EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal 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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Despite decades of research, fundamental uncertainties remain in the underlying explosion mechanism of core collapse supernovae. One of the most direct methods that might help resolve this problem is a comparison of the predicted to the observed flux of γ-rays due to decay of ^{44}Ti produced in the explosion, as it is believed this could reveal the location of the *mass cut*, a key hydrodynamical property of the explosion. Such a study is at present limited by the uncertainty in the ^{44}Ti(α,p)^{47}V reaction rate. In this experiment we propose to measure the cross section for this reaction at astrophysically relevant energies. The single previous measurement of this reaction was limited to higher energies due to low beam intensities. Here, a more intense beam will be employed, generated from ^{44}Ti reclaimed as part of the ERAWAST project at PSI.

Requested shifts: 28 shifts (to be run at the end of the 2012 beam schedule.)

1 Introduction

Core collapse supernovae are truly remarkable astronomical events, exhibiting a combination of temperature, density and energy seen nowhere else in nature. They are central to the formation of many heavy elements, and are now known to be the engines behind many, if not all, gamma ray bursts. Not surprisingly, there is immense interest in attempting to understand the physics that drives them. However, this is made extremely difficult, both by the complexity of the explosion and the fact that the key processes are occurring deep beneath the surface. Major fundamental uncertainties remain, for example, the nature of the explosion mechanism itself: is it a neutrino-driven delayed detonation [1], or is it perhaps mediated by gravitational effects as has recently been suggested [2, 3]?

A method which in principle might allow the explosion mechanism to be studied in a reasonably direct way is through comparison of the amount of ^{44}Ti observed by satellite (via its beta-delayed gamma-ray emission), to the amount predicted to have been generated in the explosion. The importance of ^{44}Ti lies in the expectation that it is synthesised in the alpha-rich freeze out that occurs in the shock-heated silicon layer that lies just above the detonating core [4]. This is also the location of the so-called mass cut [5], that is, the boundary between material that is successfully ejected and that which falls back on to the proto-neutron star. Gamma-rays from material that falls back will be unable to escape the dense environment and thus cannot be observed. Hence, comparison of the observed to the predicted production provides a measure of the location of the mass cut. The mass cut is a key hydrodynamic property of supernova models, and constraining this would be of immense help in finally understanding the explosion mechanism.

Unfortunately, before the comparison outlined above can be made, the models of core collapse supernova require better nuclear physics input. Detailed studies by The *et al.* [6], and more recently Magkotsios *et al.* [7], have explored which nuclear reactions have the most impact on the ^{44}Ti abundances produced in core collapse. Both works find that relatively few reactions contribute to the overall uncertainty in ^{44}Ti production, and of these, the reaction which most needs to be more tightly constrained is that of ^{44}Ti(α,p)^{47}V. In this proposal we plan to use the facilities of ISOLDE to conduct direct measurements of the ^{44}Ti(α,p)^{47}V, at energies relevant to core collapse.

2 Previous studies

Despite obvious experimental difficulties, the ^{44}Ti(α,p)^{47}V reaction has been measured once previously, by Sonzogni *et al.* [8]. The data are reproduced from their publication in Figure 1. The temperature of the environment within which this reaction has greatest effect is thought to range from around 2 to 4 GK, corresponding to center-of mass energies (Gamow window values) of around 3 to 7.5 MeV. Improved cross section data are therefore required, especially at lower energies where no data exist. Measurements to an accuracy of around 10% would be desirable.

In [8], and as shown in Figure 1, the measured cross sections were compared to the SMOKER Hauser Feshbach statistical model code. Despite the relatively high excitation energies being

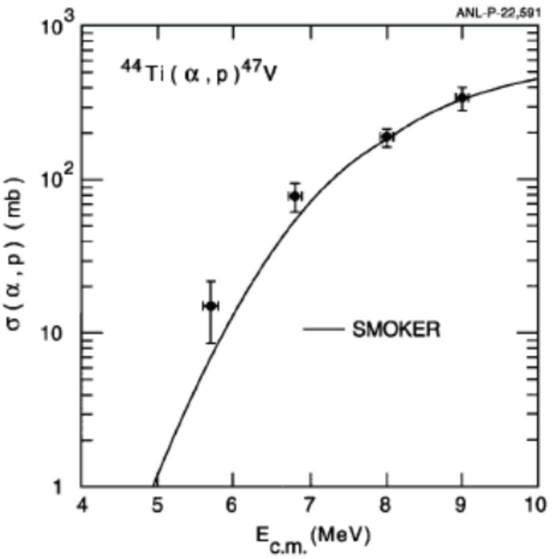

Figure 1: Measurements of the ^{44}Ti(a,p) reaction cross section, reproduced from Sonzogni *et al.* [8].

