Discovery of the Selenium Isotopes

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Abstract

Thirty-one selenium 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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1. Introduction

The discovery of the Selenium 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 $\gamma$-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 $^{64-94}\text{Se}$

Thirty-one Selenium isotopes from $A = 64 - 94$ have been discovered so far; these include 6 stable, 11 proton-rich and 14 neutron-rich isotopes. According to the HFB-14 model \[4\], $^{111}\text{Se}$ should be the last odd-even particle stable neutron-rich nucleus while the even-even particle stable neutron-rich nuclei should continue through $^{118}\text{Se}$. At the proton dripline $^{62}\text{Se}$ and $^{63}\text{Se}$ could still be particle stable and $^{61}\text{Se}$ could live long enough to be observed \[5\]. About 24 isotopes have yet to be discovered corresponding to 44% of all possible selenium isotopes.

Figure 1 summarizes the year of first discovery for all selenium 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 selenium isotopes were produced using heavy-ion fusion-evaporation reactions (FE), light-particle reactions (LP), neutron capture (NC), neutron-induced fission (NF), photo-nuclear reactions (PN) and projectile fragmentation or 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 selenium isotope is discussed in detail.

2.1. $^{64}\text{Se}$

In the 2005 paper “First observation of $^{60}\text{Ge}$ and $^{64}\text{Se}$” Stolz et al. identified the isotope $^{64}\text{Se}$ for the first time \[7\]. $^{64}\text{Se}$ was produced in the projectile fragmentation reaction of a 140 MeV/nucleon $^{78}\text{Kr}$ beam on a beryllium target at the Coupled Cyclotron Facility of the National Superconducting Cyclotron Laboratory at Michigan State University. The projectile fragments were identified with the A1900 fragment separator. “A total of four events of $^{64}\text{Se}$ were observed during 32 hours of beam on target with an average primary beam current of 13.5 pnA.”

2.2. $^{65}\text{Se}$

Batchelder et al. first observed $^{65}\text{Se}$ as reported in the 1993 paper “Beta-delayed proton decay of $^{65}\text{Se}$” \[8\]. The Berkeley 88-Inch Cyclotron was used to accelerate a 175 MeV $^{28}\text{Si}$ beam which bombarded a natural calcium target. $^{65}\text{Se}$ was produced in the fusion-evaporation reaction $^{40}\text{Ca}(^{28}\text{Si},3n)$ and the recoil products were deposited on a moving tape collector with a helium-jet setup. Beta-delayed protons were detected with a Si-Si detector telescope. “A single
Fig. 1: Selenium 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. On the proton-rich side the light blue square correspond to $^{61}$Se which is predicted to have a lifetime larger than $\sim 10^{-9}$ s.
proton group at 3.55±0.03 MeV has been observed... Combining this measurement with a Coulomb displacement energy calculation yields a mass excess for $^{65}$Se of $-33.41±0.26$ MeV.”

2.3. $^{66}$Se

In 1993, Winger et al. reported the discovery of $^{66}$Se in “Half-life measurements for $^{61}$Ga, $^{63}$Ge, and $^{65}$As and their importance in the rp process” [9]. A 75 MeV/nucleon $^{78}$Kr beam from the Michigan State Cyclotron bombarded an enriched $^{58}$Ni. $^{66}$Se was separated and identified with the A1200 fragment separator. “By using the triple gating method, we were able to observe 16 implantation events positively identified as $^{66}$Se and sufficient to demonstrate first observation of this proton-rich nucleus.”

2.4. $^{67}$Se

Mohar et al. first observed $^{67}$Se in the 1991 paper “Identification of New Nuclei near the Proton-Dripline for $31\leq Z\leq 38$” [10]. A 65 A-MeV $^{78}$Kr beam produced by the Michigan State K1200 cyclotron reacted with a $^{58}$Ni target. $^{67}$Se was identified by measuring the rigidity, $\Delta E$, $E_{\text{total}}$, and velocity in the A1200 fragment separator. “Several new isotopes at or near the proton-drip line are indicated in the mass spectra: $^{61}$Ga, $^{62}$Ge, $^{63}$Ge, $^{65}$As, $^{69}$Br, and $^{75}$Sr.” The discovery of $^{67}$Se was not explicit mentioned but it is clearly identified in the selenium mass spectrum. The authors assumed it to be known, although it was only reported in a conference abstract [11].

