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Discovery of the Titanium Isotopes

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Twentyfive titanium isotopes have so far been observed; the discovery of these isotopes is discussed. For each isotope a brief summary of the first refereed publication, including the production and identification method, is presented.

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CONTENTS

1. INTRODUCTION

The discovery of the titanium isotopes is discussed as part of the series of the discovery of isotopes which began with the cerium isotopes in 2009 [1]. The purpose of this series is to document and summarize the discovery of the isotopes. Guidelines for assigning credit for discovery are (1) clear identification, either through decay-curves and relationships to other known isotopes, particle or γ-ray spectra, or unique mass and Z-identification, and (2) publication of the discovery in a refereed journal. The authors and year of the first publication, the laboratory where the isotopes were produced as well as the production and identification methods are discussed. When appropriate, references to conference proceedings, internal reports, and theses are included. When a discovery includes a half-life measurement the measured value is compared to the currently adopted value taken from the NUBASE evaluation [2] which is based on the ENSDF database [3].

2. DISCOVERY OF $^{39-63}$TI

Twentyfive titanium isotopes from A = 39 – 63 have been discovered so far; these include 5 stable, 7 proton-rich and 13 neutron-rich isotopes. According to the HFB-14 model [4], ^{78}Ti should be the last even-even particle stable neutron-rich nucleus while the odd-even particle stable neutron-rich nuclei should continue through ^{69}Ti. The proton dripline has been reached and no more long-lived isotopes are expected to exist because ^{38}Ti has been shown to be unbound with an upper limit for the lifetime of 150 ns [5]. About 12 isotopes have yet to be discovered. Almost 70% of all possible titanium isotopes have been produced and identified so far.

Figure A summarizes the year of first discovery for all titanium isotopes identified by the method of discovery. The range of isotopes predicted to exist is indicated on the right side of the figure. The radioactive titanium isotopes were produced using heavy-ion fusion evaporation (FE), deep-inelastic

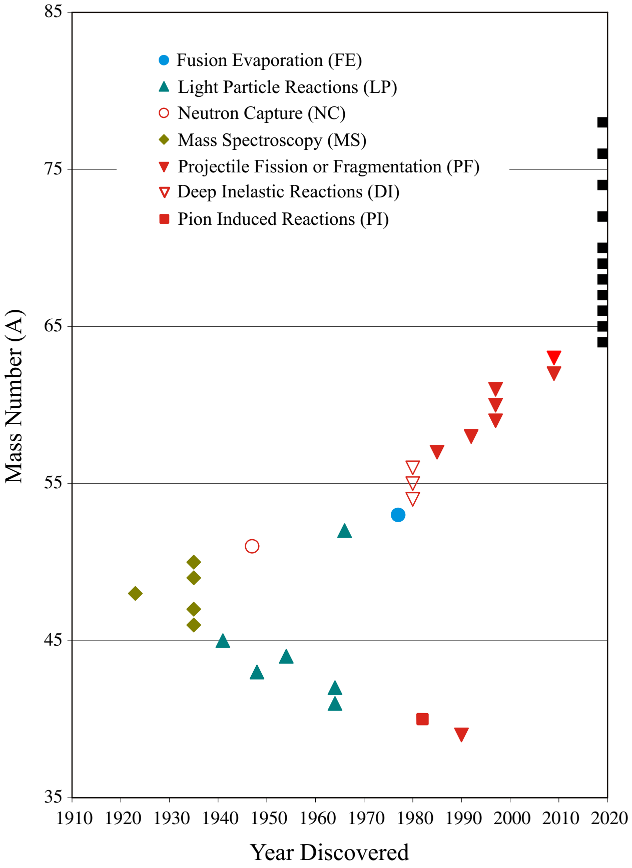

FIG. A. Titanium isotopes as a function of time when they were discovered. The different production methods are indicated. The solid black squares on the right hand side of the plot are isotopes predicted to be bound by the HFB-14 model.

reactions (DI), light-particle reactions (LP), neutron-capture (NC), projectile fragmentation of fission (PF), and pion-induced reactions (PI). Heavy ions are all nuclei with an atomic mass larger than A=4 [6]. Light particles also include neutrons produced by accelerators. In the following, the discovery of each titanium isotope is discussed in detail.