populated in the compound nucleus (Ex(^{48}Cr)=13.4 MeV for the lowest data point), the data indicate a significantly higher rate than might be expected. The SMOKER model has since been updated and replaced with the NON-SMOKER code, which includes a better treatment of isospin suppression for alpha-capture reactions on $N = Z$ nuclei such as ^{44}Ti [9]. In Figure 2 we show a comparison between the SMOKER and NON-SMOKER rates for the ^{44}Ti(α,p)^{47}V and ^{44}Ti(α,γ)^{48}Cr reactions. For the former reaction, the discrepancy between data and model remains, but is slightly reduced. For the latter reaction, the revised calculation suggests a significant decrease in rate (a factor of about 20). This is potentially significant, as it makes it even less likely that the (α,γ) rate can ever dominate over the (α,p) rate, reinforcing the latter as key to the overall production of ^{44}Ti. As lower energies are probed, the agreement between data and any statistical model may well worsen as the role of individual resonances in the compound could become quite strong; the density of states is not so high, especially given the limitations imposed by the spin-parity of the entrance channel.

2.1 Other reactions

Although identified as of somewhat less importance, and not the focus of this proposal, it is worth presenting the status of several other reactions whose uncertainties were found to contribute to the overall uncertainty in production of ^{44}Ti. The ^{40}Ca(α,γ)^{44}Ti reaction was recently successfully studied using the DRAGON spectrometer at TRIUMF [10]. The ^{44}Ti(α,γ)^{48}Cr and ^{44}Ti(p,γ)^{45}V reactions are at present completely unmeasured, but a proposal has been submitted to TRIUMF [11] in which it is hoped that with sufficient beam development, possibly including the use of ERAWAST-obtained ^{44}Ti, experiments may be performed with the DRAGON recoil spectrometer on the timescale of a few years. Somewhat unexpectedly, the ^{45}V(p,γ)^{46}Cr reaction has also been identified as being of high importance, its rate determining when the quasi-statistical equilibrium is broken among the N=22 isotones. The refractory nature of the beam required for a direct measurement makes such measurements very challenging.

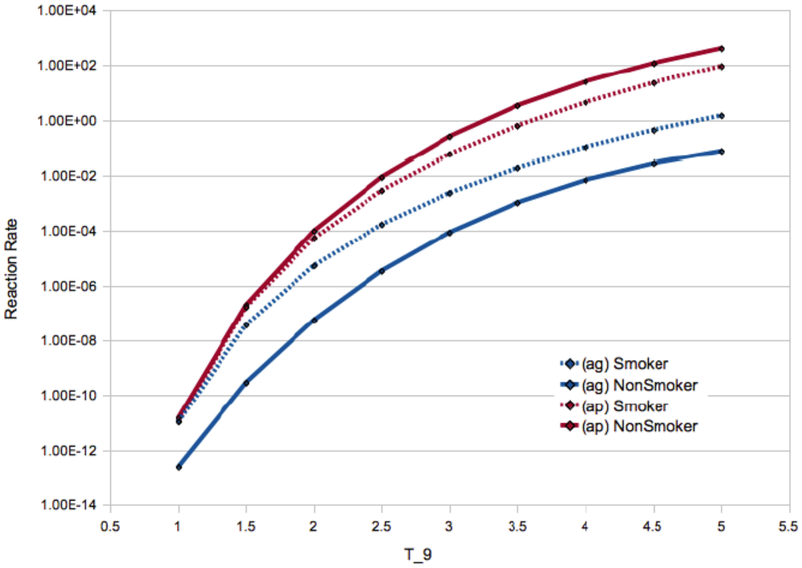

Figure 2: Comparison between SMOKER and NON-SMOKER statistical model calculations of reaction rate for the ^{44}Ti(α,p)^{47}V and ^{44}Ti(α,γ)^{48}Cr reaction rates.