2.5. $^{68}$Se

In 1990, Lister et al. reported the observation of $^{68}$Se in the paper “Shape Changes in N=Z nuclei from Germanium to Zirconium” [12]. A 175 MeV $^{58}$Ni beam from the Daresbury NSF tandem accelerator bombarded a carbon target and $^{68}$Se was produced in the fusion-evaporation reaction $^{12}$C($^{58}$Ni,2n). Gamma-rays measured with ten shielded germanium in coincidence with recoil products recorded in an ionization chamber. “The final spectrum from our experiment on $^{68}$Se is shown in [the figure]. Although the statistics are poor, several features are clear. The strongest transition is at 853.9±0.3 keV and is a candidate for the $2^+ \rightarrow 0^+$ decay.” Previous measurements of the $^{68}$Se half-life of 3.2(2) h [13] and 1.6(4) min. [14] were incorrect.

2.6. $^{69}$Se

Nolte et al. identified $^{69}$Se in the 1974 publication “Investigation of Neutron Deficient Nuclei in the Region 28<N, Z<50 with the Help of Heavy Ion Compound Reactions” [15]. The Munich MP tandem accelerator was used to bombard calcium targets with $^{32}$S beams of 90 and 100 MeV. $^{69}$Se was produced in the fusion-evaporation reaction $^{40}$Ca($^{32}$S,2pn) and identified with $\gamma$-ray and activation measurements. “The half-life of the new isotope $^{69}$Se has been found to be 27±3 sec.” This half-life agrees with the currently adopted value of 27.4(2) s. A previous measurement of 1.8 and 14 min. isomeric states [16] could not be confirmed.

2.7. $^{70}$Se

In the 1950 paper “Spallation Products of Arsenic with 190 MeV Deuterons” Hopkins identified the isotope $^{70}$Se [17]. A pure $^{75}$As target was bombarded with 190 MeV deuterons from the Berkeley 184-inch cyclotron and chemically separated and subjected to spectrographic analysis. “Table 1 contains two changes in isotope assignment differing from
those previously reported. The 44-min. selenium and 52-min. arsenic daughter are placed at mass 70 since careful
separations revealed no active germanium daughter." The measured half-life of 44 min. is in good agreement with the
presently accepted value of 41.1(3) min. In a previous paper the activity was incorrectly assigned to $^{71}\text{Se}$ [18].

2.8. $^{71}\text{Se}$

Beydon et al reported $^{71}\text{Se}$ in the 1957 publication “Mise en évidence d’un isotope nouveau de sélenium déficient
en neutrons” [19]. Nickel and Copper targets were bombarded with a $^{14}\text{N}$ beam from the Saclay cyclotron. Following
chemical separation $^{71}\text{Se}$ was identified by measuring the activity with a Geiger-Müller counter and NaI(Tl) detector.
“…nous avons pu constater la formation d’un nouvel isotope léger du sélénium, de période 5±2 mn, émetteur $\beta$, présentant
une raie $\gamma$ vers 160 keV dont la masse est sans doute 71, la masse 69 n’étant toutefois pas exclue.” [...] we observed the
formation of a new light selenium isotope, a $\beta$-emitter with a period of 5±2 min period and a 160 keV $\gamma$-ray whose
mass is probably 71, however, the mass 69 cannot be excluded.] This half-life agrees with the presently accepted value
of 4.74.(5) min. A 44 min. half-life had previously been incorrectly assigned to $^{71}\text{Se}$ [18].

2.9. $^{72}\text{Se}$

Hopkins and Cunningham first observed $^{72}\text{Se}$ in 1948, in the paper “Nuclear Reactions of Arsenic with 190-Mev
Deuterons” [18]. 190 MeV deuterons from the Berkeley 184-inch cyclotron bombarded a pure $^{75}\text{As}$ target and $^{72}\text{Se}$
was identified by measuring the activity with argon-filled Geiger-Müller counting tubes following chemical separation.
“Several new radioactivities have been observed. Mass assignments have been made by demonstration of the following
decay chains. Se$^{72} \rightarrow \text{As}^{72} \rightarrow \text{Ge}^{72}$. “ The observed half-life of 9.5 d agrees with the accepted value of 8.40(8) d.

