EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Letter of Intent to the ISOLDE and Neutron Time-of-Flight Committee

Measurement of the ^{44}Ti(α,p)^{47}V reaction cross section, of relevance to gamma-ray observation of core collapse supernovae, using reclaimed ^{44}Ti

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A. StJ. Murphy[1], T. Davinson[1], R. Dressler[2], J. Fallis[3], D. Kahl[1], C. Lederer-Woods[1], C. Seiffert[4], D. Schumann[2], T. Stora[4], P. J. Woods[1]

[1] *School of Physics and Astronomy, The University of Edinburgh, Edinburgh, EH9 3JZ, UK*
[2] *Laboratory of Radiochemistry and Environmental Chemistry, Paul Scherrer Institut, CH-5232, Switzerland*
[3] *North Island College, Courtenay, British Columbia V9N 8N6, Canada*
[4] *CERN (Organisation Européenne pour la Recherche Nucléaire), CH-1211 Genève 23, Switzerland*

Spokesperson: A. StJ. Murphy [a.s.murphy@ed.ac.uk]
Contact person: K. Johnson [karl.johnston@cern.ch]

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Abstract:
A detailed understanding of the mechanism and impact of stellar core collapse remains elusive. For the two most studied examples, Cassiopeia-A and SN1987A, a key observable is γ-ray emission from ^{44}Ti ejected during the explosion. Discrepancies remain between model and observation, despite advances in both. The largest nuclear physics uncertainty is the rate of the ^{44}Ti$(\alpha, p)^{47}$V reaction. In 2012, our team performed a direct study of this reaction using ^{44}Ti from PSI, accelerated with REX-ISOLDE, and impinged on a helium-filled gas cell (Experiment IS-543). We determined that the cross section at E_{cm}=4.15 MeV is at most half the NON-SMOKER expectation. The result has been adopted by modellers, who find that if typical at all energies this would bring model and observation of ^{44}Ti γ-ray flux into much closer agreement. Robust constraint of this reaction rate is now critical to allow advanced hydrodynamical modelling to progress. A proposal for additional beam time has been accepted, beamtime requested, and a run in late 2017 or perhaps 2018 anticipated, with the aim to make measurements (not upper-limits) of the reaction cross section at several energies within the Gamow window. Here we request consideration of further additional running during Long Shutdown 2, to push to lower energies, and explore any features seen in 2017/18 running (e.g. evidence for resonances).

Requested shifts: [14 $\times$ 12 hour] shifts
Installation: [3rd beamline]

Status

In December 2012, a first phase of Experiment IS-543 was conducted, successfully demonstrating the use of ^{44}Ti obtained by radiochemical separation of highly irradiated components at the PSI. An upper limit on the ^{44}Ti(α,p)^{47}V cross section was determined at an energy well within the Gamow window for core collapse supernovae. The value was about half of that expected from the NON-SMOKER statistical model code, and if indicative of the cross section at all energies, offers an explanation for the large amounts of ^{44}Ti observed in supernova remnants. The results have been published in Physics Letters B [1], adopted in scientific simulations, and have attracted significant wider attention, *e.g.* New Scientist [2] , The Sunday Times [3], UK News from CERN and Nuclear Physics News.

Motivation

The radionuclide ^{44}Ti is one of the very few cosmogenic nuclei to be observed in our Galaxy, and its observation is a the key goal for a number of major space missions. Distinctive γ-rays are emitted at 68, 78 and 1157 keV. The INTEGRAL satellite recently updated its observations of the Cassiopeia-A supernova remnant [4], and early results from the NuSTAR satellite have been presented for both Cassiopeia-A [5, 6] and SN1987a [7]. These confirm that the total amount of ^{44}Ti ejecta is around $1.5{\times}10^{-4}$ $M_\odot$. This is more than models are typically able to produce, around $1.0{\times}10^{-4}$ $M_\odot$ at most. Moreover, the imaging capabilities of NuSTAR have revealed clumpy, non-uniform distributions of titanium around the centre of the expansion that are spatially separated from regions of iron X-ray emission. This is an unexpected and exciting result, that may be another clue towards resolution of the long standing desire for robust models of core collapse supernovae. For robust conclusions from hydrodynamical studies it is now more important than ever that the dominant nuclear physics undertainties be removed.

