Half-Life of ^{44}Ti as a Probe for Supernova Models

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Recent measurements of galactic radioactivity with the Compton Gamma Ray Observatory reported ^{44}Ti activity from the supernova remnant Cassiopeia A. The absolute amount of ^{44}Ti provides a stringent test for current supernova models. The main uncertainty is presently the half-life of ^{44}Ti. We report a new measurement of the half-life of ^{44}Ti applying a novel technique using a mixed radioactive ion beam containing ^{44}Ti as well as ^{22}Na ions. This method allows the reliable determination of the half-life of ^{44}Ti with high accuracy, $t_{1/2} = (60.3 \pm 1.3)$ yr. The ^{44}Ti abundance determined for Cassiopeia A with this half-life agrees with theoretical predictions within the observational uncertainties. [S0031-9007(98)05581-1]

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Supernovae are one of the main sources of galactic radioactivity. The light curves of supernovae are powered by the decay of unstable nuclei, mainly ^{56}Ni and its long-lived daughter ^{56}Co, but also ^{57}Co and ^{44}Ti at a later stage. The characteristic γ radiation associated with these decays has been observed from several supernova [1–6] by space-based γ-ray detectors like COMPTEL and OSSE aboard the Compton Gamma Ray Observatory. These nuclei are thought to be created in the α-rich freeze-out during the supernova explosion. In this process, material cools in nuclear statistical equilibrium at low densities. The buildup of heavy elements from the initially large abundance of free α particles is handicapped by the slow triple α process [7–10]. The α-rich freeze-out favors the production of ^{44}Ti but the abundance depends critically on entropy and density conditions (for details see [10,11] and references therein). The observation of the 1157 keV γ line from the decay of ^{44}Ti in supernova remnants can therefore serve as a powerful tool for testing the theoretically predicted conditions for the α-rich freeze-out as well as for the mass cut between the collapsing core and the ejected layers. The only ^{44}Ti source detected with sufficient statistical significance is the supernova remnant Cassiopeia A (for a review see [6]). From the observed γ flux the ejected ^{44}Ti abundance can be determined. However, the reported range of half-life values for ^{44}Ti (46.4–66.6) yr introduces a dramatic uncertainty of a factor of 3 in the ^{44}Ti abundance from Cassiopeia A. For this reason we measured the half-life with high accuracy using a novel technique with a mixed radioactive beam containing ^{44}Ti and ^{22}Na.

The half-life of ^{44}Ti has been measured several times employing different techniques. In one method the total amount of ^{44}Ti of a sample was determined by high resolution mass spectroscopy [12,13] and accelerator mass spectroscopy [14], and the activity was measured with NaI counters [12,13] and a Ge(Li) detector [14], respectively. These experiments quote ^{44}Ti half-lives of (46.4 ± 1.7) [12], (48.2 ± 0.9) [13], and (54.2 ± 2.1) yr [14]. The two more recent experiments followed the decay curve of ^{44}Ti for periods of three [15] and two years [16] counting the activity with a proportional counter [15] or a Ge detector [16]. This approach led to half-lives of (66.6 ± 1.6) [15] and (63 ± 3) yr [16]. Meißner *et al.* [17] attempted to determine the half-life by implanting a known number of ^{44}Ti atoms into Al foils and by measuring the resulting activity with a Ge detector. However, this experiment suffered from low count rates and was sensitive to systematic errors. For these reasons it was not possible to obtain a reliable value for the half-life of ^{44}Ti. Depending on the analysis values between 39 [18] and 58 yr [17] could be obtained. Therefore, the half-life was remeasured using a relative method instead of an absolute method. In the present experiment a mixed radioactive beam was used to implant ^{44}Ti and ^{22}Na simultaneously into a stack of foils. This approach allowed a determination of the half-life of ^{44}Ti, $t_{^{44}\mathrm{Ti}}$, relative to the well-known half-life of ^{22}Na, $t_{^{22}\mathrm{Na}}$, reducing the systematic uncertainties. The determination of the ^{44}Ti half-life depends only on two ratios, the relative amount of ^{44}Ti and ^{22}Na in the beam, $N_{^{44}\mathrm{Ti}}/N_{^{22}\mathrm{Na}}$, and the resulting relative activities, $A_{^{44}\mathrm{Ti}}/A_{^{22}\mathrm{Na}}$,

$$t_{^{44}\mathrm{Ti}} = \left(\frac{A_{^{44}\mathrm{Ti}}}{A_{^{22}\mathrm{Na}}}\right)^{-1}\left(\frac{N_{^{44}\mathrm{Ti}}}{N_{^{22}\mathrm{Na}}}\right)t_{^{22}\mathrm{Na}}\,. \qquad (1)$$

