was directly observed from a point source identified as the SN remnant Cassiopeia A (Cas A) by γ- and X-ray telescopes (CGRO, RXTE, BeppoSAX) and very recently by the INTEGRAL mission (see [2,3]). Secondly, large ^{44}Ca isotopic anomalies (relative to Solar matter composition), interpreted as resulting from *in-situ* decay of live ^{44}Ti have been measured in presolar X-type grains [4]. Very recently, the value of the ^{44}Ti half-life was determined in the laboratory with improved precision [5] to be 58.9±0.3 y. Using measured values for the distance and age of the remnant, the half-life of ^{44}Ti and the combined γ flux from all observations, an initial ^{44}Ti yield of $(1.60\pm0.60)\times10^{-4}$ solar masses is implied [3]. This value is larger by a factor of 2-10 than ^{44}Ti yields calculated in current models (*e.g.* [6,7]). Various explanations have been proposed [8-10] and it seems that only multi-dimensional models can reproduce this high yield. However, the nuclear-physics information on ^{44}Ti nucleosynthesis is incomplete. Although many nuclear reactions play roles in determining the SN yield of ^{44}Ti [10,11], the major production reaction is ^{40}Ca(α,γ)^{44}Ti and its importance has been emphasized [12]. The reaction was studied in the 70's by α bombardment of Ca targets and prompt-γ spectroscopy down to E_{cm} ~3 MeV, yielding energies, spins and strengths of isolated resonances [13,14]. Rauscher et al. [15] used this information (together with that for lighter N=Z nuclei) to build an empirical model and calculate an astrophysical rate for the reaction which is currently adopted in SN-nucleosynthesis codes. The aim of the present work was to provide new experimental information on the cross section of the ^{40}Ca(α,γ)^{44}Ti reaction and on the astrophysical rate of production of ^{44}Ti in the energy range of SN nucleosynthesis [16].

2. Experimental method

We use the technique of accelerator mass spectrometry (AMS) with which we determine the integral number of ground-state residual nuclei produced in an activation run. This method has been used to measure cross sections of astrophysical relevant reactions which produce long-lived nuclides [17-19]. Our measurements were performed in inverse kinematics by bombarding a He-gas target cell with a ^{40}Ca beam and implanting forward-recoiling reaction products in a Cu catcher acting also as a beam stop. This inverse-kinematics approach has the advantage of using a high-purity target able to sustain high beam power and whose thickness can be accurately controlled by monitoring the gas pressure. In the conditions of our experiment, the power deposited in the gas (<10 mW/mm) is not expected to change its stopping power [20]. After irradiation, a 10-μm surface layer of the catcher is etched in a HNO_3 solution containing 3 mg of Ti acting as chemical carrier in order to extract the ^{44}Ti atoms implanted during activation. The solution is then passed through an ion-exchange column filled with Diphonix resin [21] which retains Ti^{4+} ions while the Cu bulk content of the solution is released. Ti is eluted from the column by a HF solution and precipitated with ammonia as hydroxide. After evaporation to dryness and ignition at 500° C, a TiO_2 sample is obtained for use in the AMS determination of the ^{44}Ti/Ti ratio. The abundance r_{44} = ^{44}Ti/Ti (in the 10^{-13}-10^{-12} range) is then measured by AMS and the total number (n_{44}) of ^{44}Ti nuclei implanted in the catcher is obtained by the relation $n_{44} = r_{44}\, n_{\mathrm{Ti}}$, where n_{Ti} denotes the number of Ti carrier atoms used.

