The Feasibility of Studying $^{44}$Ti($\alpha$,p)$^{47}$V Reaction at Astrophysical Energies

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Abstract. The gamma-ray lines from the decay of $^{44}$Ti have been observed by space-based gamma-ray telescopes from two supernova remnants. It is believed that the $^{44}$Ti($\alpha$,p)$^{47}$V reaction dominates the destruction of $^{44}$Ti. This work presents a possible technique to determine its reaction rate in forward kinematics at astrophysically relevant energies. Several online and offline measurements in parallel with Monte Carlo simulations were performed to illustrate the feasibility of performing this reaction. The results will be discussed.

1. Introduction

Core-collapse supernovae are believed to enrich the interstellar medium with heavy elements. Because of its relatively long half life ($T_{1/2} = 59.1 \pm 0.3$ y) [1], the detection of $^{44}$Ti isotope may reveal information about the nucleosynthesis processes and address the explosion mechanisms.

The remnant of Cassiopeia A supernova gives clear evidences about its production, where emitted $\gamma$-lines first from $^{44}$Ti $\rightarrow$ $^{44}$Sc at 67.9 and 78.4 keV, and then to $^{44}$Ca at 1157 keV have been detected by INTEGRAL [2] (Also BeppoSAX [3]) and COMPTEL telescopes [4] respectively. These observations are confirmed from the remnant of supernova SN1987A [5]. However, the same $\gamma$ lines could not be detected by other supernova portions or might be overestimated by theoretical predictions. Including Cas A, the asymmetry between models and observations raised the necessity to explore such stellar explosions.

The $^{44}$Ti($\alpha$,p)$^{47}$V reaction is considered the major one that has a direct impact on the synthesis of $^{44}$Ti [6]. Its importance raised from its small $Q$-value ($Q \approx -0.410$ MeV). The reaction was studied in inverse kinematics by Sonzogni et al [7]. The measured $^{44}$Ti beam energies were higher than the Gamow windows as shown in fig. 1. A similar experiment was conducted at the REX-ISOLDE facility, CERN [8], see fig. 1. The results were able only to establish an upper limit on the cross section of the $^{44}$Ti($\alpha$,p)$^{47}$V reaction at $E_{c.m.} = 4.15$ MeV. Trying to improve the reaction rate, we report here a study that investigates the feasibility of performing the $^{44}$Ti($\alpha$,p)$^{47}$V reaction in forward kinematics using $^{44}$Ti as a target.
2. Production of $^{44}$Ti target

$^{44}$Ti can be produced in great amounts via spallation reactions induced by high-energetic protons in metals with mass numbers slightly heavier than titanium. One possibility to obtain this isotope is to extract it from accelerator waste, as was proposed and carried out by the RadWasteAnalytics group at PSI [10]. Stainless steel samples, irradiated for two years in the high-power target of the spallation neutron source at PSI (SINQ) are best suited for manufacturing of highly active $^{44}$Ti samples.

For the target manufacturing, electro-deposition was implemented. Our preparatory studies were aimed to produce a target with around 10 MBq, but for the development of the method we used lower concentrations. An electro-deposition cell with a volume of 27 mL made of Teflon was prepared. As backing material stainless steel disks with a diameter of 27 mm and a thickness of 0.5 mm with a deposition spot of 14 mm were applied. The chemical procedure to produce the target is explained in [11]. Producing a radioactive target in the range of few hundreds of kBq was successful. For the experimental target an aliquot of 10 MBq $^{44}$Ti was prepared, but the deposition was thick, porous, loose and tending to disperse. Obviously, besides the stable titanium also parts of the contaminants like Fe, Ca, Mn, Cr and others tend to deposit during the electrolysis, making the target inapplicable for the planned experiment, even assuming that it will be covered by a thin gold layer.

A further ultra-purification of the electrolyte would be mandatory to produce a suitable target. An alternative solution of the problem could be the production of a $^{44}$Ti beam and following implantation into a suitable backing. This method would not only have the advantage in getting rid of the contaminating elements, but also obtaining a separation from the stable titanium isotopes.

