Author(s): Margerin, V.; Murphy, A.St.J.; Davinson, T.; Dressler, R.; Fallis, J.; Kankainen, Anu; Laird, A.M.; Lotay, G.; Mountford, D.J.; Murphy, C.D.; Seiffert, C.; Schumann, D.; Stowasser, T.; Stora, T.; Wang, C.H.-T.; Woods, P.J.

Title: Study of the Ti-44(alpha, p)V-47 reaction and implications for core collapse supernovae

Year: 2014

Version:

Please cite the original version:

Margerin, V., Murphy, A.St.J., Davinson, T., Dressler, R., Fallis, J., Kankainen, A., Laird, A.M., Lotay, G., Mountford, D.J., Murphy, C.D., Seiffert, C., Schumann, D., Stowasser, T., Stora, T., Wang, C.H.-T., & Woods, P.J. (2014). Study of the Ti-44(alpha, p)V-47 reaction and implications for core collapse supernovae. Physics Letters B, 731(April), 358-361. https://doi.org/10.1016/j.physletb.2014.03.003

Physics Letters B 731 (2014) 358–361

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Study of the ^{44}Ti(α, p)^{47}V reaction and implications for core collapse supernovae

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ARTICLE INFO

Article history:
Received 3 February 2014
Accepted 2 March 2014
Available online 12 March 2014
Editor: W.-D. Schlatter

ABSTRACT

The underlying physics triggering core collapse supernovae is not fully understood but observations of material ejected during such events helps to solve this puzzle. In particular, several satellite based γ-ray observations of the isotope ^{44}Ti have been reported recently. Conveniently, the amount of this isotope in stellar ejecta is thought to depend critically on the explosion mechanism. The most influential reaction to the amount of ^{44}Ti in supernovae is ^{44}Ti(α, p)^{47}V. Here we report on a direct study of this reaction conducted at the REX-ISOLDE facility, CERN. The experiment was performed with a ^{44}Ti beam at $E_{\mathrm{lab}} = 2.16$ MeV/u, corresponding to an energy distribution, for reacting α-particles, centred on $E_{\mathrm{cm}} = 4.15$ with a 1σ width of 0.23 MeV. This is, for the first time, well within the Gamow window for core collapse supernovae. The material from which the ^{44}Ti beam was extracted originates from highly irradiated components of the SINQ spallation neutron source of the Paul Scherrer Institute. No yield above background was observed, enabling an upper limit for the rate of this reaction to be determined. This result is below expectation, suggesting that the ^{44}Ti(α, p)^{47}V reaction proceeds more slowly than previously thought. Implications for astrophysical events, and remnant age, are discussed.

The radionuclide ^{44}Ti is one of the very few cosmogenic nuclei to be observed in our Galaxy, and in particular from remnants of core collapse supernovae (CCSNe). The γ-rays associated with the decay of ^{44}Ti have indeed been observed from the type-II supernova SN1987A by the INTEGRAL IBIB/ISGRI instrument [1]. This instrument previously detected this isotope from the type-IIb supernova Cassiopeia-A [2]. Traces of ^{44}Ti from Cassiopeia-A were further observed by the COMPTEL satellite [3] and by BeppoSAX [4].

Stars with more than about eight times the mass of our Sun, $8M_{\odot}$, suffer the fate of CCSNe. As such a star collapses and a shock wave is formed, elements in and around the core are rapidly photo-dissociated back to free protons, neutrons and α-particles. A significant fraction of the protons convert to neutrons inside the core, resulting in a burst of electron neutrinos. Thermal production, and emission, of all neutrino flavours follows over the next few seconds (see, e.g., Refs. [5,6]). This sequence of events is well understood and was confirmed by observations of SN1987A (see Refs. [7–9]). Modelling the subsequent events is a task that has proven hard to realise, such that unravelling the underlying explosion mechanism of CCSNe has become a highly topical quest in modern astrophysics. The development of a neutrino wind appears as the most compelling theory [5]. This wind would be strong enough that sufficient neutrino-nucleon interactions occur [10], powering the nuclear reaction network in the (photo-dissociated)

