Discovery of exotic nuclei: past, present and future

"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."

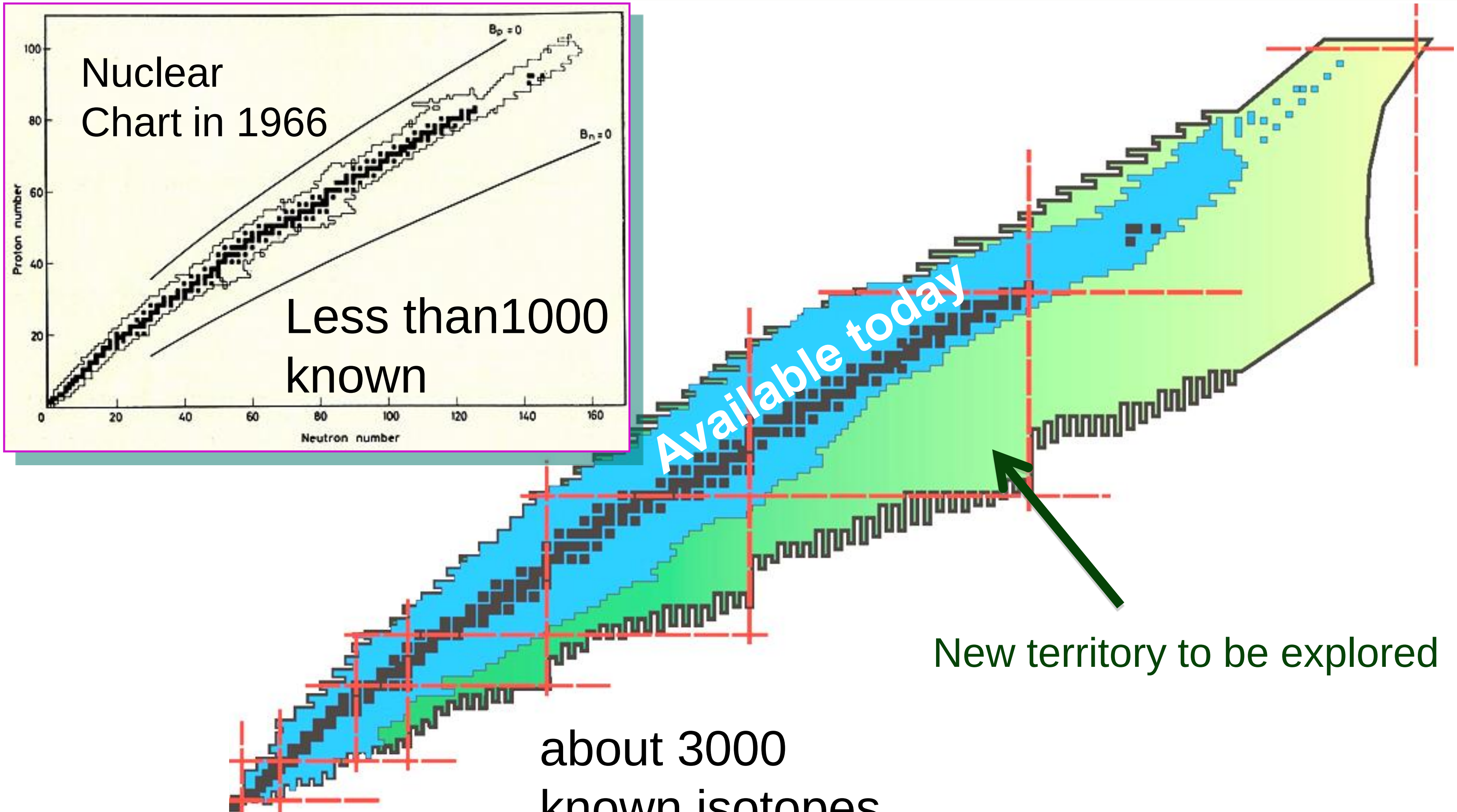
F.W. Aston, Nature **137**, 613 (1936)

Why search for new isotopes?

- First step is the discovery of new isotopes
- 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

Table of isotopes



New territory to be explored

about 3000
known isotopes

Discovery of radioactivity

PHYSIQUE. — *Sur les radiations émises par phosphorescence.* Note de M. HENRI BECQUEREL.

February 24, 1896

COMPTES RENDUS
DES SÉANCES
DE L'ACADÉMIE DES SCIENCES.

SÉANCE DU LUNDI 24 FÉVRIER 1896.

With potassium uranium sulfate, of which I have a few crystals forming a thin transparent crust, I was able to perform the following experiment: …

From these experiments we must therefore conclude that the phosphorescent substance in question emits radiation which passes through the paper which is opaque to light and reduces the silver salts.

Uranium had been known for a while…

Chemische Annalen

für die Freunde der Naturlehre, Arzneygelahrtheit, Haushaltungskunst und Manufacturen:

Helmstädt und Leipzig,
in der J. G. Müllerschen Buchhandlung.
1789.

Annals of Chemistry for the friends of natural science, medicine, home economics and manufacturing

I.

Chemische Untersuchung des Uranits, einer neuentdeckten metallischen Substanz; vom Hrn Prof. Klaproth *).

§. 1. Unter die Zahl der, ihren Bestandtheilen nach, noch unbekannten Mineralien, die aus dieser Ursach bisher weder einen bestimmten Namen, noch angemessenen Platz in den Systemen, gehabt oder haben können, gehört auch die sogenannte Pechblende von der Grube Georg Wagsfort zu Johanngeorgenstadt. Durch diesen, vom gemeinen Berg-

September 24, 1789

Radioactive substances

February 24, 1896	Uranium	H. Becquerel	^{238}U
March 24, 1898	Thorium	G.C. Schmidt	^{232}Th
July 18, 1898	Polonium	P. Curie and M. Curie	^{212}Po
December 26, 1898	Radium	P. Curie, M. Curie and G. Bemont	^{226}Ra
November 6, 1899	Radon	P. Curie and M. Curie	^{222}Rn

Subtracting the contribution of the activated plate due to the radioactive substance, it remains radioactive for several days. However, the induced radioactivity is decreasing, first very rapidly, then slower and slower and tends to disappear asymptotically.

…however, already on September 13, 1899, Rutherford performed the first half-life measurement, discovering ^{220}Rn

Exponential decay

THE

LONDON, EDINBURGH, AND DUBLIN

PHILOSOPHICAL MAGAZINE

AND

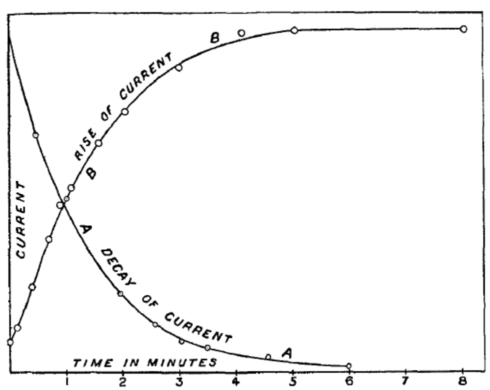
JOURNAL OF SCIENCE.

[FIFTH SERIES.]

JANUARY 1900.

I. *A Radio-active Substance emitted from Thorium Compounds. By* E. Rutherford, *M.A., B.Sc., Macdonald Professor of Physics, McGill University, Montreal* *.

McGill University, Montreal,
September 13th, 1899.



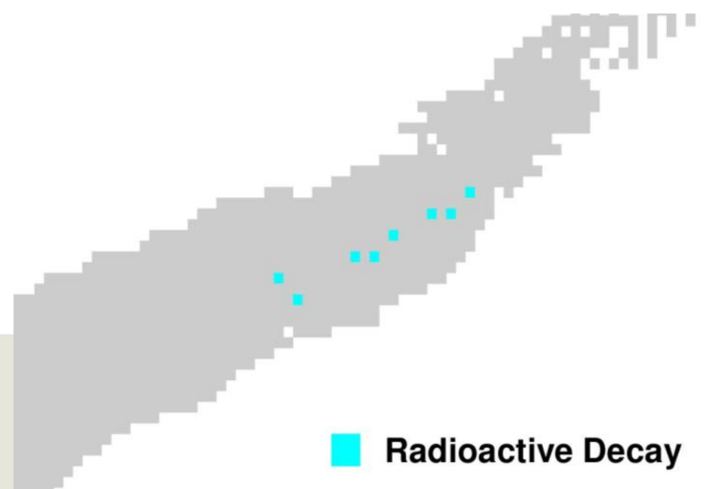
in a geometrical progression with the time. The result shows that the intensity of the radiation has fallen to one-half its value after an interval of about *one minute.* The rate of leak due to the emanation was too small for measurement after an interval of ten minutes.

When the source of the emanation is removed, $q=0$, and the decay of the number of ions produced by the emanation is given by the equation

$$\frac{dn}{dt} = -\lambda n.$$

If $n=N$ when $t=0$, it is easily seen that

$$\frac{n}{N} = e^{-\lambda t},$$

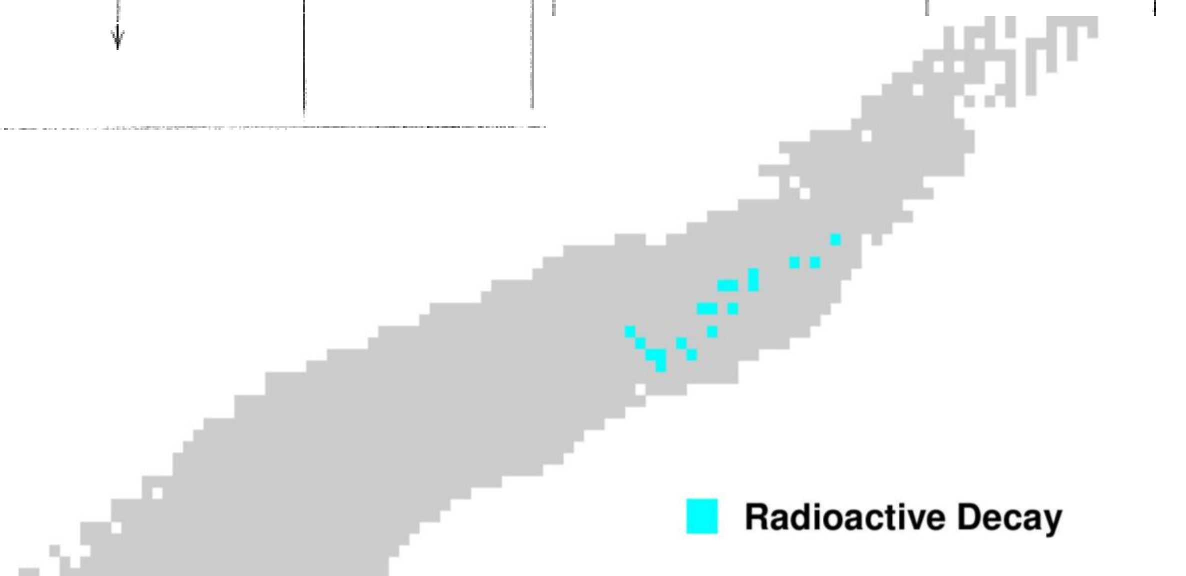


Rutherford's Bakerian lecture: May 19, 1904

Product.	T.
Uranium	10^9 years
↓ Uranium X	22 days
↓ Final product.	—
Thorium	3×10^9
↓ Thorium X	4 days
↓ Thorium emanation	1 minute
↓ Thorium A	11 hours
↓ Thorium B	55 minutes
↓ Thorium C (final product)	—

Radium	800 years
↓ Radium emanation	4 days
↓ Radium A	3 minutes
↓ Radium B	21 minutes
↓ Radium C	28 minutes
↓ Radium D	About 40 years
↓ Radium E	About 1 year
↓	

Actinium	—
↓ Actinium X ?	—
↓ Actinium emanation	3·7 seconds
↓ Actinium A	41 minutes
↓ Actinium B	1·5 minutes
↓ Actinium C (final product)	—



NSCL
National Science Foundation
Michigan State University

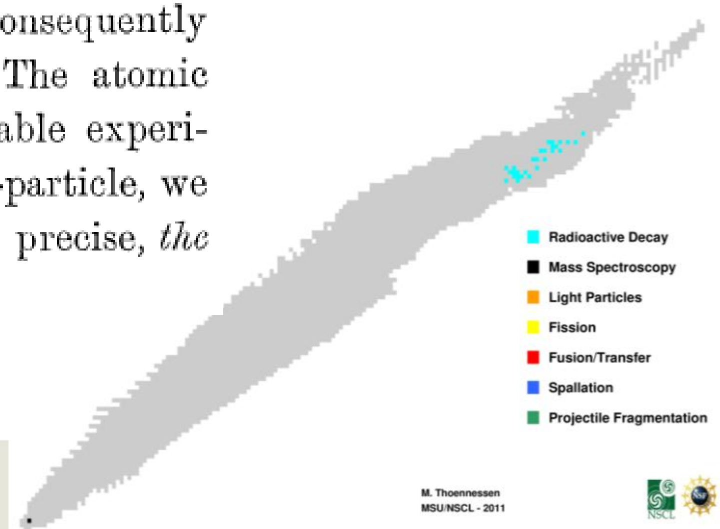
The charge and nature of the α-particle

By Professor E. Rutherford, F.R.S., and Hans Geiger, Ph.D., John Harling Fellow, University of Manchester.

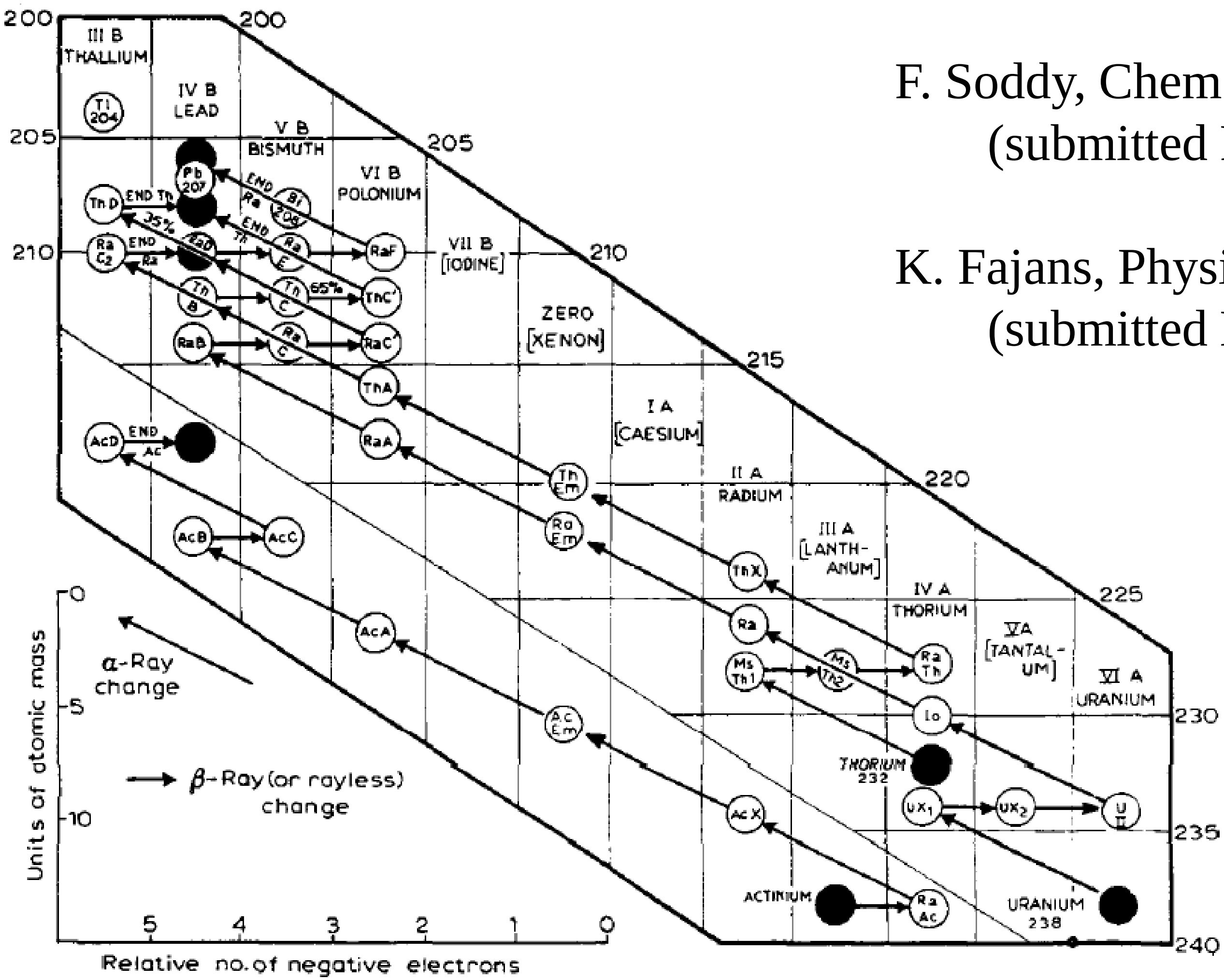
(Read June 18; MS. received July 17, 1908.)

Nature of the α-Particle.

The value of E/M—the ratio of the charge on the α-particle to its mass—has been measured by observing the deflection of the α-particle in a magnetic and in an electric field, and is equal to $5{\cdot}07 \times 10^3$ on the electromagnetic system.* The corresponding value of e/m for the hydrogen atom set free in the electrolysis of water is $9{\cdot}63 \times 10^3$. We have already seen that the evidence is strongly in favour of the view that $E = 2e$. Consequently $M = 3{\cdot}84m$, *i.e.*, the atomic weight of an α-particle is 3·84. The atomic weight of the helium atom is 3·96. Taking into account probable experimental errors in the estimates of the value of E/M for the α-particle, we may conclude that *an α-particle is a helium atom*, or, to be more precise, *the α-particle, after it has lost its positive charge, is a helium atom.*



Explanation of the decay chains



F. Soddy, Chem. News **107** (1913) 97
(submitted Feb. 18, 1913)

K. Fajans, Physik. Z. **14** (1913) 131
(submitted Dec. 31, 1912)

F. Soddy,
Nobel Lecture, 1922

Thomson's Bakerian Lecture: May 22, 1913

There can, therefore, I think, be little doubt that what has been called neon is not a simple gas but a mixture of two gases, one of which has an atomic weight about 20 and the other about 22.

