

## Discovery of the Einsteinium Isotopes

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Seventeen einsteinium 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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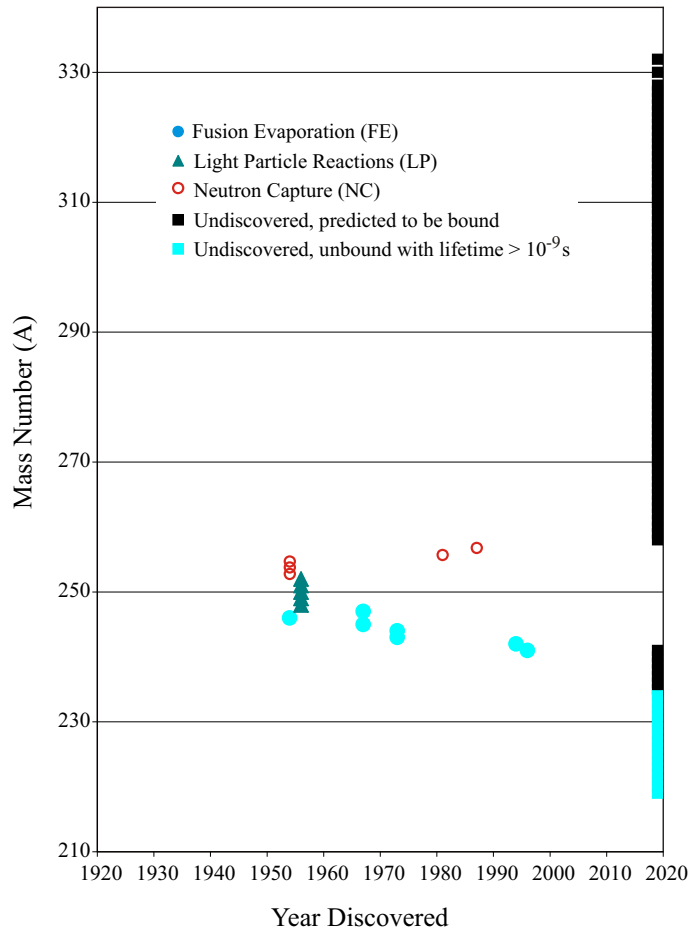
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## 1. INTRODUCTION

The sixth paper in the series of the discovery of isotopes, the discovery of the einsteinium isotopes is discussed. Previously, the discovery of cerium [1], arsenic [2], gold [3], tungsten [4] and krypton [5] isotopes was discussed. 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 included a half-life measurement, we compared the measured value to the currently adapted value taken from the NUBASE evaluation [6] which is based on ENSDF database [7]. In cases where the reported half-life differed significantly from the adapted half-life (up to approximately a factor of two), we searched the subsequent literature for indications that the measurement was erroneous. If that was not the case we credited the authors with the discovery in spite of the inaccurate half-life.

## 2. DISCOVERY OF $^{241-257}\text{ES}$

Seventeen einsteinium isotopes from  $A = 241 - 257$  have been discovered so far; there are no stable einsteinium isotopes. According to the HFB-14 model [8], einsteinium isotopes ranging from  $^{235}\text{Es}$  through  $^{328}\text{Es}$  plus  $^{330}\text{Es}$  and  $^{332}\text{Es}$  should be particle stable. Thus, there remain about 80 isotopes to be discovered. In addition, it is estimated that 16 additional nuclei beyond the proton dripline could live long enough to be observed [9]. Less than 20% of all possible einsteinium isotopes have been produced and identified so far.



**FIG. A.** Einsteinium isotopes as a function of 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 squares correspond to unbound isotopes predicted to have lifetimes larger than  $\sim 10^{-9}$  s.

Figure A summarizes the year of first discovery for all einsteinium isotopes identified by the method of discovery. The range of isotopes predicted to exist is indicated on the right side of the figure. Only three different reaction types were used to produce the radioactive einsteinium isotopes; heavy-ion fusion evaporation (FE), light-particle reactions (LP), and neutron-capture reactions (NC). Heavy ions are all nuclei with an atomic mass larger than  $A = 4$  [10]. In the following, the discovery of each einsteinium isotope is discussed in detail.

