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Discovery of the Scandium Isotopes

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Twentythree scandium 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 scandium 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 $^{39-61}$SC

Twentythree scandium isotopes from A = $39-61$ have been discovered so far; these include 1 stable, 6 proton-rich and 16 neutron-rich isotopes. According to the HFB-14 model [4], ^{68}Sc should be the last odd-odd particle stable neutron-rich nucleus while the odd-even particle stable neutron-rich nuclei should continue through ^{77}Sc. The proton dripline has been reached and no more long-lived isotopes are expected to exist because ^{39}Sc has been shown to be unbound by 580 keV [5]. About 12 isotopes have yet to be discovered corresponding to 35% of all possible scandium isotopes.

Figure A summarizes the year of first discovery for all scandium 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 scandium isotopes were produced using heavy-ion transfer reactions (TR), deep-inelastic

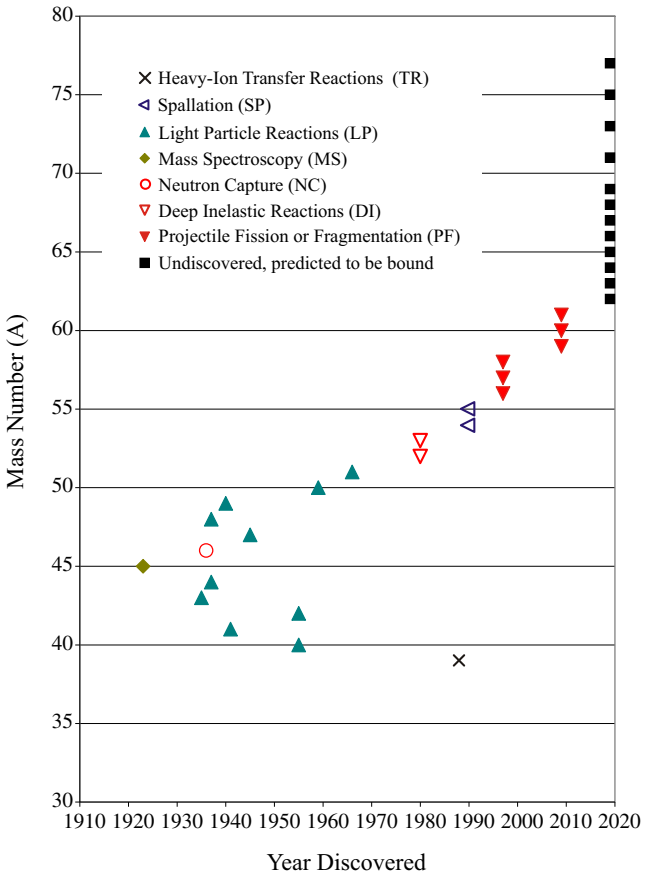

FIG. A. Scandium isotopes as a function of time when they were discovered. The different production methods are indicated. The solid black squares on the right hand side of the plot are isotopes predicted to be bound by the HFB-14 model.

reactions (DI), light-particle reactions (LP), neutron capture (NC), spallation (SP), and projectile fragmentation of fission (PF). The stable isotopes were identified using mass spectroscopy (MS). 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 scandium isotope is discussed in detail.

^{39}Sc

^{39}Sc was discovered by Woods *et al.* in 1988, and published in "A Measurement of the Mass of ^{39}Sc" [5]. A beam of 102.5 MeV ^{14}N accelerated by the 14UD pelletron accelerator at the Australian National University bombarded a ^{40}Ca target on a carbon backing and ^{39}Sc was identified by measuring the transfer reaction product ^{15}C in an Enge split-pole spectrometer. "A mass excess of -14.19 ± 0.03 MeV has been derived for ^{39}Sc from a measurement of the Q-value of the ^{40}Ca(^{14}N,^{15}C)^{39}Sc reaction." The observation of ^{39}Sc was independently submitted a month later by Mohar *et al.* [7].

^{40}Sc

Glass and Richardson discovered ^{40}Sc in "Radionuclides Al^{24}, P^{28}, Cl^{32}, and Sc^{40}" in 1955 [8]. A 20-MeV proton beam from the UCLA 41-in FM cyclotron bombarded a calcium target. The isotope was formed in the charge exchange reaction ^{40}Ca(p,n)^{40}Sc. Positron and γ-ray spectra were measured with a NaI crystal. "Sc^{40} has a half-life of 0.22$\pm$0.03 sec, threshold of 15.9$\pm$1.0 Mev,a 3.75$\pm$0.04 Mev gamma ray, and maximum positron energy of 9.0$\pm$0.4 Mev." This half-life is close to the currently adapted value of 182.3(7) ms. A previously reported observation of ^{40}Sc estimated a half-life of $\approx$0.35 s which is almost off by a factor of two and the identification was only suggested "from a simple consideration of preferred reaction type[s] and estimates of threshold[s]" [9].