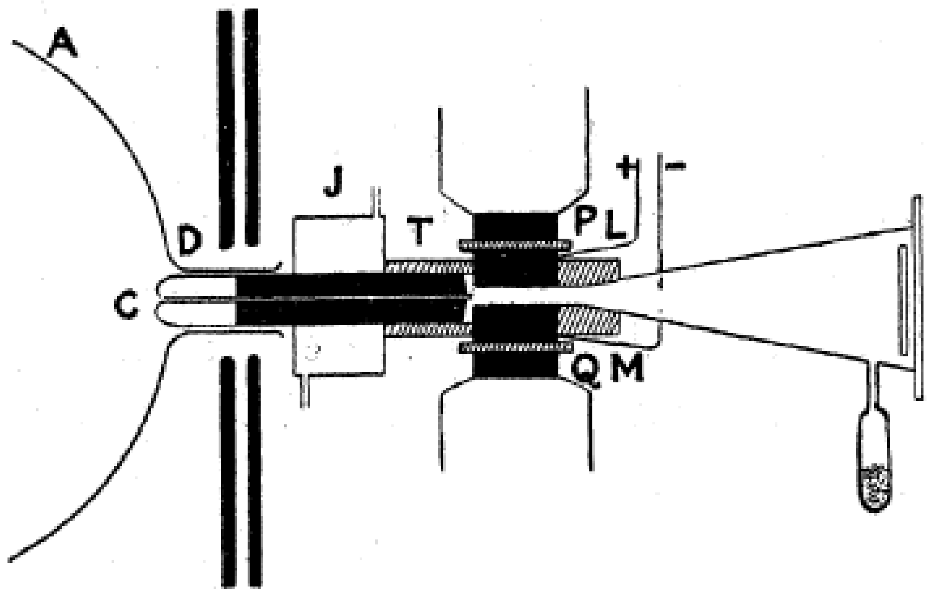
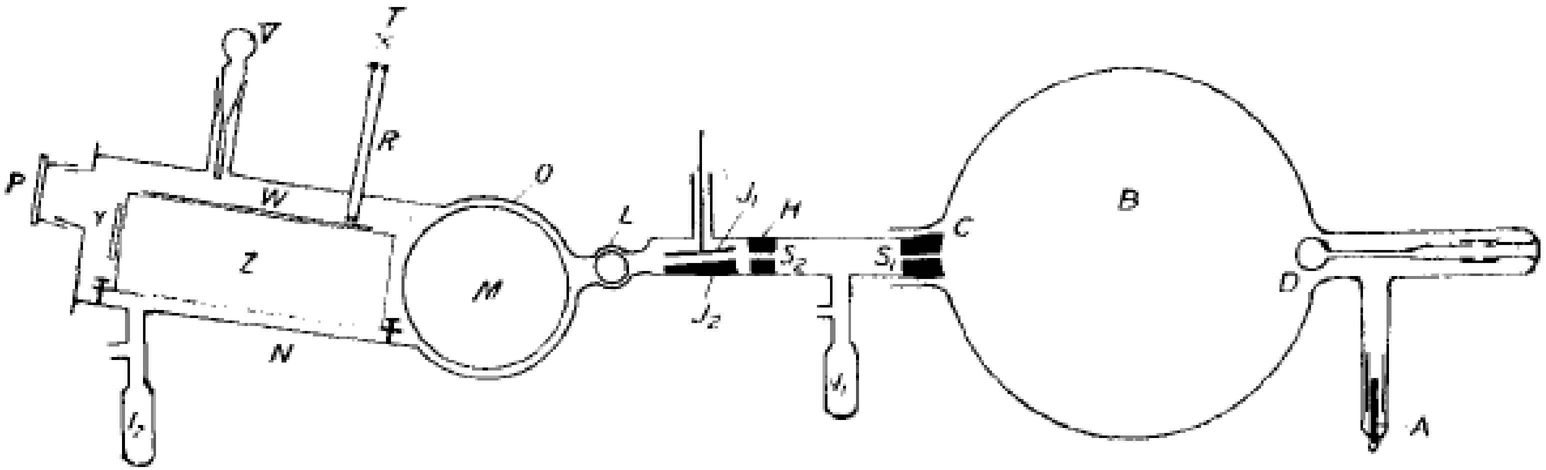


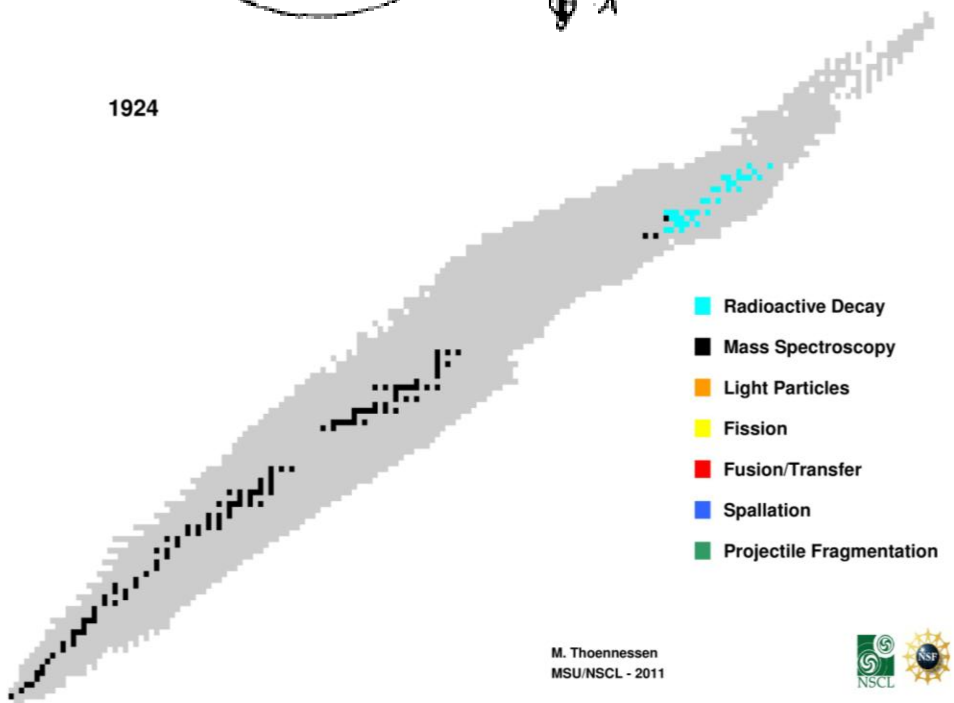
Fig. 4.

J.J. Thomson, Proc. Roy. Soc. 89 (1913) 1

Mass spectra of chemical elements



F.W. Aston, Phil. Mag. 39 (1920) 611



Nuclear transmutation

LIV. *Collision of α Particles with Light Atoms. IV. An Anomalous Effect in Nitrogen. By* Professor Sir E. Rutherford, *F.R.S.**

"From the results so far obtained it is difficult to avoid the conclusion that the long-range atoms arising from collision of particles with nitrogen are not nitrogen atoms but probably atoms of hydrogen, or atoms of mass 2"

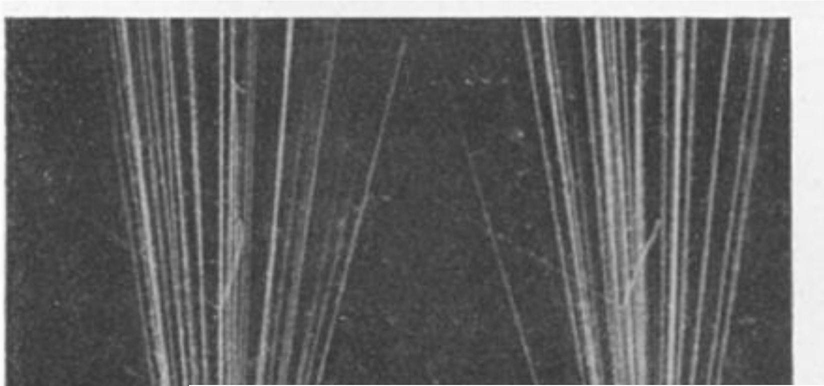
E. Rutherford, Phil. Mag. 37 (1919) 581

First new isotope in a nuclear reaction

The Ejection of Protons from Nitrogen Nuclei, Photographed by the Wilson Method.

By P. M. S. Blackett, Moseley Research Student of the Royal Society and Fellow of King's College, Cambridge.

(Communicated by Prof. Sir E. Rutherford, F.R.S.—Received December 17, 1924.



$$m_p v_p \sin \psi - m_n v_n \sin \omega = 0,$$

$$m_p v_p \cos \psi + m_n v_n \cos \omega - MV = 0,$$

$^{14}N(\alpha,p)^{17}O$

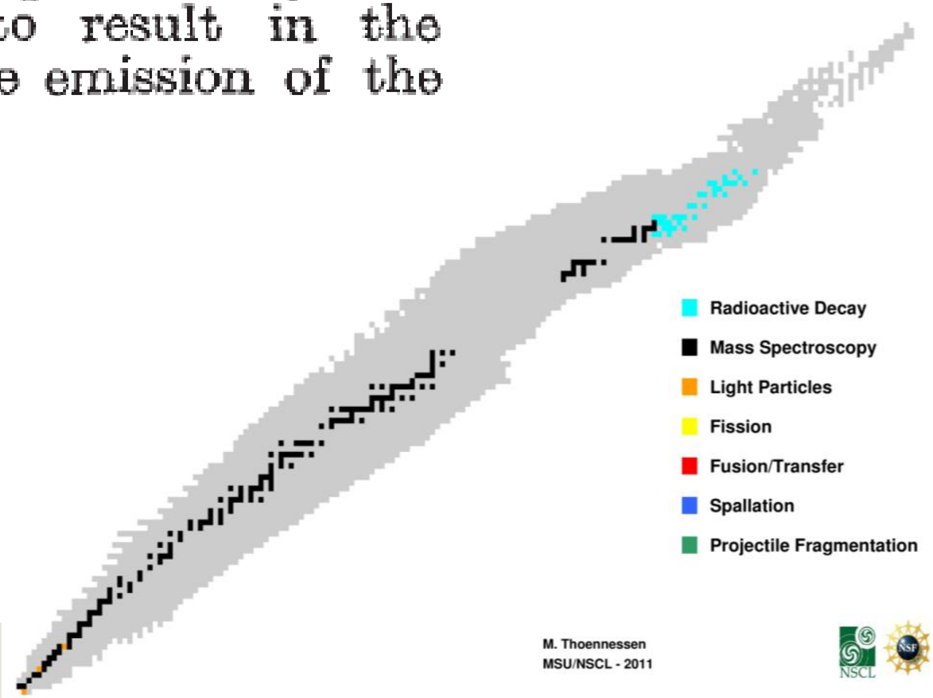
Of the nature of the integrated nucleus little can be said without further data. It must however have a mass 17, and provided no other nuclear electrons are gained or lost in the process, an atomic number 8. It ought therefore to be an isotope of oxygen. If it is stable it should exist on the earth.

Discovery of the neutron

These results, and others I have obtained in the course of the work, are very difficult to explain on the assumption that the radiation from beryllium is a quantum radiation, if energy and momentum are to be conserved in the collisions. The difficulties disappear, however, if it be assumed that the radiation consists of particles of mass 1 and charge 0, or neutrons. The capture of the α-particle by the Be^9 nucleus may be supposed to result in the formation of a C^{12} nucleus and the emission of the neutron.

J. Chadwick, Nature 129 (1932) 312

Submitted: February 17, 1932



First new isotope produced with an accelerator

Disintegration of Lithium by Swift Protons

In a previous letter to this journal[1] we have described a method of producing a steady stream of swift protons of energies up to 600 kilovolts by the application of high potentials, and have described experiments to measure the range of travel of these protons outside the tube.

$^{7}\mathrm{Li} + \mathrm{p} \longrightarrow {}^{8}\mathrm{Be} \longrightarrow 2\alpha$

The brightness of the scintillations and the density of the tracks observed in the expansion chamber suggest that the particles are normal α-particles. If this point of view turns out to be correct, it seems not unlikely that the lithium isotope of mass 7 occasionally captures a proton and the resulting nucleus of mass 8 breaks into two α-particles, each of mass four and each with an energy of about eight million electron volts.

J.D. Cockcroft and E.T.S. Walton,
Nature 129 (1932) 649

Submitted: April 16, 1932

January 15,1934: First observation of new radioactive isotopes

PHYSIQUE NUCLÉAIRE. — *Un nouveau type de radioactivité.* Note de Mme **Irène Curie** et M. F. **Joliot**, présentée par M. Jean Perrin.

Ces expériences montrent l'existence d'un nouveau type de radioactivité avec émission d'électrons positifs. Nous pensons que le processus d'émission serait le suivant pour l'aluminium :

$$^{27}_{13}Al + ^{4}_{2}He = ^{30}_{15}P + ^{1}_{0}n.$$

$^{27}Al(\alpha,n)^{30}P$

L'isotope $^{30}_{15}P$ du phosphore serait radioactif avec une période de 3m15s et émettrait des électrons positifs suivant la réaction

$$^{30}_{15}P = ^{30}_{14}Si + \overset{+}{\varepsilon}.$$

We propose for the new radio-elements formed by transmutation of boron, magnesium and aluminium, the names *radionitrogen*, *radiosilicon*, *radiophosphorus*.

Nature, February 10, 1934

March 1934

March 1: H.R. Crane and C.C. Lauritsen
Phys. Rev. 45 (1934) 430 (Caltech)

$${}_5B^{10} + {}_1H^2 \rightarrow {}_6C^{11} + {}_0n^1,$$
$${}_6C^{11} \rightarrow {}_5B^{11} + (+\epsilon).$$

March 9: M.L. Oliphant, P. Harteck and E. Rutherford
Nature 133 (1934) 413 (Cambridge)

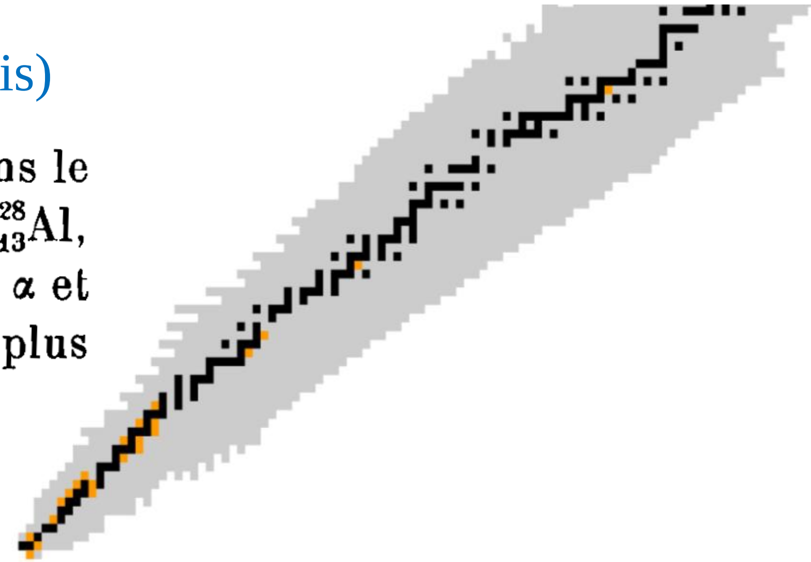
$$D^2_1 + D^2_1 \longrightarrow H^3_1 + H^1_1$$
$$D^2_1 + D^2_1 \longrightarrow He^3_2 + n^1_0$$

March 17: L. Wertenstein, Nature 133 (1934) 564 (Warsaw)

(1) ${}_7N^{14} + {}_2\alpha^4 = {}_9F^{17}$ + neutron, (2) ${}_9F^{17} = {}_8O^{17}$ + positron.

March 20: I. Curie and F. Joliet,
J. Phys. Radium 5 (1934) 153 (Paris)

Le radioélément émetteur de rayons β créé dans le magnésium irradié est probablement un noyau ${}^{28}_{13}Al$, formé à partir de ${}^{25}_{12}Mg$ par capture de la particule α et émission d'un proton. Les électrons négatifs étant plus



National Science Foundation
Michigan State University
NSCL

March 25, 1934: Fermi

RADIOACTIVITY INDUCED BY NEUTRON BOMBARDMENT.—I.

Translated from « Ric. Scientifica », 5 (1), 283 (1934) (*).

$$Al^{27} + n^{1} \rightarrow Na^{24} + He^{4}$$

2—The Experimental Method

The neutron source consisted of a sealed glass tube about 6 mm in diameter and 15 mm in length, containing beryllium powder and radon in amounts up to 800 millicuries. According to the ordinarily assumed yield of neutrons

Discovery of transuranium elements?

Possible Production of Elements of Atomic Number Higher than 92

By Prof. E. Fermi, Royal University of Rome

Nature, June 16, 1934

E. Fermi, Nobel Lecture, December 12, 1938: We concluded that the carriers were one or more elements of atomic number larger than 92 ; we, in Rome, use to call the elements 93 and 94 Ausenium and Hesperium respectively. It is known that O. Hahn and L. Meitner have investigated very carefully and extensively the decay products of irradiated uranium, and were able to trace among them elements up to the atomic number 96.*

* The discovery by Hahn and Strassmann of barium among the disintegration products of bombarded uranium, as a consequence of a process in which uranium splits into two approximately equal parts, makes it necessary to reexamine all the problems of the transuranic elements, as many of them might be found to be products of a splitting of uranium.

December 22,1938:

Über den Nachweis und das Verhalten der bei der Bestrahlung des Urans mittels Neutronen entstehenden Erdalkalimetalle[1].

Von O. Hahn und F. Strassmann, Berlin-Dahlem.

Naturwiss. 27 (1939) 11

Was die „Trans-Urane" anbelangt, so sind diese Elemente ihren niedrigeren Homologen Rhenium, Osmium, Iridium, Platin zwar chemisch verwandt, mit ihnen aber nicht gleich. Ob sie etwa mit den noch niedrigeren Homologen Masurium, Ruthenium, Rhodium, Palladium chemisch gleich sind, wurde noch nicht geprüft. Daran konnte man früher ja nicht denken. Die Summe der Massenzahlen Ba + Ma, also z. B. 138 + 101, ergibt 239!

If they correspond to technetium, ruthenium, rhodium, palladium has not been tested. One could not have thought about this earlier. The sum of the Ba+Ma mass numbers (128+101) is 239!

Als Chemiker müßten wir aus den kurz dargelegten Versuchen das oben gebrachte Schema eigentlich umbenennen und statt Ra, Ac, Th die Symbole Ba, La, Ce einsetzen. Als der Physik in gewisser Weise nahestehende „Kernchemiker" können wir uns zu diesem, allen bisherigen Erfahrungen der Kernphysik widersprechenden, Sprung noch nicht entschließen. Es könnten doch noch vielleicht eine Reihe seltsamer Zufälle unsere Ergebnisse vorgetäuscht haben.

As chemist we should rename Ra, Ac, Th to Ba, La, Ce. As "nuclear chemists" close to physics, we cannot take this step, because it contradicts all present knowledge of nuclear physics.

January 28, 1939: Discovery of ^{140}Ba

Nachweis der Entstehung aktiver Bariumisotope aus Uran und Thorium durch Neutronenbestrahlung; Nachweis weiterer aktiver Bruchstücke bei der Uranspaltung[1].

Von OTTO HAHN und FRITZ STRASSMANN, Berlin-Dahlem.

A. Endgültiger Beweis für das Entstehen von Barium aus dem Uran.

In einer vor kurzem in dieser Zeitschrift erschienenen Mitteilung[1] haben wir angegeben, daß die bei der Bestrahlung des Urans mittels Neutronen entstehenden, anfangs für Radiumisotope gehaltenen

[1] Aus dem Kaiser Wilhelm-Institut für Chemie in Berlin-Dahlem. Eingegangen am 28. Januar 1939.