2.10. $^{73}\text{Se}$

In the 1948 paper “Artificially Radioactive $^{73}\text{Se}$ and $^{75}\text{Se}$” Cowart et al. first identified $^{73}\text{Se}$ [20]. Germanium targets
were bombarded with $\alpha$ particles from the Ohio State cyclotron. Half-lives of X-rays, $\gamma$-rays and $\beta$-particles were
measured to identify $^{73}\text{Se}$. “Because of the positron emission, the 7.1-hour activity could be placed in mass 73 or 75
of selenium. An attempt was made to produce this short period by bombardment of As$^{75}$ with deuterons. Since this
period was not found as a result of such bombardments, mass 73 is most probable.” This assignment was confirmed by
$\alpha$ bombardment of enriched $^{70}\text{Ge}$ targets. The measured half-life of 7.1 h agrees with the accepted value of 7.15(8) h.

2.11. $^{74}\text{Se}$

Aston discovered $^{74}\text{Se}$ in 1922 as reported in “The Isotopes of Selenium and some other Elements” [21]. Selenium
was vaporized in a discharge tube to obtain suitable spectra with the Cavendish mass spectrometer. “The interpretation
of these is quite simple and definite, so that the results may be stated with every confidence. Selenium consists of six
isotopes, giving lines at $74(f), 76(c), 77(e), 78(b), 80(a), 82(d)$. The line at 74 is extremely faint. The intensities of the
lines are in the order indicated by the letters, and agree well enough with the chemical atomic weight 79.2.”
2.12. $^{75}\text{Se}$

Friedlander et al. reported the first observation of $^{75}\text{Se}$ in the 1947 paper “Evidence for, an Cross Section of 115 Day $^{75}\text{Se}$” [22]. Selenium was irradiated in the Argonne pile and $^{75}\text{Ar}$ was produced by neutron capture reactions. Samples mounted on scotch tape foils were counted with a Geiger counter. “Evidence has been given to show that the 115-day activity produced in selenium by thermal neutrons is due to $^{75}\text{Se}$ which decays by K electron capture to $^{75}\text{As}$, accompanied by a 0.4 Mev $\gamma$-ray.” The half-life of 115(5) d agrees with the presently accepted value of 119.779(4) d. The 1944 table of isotopes [23] had listed half-lives of 48 d and 160 d which were based on a private communication and a conference abstract, respectively. In addition, the headquarters of the Manhattan project listed $^{75}\text{Se}$ as an available isotope with a half-life of 125 d [24], which was based on a classified report [25].

2.13. $^{76}$–$^{78}\text{Se}$

Aston discovered $^{76}\text{Se}$, $^{77}\text{Se}$, and $^{78}\text{Se}$ in 1922 as reported in “The Isotopes of Selenium and some other Elements” [21]. Selenium was vaporized in a discharge tube to obtain suitable spectra with the Cavendish mass spectrometer. “The interpretation of these is quite simple and definite, so that the results may be stated with every confidence. Selenium consists of six isotopes, giving lines at 74(f), 76(c), 77(e), 78(b), 80(a), 82(d). The line at 74 is extremely faint. The intensities of the lines are in the order indicated by the letters, and agree well enough with the chemical atomic weight 79.2.”

2.14. $^{79}\text{Se}$

$^{79}\text{Se}$ was identified in the 1950 paper “Bestimmung der Massenzahl der 3,9-min-Aktivität des Selens” by Flammersfeld and Herr [26]. A BrH solution was irradiated by neutrons produced by Li+d and Be+d reactions with 1.4 MeV deuterons at Mainz, Germany. The selenium activity was measured with a Geiger Müller counter following chemical separation. “Die geschilderten Tatsachen scheinen hinreichend, die Zuordnung der 3,9-min-Aktivität zur Massenzahl 79 zu gestatten, so daß diese also als $^{79}\text{Se}^*$ zu betrachten ist.” [These facts seem sufficient to assign the 3.9 min. activity to mass 79, therefore it would correspond to $^{79}\text{Se}^*$.] The half-life agrees with the accepted value of 3.92(1) min. for the isomeric state. The half-life had been observed before, however, without a unique mass assignment. It was not possible to distinguish between $^{79}\text{Se}$ and $^{81}\text{Se}$ [27].