Furthermore, in [12] it was shown that an elastic scattering measurement, to identify the spectroscopic properties of states in the resonant nucleus through which capture occurs, would also be very challenging. Measurement of this reaction remains an aspiration, but is not proposed. The remaining reactions that are of highest importance are those of wider impact to the onset of the explosion itself, namely the triple-alpha and ^{12}C(α,γ)^{16}O reactions. These are of course the focus of ongoing extensive experimental effort.

3 Beam Development and the ERAWAST project

A key difficulty is the provision of an intense, low energy radioactive nuclear beam of the isotope ^{44}Ti. One exciting option has been made possible through the Exotic Radionuclides from Accelerator Waste (ERAWAST) project [13]. Here, an attempt is being made to see what use there is for the radioactivity that has built up over the years in highly irradiated accelerator parts. The first phase of this involved a used copper beam dump from the 590 MeV ring cyclotron at PSI. This has had an average exposure of 1.5 mA protons over 12 years. Extraction of ^{44}Ti from this beam dump delivered around 10^{16} atoms of ^{44}Ti, in a solution of 20 ml 1M nitric acid. Subsequently, further much greater extractions have been performed on highly irradiated steel components, leading to samples now amounting to around 10^{18} atoms being available. Additionally, the extractions from steel have been made with significantly less ^{60}Co contaminant included.

The previous measurement of this reaction was based on a beam intensity of $\sim 5\times 10^5$ pps: extrapolating their level of statistics and measured cross section to lower energies suggests that a time-integrated total of a few $\times 10^{12}$ ions delivered on to a helium gas cell would allow a meaningful measurement at an energy significantly lower than the lowest energy previous data point. Discussion with the Beam Development Group, based on earlier beam tests with stable Ti, suggest that with the quantity of isotope now available, and the likely beam production efficiency, a beam intensity of 10^7 pps, delivered to the experimental target should be achievable. This will be sufficient for measurements at even lower energies. The suggestion is that a tantalum foil with a surface deposit of the ^{44}Ti be placed within an (upgraded) Mk-5 Febiad, and a CF_4 leak be used to initiate a molecular beam of TiF^+. The only expected contaminant is ^{22}Ne from the buffer gas; the use of a ^{20}Ne enriched gas would reduce this contamination by a further two orders of magnitude. Such a measure will be necessary as elastically scattered protons (from the Mylar entrance window, or from hydrocarbon buildup) will have similar energies to those emitted from the ^{44}Ti(α,p) reaction. Given the strongly negative Q-value of the ^{22}Ne(α,p) reaction, reaction protons are, however, unlikely to be an issue. An initial estimate of the acceptable level of contamination is that ^{22}Ne should ideally contribute less than 1% of the beam, and at most a few percent.

The proposed method of depositing the radioactive ^{44}Ti on a tantalum foil at PSI has the advantage that this can be performed at PSI, from which the foil can then be transported to CERN and inserted into the ion source with minimal handling exposure. Additionally, most ($\sim$90%) of the ^{44}Ti emitted from the ion source will end up in the pumps on the low energy section of the accelerator, and most of the remainder will be in pumps after the low energy section. Given the enduring value of this ^{44}Ti radioisotope, following the suggestions of the relevant personnel at PSI and CERN, we plan to install filters and/or absorbers on the pumps to facilitate this. These will be transported back to PSI after the experiment for recovery to be performed.

4 Experimental set up.

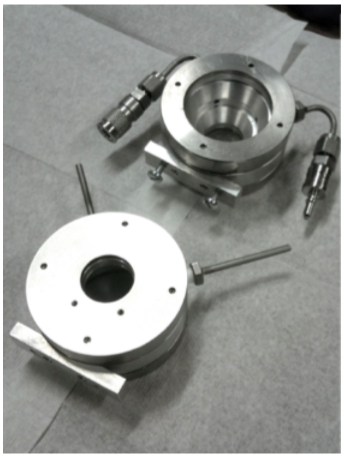

Figure 3: The Edinburgh gas cell, proposed for use in this experiment.

