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Measurement of the ^{44}Ti Half-life and its Significance for Supernova*

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Supernova events are one of the main processes which generate galactic radioactivities. The light curves of the supernova are initially powered [Su92] by the radioactive decays of ^{56}Ni (5.9 d) and its daughter ^{56}Co (77.3 d), and later by the 272-d ^{57}Co and 59-y ^{44}Ti. Theoretical models have, over the years, been developed to explain the production of these elements in supernova. ^{44}Ti is one of the nuclei produced in the supernova ejecta. Its synthesis requires exceptionally high temperatures, at least 5×10^9 K. This implies that it is produced in the deepest layers ejected from a supernova [Wo98], near the so-called "mass cut" that separates the remnant from the ejected supernova. Thus a knowledge of the amount of ^{44}Ti produced in a supernova provides a very critical information to check validity of theoretical models. An accurate value of ^{44}Ti half-life is also needed to determine the amount of ^{44}Ti produced by cosmic rays in meteorites [Bo95].

The nucleus ^{44}Ti decays to ^{44}Sc, which in turn decays to ^{44}Ca (Fig. 1) and a gamma ray of 1157.0 keV is emitted in this decay. The amount of ^{44}Ti in a sample can be determined by measuring the 1157.0 keV gamma ray intensity. The half-life of ^{44}Ti can be determined either by specific activity method or by following the decay of the 1157.0 keV gamma line. Until the early nineties, there was no consensus among the published values of the ^{44}Ti half-life. The earliest three values [Wi65, Mo65, Fr83] were determined by the specific activity method, where the number of atoms in a sample and its decay rate were measured. The last two values [Al90, No97], shown in Fig. 2, were obtained from direct decay method. In ref. [Al90] the activity of a ^{44}Ti sample was measured with a proportional counter at regular intervals over a period of 3 years. It is obvious that the disagreement among the five values is caused by systematic uncertainties which, by their nature, are difficult to evaluate. Another impetus for a remeasurement of the ^{44}Ti half-life came from the launching of space-based gamma ray spectrometers COMPTEL [So93] and OSSE to observe ^{44}Ti gamma ray lines.

The characteristic γ ray of 1157.0 keV has been observed in the supernova Cassiopeia A both by the COMPTEL [Iy94, Sc96, Du97] and by OSSE [Th96] detectors. This supernova was first sighted in 1680. More recently, the ^{44}Ti gamma line has been identified [Iy98] in a previously unknown supernova in the Vela region. The age of this supernova is estimated to be about 680 years and its distance ~200 pc and it is the nearest known young supernova remnant. The abundance of ^{44}Ti in a supernova can be determined from the known gamma ray flux from the supernova, its distance from earth and its half-life. The half-life enters the calculations twice: once to apply decay correction to determine the flux at the time when the supernova was first seen and secondly to covert the decay rate to the number of atoms.

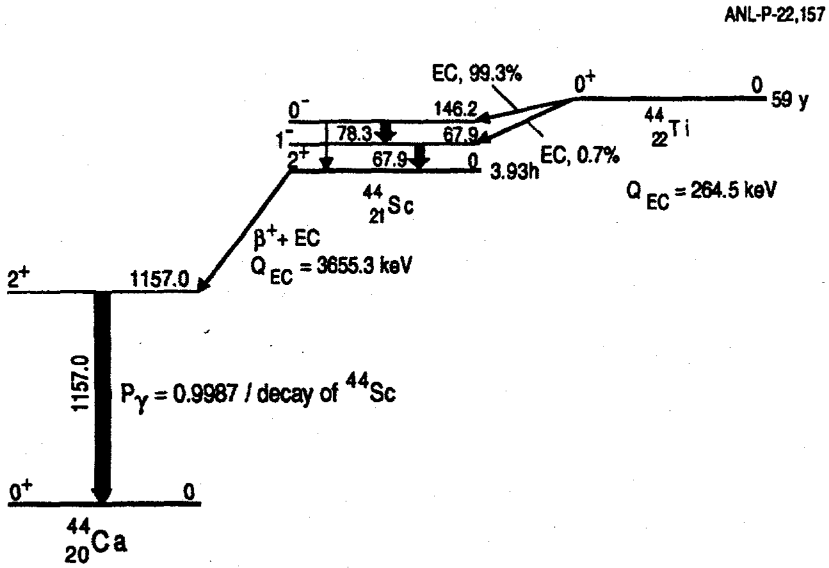

Fig. 1. Decay schemes of ^{44}Ti and ^{44}Sc.

