EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

IS543 - 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 from radioactive waste

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Abstract: In 2012, the ^{44}Ti)α, p)^{47}V reaction was studied at 4.15 MeV in the centre of mass of the α-particle at the REX-ISOLDE. The conclusion of that experiment hinted at a higher production rate for ^{44}Ti by models tackling the issue of core collapse supernovae. Yet the experiment was not completed due to the CERN shutdown. We propose here modifications and new developments to the experiment for the new phase. We also request an extended number of shifts to complete our study.

Requested shifts: 24 shifts.

1 Status

In December 2012, a first phase of Experiment IS-543 was conducted. This successfully demonstrated the use of ^{44}Ti obtained by radiochemical separation of highly irradiated components at the PSI, inserted in to a FEBIAD ion source, and accelerated on the REX-ISOLDE beamline. A beam of about 2×10^{6} pps, dropping to 5×10^{5} pps was delivered to a helium filled gas cell. 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, and was about a factor of two below the expectation of the NON-SMOKER statistical model code. This is a significant advance on the only previous study, and if indicative of the cross section at all energies, offers an explanation for the large abundances of ^{44}Ti observed from supernovae. The results have been published in Physics Letters B [1], and have attracted significant wider attention, *e.g.* New Scientist [2] , The Sunday Times [3], UK News from CERN and Nuclear Physics News.
Here we request further beamtime, with the expectation that a statistically significant measurement, at several energies deep in to the Gamow window, is likely. Achieving an upper limit for the cross section *below* the NON-SMOKER expectation suggests we were somewhat unlucky last time. Secondly, the beam development team believe a significantly more intense beam can be delivered (a factor of $\times10$–$\times100$), resulting from the experience they gained from the first effort, and as it appears that there was a fault in the ion source last time.

2 Motivation

2.1 Core collapse supernovae (CCSNe) events

The radionucleide ^{44}Ti is one of the very few cosmogenic nuclei to be observed in our Galaxy. Cosmic γ-rays associated with the decay of ^{44}Ti have been observed from SN1987A by the INTEGRAL IBIB/ISGRI instrument [4], previously used to detect this isotope from Cassiopeia-A [5]. Traces of ^{44}Ti from Cassiopeia-A were also observed by the CGRO instrument onboard the COMPTEL satellite [6] and by the PDS system on board BeppoSAX [7]. Earlier this year novel investigation of ^{44}Ti isotopic content from Cassiopeia-A, using the space based Nuclear Spectroscopic Telescope Array (NuSTAR), highlighted the asymmetry of the explosion and hence of the ^{44}Ti ejecta content [8]. As a result ^{44}Ti is a versatile tool for providing insight to a specific astrophysical environment.

Unravelling the underlying explosion mechanism of CCSNe is a highly topical quest in modern astrophysics. The sequence of events leading to moments before the explosion is very well understood and was confirmed by observations of SN1987A (see Refs. [9, 10, 11]). Modelling the subsequent physics is a task that has proven to be much harder to realise. In particular robust explosion of the star still has to be artificially generated rather than obtained naturally by the models. Despite those difficulties, the development of a neutrino wind appears as the most compelling theory [12]. This would be dense enough that sufficient neutrino-nucleon interactions occur [13], re-igniting the nuclear reaction network in the "frozen" outer layer of the core. New Physics, for example acoustic coupling of gravity waves [14, 15, 16] or the dynamical trapping and relaxation of scalar fields [17] have also been invoked as a mechanisms to enable successful core collapse supernovae explosions.

If the underlying explosion mechanism could be resolved through observational data, then it would not be from signatures such as light curves and (near)optical spectra. Indeed, those show little sensitivity to the detail of the explosion mechanism. In contrast, observations of γ-rays from the long lived isotope ^{44}Ti ejected into the interstellar medium might provide such sensitivity. The ^{44}Ti nucleus is produced in α-rich freeze out regions as the QSE phase ends [18]. The amount of newly produced ^{44}Ti which gets trapped into the proto-neutron star or the forming black hole is linked to the hydrodynamics of the star. Thereby, ^{44}Ti 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 in to space. Despite this sensitivity, it is difficult to eject more than 1×10^{-4}M$_\odot$, with existing models, even assuming a wide range of progenitor models and masses [19, 18, 20].