[1] O. HAHN u. F. STRASSMANN, Naturwiss. 27, 11 (1939).

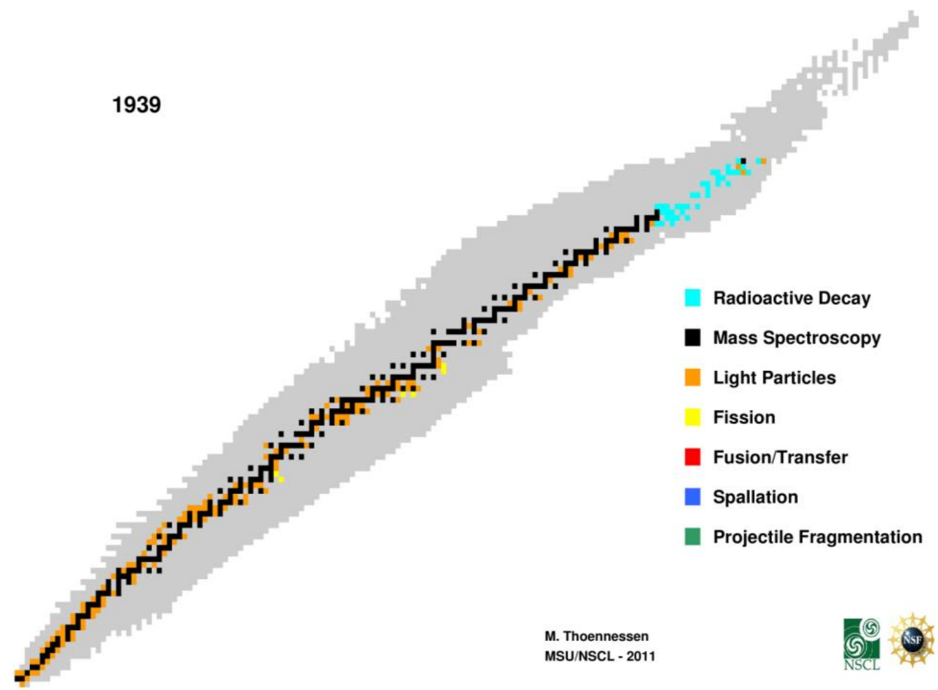
FEB. 11, 1939 NATURE

Disintegration of Uranium by Neutrons: a New Type of Nuclear Reaction

On the basis, however, of present ideas about the behaviour of heavy nuclei[6], an entirely different and essentially classical picture of these new disintegration processes suggests itself. On account of their close packing and strong energy exchange, the particles in a heavy nucleus would be expected to move in a collective way which has some resemblance to the movement of a liquid drop. If the movement is made sufficiently violent by adding energy, such a drop may divide itself into two smaller drops.

Jan. 16.

LISE MEITNER.
O. R. FRISCH.



Interesting quotes I:

At the suggestion of Dr. J. G. Hamilton and with his aid we have injected known amounts of the supposed eka-iodine into two hyperthyroid guinea pigs, on the chance that it might behave like iodine and be concentrated in the thyroid. The guinea pigs were killed about 4.5 hours after administration of the radioactive material and various portions of the bodies were examined for activity. In one animal the thyroid contained roughly 100 times as much activity as equal masses of other portions of the body.

D.R. Corson *et al.*, Phys. Rev. **57** (1940) 459

Interesting quotes II:

Irradiation was carried out by allowing relatively large quantities (about a pound each) of sodium chlorate or of sodium perchlorate to stand in the neighborhood of the target holder of the Berkeley 37-inch cyclotron for periods of six months or more while the cyclotron was in use for other purposes.

D.C. Grahame and H. J. Walke, Phys. Rev. **60** (1941) 909

Interesting quotes III:

McMillan[10] found a long-lived soft radiation from metal scraped from inside the cyclotron vacuum chamber and suggested it might be due to C^{14} formed by the reaction

$$D_1^2 + C_6^{13} \rightarrow C_6^{14} + H_1^1 + Q_2. \quad (2)$$

S. Ruben *et al.*, Phys. Rev. **59** (1941) 349

First spallation reaction: $^{63}Cu(d,4p9n)^{52}Fe$

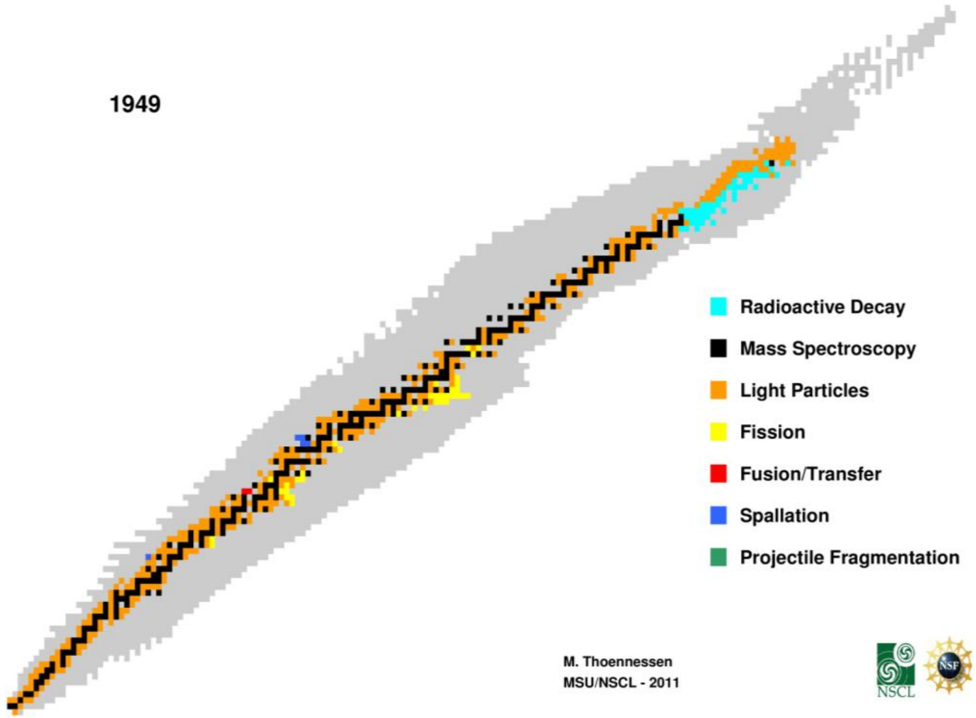
Products of High Energy Deuteron and Helium Ion Bombardments of Copper

D. R. MILLER, R. C. THOMPSON,[1] AND B. B. CUNNINGHAM
Department of Chemistry and Radiation Laboratory, University of California, Berkeley, California

June 17, 1948

TABLE I. Isotopes observed as products of the bombardment of natural copper with 190-Mev deuterons.

Isotope	Type of radiation[a]	Half-life Literature[b]	Half-life Observed	Yield[c] relative to Cu^{61}	Change in A and Z from Cu^{65}: A	Change in A and Z from Cu^{65}: Z
$_{30}Zn^{62}$	(K)	—	9.5 h.	0.035	−3	+1
Zn^{63}	(β^+)	38 m.	36 m.	0.05	−2	+1
$_{29}Cu^{60}$	(β^+)	24.5 m.[d]	*ca.* 25 m.	0.3	−5	0
Cu^{61}	β^+, (K)	3.4 h.	3.3 h.	1.0	−4	0
Cu^{62}	β^+	10.5 m.	*ca.* 11 m.	2.3	−3	0
Cu^{64}	(β^+, β^-, K)	12.8 h.	13 h.	0.6	−1	0
$_{28}Ni^{57}$	β^+	36 h.	37 h.	0.04	−8	−1
Ni^{65}	β^-	2.6 h.[e]	2.5 h.	0.04	0	−1
$_{27}Co^{55}$	β^+	18.2 h.	17 h.	0.04	−10	−2
Co^{61}	β^-	1.8 h.[f]	1.7 h.	0.14	−4	−2
$_{26}Fe^{52}$	β^+	—	7.8 h.	0.003	−13	−3
Fe^{53}	(β^+)	8.9 m.	9 m.	0.07	−12	−3
Fe^{59}	β^-	47 d.	49 d.	0.07	−6	−3
$_{25}Mn^{51}$	(β^+)	46 m.	45 m.	0.04[g]	−14	−4
Mn^{52}	β^+, (K)	6.5 d.	6 d.	0.1	−13	−4
Mn^{56}	β^-	2.59 h.	2.5 h.	0.15	−9	−4
$_{24}Cr^{49}$	β^+	41.9 m.	41 m.	0.01	−16	−5
Cr^{51}	(K)	26.5 d.	27 d.	*ca.* 0.02[g,h]	−14	−5
$_{23}V^{48}$	β^+, (K)	16 d.	16 d.	0.05[g]	−17	−6
$_{17}Cl^{38}$	β^-	37 m.	38 m.	0.0005	−27	−12
$_{15}P^{32}$	(β^-)	14.30 d.	15 d.	0.0005[g]	−33	−14



Fusion-evaporation

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

Phys. Rev. 80 (1950) 486

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.

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

Phys. Rev. 81 (1951) 154

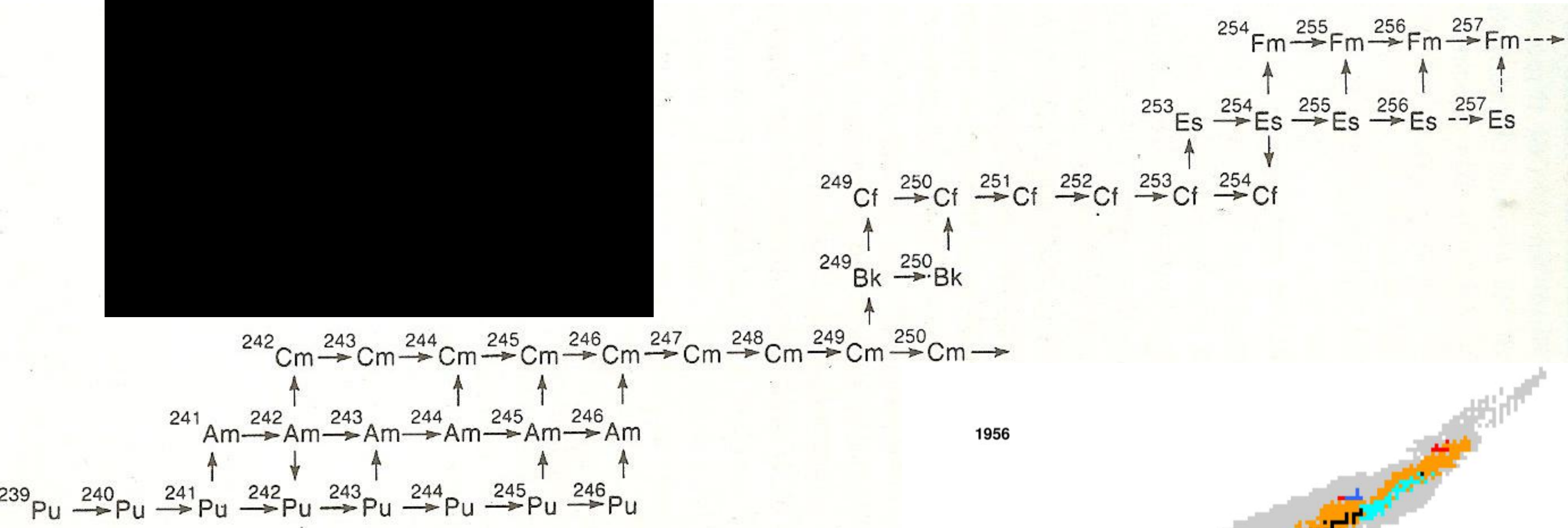
^{248}Cf

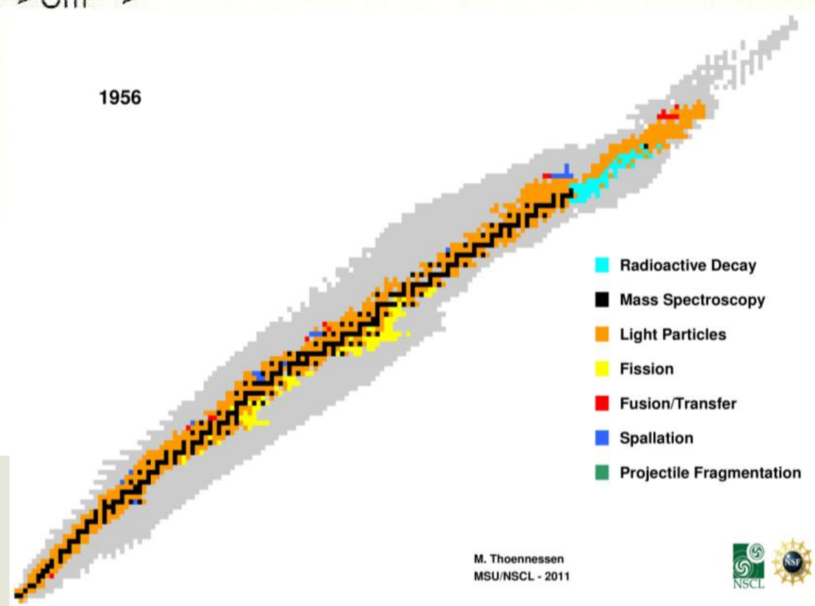
THE recent production and identification[1] of isotopes of elements with atomic numbers up to six higher than the target element through bombardment with approximately 120-Mev carbon (+6) ions made it seem worth while to apply this technique to the transuranium region.

Nuclear explosions

http://www.youtube.com/watch?v=-22tna7KHzI

Rapid neutron capture





“The elements beyond uranium”,
G.T. Seaborg and W.D. Loveland (Wiley1990)

1 GeV p+U: Light neutron-rich isotopes

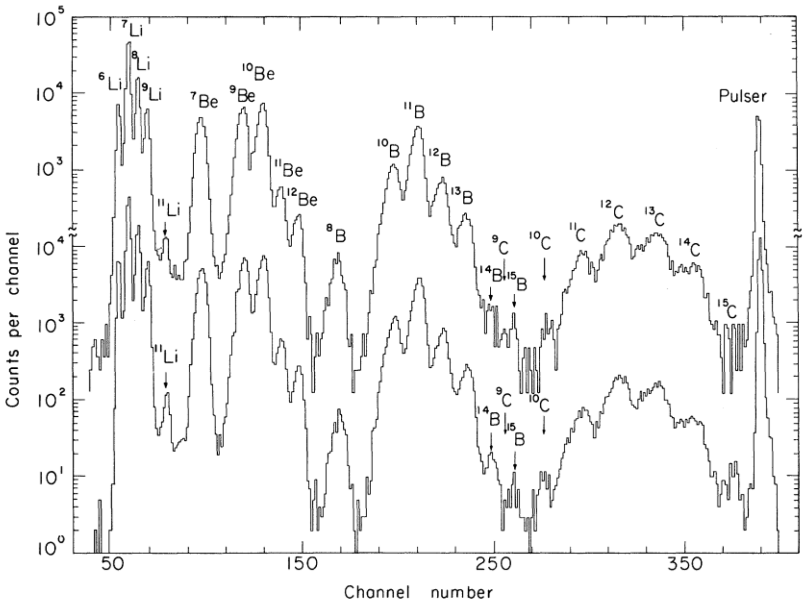
VOLUME 17, NUMBER 25 PHYSICAL REVIEW LETTERS 19 DECEMBER 1966

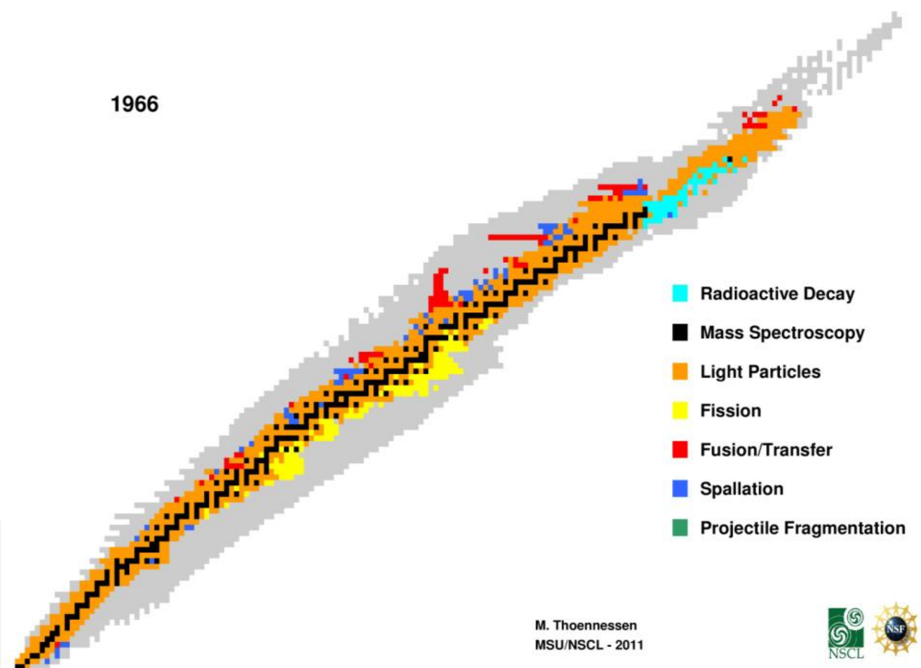
NEW ISOTOPES: ^{11}Li, ^{14}B, AND ^{15}B†

A. M. Poskanzer, S. W. Cosper, and Earl K. Hyde
Nuclear Chemistry Division, Lawrence Radiation Laboratory, University of California, Berkeley, California

and

Joseph Cerny
Department of Chemistry and Lawrence Radiation Laboratory, University of California, Berkeley, California
(Received 14 November 1966)





ISOL: Isotope separation on-line

Short-Lived Krypton Isotopes and Their Daughter Substances

O. Kofoed-Hansen and K. O. Nielsen
Institute for Theoretical Physics, University of Copenhagen, Copenhagen, Denmark
(Received February 9, 1951)

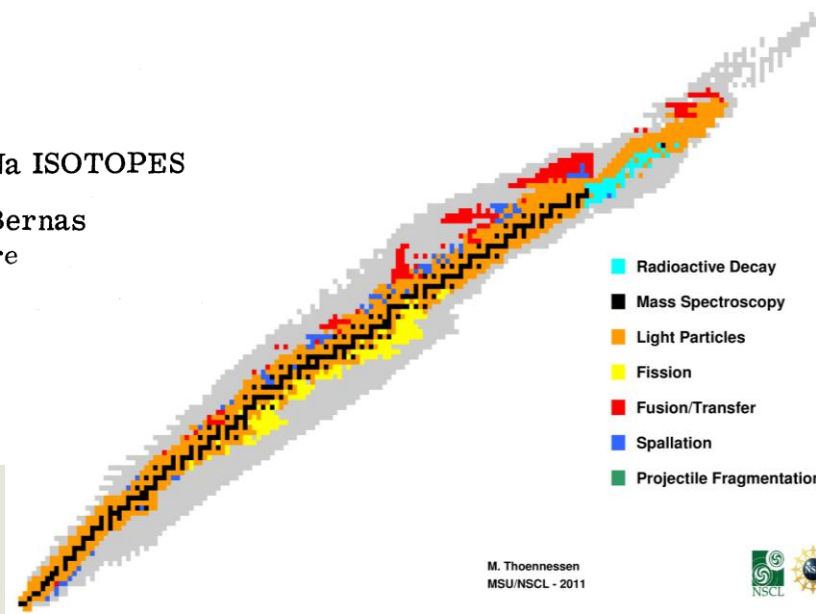
THE isotopes Kr[89], Kr[90], Kr[91], and their daughter substances have been investigated. Krypton formed in fission of uranium was pumped through a 10-m long tube directly from the cyclotron into the ion source of the isotope separator. The cyclotron and the isotope separator were operated simultaneously, and the counting could begin immediately after the interruption of the separation. The rubidium and strontium daughter substances were separated chemically; strontium was precipitated as carbonate. Half-lives were measured and an absorption analysis of the radiations was carried out. The results are given in Table I.

