PROCEEDINGS OF SCIENCE

The abundance of ^{44}Ti in Core Collapse Supernovae: Measuring the ^{44}Ti(α, p)^{47}V Reaction

A. St. J Murphy*, **T. Davinson, A. Kankainen, G. Lotay, D. J. Mountford, C. D. Murphy, P. J. Woods**
School of Physics and Astronomy, The University of Edinburgh, Edinburgh, EH9 3JZ, United Kingdom
E-mail: a.s.murphy@ed.ac.uk

R. Dressler, D. Schumann, T. Stowasser
Laboratory of Radiochemistry and Environmental Chemistry, Paul Scherrer Institut, CH-5232, Switzerland

J. Fallis
TRIUMF, Vancouver, British Columbia V6T 2A3, Canada

A. M. Laird
Department of Physics, University of York, York, YO10 5DD, United Kingdom

C. Seiffert, T. Stora
CERN (Organisation Europenne pour la Recherche Nucleaire), CH-1211 Geneve 23, Switzerland

C. H.-T. Wang
Department of Physics, Aberdeen University, Aberdeen, AB24 3UE, United Kingdom

Space-based γ-ray satellites such as BeppoSAX, COMPTEL and INTEGRAL have reported detection of $^{\mathbf{44}}$Ti in the Cassiopeia-A and SN1987a core-collapse supernova remnants. The NuSTAR satellite has recently measured the distribution of ^{44}Ti γ-ray emission in Cassiopeia-A finding a highly asymmetric distribution. In all cases, the amounts of ^{44}Ti inferred in the ejecta are higher than expected, even assuming a wide range of progenitor models and masses. The dominant nuclear uncertainty within such models is the rate of the ^{44}Ti(α, p)^{47}V nuclear reaction rate.

Through radiochemical separation, a sample of ^{44}Ti was obtained from highly-irradiated martensitic steel accelerator components of the Paul Scherrer Institute. Transported to CERN, this material was then developed into a beam at the REX-ISOLDE facility and directed onto a gas filled cell. This enabled a study of the ^{44}Ti(α, p)^{47}V reaction at an energy of E_{cm}=4.15 MeV, finding an upper limit for the cross section of 40 μb (68% c.l.). Possible implications for core collapse supernovae are presented.

PoS(NIC XIII)126

XIII Nuclei in the Cosmos,
7-11 July, 2014
Debrecen, Hungary

*Speaker.

1. Introduction

Titanium-44 is a radionuclide with a half life of 59 years that is produced in core collapse supernovae. Its β-decay to ^{44}Sc and then ^{44}Ca leads to γ-rays being emitted, at 68, 78 and 1157 keV, that are detectable in space. These have been measured by γ-ray observatories hosted on satellites, for example ESA's INTEGRAL and NASA's NuSTAR satellites. However, where measurements of the amount of ^{44}Ti in the ejecta of collapse supernovae have been made, the values are significantly higher than models predict. Recently reported measurements and model predictions are presented in table 1.

Observations		$\times 10^{-4} M_{\odot}$
Cas-A	NuSTAR [1]	1.25(0.3)
Cas-A	COMPTEL [2]	$1.6(^{0.6}_{-0.3})$
SN1987a	INTEGRAL [3]	3.1(0.8)
Models		
Maximum	e.g. Tur *et al.* [4]	1.0
Typical	e.g. Tur *et al.* [4]	0.2 – 0.4

Table 1: Observed and estimated quantities of ^{44}Ti to be present in the Cassiopeia-A and Sn1987a core collapse supernova remnants.

Could this discrepancy be due to unknown nuclear physics? The models that predict the amount of ^{44}Ti produced include nuclear reaction rates for processes that produce the isotope, and reaction rates for those that destroy ^{44}Ti. Each of these has an uncertainty, but the one whose uncertainty is most important is that of ^{44}Ti(α, p)^{47}V. The relevant energy range over which the cross section is required is known as the Gamow window, and for the regions of core-collapse supernovae within which ^{44}Ti is most efficiently synthesised, this spans temperatures between 2 and 4 GK, and energies between 2 and 6 MeV$_{cm}$. Only one measurement exists [5], and this does not cover the relevant range of energies, having a single lower data point at the upper end of the Gamow window, at 5.7 MeV$_{cm}$.