The custom built Edinburgh helium gas cell will be used, pictured in Figure 3, with which we have now developed significant experience. This consists of a stainless steel housing for a 2 cm long helium filled gas volume, at a pressure of typically 200 Torr (*i.e.* an areal target thickness of 1.4x10^{19} helium atoms per cm^2). We typically use a 5 μm Mylar entrance window over a small aperture, and a 15 μm aluminium foil for the larger rear aperture. A thin gold

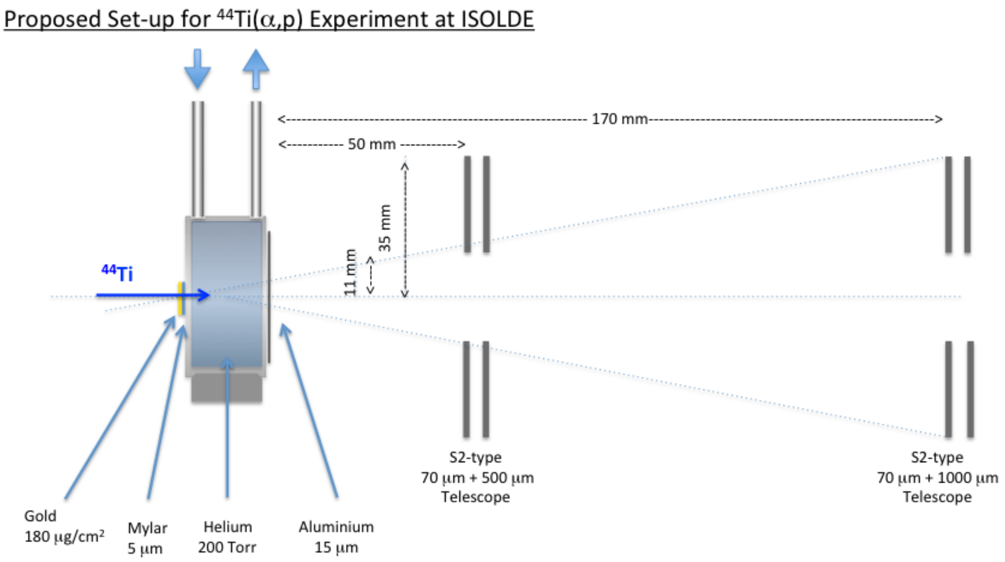

Figure 4: Schematic diagram of the proposed experimental set up.

foil precedes the front window to allow absolute beam intensity monitoring via Rutherford scattering into upstream silicon diodes. Un-reacted ^{44}Ti beam particles, ^{44}Ti ions elastically scattering from either the entrance window material or ^{4}He target atoms, and ^{47}V recoil ions from (α,p) reactions are all stopped in the exit window. Protons and alpha particles are detected downstream in S2-type silicon detector telescopes. With only these light ions escaping the gas cell, the detector event rates are low, minimising dead-time and potential radiation damage of the detectors. The use of E-ΔE detector telescopes will allow protons and alpha particles to be clearly identified. The entire set-up will be housed within a cylindrical vacuum chamber provided by Edinburgh. This will be installed on the stub beam line near MINIBALL.

The use of inverse kinematics enhances the efficiency of this geometry for the light ions, but to quantify this, and to provide an expectation of the likely energies of protons and alpha particles being detected, a Monte Carlo simulation of the set up has been performed. Of particular interest is the ability to separate, on the basis of the energy-angle systematics, those protons originating from the reaction of interest from those originating from elastic scattering of the beam with protons in the material of the cell windows (or from deposits on the cell windows due to water condensation or hydrocarbon buildup). The simulation includes energy losses based on SRIM and energy stragglings approximated by the Bohr formula. Reactions are simulated at random depths within the gas cell, and the angular distribution of emitted particles is assumed to be isotropic in the center of mass. Detector dead-layers and intrinsic energy resolutions are included, and 'good events' include only those depositing energy in both the ΔE and the E detectors above a minimum threshold of 300 keV. Some results are shown in Figures 5 and 6 below.

