FUSION17

International conference on heavy-ion collisions at near-barrier energies
Hobart, Tasmania, 20-24 February 2017

Fusion and the Discovery of Isotopes

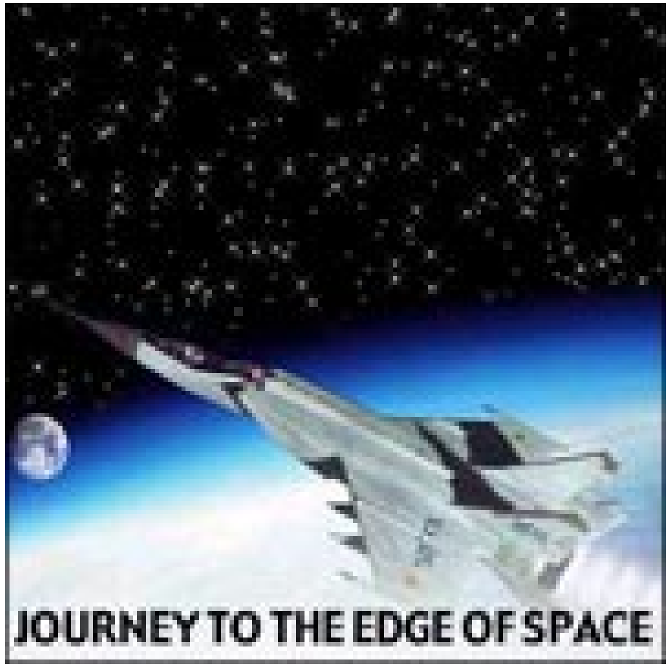
Michael Thoennessen
FRIB/NSCL
Michigan State University

Hobart, Tasmania
20-24 February 2017

NSCL FRIB
U.S. Department of Energy Office of Science
National Science Foundation
Michigan State University

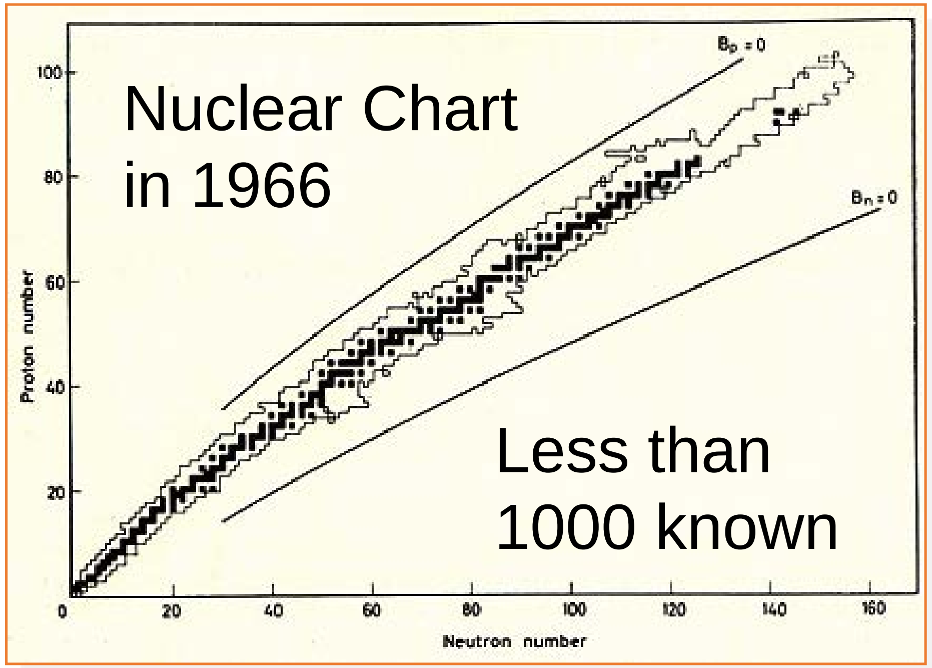
Why search for new isotopes?

- Before you can study them you have to make them!!
- Develop new production, identification and purification techniques
- As techniques become more routine and beam intensities increase, one can start to measure nuclear properties:
  - Lifetimes
  - Masses
  - Structure

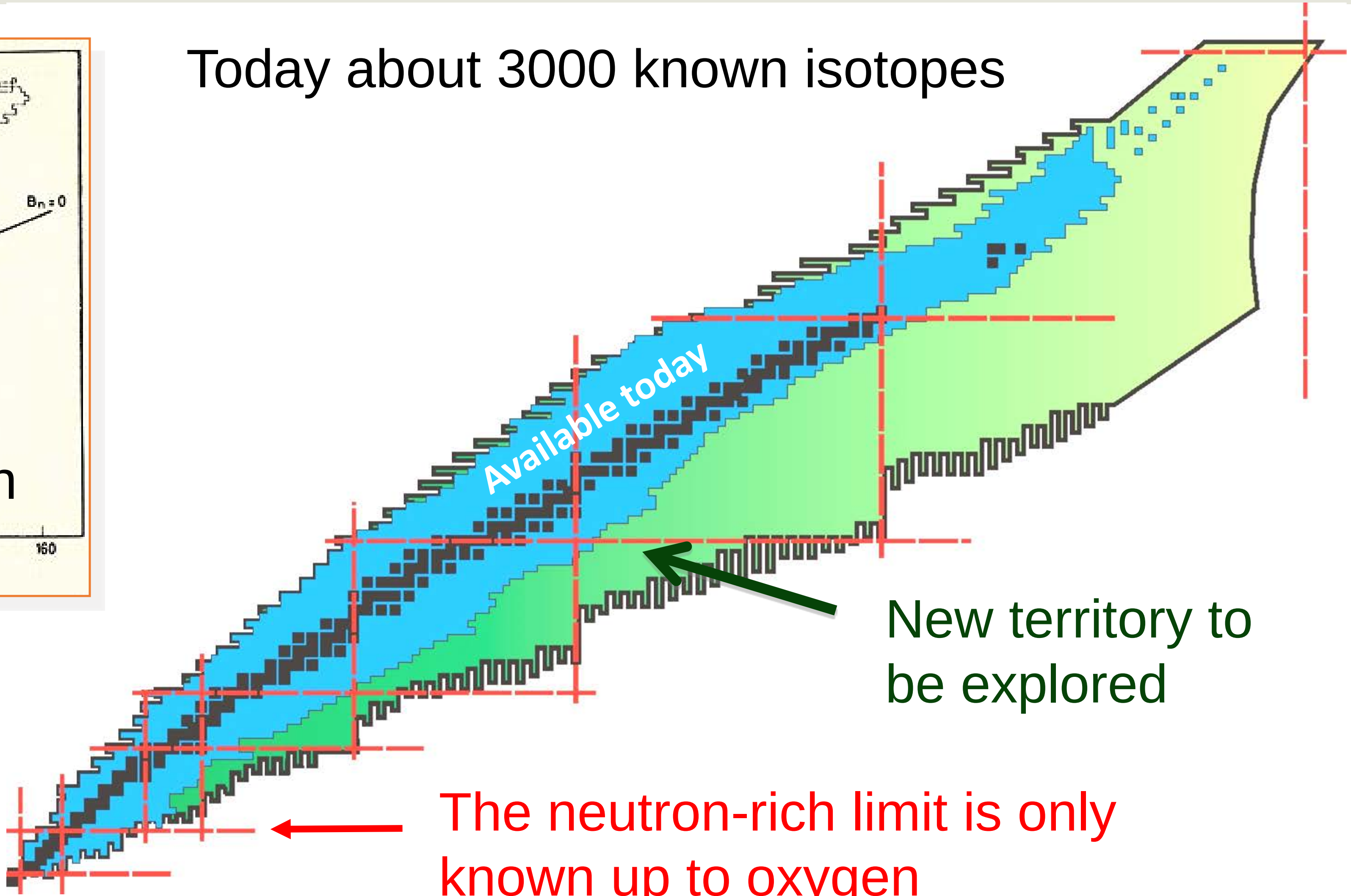


The quest for the unknown is a driving force for discovery

Discovery potential



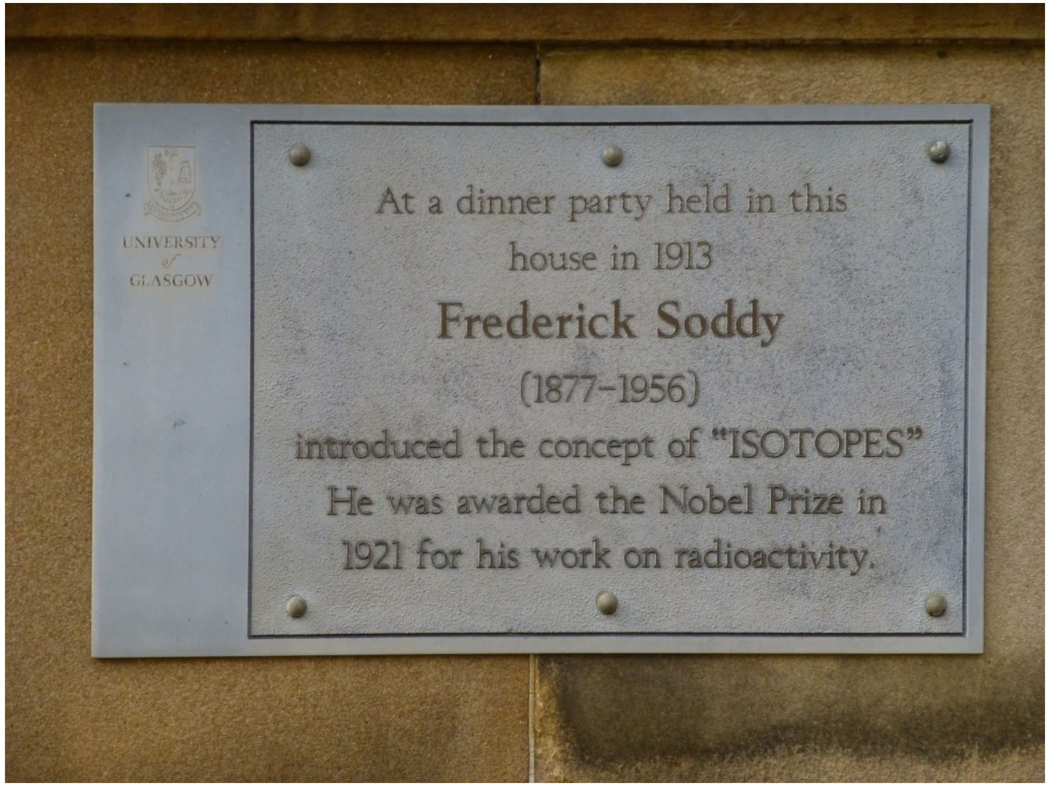
Today about 3000 known isotopes



New territory to be explored

The neutron-rich limit is only known up to oxygen

Origin of the term isotope



B. F. Thornton and Shawn C. Burdette, Nature Chemistry, **5** (2013) 979
http://blogs.nature.com/thescepticalchymist/2013/11/isotope-day.html

Nature: December 4, 1913

LETTERS TO THE EDITOR.

So far as I personally am concerned, this has resulted in a great clarification of my ideas, and it may be helpful to others, though no doubt there is little originality in it. The same algebraic sum of the positive and negative charges in the nucleus, when the arithmetical sum is different, gives what I call "isotopes" or "isotopic elements," because they occupy the same place in the periodic table. They are chemically identical, and save only as regards the relatively few physical properties which depend upon atomic mass directly, physically identical also. Unit changes of this nuclear charge, so reckoned algebraic-

December 4: Isotope Day

University of Glasgow | The Hunterian

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Isotope Day - 4 December 2013

Isotopes were introduced to the world in a letter to the journal 'Nature', published on 4 December 1913 by University of Glasgow chemist Frederick Soddy.

He realised that a single chemical element could occur as atoms with different atomic weights, with different nuclear properties, such as radioactive half-life. He thus reconciled the periodic table with the newly-discovered phenomena of radioactivity, and atomic transformation. He later received the Nobel Prize in Chemistry for this work.

The word 'isotope' itself had been suggested to him by Margaret Todd, a Glasgow GP, during a dinner at 11 University Gardens. Isotope science was truly born at the University of Glasgow.

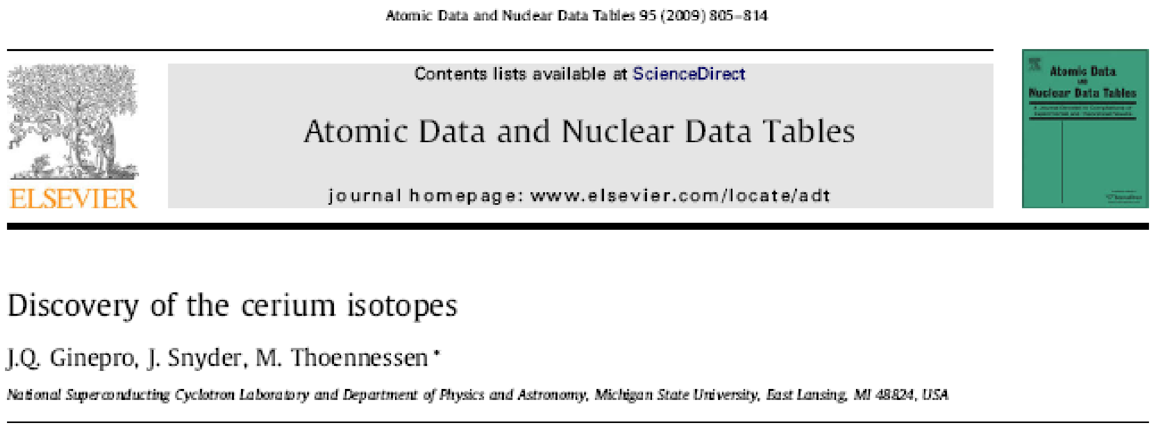
http://www.gla.ac.uk/hunterian/visit/events/headline_296351_en.html

Renaissance of the discovery of isotopes

"Owing to the rapid advance in research on disintegration and the theory of nuclear structure, the existence or non-existence of rare isotopes has acquired an entirely unexpected importance and calls for a short review of their present situation."