2. Experiment at REX-ISOLDE

A direct measurement of this reaction is difficult because the beam-target combination is troublesome, requiring either a radioactive target, or a radioactive beam and a gas target. In addition, the energies corresponding to those found in core collapse supernovae are relatively low, meaning cross sections will be small. For this experiment, the ERAWAST project [6] provided ^{44}Ti that had been extracted from components of the PSI synchrotron facility. This was transported to CERN where the the REX-ISOLDE facility was used to develop a beam with the required energy. For a period of ~70 hours total beam exposure, this was then impinged on a helium filled gas cell, with reaction protons and elastically scattered α-particles detected with double sided silicon strip detectors, see Figure 1.

PoS(NIC XIII)126

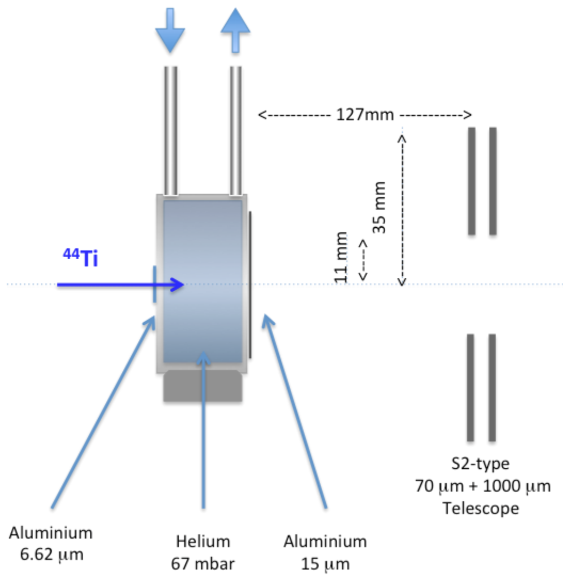

Figure 1: Schematic diagram of the experimental set up used for this measurement. .

About 50 MBq (1.35 $\times 10^{17}$ atoms) of ^{44}Ti was used. From this a beam with intensity varying from 5×10^5 to 2×10^6 pps was obtained (higher at the start, decreasing through the run) and accelerated to 92.4 MeV. Passing through the 6.62 μm Al entrance foil reduced this to 49.8 MeV, with an energy width of 2.8 MeV (1σ). The gas cell, 2 cm in length, could be filled with natural helium up to pressures of $\sim$100 mbar. An exit window consisted of 15 μm of Al, stopping all but protons and α-particles. Downstream, particles were detected in a telescope consisting of a 65 μm and a 1000 μm thick S2-type [7] detectors.

3. Results

Data were collected both with the gas cell evacuated, and with it containing 67 mbar of natural helium. Figure 2 plots the values of the energy signals of the two silicon detectors against one another, thus separating particle species. In the upper panel the data accrued with helium gas present in the gas cell are shown. The band labelled C corresponds to helium ions. The lower band, labelled A, B and D, corresponds to protons being detected. The lower panel shows data collected when there was no helium in the gas cell. The absence of events in the position of band C clearly indicates that these events arise from elastic scattering of the helium gas with beam. Prior to the experiment extensive Monte Carlo simulations had been performed, and the location and rate of events closely matches this hypothesis. Since the cross section for elastic scattering is known, the yield of α-particles in the gas-in runs provides an accurate cross-section calibration for other particle species in those runs. The same simulations had predicted features A and B corresponding to protons ejected by the ^{44}Ti beam impinging hydrogen in oil or water deposits on the gas cell windows. B is from the front of the front window, while A is from the rear of the front window.