In Figure 5, the energy-angle systematics for the three reactions are shown, for three proposed beam energy settings, corresponding to centre of mass energies (for ^{44}Ti+^{4}He) of 3, 4 and 5 MeV. At the lowest energy, alpha particles from ^{44}Ti(α,α)^{44}Ti are of too low energy to

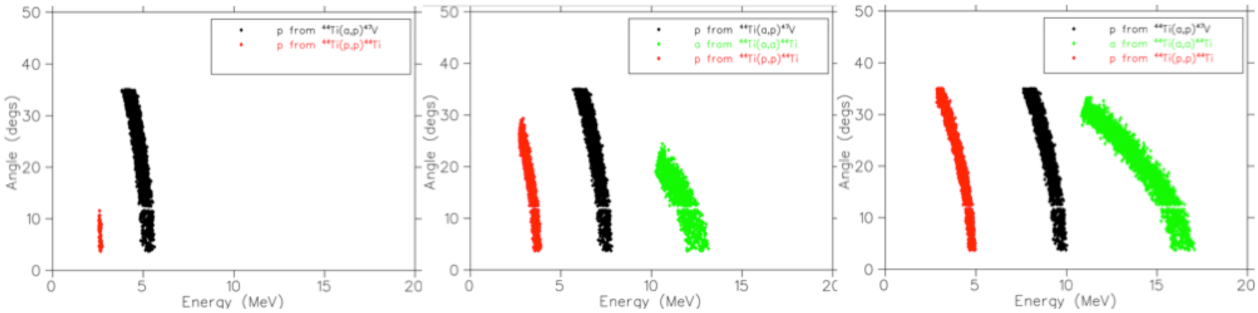

Figure 5: Monte Carlo simulation of energy-angle kinematics of events from ^{44}Ti(α,p)^{47}V (black data points), ^{44}Ti(α,α)^{44}Ti (green), and ^{44}Ti(p,p)^{44}Ti (red), at centre of mass energies of 3 (left panel), 4 (middle) and 5 MeV (right) (at the entrance to the gas cell). Here it is assumed that only the ground state of the recoiling heavy ion (undetected) is populated.

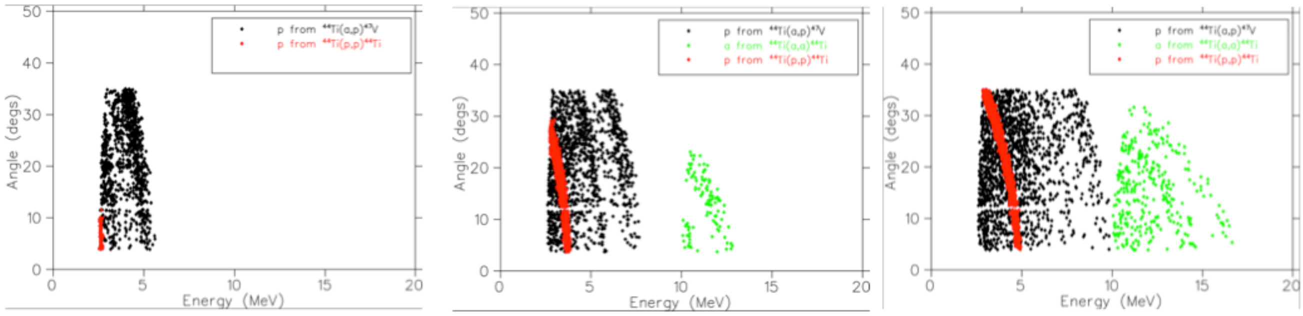

Figure 6: Monte Carlo simulation of energy-angle kinematics of events from ^{44}Ti(α,p)^{47}V (black data points), ^{44}Ti(α,α)^{44}Ti (green), and ^{44}Ti(p,p)^{44}Ti (red), at centre of mass energies of 3 (left panel), 4 (middle) and 5 MeV (right) (at the entrance to the gas cell). Here it is assumed that all accessible excited states of the recoiling heavy ion (undetected) are populated with equal probability.

pass through the delta-E detector, and thus cannot contaminate the spectra. Protons from elastic scattering of the beam with the entrance window only contributes occasionally, and at the lowest energy, leaving the protons of interest from ^{44}Ti(α,p)^{47}V well separated. At the higher energy settings, the alpha particles from elastic scattering are now able to penetrate through to the thicker detector, but still do not contaminate the proton loci, and the protons from elastic scattering from the front window and from the reaction of interest remain well separated. Despite energy and angular straggling being included in the Monte Carlo, this is of course still something of an idealised situation. The rate of protons from the Mylar is likely to be hugely larger than from the reaction of interest. We are therefore exploring replacement of the entrance Mylar foil with one of no hydrogen content. Even so, protons from water hydrocarbon deposits on the window remain an issue, so the separation shown here is highly useful.