F.W. Aston, Nature **137**, 613 (1936)

Discovery project


Atomic Data and Nuclear Data Tables 95 (2009) 805–814

Contents lists available at ScienceDirect

Atomic Data and Nuclear Data Tables

journal homepage: www.elsevier.com/locate/adt

ELSEVIER

Discovery of the cerium isotopes

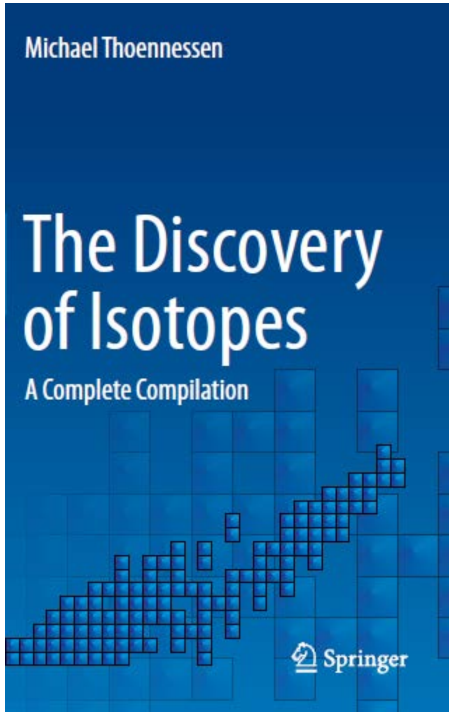
J.Q. Ginepro, J. Snyder, M. Thoennessen *

National Superconducting Cyclotron Laboratory and Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48824, USA

- Important to document the history
- Contrary to common perception not easily accessible
- Comprehensive compilation has only recently been possible

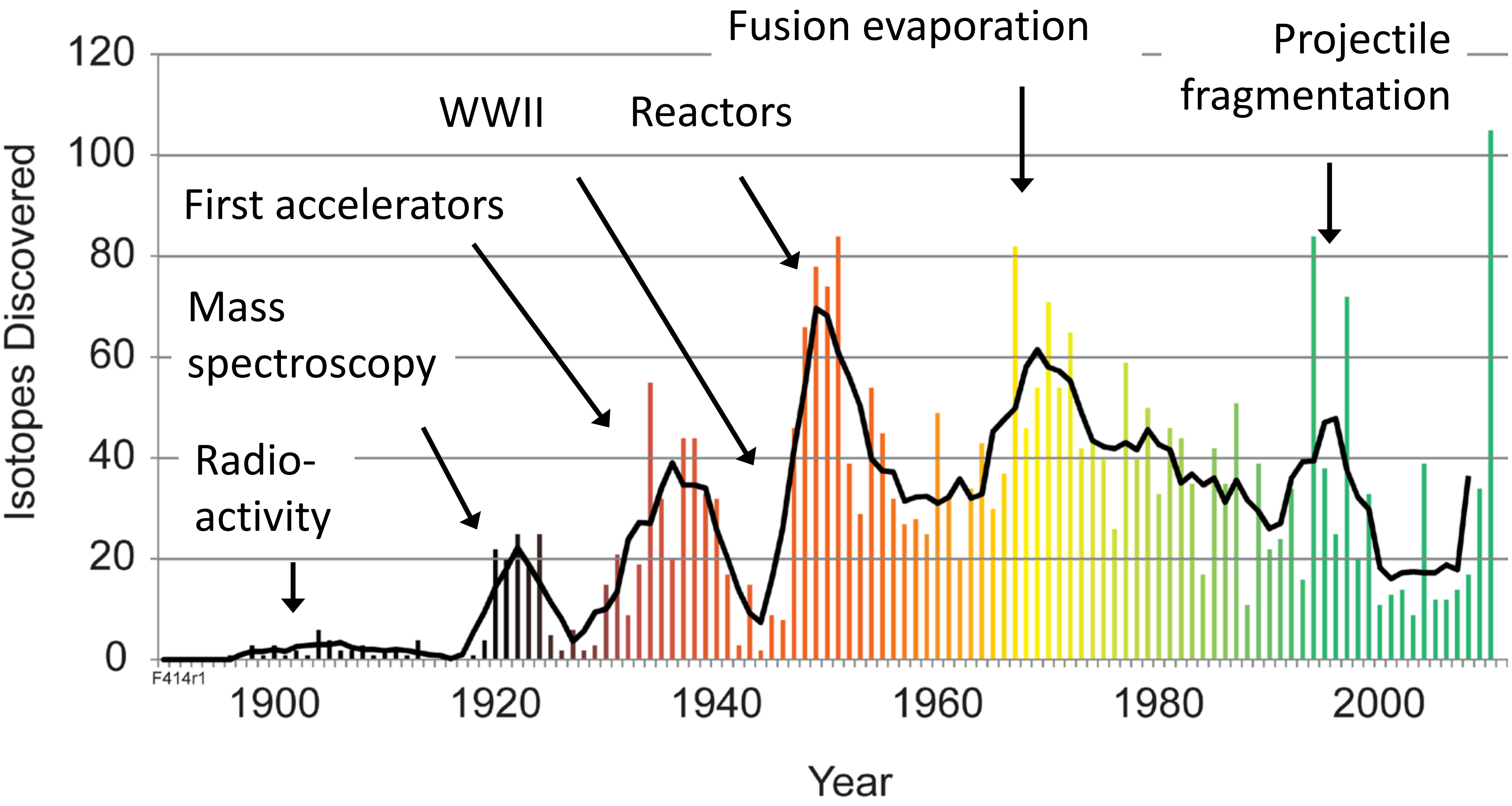
<u>Criteria:</u>

- Clear identification, either through decay-curves and relationships to other known isotopes, particle or γ-ray spectra, or unique mass and Z-identification
- Publish in refereed journals
- Not as strict as discovery of elements
- First observation until proven incorrect

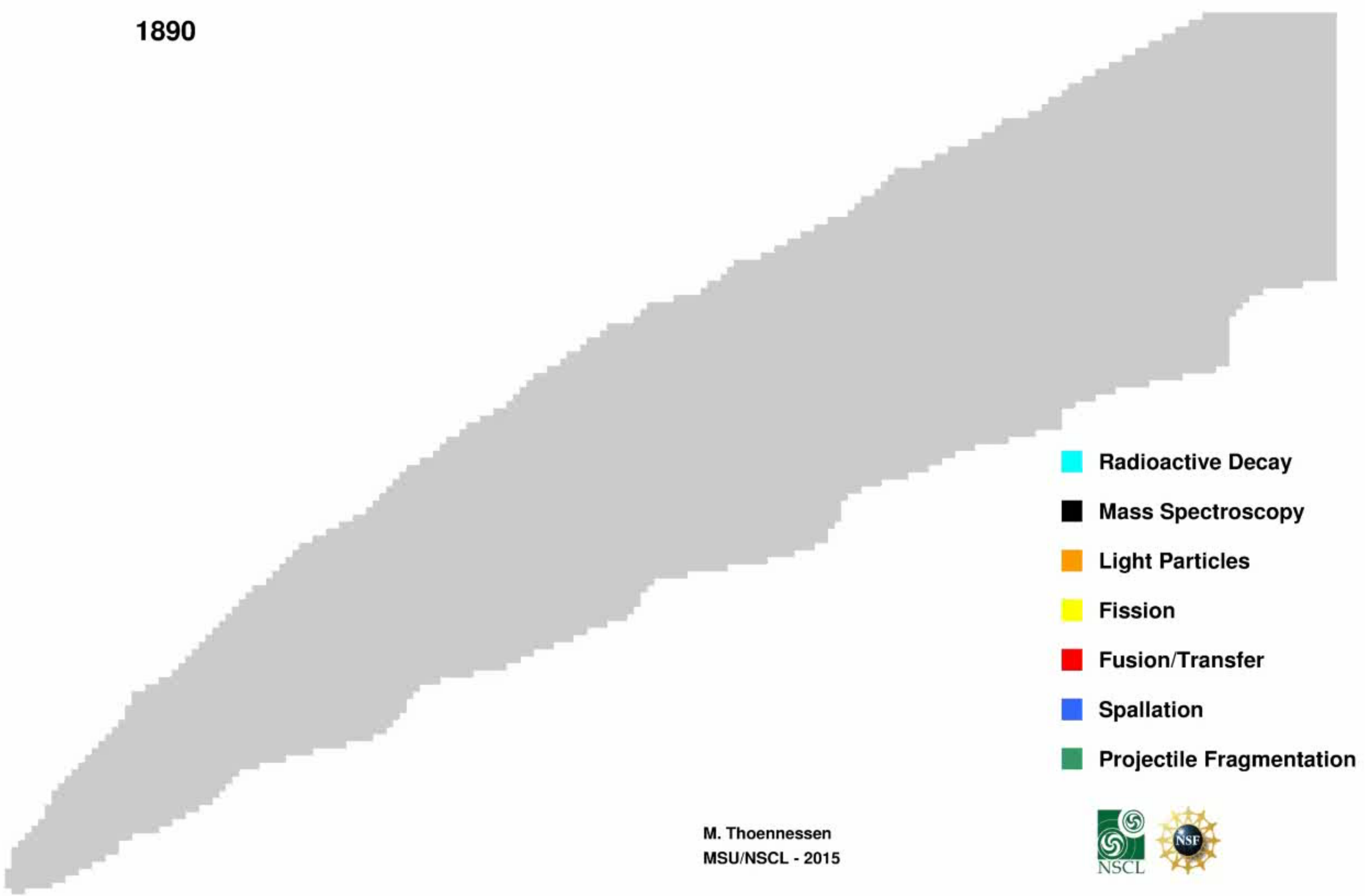


http://www.nscl.msu.edu/~thoennes/isotopes/

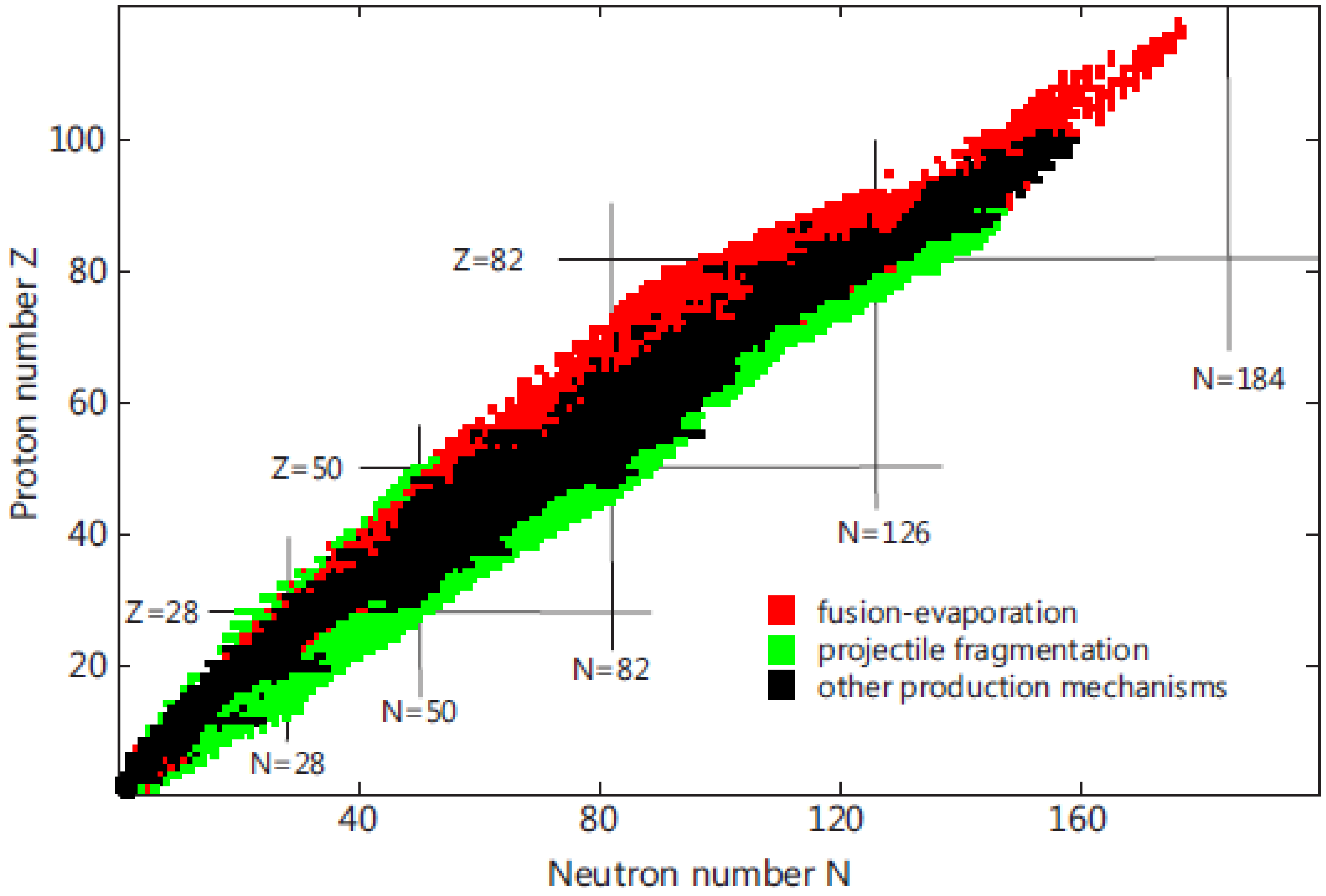
Technological advances drive discoveries



M. T. and B.M. Sherrill, Nature 473 (2011) 25


1890
Radioactive Decay
Mass Spectroscopy
Light Particles
Fission
Fusion/Transfer
Spallation
Projectile Fragmentation
M. Thoennessen
MSU/NSCL - 2015
NSCL
NSF

Most isotopes have been discovered by fusion evaporation



23.8% Fusion evaporation
18.4% Projectile fragmentation

First acceleration of heavy ions

JULY 15, 1940 PHYSICAL REVIEW VOLUME 58

Proceedings of the American Physical Society

Minutes of the Seattle, Washington, Meeting, June 18–21, 1940

27. High Energy Carbon Nuclei. Luis W. Alvarez, University of California.—The 37-inch cyclotron chamber was filled with CH_4 and a beam of 50 Mev $_6C^{12++++++}$ ions was detected with a linear amplifier. To resolve these ions from alpha-particles, it was necessary to reduce the dee voltage and to adjust the magnetic field to the low side of the alpha-particle peak. Under these conditions, about 500 carbon nuclei entered the ionization chamber per minute.