^{41}Sc

^{41}Sc was discovered by Elliot and King in 1941 and published in "Radionuclides $_{21}$Sc^{41}, $_{18}$Al^{35}, and $_{16}$S^{31}" [10]. ^{41}Sc was produced in the reaction ^{40}Ca(d,n) using 8 MeV deuterons from the Purdue University cyclotron [11]. The half-life and the energy spectrum of the positrons were measured. "Because Sc^{41} cannot be reached by any other of the usual nuclear reactions its identification is mostly one of elimination. All other probable Ca(d,$-$) reactions have been investigated carefully" [11]. The measured half life of 0.87(3) s is close to the adapted value of 593.6(17) ms. Previously, a half-life of 52(2) h had been reported which was changed to 53(3) m in a note added in proof [12]. The assignment was based on the assumption that ^{44}Ca was the heaviest stable isotope.

^{42}Sc

Morinaga identified ^{42}Sc correctly for the first time in "New Radioactive Isotope Scandium-42" in 1955 [13]. At Purdue University a potassium target was bombarded with 18 MeV α particles. Decay curves of positrons and the annihilation radiation were measured with an anthracene and NaI crystal, respectively. "A strong activity with a half-life of 0.62$\pm$0.05 sec (error limit) was found." This half-life agrees with the presently accepted value of 681.3(7) ms. Previously, half-lives of 4.1(1) h [14] and 13.5(3) d [15] had incorrectly been assigned to ^{42}Sc.

^{43}Sc

^{43}Sc was discovered in 1935 by Frisch as reported in the paper "Induced Radioactivity of Fluorine and Calcium" [16]. Alpha-particles from a 600 mCi radon source were used to irradiate calcium and ^{43}Sc was formed in the reaction ^{40}Ca(α,p). "From the great intensity, one may say that the effect is due to the main isotope of calcium, Ca^{40}. Capture of the alpha particle, with subsequent emission of a proton or neutron, would lead to the formation of Sc^{43} or Ti^{43}, respectively. A chemical separation, kindly carried out by Prof. G. von Hevesy, showed that the active body follows the reactions of scandium. Therefore the 4.4 hours activity certainly corresponds to Sc^{43}." This half-life, quoted with a possible error of 10% agrees with the currently adapted value of 3.891(12) h.

^{44}Sc

In 1937 Walke observed ^{44}Sc as described in the paper "The Induced Radioactivity of Calcium" [12]. ^{44}Sc was identified in the reaction ^{41}K(α,n) by bombarding potassium fluoride with 11 MeV α

particles from the Berkeley cyclotron as described in a note added in proof: "By deflecting the emitted particles in a magnetic field it has been established that they are positrons. The decay curve shows the presence of two isotopes with half-lives of 4.1±0.2 hours and 52±2 hours. As the long period agrees with that observed in the scandium precipitate from calcium + deuterons it must be associated with Sc^{44}..." This half-life agrees with the currently accepted values of 3.97(4) h. In the main text of the paper ^{44}Sc had been assigned a half-life of 53±3 m. A 3 hour half-life had been reported earlier but it was assigned only to either ^{42}Sc or ^{44}Sc [17].

^{45}Sc

Aston reported the discovery of ^{45}Sc in the 1923 paper "Further Determinations of the Constitution of the Elements by the Method of Accelerated Anode Rays" [18]. The mass determination was made using the method of accelerated anode rays with a spectrograph: "Scandium was successfully attacked by the use of material kindly supplied by Prof. Urbain, of Paris. The only line obtained was at 45. It may be taken provisionally to be a simple element, but the effects are not strong enough to disprove the presence of small quantities of another constituent."

^{46}Sc

^{46}Sc was discovered in 1936 by Hevesy and Levi reported in the paper "The action of neutrons on the rare earth elements" [19]. Scandium was irradiated by a 200-300 mCi radon-beryllium source and the activity was measured following chemical separation. "The activities are due to the formation of ${}^{46}_{21}$Sc and ${}^{42}_{19}$K, respectively; the reaction leading to these products are ${}^{45}_{21}\mathrm{Sc} + {}^{1}_{0}\mathrm{n} = {}^{46}_{21}\mathrm{Sc}$ and ${}^{45}_{21}\mathrm{Sc} + {}^{1}_{0}\mathrm{n} = {}^{46}_{19}\mathrm{K} + {}^{4}_{2}\alpha$. The mass numbers occuring in these equations follows from the fact that scandium has only one stable isotope, ${}^{45}_{21}$Sc... The activity which cannot be separated from scandium is presumable due to ${}^{46}_{21}$Sc; most of this activity decays with a period of about two months but a small part does not decay appreciably within a year or two." The half-life is close to the present value of 83.79(4) d.