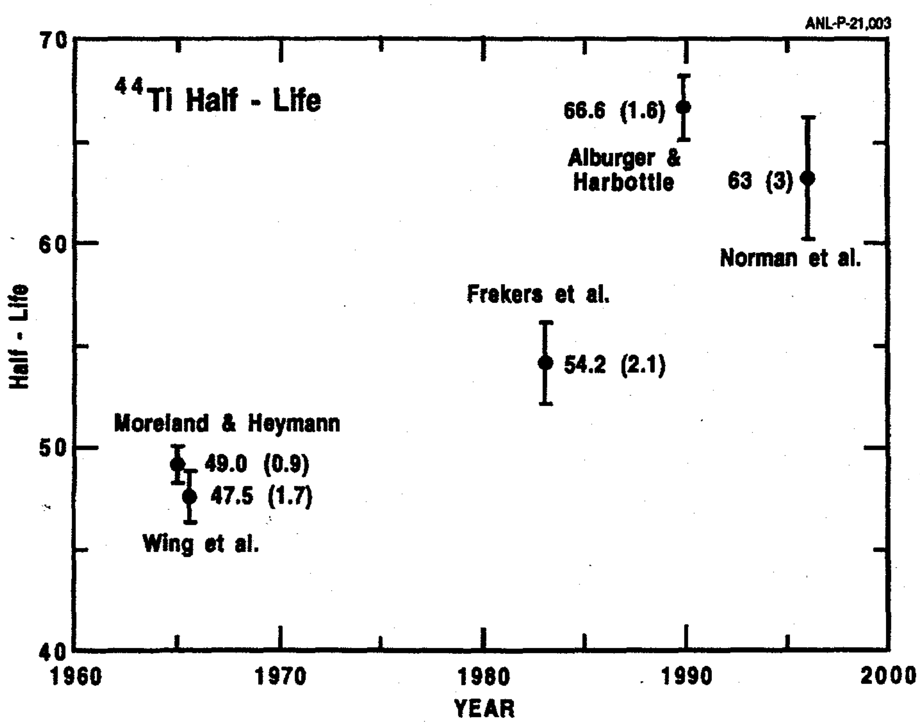

Fig. 2. Values of ^{44}Ti half-life published before 1998.

European Space Agency (ESA) is planning to launch a new gamma-ray system in space in the year 2001. The International Gamma-Ray Astrophysical Laboratory, INTEGRAL [Wi96], will use an array of high-resolution germanium detectors which has about ten times greater sensitivity than the COMPTEL. As displayed in Fig. 3, because of the higher sensitivity, more distant

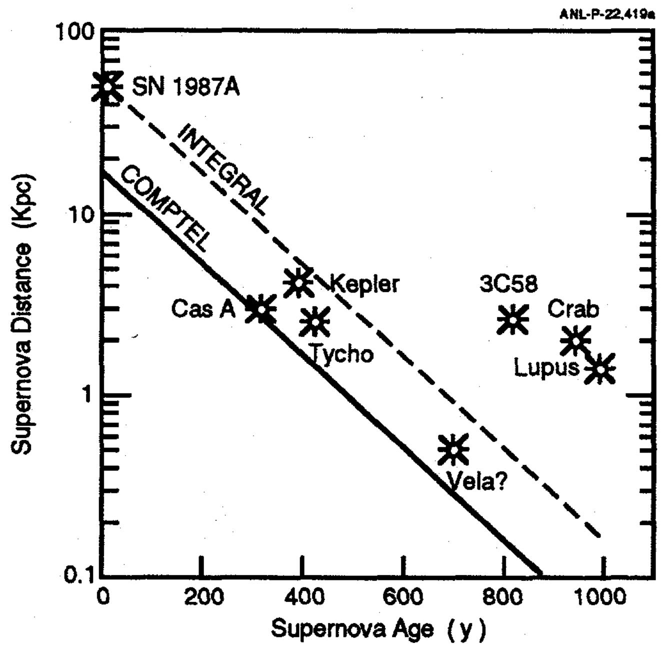

Fig. 3. Sensitivities of the COMPTEL and INTEGRAL spectrometers. The instruments will be able to detect supernova explosions with distance and age below the line.

and older supernovae are likely to be detected [So99]. For supernova which occurred 500-1000 years ago, the uncertainty in the ^{44}Ti half-life assumes greater importance. If we use the two published extreme values of ^{44}Ti half-life before 1998, the calculated ^{44}Ti abundance can differ by an order of magnitude [Fig. 4]. Because of these reasons, several experiments were initiated in early nineties to remeasure the ^{44}Ti half-life.