### $^{241}\text{Es}$

In 1996, Ninov *et al.* discovered  $^{241}\text{Es}$  at the Gesellschaft für Schwerionenforschung (GSI) in Darmstadt, Germany, as reported in the paper *Identification of new mendelevium and einsteinium isotopes in bombardments of  $^{209}\text{Bi}$  with  $^{40}\text{Ar}$*  [11].  $^{40}\text{Ar}$  beams were accelerated to 4.78, 4.93, and 5.12 A·MeV with the UNILAC accelerator and bombarded  $^{209}\text{Bi}$  targets.  $^{241}\text{Es}$  was created via the  $\alpha$ -decay of  $^{245}\text{Md}$  which was produced in the fusion-evaporation reaction  $^{209}\text{Bi}(^{40}\text{Ar},4n)$ . The time and position correlation of  $\alpha$ -particles with evaporation residues were measured. “Since the chosen bombarding energy further coincided with the maximum of the 4n deexcitation channel, we assign this decay sequence to  $^{245}\text{Md}$  and its daughter  $^{241}\text{Es}$ .” The half-life of  $8_{-4}^{+6}$  s is currently the only measured value for  $^{241}\text{Es}$ .

### $^{242}\text{Es}$

The discovery of  $^{242}\text{Es}$  was reported in 1994 by Lazarev *et al.* in *Cross sections of the (HI, $\alpha$ n) channel in the cold-fusion-type reactions  $^{209}\text{Bi} + ^{40}\text{Ar}$  and  $^{208}\text{Pb} + ^{37}\text{Cl}$*  [12]. The isotope was identified using the catcher technique with off-line chemical separation following the irradiation of the targets with beams from the U400 cyclotron of the JINR Laboratory of Nuclear Reactions at Dubna. “The most probable explanation of this activity seems to be the EC-delayed fission in the decay chain  $^{242}\text{Es} \rightarrow ^{242}\text{Cf}$ .” The extracted half-life is close to the accepted values of 13.5(25) s. It should be mentioned that the observation of  $^{242}\text{Es}$  had been reported nine years earlier in an unpublished report [13]. Ninov *et al.* [11] does not refer to the work by Lazarev *et al.* in their 1996 paper about the production of the new neutron deficient isotopes  $^{241}\text{Es}$  and  $^{242}\text{Es}$ .

### $^{243,244}\text{Es}$

In 1973, Eskola *et al.* reported the discovery of  $^{243}\text{Es}$  and  $^{244}\text{Es}$  in *Two new isotopes of einsteinium,  $^{243}\text{Es}$  and  $^{244}\text{Es}$*  [14]. A  $^{233}\text{U}$  target was bombarded with  $^{15}\text{N}$  ions from the Berkeley HILAC and the isotopes were produced in the fusion evaporation reactions  $^{233}\text{U}(^{15}\text{N},5n)^{243}\text{Es}$  and  $^{233}\text{U}(^{15}\text{N},4n)^{244}\text{Es}$ . The isotopes were identified from the excitation functions, and  $\alpha$ -spectra were measured. “The  $\alpha$ -particle group at 7.89 MeV has been assigned to  $^{243}\text{Es}$  and that at 7.57 MeV to  $^{244}\text{Es}$ .” The measured half-lives of 21(2) s and 37(4) s for  $^{243}\text{Es}$  and  $^{244}\text{Es}$ , respectively, correspond to the currently accepted values.

### $^{245}\text{Es}$

The discovery of  $^{245}\text{Es}$  was first published by Mikheev *et al.* in 1967 in *Synthesis of Einsteinium Isotopes in Reactions with Nitrogen Ions* [15].  $^{245}\text{Es}$  was produced in the fusion-evaporation reaction  $^{238}\text{U}(^{14}\text{N},7n)^{245}\text{Es}$  following the acceleration of the  $^{14}\text{N}$  ions by the JINR cyclotron in Dubna. The recoil atoms were transported in front of charged-particle detectors with a helium jet. “The half-life  $1.33 \pm 0.15$  min, obtained by the maximum-likelihood method, is also in good agreement with the published data on  $\text{Es}^{245}$ .” The measured half-life agrees with the currently accepted value of 1.1(1) min. The “published” data that Mikheev *et al.* refer to are unpublished results that were subsequently quoted in a review [16].