Phys. Rev. 58 (1940) 192

Additional efforts at Berkeley

Proceedings of the American Physical Society

Meeting at Berkeley, California, July 11, 1942

7. A Cloud-Chamber Study of Heavy Particles Accelerated in the Cyclotron. Richard Condit, Radiation Laboratory, University of California. (Introduced by E. O. Lawrence.)—It has been found possible to produce $^{12}C^{6+}$ of energy 85 Mev and $^{16}O^{8+}$ of energy 113 Mev with the 60" Berkeley cyclotron. Very small beams of these high speed particles were led from the cyclotron through a thin window into a Wilson cloud chamber of conventional design.

Phys. Rev. 62 (1942) 301

Proceedings of the American Physical Society

Minutes of the Meeting at Berkeley, California, July 12–13, 1946

B4. Acceleration of Stripped Light Nuclei in the Cyclotron. Herbert York, Roger Hildebrand, Thomas Putnam, and J. G. Hamilton. Radiation Laboratory, University of California. – Experiments have been done to produce accelerated stripped light nuclei with the 60'' Berkeley cyclotron for use in nuclear experiments. Two types of sources have been investigated: an arc source such as that normally used in cyclotrons and a spark source similar to that used in spectroscopic investigations of highly ionized atoms. Typical yields from an arc source are 1000 $C^{12,+6}$ 146-Mev ions per second and 100,000 $C^{12,+6}$ 135-Mev ions per second…

Phys. Rev. 70 (1946) 446

First fusion-evaporation reaction

Acceleration of Stripped C^{12} and C^{13} Nuclei in the Cyclotron*

J. F. Miller, J. G. Hamilton, T. M. Purnam, H. R. Haymond, and G. B. Rossi
Crocker Laboratory, Divisions of Physics, Medical Physics, Medicine, and Radiology, University of California, Berkeley and San Francisco, California

September 11, 1950

THE acceleration of stripped C^{12} and O^{16} nuclei in the cyclotron has been reported.[1–4] The significance of this feat was limited by the fact that the obtainable intensities were far too small to produce a sufficient number of nuclear reactions to permit the detection of radio-isotopes formed by the transmutation of target nuclei by these heavy ions. The discovery of the trans-

$^{238}U(^{12}C,4n)^{246}Cf$

Californium Isotopes from Bombardment of Uranium with Carbon Ions*

A. Ghiorso, S. G. Thompson, K. Street, Jr., and G. T. Seaborg
Radiation Laboratory and Department of Chemistry, University of California, Berkeley, California

November 8, 1950

THE recent production and identification[1] of isotopes of elements with atomic numbers up to six higher than the target element through bombardment with approximately 120-Mev carbon (+6) ions made it seem worth while to apply this technique to the transuranium region.

First correct identification of a californium isotope

Phys. Rev. 80 (1950) 486

Phys. Rev. 81 (1951) 154

Discovery of the element californium

Element 98*

S. G. Thompson, K. Street, Jr., A. Ghiorso, and G. T. Seaborg
Radiation Laboratory and Department of Chemistry, University of California, Berkeley, California
March 15, 1950

DEFINITE identification has been made of an isotope of the element with atomic number 98 through the irradiation of Cm^{242} with 35-Mev helium ions in the Berkeley Crocker Laboratory 60-inch cyclotron. The isotope which has been identified has an observed half-life of about 45 minutes and probably has the mass number 244. The observed mode of decay of the 98^{244} is through the emission of alpha-particles, with energy about 7.1 Mev, which agrees with predictions, and other considerations involving the systematic of radioactivity in this region indicate that it should also be unstable toward decay by electron-capture.

Initial mass assignment of 244 was later revised to 245

Mass Assignment of the 44-Minute Californium-245 and the New Isotope Californium-244†

Alfred Chetham-Strode, Jr., Gregory R. Choppin, and Bernard G. Harvey
Radiation Laboratory and Department of Chemistry, University of California, Berkeley, California
(Received January 16, 1956)

The 44-minute californium alpha emitter previously thought to be Cf^{244} has been reassigned to mass number 245 on the basis of milking experiments, excitation functions, cross bombardments, and decay-scheme studies. Californium-245 decays by the emission of (7.11±0.02)-Mev alpha particles (~30%) and by orbital electron capture (~70%). The new isotope Cf^{244} was also identified and found to decay by the emission of (7.17±0.02)-Mev alpha particles with a half-life of 25±3 minutes. The mass assignment of this isotope was established by its genetic relationship to Cm^{240} and by the excitation function for its formation by the $(\alpha,4n)$ reaction on Cm^{244}.

Phys. Rev. 78 (1950) 298

Phys. Rev. 102 (1956) 747

Discovery of Einsteinium

Reactions of U^{238} with Cyclotron-Produced Nitrogen Ions*

ALBERT GHIORSO, G. BERNARD ROSSI, BERNARD G. HARVEY, AND STANLEY G. THOMPSON
Radiation Laboratory and Department of Chemistry, University of California, Berkeley, California

(Received November 25, 1953)

THE acceleration of $N^{14}(+6)$ ions with the Berkeley Crocker Laboratory 60-inch cyclotron[1] has made it possible to study nuclear reactions of these ions with U^{238}.

The following transmutation products have been observed: $99^{247(?)}$, 99^{246}, Cf^{244}, Cf^{246}, $Cf^{247(?)}$, Cf^{248}, Bk^{243}, and other berkelium isotopes not yet identified. The identification of the elements

$^{238}U(^{14}N,6n)^{246}Es$

[4] 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.

Phys. Rev. 93 (1954) 257

New Elements Einsteinium and Fermium, Atomic Numbers 99 and 100

A. GHIORSO, S. G. THOMPSON, G. H. HIGGINS, AND G. T. SEABORG, *Radiation Laboratory and Department of Chemistry, University of California, Berkeley, California*

M. H. STUDIER, P. R. FIELDS, S. M. FRIED, H. DIAMOND, J. F. MECH, G. L. PYLE, J. R. HUIZENGA, A. HIRSCH, AND W. M. MANNING, *Argonne National Laboratory, Lemont, Illinois*

AND

C. I. BROWNE, H. L. SMITH, AND R. W. SPENCE, *Los Alamos Scientific Laboratory, Los Alamos, New Mexico*

(Received June 20, 1955)

THIS communication is a description of the results of experiments performed in December, 1952 and the following months at the University of California Radiation Laboratory (UCRL), Argonne National Laboratory (ANL), and Los Alamos Scientific Laboratory (LASL), which represent the discovery of the elements with the atomic numbers 99 and 100.

Phys. Rev. 99 (1955) 1048

Competition for the discovery of Einsteinium

Element 100 Produced by Means of Cyclotron-Accelerated Oxygen Ions

HUGO ATTERLING, WILHELM FORSLING, LENNART W. HOLM, LARS MELANDER, AND BJÖRN ÅSTRÖM
Nobel Institute of Physics, Stockholm, Sweden

(Received May 18, 1954)

THE beam of high-energy $(O^{16})^{6+}$ ions produced by the 225-cm cyclotron of this institute[1] has been used to bombard uranium targets. An alpha activity which is ascribed to an isotope of element 100 has been found among the transmutation products formed in this way.

Phys. Rev. 95 (1954) 585

Discovery of ^{79}Rb

Nuclear Physics 2 (1956/57) 593—618
Nuclear Physics 2 (1956/57) 619—623
Nuclear Physics 2 (1956/57) 624—633
Nuclear Physics 2 (1956/57) 634—639

ETUDE DE LA TRANSMUTATION DU CUIVRE PAR L'AZOTE ET L'OXYGENE

J. BEYDON, R. CHAMINADE, M. CRUT †,
H. FARAGGI, J. OLKOWSKY et A. PAPINEAU
Centre d'Études Nucléaires de Saclay, Gif-sur-Yvette

TRANSMUTATION DU CUIVRE PAR LE CARBONE, L'OXYGENE ET LE NEON

H. ATTERLING
Institut Nobel de Physique, Stockholm
et
J. BEYDON, M. CRUT † et J. OLKOWSKY
Centre d'Études Nucléaires de Saclay, Gif-sur-Yvette

COMPARAISON DES REACTIONS ^{59}Co+^{20}Ne et ^{63}Cu+^{16}O

M. CRUT †, H. FARAGGI et J. OLKOWSKY
Centre d'Études Nucléaires de Saclay, Gif-sur-Yvette
et
H. ATTERLING
Institut Nobel de Physique, Stockholm

MISE EN EVIDENCE D'UN ISOTOPE LEGER DE RUBIDIUM

R. CHAMINADE, M. CROS, I. GRATOT et M. LE PAPE
Centre d'Études Nucléaires de Saclay, Gif-sur-Yvette

Reçu le 28 septembre 1956

Discovery of ^{71}Se

What is noteworthy about the discovery of ^{71}Se?

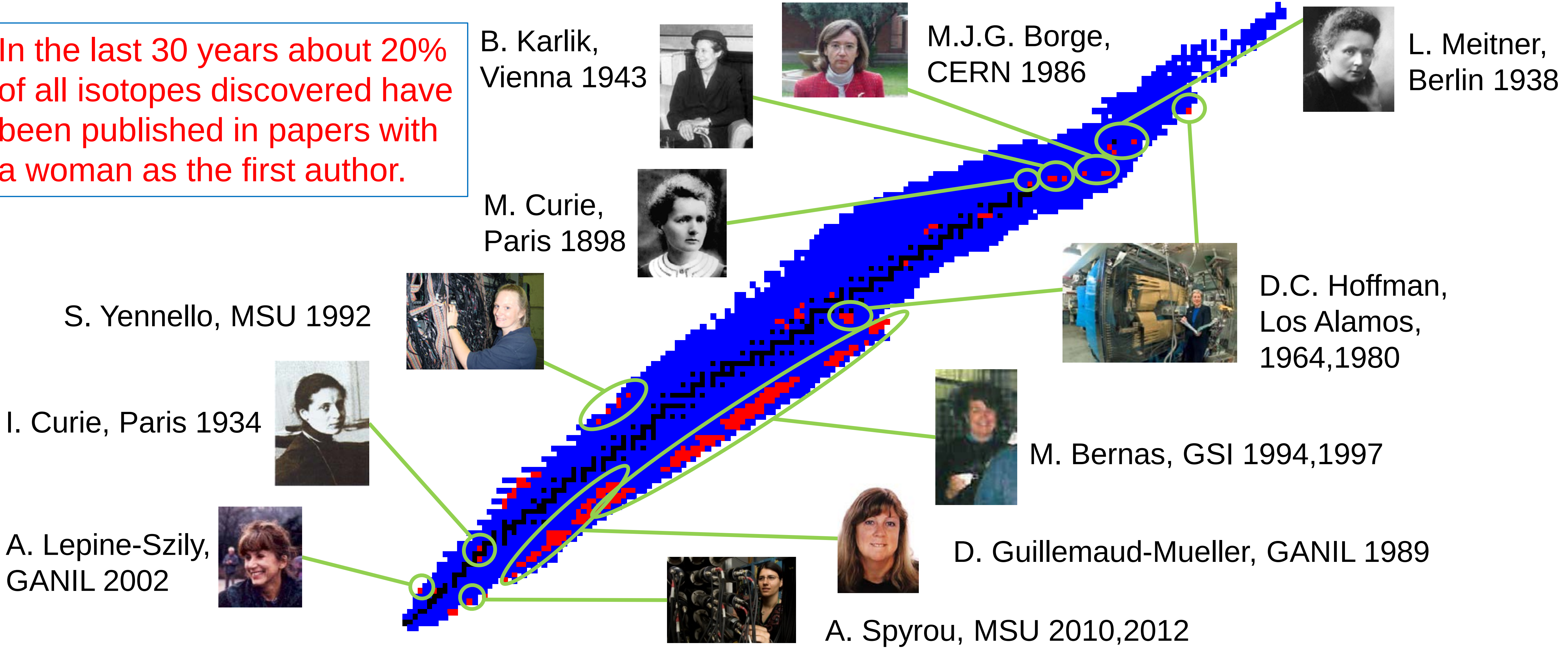
PHYSIQUE NUCLÉAIRE. — *Mise en évidence d'un isotope nouveau de sélénium déficient en neutrons*. Note (*) de Mlle **Jacqueline Beydon**, Mmes **Henriette Faraggi**, **Irène Gratot** et **Marguerite Le Pape**, présentée par M. Francis Perrin.

Dans la transmutation du cuivre par l'azote, nous avons pu constater la formation d'un nouvel isotope léger du sélénium, de période 5 ± 2 mn, émetteur β, présentant une raie γ vers 160 keV dont la masse est sans doute 71, la masse 69 n'étant toutefois pas exclue.

…all authors are female researchers!