We started our measurement of the ^{44}Ti half-life in 1992 at three laboratories-Argonne, Jerusalem and Torino. The aim of our experiment was to measure the ^{44}Ti half-life relative the half-life of ^{60}Co. The reference isotope ^{60}Co was chosen because its γ ray of 1173.2 keV is quite close to the ^{44}Ti gamma line of 1157.0 keV and its half-life is quite accurately known [Ki93] (5.2714 ± 0.0005 yr). Because of the small difference in the ^{44}Ti (1157.0) and ^{60}Co (1173.2 keV) γ-ray energies, small variations in the Ge detector efficiency will have a negligible effect.

The ^{44}Ti activity was produced by the ^{45}Sc(p,2n) reaction and details of its production have been described in ref. [Fr83]. The purity of ^{44}Ti and also ^{60}Co was checked by measuring their gamma-ray spectra with a Ge detector placed in a very low-background shield. Three samples continuing 0.3 μCi ^{44}Ti and 0.3 μCi ^{60}Co were prepared at Argonne and were distributed to the three laboratories. A sample of pure ^{44}Ti and a sample of pure ^{60}Co were also prepared and their spectra were measured at Argonne at regular intervals. At Argonne, the γ-ray spectra of the mixed ^{44}Ti + ^{60}Co source and the two pure sources of ^{44}Ti and ^{60}Co were measured with a 25% Ge spectrometer, which had a resolution [FWHM] of 1.80 keV at 1.3 MeV. No shield was built around the Ge spectrometer because low background count rate was expected above 1-MeV region. The total background rate was 110 Hz. A plastic holder was placed on the detector cap and held with plastic screws. The source in a Lucite disk was placed in an aluminum holder,

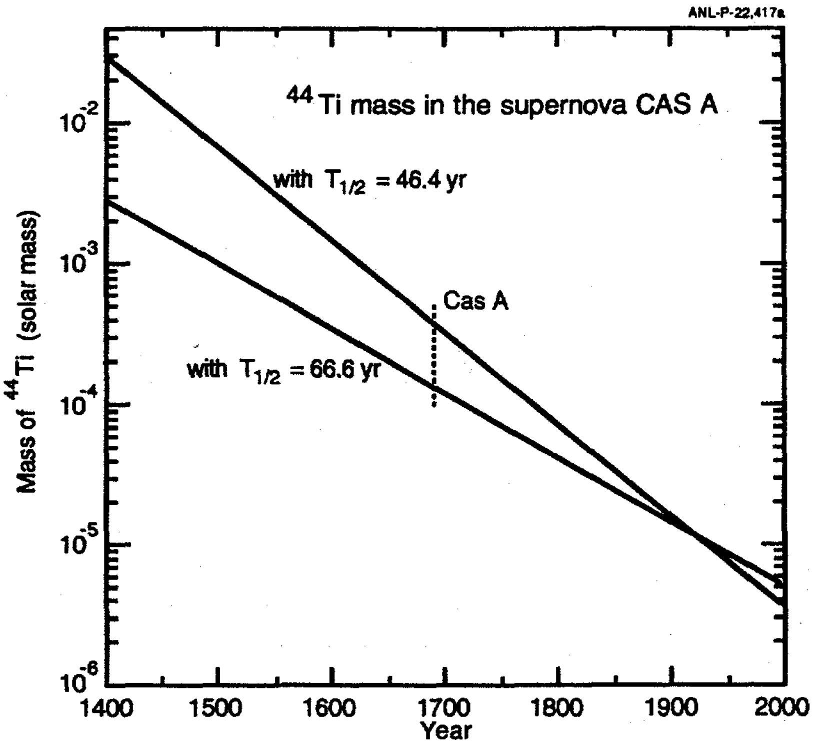

Fig. 4. Effect of the ^{44}Ti half-life on the mass of ^{44}Ti in supernova remnants.

taped, and placed in one of the slots of the plastic holder such that the source-to-detector distance was 10.2 cm. In this arrangement, the source material was facing the Ge crystal. Each sample was counted for 48 h live time. In addition, a background spectrum with the source removed, but all holder materials in place, was also measured for 48 h. After measuring a set of four spectra, the source-to-detector distance was changed to 5.2 cm, and another set of four spectra were taken. These sets of spectra were measured approximately every six months between February 1993 and June 1997, covering a period of 4 years. The γ-ray spectra of a mixed ^{44}Ti + ^{60}Co source, recorded at the start of the half-life measurement and at the present time, are displayed in Fig. 5.