^{39}Ti

^{39}Ti was discovered by Détraz *et al.* in 1990, and published in *Search for Direct Two-Proton Radioactivity from Ti Isotopes at the Proton Drip Line*[7]. ^{39}Ti was produced by fragmenting ^{58}Ni with the Grand Acclrateur National d'Ions Lourds at Caen, France. The isotope was separated with the LISE spectrometer and identified by the observation of β-delayed particle emission. "About 190 ^{40}Ti ions and 75 ^{39}Ti ions were collected during beam times of 3 and 24 hours, respectively." The measured half-life of 26^{+8}_{-7} ms agrees with the adapted value of 31^{+6}_{-4} ms.

^{40}Ti

Morris *et al.* discovered ^{40}Ti in *Target mass dependence of isotensor double charge exchange: Evidence for deltas in nuclei* in 1982 [8]. ^{40}Ti was produced by the pion induced double charge exchange reaction ^{40}Ca(π^+,π^-) and the negative pions were anlysed with the Energetic Pion Channel and Spectrometer EPICS. "Byproducts of the present measurements are values of the masses of ^{28}S and ^{40}Ti. Our measured mass excesses are 4.13±0.16 and $-$8.79±0.16 MeV for ^{28}S and ^{40}Ti, respectively."

^{41}Ti

In 1964 Reeder *et al.* reported the discovery of ^{41}Ti in *New Delayed-Photon Emitters: Ti^{41}, Ca^{37}, and Ar^{33}* [9]. Solid calcium targets were bombarded with 31.8 MeV ^{3}He ions from the Brookhaven 60-inch cyclotron and ^{41}Ti was produced in the reaction ^{40}Ca(^{3}He,2n). Surface-barrier detectors recorded proton spectra as a function of time. "Three new nuclides, Ti^{41}, Ca^{37}, and Ar^{33}, have been observed to be delayed proton emitters." The measured half-life of 90.5(20) ms agrees with the adopted value of 80.4(9) ms.

^{42}Ti

Bryant *et al.* discovered ^{42}Ti in *(He^3,n) Reactions on Various Light Nuclei* in 1964 [10]. 25 MeV ^{3}He ions from the Los Alamos variable energy cyclotron bombarded a solid calcium target and the excitation energy spectrum of ^{42}Ti was extracted by measuring neutron energies with a bubble chamber. "The neutron spectrum from [the ^{40}Ca(^{3}He,n)^{42}Ti] reaction is particularly interesting because, to our knowledge, the Ti^{42} nucleus has not been previously studied. The energy of the neutrons corresponding to the ground state was estimated from the mass defect of $-$25.20 MeV (C^{12} scale) predicted for Ti^{42} ... which leads to a Q for the above reaction of $-$2.79 MeV."

^{43}Ti

The discovery of ^{43}Ti was reported in 1948 by Schelberg *et al.* in *A Method for Measuring Short Period Activities* [11]. 23 MeV α particles accelerated by the Indiana University 45-inch cyclotron bombarded metallic calcium and ^{43}Ti was produced in the reaction ^{40}Ca(α,n)^{43}Ti reaction. The pulses of a Geiger counter were stored in an oscilloscope and recorded by photographing the cathode-ray tube of the oscilloscope. "The result obtained for Ti^{43} is thus in quite good agreement with the value to be expected according to the analysis of Konopinski and Dickson." The measured half-life of 0.58(4) s is consistent with the adopted value of 0.509(5) s.

^{44}Ti

In the 1954 paper *A New Titanium Nuclide: Ti^{44}* Sharp and Diamond announced the first observation of ^{44}Ti [12]. Scandium oxide was bombarded with 30-45 MeV protons from the Harvard 95-inch synchrocyclotron. Activities were measured with a Geiger counter, a proportional counter and a NaI scintillation counter following chemical separation. "Decay measurements made over a period of one half-year indicate, by a least-squares analysis, a half-life of 2.7 years with a rather large estimated error of ±0.7 years because of the small amount of titanium activity available." This value was later changed to a half-life of larger than 23 years in an erratum [13]. This is consistent with the presently accepted value of 60.0(11) y.