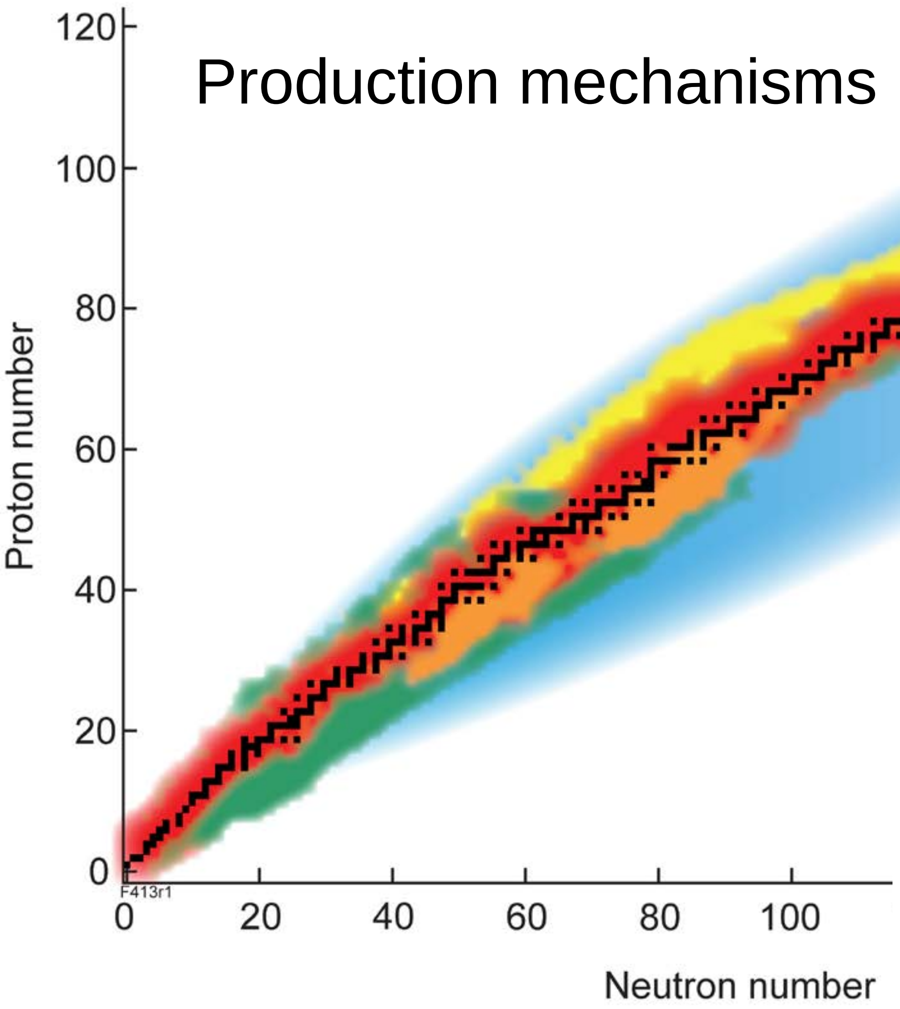
Isotopes discovered by women as first authors

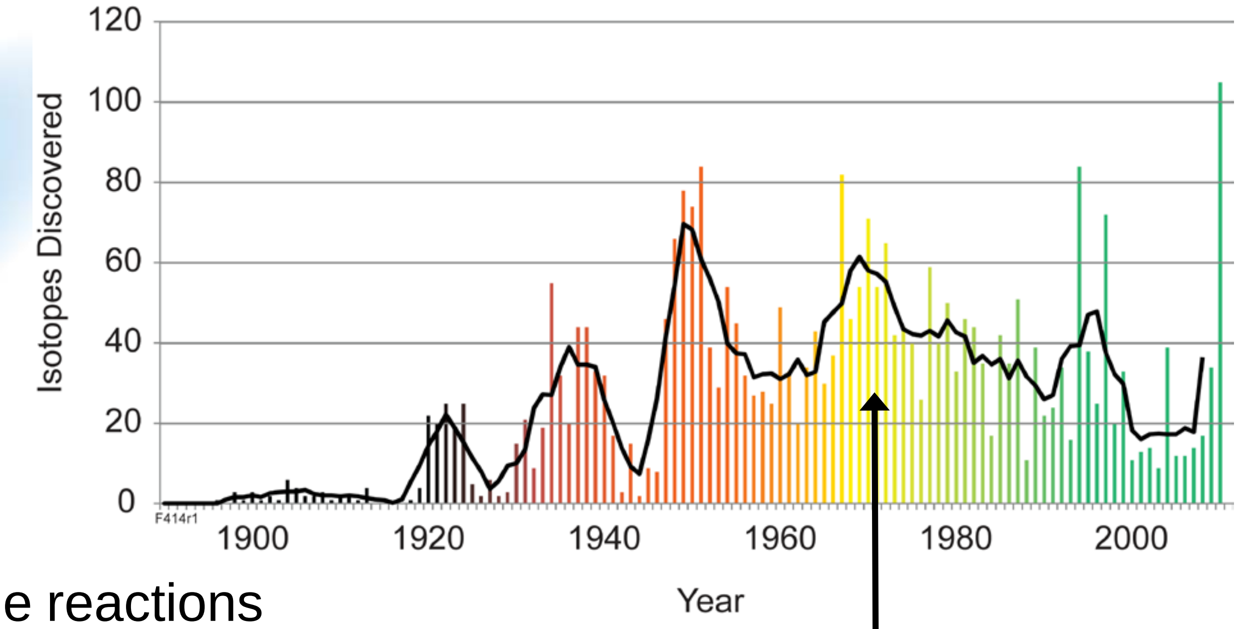
In the last 30 years about 20% of all isotopes discovered have been published in papers with a woman as the first author.



Current status

Production mechanisms

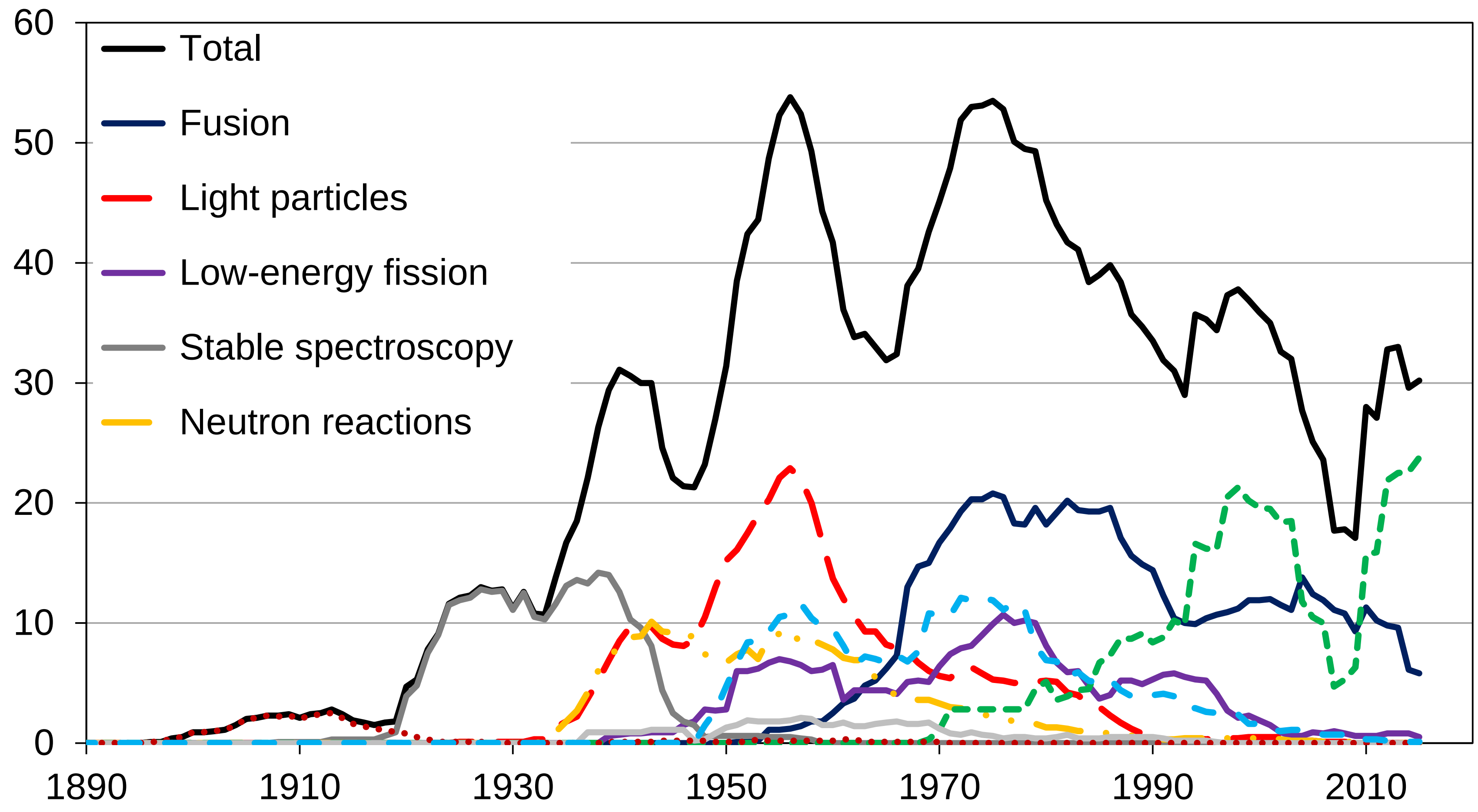




Fusion evaporation

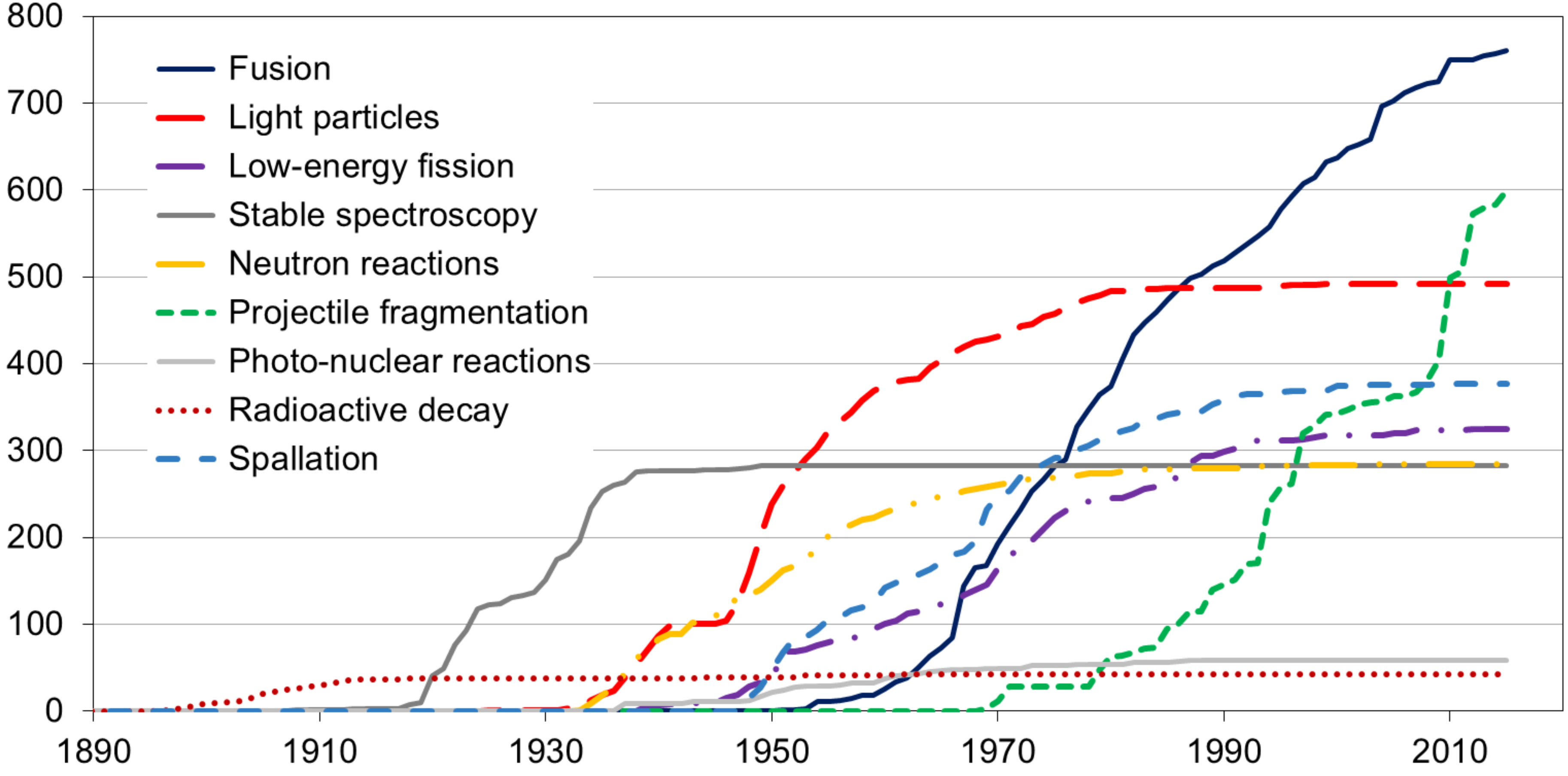
- Light-particle reactions
- Neutron reactions
- Fusion-evaporation
- Fragmentation/spallation
- Stable and naturally occurring radioactive isotopes