For the analysis, the respective background spectra were subtracted from the three sample spectra and the counts in the 1157.0, 1173.2, and 1332.5 keV peaks were determined. The peak counts were obtained by drawing a straight line between counts on the left side and counts on the right side of the peak and subtracting the background counts from the peak counts. The ratios of the counts in the 1157.0 keV peak to the counts in the 1173.2-keV peak were fitted as a function of time with an exponential function. The slope of the line (Fig. 6) gave the difference between the decay constants $\lambda(^{60}Co) - \lambda(^{44}Ti)$. Using the known half-life of ^{60}Co, 5.2714 ± 0.0005 yr, the half-life of ^{44}Ti was deduced. The half-life was also determined from the 1157.0/1332.5 peak area ratios. In this way eight values of half-life were obtained from the Argonne data set and a weighted average gave a value of 59.0 ± 0.8 yr.

At Jerusalem, sets of spectra of a mixed source and a pure ^{60}Co source, and background spectra were measured with a 35% Ge(Li) spectrometer at a source-to-detector distance of 6.7 cm. Again, the detector was not shielded. Thirteen sets of spectra were measured over a period of 5 years. Each spectrum was analyzed with a peak fitting routine, using as a peak model for the shape of the 1157.0 keV line the shape of the 1173.2 keV peak measured in the same data set with

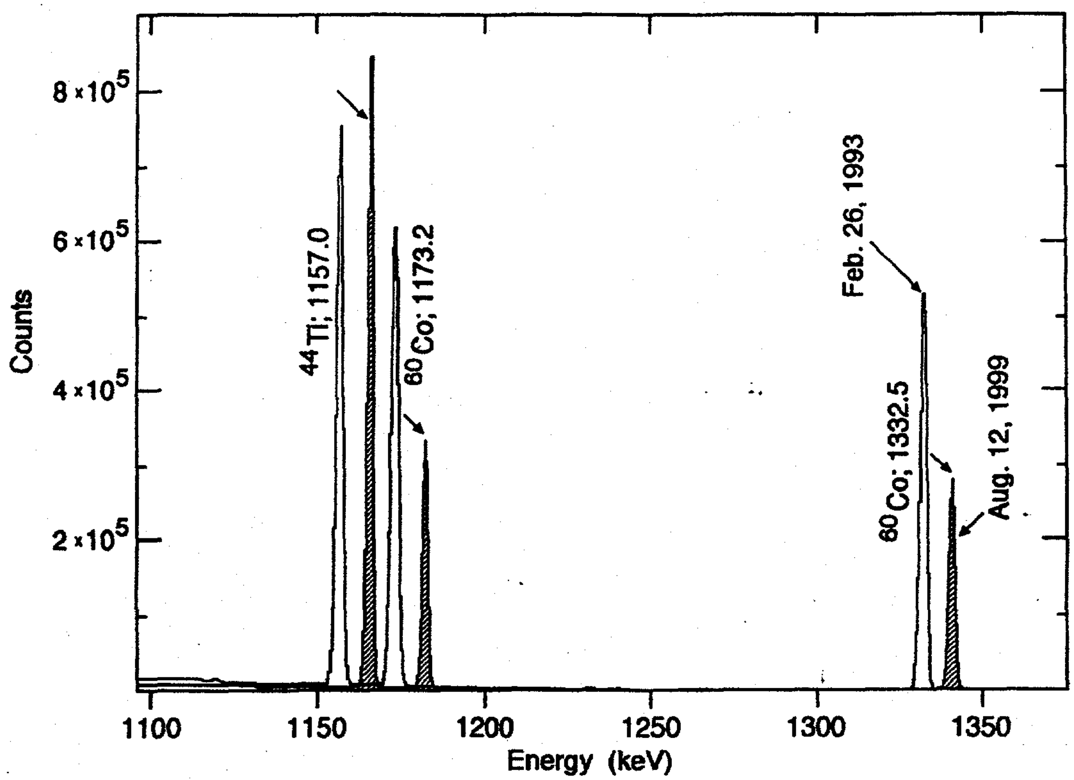

Fig. 5. Gamma-ray spectra of the ^{60}Co+^{44}Ti sample measured with a 25% Ge detector at Argonne at the start of the measurement and at present. The 1999 spectrum is offset to the right.