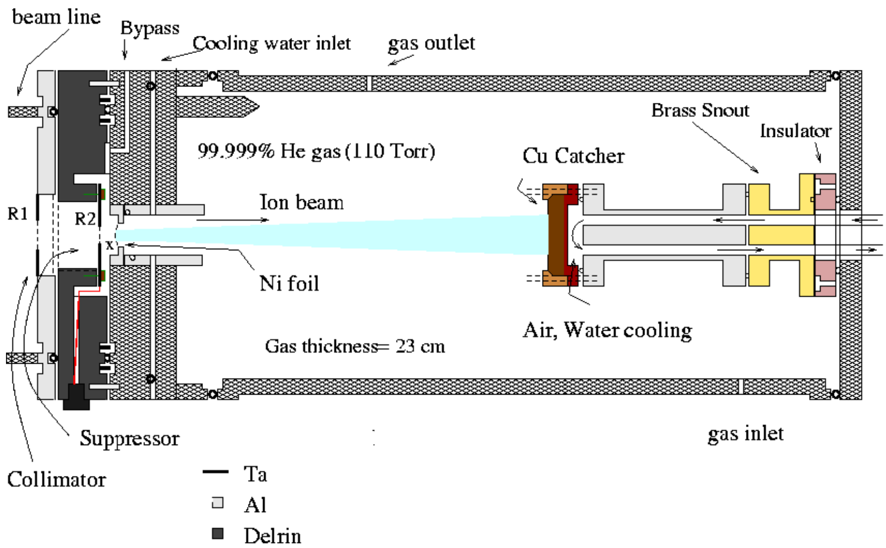

Figure 1: Gas cell and catcher assembly used for the ^{40}Ca + ^{4}He activation at the Koffler accelerator (see text). The cell was filled with He (99.999%) gas at 110 Torr. R1 (8 mm diameter) at ground potential is used for beam collimation, R2 (14 mm diameter) insulated from ground and at a potential of –120 V relative to the chamber acts as a secondary-electron suppressor. A pinhole-free Ni foil, 1.5 mg/cm^2 thick, is used as window. The whole chamber assembly is electrically insulated and serves as a Faraday cup for beam charge integration. Forward recoiling ^{44}Ti ions produced by the ^{40}Ca(α,γ)^{44}Ti reaction are implanted in a high-purity Cu (99.9 %) catcher (6.3 mm thick), cooled by forced air or de-ionized water.

Importantly, this result, based on the ^{44}Ti/Ti isotopic ratio, is independent of chemical or counting efficiencies [17].

The ^{40}Ca irradiations were performed at two different accelerators. Using the electron-cyclotron ion source and the ATLAS linac at Argonne National Laboratory, an intense $^{40}Ca^{11+}$ beam (~1 eμA on target) was used to populate a group of strong resonances near E_{cm}= 4.1 MeV [14] whose resonance strengths were measured by prompt γ-ray spectroscopy. The energy of the incident ^{40}Ca beam (70.9 MeV) and the energy after the Ni foil (1.5 mg/cm^2 thick Ni) used as gas window (46.1 MeV, fwhm= 2.8 MeV) were carefully measured with an Enge magnetic spectrograph. During irradiation, the gas window was rotated eccentrically to the beam in order to dissipate the beam power loss. An activation was also made at a slightly lower off-resonance energy. In order to check for possible background production of ^{44}Ti during the experiment, a separate activation was performed in similar energy conditions and the same setup but using Ar