^{45}Ti

^{45}Ti was discovered by Allen *et al.* in *Artificial Radioactivity of Ti*^{45} in 1941 [14]. ^{45}Ti was produced by bombarding scandium oxide with 5 MeV protons from the Ohio State University 42-inch cyclotron. A Wulf electrometer with an ionization chamber recorded activities following chemical separation. "The decay has been followed for more than eleven half-lives to an intensity of one-fourth background. The period obtained from this curve is 3.02 hours. Values determined for other samples bombarded under similar conditions are 3.17 and 3.10 hours... Since scandium has but a single stable isotope, the reaction Sc^{45}(p,n)Ti^{45} should be the first considered." The measured half-life of 3.08(6) h agrees with the adopted value of 3.08(1) h.

^{46,47}Ti

^{46}Ti and ^{47}Ti were discovered by Aston in 1935 and published in *The Isotopic Constitution and Atomic Weights of Hafnium, Thorium, Rhodium, Titanium, Zirconium, Calcium, Gallium, Silver, Carbon, Nickel, Cadmium, Iron and Indium* [15]. The mass determination was made using a spectrograph with a discharge in titanium fluoride. "The strong line 48 was found flanked by weak symmetrical pairs of satellites 46, 47, 49, 50, the whole forming a group of striking appearance."

^{48}Ti

Aston reported the discovery of ^{48}Ti in the 1923 paper *Further Determinations of the Constitution of the Elements by the Method of Accelerated Anode Rays* [16]. The mass determination was made using a spectrograph. "Titanium gives a strong line at 48."

^{49,50}Ti

^{49}Ti and ^{50}Ti were discovered by Aston in 1935 and published in *The Isotopic Constitution and Atomic Weights of Hafnium, Thorium, Rhodium, Titanium, Zirconium, Calcium, Gallium, Silver, Carbon, Nickel, Cadmium, Iron and Indium* [15]. The mass determination was made using a spectrograph with a discharge in titanium fluoride. "The strong line 48 was found flanked by weak symmetrical pairs of satellites 46, 47, 49, 50, the whole forming a group of striking appearance."

^{51}Ti

The first correct identification of ^{51}Ti was reported in 1947 by Seren et al. in *Thermal Neutron Activation Cross Sections* [17]. Titanium metal powder was irradiated with thermal neutrons in the Argonne graphite pile reactor. Decay curves, and γ- and β-rays were measured. The observation of ^{51}Ti is not specifically discussed among the 65 elements studied except in the main table: "half-life previously reported 2.8 min. We find 6 min. over 3 half lifes." This half-life agrees with the presently accepted value of 5.76(1) m. The quoted half-life of 2.8 m had been reported earlier [18] and could not be confirmed.

^{52}Ti

Williams *et al.* discovered ^{52}Ti in *The (t,p) and (t,α) Reactions on ^{48}Ca and ^{50}Ti* in 1966 [19]. Tritons were accelerated to 7.5 MeV by the Los Alamos Van de Graaff Accelerator and bombarded a ^{50}Ti target. ^{52}Ti was produced in the (t,p) reaction and identified by measuring protons in a E-ΔE solid-state detector system. “For the ^{50}Ti$(t,p)^{52}$Ti reaction, Q_0 was found to be 5.698 ± 0.010 MeV.” An earlier report of a 49(3) m half-life [20] has not been confirmed.

^{53}Ti

^{53}Ti was discovered by Parks *et al.* in 1977 and published in *β decay and mass of the new neutron-rich isotope ^{53}Ti* [21].^{53}Ti was produced in the fusion evaporation reaction ^{48}Ca(^{7}Li,pn) reaction at the Argonne FN tandem Van de Graaff accelerator. β rays and β-delayed γ-ray were measured and “The half-life of the decay of ^{53}Ti was determined by following the decays of the β-delayed 101-, 127-, and 228-keV γ rays. After correction for dead time, the composite decay curve for these three γ rays yielded a half-life of 32.7±0.9 s.” This half-life measurement is currently the only one for ^{53}Ti.

^{54,55}Ti

Guerreau *et al.* reported the discovery of ^{54}Ti and ^{55}Ti in the 1980 paper *Seven New Neutron Rich Nuclides Observed in Deep Inelastic Collisions of 340 MeV ^{40}Ar on ^{238}U* [22]. A 340 MeV ^{40}Ar beam accelerated by the Orsay ALICE accelerator facility bombarded a 1.2 mg/cm^2 thick UF$_4$ target supported by an aluminum foil. The isotopes were identified using two ΔE-E telescopes and two time of flight measurements. “The new nuclides ^{54}Ti, ^{56}V, $^{58-59}$Cr, ^{61}Mn, $^{63-64}$Fe, have been produced through ^{40}Ar + ^{238}U reactions.” At least twenty counts were recorded for ^{54}Ti. The identification of ^{55}Ti was only tentative. Breuer *et al.* detected both isotopes independently only a few months later [23].