### <sup>246</sup>Es

Ghiorso *et al.* discovered <sup>246</sup>Es in 1954 as reported in *Reactions of U<sup>238</sup> with Cyclotron-Produced Nitrogen Ions* [17]. The Berkeley Crocker Laboratory 60-inch cyclotron produced <sup>14</sup>N beams that bombarded <sup>238</sup>U targets and <sup>246</sup>Es was produced in the fusion-evaporation reaction <sup>238</sup>U(<sup>14</sup>N,6n). Electron-capture and  $\alpha$ -particles were detected following chemical separation. <sup>246</sup>Es was “observed only through growth of its 1.5-day Cf<sup>246</sup> daughter.” Electron-capture with a half-life of “minutes” was measured. The currently accepted half-life is 7.7(5) min. The paper was the first unclassified publication of an einsteinium isotope. However, the paper states in a footnote that “There is unpublished information relevant to element 99 at the University of California, Argonne National Laboratory, and Los Alamos Scientific Laboratory. Until this information is published the question of the first preparation should not be prejudged on the basis of this paper.” The official announcement of the discovery of the new element with Z = 99 was made in 1955 [18]. <sup>253</sup>Es was identified on December 19-20, 1952 from uranium which had been irradiated by neutrons in the “Mike” thermonuclear explosion in November 1952.

### <sup>247</sup>Es

<sup>247</sup>Es was identified for the first time by Mikheev *et al.* in 1967 in the same paper in which they reported the first observation of <sup>245</sup>Es: *Synthesis of Einsteinium Isotopes in Reactions with Nitrogen Ions* [15]. <sup>247</sup>Es was produced in the fusion-evaporation reaction <sup>238</sup>U(<sup>14</sup>N,5n)<sup>247</sup>Es following the acceleration of the <sup>14</sup>N ions by the JINR cyclotron in Dubna. The recoil atoms were transported in front of charged-particle detectors with a helium jet. “Our results show that the isotopes Es<sup>247</sup> and Es<sup>246</sup> have practically identical energies of the main  $\alpha$ -particle groups,  $7.33 \pm 0.03$  MeV, and nearly equal half-lives,  $5.0 \pm 0.3$  and  $7.7 \pm 0.5$  min.” The measured half-life agrees with the currently accepted value of 4.55(26) m. In 1954 Ghiorso *et al.* [17] had observed a 7.3 m half-life which was tentatively assigned to <sup>247</sup>Es, where the mass identification was based only on nuclear systematics. Thus it is probably that the observed half-life corresponded to the decay of <sup>246</sup>Es.

### <sup>248</sup>Es

Chetham-Strode and Hold reported the first observation of <sup>248</sup>Es in 1956 in *New Isotope Einsteinium-248* [19]. Deuterons between 18 and 22 MeV were accelerated by the 60-inch cyclotron of the Berkeley Crocker Laboratory and bombarded a target containing  $10^{13}$  atoms of monoisotopic <sup>249</sup>Cf. <sup>248</sup>Es was produced in the reaction <sup>249</sup>Cf(d,3n) and identified on the basis of partial excitation function. “A new isotope of einsteinium, E<sup>248</sup>, has been identified among the products of the bombardment of Cf<sup>249</sup> with 18- to 22-Mev deuterons. It decays principally by electron capture with a half-life of  $25 \pm 5$  minutes and also by the emission of  $(6.87 \pm 0.02)$ -Mev alpha particles.” The measured half-life is included in the average for the currently accepted value of 27(5) m.

### <sup>249–252</sup>Es

The isotopes <sup>249</sup>Es, <sup>250</sup>Es, <sup>251</sup>Es, and <sup>252</sup>Es were produced by Harvey *et al.* in 1956 as reported in *New Isotopes of Einsteinium* [20]. A gold foil deposited with  $3 \times 10^{13}$  atoms of <sup>249</sup>Bk was bombarded with 20–40 MeV  $\alpha$ -particles accelerated by the Berkeley Crocker Laboratory 60-inch cyclotron: “... the 280-day  $\beta^-$ -emitter Bk<sup>249</sup> was bombarded with helium ions from 20 to 40 Mev, and reactions of the type ( $\alpha$ ,xn) were studied radiochemically. Such reactions can produce four previously unobserved

isotopes of einsteinium (symbol E, atomic number 99) with mass numbers from 249 to 252.” The isotopes were chemically separated and their decay via electron capture and/or  $\alpha$ -particles measured. The quoted half-lives of 2 h ( $^{249}\text{Es}$ ), 8 h ( $^{250}\text{Es}$ ), and 1.5 d ( $^{251}\text{Es}$ ), agree with the presently accepted values of 102.2(6) m, 8.6(1) h, and 33(1) h, respectively. Although the estimated half-life of  $\sim 140$  d for  $^{252}\text{Es}$  is significantly shorter than the adapted value of 471.7(19) d we still credit Harvey *et al.* with the discovery because the measured  $\alpha$ -particle energy (6.64 MeV) agrees with later measurements [21].

