EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Clarification 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.St J. Murphy[1], M. Aliotta[1], B. Bastin[3], D. Bemmerer[4], P. Butler[5], R. Catherall[6], T.E. Cocolios[6], T. Davinson[1], P. Delahaye[3], A. Dorsival[6], R. Dressler[2], J. Fallis[8], S. Fox[9], B.R. Fulton[9], M. Kowalska[6], A. Laird[9], G. Lotay[1] M.G. Saint Laurent[3], V. Margerin[1], J.T. Mendonca[10], F. de Oliveira[3], R. Raabe[6], T. Roger[3], C. Ruiz[8], L. Sahin[11], D. Schumann[2], N. de Sereville[12], O. Sorlin[3], T. Stora[6], E. Traykov[3], D. Voulot[6], C. H-T Wang[13], F.J.C. Wenander[6], P.J. Woods[1]

[1] *School of Physics and Astronomy, University of Edinburgh, Edinburgh, EH9 3JZ, UK*
[2] *Paul Scherrer Institut, 5232 Villigen, Switzerland*
[3] *Grand Accelerateur National d'Ions Lourds (GANIL), Caen, France*
[4] *Helmholtz-Zentrum Dresden-Rossendorf, 01314 Dresden, Germany*
[5] *Department of Physics, University of Liverpool, Liverpool, L69 7ZE, UK*
[6] *CERN, CH-1211 Geneva, Switzerland*
[7] *Instituut voor Kern en Stralingsfysica, University of Leuven, Leuven, Belgium*
[8] *TRIUMF, Vancouver, British Columbia V6T 2A3, Canada*
[9] *Department of Physics, University of York, York YO10 5DD, UK*
[10] *GOLP/Centro de Fisica de Plasmas, Instituto Superior Tecnico, 1049-001 Lisboa, Portugal*
[11] *Department of Physics, Dumlupinar University, Turkey.*
[12] *Institut de Physique Nucleaire, Universite Paris-Sud, F-91406 Orsay, France*
[13] *Department of Physics, University of Aberdeen, Aberdeen AB24 3UE, UK*

Spokesperson: Alexander Murphy [a.s.murphy@ed.ac.uk]
Contact person: Magdalena Kowalska [Magdalena.Kowalska@cern.ch]

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Abstract: This letter provides clarification to a number of issues raised in the Minutes of the 47th meeting of the INTC held on Wednesday, June 25, and Thursday, June 26, 2014, regards INTC-P-335-ADD-1, *"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"*.

Brief update to Science Case

The launch of the NuSTAR satellite in 2012 has allowed for a precise tracking of the decay of ^{44}Ti from supernovae remnants. Last year, observations of γ-rays from the decay of ^{44}Ti from Cas-A [1] by this telescope were reported by B.W. Grefenstette. A yield of $1.25\pm0.3\times10^{-4}M_\odot$ was determined and clear signatures of asymmetric explosion presented. Earlier this year, S. Boggs *et al.* (Science **348** (2015) 670-671)[2] reported NuSTAR observations of ^{44}Ti in the ejecta of SN1987A, measuring a yield of $1.5\pm0.3\times10^{-4}M_\odot$. While this is less than the $3.1\pm0.8\times10^{-4}M_\odot$ measured by INTEGRAL (S. A. Grebenev *et al.* Nature 490 (2012) 373-375)[3] it is still significantly higher than is produced in most models of such explosions. Perego *et al.* (arXiv:1501.02845)[4] has explicitly modelled the SN1987A explosion, showing that a reduction in the rate of the ^{44}Ti(α,p)^{47}V reaction by the level suggested by our first run (Margerin *et al.* Phys. Lett. B **731** (2014) 358)[5], the yield of ^{44}Ti could be brought into much closer agreement with observation. This exciting conclusion relies on the extrapolation of our upper limit at a single energy to a consistent reduction in cross section at all energies within the Gamow window. The aim of future experimental work will be to provide measurements, not limits, and to do so at several energies to see whether the assumption of a reduced reaction rate at all relevant energies is valid.