In the following we describe the experimental setup and analysis of the data followed by a discussion of the results.

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A secondary beam of radioactive ions was produced at the National Superconducting Cyclotron Laboratory at Michigan State University by projectile fragmentation. A primary beam of ^{46}Ti with an energy of $E/A = 70.6$ MeV/u and an intensity of about 4 particle-nA was directed onto a ^{9}Be target with a thickness of 202 mg/cm^2 located at the target position of the A1200 projectile fragment separator [19]. The A1200 was operated in the medium acceptance mode and optimized for maximum ^{44}Ti intensity at the focal plane. With this setting all other $N = Z$ fragments are also transmitted to the focal plane of the separator (see Fig. 1). The experiment was run in two modes. In the first, all fragments were implanted into a stack of Al foils located at the focal plane behind a collimator with a diameter of 2 cm. The stack consisted of seven Al foils (chemical purity 99.0%), each with a thickness of 457 μm except for the fifth foil. Here, a thickness of 50 μm was selected to implant the ^{22}Na in the center of the sixth foil. The second mode provided for particle identification of the implanted species. In this mode a 300 μm Si detector and a position-sensitive parallel-plate avalanche counter (PPAC) were placed in front of the collimator and a plastic detector replaced the Al stack. The last detector measured the particle energy and served as the trigger for the data acquisition; particles were recorded only if they passed through the collimator. This identified the different particle groups at the implantation spot by means of their energy loss, total energy, and their time of flight through the separator (see Fig. 1), and also provided a determination of the fragment intensity across the collimator aperture. The time of flight was triggered by the plastic detector, and a signal of every second cyclotron pulse was used as a stop [19] to ensure that no signals were lost from the time window. This leads to a wraparound in the time of flight (Fig. 1) resulting in two groups for each observed fragment which were both analyzed for each fragment of interest.

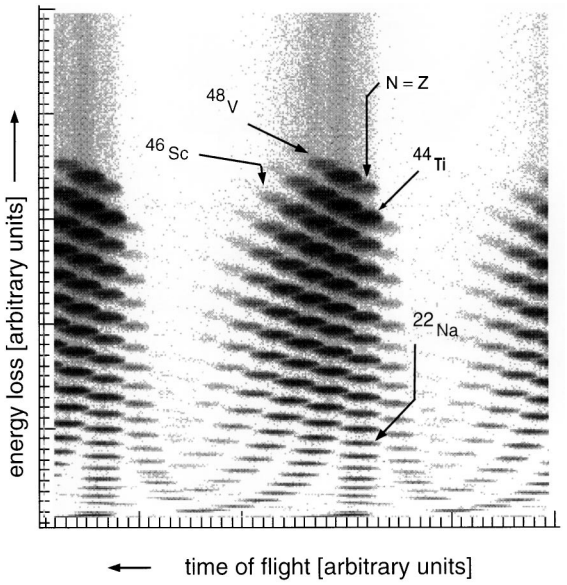

FIG. 1. Particle identification at the focal plane of the A1200 fragment mass separator based on energy loss versus time of flight (for details see text).