Five-year running average by production mechanism

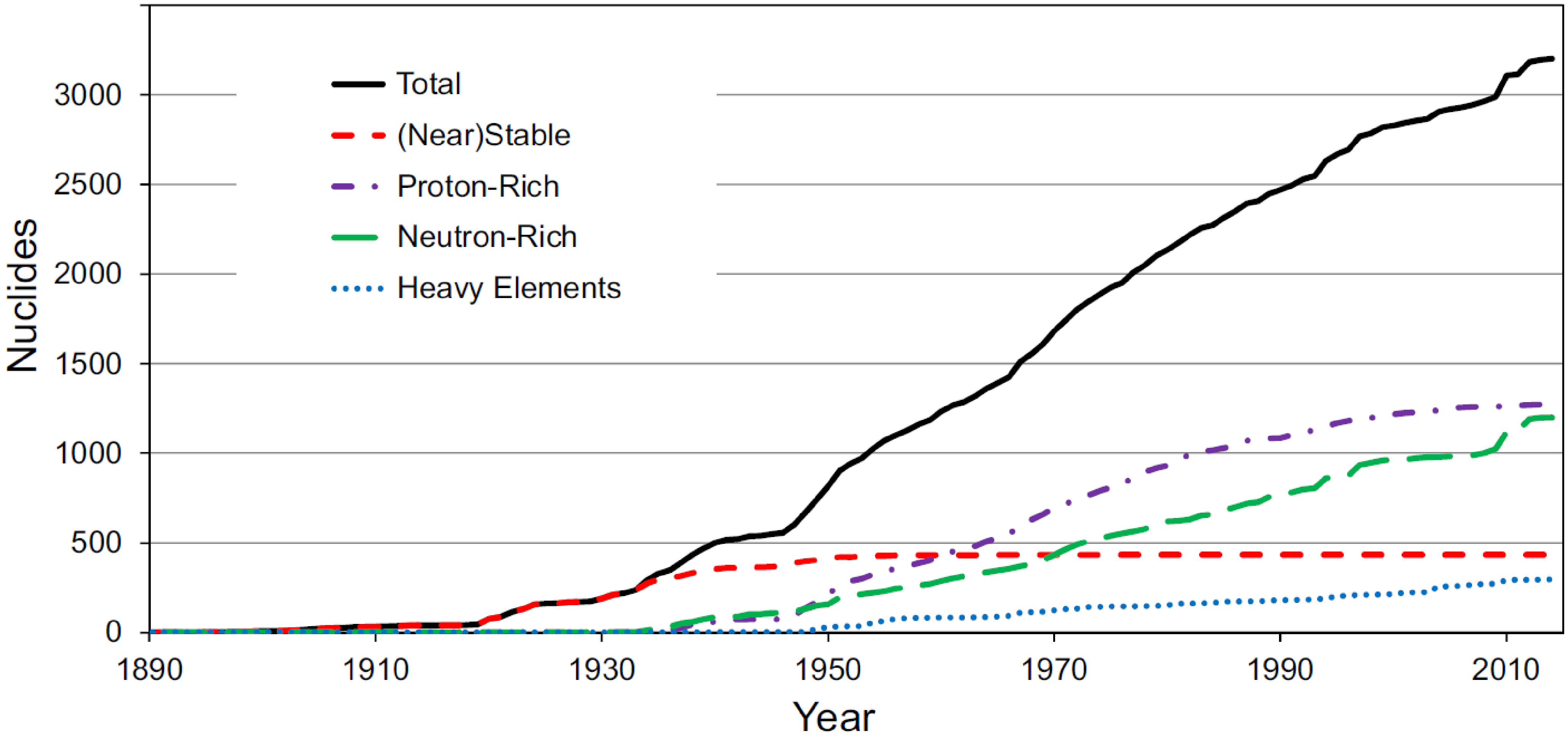


NSCL
FRIB
U.S. Department of Energy Office of Science
National Science Foundation
Michigan State University

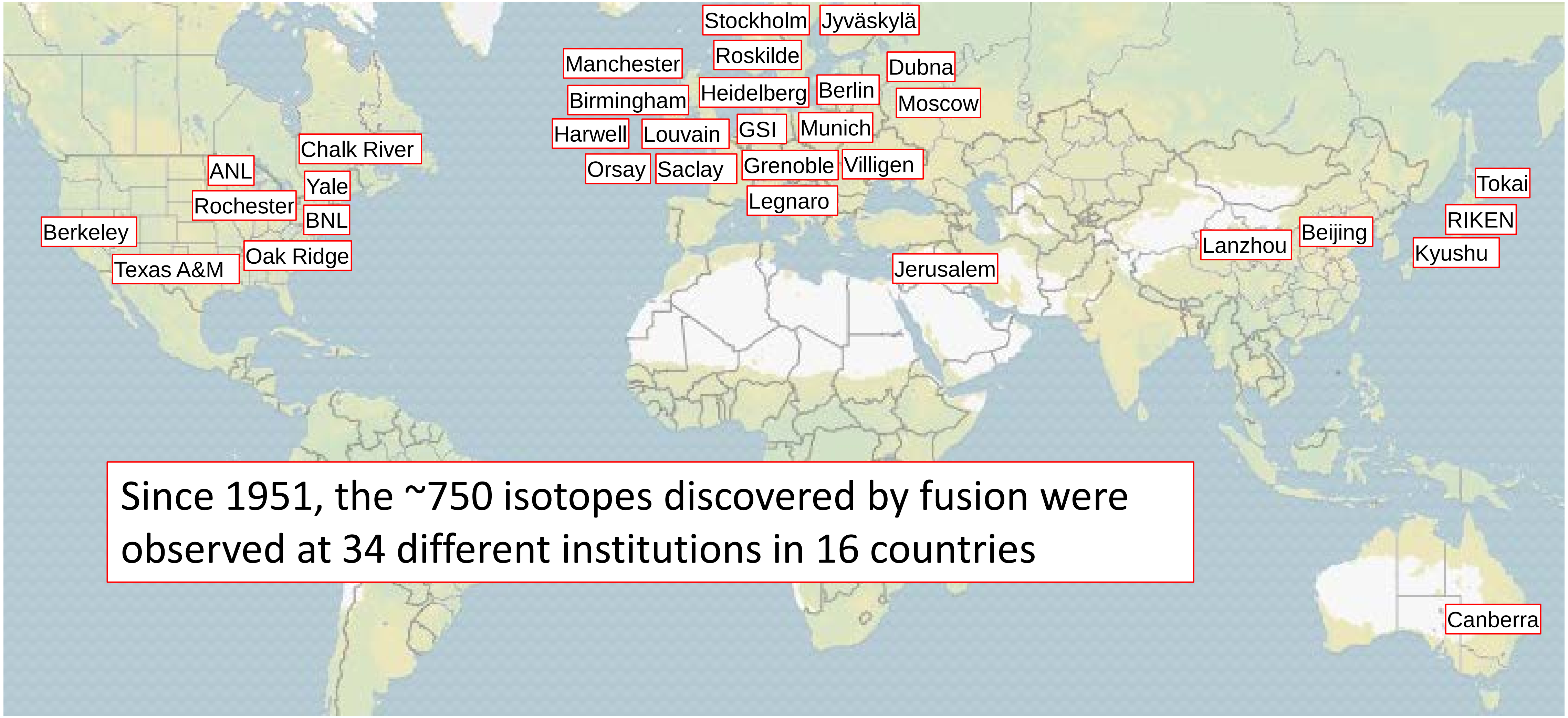
Known isotopes by production mechanism



Known isotopes by location in chart



Contributions from “small” accelerators

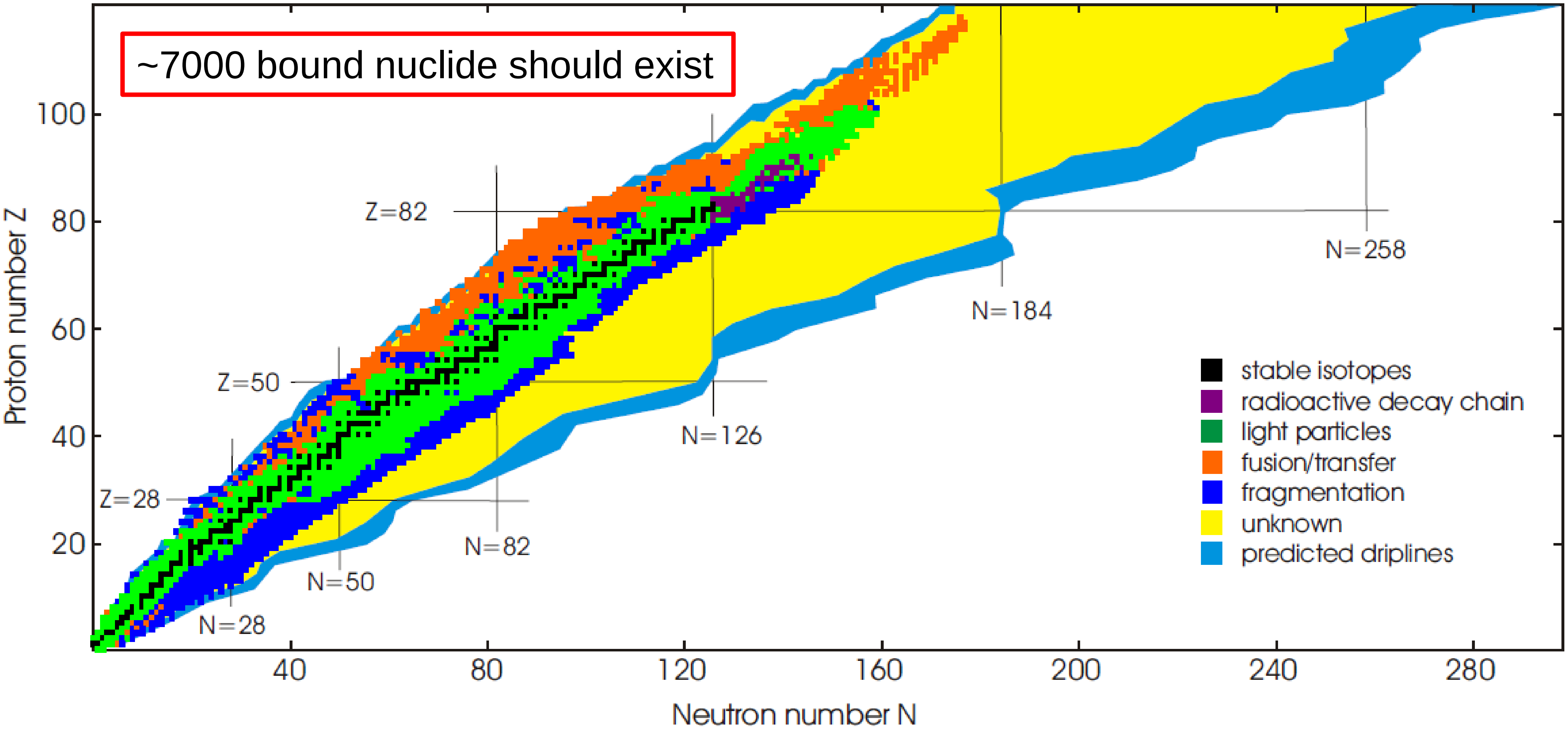


Since 1951, the ~750 isotopes discovered by fusion were observed at 34 different institutions in 16 countries

Isotopes discovered by FUSION17 speakers

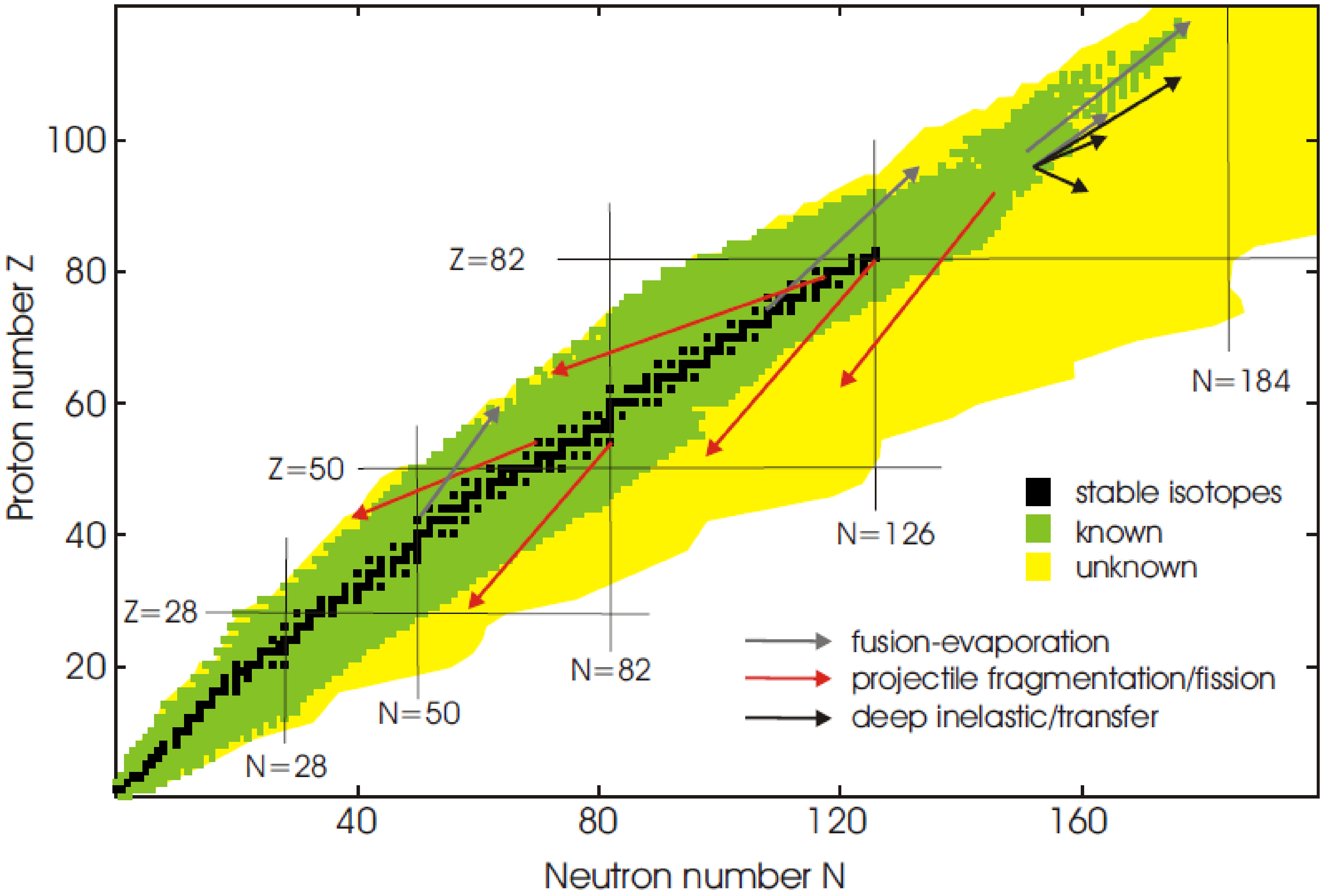
P. D. Stevenson	4
K. Hagino	2
K. Nishio	13
M. Dasgupta	3
Ch. Theisen	2
J. Khuyagbaatar	14
W. Loveland	7
Y. Aritomo	1
D. Ackermann	31
D. Jacquet	1
J. M. Gates	11
D. Bazin	141
M. Block	5
D. J. Hinde	3
M. Caamaño	1
C. E. Düllmann	12
T. Kawabata	1
S. G. Zhou	3
W. Mittig	5
L. Corradi	2
A. E. Stuchbery	1
E. Fioretto	1
S. Szilner	1
A. Di Pietro	1
S. Courtin	1

How many more nuclides are there?