Regarding our finding of a cross section that is at least a factor of ~ 2 (68%c.l.) below that calculated with NON-SMOKER, a recent study (Mohr, EPJ submitted, arXiv:1505.00097)[6] found that such a reduced cross section is reasonable, given the global behaviour of alpha-particle induced reactions.

There are several other interesting features in the most recent observations of ^{44}Ti, such as the strong asymmetries seen. Again, a better knowledge of the underlying nuclear physics will be important for meaningful interpretation of these findings.

Responses to issues raised

- *"It was not clear whether the presented results include systematic uncertainties"*

  Yes, systematic uncertainties were included, although they were in all case small compared to the 'statistical' uncertainties.

  We assume this refers to the results from the first experiment [5]. Essentially we obtained an upper limit on the cross section at a single energy. The energy of this data point, E_{cm} =4.15 MeV, has an uncertainty propagating from the discussions below about how the beam energy is determined. This is small relative to the energy-width of the beam, which was estimated as 0.23 MeVcm. This was derived from the Monte Carlo of the experiment, but is validated by the Monte Carlo accurately reproducing the widths of other features seen in the data (proton scattering from hydrogen contaminents in the windows, and α-particles recoiling from ^{44}Ti ions elastically scattering in the gas. The Monte Carlo was used to systematically test how the energy of ions entering the gas cell varied as a function of target-detector geometry. The effect from this turns out to be negligible.

  The upper limit on the cross section is reported as 40 μbarn with a 68% confidence limit, using Feldman-Cousins. Two sources of systematic error contribution to this value were considered. The first is that the scaling between counts and cross section was obtained by comparing the number of proton events in the region of interest to the number of events in the α-particle locus that results from ^{44}Ti elastic scattering. These latter events are pure Rutherford scattering, which has known cross section, but in turn suffers from systematic uncertainties in target-detector geometry. This was estimated with the Monte Carlo, but found to be contribute very little additional uncertainty, negligibly altering the upper limit.

The second contribution arises because the experimental efficiency for detecting α-particles elastically scattered from the gas is different from the efficiency for detecting protons emitted from ^{44}Ti(α,p) reactions. This difference in efficiency was calculated using the simulation, assuming isotropic scattering for both scenarios, and was included in the data analysis. We did not consider a systematic uncertainty due to other possible angular distributions. The α-particle data were projected against angle, and a good agreement with the Monte Carlo calculation found, over the range of angles measured.

- *"How will the beam energy be determined in the planned studies and what is its expected uncertainty"*

  (Short answer) The initial estimate for the energy of the ^{44}Ti nuclei after acceleration (*i.e.* entering the experimental area) was provided by the accelerator parameters, suggesting an energy of 2.10 MeV/u. However, use of this energy provided a very poor description of the experimental data, and essentially the method of determining the beam energy was to find the best beam energy that provided a consistent description of all the data. This was 2.16$\pm$0.02 MeV/u.

  (Longer answer) Figure 1 reproduces one of the plots from the first results paper. The experimental data are the black histogram. As expected, the experimental data exhibited features consistent with hydrogen contamination (water or hydrocarbons) on both the inner and outer surfaces of the gas cell aluminium window material. Feature B corresponds to protons scattered from the front (upstream) face of the front gas cell window, while events in feature A are protons scattered from the rear face of the gas cell entrance window (and possibly protons from the front face of the downstream, exit gas cell window). Feature C are α-particles (elastic scattering of He gas cell ions) and feature D is the result of simulations of the hoped for ^{44}Ti(α,p) events.

  Considering events in feature B in more detail, these protons arise from hydrogen on the front face of the gas cell entrance window being scattering by ions in the ^{44}Ti beam, with their full energy. The protons then have energies determined by two-body kinematics, and sffer relatively small energy losses as they subsequently pass through the entrance window, the gas in the cell, the exit window, and a detector dead layer. The width of the peak is due to (small) energy straggling, and the range of angles covered by the detector. A ^{44}Ti beam with an initial energy of 2.16 MeV/u (94.95 MeVlab) scatters protons to an angle of 11 degrees with energies of 8.026 MeV. The protons then suffer typical energy losses in the entrance foil, the gas cell, the exit window and detector dead layer, totalling $\sim$420 keV. The protons thus have detected energies of $\sim$7.61 MeV, as observed.