Fragments were implanted for an accumulated time of 29 h in the first mode. About every three hours the implantation foils were replaced by the detector stack, switching to the second mode, to measure the relative intensity of the implanted fragments. Since the total fragment intensity at the focal plane (in the first mode) was approximately 8×10^6 s^{-1}, the beam was reduced during the second mode runs by inserting a beam attenuator between the ion source and the cyclotron. This can in principle lead to a change of the position of the beam on the production target and could thus influence the relative intensities of the fragments. As a test the beam was steered to several locations on the target, and the ratio of the ^{44}Ti and ^{22}Na intensities was measured at each position. The relative intensities did not change by more than the statistical error. After projection of the Ti group onto the energy loss axis, the ^{44}Ti line was well separated from the other Ti isotopes. The mean ratio $N_{^{44}\mathrm{Ti}}/N_{^{22}\mathrm{Na}}$ of all runs is 76.78 with 1σ errors of ± 0.73 (internal [20]) and ± 0.78 (external [20]). The absolute ^{44}Ti intensity was $\approx 5 \times 10^5$ s^{-1} or about 5% of the total intensity yielding a total of $\approx 5 \times 10^{10}$ ^{44}Ti ions implanted. The position spectra of the PPAC gated on the ^{44}Ti and ^{22}Na groups showed the same distribution of the implanted particles for both fragments. In addition to ^{44}Ti and ^{22}Na two other long-lived γ emitters were implanted, ^{46}Sc [$t_{1/2} = (83.81 \pm 0.01)$ days [21]] and ^{48}V [$t_{1/2} = (15.9735 \pm 0.0025)$ days [22]] (see Fig. 1) (both were implanted in the third foil). The ^{46}Sc group was too weak and too close to several strong Sc groups for a reliable extraction of the number of implanted ^{46}Sc ions to be made. The ^{48}V group is about a factor of 10 stronger and can be used as a check on the half-life determination. A relative intensity of $N_{^{44}\mathrm{Ti}}/N_{^{48}\mathrm{V}} = 50.3 \pm 1.9$ was found.

Range calculations with the code LISE [23] predict that the ^{44}Ti and ^{48}V ions would be stopped approximately in the center of the third foil with a range distribution of ± 60 μm and ^{22}Na in the center of the sixth foil with a range distribution of ± 125 μm. This was confirmed in the off-line measurement of the γ activities in the different foils (see below). Only upper limits of 0.2% (2σ limit) of the activity of foil three were found for the ^{44}Ti activities of the first, second, and fourth foils, respectively. However, additional ^{22}Na activity was also found in the first five foils: 17.2%, 22.7%, 15.6%, 5.8%, and 2.0% of the activity of the sixth foil. The quoted value for foil five with a thickness of 50 μm is the activity normalized to the same path length as the other foils; the measured activity for this foil is 0.22% of the activity of foil six. No activity was found in the seventh foil. The short-lived ^{24}Na, which was implanted into foils four and five, showed a similar activity distribution: 15%, 20%, and 20% for the first three foils, respectively, and 2% in foil six. The secondary

activities are caused by reactions of the radioactive beam with the Al foils, and their distribution can be understood qualitatively. Assuming an energy independent reaction cross section of 60 mb [24], an activity of 22% is expected in each of the first three foils which are exposed to the full beam intensity. Most fragments are stopped before reaching foil six. Here, the beam intensity is only ≈2% of the original value and an activity of ≈0.3% is expected in this simple picture. The amount of secondary ^{22}Na activity in the ^{22}Na implantation foil was estimated by interpolating between the activities of the two neighboring foils (2% in foil five, ≤0.3% in foil seven). The ^{22}Na activity in the implantation foil was corrected by subtracting 1% of the measured activity and a systematic error of 1% was added to the error of this activity.

The specific γ activities of the implanted foils were measured by detecting the characteristic γ-decay lines of the radioisotopes using a Ge detector with a relative efficiency of 31% and an energy resolution of 2.0 keV at a γ energy of 1333 keV. Figure 2 shows the relevant part of typical γ spectra measured for the ^{44}Ti foil (foil three) and the ^{22}Na foil (foil six), respectively. The detector was completely shielded with 10 cm of Pb to reduce the room background. A sample holder allowed the placement of the foils at distances of 13.9, 23.9, 44.0, and 83.9 mm from the surface of the Ge crystal.