2.15. $^{80}\text{Se}$

Aston discovered $^{80}\text{Se}$ in 1922 as reported in “The Isotopes of Selenium and some other Elements” [21]. Selenium was vaporized in a discharge tube to obtain suitable spectra with the Cavendish mass spectrometer. “The interpretation of these is quite simple and definite, so that the results may be stated with every confidence. Selenium consists of six isotopes, giving lines at 74(f), 76(c), 77(e), 78(b), 80(a), 82(d). The line at 74 is extremely faint. The intensities of the lines are in the order indicated by the letters, and agree well enough with the chemical atomic weight 79.2.”

2.16. $^{81}\text{Se}$

The first identification of $^{81}\text{Se}$ was reported by Wäfler and Hirzel in “Relative Wirkungsquerschnitte für den ($\gamma$,n)-Prozess mit der Lithium-Gamma-Strahlung (Quantenenergie $h\nu = 17.5 \text{ MeV}$)” [28]. $^{81}\text{Se}$ was produced with the photono nuclear reaction with lithium $\gamma$-rays on $^{82}\text{Se}$ targets and identified by measuring the resulting activities. “Der Nachweis
des \((\gamma,\text{n})\)-Prozesses erfolgte jeweils vermittelt der Radioaktivität des Endkerns.” [The identification of the \((\gamma,\text{n})\) process was made by the activity of the final nucleus.] Many isotopes were measured and the results are not discussed individually but summarized in a table. For \(^{81}\text{Se}\) half-lives of 56.5 and 13.6 min. were listed, where the former corresponds to an isomeric state. These values are close to the presently accepted values of 57.28(2) and 18.45(12) min., respectively. Previously, half-lives of 57 min. \([29, 30]\) and 19 min. \([30]\) were reported but only assigned to either \(^{79}\text{Se}\) or \(^{81}\text{Se}\). In addition, half-lives of 57 and 17 min. could only be assigned to selenium masses of lighter than 82 \([31]\).

2.17. \(^{82}\text{Se}\)

Aston discovered \(^{82}\text{Se}\) in 1922 as reported in “The Isotopes of Selenium and some other Elements” \([21]\). Selenium was vaporized in a discharge tube to obtain suitable spectra with the Cavendish mass spectrometer. “The interpretation of these is quite simple and definite, so that the results may be stated with every confidence. Selenium consists of six isotopes, giving lines at 74(f), 76(c), 77(e), 78(b), 80(a), 82(d). The line at 74 is extremely faint. The intensities of the lines are in the order indicated by the letters, and agree well enough with the chemical atomic weight 79.2.”

2.18. \(^{83}\text{Se}\)

Snell discovered \(^{83}\text{Se}\) in 1937 as reported in “The Radioactive Isotopes of Bromine: Isomeric Forms of Bromine 80” \([29]\). The Berkeley cyclotron was used to bombard selenium targets with 5.5 MeV deuterons and \(^{83}\text{Se}\) was produced in the reaction \(^{82}\text{Se}(\text{d},\text{p})^{83}\text{Se}\). The activities were measured with a quartz-fiber electroscope following chemical separation. The observation of \(^{83}\text{Se}\) was discussed in the context of the observation of \(^{83}\text{Br}\) which was proposed to be produced in the decay of \(^{83}\text{Se}\). “...By growth from a hitherto unknown selenium 83; i.e., the bromine 83 would be the second member in a pair of successive \(\beta\)-emitters, the reactions being \(\text{Se}^{82}(\text{D},\text{p})\text{Se}^{83}, \text{Se}^{83} \rightarrow \text{Br}^{83} + e^-\), \(\text{Br}^{83} \rightarrow \text{Kr}^{83} + e^-\). There was evidence for the second process in the decay curves of the selenium fractions obtained in the experiments, and it appeared that the selenium 83 had a half-life of 17\(\pm\)5 minutes.” This half-life is consistent with the accepted half-life of 22.3(3) min.