Phys. Rev. 82 (1951) 96

ISOTOPIC DISTRIBUTION OF SODIUM FRAGMENTS EMITTED IN HIGH-ENERGY NUCLEAR REACTIONS. IDENTIFICATION OF ^{27}Na AND POSSIBLE EXISTENCE OF HEAVIER Na ISOTOPES

R. Klapisch, C. Philippe, J. Suchorzewska,* C. Detraz, and R. Bernas
Institut de Physique Nucléaire and Centre de Spectrométrie Nucléaire et de Spectrométrie de Masse, Orsay, France
(Received 29 January 1968)

Phys. Rev. Lett. 20 (1968) 740



Projectile fragmentation

VOLUME 43, NUMBER 25 PHYSICAL REVIEW LETTERS 17 DECEMBER 1979

Production of Neutron-Rich Nuclides by Fragmentation of 212-MeV/amu ^{48}Ca

G. D. Westfall, T. J. M. Symons, D. E. Greiner, H. H. Heckman,
P. J. Lindstrom, J. Mahoney, A. C. Shotter,[a] and D. K. Scott
Nuclear Science Division, Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720

and

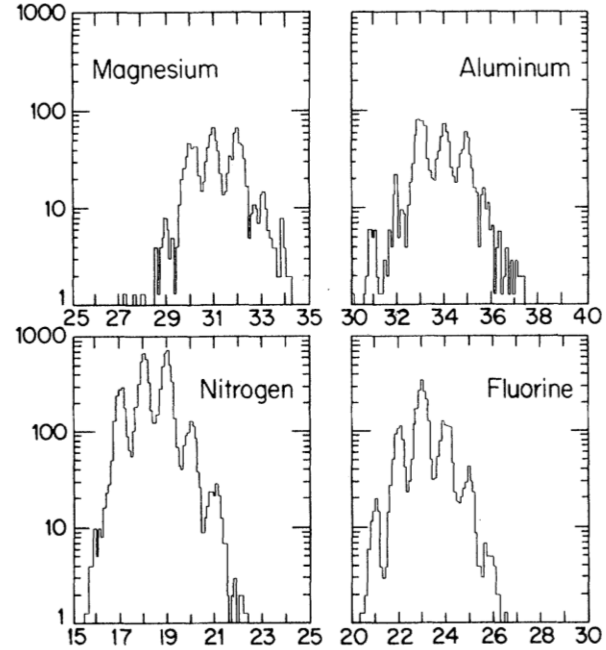
H. J. Crawford and C. McParland
Space Sciences Laboratory, University of California, Berkeley, California 94720

and

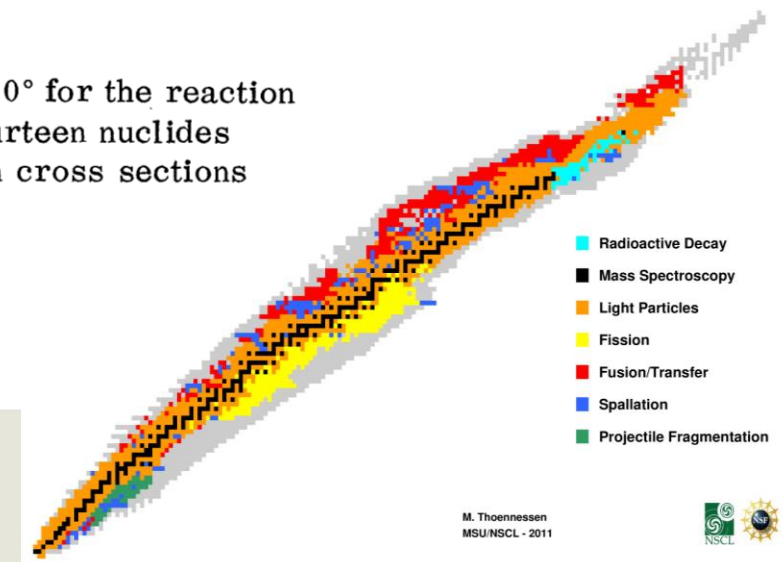
T. C. Awes and C. K. Gelbke
Heavy Ion Laboratory, Michigan State University, East Lansing, Michigan 48824

and

J. M. Kidd
U. S. Naval Research Laboratory, Washington, D. C. 20375
(Received 15 October 1979)



Yields of neutron-rich projectile fragments have been measured at 0° for the reaction of 212-MeV/amu ^{48}Ca ions on an 890-mg-cm^{-2} beryllium target. Fourteen nuclides have been observed for the first time. The systematics of production cross sections are discussed.



Secondary beams

Observation of ^{10}He

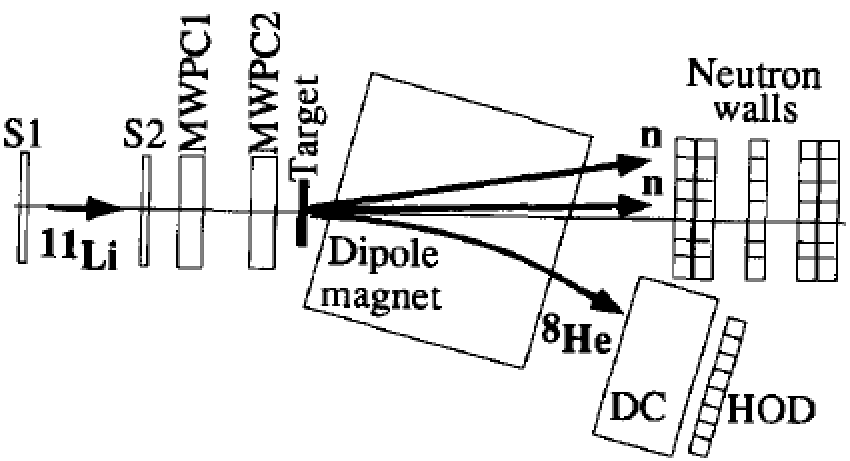
A.A. Korsheninnikov [a], K. Yoshida [b], D.V. Aleksandrov [a], N. Aoi [c], Y. Doki [c], N. Inabe [b], M. Fujimaki [b], T. Kobayashi [b], H. Kumagai [b], C.-B. Moon [d], E.Yu. Nikolskii [a], M.M. Obuti [b], A.A. Ogloblin [a], A. Ozawa [b], S. Shimoura [e], T. Suzuki [b], I. Tanihata [b], Y. Watanabe [b], M. Yanokura [b]

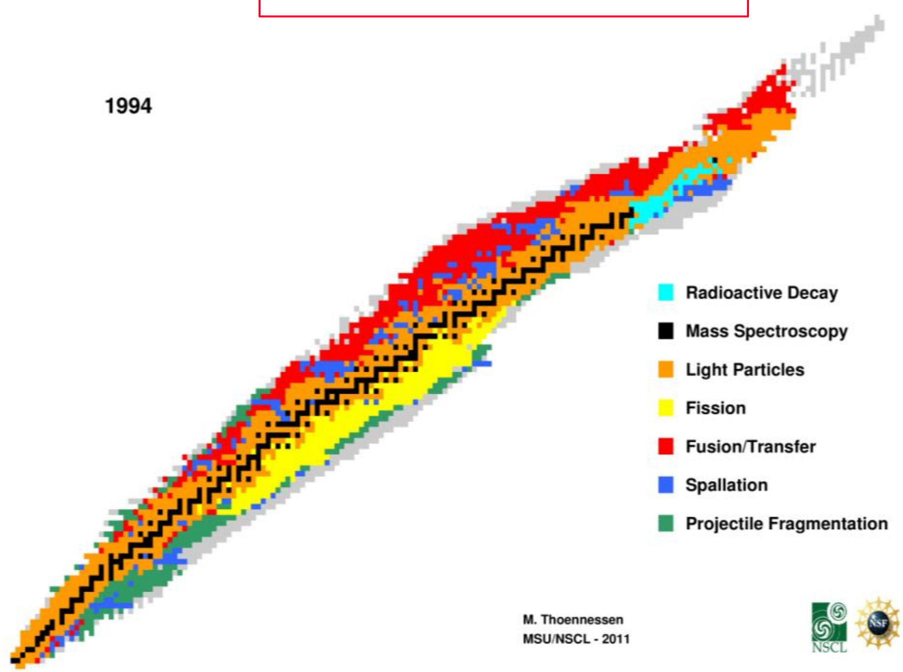
[a] *Kurchatov Institute, 123182 Moscow, Russia*
[b] *RIKEN, Hirosawa, Wako, Saitama 351-01, Japan*
[c] *Department of Physics, University of Tokyo, Hongo, Tokyo 113, Japan*
[d] *Department of Physics, Hoseo University, Chungnam 337-850, South Korea*
[e] *Department of Physics, Rikkyo University, Toshima, Tokyo 171, Japan*

Received 15 October 1993; revised manuscript received 21 February 1994
Editor: J.P. Schiffer

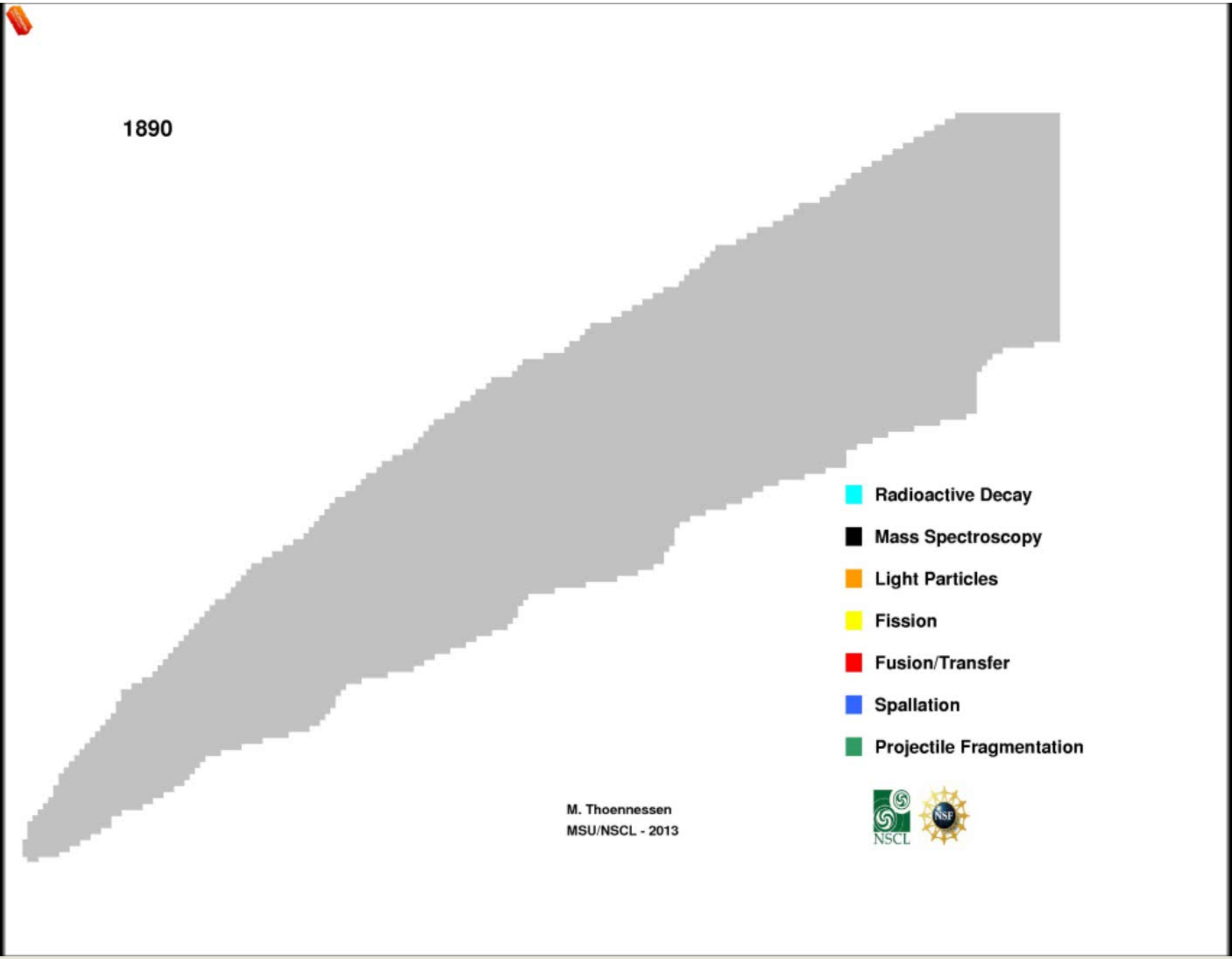
$$^{18}\mathrm{O} \longrightarrow {}^{11}\mathrm{Li}+\mathrm{C} \longrightarrow {}^{10}\mathrm{He}+\mathrm{X}$$

$$^{10}\mathrm{He} \longrightarrow {}^{8}\mathrm{He}+\mathrm{n}+\mathrm{n}$$



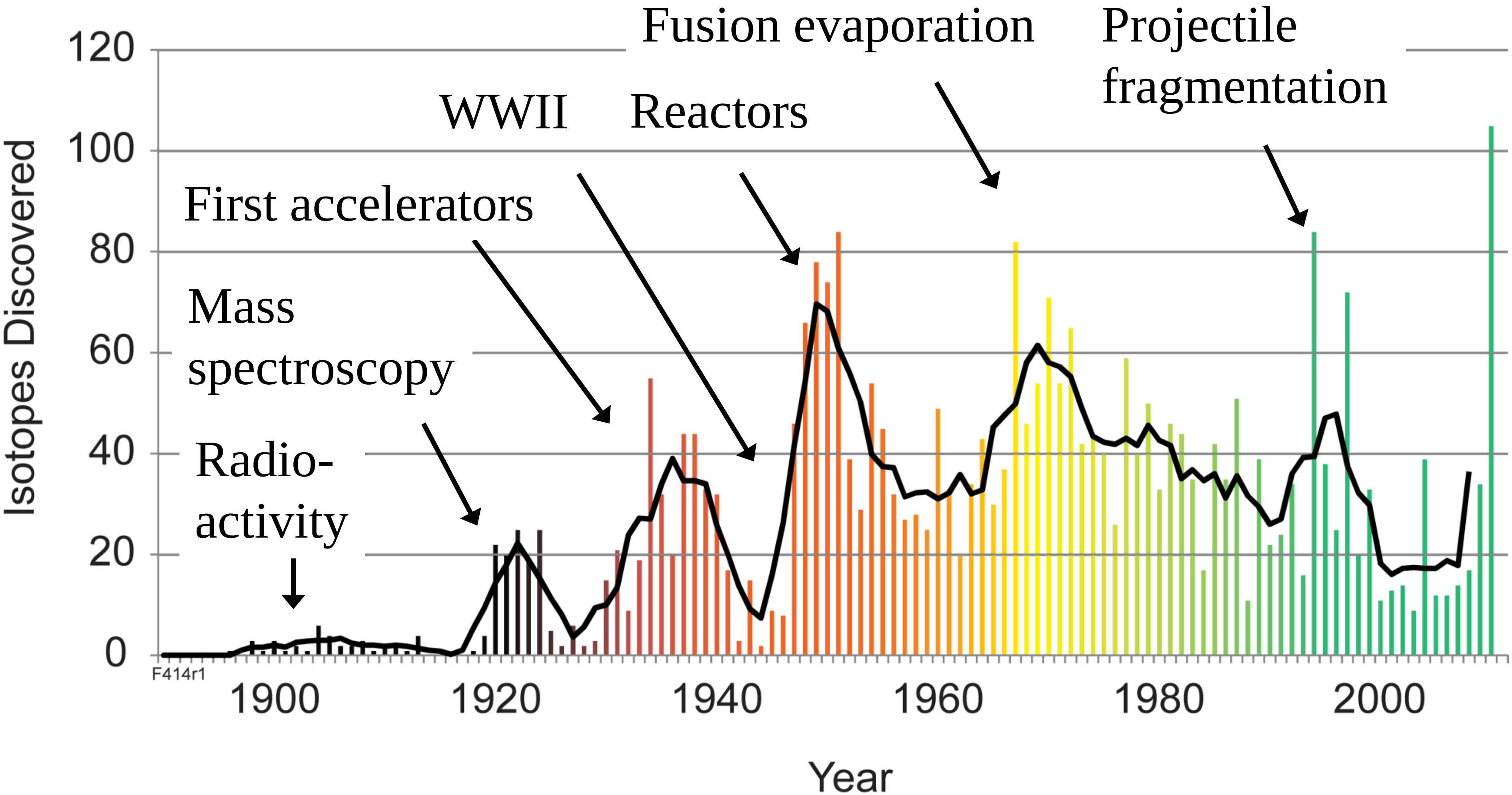


Timeline movie



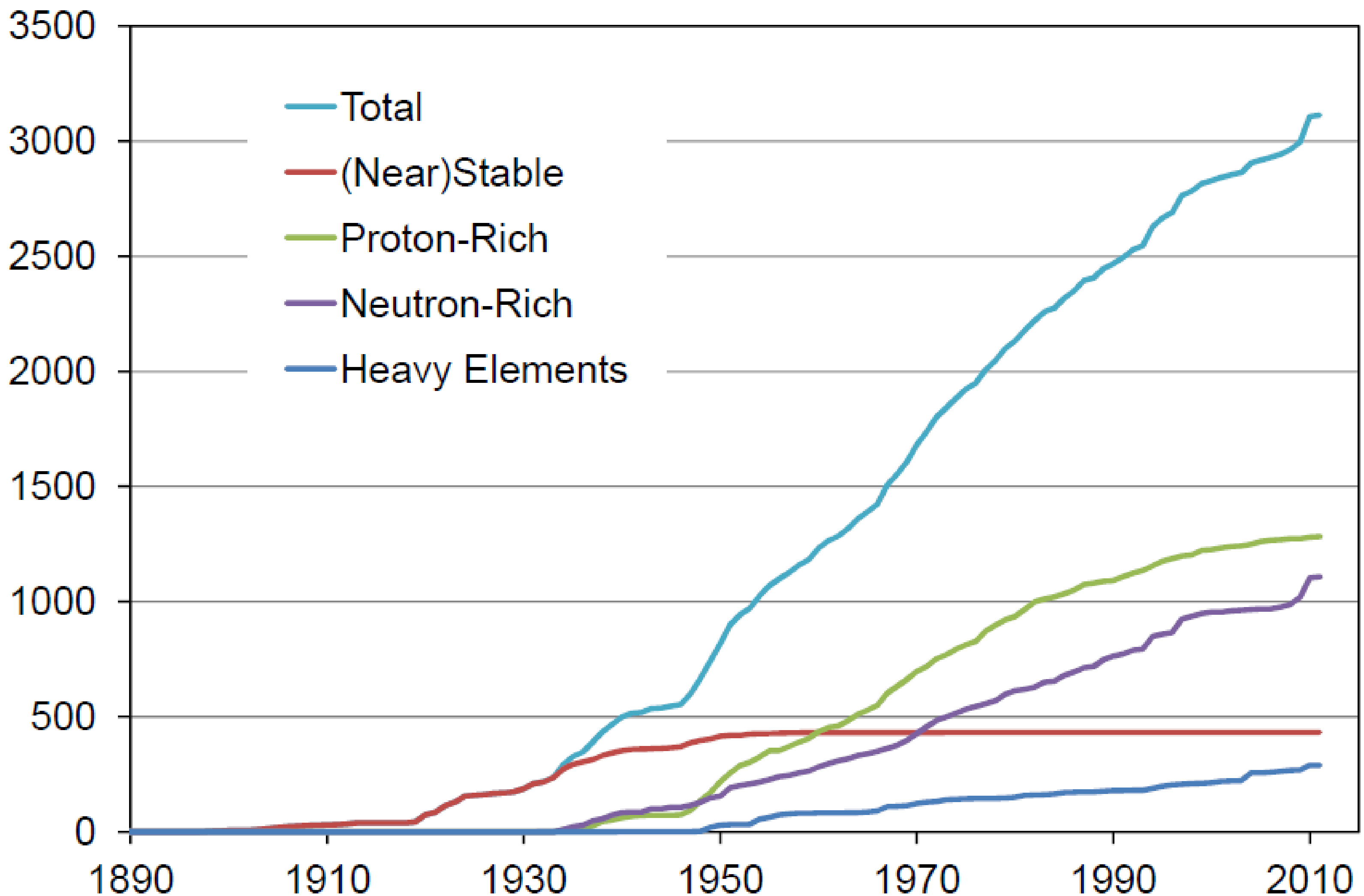
http://www.youtube.com/watch?v=ZvuMRwvJhHw