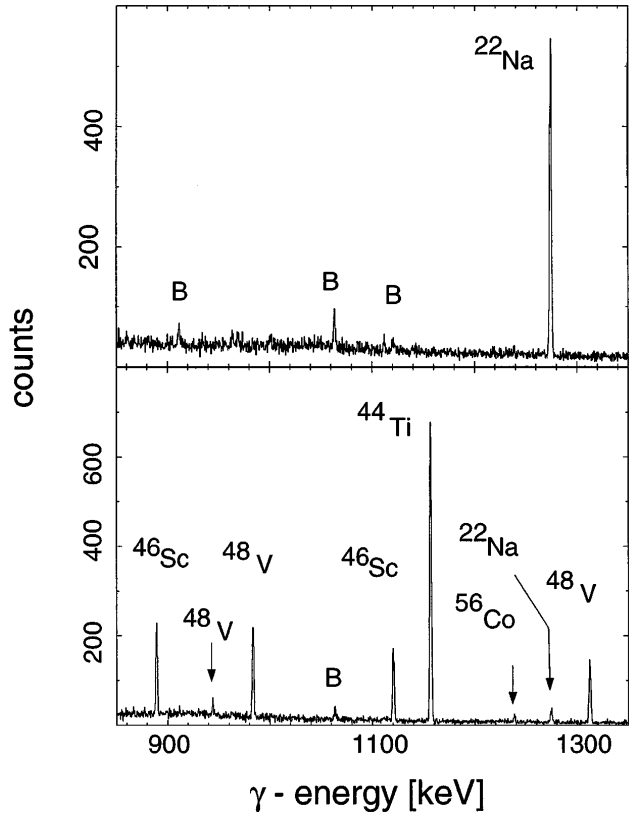

FIG. 2. Relevant portion of the γ-ray spectra measured for the sixth foil implanted with ^{22}Na (top panel) and the third foil implanted with ^{44}Ti, ^{46}Sc, and ^{48}V (bottom panel). Known, room background lines are marked with *B*.

Short-lived activities were allowed to decay during a 3-month period between the end of the implantation and the beginning of the activity measurement. The activities were measured in four cycles. During every cycle the foils were placed in each of the four positions. Between the measurements a weak ^{60}Co source was mounted at the same position to monitor the energy resolution and the relative efficiency of the detector. The total count rate in the Ge detector with a foil in place was ≤50 Hz, and each individual measurement lasted between 2 hours and $2\frac{1}{2}$ days depending on the counting position.

The γ activity following the decay of ^{44}Ti and ^{22}Na is very similar, and for this reason only small corrections to the ratio of the γ intensities are necessary to obtain the ratio of their activities. ^{44}Ti decays by electron capture (EC) to the 146 keV state in ^{44}Sc which deexcites by a 2γ cascade (68 and 78 keV) to the ground state [25]. The short-lived daughter ($t_{1/2} = 39.3$ h) decays by EC and β^+ decay to excited states in ^{44}Ca and the daughter activity is in equilibrium with the ^{44}Ti activity within a day. In (99.87 ± 0.06)% of the ^{44}Sc decays a γ ray with an energy of 1157 keV is emitted [25]. ^{22}Na has a half-life of $t_{1/2} = (2.6088 \pm 0.0014)$ yr and decays by EC and β^+ decay to the ground state and the first excited state in ^{22}Ne emitting a γ-ray with an energy of 1274 keV in (99.94 ± 0.015)% of the decays [25]. Therefore, the intensity ratio of the 1157 and 1274 keV lines have to be corrected only for the γ branching ratios and the relative efficiency. The relative efficiency was determined from the ratio of the 1173 and 1333 keV lines from the decay of the ^{60}Co source after corrections for angular correlation and summing effects (≤0.6%) [26]. This ratio was extrapolated to the γ energies E_γ of interest using the relation $\epsilon_1/\epsilon_2 = (E_{\gamma,1}/E_{\gamma,2})^x$ (where x is a fit parameter) which is valid in the energy range of interest (800–2000 keV). The resulting relative efficiency for the 1157 and the 1274 keV γ lines is 1.090 ± 0.002. The effect of self-absorption on the relative efficiency resulting from the different implantation profiles of ^{22}Na and ^{44}Ti has been estimated to ≤0.1%. In addition, the ^{22}Na activity was corrected for decay which has occurred since the end of the implantation. Because of the similarity of the decays, summing effects do not influence the ratio of the γ intensities. This is evident from the fact that this ratio is independent of the sample distance from the detector within the statistical uncertainty (position 1: 3.321 ± 0.036, position 2: 3.252 ± 0.041, position 3: 3.303 ± 0.040, and position 4: 3.268 ± 0.046). The average ratio of the ^{44}Ti and the ^{22}Na activities is 3.289 with a statistical 1σ error of 0.021. The ratio has to be corrected for the contribution to the ^{22}Na activity caused by the activation of the foils by light particles (see above). This results in a final ratio of the activities of $A_{^{44}\mathrm{Ti}}/A_{^{22}\mathrm{Na}} = 3.322 \pm 0.054$. The systematic error of 1% due to this correction has been added linearly. In addition, the activity of ^{48}V [22] has been analyzed. After corrections for cascade summing and the decay