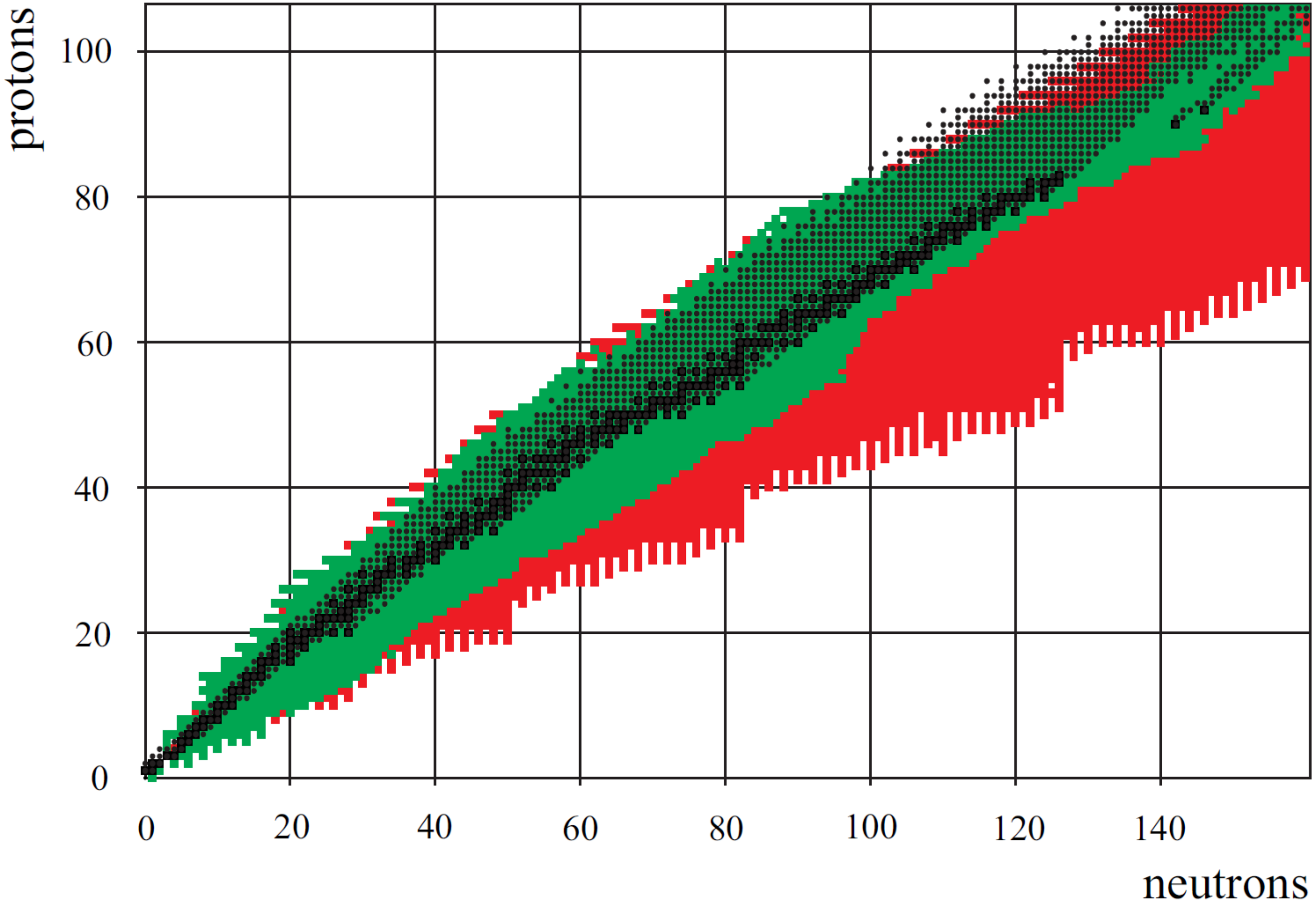
Erler *et al.*,Nature 486 (2012), 509)

How can new nuclides be discovered?



M. Thoennessen, Nucl. Data Sheets 118 (2014) 85

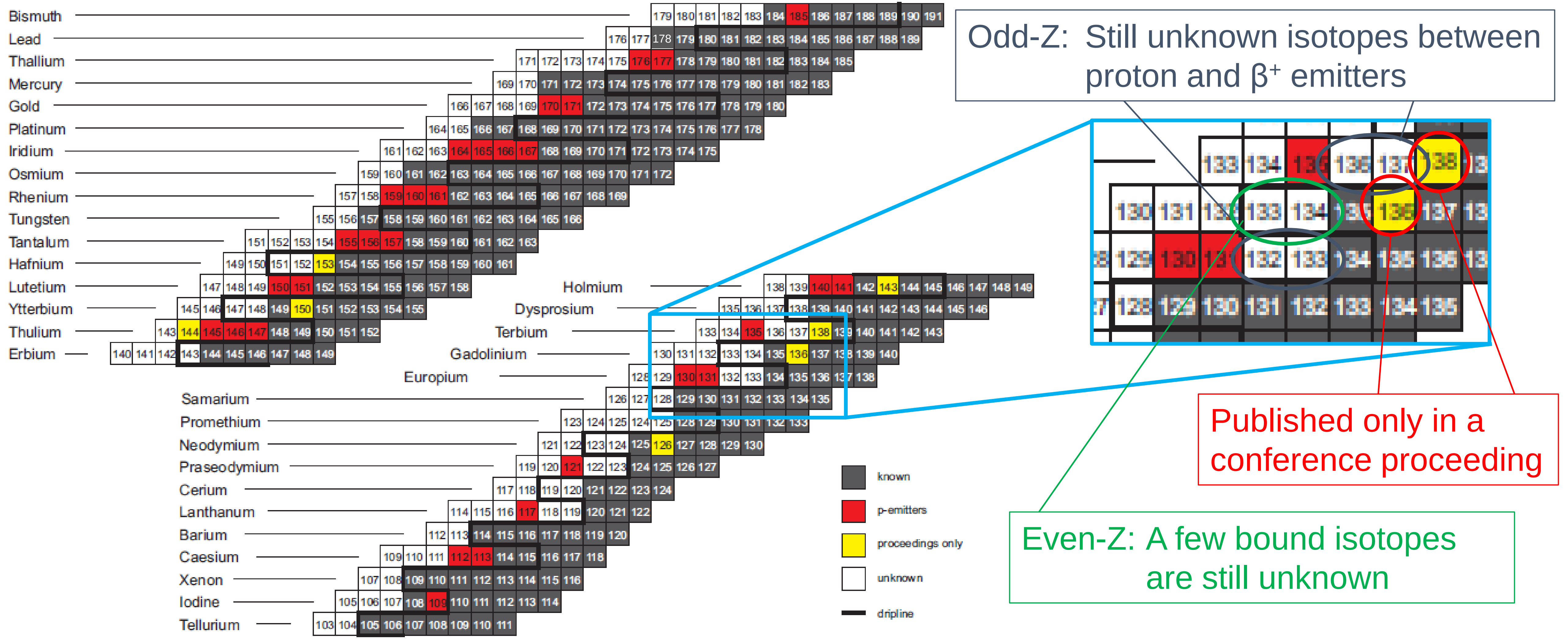
Discovery potential with fusion evaporation reactions



- Stable and naturally occurring radioactive isotopes
- Known isotopes
- Unknown isotopes
- Isotopes reachable by fusion with stable beam and targets

M. Thoennessen, Rep. Prog. Phys. 67 (2004) 1187

Mid-mass region: 51<Z<84



No conference proceedings

Physica Scripta. Vol. T88, 153–156, 2000

Formation and Studies of New Proton Emitters via Intermediate-Energy Fragmentation of Heavy-Element Beams

G. A. Souliotis*

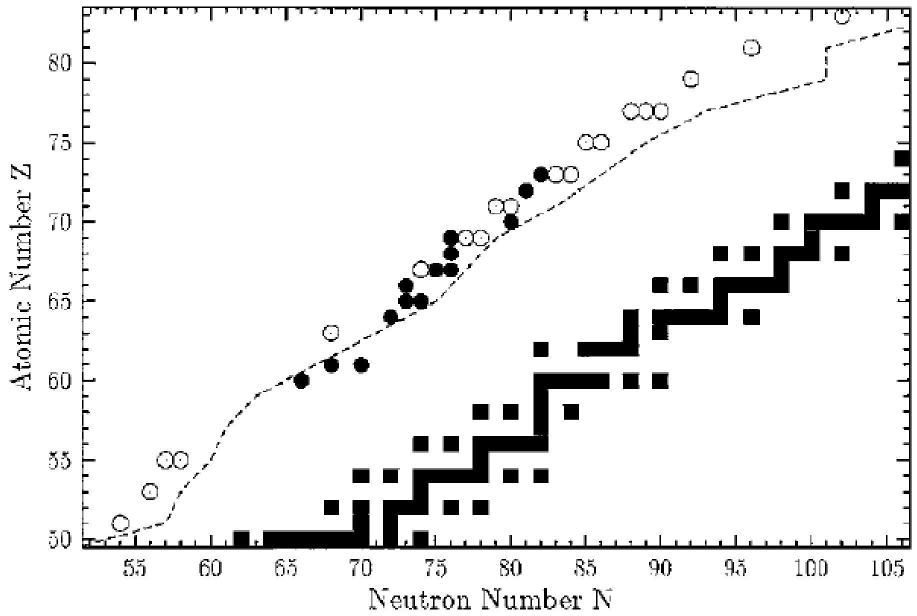
Institute of Nuclear Physics, NCSR Demokritos, Athens, Greece.

NCSR Demokritos, Athens, Greece

Received October 15, 1999

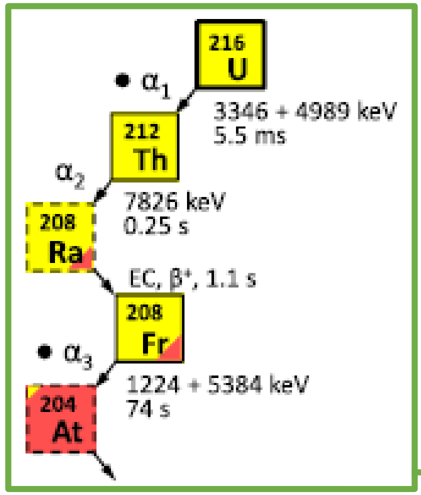
Abstract

The possibility of generating and studying new proton-emitting nuclei using projectile fragmentation of very-heavy beams is investigated in this work. The charge, mass and velocity distributions of heavy residues from the interaction of 30 MeV/nucleon ^{197}Au projectiles with ^{90}Zr have been measured with high-resolution using the MSU A1200 fragment separator. A broad range of proton-rich nuclei are produced in this reaction. A number of new p-rich nuclei (14, of which 6 are expected to be proton emitters) are observed in the region $Z = 60 - 73$. The opportunity of studying proton rich nuclei produced by this approach is discussed.