  Events in feature A correspond to ^{44}Ti ions that scatter from hydrogen after they have passed through the entrance window. Being heavy ions, the energy loss of ^{44}Ti ions through the entrance window is significant. This is of course useful (necessary even) in that it reduces the beam energy to the region of interest for determination of the stellar reaction rate. In the first run, the initial 2.16 MeV/u beam was degraded to an energy of 1.13 MeV/u, E_{cm}=4.15 MeV. The scattered protons in this case end up with energies around 4 MeV, and are distributed over a wider energy range due to increased straggling.

Events in feature C correspond to ^{44}Ti ions that passed through the entrance window, and scatter alpha particles in to the detectors. In this case the kinematics and energy losses result in energy depositions around 12-15 MeV.

A full Monte Carlo of the experiment was performed to develop a more quantitative and useful treatment of the above discussion. It was found that a consistent treatment of the three features described was possible only with a beam energy of 2.16±0.02 MeV/u.

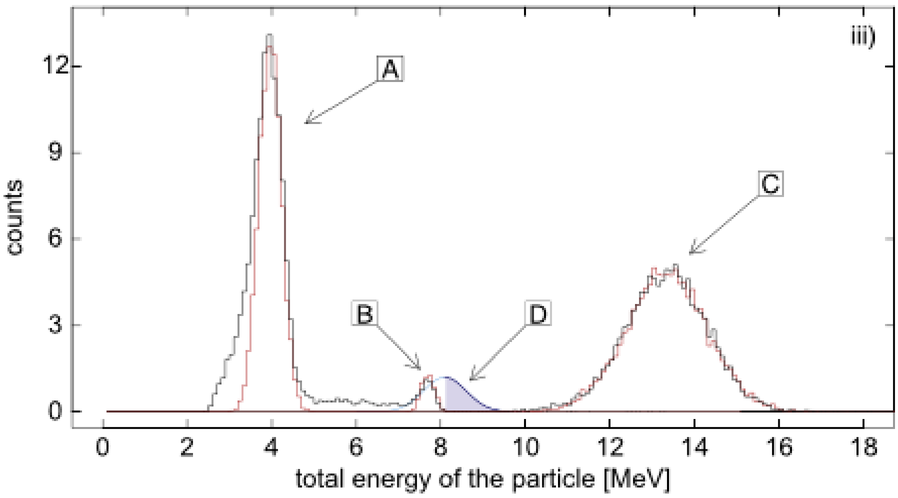

Figure 1: Figure from first results paper, Margerin *et al.* Phys. Lett. B **731** (2014) 358)[5], showing the total energy deposited in the silicon detectors used in the first experiment. See text for discussion.

The accuracy of this procedure relies in part on the accuracy of the silicon detector calibration. This uses an established technique with a triple-α source (and here it was used in conjunction with a ^{148}Gd source), and a correction for the pulse height defect of α-particles compared to protons. The contribution in uncertainty due to the the energy calibration is included. The validity of the Monte Carlo has recently been demonstrated in work by Jessica Tomlinson, York, who has used it in analysis of data from a measurement of ^{23}Na(α,p), performed at TRIUMF but using the same gas cell and similar detector geometry: see Figure 2. The Monte Carlo was used to estimate the uncertainty in the beam energy reconstruction due to the uncertainty in geometry; this has also been included in the uncertainty estimate. A final contribution to the uncertainty arose from the ability to locate the peak position of the scattered protons; this too is included. All contributions to uncertainty have been added in quadrature.

Finally, we note that while direct determination of the ^{44}Ti ion energies in a silicon detector placed at zero degrees could be attempted, this would not be very accurate because of the poorly known pulse height defect.