Discoveries per year

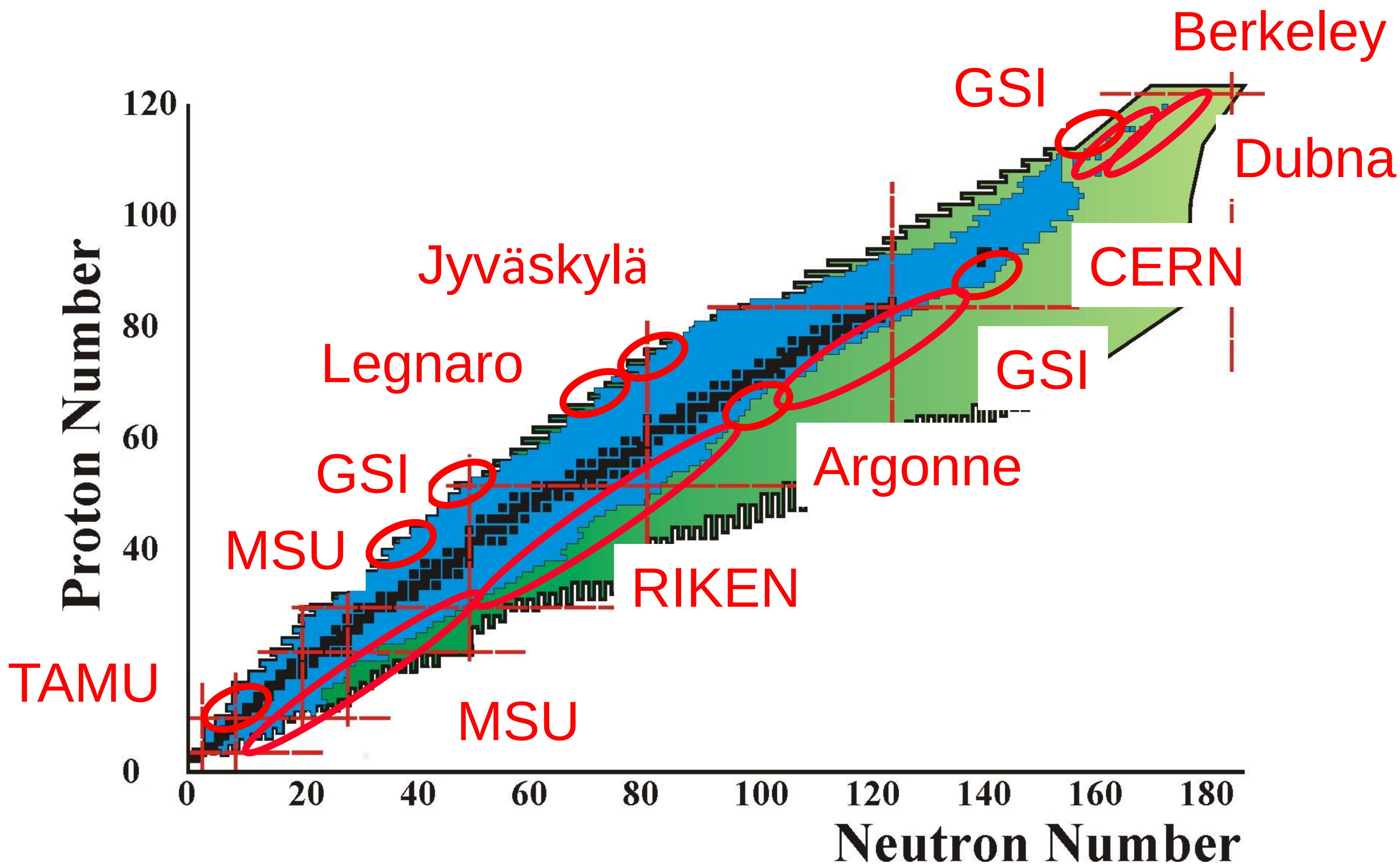


M. T. and B.M. Sherrill, Nature 473 (2011) 25

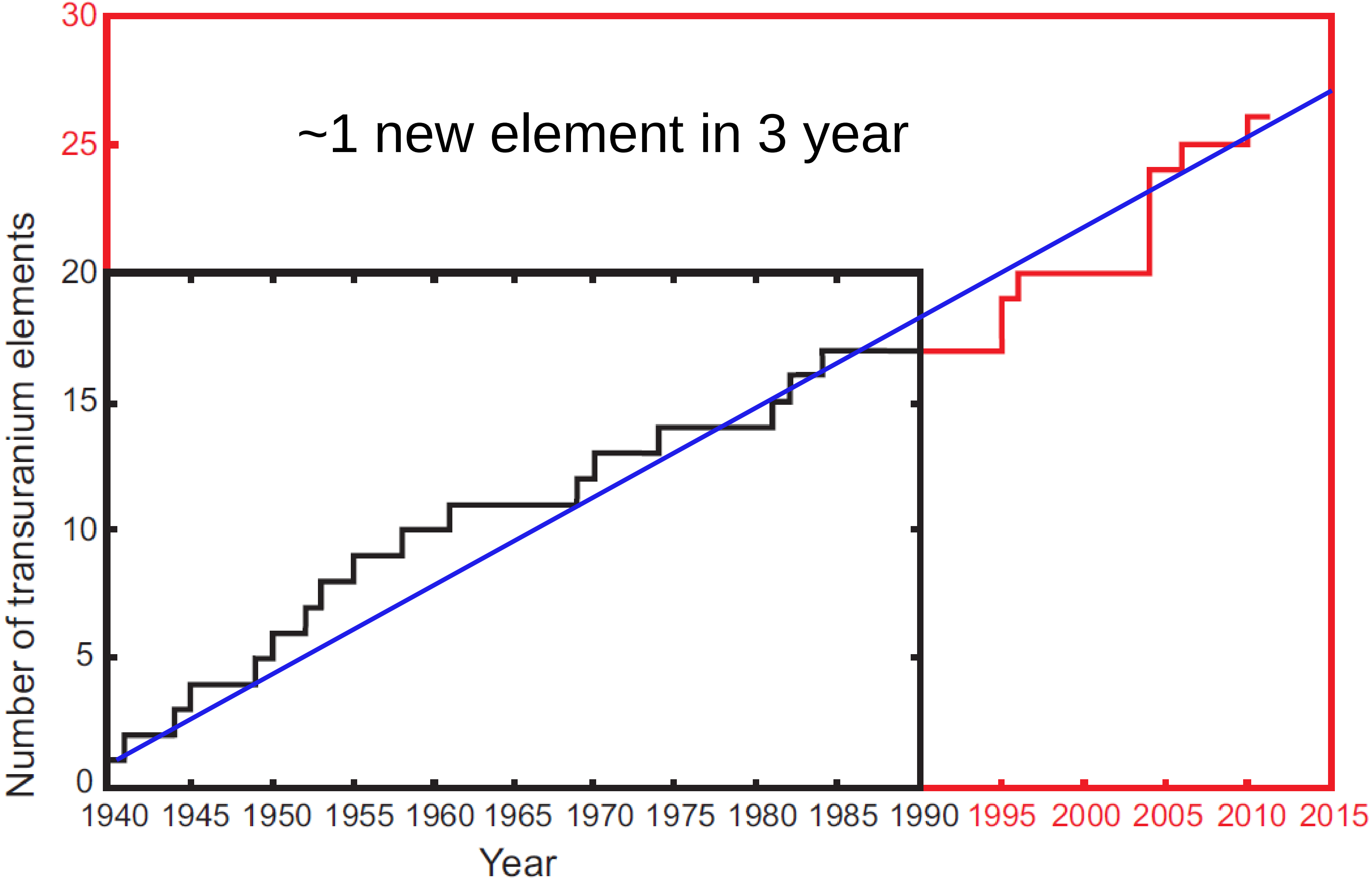
Nuclide discovery by region



Discoveries since 2009



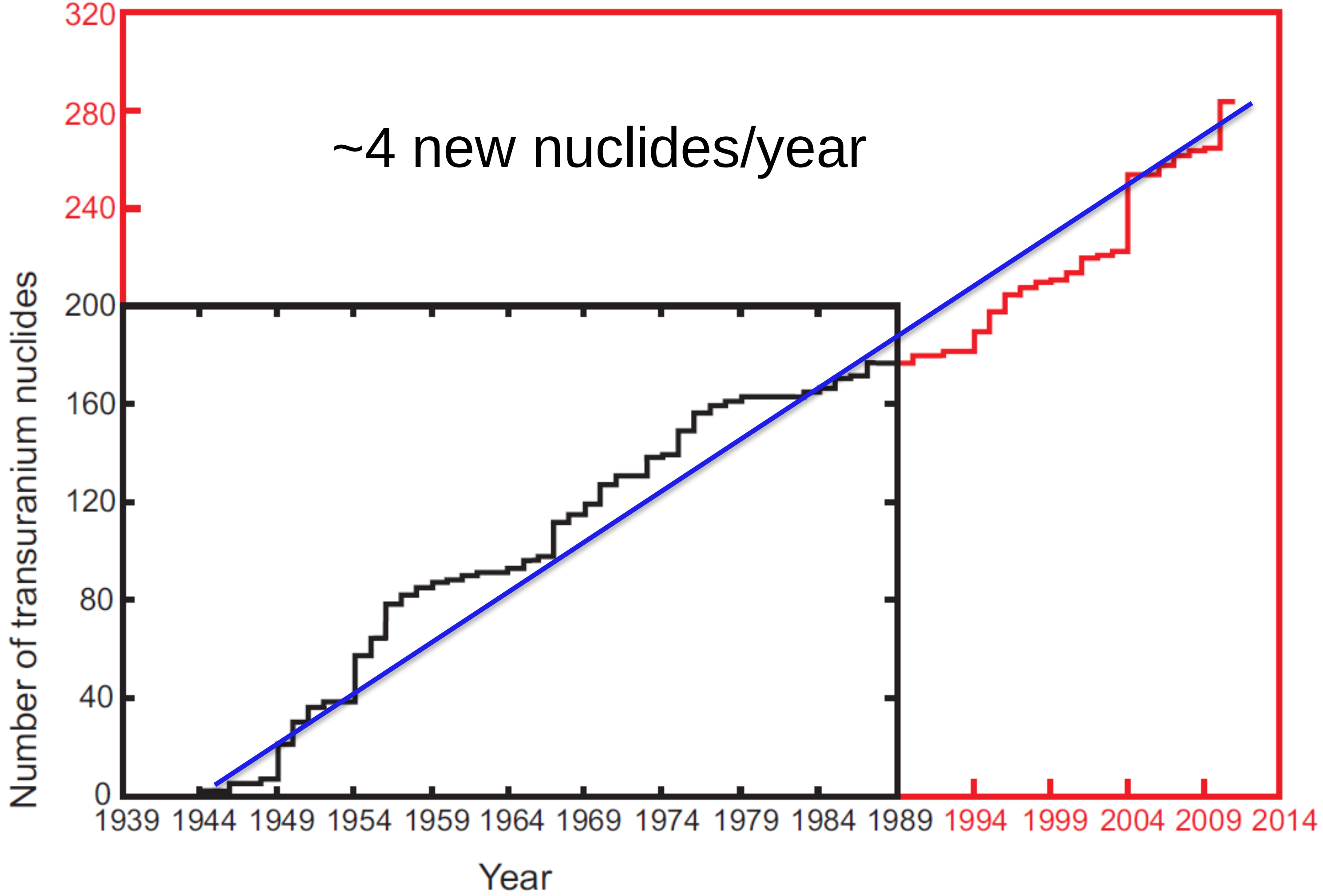
Discovery of superheavy elements



National Science Foundation
Michigan State University

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)

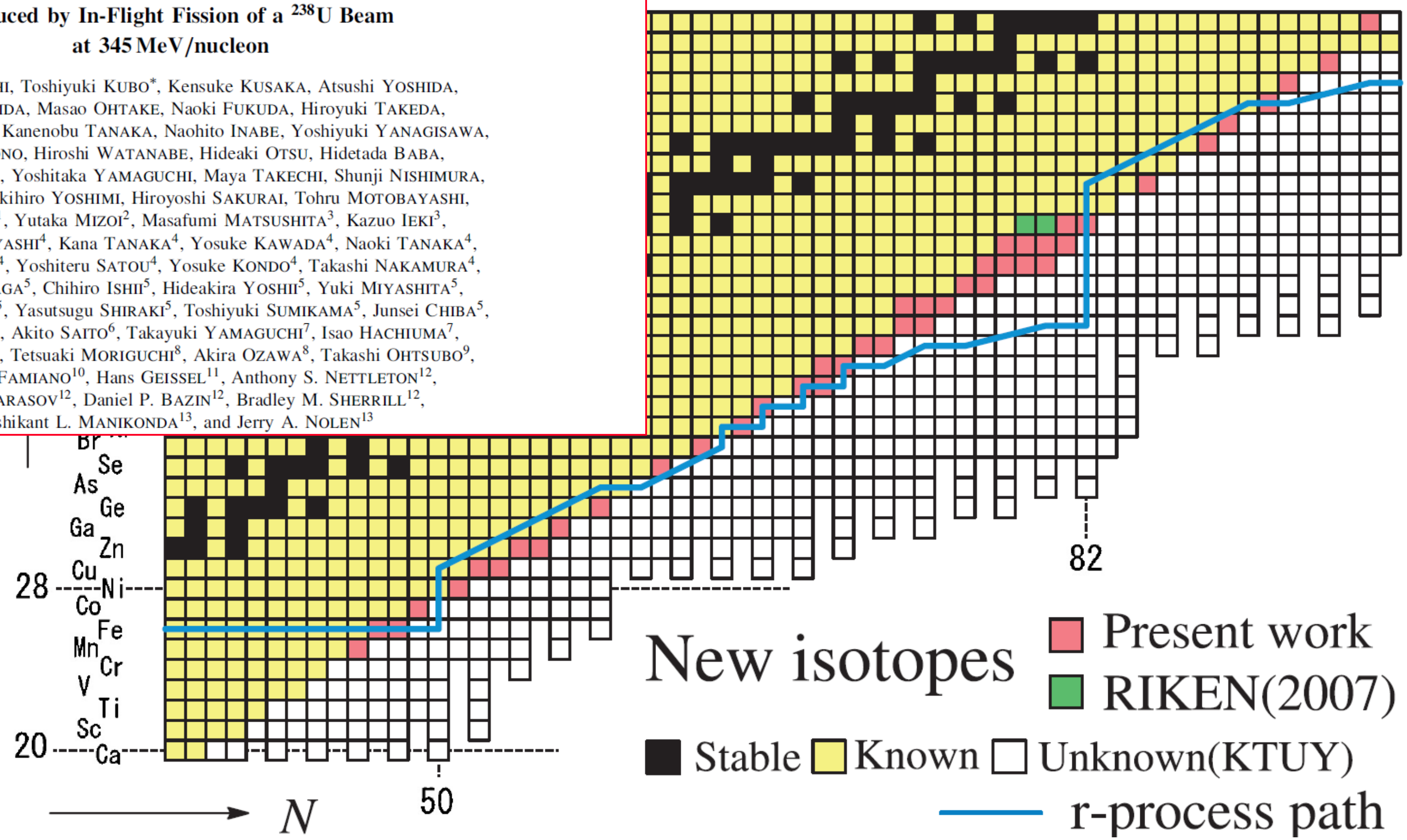
RIKEN 2010

Journal of the Physical Society of Japan
Vol. 79, No. 7, July, 2010, 073201

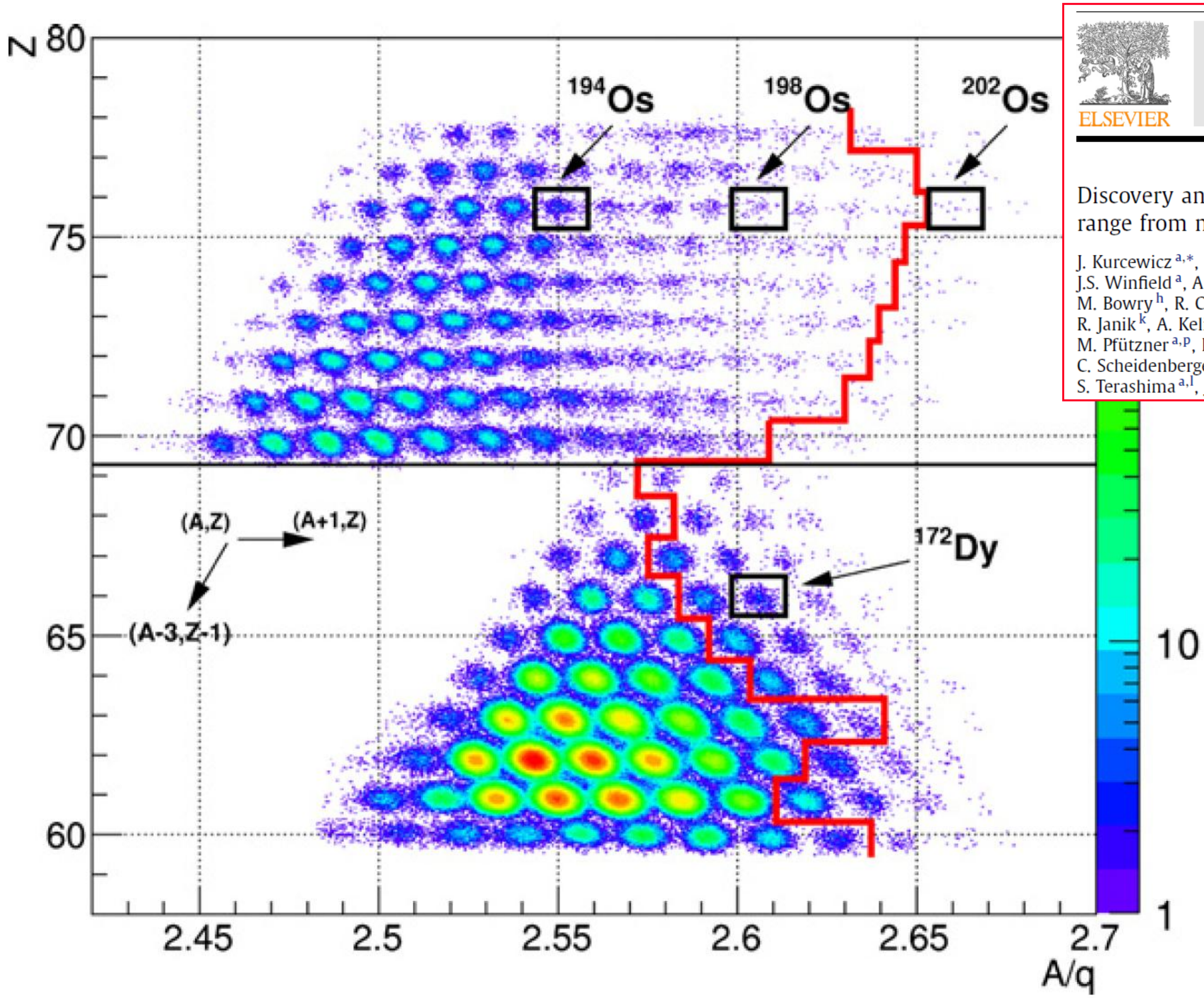
LETTERS

Identification of 45 New Neutron-Rich Isotopes Produced by In-Flight Fission of a ^{238}U Beam at 345 MeV/nucleon