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http://dx.doi.org/10.1016/j.physletb.2014.03.003

outer layer of the core. New Physics, for example acoustic coupling of gravity waves [11–13] or the dynamical trapping and relaxation of scalar fields [14], have also been invoked as mechanisms to enable successful core collapse supernovae explosions. Signatures such as light curves and (near-)optical spectra show little sensitivity to the detail of the explosion mechanism. In contrast, observations of γ-rays from the long lived isotope ^{44}Ti, $\tau = 85.3(4)$ years [15], ejected into the interstellar medium, might provide such sensitivity. In particular, the ^{44}Ti nucleus is produced in α-rich regions, generated near the core, when they cool down after the explosion and the cessation of the quasi-static equilibrium between nuclear reactions and their inverse [6]. The deep, thermalised, core is doomed to evolve to a neutron star or a black hole, but how much of the newly produced ^{44}Ti would be caught in this fate is linked to the hydrodynamics of the star. Thereby, the amount of ^{44}Ti ejected is a gauge for the position of the mass cut of the star, which determines the boundary between material that falls back and that which is ejected into space. It has been shown, in detailed studies by The et al. [19] and Magkotsios et al. [6], that the nucleosynthesis of ^{44}Ti hinges upon a few reactions, the triple-α reaction, ^{40}Ca$(\alpha,\gamma)^{44}$Ti (producing ^{44}Ti) and ^{44}Ti$(\alpha,p)^{47}$V (consuming ^{44}Ti). Critically, the final amount of ^{44}Ti depends most sensitively, by a significant margin, on the reaction rate for ^{44}Ti$(\alpha,p)^{47}$V. As a result, the measurement of the cross section for this reaction is a versatile tool for providing insight to a specific astrophysical environment.

Existing CCSNe models predict that the maximal ejecta content in ^{44}Ti does not exceed $1\times10^{-4}M_\odot$, even assuming a wide range of progenitor models and masses [6,16,17]. Observations, however, conducted by satellite-based γ-ray observatories, report significantly larger values. In the sequence of β-decays from ^{44}Ti to ^{44}Ca several γ-rays are emitted, at 68, 78 and 1157 keV, and are detectable in space. Combining the different observations of Cassiopeia-A, the estimated mass of ^{44}Ti ejected is $1.6^{+0.6}_{-0.3}\times10^{-4}M_\odot$ [2] while observations of SN1987A indicate the presence of $(3.1\pm0.8)\times10^{-4}M_\odot$ of ^{44}Ti in the ejecta. The latter amounts of ^{44}Ti are higher than any theoretical model predictions. Age and/or distance determination for supernova remnants (SNRs) also critically depend on the amount of ^{44}Ti observed in the ejecta. An intriguing example lies in the observation of a previously unknown SNR located in the Vela region from the COMPTEL γ-ray data [18]. Given the distance to this object, 200 pc, and a 'standard' ^{44}Ti yield of $5\times10^{-5}M_\odot$, the suggested age for the remnant was ~700 years. For the relative proximity, and the period in history, it has been noted that it is somewhat surprising that no record of a corresponding supernova explosion observation exists.

In this Letter we report on a recent experiment conducted at CERN aimed at providing the first direct measurement of the ^{44}Ti$(\alpha,p)^{47}$V reaction at energies corresponding to the actual production site of ^{44}Ti. The only previous measurement of the ^{44}Ti$(\alpha,p)^{47}$V cross section was by Sonzogni et al. [20]. In order to perform such an experiment they irradiated a ^{45}Sc disk with protons from Argonne's Intense Pulsed Neutron Source facility. The ^{44}Ti content was chemically extracted and later impinged on a gas cell filled with helium gas. A ^{44}Ti beam intensity of 5×10^5 pps was achieved. The recoil nuclei were analysed and the cross section for the ^{44}Ti$(\alpha,p)^{47}$V reaction extracted at various centre of mass energies, between 5.7 and 9.0 MeV, with the different energies reached by using appropriate thicknesses of titanium degrader foil. However, to evaluate the reaction rate at energies reached in CCSNe when and where ^{44}Ti is most efficiently synthesised (the temperature in the corresponding regions of the star are in the range $2.0 \lesssim T_9 \lesssim 4.0$), the reaction must be studied in the Gamow window corresponding to the 2–6 MeV range [21], which requires a higher intensity at low beam energies.