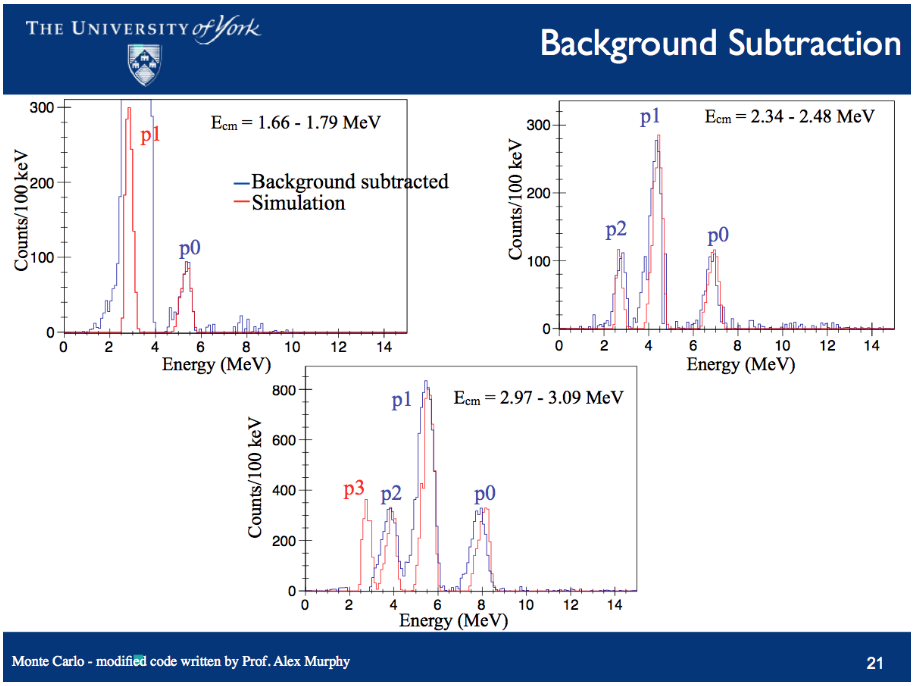

Figure 2: A Monte Carlo simulation was written to assist in analysis of data from the first ISOLDE ^{44}Ti run, that includes kinematics, beam divergence, energy losses, energy and angle straggling and detector resolutions. The above figure is taken from a talk presented by Jessica Tomlinson at the *Nuclear Physics in Astrophysics VII* conference, in which the same Monte Carlo (modified for the reaction channel), is used to simulate events from a measurement of ^{23}Na(α,p), performed at TRIUMF but using the same gas cell and similar detector geometry. Note that the large discrepancy in the left hand peak of the upper left panel is due to a not-simulated background contribution.

- *"How was the energy of reacting 44Ti nuclei determined (and what was the energy uncertainty)"*

  These will be determined in the same way as was successfully achieved in the first run.

  The methodology is essentially the same as above, in which a Monte Carlo simulation is compared to the experimental data, and a variational technique used to determine the key parameters.

  We note that energy losses for ^{44}Ti ions through the entrance window were estimated using SRIM. The SRIM energy loss values have uncertainties at the 5% level, however, these have very small effect on the precision with which centre of mass scattering energies are calculated; the main influence is on the value of degrader thickness calculated, while the important parameter is the amount of energy lost in the degrader, which stays the same.

- *"It was not however clear which window thickness would be used"*

  Under the assumption that the same lowest beam energy is delivered (around 2 MeV/u), the default assumption is that same $\sim$6.5μm aluminium foils will be used, as they are necessary to degrade the beam to the astrophysically important beam energy range (though see comment below). Several foils will be available, and will be matched to the beam energy provided to obtain the required beam energy. If a lower initial beam energy can be delivered, a thinner *entrance* window could be used, for example 3 μm of Mylar. This would be beneficial as the significant energy loss is the dominant contribution to the large energy width of the beam on entering the gas cell. A narrower energy-width would allow cleaner separation of reaction channels, and measurement of a cross section at a more precise centre of mass energy. We have some evidence that silicon carbide foils also generate less energy straggling for the same energy degradation, and can offer sufficient strength and be pin-hole free. We will prepare such foils in anticipation.