Tetsuya OHNISHI, Toshiyuki KUBO*, Kensuke KUSAKA, Atsushi YOSHIDA, Koichi YOSHIDA, Masao OHTAKE, Naoki FUKUDA, Hiroyuki TAKEDA, Daisuke KAMEDA, Kanenobu TANAKA, Naohito INABE, Yoshiyuki YANAGISAWA, Yasuyuki GONO, Hiroshi WATANABE, Hideaki OTSU, Hidetada BABA, Takashi ICHIHARA, Yoshitaka YAMAGUCHI, Maya TAKECHI, Shunji NISHIMURA, Hideki UENO, Akihiro YOSHIMI, Hiroyoshi SAKURAI, Tohru MOTOBAYASHI, Taro NAKAO[1], Yutaka MIZOI[2], Masafumi MATSUSHITA[3], Kazuo IEKI[3], Nobuyuki KOBAYASHI[4], Kana TANAKA[4], Yosuke KAWADA[4], Naoki TANAKA[4], Shigeki DEGUCHI[4], Yoshiteru SATOU[4], Yosuke KONDO[4], Takashi NAKAMURA[4], Kenta YOSHINAGA[5], Chihiro ISHII[5], Hideakira YOSHII[5], Yuki MIYASHITA[5], Nobuya UEMATSU[5], Yasutsugu SHIRAKI[5], Toshiyuki SUMIKAMA[5], Junsei CHIBA[5], Eiji IDEGUCHI[6], Akito SAITO[6], Takayuki YAMAGUCHI[7], Isao HACHIUMA[7], Takeshi SUZUKI[7], Tetsuaki MORIGUCHI[8], Akira OZAWA[8], Takashi OHTSUBO[9], Michael A. FAMIANO[10], Hans GEISSEL[11], Anthony S. NETTLETON[12], Oleg B. TARASOV[12], Daniel P. BAZIN[12], Bradley M. SHERRILL[12], Shashikant L. MANIKONDA[13], and Jerry A. NOLEN[13]



GSI 2012



Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

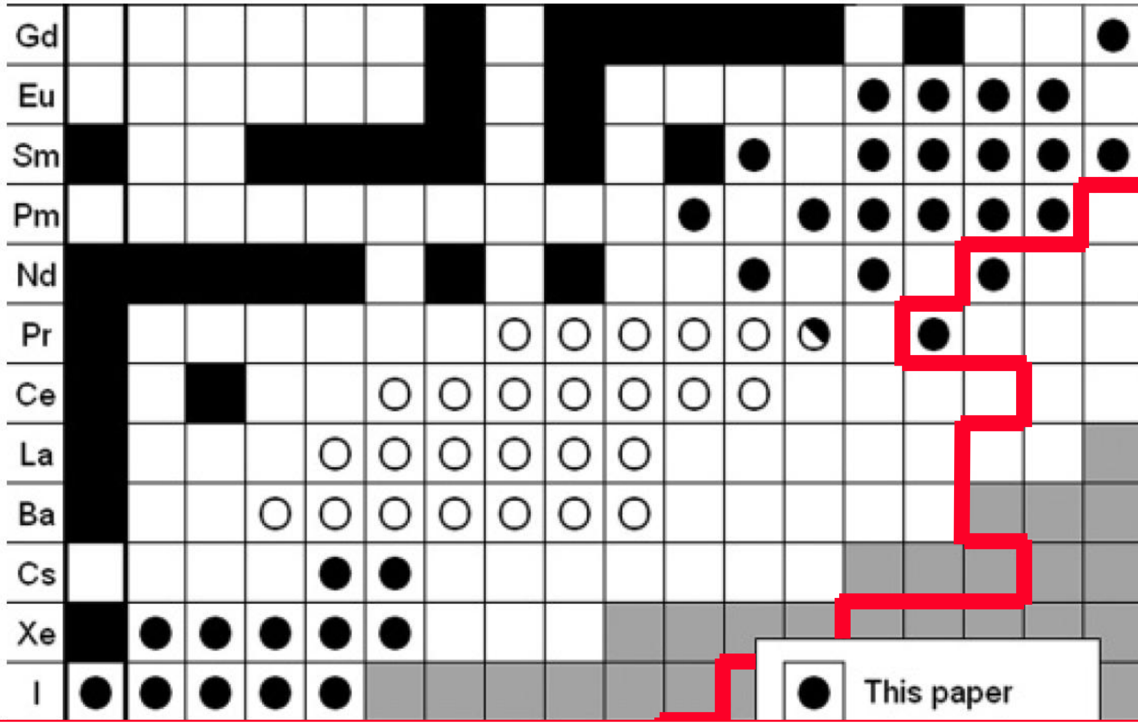
Discovery and cross-section measurement of neutron-rich isotopes in the element range from neodymium to platinum with the FRS

J. Kurcewicz[a,*], F. Farinon[a,b,1], H. Geissel[a,b], S. Pietri[a], C. Nociforo[a], A. Prochazka[a,b], H. Weick[a], J.S. Winfield[a], A. Estradé[a,c], P.R.P. Allegro[d], A. Bail[e], G. Bélier[e], J. Benlliure[f], G. Benzoni[g], M. Bunce[h], M. Bowry[h], R. Caballero-Folch[i], I. Dillmann[a,b], A. Evdokimov[a,b], J. Gerl[a], A. Gottardo[j], E. Gregor[a], R. Janik[k], A. Kelić-Heil[a], R. Knöbel[a], T. Kubo[l], Yu.A. Litvinov[a,m], E. Merchan[a,n], I. Mukha[a], F. Naqvi[a,o], M. Pfützner[a,p], M. Pomorski[p], Zs. Podolyák[h], P.H. Regan[h], B. Riese[a,b], M.V. Ricciardi[a], C. Scheidenberger[a,b], B. Sitar[k], P. Spiller[a], J. Stadlmann[a], P. Strmen[k], B. Sun[b,q], I. Szarka[k], J. Taïeb[e], S. Terashima[a,l], J.J. Valiente-Dobón[j], M. Winkler[a], Ph. Woods[r]

Using the high-resolution performance of the fragment separator FRS at GSI we have discovered 60 new neutron-rich isotopes…

Received 1 December 2011

ANL 2012



Received 1 July 2011

PHYSICAL REVIEW C **85**, 045805 (2012)

Mass measurements near the *r*-process path using the Canadian Penning Trap mass spectrometer

J. Van Schelt,[1,2] D. Lascar,[3,2] G. Savard,[1,2] J. A. Clark,[2] S. Caldwell,[1,2] A. Chaudhuri,[4,2] J. Fallis,[4,2] J. P. Greene,[2] A. F. Levand,[2] G. Li,[5,2] K. S. Sharma,[4] M. G. Sternberg,[1,2] T. Sun,[2] and B. J. Zabransky[2]

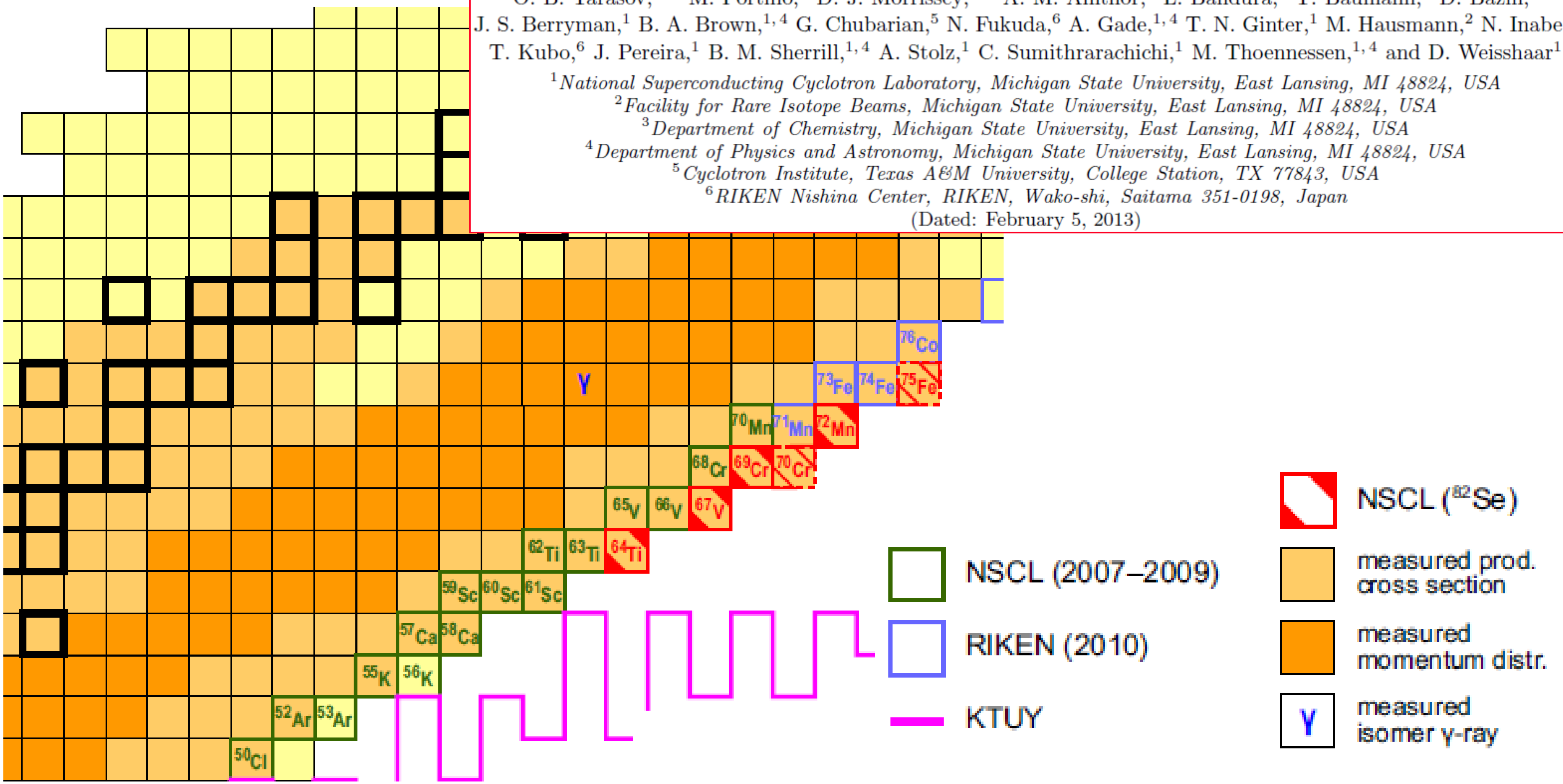
MSU: 2013

Production cross sections from ^{82}Se fragmentation as indications of shell effects in neutron-rich isotopes close to the drip-line

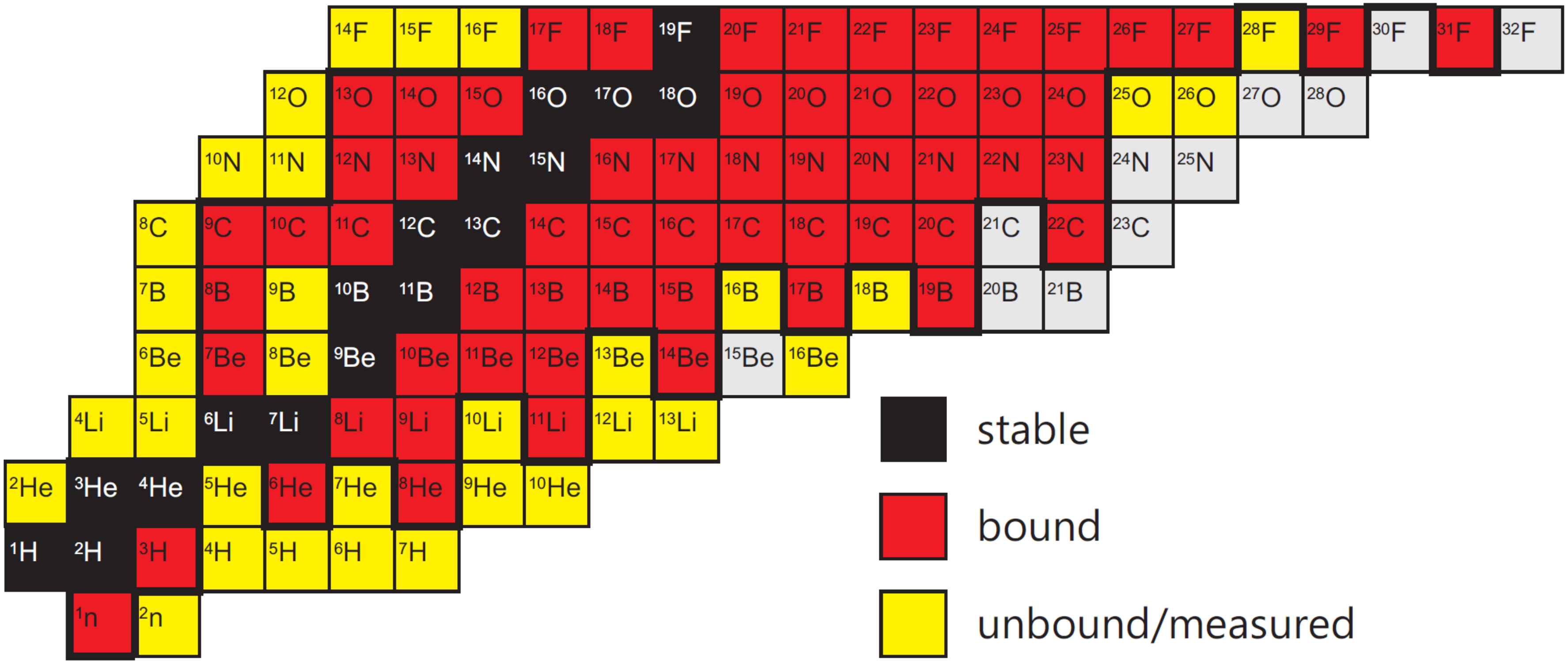
O. B. Tarasov,[1,*] M. Portillo,[2] D. J. Morrissey,[1,3] A. M. Amthor,[2] L. Bandura,[2] T. Baumann,[1] D. Bazin,[1] J. S. Berryman,[1] B. A. Brown,[1,4] G. Chubarian,[5] N. Fukuda,[6] A. Gade,[1,4] T. N. Ginter,[1] M. Hausmann,[2] N. Inabe,[6] T. Kubo,[6] J. Pereira,[1] B. M. Sherrill,[1,4] A. Stolz,[1] C. Sumithrarachichi,[1] M. Thoennessen,[1,4] and D. Weisshaar[1]

[1]*National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824, USA*
[2]*Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI 48824, USA*
[3]*Department of Chemistry, Michigan State University, East Lansing, MI 48824, USA*
[4]*Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48824, USA*
[5]*Cyclotron Institute, Texas A&M University, College Station, TX 77843, USA*
[6]*RIKEN Nishina Center, RIKEN, Wako-shi, Saitama 351-0198, Japan*

(Dated: February 5, 2013)