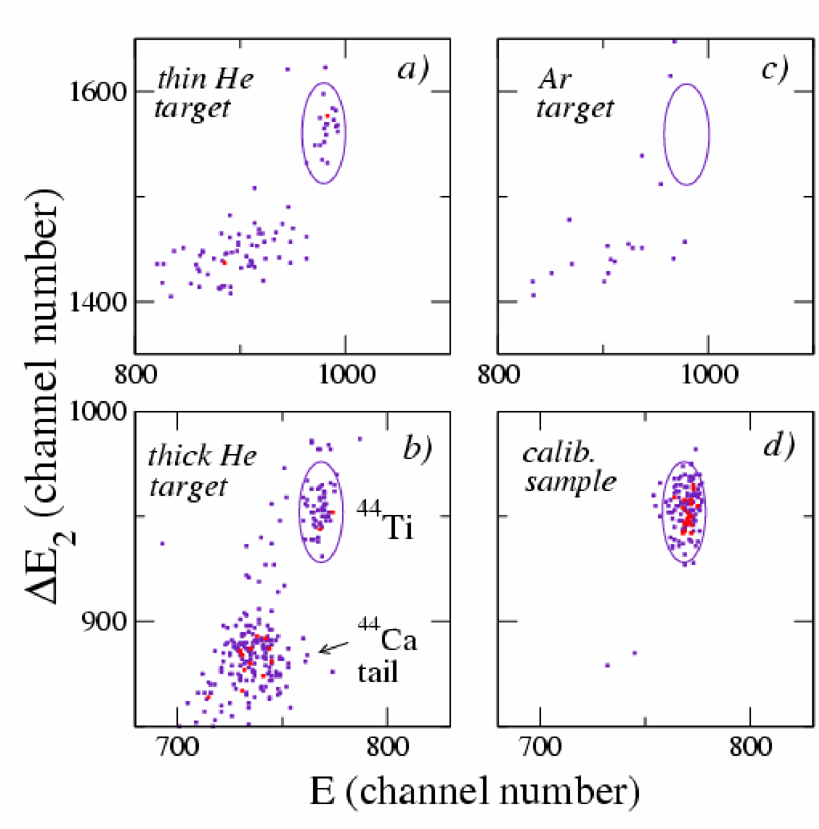

Figure 2 : Identification spectra of ^{44}Ti : E and ΔE_2 are energy and energy-loss signals, respectively. The data shown have been filtered through a software condition set by additional energy-loss signals which reduces the intensity of the ^{44}Ca tail (shown) and correspond to runs: a) ATLAS run; b) Koffler runs; c) background measurement; d) calibration sample ($^{44}Ti/Ti$ = 3.66 x 10^{-11}, determined by γ-spectrometry and isotopic dilution, see [16]).

as the target gas. The other irradiations were performed at the Koffler Tandem accelerator (Weizmann Institute), using a (isobarically pure) $^{40}Ca^{8+}$ beam with an average intensity of ~120 enA on target [22]. The He (99.999%) gas target and the water-cooled Cu catcher were contained in an electrically insulated and secondary-electron suppressed chamber acting as a Faraday cup for beam charge integration (fig. 1). The incident energy of the beam was set to 72.0 MeV and the thickness of the ^{4}He gas target (110 Torr, 23 cm) was selected to integrate the reaction yield from E_{cm}= 4.2 MeV (after the vacuum window) down to E_{cm}= 2.1 MeV, covering a large part of the SN nucleosynthesis energy range. The ^{44}Ti analysis and measurement of the isotopic ratios r_{44} were performed using the Hebrew University AMS facility [23] at the Koffler accelerator (Weizmann Institute). $^{44,46}Ti^{-}$ ions were alternately accelerated at a terminal voltage of 12 MV and $^{A}Ti^{10+}$ ions, produced by stripping in a 2 μg/cm^2 thick C foil, were accelerated to 132 MeV and transported to the detection system. ^{44}Ti was discriminated from the dominant ^{44}Ca isobaric background and counted in a multi-anode ionization chamber and alternatively, the $^{46}Ti^{10+}$ charge current was measured in a Faraday cup , leading to the $^{44}Ti/Ti$ ratio. In order to reduce systematic errors in the final r_{44} values, the ratios were normalized to those measured for a calibration sample. Blank samples (having gone through the same chemical procedures, but containing no ^{44}Ti) were used to ensure that no background is present in the measurements. Identification spectra are shown in Fig. 2. More details on the AMS analysis and the experiments can be found in [16] and references therein.

3. Results and discussion

We derive from the ATLAS run (thin He target, fig.2a) a resonance strength $\omega\gamma$ = 8.8 ± 3.0 eV, consistent with the results of prompt-γ measurements [14] for the two close-by resonances in ^{44}Ti at an excitation energy of E_x= 9.227 and 9.239 MeV ($\omega\gamma$ =5.8 and 2.0 eV, respectively). However, the integrated yield measured between Ecm= 4.2 and 2.1 MeV (Fig. 2b) is significantly larger than implied by the prompt-γ data. Figure 3 shows a comparison between the resonance strengths measured in [13,14] and the range of total resonance strength (30 to 63 eV, depending on the positions of the possible resonance energies) obtained from our experiment.