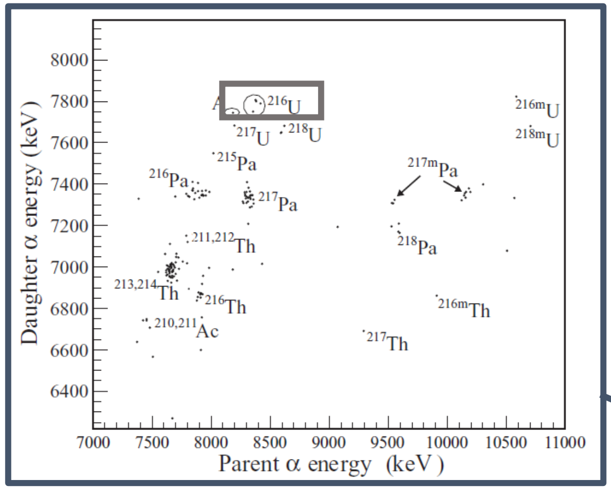
MSU A1200 fragment separator

Heavy mass region: 83<Z<93

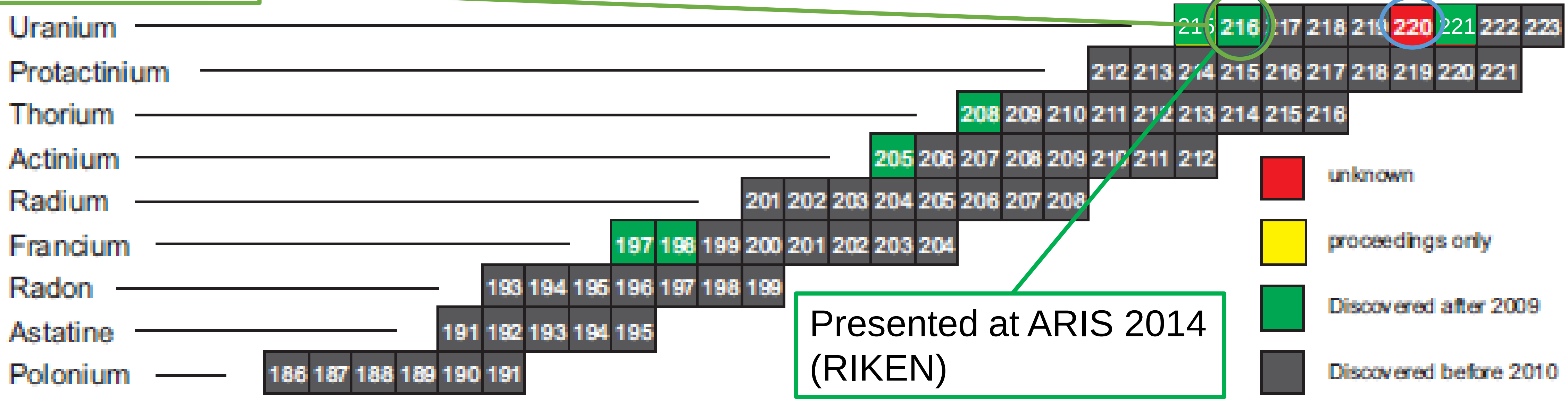


5 May 2015
(GSI)

9 April 2015
(Lanzhou)



^{222}U was discovered with the reaction $^{186}W(^{40}Ar,4n)$ so ^{220}U should be accessible with $^{184}W(^{40}Ar,4n)$.

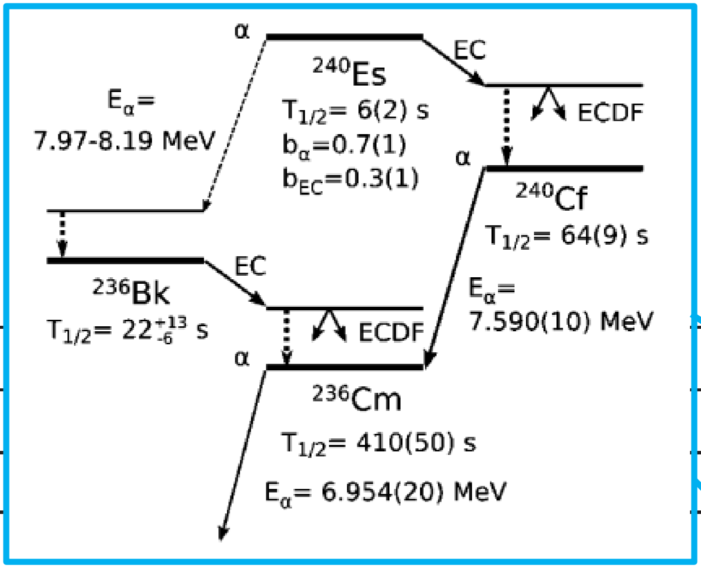


Presented at ARIS 2014
(RIKEN)

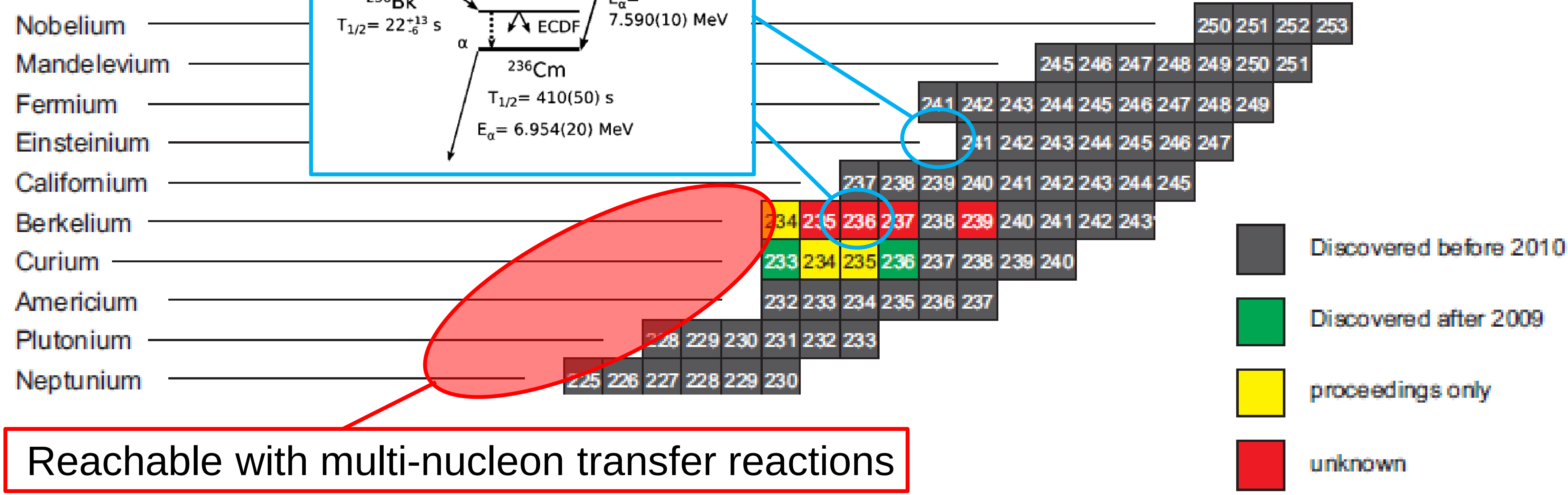
L. Ma et al., Phys. Rev. C 91 (2015) 051302(R)
H.M. Devaraja et al., Phys. Lett. B 748 (2015) 199
R. Hingmann et al., Z. Phys. A 313 (1983) 141
Y. Wakabayashi et al., ARIS-2014, PS1-B037 (2014)

Transuranium region: 92<Z<103

$^{209}Bi(^{34}S,3n)^{240}Es$



- First new isotopes in 2017
- Reach milestone of 300 transuranium isotopes

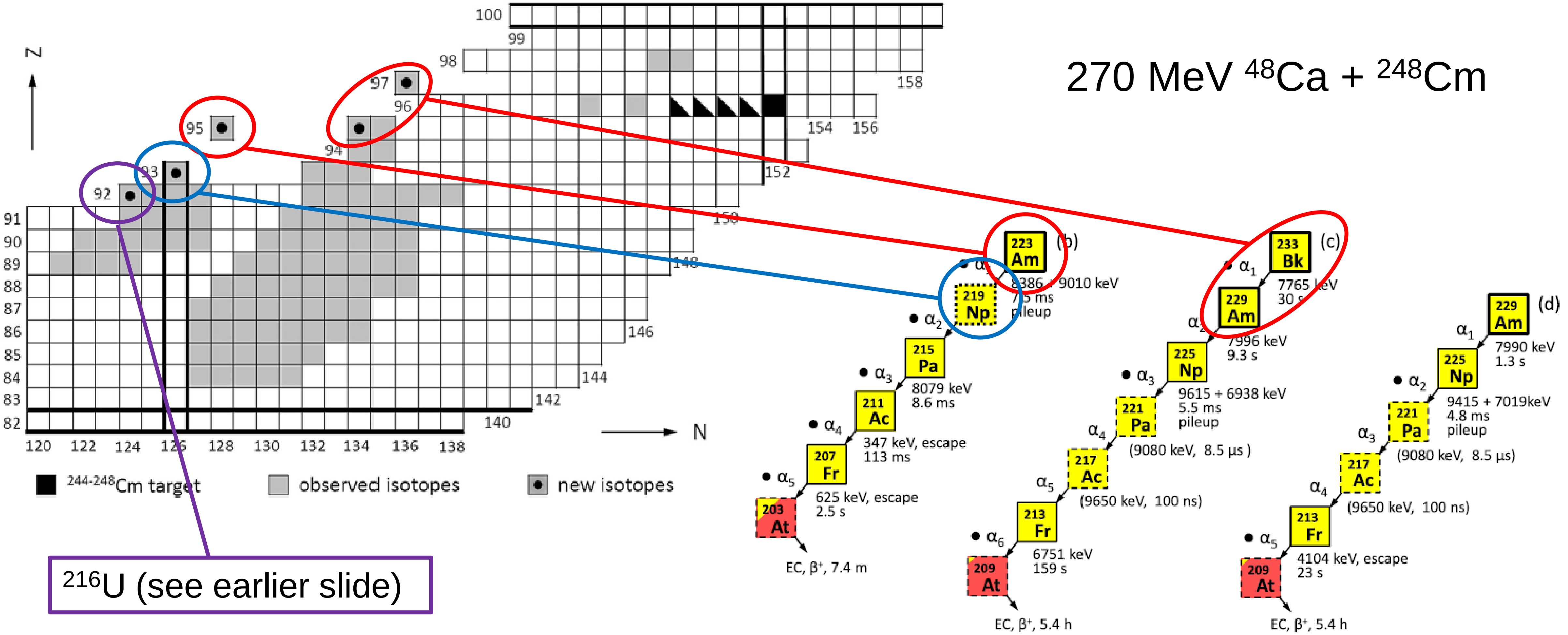


Reachable with multi-nucleon transfer reactions

J. Konki et al., Phys. Lett. B 764 (2017) 265

Multi-nucleon transfer reactions

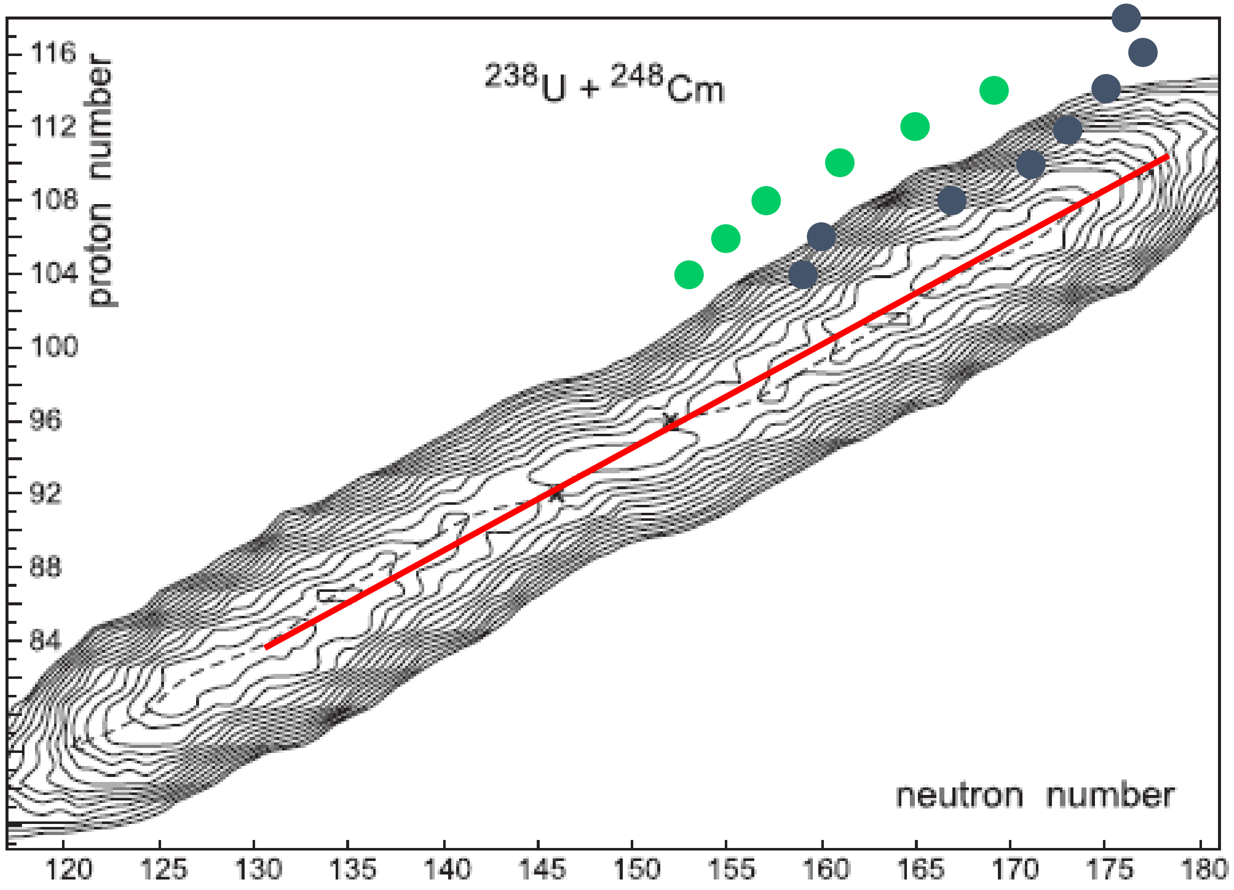
270 MeV $^{48}Ca + ^{248}Cm$



^{216}U (see earlier slide)