  For the exit window, the same foil as used in the first run will be used (15 μm). It was suitable robust, thick enough to stop the beam, and allows protons and α-particles to pass through to be detected.

- *"Why are studies with four energies planned?"*

  The astrophysical requirement is determination of the reaction rate over the range of the Gamow window. At present we have established an upper limit of the cross section at a single energy. Extrapolation of this result as being representative over the entire energy range is not acceptable for a firm astrophysical conclusion. Indeed, since the entrance channel here will mean population of low-spin natural-parity states only, even at relatively high excitation individual resonances may be important. The choice of 4 energies is a trade off between a manageable number of energy settings and a sufficient number to provide confidence of systematics.

- *"Detailed justification of the requested beam time (efficiencies, cross-sections)"*

  The event rates as presented in the submission made in May 2014 are reproduced below. The use of a mylar window foil would allow a greater pressure to be maintained in the gas cell. However, it should be noted that the background from the hydrogen content of the Mylar material would be significantly higher (we are exploring modifications to the scattering chamber design to obviate this).

  Cross sections The best estimate for the cross sections comes from the NON-SMOKER code (http://nucastro.org/nonsmoker.html) with the FRDM mass library. As noted above, we have already established this is somewhat too high at low energies, by about a factor of 2 at least. However, the recent work of Möhr[6] suggests this is in line with other (α,p) reactions - *i.e.* it is unlikely the cross-section is much smaller still.

  Beam intensity We have assumed 5×10^7 pps incident on the experimetal target. The subsequent rates will scale in proportion to what is achieved. Should only significantly weaker beam intensities be realised, the lowest energy to run at will be modified to compensate.

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

Target ions This is simply calculated assuming a 2 cm long gas cell volume, with the pressure indicated. This translates to 3.75×10^{18} and 1.07×10^{19} helium ions/cm^2 for 70 and 200 mbar pressures, respectively.

Efficiencies For alpha particles from the ^{44}Ti(α,p) reaction, assuming the scattering is isotropic in the centre of mass, a typical detection efficiency of 12.5% is achieved (with some energy dependence). Due to a space constraints in the chamber, this was not achieved in the first run. We should be able to get a better efficiency this time. This is essentially a geometric efficiency only as the data selection is simply 'singles', and once ejectiles hit the detectors (ΔE-E telescopes) the efficiency for 'good' hits is close to 100% (there is a small loss in requiring front-back energy agreement in each silicon wafer, and coincident ΔE - E hits).

- *"Radioprotection aspects for the accelerator due much more collected 44Ti"*

  ^{44}Ti decays by electron capture to ^{44}Sc predominantly emitting two low-energy gamma rays (68 & 78 keV, BR ∼100% each). ^{44}Sc then decays also by electron capture, predominantly emitting a 1.157 MeV gamma ray (BR ∼100%).

  The amount of ^{44}Ti located within the ion source is expected to be similar to that in the first run, namely around 30–50 MBq. In the first run, this was sent as a sample from PSI and inserted to the ISOLDE oven at CERN. Should it be required, an ion source could be taken to PSI and the ^{44}Ti inserted there. The sealed ion source would then be transported to CERN for installation at ISOLDE.

  Achieving a higher extraction efficiency from the ion source is obviously desirable. However, regardless of extraction efficiency improvements, it seems likely that the majority of the radiation will remain within the ion source. Before the last run, an option of inserting a liner was considered, but ultimately thought unnecessary.

See the next question response for more details on accelerator components being irradiated.

- *"Since the beam is long lived, there was also concern about the amount of activity deposited in the different elements of the accelerator"*

  Approximately 1% of the ^{44}Ti may be expected to leave the ion source, i.e. $\sim 10^5$ Bq. In addition to the final experimental gas cell, beam exiting the ion source is likely to become located on tuning slits, Faraday cups and in the oil of vacuum pumps. Before the first experiment in Dec 2012, there were suggestions of recovering the oil, and providing aluminium foil shields on area likely to become contaminated. A motivation for this was the recovery of the (valuable) ^{44}Ti, to be returned to PSI. In the end, with the realisation that so little would leave the ion source, neither of these was done, but the principle was established.