In the present study, a ^{44}Ti beam was produced in a novel way. As part of the ERAWAST initiative [22] highly irradiated components from accelerator devices at the Paul Scherrer Institute (PSI) were exploited as a source of exotic radio isotopes. Radiochemical separations, combining liquid–liquid extraction and ion-exchange chromatography, were used to extract ^{44}Ti from martensitic steel specimens. A sample of around 50 MBq of ^{44}Ti was obtained and dissolved in diluted HF solution (see Ref. [23]). This sample was then evaporated on a molybdenum foil, and transported from PSI to CERN. It was inserted into a standard target container in the ISOLDE Class A target laboratory, connected to a VADIS FEBIAD ion source in the VD5 configuration, and equipped with a large CF_4 gas leak to allow for the production of Ti beams as TiF_x molecular ions [24]. The unit was then installed on the General Purpose (mass) Separator front end at ISOLDE. The extracted $^{44}TiF_3^+$ molecular beam was bunched and cooled in the REX-TRAP Penning trap and dissociated, in the electron beam ion source [24], before acceleration in the linear accelerator of the REX-ISOLDE facility. ^{44}Ti^{13+} beams of 5×10^5 to 2×10^6 pps, with no apparent isobaric contamination, were provided to the experimental apparatus for 4 days. The beam was accelerated to about 2.1 MeV/u and impinged upon on an aluminium windowed gas cell (2 cm wide). An entrance window thickness of ≈6 μm was chosen to minimise the additional beam energy required to account for the energy loss through the window and, consequently, to remain below the Coulomb barrier for the fusion of ^{44}Ti with ^{27}Al (107 MeV), as well as ^{44}Ti with ^{16}O (99 MeV) and ^{12}C (95 MeV), from water and oil condensation. For such a thickness it was chosen to operate the gas cell at a safe pressure of ≈67 mbar of helium gas. A thicker exit window, 15 μm, was used ensuring that all recoils and the unreacted beam would not escape the cell while light particles could do so.

For the detection of light particles a ΔE–E telescope, consisting of two Micron Semiconductor Ltd S2-type silicon detectors [25] of 65 μm and 1000 μm thickness, respectively, was positioned 12.7 cm downstream with respect to the exit window of the gas cell. The two components of the telescope each provided position information with 48 circular strips ($\theta_{\text{lab}} = 5.3$–$15.3^\circ$) and 16 azimuthal sectors, enabling kinematic reconstruction of event-by-event data to be performed. Energy calibration was made using a triple-α source; a quenching factor of 0.986 was then applied to protons. Events were required to satisfy the criteria of a coincident energy deposition in both sides of the telescope, as well as being spatially coincident between both detectors (±3 strips, ±1 sector). The different particle species could be identified by plotting the ΔE signal against the E signal, with a clear separation of protons and α-particles achieved. Protons arising from elastic scattering of the beam with surface hydrogen deposits on inner and outer faces of the gas cell windows deposit less energy in the ΔE detector than elastically scattered α-particles, as observed in Fig. 1(i). A series of runs was conducted with the helium gas evacuated from the cell, from which only elastically scattered protons were detected; this is presented in Fig. 1(ii). Seeing as essentially no α-particles were observed in the gas out data, cross section normalisation for the reported measurement was made by scaling to the Rutherford cross section for the ^{44}Ti$(\alpha,\alpha)^{44}$Ti reaction. The observed number of α-particles from elastic scattering, 1.18×10^4, implied a beam current that is in good agreement with other measurements including Faraday cup readings, run by run measurement of the 1157 keV γ-ray intensity, and the measurement of induced ^{44}Ti activity on the exit window post-experiment. The main source of uncertainty in the measured cross sections arises from the accuracy of the geometry, ~4%.