Several recent simulation studies have explicitly focused on the production of ^{44}Ti and other important radioisotopes. In 2015, Perego *et al.* [8], using a spherically symmetric 1-D hydrodynamical simulation of 18-21 $M_\odot$ progenitors, explored the astrophysical impact of our finding of a reduced ^{44}Ti(α, p)^{47}V cross section. Assuming that the reduction in cross section is typical for all energies within the Gamow window, the yield of ejected ^{44}Ti rose by 43%. This value is then only marginally below the observational data. Also in 2015, Wongwathanarat *et al.* [9] simulated the explosions of several 15 and 20 $M_\odot$ red and blue supergiants. One of their models adequately reproduced the observed Cassiopeia-A and SN1987A titanium and iron spatial distributions and variability, as well as features such as the velocity fields and neutron star kicks. Then in 2016, Wongwathanarat *et al.* [10] performed 3D models that deliberately resembled the progenitor of Cassiopeia-A, using our result to guide a reduction in the forward and inverse rates of ^{44}Ti(α, p)^{47}V. They found a 50% increase in the ejected ^{44}Ti abundance, again bringing model and observation in to closer ageement. Other mechanisms to increase the final abundance of ^{44}Ti have also been explored, for example, Chieffi *et al.* 2017 [11] explored the role of rotation, finding that in most cases, the thickness of the region exposed to the incomplete explosive Si burning increased in rotating models, leading to a decrease in the amount of ^{44}Ti relative to ^{56}Ni (from which the iron producing X-ray emission is derived). However, some rotating models developed extended convective shells that preserved the ^{44}Ti. The paper again emphasised the importance of constraining the nuclear reaction rates.

In summary, observations and models of core collapse supernovae are progressing. ^{44}Ti observations are proving to be useful to explore the complex physics, but further progress requires the key ^{44}Ti(α, p)^{47}V reaction rate uncertainty to be reduced.

Experimental methods

The Edinburgh-PSI-CERN collaboration has developed a novel technique to obtain and then accelerate ^{44}Ti ions [12]. A ^{44}Ti sample was obtained through the ERAWAST initiative [13]. ^{44}Ti is extracted from irradiated components, diluted into an HF solution, evaporated on a molybdenum foil, and transported from PSI to CERN. A TiF_3^+ molecular beam is extracted from the unit installed on the General Purpose (mass) Separator front end at ISOLDE and then bunched and cooled in the REX-TRAP Penning trap and dissociated in the electron beam ion source [14], before acceleration in the linear accelerator of the REX-ISOLDE facility. In the first run, $^{44}Ti^{13+}$ 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 $\approx$ 2.1 MeV/u and impacted upon on an aluminium windowed gas cell containing $\approx$67 mbar of helium gas. A thin entrance window was used so as to minimise the required incident beam energy and thus minimise fusion-evaporation from carbon and oxygen contaminants, but a relatively thick exit window ensures that all recoils and the unreacted beam does not escape the cell while light particles may do so. For the detection of light particles a ΔE-E telescope, consisting of two Micron Semiconductor Ltd S2-type silicon detectors [15] of 65 μm and 1000 μm thickness, respectively, was positioned at 12.7 cm downstream with respect to the exit window of the gas cell. The two components of the telescope each provided 48 circular strips and 16 azimuthal sectors, allowing criteria to be set for gating on recorded events.

Next phases of IS-543

A new vacuum chamber has been built to house the helium gas cell and detectors, which is in fact the same chamber as will be used in IS-607 (PI Lederer-Woods, Edinburgh) that is scheduled to run in November 2017. Additional beam time for IS-543 was most recently requested in February 2017, and we are optimistic that a run might be scheduled at the end of the year, both due to the scientific priority and to optimise logistics. Several minor improvements on the apparatus used in 2012 are planned, for example alternate window material, the possible use argon to fill the gas cell during calibration runs, but the overall (proven) technique remains unchanged. (The greatest change is the anticipated significant increase in beam intensity). The shift request amounted to a total of 168 hours, which would allow measurements and calibrations at four beam energies. This will confirm the first result, is expected to result in measurements not uppoer limits, and will provide a data point at a high energy to compare with previous work. Data at a low centre of mass energy, most deeply in the Gamow window and important for confirming the overall energy dependence, will be attempted. The precise energy chosen will depend on the beam intensity realised at the time of the run. However, additonal beam time to push further down in energy will always increase the scientific relevance of the data. Moreover, given the alpha-conjugate nature of both beam and target, it is reasonable to anticipate that the energy dependence might not be completely smooth, even allowing for the finite energy bite of each measurement. The energy-width of the beam after pasing through the new entrance window is expected to be ~100 keV, enabling posisble exploration of broader resonant structures. Given this, runs at 4 energies may well not prove definitive.

Consequently, **we strongly support the suggesion of experimental operations during the Long Shutdown #2**, and request 14 12-hour shifts for direct measurement of the ^{44}Ti(α, p)^{47}V cross section. The ^{44}Ti samples have already been produced and are available for use. In the absence of data on which to base rate calculations, we assume cross sections that are half of NON-SMOKER values (*i.e.* per the result of our first run), a beam intensity of 10^7 pps, an overall 30% detection efficiency and have included periods for gas-out calibration runs. This results in an anticipated count rate of 10 events per 12 hour shift at 3.8 MeV$_{cm}$, approximately matching our sensitivity limit (see Appendix). Data from 2017/18, and from the first data sets in LS#2, would be at higher energies, providing better guidance to estimate the low-energy cross section, thus informing the choice of lowest energy attempted (as would the actual delivered beam intensity).