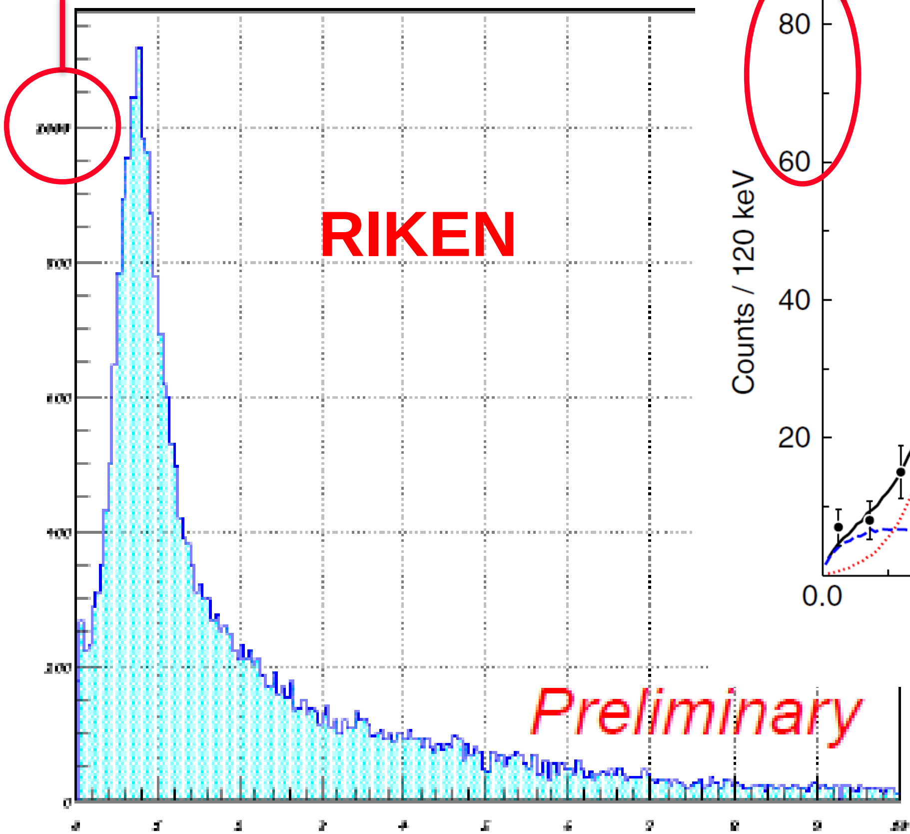
Nuclide beyond the dripline

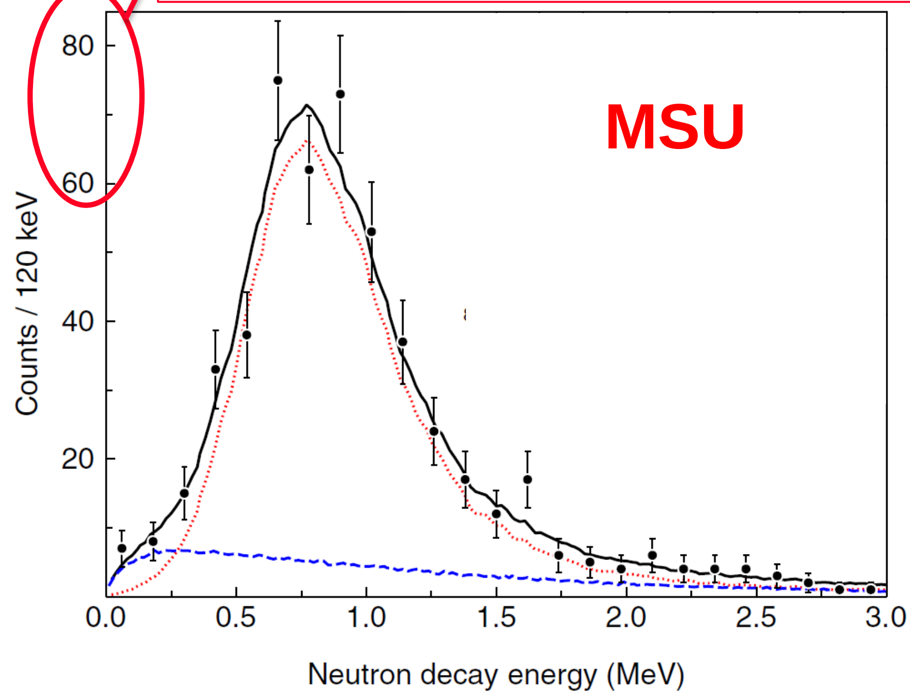


Neutron unbound ^{25}O

>1000counts/50keV in 2012

~60counts/100keV in 2008

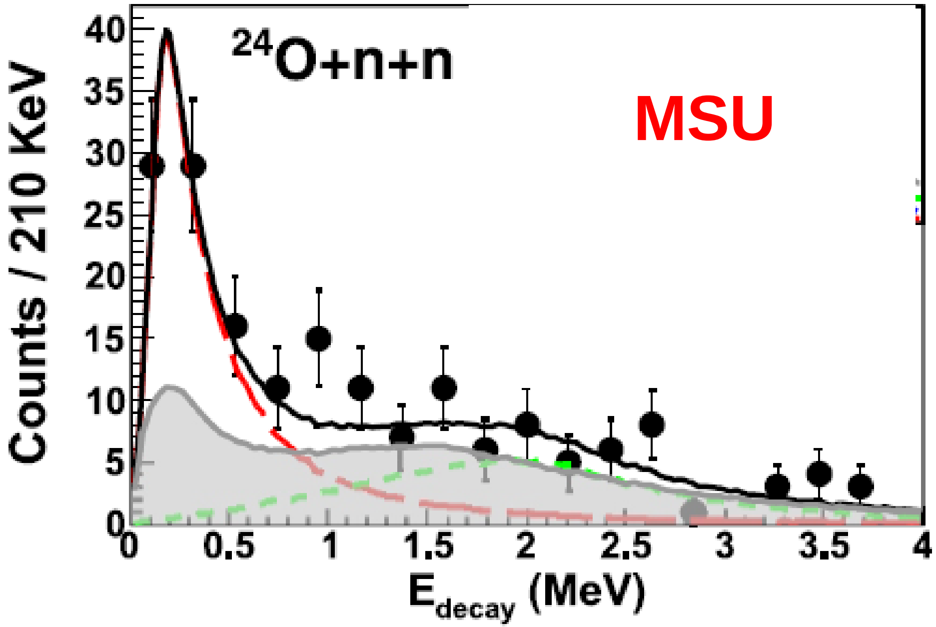




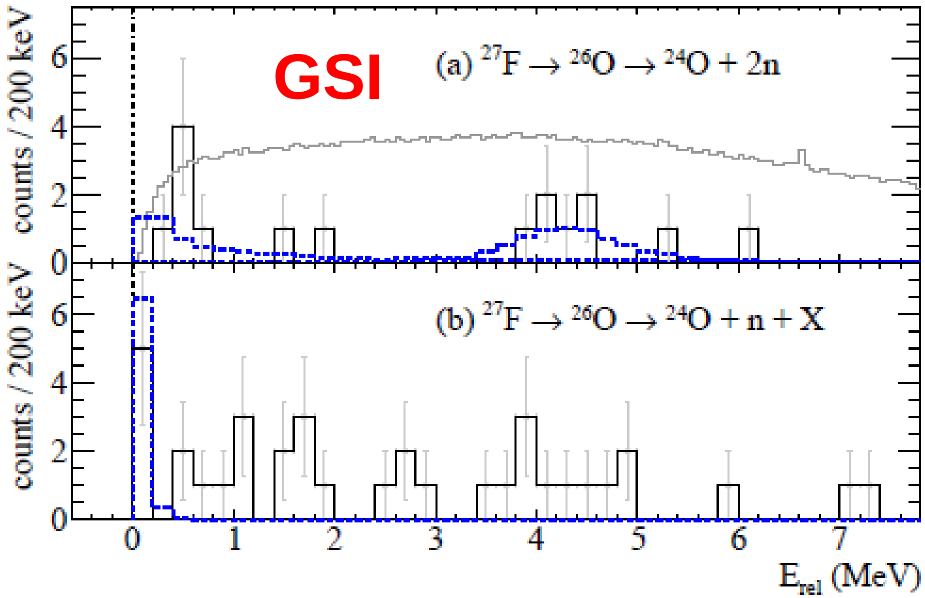
C.R.Hoffman et al.,
Phys. Rev. Lett. **100** (2008) 152502

Y. Kondo et al., COMEX4, Oct.2012

Reconstructing ^{26}O



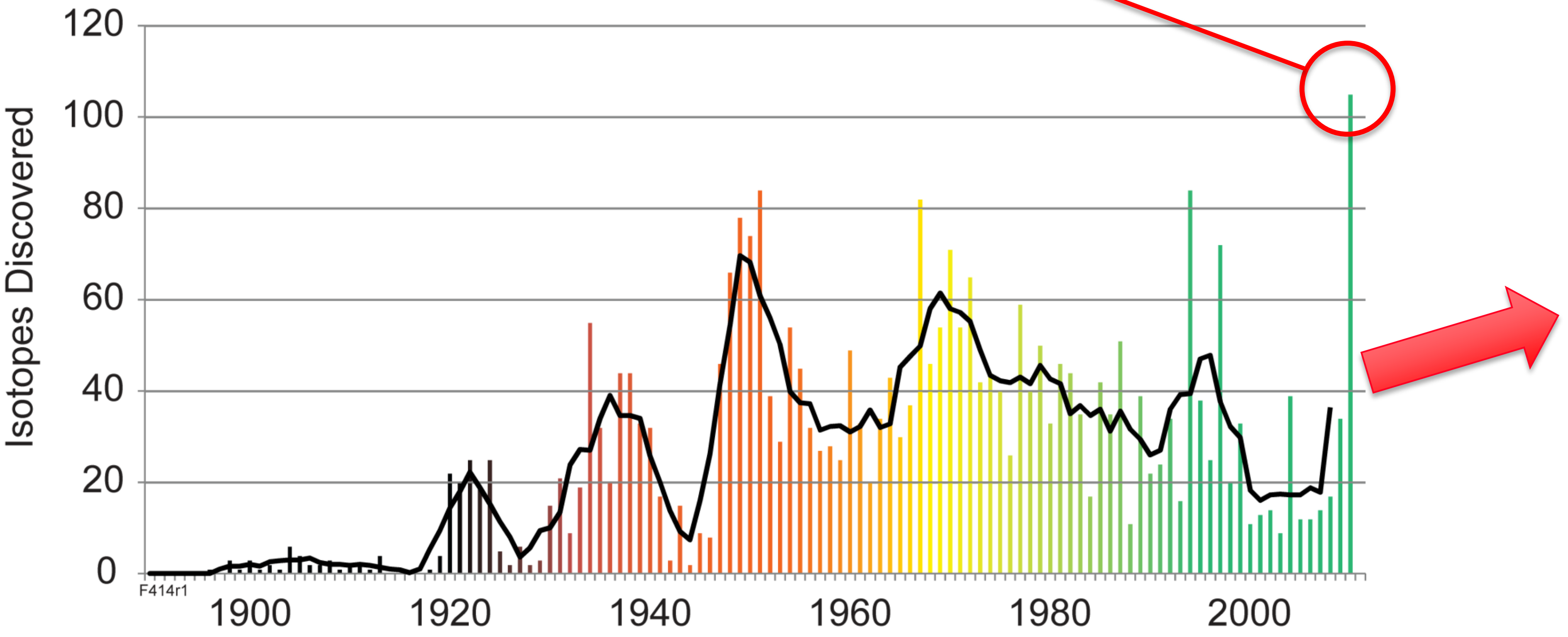
C. Caesar et al., arXiv:1209.0156



E. Lunderberg et al.,
Phys. Rev. Lett. **108** (2012) 142503

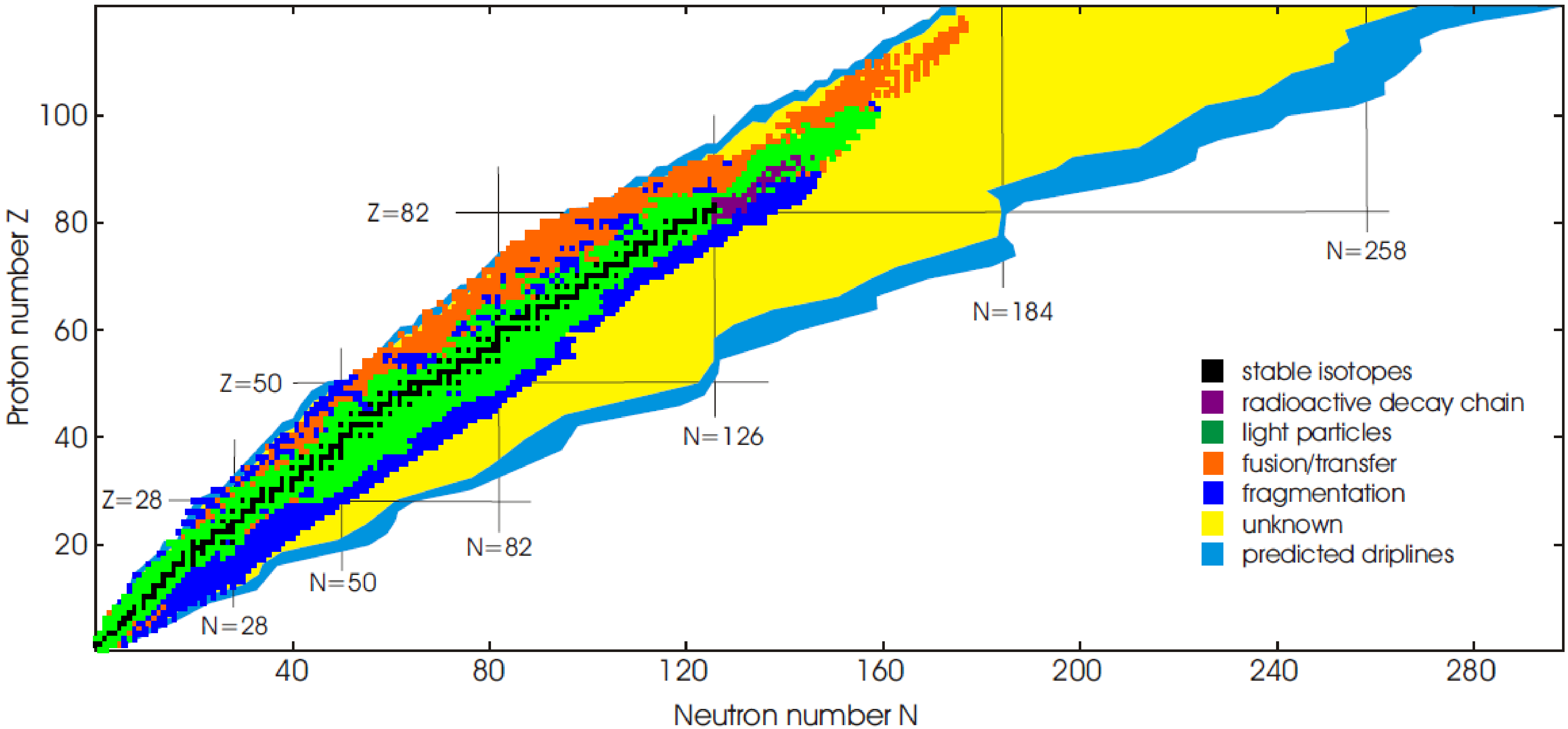
Future

Most isotopes discovered per year ever!
First time more than 100!!



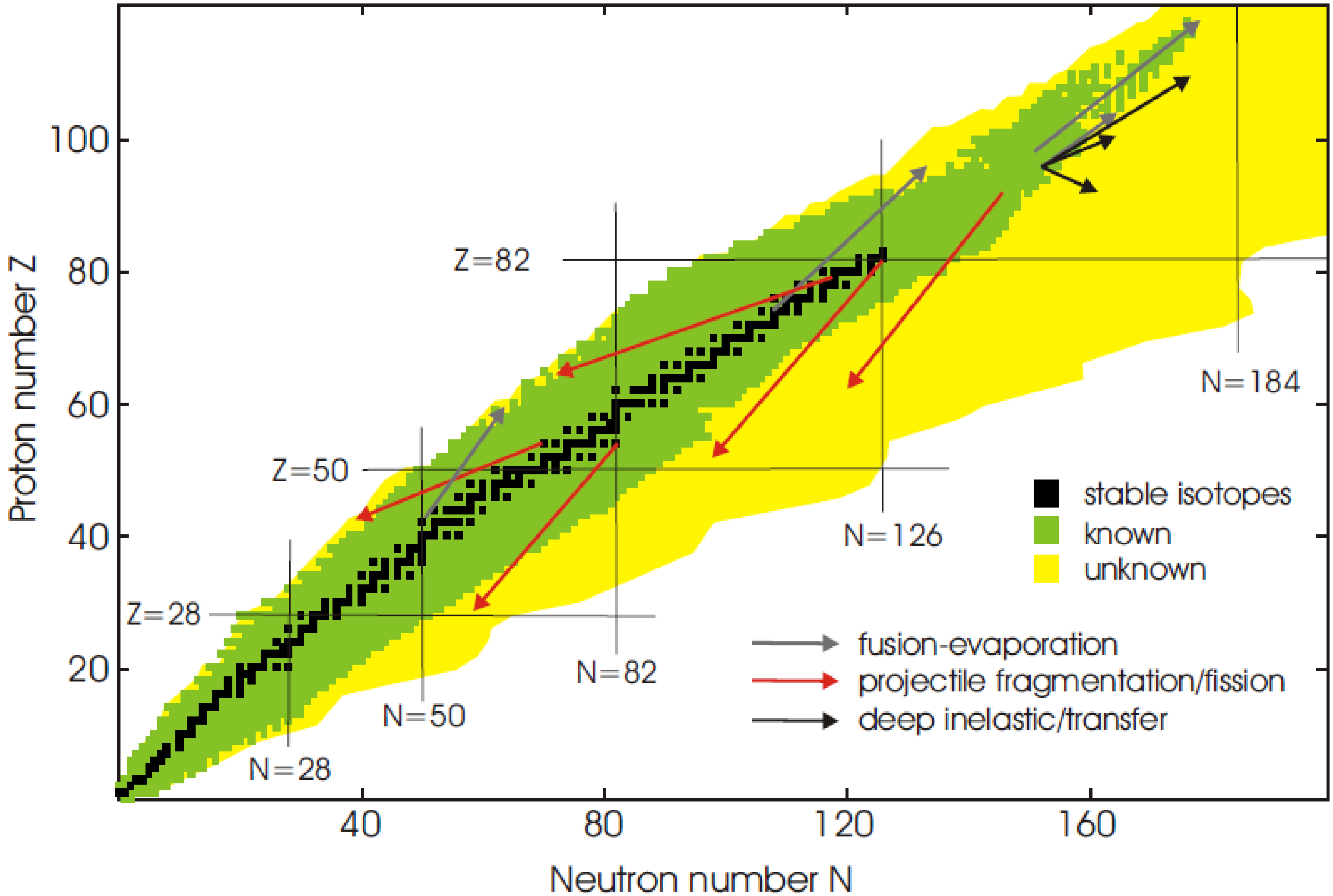
M. T. and B.M. Sherrill, Nature 473 (2011) 25

How many more nuclides are there?

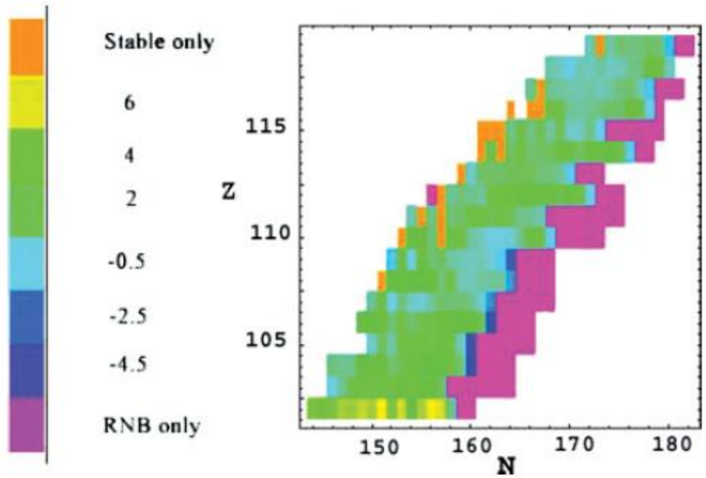


7000 bound nuclide should exist (Erler *et al.*,Nature 486 (2012) 509)

How can new nuclides be discovered?