^{56}Ti

^{56}Ti was first observed by Breuer *et al.* in 1980 as described in *Production of neutron-excess nuclei in ^{56}Fe-induced reactions* [23]. ^{56}Fe ions were accelerated to 8.3 MeV/u by the Berkeley Laboratory SuperHILAC accelerator and bombarded self-supporting ^{238}U targets. New isotopes were produced in deep-inelastic collisions and identified with a ΔE-E time-of-flight semiconductor detector telescope. “In addition, tentative evidence is found for ^{56}Ti, $^{57-58}$V, ^{60}Cr, ^{61}Mn, and ^{63}Fe.” 13±5 events of ^{56}Ti were observed.

^{57}Ti

Guillemaud-Mueller *et al.* announced the discovery of ^{57}Ti in the 1985 article *Production and Identification of New Neutron-Rich Fragments from 33 MeV/u ^{86}Kr Beam in the 18$\leq$Z$\leq$27 Region* [24]. At GANIL in Caen, France, a 33 MeV/u ^{86}Kr beam was fragmented and the fragments were separated by the triple-focusing analyser LISE. “Each particle is identified by an event-by-event analysis. The mass A is determined from the total energy and the time of flight, and Z by the δE and E measurements... In addition to that are identified the following new isotopes: ^{47}Ar, ^{57}Ti, ^{59,60}V, ^{61,62}Cr, ^{64,65}Mn, ^{66,67,68}Fe, ^{68,69,70}Co.” At least four counts of ^{57}Ti were observed.

^{58}Ti

In their paper *New neutron-rich isotopes in the scandium-to-nickel region, produced by fragmentation of a 500 MeV/u ^{86}Kr beam*, Weber *et al.* presented the first observation of ^{58}Ti in 1992 at GSI [25]. ^{58}Ti was produced in the fragmentation reaction of a 500 A·MeV ^{86}Kr beam from the heavy-ion synchroton SIS on a beryllium target and separated with the zero-degree spectrometer FRS. “The isotope identification was based on combining the values of Bρ, time of flight (TOF), and energy loss ($\triangle$E) that were measured for each ion passing through the FRS and its associated detector array... The results ... represent unambiguous evidence for the production of the very neutron-rich isotopes ^{58}Ti, ^{61}V, ^{63}Cr, ^{66}Mn, ^{69}Fe, and ^{71}*Co*...” Eleven events of ^{58}Ti were observed.

$^{59-61}$Ti

Bernas *et al.* observed ^{59}Ti, ^{60}Ti, and ^{61}Ti for the first time in 1997 as reported in their paper *Discovery and cross-section measurement of 58 new fission products in projectile-fission of 750·A MeV ^{238}U* [26]. Uranium ions were accelerated to 750 A·MeV by the GSI UNILAC/SIS accelerator facility and bombarded a beryllium target. The isotopes produced in the projectile-fission reaction were separated using the fragment separator FRS and the nuclear charge Z for each was determined by the energy loss measurement in an ionization chamber. “The mass identification was carried out by measuring the time of flight (TOF) and the magnetic rigidity Bρ with an accuracy of 10^{-4}.” 115, 40 and 9 counts of ^{59}Ti, ^{60}Ti and ^{61}Ti were observed, respectively.

^{62,63}Ti

^{62}Ti and ^{63}Ti were discovered by Tarasov *et al.* in 2009 and published in *Evidence for a change in the nuclear mass surface with the discovery of the most neutron-rich nuclei with 17 $\leq$ Z $\leq$ 25* [27]. ^{9}Be targets were bombarded with 132 MeV/u ^{76}Ge ions accelerated by the Coupled Cyclotron Facility at the National Superconducting Cyclotron Laboratory at Michigan State University. ^{62}Ti and ^{63}Ti were produced in projectile fragmentation reactions and identified with a two-stage separator consisting of the A1900 fragment separator and the S800 analysis beam line. “The observed fragments include fifteen new isotopes that are the most neutron-rich nuclides of the elements chlorine to manganese (^{50}Cl, ^{53}Ar, ^{55,56}K, ^{57,58}Ca, ^{59,60,61}Sc, ^{62,63}Ti, ^{65,66}V, ^{68}Cr, ^{70}Mn).”