References

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[14] T. Stora, Nucl. Instr. Meth. B **317** (2013), 402.

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

Appendix

COUNT RATE

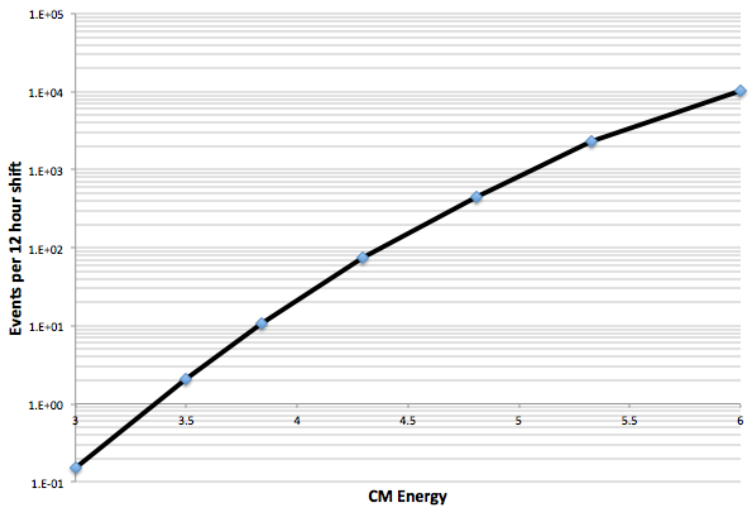

Figure 1: Estimated number of counts per 12 hour shift. The calculation assumes cross sections that are half of that given by NON-SMOKER, 10^7 beam particles per second, an efficincy of 30% and a 2-cm long gas cell filled will 70 Torr of helium.

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: *(name the fixed-ISOLDE installations, as well as flexible elements of the experiment.*

<table>
<tr><th>Part of the</th><th>Availability</th><th>Design and manufacturing</th></tr>
<tr><td>Dedicated vacuum chamber to be attached to XT03</td><td>☑ Existing</td><td>☑ To be used without any modification</td></tr>
<tr><td rowspan="2">Chamber, Detectors, DAq system</td><td>☐ Existing</td><td>☐ To be used without any modification
☐ To be modified</td></tr>
<tr><td>☑ New</td><td>☑ Provided by the Edinburgh group
☐ Standard equipment supplied by a manufacturer
☐ CERN/collaboration responsible for the design and/or manufacturing</td></tr>
<tr><td rowspan="2">^{44}Ti on tantalum foils</td><td>☐ Existing</td><td>☐ To be used without any modification
☐ To be modified</td></tr>
<tr><td>☑ New</td><td>☐ Standard equipment supplied by a manufacturer
☑ CERN/collaboration responsible for the design and/or manufacturing</td></tr>
<tr><td>[insert lines if needed]</td><td></td><td></td></tr>
</table>

HAZARDS GENERATED BY THE EXPERIMENT

Additional hazards:

Hazards	[Part 1 of experiment/ equipment]	[Part 2 of experiment/ equipment]	[Part 3 of experiment/ equipment]
Thermodynamic and fluidic: NONE UNUSUAL			
Electrical and electromagnetic: NON UNUSUAL			
Ionizing radiation			
Target material [material]	^{4}He (200 mBar)	^{4}He (200 mBar)	^{4}He (200 mBar)
Beam particle type (e, p, ions, etc)	^{44}Ti	^{44}Ti	^{44}Ti
Beam intensity	50×10^{6} pps	50×10^{6} pps	50×10^{6} pps
Beam energy	1.2 MeV/u	1.36 MeV/u	1.64 MeV/u
Cooling liquids	water	water	water
Gases	helium	helium	helium
Calibration sources:	☑		
• Open source	☐		
• Sealed source	☑ [ISO standard]		
• Isotope	^{60}Co	^{137}Cs	
• Activity			
Use of activated material:			
• Description	☐		
• Dose rate on contact and in 10 cm distance	[dose][mSV]		
• Isotope			
• Activity			
Non-ionizing radiation: NONE UNUSUAL			
Chemical: NONE UNUSUAL			
Mechanical: NONE UNUSUAL			
Noise: NONE UNUSUAL			
Physical: NONE UNUSUAL			

Hazard identification:

Average electrical power requirements (excluding fixed ISOLDE-installation mentioned above): [Minimal]