3. Experimental Setup

The experiment is planned to be performed using the $^4$He$^{++}$ beam provided by the 3 MV Tandetron accelerator at Helmholtz-Zentrum Dresden-Rossendorf (HZDR). With an intensity of 1 – 2 μA, the beam energy will be from 0.1 to 3.3 MV. Four totally depleted silicon surface barrier detectors, each with an active area of 300 mm$^2$ and thickness of 50 μm, are planned to be placed on the same plane around the target. They will be equally spaced and placed at 61°, 93°, 125° and 157° angles with respect to the incident $\alpha$-beam as shown in Fig. 2. All four detectors will be backed by 300-μm-thick partially Passivated Implanted Planar Silicon...
Figure 2. Schematic diagram of the experimental setup shows the path of the α-beam (red line from the right) and the positions of the telescopes (yellow) with respect to the target.

(PIPS) detectors. Together, the 50 μm and 300 μm detectors form a particle telescope providing particle identification information (ΔE,E). Each telescope will sit on a trail track to vary its distance from the target. Aluminum foils of thicknesses range from 15 – 80 μm will be inserted in front of the telescopes to block the scattered alpha particles. The emitted γ rays during the bombardment will be identified using a high-purity germanium (HPGe) detector placed behind the target at 55° with respect to the beam axis. Monitoring γ rays gives additional information about the stability of the target and how the target evolves under the intense beam.

4. Sputtering Radioactive Target

One of the fundamental concerns during the measurements is filling the experimental setup with sputtered ⁴⁴Ti, especially if the activity of the sputtered ⁴⁴Ti exceeds the safety regulation limit in the lab. This issue was investigated by online and offline studies using ⁴⁸Ti as a target to avoid any contamination.

Stable ⁴⁸Ti+ ions was implanted at 60 keV energy into a thin Ta disk at room temperature with a fluence of 10¹⁶ cm⁻². The target was then mounted in an apparatus. The surface of the device was tilted to allow the ion beam to impinge on the target at 55°. After preparation, the target was installed in a vacuum chamber pumped down to a pressure of a few times 10⁻⁷ mbar. A 5.0-MeV α beam with an intensity of 1 μA was then sent on the target for 11 hours. The beam spot was approximately 3.0 mm in diameter and its position was varied to irradiate the whole surface. The ejected atoms were collected by polyester foil which surrounded the target and was thick enough to stop the sputtered atoms. Using the ICP-MS technique, the number of sputtered Ti from the target relative to the beam’s current is around (10±3) × 10⁻⁵ atoms/ion.

The above sputtering process was simulated using the SRIM 2013 version of the TRIM [12] and TRIDYN [13] codes. Since the sputtering is negligible deep in the target, the depth of the target is chosen to be 0.1 μm. Sufficient statistical qualities and precision could be achieved with 5.4 × 10¹⁸ cm⁻² total fluence and 4 × 10⁷ corresponding number of pseudoprojectiles. The SPYL of Ti and Ta atoms were determined to be 6.35 × 10⁻⁵ and 1.79 × 10⁻³ atoms/ion, respectively. Neither varying the width of the slabs nor oxidizing the whole target changed the above results by more than 20%. Both codes agree within uncertainty of 20%. The results are shown in Fig. 3.

The simulated calculation and ICP-MS results coincide very well. This infers that TRIDYN and TRIM codes are reliable to predict the SPYL when the beam irradiates the ⁴⁴Ti target. If 1.0 μA of α particles bombarding the radioactive target for 10 days, the yield will be 5 × 10⁻⁵
5. Offline Measurements and Simulations