Distinctive γ-rays are emitted as ^{44}Ti β-decays to ^{44}Sc*, τ=85.3(4) years (see Ref. [21]), with the subsequent emission of two fast γ-rays at 68 and 78 keV. ^{44}Sc also β-decays to ^{44}Ca*, τ=5.73(6) hrs [22], resulting in the emission of a 1157 keV γ-ray. This enables space-based observatory to track the isotope in order to measure ^{44}Ti yield from supernovae, whether known or newly discovered. For instance observations of SN1987A indicate the presence of $(3.1\pm0.8)\times10^{-4}$M$_\odot$ of ^{44}Ti in the ejecta. In the recent study of Grefenstette *et al.* [8] the ^{44}Ti yield is measured at 1.25(30) M$_\odot$. The latter measurement demonstrates the progress of observations which incorporates thorough mapping of the emission locus. Consequently the pressure for precise measurement of nuclear reactions involved keeps growing, as a significant discrepancy between observations and the model predictions persists. Age and/or distance determination for CCSNe also critically depends on the amount of ^{44}Ti observed in the ejecta. An intriguing example lies in the observation a previously unknown supernova remnant located in the Vela region from the COMPTEL γ-ray data [23]. Assuming the distance to be that of a possible optical counterpart at 200 pc, and a 'standard' ^{44}Ti yield of 5×10^{-5} M$_\odot$, the suggested age for the remnant was $\sim$700 years. Given the relative proximity, and the period in history, it has been noted that it is somewhat surprising that no record of a corresponding supernova explosion observation exists. As a result the experimental determination of the ^{44}Ti yield in CCSNe ejecta might bring clues to those open questions. By addressing the influence of hundreds of reactions to the final amount of ^{44}Ti it has been shown by, for example, The *et al.* [24] and Magkotsios *et al.* [18], that the most critical reaction was the ^{44}Ti$(\alpha, p)^{47}$V destructive site on top of ^{40}Ca$(\alpha, \gamma)^{44}$Ti and the triple-α reaction.

2.2 Results from IS-543-I

Investigation of the reaction cross section was performed at the REX-ISOLDE facility in December 2012. Due to the proximity of the shut down only 10 of the 27 shifts given to the IS543 experiment could be used. In this limited time and considering the novel beam development technique, extracting meaningful results was challenging. However the measurement of the cross section was recently reported [1]. Only an upper limit at an energy well within the Gamow window (4.15 MeV) could be obtained. The upper limit of 40 μbarn, at a 67%

confidence level, is almost twice lower than the prediction from the `NON-SMOKER` statistical reaction model. Such a lowering of the destruction rate of ^{44}Ti in CCSNe environment would lead to a 30% increase of the total ^{44}Ti yield. In the case of Cas-A this would virtually bring models and observations into agreement.

3 Experimental methods

3.1 Details of IS-543-I

In order to perform the first experiment the (mainly) Edinburgh-PSI-CERN collaboration developed a novel technique to obtain and then accelerate ^{44}Ti ions. As the reaction was studied at low energy with (predicted) sub mbarn cross section, it is crucial to be in possession of a rich ^{44}Ti sample. The sample was obtained through the ERAWAST initiative [25] that exploits highly irradiated components from the high intensity proton accelerator on site and turn them into sources of exotic radio isotopes, see Ref. [26] for more details. The extracted ^{44}Ti was diluted into an HF solution, evaporated on a molybdenum foil, and transported from PSI to CERN where the accelerator team developed a technique for the production of TiF_x molecular ions [27]. A TiF_3^+ molecular beam was then 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 [27], before acceleration in the linear accelerator of the REX-ISOLDE facility. $^{44}\mathrm{Ti}^{13+}$ 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 a aluminium windowed gas cell containing $\approx$67 mbar of helium gas. The rather low Coulomb barrier for the fusion of ^{44}Ti and ^{27}Al (107 MeV), ^{16}O (99 MeV) or ^{12}C (95 MeV) – the last two nuclei are contaminants from water and oil condensation on the aluminium windows – necessitated the use of a thin ($\approx$6 μm) entrance window to minimise the additional beam energy required to compensate for the loss in the entrance window. Note that the fusion evaporation channels of both reactions are dominated by the emission of several protons. 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 [28] 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.