If there are protons arising from the reaction of interest, ^{44}Ti(α, p)^{47}V, these too are expected in Figure 2, with the region labelled D indicating where. Figure 3 shows the total energy of de-

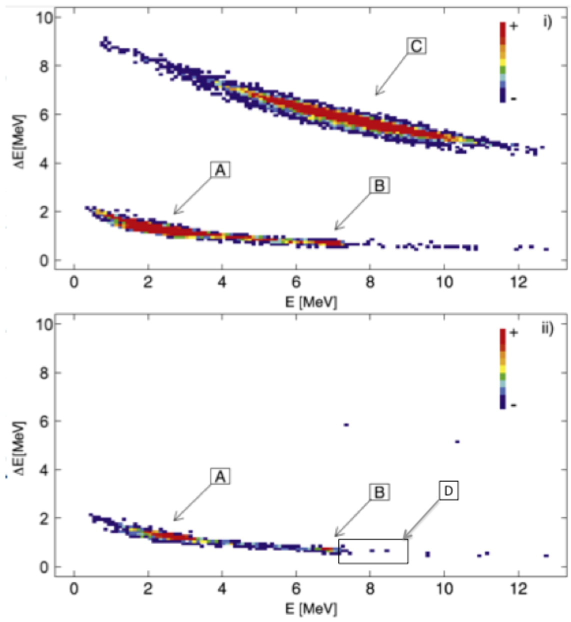

Figure 2: Plot of the energy signals recorded in the thin (transmission) and thick (stopping) components of the detector telescope. The labelled groups represent the elastic protons emitted from the back of the front window and the front of the back window (A), the elastic protons emitted from the front of the front window (B), and the elastically scattered α-particles (C). Region (D) is where events from the reaction of interest might be expected to appear. Upper panel gas in; lower panel gas out.

tected ions (the sum of the energies recorded in the two detectors) in the region where such events would be expected. The experimentally observed data are shown by the black histogram. The red histogram shows the result of a Monte Carlo simulation of the protons expected from ^{44}Ti scattering with hydrogen in oil or water deposits on the gas cell entrance foil (feature B), and reproduces the data well. The blue line shows the expected location of protons emitted from ^{44}Ti(α, p)^{47}V reactions in the gas, scaled to an arbitrarily large reaction cross section to aid the eye, and is labelled feature D. The simulation includes energy losses and energy and angular straggling as well as the relevant kinematics, and predicts the reaction protons of interest will be detected over a significant range of energies, that partially overlaps feature B. However, almost exactly half of the events are expected above feature B, in a nearly event free region. The yield of events that is observed in this region is consistent with the yield that was observed in the gas-out exposure. Consequently, it was possible to calculate an upper limit for the reaction cross section. The Feldman-Cousins [8] approach was used, finding that, given the known background, there could be a maximum of 5.3 counts due to ^{44}Ti(α, p)^{47}V reactions in the blue-shaded region shown in the upper panel of Figure 3 (at 1 sigma). Using the cross section calibration available from the known cross section for the measured ^{44}Ti(^{4}He, ^{4}He) reaction, and a factor to account for the change in geometric efficiency for the two reactions, this corresponds to an upper limit on the ^{44}Ti(α, p)^{47}V reaction cross section of 40 μb.