One of the concerns regarding the reaction products of $\alpha + ^{44}\text{Ti}$ is to estimate the continuum background from $\beta^+$ decay of the $^{44}\text{Ti}$ targets daughter, and their consequences on the detection system. The experiment will be performed with incident $\alpha$-beam at 3 – 8 MeV. The kinematics give the ejected protons at $125^\circ$ energies from 2.16 – 6.42 MeV before the telescope. The possible interference between the proton peaks and the $\beta^+$ background produced is investigated. For this study, a mixed-radioactive source containing $^{239}\text{Pu}$, $^{241}\text{Am}$ and $^{244}\text{Cm}$ with main energies of $\alpha$-particles of 5.157, 5.485, and 5.805 MeV, respectively, was first inserted below a detector telescope. The telescope consisted of two PIPS detectors: 25 m and 300 m thick Ortec ED-100-450-25 and CU-023-600-300 used as $\Delta E$ and E detectors, respectively. All the tests were performed under $10^{-6}$ mbar vacuum. A $^{44}\text{Ti}/^{44}\text{Sc}$ sample was placed below the telescope and near the mixed-source. The activity of the sample is $83.1 \pm 1.2$ kBq. Several test runs were performed using these $\alpha$ and $\beta$ sources. Data were collected when both were seen by $E$-detector, when only one of them was placed in the chamber and when none of them were close to the detector. The energy calibration was achieved by identifying the $\alpha$ peaks in the spectrums of $\Delta E$ versus $E + \Delta E$. The data for the three peaks is shown in Fig. 4.

To count for the 1 MBq activity, the spectrum from $^{44}\text{Ti}$ will be increased by almost one order of magnitude. Using of the telescope as estimated in Fig. 4 shows a very good separation between proton spots and continuum background radiations due to $\beta^+$ emissions for all incident $E_\alpha$. Hence, those protons are possible to be observed with the suggested experimental setup.

On the other hand, naturally occurring Ti, which is already present in accelerator waste, will act as a carrier during the chemical separations. Five Ti isotopes (abundance), $^{46}\text{Ti}(8.0\%)$, $^{47}\text{Ti}(7.3\%)$, $^{48}\text{Ti}(73.8\%)$, $^{49}\text{Ti}(5.5\%)$, and $^{50}\text{Ti}(5.4\%)$, are considered as impurities in the $^{44}\text{Ti}$ target. Because of the small variations in the $Q$-values when $^{44-49}\text{Ti}$ are involved, and very

![Figure 3](image-url)
Figure 4. $\Delta E$ vs. $E + \Delta E$ plot of the experimental results when both sources are below the telescope. The data inside the box are the result of simulations.

comparable cross-sections, on average 0.57 mb, there will be a possible interference in the reaction products.

A Monte Carlo simulation using the GEANT4 toolkit was carried out to model the experimental setup. The code included those parts of the system which might effect the trajectory, the angular and energy straggling of the ejected particles, namely the target, the Si detectors with their housings and the Al degrader foils in front of the telescopes. The protons were ejected according to two-body kinematics using a monochromatic $\alpha-$beam. Assuming the worst-case scenario the particles were started from a depth of 600Å while the lateral distribution was chosen to be 3 mm which resembled the expected beam spot size. No excitation of the heavy ions leaving the reaction was considered. For the different isotopes, separate runs were carried out presuming 100% purity. For each case the same number of initial particles were initiated. As a result, a clear separation between the protons originating from $(\alpha, p)$ reactions on different isotopes in the target can be seen. The above simulation assumed similar concentrations to the radioactive and stable Ti in the target. To observe the $^{44}$Ti$(\alpha, p)^{47}$V reaction, the amount of impurities in the target must be low.

6. Conclusion
We have discussed the possibility of studying $^{44}$Ti$(\alpha, p)^{47}$V reaction directly in forward kinematics. The proposed experimental setup consists of a 1 MBq $^{44}$Ti target and four detector telescopes at specific backward angles. The biggest challenge in the study is to prepare a radioactive target with minimum amount of naturally occurring Ti and high $^{44}$Ti activity. Estimating the continuum of the background radiation, mainly due to the $\beta^+$ emission, by offline measurements using $E$ and $\Delta E$ PIPS-detectors and radioactive sources show that events from $^{44}$Ti$(\alpha, p)^{47}$V are well separated, and thus can be observed. Summarizing, the experiment is found to be safe and feasible.

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