occurring during and since the implantation, a ratio of $A_{^{44}\mathrm{Ti}}/A_{^{48}\mathrm{V}} = 0.0378 \pm 0.0007$ was obtained.

The half-life of ^{44}Ti can be determined relative to the half-life of the reference source from the observed implantation and activity ratios using Eq. (1). The measurement relative to ^{22}Na yields a half-life of $t_{1/2}^{^{44}\mathrm{Ti}} = (60.3 \pm 1.3)$ yr. The error is the linear sum of the 1σ statistical error of 0.7 yr and the systematic error of 0.6 yr. This result is confirmed by the ^{48}V value of $t_{1/2}^{^{44}\mathrm{Ti}} = (58.2 \pm 3.0)$ yr. Since both values are not independent, we adopted the ^{22}Na result for the half-life of ^{44}Ti, $t_{1/2}^{^{44}\mathrm{Ti}} = (60.3 \pm 1.3)$ yr. The present half-life of ^{44}Ti is in good agreement with the most recent value of Norman *et al.* [16]. All other previous results differ by 2 standard deviations or more from the present value.

The amount of ^{44}Ti, $M_{^{44}\mathrm{Ti}}$, observed from a supernova depends on the lifetime $\tau = t_{1/2}/(\ln 2)$, the observed γ-flux F_γ, and on the distance D and age t of the supernova [6],

$$M_{^{44}\mathrm{Ti}} = 1.39 \times 10^{-4} F_\gamma D^2 \tau e^{t/\tau}, \qquad (2)$$

with $M_{^{44}\mathrm{Ti}}$ in solar masses $M_\odot$, F_γ in $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, D in kpc, and t and τ in yr. With the present value for the half-life of ^{44}Ti, a γ flux of $(3.4 \pm 0.9) \times 10^{-5}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ observed for the 1157 keV line from Cas A [6], a date of A.D. 1680 for the explosion [27], and a distance of $(3.4^{+0.3}_{-0.1})$ kpc [28], supernova Cas A ejected a ^{44}Ti mass of $(1.72^{+0.56}_{-0.48}) \times 10^{-4} M_\odot$. With the present result the error in the half-life of ^{44}Ti contributes only a little (6%) to the uncertainty, which is now dominated by the experimental errors of the γ flux and the distance measurements. The amount of ^{44}Ti is in excellent agreement with the core collapse supernova model predictions of Thielemann *et al.* [11] ($1.7 \times 10^{-4} M_\odot$ for progenitor mass of $20 M_\odot$), who adjusted their mass cut to reproduce the ^{56}Ni abundance observed for supernovae. The piston model for a core collapse supernova of Woosley and Weaver [29] leads to smaller values for the amount of ^{44}Ti (for a discussion of the differences of the two models see [10]). The modified piston model by Woosley, Langer, and Weaver [30] simulating a type Ib core collapse supernova predicts a ^{44}Ti mass of only $(0.6\text{–}0.8) \times 10^{-4} M_\odot$. However, before the observed ^{44}Ti mass can be used to test and calibrate the supernova models, an improvement in the accuracy of the astrophysical input parameters is necessary.

Future γ-ray missions, such as INTEGRAL [31], should improve the situation for Cas A, and might lead to the observation of ^{44}Ti γ-ray emission from additional supernovae. These, together with the present result for the ^{44}Ti half-life, will provide considerably more stringent tests of supernova models than presently exist.

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