2.19. \(^{84,85}\text{Se}\)

In the 1960 paper “Short-lived Bromine and Selenium Nuclides From Fission” Sattizahn et al. reported the discovery of \(^{84}\text{Se}\) and \(^{85}\text{Se}\) \([32]\). The isotopes were produced by irradiation of 95\% \(^{235}\text{U}\) in the Los Alamos Water Boiler. Decay curves were measured with methane-flow proportional counters following chemical separation. “The half-lives of \(^{84}\text{Se}\) and \(^{85}\text{Se}\) were determined by periodic extraction and measurement of the daughter 31.7 min. and 3.0 min. bromine activities which grow from fission-product selenium.” The observed half-life of 3.3(3) min. for \(^{84}\text{Se}\) is included in the calculation of the currently accepted average value of 3.1(1) min. and the half-life of 39(4) s for \(^{85}\text{Se}\) agrees with the present value of 31.7(9) s. The 1948 Table of Isotopes \([33]\) quotes half-lives of 2.5 min \([34]\) and <10 min. \([35]\) for \(^{84}\text{Se}\) attributed to results from the Manhattan project. Both were classified reports, and only the latter one quoting an upper limit for the half-life was included in the unclassified publication of the Plutonium Project Records \([36]\).

2.20. \(^{86}\text{Se}\)

Tamai et al. observed \(^{86}\text{Se}\) in 1973 as reported in “Gamma-Ray Energies of Se-85 and Se-86” \([37]\). A 90\% enriched uranyl nitrate solution was irradiated with thermal neutrons in the Kyoto University Reactor. Gamma-ray spectra
were measured with a Ge(Li) detector following chemical separation. In the text of the article the assignment is not convincing: “The photopeaks with half-life of 15 s are not necessarily due to the γ-ray from 86Se because the half-life of 88Br(17.5 s) is nearly the same as that of 86Se(16 s). Accordingly from the half-lives alone 86Se cannot be distinguished from 86Br.” However, the figures and the last table clearly assign γ-rays to 86Se and the current data evaluations concur with this assignment for the lowest three energies. The 16 s half-life mentioned in the quote had initially been assigned to 87Se [32]. It is not clear when this assignment was changed. While the 1967 table of isotopes [38] still listed it for 87Se, the 1969 review article by Herrmann and Denschlag [39] assigned the 16 s half-life to 86Se.

2.21. 87Se

Tomlinson discovered 87Se in the 1968 paper “Delayed Neutron Precursors-III Selenium-87” [40]. 87Se was produced by neutron irradiation in the LIDO reactor at Harwell, England. The half-life of 87Se was measured “…by separating selenium in the trap at various times after irradiation and counting the neutrons from 87Br grown in from 87Se... A least-squares fit gave a half-life (with standard deviation of 5.8 ± 0.5 sec for 87Se,...”. This half-life agrees with the presently accepted value of 5.50(12) s. Previously, a 16 s half-life - most likely 86Se - had been assigned incorrectly to 87Se [32].

2.22. 88Se

In the 1970 paper “Identification of 88Se and search for Delayed Neutron Emission from 87Se and 88Se”, del Marmol and Perricos reported the discovery of 88Se [41]. 235U was irradiated with thermal neutrons in the core of the BR1 reactor in Mol, Belgium. The half-life was determined from the neutron activities of the bromine daughter following chemical separation. “From a set of experiments with a 5.05 sec irradiation time... a first estimate of about 1.7 sec was obtained for the half-life of 88Se... Although the latter measurements [(1.1(1) s for 3.05 sec irradiation times)] are believed to be more reliable than those for the 5.05 sec irradiation time a conservative estimate of 1.3 ± 0.3 sec was taken for the half-life of 88Se.” This half-life is in agreement with the accepted value of 1.53(6) s.