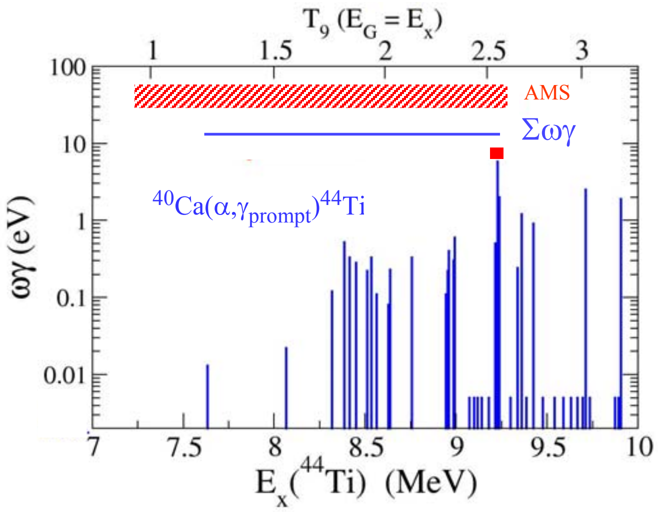

Figure 3 : Comparison of the resonance strengths measured for the $^{40}Ca(\alpha,\gamma)^{44}Ti$ reaction by prompt-γ spectroscopy [13,14] (blue bars) and the range of values derived from the present experiment by AMS counting of ^{44}Ti nuclei for the thin target (solid red box) and thick target (hatched red box). The low blue bars (at ωγ=0.005 eV) represent resonances observed in [14] whose strengths were not measured. The lower horizontal axis represents the excitation energy in ^{44}Ti and the upper horizontal axis the stellar temperature at which a given excitation energy equals the Gamow peak energy E_G.

This yield can also be interpreted as resulting from closely spaced states in ^{44}Ti (E_x(^{44}Ti) = 7.2 - 9.3 MeV), not resolved in experiments. In such a case, it becomes justified to express the data in terms of an energy-averaged cross section and to compare it with statistical Hauser-Feschbach calculations. Figure 4 compares the average cross section (8.0 ± 1.1 μb) derived from the present data with the expression $\sigma_{ave} = \int_{E\,min}^{E\,max} \sigma(E)(dE/dx)^{-1} dE/\Delta x$, where $\sigma(E)$ is calculated with different models. The present data support the BRUSLIB model [24] which incorporates a microscopic model of nuclear level densities [25] and of the γ-ray strength function [26], and a global α-nucleus optical-model potential [27]. The scaled BRUSLIB calculation (Fig. 4a) was modified to reproduce the experimental average cross section by