3.2 Next phase of IS-543

While the detection technique is not expected to be profoundly modified, apart from the likely addition of a second S2-telescope, a new gas cell entrance window using thin (2-4 μm) Mylar foil will be used. It is expected that elastically scattered protons from the scattering centres of the Mylar molecule (a $\mathrm{C}_x\mathrm{H}_y\mathrm{O}_z$ composite), and the oil/water condensation on the window will generate, considering a 60 MeV beam, a 5 kHz count rate, below the detectors limit of 10 kHz. Note that due to the $1/E^2$ dependance of the Rutherford cross section, a higher beam energy will only lower this background rate. The exit window will not be changed (a 15 μm thick aluminium foil) as this effectively stops the recoil and only generates background counts from water/oil condensation on the inner side of the window.

Previous work from the Edinburgh group has used thin Mylar foils with 300 mBar pressure which is $\sim$5 times higher than was used in the first phase of IS543. Our preliminary tests indicate that the gas cell with its new entrance window can handle this pressure and we anticipate to run at 150-200 mBar. For the experiment we would be in possession of a 30 MBq sample of ^{44}Ti, similar to what provided for the first experiment, but it is thought that little of the source material was successfully extracted and delivered to the gas cell [29]. With better efficiency, a significantly stronger beam intensity is expected.

The use of Mylar foils leads to a lower energy beam being required to deliver the the same reaction energy, as compared to aluminium foils. This is due to different energy loss in the respective materials. In case such lowering of the beam energy is unfeasible at this stage of development of ISOLDE, we would have to return to the Aluminium entrance window, with 6 μm thickness (as given by the manufacturer), the smaller thickness that resisted a range of pressure tests that we conducted before IS543-I. However we stress that this would constrain us to high energies, with regards to the Gamow window, which would not necessarily fulfil the scientific case.

In the ideal case, we propose to explore the cross section for the ^{44}Ti(α, p)^{47}V reaction at 4 energies, given here in the centre of mass frame for the α-particle: 6 MeV, 5.5 MeV, 5 MeV, and 4 MeV. The motivation for this choice is to 1) corroborate the results from Sonzogni *et al.* at 6 MeV, the high energy end of the Gamow window, 2) map out the cross section behaviour in the 5-6 MeV region of the Gamow window, where the cross section is high, 3) confirm and obtain a cross section value at the 4 MeV, the energy used in the first phase of IS543. Upon obtaining of meaningful measurements, lower reaction energies could potentially be investigated, we note that those represent a very demanding and exciting technical challenge.

The progress made by the CERN beam development team in understanding the ^{44}Ti source means that it is not foolish to seek for an increase of a factor of 10 to 100 in beam intensity. For an increase of a factor of 50, the beam intensity would be in the range 25 to 100×10^6 pps, the expected count rate for the ^{44}Ti(α, p)^{47}V is presented in Table 1. (The figures shown there are drawn considering a similar increase of the cross section at 6 MeV to that measured by Sonzogni *et al.* value at 5.8 MeV, the `NON-SMOKER` prediction at 5.5 and 5 MeV, and our upper limit from the previous measurement at 4.15 MeV.) Upon measuring the reaction at those 4 energies successfully, we could then consider to investigate the reaction at another energy either between 4 and 5 MeV or several hundreds of keV below 4 MeV depending on beam time available.

We therefore request, in total and including the time that could not be used in the first experiment due to the CERN shutdown, 12 days of beam time which would allow us to firmly set the cross section for the reaction. The unusually long requirement is motivated by the need for several beam energy changes and the low cross section giving a very slow count rate for the reaction as shown before.