Fig. 1(iii) presents the summed $\Delta E + E$ values, and the results of a detailed Monte Carlo simulation of the experiment. The latter incorporated energy losses from the evaluation tables of SRIM [26],

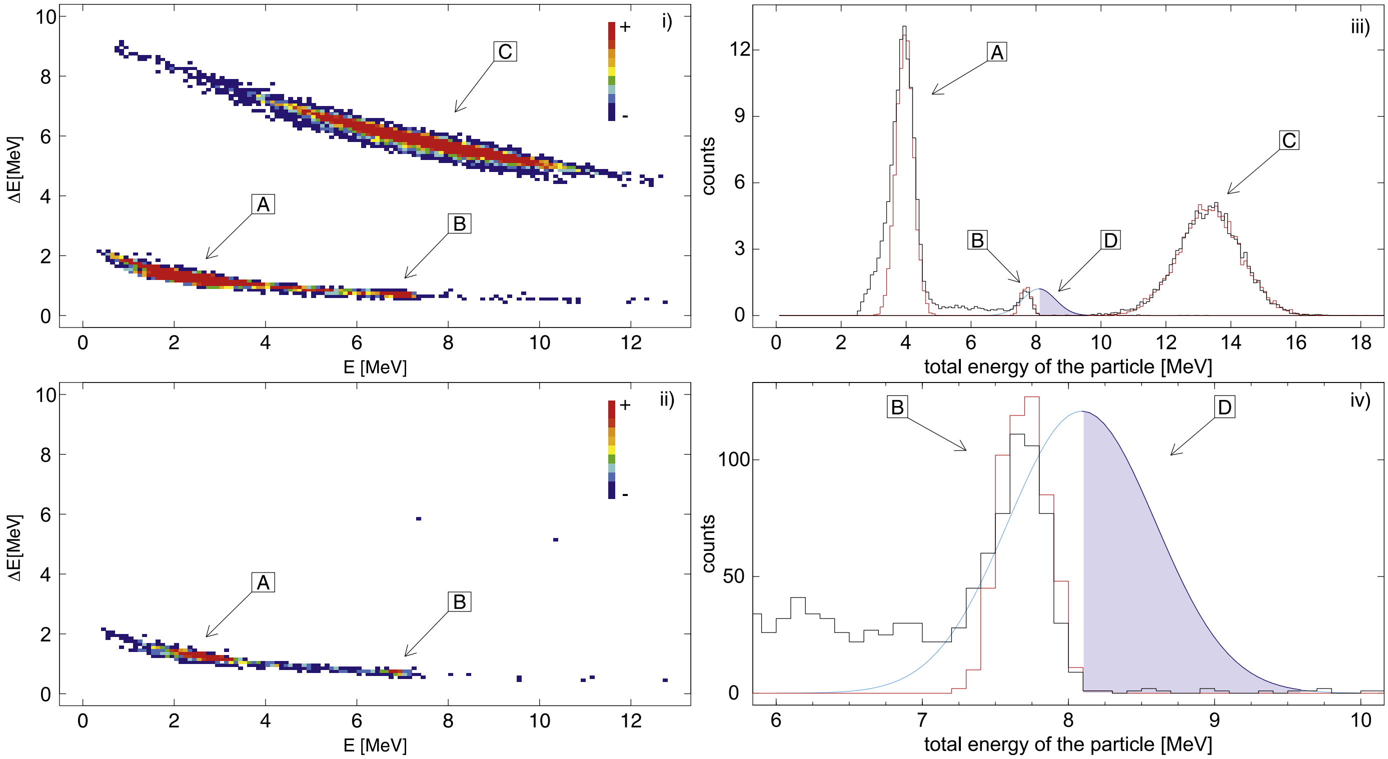

Fig. 1. (Colour online) (i) ΔE vs. E plot of the experimental results for a beam energy of 2.16 MeV/u (before the entrance window) and with ≈67 mbar of helium gas in the cell. The labelled groups represent the elastic protons emitted from the back of the front window and the front of the back window (A), the elastic protons emitted from the front of the front window (B), and the elastically scattered α-particles (C). (ii) ΔE vs. E plot of the experimental results for a beam energy of 2.16 MeV/u and an empty gas cell (background measurement). The labels stand as previously. (iii) Comparison between Monte Carlo simulation (in red and with the (α, p) reaction turned off) and experiment intensity (in black), with ≈67 mbar of helium gas in the cell, of the different reactions against the total energy $(E + \Delta E)$ of the detected particles. The labels A, B and C stand as previously. The D label denotes the simulated distribution of the expected (α, p) events (in blue), for a deliberately high cross section. The darker section shows the region of interest (centroid to 3σ), see text. (iv) Magnification of the region of interest in (iii). The shaded area represents the centroid plus three sigma width energy region where the Monte-Carlo simulation (red) predicts the elastically scattered protons to contribute less than one count.

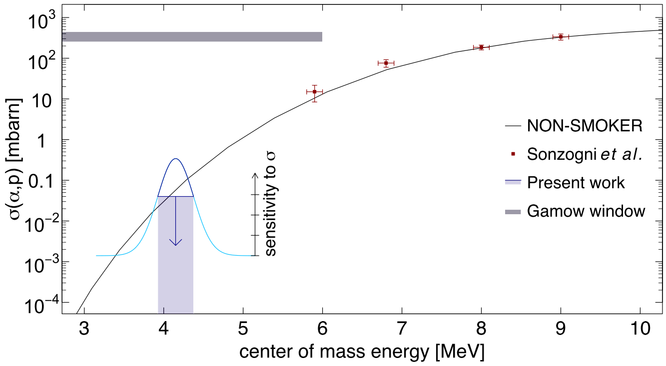

Fig. 2. (Colour online) Comparison of the measured cross section and the NON-SMOKER prediction, black line, for the $^{44}\mathrm{Ti}(\alpha, p)^{47}\mathrm{V}$ reaction. The red points are taken from Sonzogni et al. [20] while the shaded area represents the constrained region for the cross-section from our measurement. Note that the Gaussian represents the energy spanned by the beam when it passes through the gas cell, see text.

energy straggling from the Bohr formula (scaled to experimental calibration data), angular dispersion of the beam determined by the beam focusing geometry, with application of Gaussian smearing to relevant parameters. Scattering was assumed to be isotropic in the centre of mass, detector dead-layers set at 0.8 μm and intrinsic energy resolutions of 15 keV for protons and 25 keV for α-particles assumed. Separate simulations for each of the expected reactions were performed and included