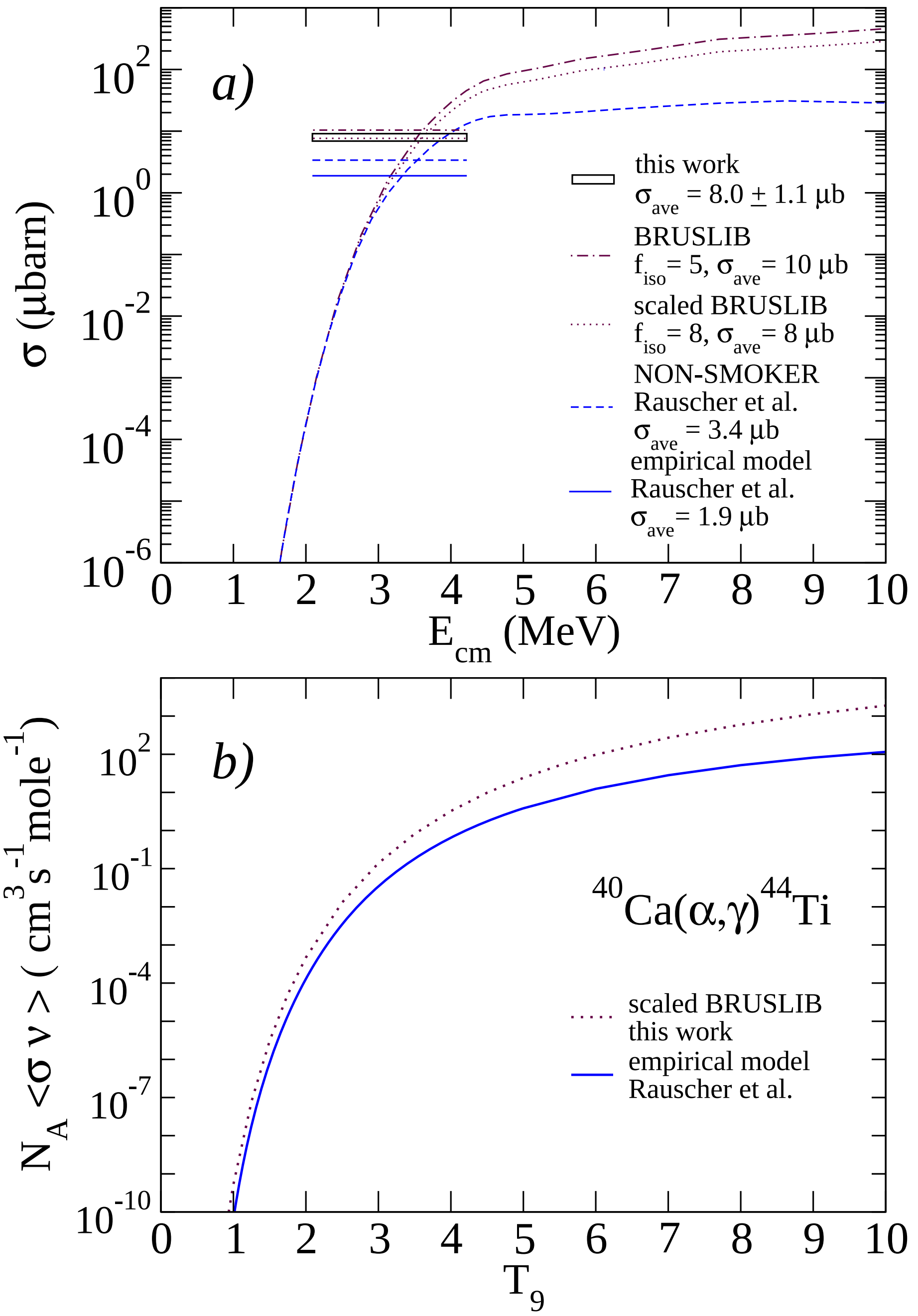

Figure 4: a) Comparison of the average cross section of the $^{40}Ca(\alpha,\gamma)^{44}Ti$ reaction measured in the present experiment (open box) with current models. The horizontal bars represent the average cross section over the experimental energy range, calculated with the different models; b) astrophysical rate of the reaction calculated with the scaled BRUSLIB model (this work) and with the empirical model of Rauscher et al. [15], currently used in stellar calculations.

adjusting the suppression factor of electromagnetic transitions in N=Z nuclei to f_{iso}=8. This value confirms the large reduction of dipolar electromagnetic strength in a self-conjugate nucleus and represents an experimental measure of the degree of mixing of the T=0 into the T=1 states (T denotes isospin). The cross section σ(E) obtained from the scaled BRUSLIB calculation was integrated to yield the astrophysical rate of the ^{40}Ca(α,γ)^{44}Ti reaction (Fig.3b). The rate is higher by a factor 5-10 than that calculated with the model [15] over the range of temperatures of SN nucleosynthesis. This new rate was used in a SN nucleosynthesis calculation with spherical hydrodynamics, as those described in ref. [28], with the KEPLER code [29]. For progenitors of 15 and 25 solar masses, the SN ^{44}Ti yield in the ejecta increases by a factor ~ 2 from 0.14×10^{-4} to 0.27×10^{-4} and from 0.16×10^{-4} to 0.24×10^{-4} solar masses, respectively, while the ^{56}Ni yield is kept constant. Thus, both the absolute ^{44}Ti yield and the ^{44}Ti/^{56}Ni ratio are brought closer to the values inferred from γ-ray astronomy observations. This is particularly important for the ^{44}Ti/^{56}Ni ratio since it fits better the solar ^{44}Ca/^{56}Fe ratio. Interestingly, a factor of ~2 increase in ^{44}Ti is found also in the calculated fall back material. Multi-dimensional simulations proposed to explain the ^{44}Ti yield of Cas A may show a similarly enhanced yield, due to the mixing and ejection of deeper layers by Rayleigh-Taylor instabilities.

In summary, we measured the integrated yield of the ^{40}Ca(α,γ)^{44}Ti reaction over a large range of SN nucleosynthesis energies by direct counting of ^{44}Ti ground-state nuclei using accelerator mass spectrometry. The observed yield is significantly higher than previously measured and results in a factor of ~2 increase by in the calculated production of ^{44}Ti in a supernova explosion. A series of continuing experiments using the same technique but in smaller energy ranges is being performed at Technical University of Munich.

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