3. SUMMARY

The discoveries of the known titanium isotopes have been compiled and the methods of their production discussed. The limit for observing long lived isotopes beyond the proton dripline which can be measured by implantation decay studies has most likely been reached with the discovery of ^{39}Ti and the non-observation of ^{38}Ti. The discovery of the titanium isotopes was straight forward. Only the half-life of ^{51}Ti was initially incorrect.

Acknowledgments

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EXPLANATION OF TABLE

TABLE I. Discovery of Titanium Isotopes

Isotope	Titanium isotope
Author	First author of refereed publication
Journal	Journal of publication
Ref.	Reference
Method	Production method used in the discovery: FE: fusion evaporation LP: light-particle reactions (including neutrons) MS: mass spectroscopy PI: pion induced reactions DI: deep-inelastic reactions PF: projectile fragmentation or fission NC: neutron-capture reactions
Laboratory	Laboratory where the experiment was performed
Country	Country of laboratory
Year	Year of discovery

TABLE I. Discovery of Titanium isotopes

See page 10 for Explanation of Tables

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Isotope	Author	Journal	Ref.	Method	Laboratory	Country	Year
^{39}Ti	C. Detraz	Nucl. Phys. A	Det90	PF	GANIL	France	1990
^{40}Ti	C.L. Morris	Phys. Rev. C	Mor82	PI	Los Alamos	USA	1982
^{41}Ti	P.L. Reeder	Phys. Rev. Lett.	Ree64	LP	Brookhaven	USA	1964
^{42}Ti	H.C. Bryant	Nucl. Phys.	Bry64	LP	Los Alamos	USA	1964
^{43}Ti	A.D. Schelberg	Rev. Sci. Instrum.	Sch48	LP	Indiana	USA	1948
^{44}Ti	R.A. Sharp	Phys. Rev.	Sha54	LP	Harvard	USA	1954
^{45}Ti	J.S.V. Allen	Phys. Rev.	All41	LP	Ohio State	USA	1941
^{46}Ti	F.W. Aston	Proc. Roy. Soc.	Ast35	MS	Cambridge	UK	1935
^{47}Ti	F.W. Aston	Proc. Roy. Soc.	Ast35	MS	Cambridge	UK	1935
^{48}Ti	F.W. Aston	Nature	Ast23	MS	Cambridge	UK	1923
^{49}Ti	F.W. Aston	Proc. Roy. Soc.	Ast35	MS	Cambridge	UK	1935
^{50}Ti	F.W. Aston	Proc. Roy. Soc.	Ast35	MS	Cambridge	UK	1935
^{51}Ti	L. Seren	Phys. Rev.	Ser47	NC	Argonne	USA	1947
^{52}Ti	D.C. Williams	Phys. Lett.	Wil66	LP	Los Alamos	USA	1966
^{53}Ti	L.A. Parks	Phys. Rev. C	Par77	FE	Argonne	USA	1977
^{54}Ti	D. Guerreau	Z. Phys. A	Gue80	DI	Orsay	France	1980
^{55}Ti	D. Guerreau	Z. Phys. A	Gue80	DI	Orsay	France	1980
^{56}Ti	H. Breuer	Phys. Rev. C	Bre80	DI	Berkeley	USA	1980
^{57}Ti	D. Guillemaud-Mueller	Z. Phys. A	Gui85	PF	GANIL	France	1985
^{58}Ti	M. Weber	Z. Phys. A	Web92	PF	Darmstadt	Germany	1992
^{59}Ti	M. Bernas	Phys. Lett. B	Ber97	PF	Darmstadt	Germany	1997
^{60}Ti	M. Bernas	Phys. Lett. B	Ber97	PF	Darmstadt	Germany	1997
^{61}Ti	M. Bernas	Phys. Lett. B	Ber97	PF	Darmstadt	Germany	1997
^{62}Ti	O.B. Tarasov	Phys. Rev. Lett.	Tar09	PF	Michigan State	USA	2009
^{63}Ti	O.B. Tarasov	Phys. Rev. Lett.	Tar09	PF	Michigan State	USA	2009

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