2.23. 89Se

Tomlinson and Hurdus observed 89Se as reported in the 1971 paper “Delayed Neutron Precursors-IV 87Se, 88Se and 89Se Half-lives, neutron emission probabilities and Fission Yields” [42]. 89Se was produced by neutron irradiation in the LIDO reactor at Harwell, England. Delayed neutron emission was measured following rapid chemical separation. “The following data have been obtained:... 89Se: half-life, 0.41 ± 0.04 sec;... 89Se is a new nuclide, identified for the first time in this work.” This half-life corresponds to the presently accepted value.

2.24. 90Se

Bernas et al. reported the discovery of 90Se in the 1994 paper “Projectile Fission at Relativistic Velocities: A Novel and Powerful Source of Neutron-Rich Isotopes Well Suited for In-Flight Isotopic Separation” [43]. The isotope was produced using projectile fission of 238U at 750 MeV/nucleon on a lead target at GSI, Germany. “Forward emitted fragments from 86Zn up to 155Ce were analyzed with the Fragment Separator (FRS) and unambiguously identified by their energy-loss and time-of-flight.” The experiment yielded 409 individual counts of 90Se.
2.25. $^{91}\text{Se}$

In the 1975 publication “The P$_n$ Values of the $^{235}\text{U}(n_{th},f)$ Produced Precursors in the Mass Chains 90, 91, 93-95, 99, 134 and 137-139” Asghar et al. reported the first observation of $^{91}\text{Se}$ [44]. The isotope was produced by thermal neutron fission of $^{235}\text{U}$ in the Grenoble high flux reactor and identified with the mass separator Lohengrin. “The present work led to: (i) three new periods corresponding to the new isotopes of selenium ($^{91}\text{Se}, T_{1/2} = 0.27\pm0.05 \text{ sec}$), strontium ($^{99}\text{Sr}, T_{1/2} = 0.6\pm0.2 \text{ sec}$) and tellurium ($^{138}\text{Te}, T_{1/2} = 1.3\pm0.3 \text{ sec}$)...” The half-life corresponds to the presently accepted value.

2.26. $^{92-94}\text{Se}$

$^{92-94}\text{Se}$ were discovered by Bernas et al. in 1997 reported in “Discovery and Cross-Section Measurement of 58 New Fission Products in Projectile-Fission of 750-AMeV $^{238}\text{U}$” [45]. The experiment was performed using projectile fission of $^{238}\text{U}$ at 750 MeV/nucleon on a beryllium target at GSI in Germany. “Fission fragments were separated using the fragment separator FRS tuned in an achromatic mode and identified by event-by-event measurements of $\Delta E$-$B$-ToF and trajectory.” During the experiment, individual counts for $^{92}\text{Se}$ (1061), $^{93}\text{Se}$ (117), and $^{94}\text{Se}$ (31) were recorded.

3. Summary

The discoveries of the known selenium isotopes have been compiled and the methods of their production discussed. The identification of the isotopes was difficult. The half-lives of $^{68}\text{Se}$, $^{69}\text{Se}$ and $^{86}\text{Se}$ were initially incorrect and the half-lives of $^{79}\text{Se}$ and $^{81}\text{Se}$ could at first not be assigned to a unique mass. The half-lives of $^{70}\text{Se}$ and $^{86}\text{Se}$ were first assigned to $^{71}\text{Se}$ and $^{87}\text{Se}$, respectively. Finally, the first studies of $^{75}\text{Se}$ and $^{84}\text{Se}$ were reported in classified reports of the Manhattan Project.

Acknowledgments

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References


**Explanation of Tables**

**Table 1. Discovery of selenium isotopes**

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Selenium isotope</th>
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<tbody>
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<td>Author</td>
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<td>Method</td>
<td>Production method used in the discovery:</td>
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<td>FE: fusion evaporation</td>
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<td>LP: light-particle reactions (including neutrons)</td>
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<td>MS: mass spectroscopy</td>
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<td>NC: neutron capture reactions</td>
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<td>NF: neutron-induced fission</td>
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<td>PF: projectile fragmentation or fission</td>
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<td>PN: photo-nuclear reactions</td>
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