Table 1: Expected event rate, in the S2-telescope, for the ^{44}Ti(α, p)^{47}V reaction at 4, 5, 5.5 and 6 MeV in the centre of mass of the reacting α-particle, for a beam intensity of 50×10^6 pps. The rates are given following two possible entrance foil materials. It is assumed that the detector is at 12 cm downstream and that its efficiency is 100%

Entrance window foil	^{4}He gas pressure [mBar]	Reaction energy [MeV]	E_{beam} [MeV/u]	σ [mbarn]	Event rate [counts/s]
Mylar (3 μm)					
	200	4	1.09	<0.05	~0.003
	200	5	1.36	0.7	~0.04
	200	5.5	1.50	3.5	~0.2
	200	6	1.64	15	~1
Al (6 μm)					
	70	4	2.08	<0.05	~0.001
	70	5	2.60	0.7	~0.02
	70	5.5	2.86	3.5	~0.08
	70	6	3.12	15	~0.3

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

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

Part of the	Availability	Design and manufacturing
(if relevant, name fixed ISOLDE installation: COLLAPS, CRIS, ISOLTRAP, MINIBALL + only CD, MINIBALL + T-REX, NICOLE, SSP-GLM chamber, SSP-GHM chamber, or WITCH)	☑ Existing	☑ To be used without any modification
Chamber, Detectors, DAq system	☐ Existing	☐ To be used without any modification ☐ To be modified
	☑ New	☑ Provided by the Edinburgh group ☐ Standard equipment supplied by a manufacturer ☐ CERN/collaboration responsible for the design and/or manufacturing
^{44}Ti on tantalum foils	☐ Existing	☐ To be used without any modification ☐ To be modified
	☑ New	☐ Standard equipment supplied by a manufacturer ☑ CERN/collaboration responsible for the design and/or manufacturing
[insert lines if needed]		

HAZARDS GENERATED BY THE EXPERIMENT (if using fixed installation:) Hazards named in the document relevant for the fixed [COLLAPS, CRIS, ISOLTRAP, MINIBALL + only CD, MINIBALL + T-REX, NICOLE, SSP-GLM chamber, SSP-GHM chamber, or WITCH] installation.

Additional hazards:

Hazards	[Part 1 of experiment/ equipment]	[Part 2 of experiment/ equipment]	[Part 3 of experiment/ equipment]
Thermodynamic and fluidic			
Pressure	[pressure][Bar], [volume][l]		
Vacuum			
Temperature	[temperature] [K]		
Heat transfer			
Thermal properties of materials			

Cryogenic fluid	[fluid], [pressure][Bar], [volume][l]		
Electrical and electromagnetic			
Electricity	[voltage] [V], [current][A]		
Static electricity			
Magnetic field	[magnetic field] [T]		
Batteries	☐		
Capacitors	☐		
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	1.36 MeV/u	1.50 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			
Laser			
UV light			
Microwaves (300MHz-30 GHz)			
Radiofrequency (1-300 MHz)			
Chemical			
Toxic	[chemical agent], [quantity]		
Harmful	[chem. agent], [quant.]		
CMR (carcinogens, mutagens and substances toxic to reproduction)	[chem. agent], [quant.]		
Corrosive	[chem. agent], [quant.]		
Irritant	[chem. agent], [quant.]		
Flammable	[chem. agent], [quant.]		
Oxidizing	[chem. agent], [quant.]		

Explosiveness	[chem. agent], [quant.]		
Asphyxiant	[chem. agent], [quant.]		
Dangerous for the environment	[chem. agent], [quant.]		
Mechanical			
Physical impact or mechanical energy (moving parts)	[location]		
Mechanical properties (Sharp, rough, slippery)	[location]		
Vibration	[location]		
Vehicles and Means of Transport	[location]		
Noise			
Frequency	[frequency],[Hz]		
Intensity			
Physical			
Confined spaces	[location]		
High workplaces	[location]		
Access to high workplaces	[location]		
Obstructions in passageways	[location]		
Manual handling	[location]		
Poor ergonomics	[location]		

Hazard identification:

Average electrical power requirements (excluding fixed ISOLDE-installation mentioned above): [make a rough estimate of the total power consumption of the additional equipment used in the experiment]