H.M. Devaraja et al., Phys. Lett. B748 (2015) 199

Superheavy nuclides: Multi nucleon transfer



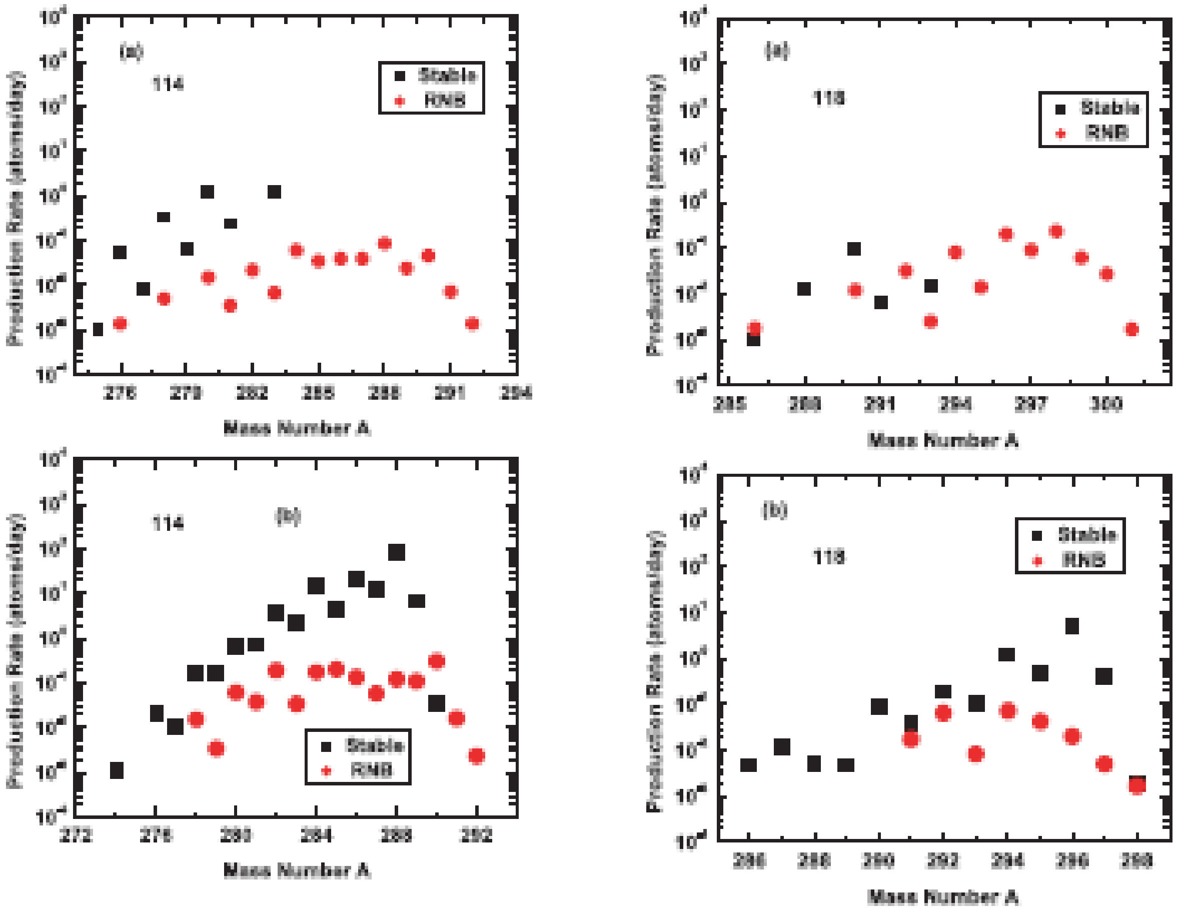
- Cold fusion
- Hot fusion
- Multi-nucleon transfer

Walter Greiner
(1935-2016)

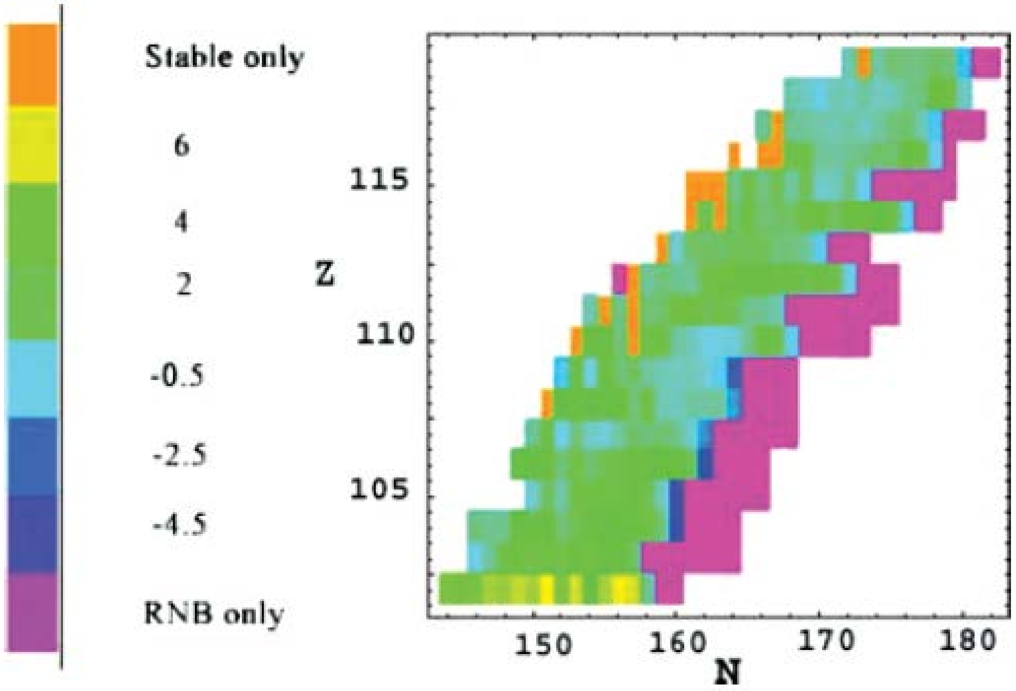
Valery Ivanovich Zagrebaev
(1950-2015)

V. Zagrebaev and W. Greiner, Phys. Rev. C 78 (2008) 34610

Superheavy nuclides: Fusion with radioactive beams



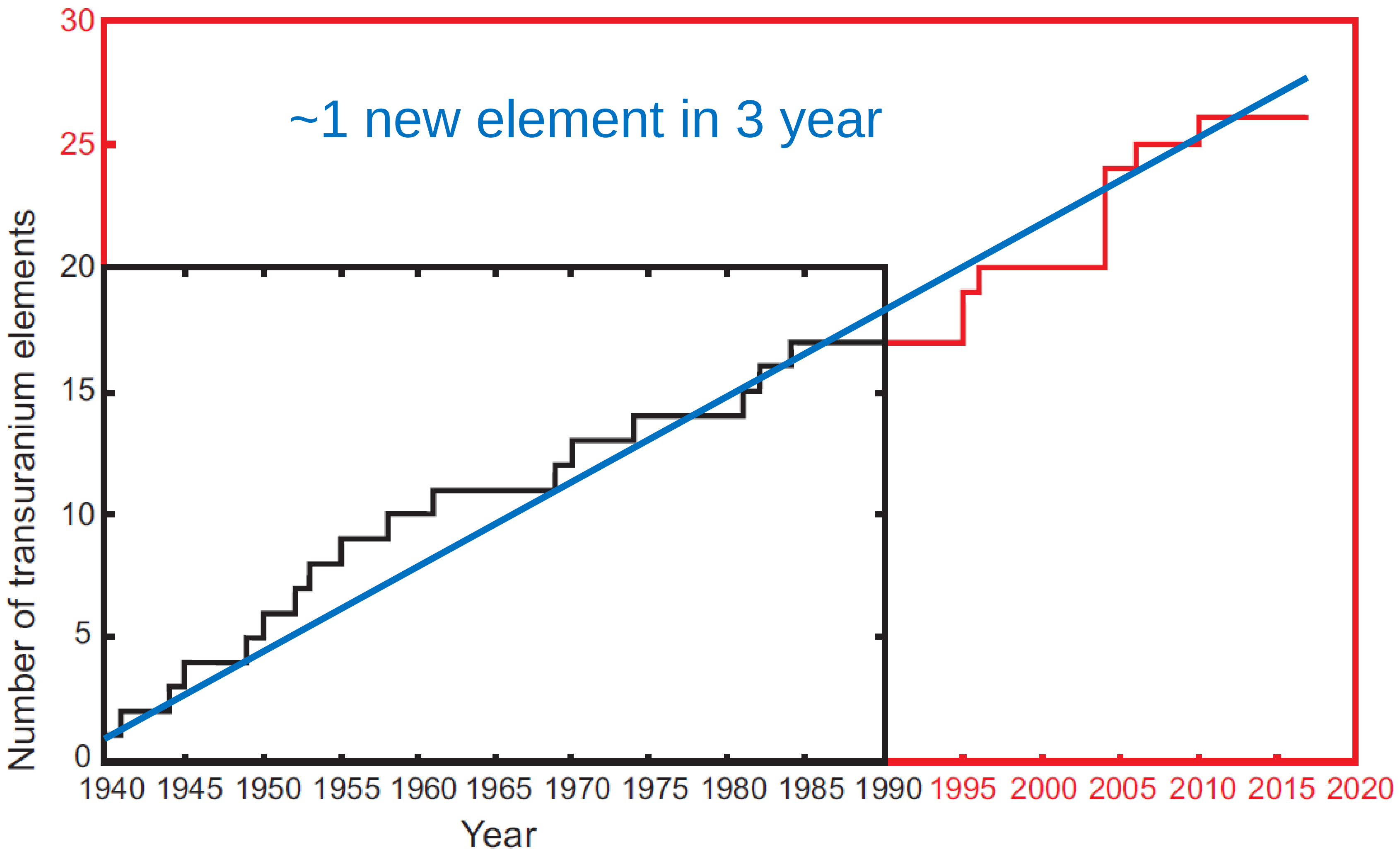
(a) Cold fusion (b) Hot fusion



"…until radioactive beam facilities produce beams of intensities comparable to those given in Ref. [22], their impact on heavy element research will not be great."

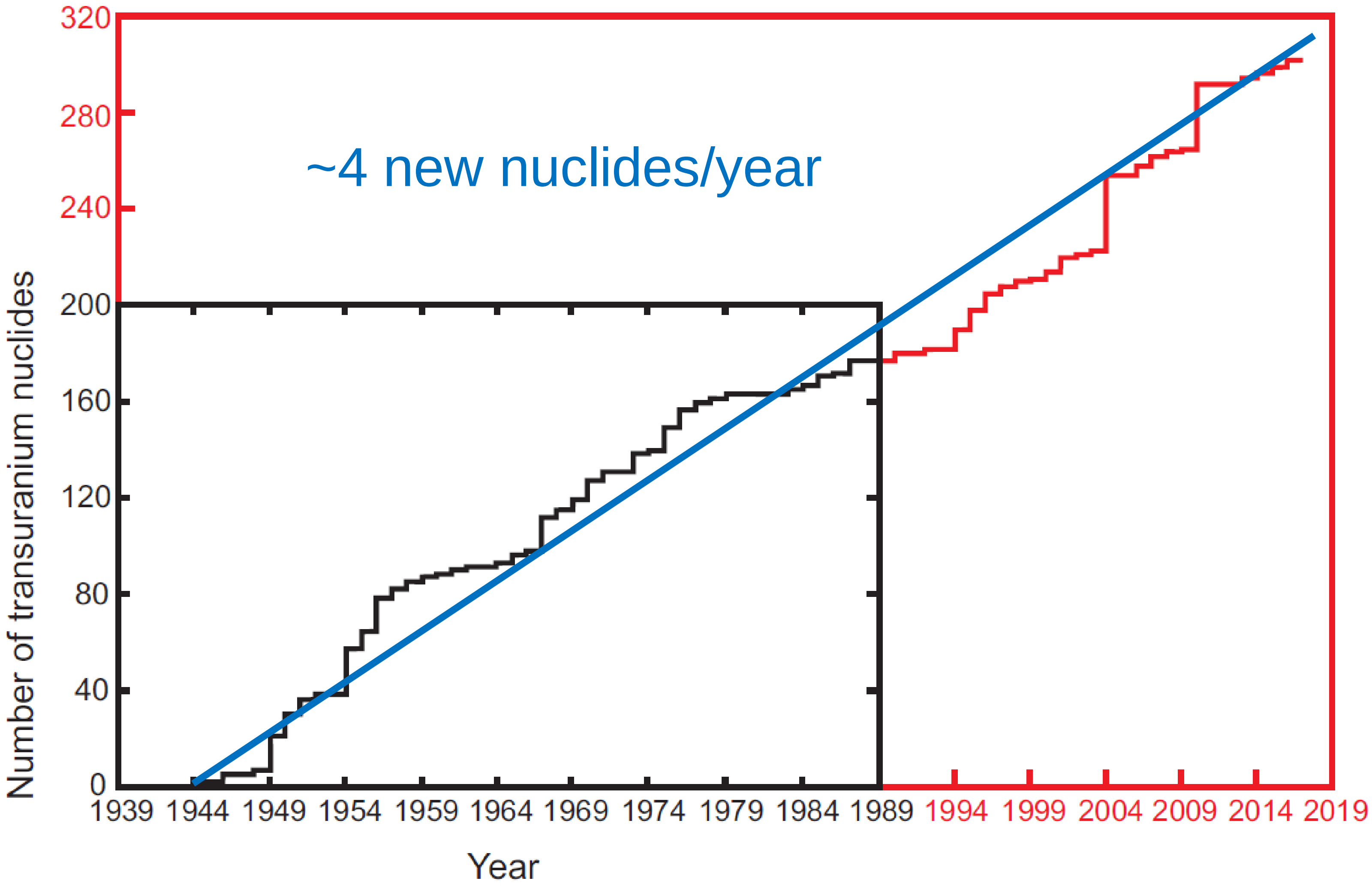
W. Loveland, Phys. Rev. C 76 (2007) 014612

Discovery of superheavy elements



G. T. Seaborg and W. D. Loveland, “The elements beyond uranium", Wiley, New York, New York (1990)

Discovery of super heavy nuclides



G. T. Seaborg and W. D. Loveland, “The elements beyond uranium", Wiley, New York, New York (1990)

Summary

- The discovery of isotopes is the first necessary step towards their exploration
- The quest for new discoveries pushes new technical developments
- New accelerators and detection techniques are critical
- Fusion evaporation reactions continue to be an important reaction mechanism to discover proton-rich isotopes
- Multi nucleon transfer reactions can populate new proton- and maybe neutron-rich isotopes in the transuranium region