^{47}Sc

^{47}Sc was identified correctly for the first time by Hibdon and Pool in the 1945 paper "Radioactive Scandium. II" [20]. 20 MeV α-particles, 10 MeV deuterons and 5 MeV protons were accelerated by the Ohio State University 42-inch cyclotron and decay curves were measured with a Wulf unifilar electrometer [21]. "This radioactive isotope [Sc^{47}] has been reported to have a half-life of 2.62 days and to emit 1.1 Mev electrons. These observations are not confirmed. A new radioactive isotope has, however, been produced by bombarding calcium with alpha-particles and to some extent by bombarding calcium with deuteron and proton. It emits beta-rays of 0.46 Mev and has a half-life of 3.4 days. This assignment is made to Sc^{47}." This half-life agrees with the presently adopted value of 3.3492(6) d. In addition to the mentioned incorrect observation published in 1940 [15], a 1938 paper had tentatively assigned the half-life of 28 h meausured by Pool *et al.* [22] to ^{47}Sc [23].

^{48}Sc

In 1937 the observation of ^{48}Sc was reported in the paper "The Induced Radioactivity of Titanium and Vanadium" by H. Walke [24]. 14-20 MeV neutrons from the bombardment of 5.5 MeV deuterons

on lithium at the Berkeley cyclotron were used to activate titanium and vanadium targets. ^{48}Sc was produced in the reactions ^{48}Ti(n,p) and ^{51}V(n,α). Decay and absorption measurements were performed with a Lauritsen type quartz fiber electroscope. "When bombarded with fast neutrons it seems likely that Ca^{45}, Sc^{48} and Sc^{46} are formed from titanium. Sc^{48} is also produced by the transmutation $V^{51} + n^1 \rightarrow Sc^{48} + He^4$, its half-life being 41$\pm$3 hours." This half-life agrees with the currently accepted value of 43.67(9) h.

^{49}Sc

In 1940 Walke correctly identified ^{49}Sc in the paper "The Radioactive Isotopes of Scandium and Their Properties" [15]. ^{49}Sc was produced by bombarding calcium with 8 MeV deuterons from the 37-inch Berkeley cyclotron. ^{49}Ca was identified by measuring the decay and absorption with a Lauritsen quartz fiber electroscope. The assignment was confirmed in the β-decay of ^{49}Ca formed by neutron capture of ^{48}Ca and in the reaction ^{49}Ti(n,p)^{49}Sc. "The activity of half-life 53$\pm$3 min., now measured accurately as 57$\pm$2 min., produced by bombarding calcium with deuterons, which emits β-particles of energy 1.8$\pm$0.1 MeV previously assigned to Sc^{41} is shown to be probably due to Sc^{49}." The half-life of 57(2) m agrees with the currently accepted value of 57.2(2) m. The mentioned 53(3) m half-life was originally assigned to ^{44}Sc but changed to ^{41}Sc in a note added in proof [12] which was still incorrect.

^{50}Sc

^{50}Sc was discovered in 1959 by Poularikas and Fink in "Absolute Activation Cross Sections for Reactions of Bismuth, Copper, Titanium, and Aluminum with 14.8-Mev Neutrons" [25]. Deuterons from the University of Arkansas 400-kV Cockroft-Walton Accelerator produced 14.8 MeV monoenergetic neutrons via the reaction ^{3}H(d,n)^{4}He and ^{50}Sc was produced in the reaction ^{50}Ti(n,p). Decay curves were measured with a beta-proportional counter. A half-life of 1.80(20) m was quoted for ^{50}Sc in a table. This half-life is consistent with the presently accepted value of 102.5(5) s. A second half-life of 22(3) m tentatively assigned to ^{50}Sc could not be confirmed [26,27]. Poularikas and Fink did not acknowledge a previous half-life measurement of 1.8(2) m only reported at a conference [28] and in an internal report [29].

^{51}Sc

Erskine *et al.* reported the first measurement of ^{51}Sc in the 1966 paper "Energy Levels in Sc^{49} from $Ca^{48}(He^3,d)Sc^{49}$ and Other Reactions Proceeding from Ca^{48} [30]. Alpha-particles from the Argonne tandem Van de Graaff accelerator bombarded evaporated ^{48}Ca targets on a carbon backing. Ground-state Q-values and excited states were measured using the Argonne broad-range magnetic spectrograph. "The isotope Sc^{51} is observed here for the first time in the study of the $Ca^{48}(\alpha,p)Sc^{51}$ reaction. A ground-state Q-value of -5.860 ± 0.020 MeV was measured". The first decay measurement of ^{51}Sc was submitted only five months later [31].