calculations for protons arising from (α, p) reactions of the beam with the helium gas (assuming no energy dependence for this reaction cross section). Using a beam energy of 2.16 MeV/u and an entrance window thickness of 6.62 μm, differing from the nominal thickness of 6.0 μm by significantly less than the manufacturing uncertainty of 25%, yielded the most accurate reproduction of experimental results, see Fig. 1(iii). The effectively monochromatic $^{44}\mathrm{Ti}$ beam, having passed through the entrance window, is reduced in energy and broadened due to energy straggling in this thickness of aluminium. The widths of the peaks in Fig. 1(iii) are dominated by this effect and are well reproduced by the Monte Carlo simulation.

In Figs. 1(iii) and (iv), feature D shows the simulated distribution for events from $^{44}\mathrm{Ti}(\alpha, p)^{47}\mathrm{V}$ reactions, under the same parameter set as used to accurately reproduce features A, B and C. Ejectile protons are expected to be detected with a broadly Gaussian distribution of energies centred at $E_{\mathrm{lab}} = 8.09$ MeV with a 1σ width of 0.50 MeV. The corresponding centre of mass energy distribution for the reacting α-particles, within the gas cell, is centred at $E_{\mathrm{cm}} = 4.15$ MeV and has a 1σ width of 0.23 MeV. A fit of the peak resulting from elastic scattering of protons on the outside of the entrance window (feature B) suggests that the protons from this source contribute less than one count to the data above an energy of 8.09 MeV. The region bounded from the peak energy for the $^{44}\mathrm{Ti}(\alpha, p)^{47}\mathrm{V}$ reaction to the peak plus the 3σ width energy is taken as a region where $^{44}\mathrm{Ti}(\alpha, p)^{47}\mathrm{V}$ reaction events would be expected, while contamination from elastically scattered protons would not be present. In this energy region, the numbers of events in the gas-in (12 counts) to the gas-out (3 counts) data sets is consistent with the numbers of elastically scattered protons seen in the gas-in and gas-out data in feature B (ratio of 3.7(2)), and corresponds to the respective beam exposures for the gas-in and gas-out runs. Potential ^{44}Ti(α, p)^{47}V events can therefore only be within the background signal uncertainty, and applying the Feldman–Cousins statistical approach [27] this represents a maximum of 5.3 counts (8.0 counts), or 10.6 in the whole peak (16), at a 68% (90%) confidence limit. The resulting upper limit on the ^{44}Ti(α, p)^{47}V reaction cross section is 40 μbarn (60 μbarn), see Fig. 2.