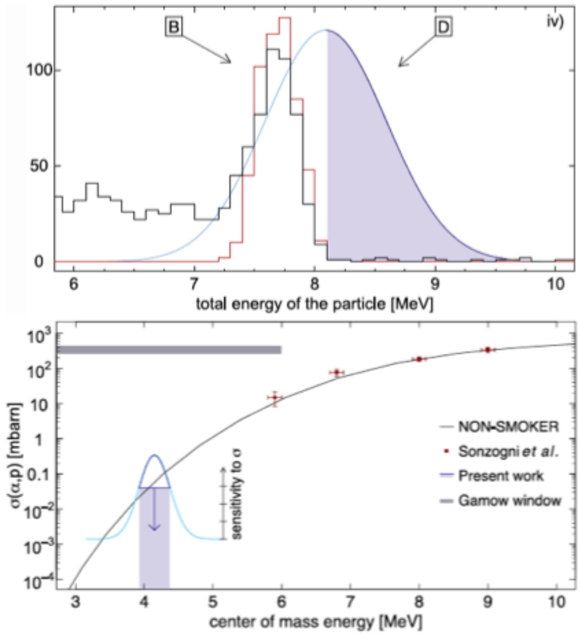

Figure 3: Upper panel: Yield of detected particles as a function of the total energy detected. Experimental data are shown as the black histogram while the red histogram shows the result of a Monte Carlo simulation of ^{44}Ti(^{1}H, p)^{44}Ti reactions occurring on the surface of the gas cell window, as may be expected from the presence of surface oil or water deposits. The D label denotes the simulated distribution of the expected ^{44}Ti(α,p)^{47}V events (in blue), for a deliberately high cross section. The darker section shows the region of interest (centroid to 3 sigma), see text. Lower panel: Comparison the present result and cross sections measured by Sonzogni *et al.* [5] and the NON-SMOKER prediction, black line, for the ^{44}Ti(α, p)^{47}V reaction. Note that the Gaussian represents the energy spanned by the beam as it passes through the gas cell, see text.

4. Discussion

The lower pane of Figure 3 presents the measured cross section together with previous data points [5] and the cross section predicted by the NON-SMOKER statistical model [9]. In the present experiment, the significant energy loss, and thus energy-straggling, encountered by the beam in passing through the entrance window of the gas cell has led to the ^{44}Ti ions having a broad range of energies, and thus the possibility for reactions to occur over a broad range of centre of mass energies. This is illustrated by the Gaussian profile presented with the data point in the lower panel of Figure 3, and corresponds to the profile generated in the Monte Carlo simulation. A calculation that assumes the cross section illustrated by the NON-SMOKER curve, and the profile of beam energies given by the Gaussian in Figure 3, shows that the present experiment would have recorded a cross section of 88 μb. We therefore conclude that the present result indicates a cross section smaller by a factor of at least 2.2 compared to the NON-SMOKER expectation. Furthermore, these new data may indicate that the energy dependence of the cross section is steeper than previously considered, at least at low centre of mass energies.

The dependency of the final ^{44}Ti abundance produced in core collapse supernovae was studied in detail by The *et al.* [10]. 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, following the dependence outlined in The *et al.*, is at least 30%. 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.

A more detailed account of this work is published in [11]. In the near future, it is hoped that a second measurement may be performed using essentially the same experimental technique and facilities, but incorporating significantly greater beam intensity due to anticipated improvements in ion source extraction efficiency. Given the sensitivity already achieved, we expect to be able to make a definitive measurement of the cross section for the ^{44}Ti(α,p)^{47}V reaction over a significant fraction of the Gamow window.

References

[1] B. W. Grefenstette *et al.* Nature 506 (2014) 339-342

[2] R. Renaud *et al.* Astrophys. J. (647) 2006 L41-L44

[3] S. A. Grebenev, A. A. Lutovinov, S. S.Tsygankov, C. Winkler, Nature 490 (2012)373-375

[4] C. Tur, A. Heger, S. M. Austin, Astrophys. J. 718 (2010) 357-367

[5] A. A. Sonzogni, *et al.*, Phys. Rev. Lett. 84 (2000) 1651

[6] http://www.psi.ch/lch/erawast-i

[7] Micron Semiconductor Ltd., http://www.micronsemiconductor.co.uk

[8] G. J. Feldman, R. D. Cousins, Phys. Rev. D57 (1998) 3873 - 3889

[9] T. Rauscher, F.-K. Thielemann, At. Data Nucl. Data Tables 75 (2000) 1; *ibid.* At. Data Nucl. Data Tables 79 (2001) 47

[10] L.-S. The, D. D. Clayton, L. Jin ,B. S. Mayer, Astrophys. J. 504 (1998) 500

[11] V. Margerin *et al.* Phys. Lett. B 731 (2014) 358-361