### $^{253}\text{Es}$

Thompson *et al.* from Berkeley were the first to publish unclassified evidence for the existence of  $^{253}\text{Es}$  in 1954 in their paper *Transcurium Isotopes Produced in the Neutron Irradiation of Plutonium* [22].  $^{239}\text{Pu}$  was irradiated with neutrons in the Idaho Materials Testing Reactor and  $^{253}\text{Cf}$  was chemically separated. “The isotope of element 99 emitting 6.6-MeV alpha particles is logically assigned as  $99^{253}$ . A reasonable half-life estimated from systematics, assuming a hindrance factor of ten, would be very roughly a month.” The currently accepted half-life is 20.47(3) d. The paper was published shortly after the report on the discovery of  $^{246}\text{Es}$  and contained the same statement regarding the discovery of element 99: “There is unpublished information relevant to element 99 at the University of California, Argonne National Laboratory, and Los Alamos Scientific Laboratory. Until this information is published the question of the first preparation should not be prejudged on the basis of this paper.” The Argonne group [23] published their results on  $^{253}\text{Es}$  only a few weeks later, stating “A number of arguments indicate that the probable mass assignment of the element-99 isotope is 253.” The paper included a footnote with regards to the discovery of the new element: “These elements (99 and 100) have previously been discovered in other work at Argonne National Laboratory, University of California Radiation Laboratory, and Los Alamos Scientific Laboratory, not yet published.”  $^{253}\text{Es}$  was the einsteinium isotope credited with the discovery of element 99, published in 1955 [18]. It was identified on December 19-20, 1952 from uranium which had been irradiated by neutrons in the “Mike” thermonuclear explosion in November 1952.

### $^{254}\text{Es}$

The observation of  $^{254}\text{Es}$  was reported in 1954 by Fields *et al.* from Argonne in the paper *Additional Properties of Isotopes of Elements 99 and 100* [24]. “This note describes the results obtained from a four-day irradiation of an element-99 fraction with californium impurity in the Materials Testing Reactor (MTR) at Arco, Idaho to produce the following reaction:  $99^{253}(\text{n},\gamma)99^{254} \xrightarrow{\beta} 100^{254}$ .” The half-life was measured to be 37(1) h and corresponds to an isomer. A few weeks earlier the Berkeley group had described the formation of  $100^{254}$  and the “... possible reaction sequence leading to its production might be the following ...” included  $^{254}\text{Es}$  [25]. However, no properties of  $^{254}\text{Es}$  were reported. The Berkeley group confirmed the half-life measurement only a few weeks following the Argonne paper [26].

### $^{255}\text{Es}$

Choppin *et al.* from Berkeley reported the first observation of  $^{255}\text{Es}$  in 1954 in their paper *Nuclear Properties of Some Isotopes of Californium, Elements 99 and 100* [26]. The isotope was formed in

intense neutron bombardments of plutonium and high-mass nuclides. “The 7.1-Mev alpha activity was also observed in purified element-99 fractions, and thus it was deduced that it also has a  $\beta^-$  emitting parent. Rough decay measurements of this activity in the element-99 fraction indicate that the half-life of this parent, presumably  $99^{255}$ , is approximately one month.” The presently adapted half-life is 39.8(12) d.

### $^{256}\text{Es}$

In 1981 Loughheed *et al.* from Lawrence Livermore National Laboratory discovered  $^{256}\text{Es}$  as reported in *Two new isotopes with  $N = 157$ :  $^{256}\text{Es}$  and  $^{255}\text{Cf}$*  [27]. A beryllium foil containing  $^{255}\text{Es}$  was irradiated by neutrons in the core of the Livermore Pool-Type Reactor and einsteinium was then chemically separated: “... we have identified ...  $^{256}\text{Es}$  with a half life of  $25 \pm 2.4$  min. Our identification is based on chemical identification of the elements and on the known nuclear properties of their daughters.” This half-life is currently the only measurement of  $^{256}\text{Es}$ . Indirect evidence for the existence of  $^{256}\text{Es}$  had been shown in 1955 in the production of  $^{256}\text{Fm}$  by neutron capture on  $^{255}\text{Es}$  [28].