The previous measurements by Sonzogni et al. are also presented in Fig. 2 alongside the cross-section energy dependence obtained from the `NON-SMOKER` Hauser–Feshbach statistical model code (used with standard parameters) [28,29]. An evaluation of the reaction rates implied by the previous data and by the statistical model [21] concluded that a factor of three uncertainty remained, and that additional data at lower energy were needed. The new upper limit, at significant lower energy, is presented as the horizontal bar in Fig. 2. Folding the distribution of ion energies and an energy dependent cross section provided by the `NON-SMOKER` calculation, the predicted cross section would have been 88 μbarn. We therefore conclude that the present result indicates a cross section smaller by, at a 68% (90%) confidence level, at least a factor of 2.2 (1.3) compared to the `NON-SMOKER` expectation, considering our reaction distribution, incidentally near the lower limit for `NON-SMOKER`. (At a 99% confidence level, the measured upper limit, 85 μbarn, is still below the `NON-SMOKER` prediction.)

The dependency of the final ^{44}Ti abundance produced in core collapse supernovae was studied in detail by The et al. [19]. The study showed that lowering the ^{44}Ti(α, p)^{47}V reaction rate by a factor of 10 lead to a doubling of the ^{44}Ti abundance in the ejecta. Under the assumption that the present upper limit implies a minimum reduction in the cross section at all energies (within the Gamow window), then the consequent increase in the amount of ^{44}Ti ejected is $\gtrsim$30%, i.e., for the highest model predictions, $\gtrsim 1.3 M_\odot$. This rate increase would bring the observation of ^{44}Ti produced in SN1987A, and especially Cassiopeia A, into closer agreement with the amount predicted by core collapse supernovae models. Finally it is also worth noting that, by applying this factor to the highest model prediction for the CCSNe ^{44}Ti yield, the age of the recently discovered Vela SNR may rather be $\gtrsim$800 years.

In summary we have conducted the first study of the ^{44}Ti(α, p)^{47}V reaction at energies of interest for core collapse supernovae. To achieve this, a novel beam production technique was developed, and we report on its very first results. At PSI, Switzerland, the ERAWAST initiative made a TiF sample containing ^{44}Ti in sufficient quantity that it could be accelerated (at the low energies available) at ISOLDE. This allowed a study at a centre of mass energy of 4.15 MeV, below the lowest energy of the previous study and, for the first time, well within the relevant Gamow window. A detailed analysis found no evidence for the presence of ^{44}Ti(α, p)^{47}V reactions in the data, leading to an upper limit of 40 μbarn, at a 68 % confidence limit. This is about half the `NON-SMOKER` prediction, and constitutes a step towards explaining the ^{44}Ti excesses already observed in CCSNe. Future experimental studies utilising this and other isotopes reclaimed from accelerator waste are anticipated, with improved beam intensities expected.

Acknowledgements

The authors would like to thank the beam development and ISOLDE operations groups of CERN, and in particular Dr. M. Kowalska for helping us with the preparations for the experiment. UK personnel were supported by the Science and Technologies Facilities Council (UK); Canadian personnel were supported by the Natural Sciences and Engineering Research Council of Canada, VM, AStM, TD, AK, GL, DJM and PJW acknowledge support from the European Commission through the ENSAR funding scheme. CW is grateful to EPSRC for support.

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