  The experiment does not require tight collimation of the beam – simply that it enters the gas cell through the 13 mm diameter gas cell entrance window. This may limit some activation of slits.

  Titanium reaching the gas cell is stopped on the exit foil (or on the gas cell frame surrounding the entrance foil). After the experiment, these parts are measured with HPGe counters to estimate the total beam delivered. This is a useful cross check of the beam current monitoring. We would expect to conduct these measurements at Edinburgh. The Edinburgh University Health and Safety Department has regulations for the transport or radioactive material, with most item exempt from the regulations if the activity contained is less than 1 MBq. Since ^{44}Ti is not a standard isotope, the exact exemption limit may differ from 1 MBq, and is just 2 kBq in Switzerland – clarification is being sought. If the activity is higher than the exemption limit, this does not preclude transport; rather it simply means a stricter procedure will have to be followed. Ultimately, once counting has been performed, any useful quantities of the isotope will be returned to PSI (valuable to them, and removing disposal issues at Edinburgh).

- *"There was also concern whether a beam intensity of 10^7 pps can be provided over the full time of the experiment."*

  It is our undertanding that the reduced beam intensity observed in the first run was due to a fault (small vacuum leak) in the ion source, that severely impacted the extraction efficiency. With a fully functioning ion source, we understand that the required beam intensity is expected, for the full duration of the run. However, we defer here to the expertise of the beam development team, led by Thierry Stora for further details.

Readiness: In the first run we used the Miniball stub line, and we would anticipate doing so again. We provided a scattering chamber and the helium gas cell. Before running again we will have to construct a new scattering chamber, as the one used last time is now employed at Geel in Belgium. We have begun a preliminary design of this new chamber, but anticipate it will not be ready before December 2015, earliest.

Requested shifts: We request a total of 14 twelve-hour shifts in a single period.

This is based on the assumptions made below. An initial 12-hour shift is anticipated for setting up of the beam (using reduced-intensity ^{44}Ti as a pilot on to in-chamber monitor detectors). As indicated in the table below, the initial energy setting should correspond to a centre of mass reaction energy at which a positive result is expected, but which maintain significant astrophysical interest to ensure early science return should the experiement end early, due to diminishing beam intensity for example. A detailed understanding of the backgrounds (principally from scattering of hydrogen contaminents on the gas cell windows) is required, and thus equal beam exposures are required for background runs at all energies. The main usage of beam time will be at the lowest, most astrophysically intersting energy. We assume that the time required for beam energy changes after the initial set up is relatively small, and can be accommodated within the shift times indicated.

Table 2: Basis of shift requests

Reaction energy [MeV]	E_{beam} [MeV/u]	^{4}He gas pressure [mBar]	Event rate [counts/s]	Yield [counts]	Time required [hours]	# shifts [12 hour]
5.0	2.60	0	Beam tuning		12	1
5.0	2.60	0	background		17	1.5
5.0	2.60	70	0.08	1000	17	1.5
5.5	2.86	0	background		3.5	0.5
5.5	2.86	70	0.02	1000	3.5	0.5
4.0	2.08	0	backgournd		40	4
4.0	2.08	70	0.001	100	40	4
6.0	3.12	0	background		0.8	0.5
6.0	3.12	70	0.3	1000	0.8	0.5

References

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

[2] S. E. Boggs *et al.* Science **348** (2015) 670-671

[3] S. A. Grebenev *et al.* Nature **490** (2012) 373-375

[4] Perego *et al.* arXiv:1501.02845

[5] Margerin *et al.* Phys. Lett. B **731** (2014) 358),

[6] Mohr, EPJ submitted, arXiv:1505.00097

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	2.08 MeV/u	2.60 MeV/u	2.86 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]