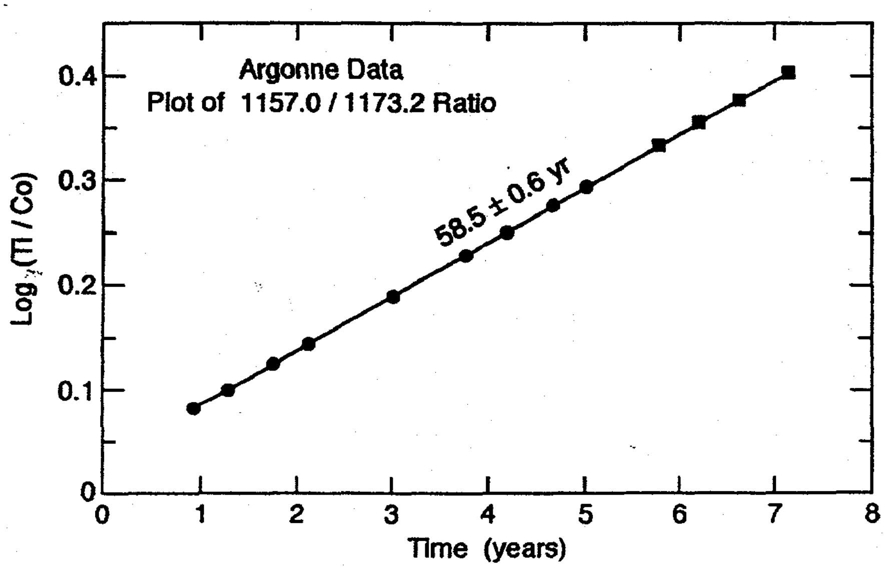

Fig. 6. A semilogarithmic plot of the ratio of the counts in the 1157.0 keV peak to the counts in the 1173.2 keV peak measured as a function of time. The points with square symbol were measured after the publication of the paper [Ah98] in 1998. This line represents one of eight decay curves.

a pure ^{60}Co source. A 60-keV region around the 1157.0 and 1173.2 keV lines, measured with the mixed source, was fitted to the sum of the two peak shapes scaled in energy and intensity and a linear component representing the background spectrum. The procedure gave excellent fits, and the ratio of the peak areas of the 1157.0 and 1173.2 keV lines was obtained directly from the scaling factors. The ratios were corrected for the very small contribution of the 1155.0 keV background line of ^{214}Bi (decay product of natural occurring ^{238}U) which sits under the 1157.0 keV peak. The ratios of the peak areas were analyzed in the same way as the Argonne data to deduce ^{44}Ti half-life. Half-life values were obtained both from the 1157/1173 and 1157/1332 ratios. The Jerusalem data gave a value of 58.9 ± 1.0 yr.

At Torino, only two sets of spectra, separated by ~3 yr, were measured which gave a half-life of 59.4 ± 1.4 yr. The weighted average of the Argonne, Jerusalem and Torino values gave a final value of 59.0±0.6 yr (1σ error) which was published in 1998 [Ah98]. Three more measurements of ^{44}Ti half-life were reported between 1998 and 1999. All three values - 60.3 ± 1.3 yr [Go98], 62 ± 2 yr [No98], 60.7 ± 1.2 yr [Wi99] - are in excellent agreement with our value.

In all the decay measurements, the decay of ^{44}Ti has been followed for only a small fraction of the half-life. For measurements over such a short interval, it is difficult to observe systematic errors. Measurement over longer period is more likely to display systematic errors. For this reason, we have continued the measurement of the ^{44}Ti half-life by measuring the spectra of the ^{60}Co+^{44}Ti mixed samples at Argonne and Jerusalem using the same setup which was used to determine the published value of the half-life. We have data points for additional 2 years; at Argonne we have measured four points and at Jerusalem two points. As discussed in our previous publication [Ah98], we have eight half-life values at Argonne and two half-life values at Jerusalem. One of the decay curves from Argonne is displayed in Fig. 6. We obtain a value of 58.5 ± 0.6 yr from this decay curve which is in excellent agreement with our published value of 59.0 ± 0.6 yr. We have obtained a weighted average value, which agrees with the published value within one standard deviation. We plan to publish the new value of the ^{44}Ti half-life in the year 2000.

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