^{52,53}Sc

^{52}Sc and ^{53}Sc were first observed by Breuer *et al.* in 1980 as described in *Production of neutron-excess nuclei in ^{56}Fe-induced reactions* [32]. ^{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: "...the identification of seven new isotopes is reported: $^{52-53}$Sc, $^{54-55}$Ti, ^{56}V, and $^{58-59}$Cr." 30±8 and 19±6 events of ^{52}Sc and ^{53}Sc were observed, respectively.

^{54,55}Sc

^{54}Sc and ^{55}Sc were discovered in 1990 by Tu *et al.*: "Direct mass measurement of the neutron-rich isotopes of chlorine through iron" [33]. 800 MeV protons from the Los Alamos Meson Physics Facility LAMPF bombarded a ^{nat}Th target and the isotopes were identified using the TOFI spectrometer. The mass excesses for 29 neutron-rich isotopes from chlorine to iron (including ^{54}Sc and ^{55}Sc) were measured for the first time and presented in a table.

$^{56-58}$Sc

Bernas *et al.* observed ^{56}Sc, ^{57}Sc, and ^{58}Sc 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" [34]. 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}." 68, 30 and 11 counts of ^{55}Sc, ^{56}Sc and ^{57}Sc were observed, respectively.

$^{59-61}$Sc

^{59}Sc, ^{60}Sc and ^{61}Sc 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 $17 \leq Z \leq 25$" [35]. ^{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. ^{58}Sc, ^{59}Sc and ^{60}Sc 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 scandium 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 ^{40}Sc and the observation that of ^{39}Sc is unbound with respect to proton emission by 580 keV. The discovery of especially the light scandium isotopes was difficult. Five isotopes - two of twice - were initially

identified incorrectly ($^{40-42}$Sc, ^{44}Sc and ^{47}Sc). The half-life of ^{49}Sc had first been assigned to ^{44}Sc and then to ^{41}Sc.

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EXPLANATION OF TABLE

TABLE I. Discovery of scandium isotopes

Isotope	Scandium 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 NC: neutron capture 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 Scandium Isotopes

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Isotope	Author	Journal	Ref.	Method	Laboratory	Country	Year
^{39}Sc	C.L. Woods	Nucl. Phys. A	Woo88	TR	Canberra	Australia	1988
^{40}Sc	N.W. Glass	Phys. Rev.	Gla55	LP	UCLA	USA	1955
^{41}Sc	D.R. Elliott	Phys. Rev.	Ell41	LP	Purdue	USA	1941
^{42}Sc	H. Morinaga	Phys. Rev.	Mor55	LP	Purdue	USA	1955
^{43}Sc	O.R. Frisch	Nature	Fri35	LP	Copenhagen	Denmark	1935
^{44}Sc	H. Walke	Phys. Rev.	Wal37a	LP	Berkeley	USA	1937
^{45}Sc	F.W. Aston	Nature	Ast23	MS	Cambridge	UK	1923
^{46}Sc	G. Hevesy	Mat.-fys. Medd.	Hev36	NC	Copenhagen	Denmark	1936
^{47}Sc	C.T. Hibdon	Phys. Rev.	Hib45	LP	Ohio State	USA	1945
^{48}Sc	H. Walke	Phys. Rev.	Wal37b	LP	Berkeley	USA	1937
^{49}Sc	H. Walke	Phys. Rev.	Wal40	LP	Berkeley	USA	1940
^{50}Sc	A. Poularikas	Phys. Rev.	Pol59	LP	Arkansas	USA	1959
^{51}Sc	J.R. Erskine	Phys. Rev.	Ers66	LP	Argonne	USA	1966
^{52}Sc	H. Breuer	Phys. Rev. C	Bre80	DI	Berkeley	USA	1980
^{53}Sc	H. Breuer	Phys. Rev. C	Bre80	DI	Berkeley	USA	1980
^{54}Sc	X.L. Tu	Z. Phys. A	Tu80	SP	Los Alamos	USA	1990
^{55}Sc	X.L. Tu	Z. Phys. A	Tu80	SP	Los Alamos	USA	1990
^{56}Sc	M. Bernas	Phys. Lett. B	Ber97	PF	Darmstadt	Germany	1997
^{57}Sc	M. Bernas	Phys. Lett. B	Ber97	PF	Darmstadt	Germany	1997
^{58}Sc	M. Bernas	Phys. Lett. B	Ber97	PF	Darmstadt	Germany	1997
^{59}Sc	O.B. Tarasov	Phys. Rev. Lett.	Tar09	PF	Michigan State	USA	2009
^{60}Sc	O.B. Tarasov	Phys. Rev. Lett.	Tar09	PF	Michigan State	USA	2009
^{61}Sc	O.B. Tarasov	Phys. Rev. Lett.	Tar09	PF	Michigan State	USA	2009

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