### $^{257}\text{Es}$

$^{257}\text{Es}$  was discovered in 1987 by Popov *et al.* from Dimitrovgrad, Russia, and described in the paper *Determining the half-lives of  $^{253}\text{Es}$ ,  $^{254}\text{Es}$ ,  $^{254m}\text{Es}$ ,  $^{255}\text{Es}$ ,  $^{257}\text{Es}$ ,  $^{256}\text{Fm}$*  [29].  $^{257}\text{Es}$  was produced by neutron irradiation of  $^{252}\text{Cf}$  targets in the high-flux SM-2 reactor of the Research Institute of Nuclear Reactors and identified following chemical separation using X-ray,  $\gamma$ - and  $\alpha$ -spectrometry. “The gamma lines at 6.5, 7.3, 25.7, 45.2, 46.0 and 49.0 keV evidently accompany the beta decay of  $^{257}\text{Es}$ . Here  $T_\beta$  for  $^{257}\text{Es}$  is found as  $7.7 \pm 0.2$  d.” This is currently the only half-life measurement of  $^{257}\text{Es}$ .

## 3. SUMMARY

The discovery of the element einsteinium is credited to A. Ghiorso *et al.*, who observed  $^{253}\text{Es}$  in uranium which had been irradiated by neutrons in the “Mike” thermonuclear explosion in November 1952 [18]. However, this classified work was not published until 1954. In the meantime several groups succeeded in producing einsteinium isotopes in fusion-evaporation reactions ( $^{246}\text{Es}$ ) and neutron-capture reactions ( $^{253}\text{Es}$ ). These publications always are careful to point out that their observations should not be considered as the discovery of einsteinium. Nevertheless, following our guidelines to acknowledge first publications in refereed journals we credit these papers with the first observation of the specific isotope. This should not be controversial since A. Ghiorso is the first author on both publications regarding  $^{253}\text{Es}$ . Two einsteinium isotopes were discovered years prior to the first refereed publications; however, the results had only been presented in internal reports ( $^{242}\text{Es}$ ) or unpublished work quoted in a review article ( $^{245}\text{Es}$ ).

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## EXPLANATION OF TABLE

**TABLE I. Discovery of Einsteinium Isotopes**

Isotope	Einsteinium 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 NC: neutron-capture reactions
Laboratory	Laboratory where the experiment was performed
Country	Country of laboratory
Year	Year of discovery

TABLE I. Discovery of Einsteinium isotopes

See page 10 for Explanation of Tables

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Isotope	Author	Journal	Ref.	Method	Laboratory	Country	Year
<sup>241</sup> Es	V. Ninov	Z. Phys. A	Nin96	FE	Darmstadt	Germany	1996
<sup>242</sup> Es	Yu.A. Lazarev	Nucl. Phys. A	Laz94	FE	Dubna	Russia	1994
<sup>243</sup> Es	P. Eskola	Physica Fennica	Esk73	FE	Berkeley	USA	1973
<sup>244</sup> Es	P. Eskola	Physica Fennica	Esk73	FE	Berkeley	USA	1973
<sup>245</sup> Es	V.L. Mikheev	Sov. J. Nucl. Phys.	Mik67	FE	Dubna	Russia	1967
<sup>246</sup> Es	A. Ghiorso	Phys. Rev.	Ghi54	FE	Berkeley	USA	1954
<sup>247</sup> Es	V.L. Mikheev	Sov. J. Nucl. Phys.	Mik67	FE	Dubna	Russia	1967
<sup>248</sup> Es	A. Chetham	Phys. Rev.	Che56	LP	Berkeley	USA	1956
<sup>249</sup> Es	B.G. Harvey	Phys. Rev.	Har56	LP	Berkeley	USA	1956
<sup>250</sup> Es	B.G. Harvey	Phys. Rev.	Har56	LP	Berkeley	USA	1956
<sup>251</sup> Es	B.G. Harvey	Phys. Rev.	Har56	LP	Berkeley	USA	1956
<sup>252</sup> Es	B.G. Harvey	Phys. Rev.	Har56	LP	Berkeley	USA	1956
<sup>253</sup> Es	S.G. Thompson	Phys. Rev.	Tho54	NC	Berkeley	USA	1954
<sup>254</sup> Es	P.R. Fields	Phys. Rev.	Fie54	NC	Argonne	USA	1954
<sup>255</sup> Es	G.R. Choppin	Phys. Rev.	Cho54	NC	Berkeley	USA	1954
<sup>256</sup> Es	R.W. Lougheed	J. Inorg. Nucl. Chem.	Lou81	NC	Livermore	USA	1981
<sup>257</sup> Es	Yu.S. Popov	Sov. J. Radiochem..	Pop87	NC	Dimitrovgrad	Russia	1987

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