A second issue that is likely to arise is that it is not only the ground state of the recoiling heavy ion which is likely to be populated. In Figure 6, the simulations are shown in which any of the available excited states of the recoil ions have been populated with equal probability. In

Table 1: Summary of expected rates of events.

Beam energy[1] (MeV/u)	CM Energy[2] (MeV)	Efficiency (%)	Cross section[3] (mb)	Rate (min^{-1})	Rate ($hour^{-1}$)	Rate (day^{-1})
1.41	3.0	19.2	0.004	0.005	0.29	9
1.67	4.0	18.9	0.1	0.16	9.5	229
1.93	5.0	18.6	2.0	3.1	187	4500

[1] Beam energy to be supplied by ISOLDE.

[2] Centre of mass energy for ^{44}Ti(α,p) reactions at the start of the gas cell.

[3] Estimated by extrapolation of Sonzogni *et al.*.

such cases, the light ion ejectiles are emitted with lower energy, such that some overlap of the two proton loci begins to occur. Fortunately, the locus of protons from ^{44}Ti(p,p) scattering remains tight, due to the lower centre of mass energy and the consequent lack of available states in ^{44}Ti. If the energy resolution achieved in the experiment is as suggested by the Monte Carlo, then the possibility of measuring individual cross sections to the lowest few excited states in ^{47}V is a possibility.

The simulations above have been performed assuming the use of two S2-type detector telescopes, one located 50 mm downstream of the exit window of the gas cell, and another 170 mm downstream. This is as close a geometry as reasonably achievable, thus attaining the highest efficiency. Based on isotropic scattering in the centre of mass, the efficiency estimated from the Monte Carlo is slightly less than 20%, changing only slightly for the different beam energy settings. Some events at the lowest energy setting are lost due to the assumed detector threshold of 300 keV; if this can be reduced, a small improvement in the efficiency is achievable. The energies of the protons requires E-detectors to 1 mm thickness, preventing punch-through which could otherwise result in the two proton loci overlapping, especially at the higher energy settings.

Summary of requested shifts: Based on the above discussion, we propose to perform measurements at three energy settings, summarised in table 1. Firstly, a measurement with a beam energy such that ^{44}Ti+α reactions at the start of the gas cell have a centre of mass energy of 5 MeV (the delivered beam energy has to be increased to allow for energy losses incurred by the foils at the entrance to the gas cell). The rate at this energy, even given the uncertainty in extrapolation of cross section from the lowest data point of Sonzogni *et al.*, should allow a single shift (of 12 hours) with the expected beam intensity of 10^7 pps to allow measurement of accuracy limited by systematics, not statistics. A second measurement at 4 MeV$_{cm}$ can be achieved in two further shifts. The third, most difficult but most scientifically rewarding measurement at just 3 MeV$_{cm}$ will require around a week of running to achieve a 10% statistical uncertainty. A total of 6 additional shifts are required for ‘gas-out’ runs, to allow adequate evaluation of any backgrounds due to scattering from the gas cell itself, and together with pilot beam runs of 1 shift prior to each energy, a total request of **28 shifts** is made.

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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)	Not applicable	
Chamber, detectors, DAq	☐ Existing	☐ To be used without any modification ☐ To be modified
	☒ New	☒ To be provided by Edinburgh. ☐ CERN/collaboration responsible for the design and/or manufacturing
^{44}Ti isotope 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	^{4}He (200 Torr)	^{4}He (200 Torr)	^{4}He (200 Torr)
Beam particle type	^{44}Ti	^{44}Ti	^{44}Ti
Beam intensity	10^{7} pps	10^{7} pps	10^{7} pps
Beam energy	1.93 MeV/u	1.67 MeV/u	1.40 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]