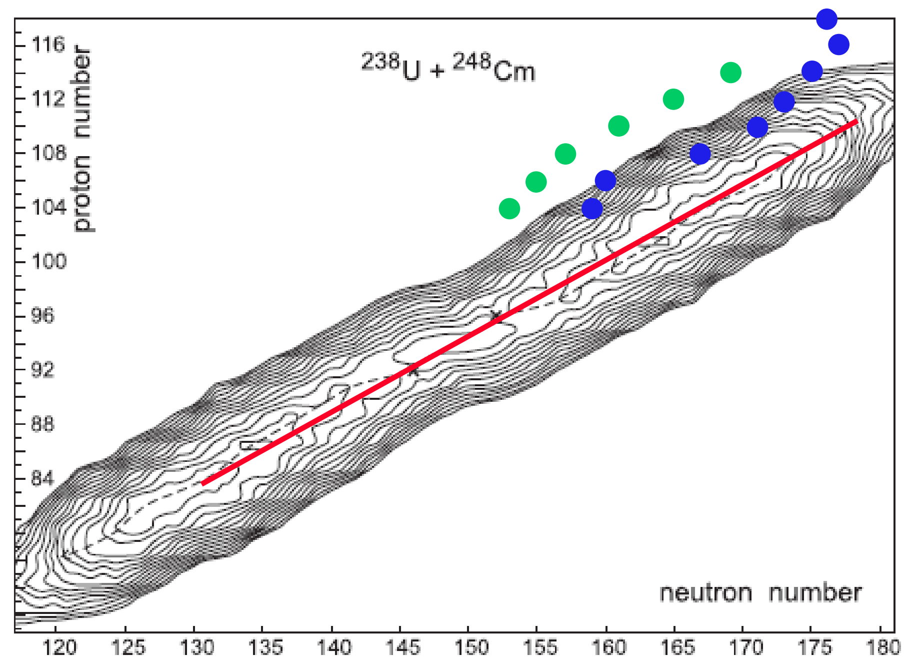


How produce new superheavy nuclides



fusion with radioactive beams

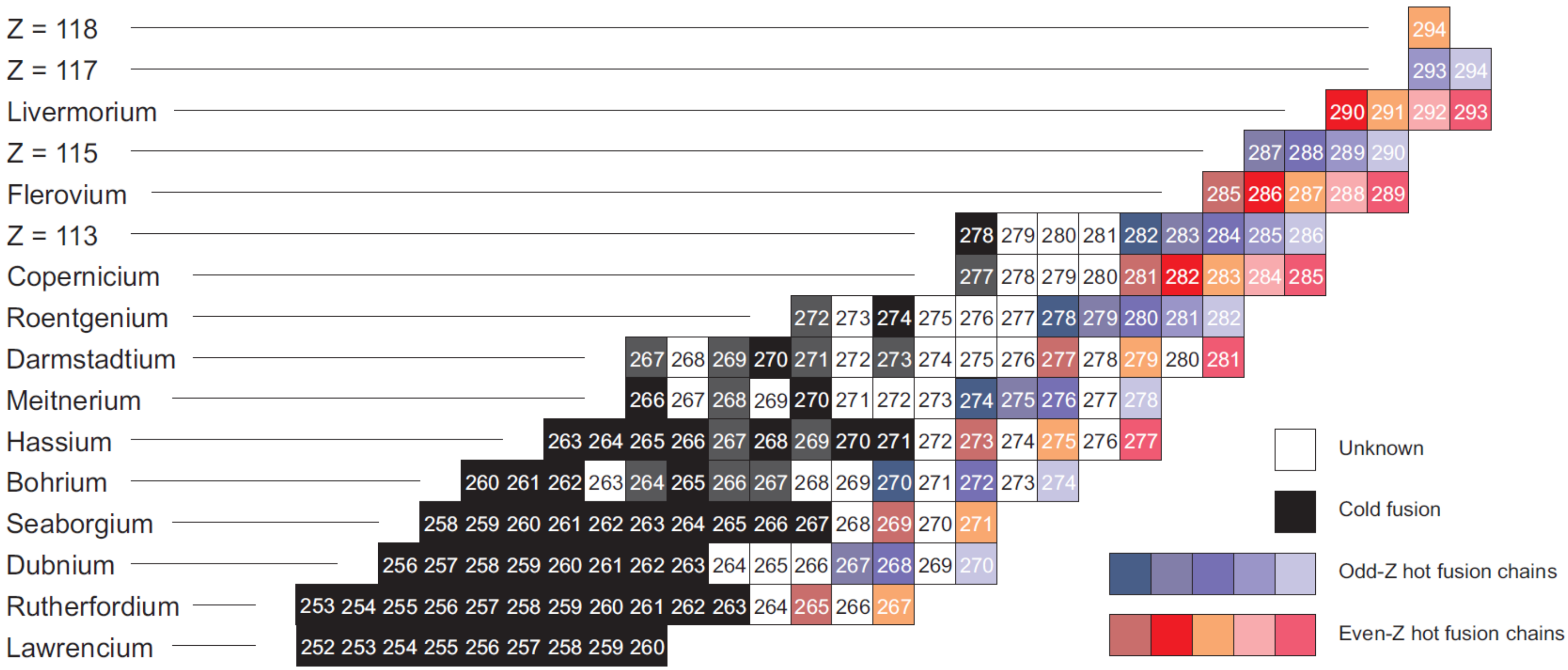
W. Loveland,
Phys. Rev. C 76 (2007) 014612



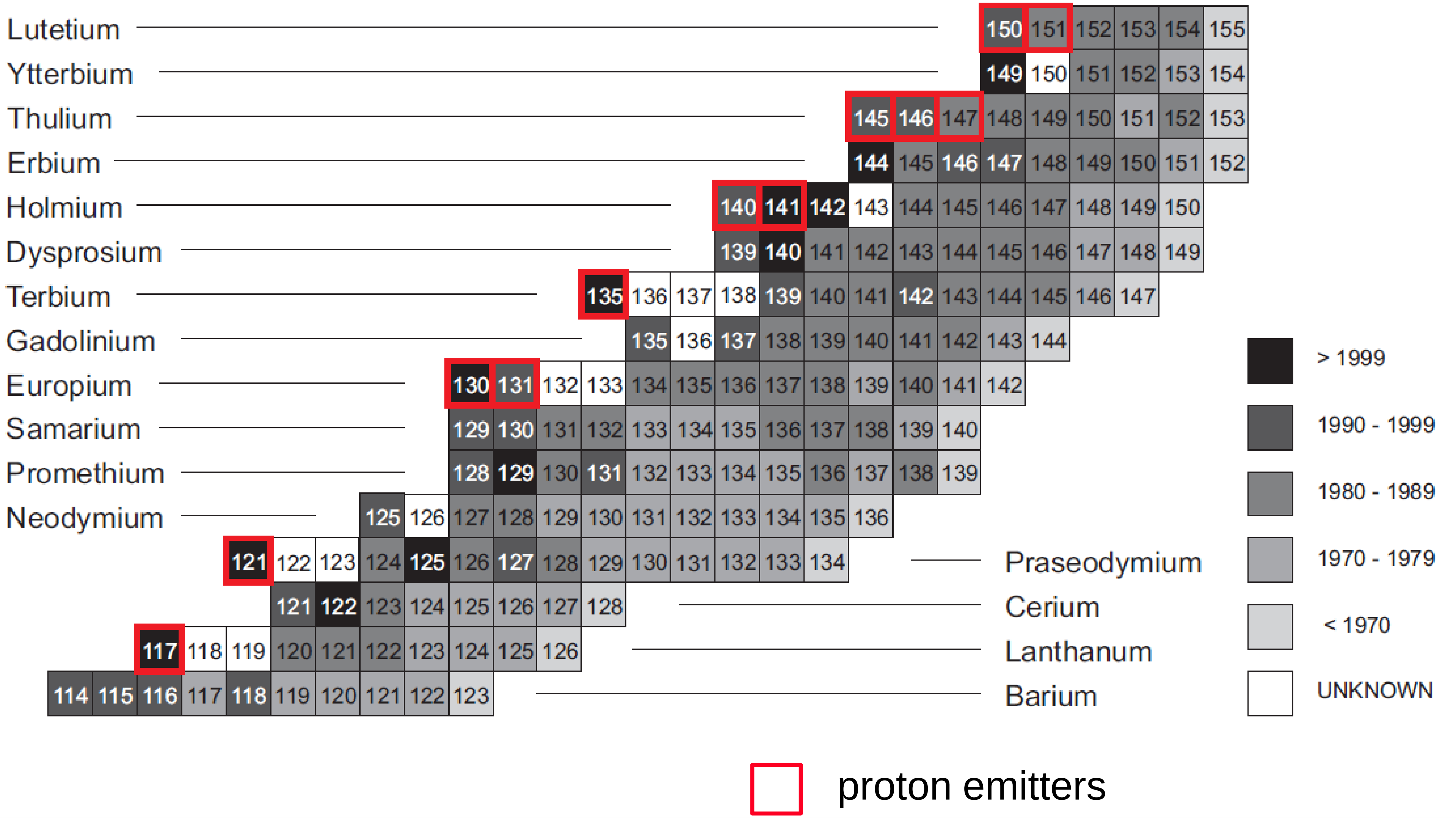
- cold fusion
- hot fusion
- multi-nucleon transfer

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

Connect hot and cold fusion results



Medium mass proton-rich nuclides



NSCL
National Science Foundation
Michigan State University

Projectile fragmentation instead of fusion evaporation reactions

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

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

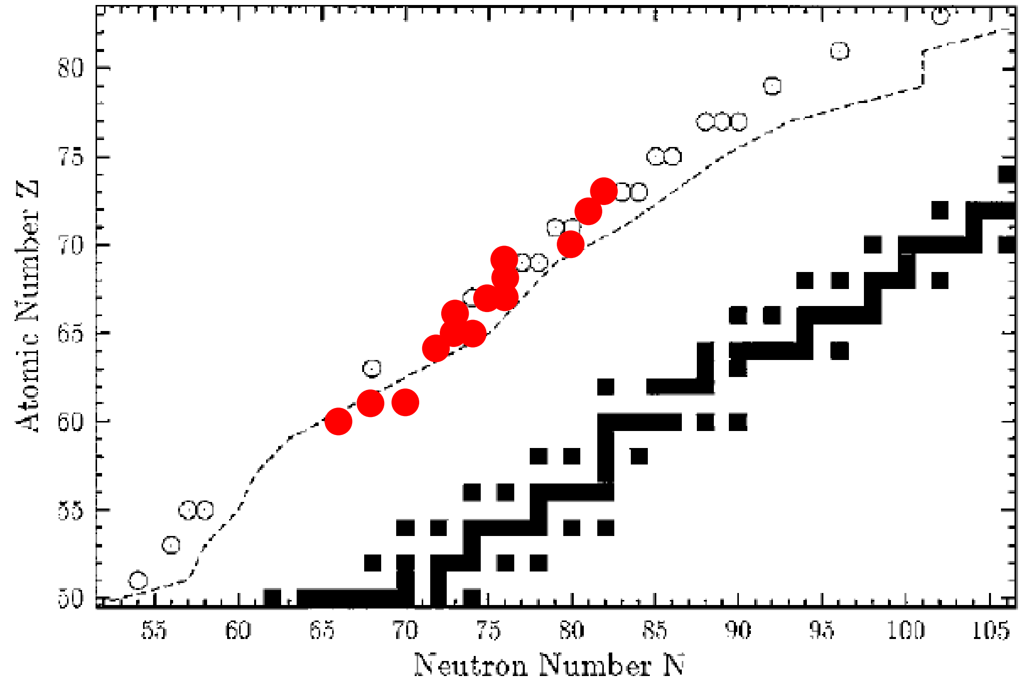
G. A. Souliotis*

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

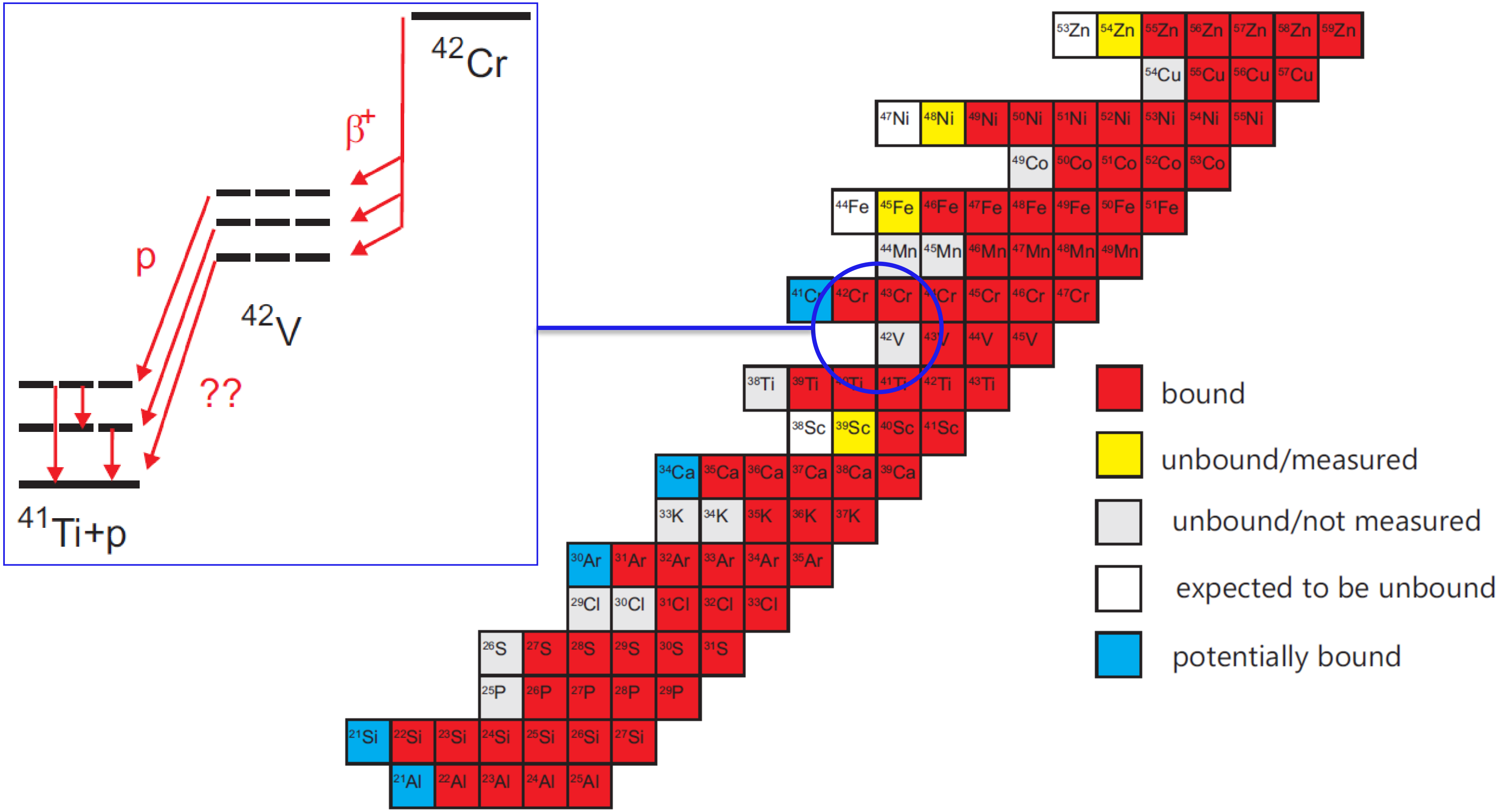
Received October 15, 1999

- New nuclides

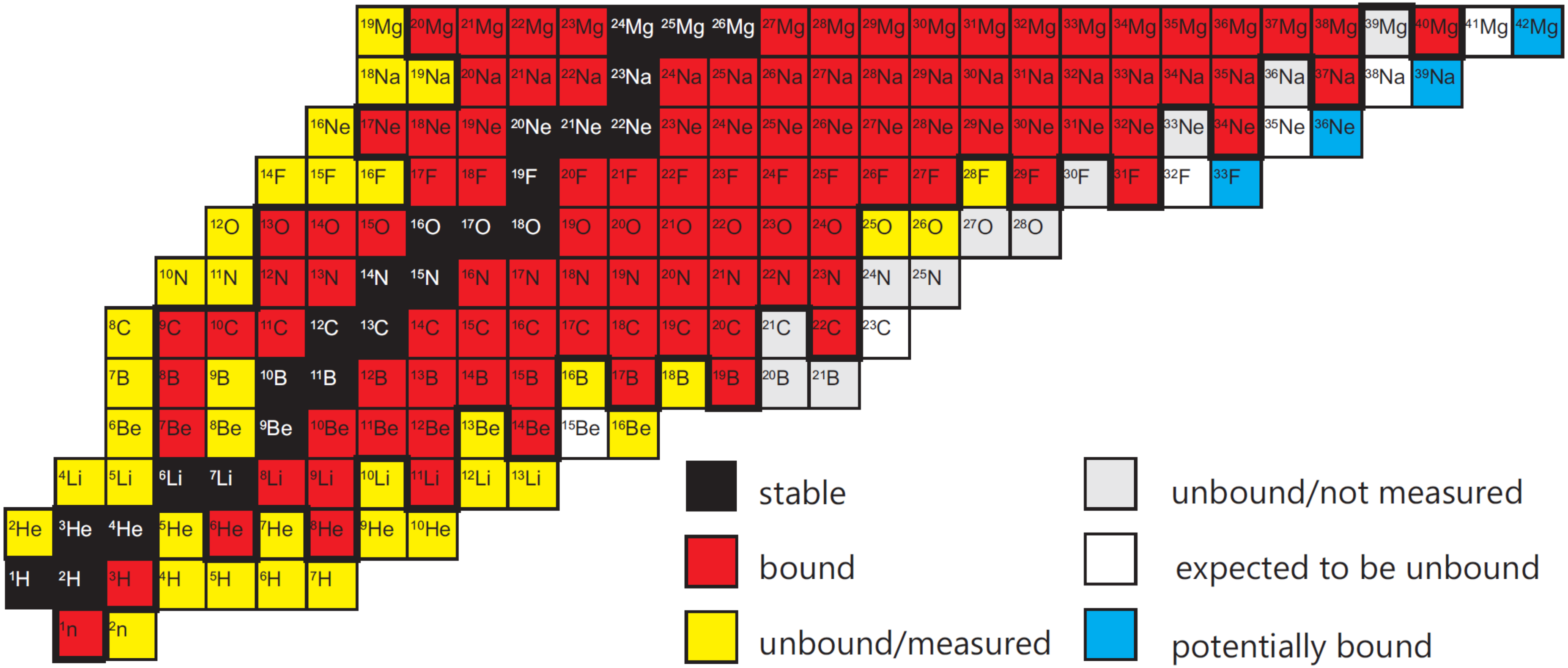
Only published in a Conference Proceeding, possible charge-state contamination could not be excluded.



Light proton-rich nuclides



Neutron-rich nuclides



New facilities

FAIR

FAIR Facility for Antiproton and Ion Research

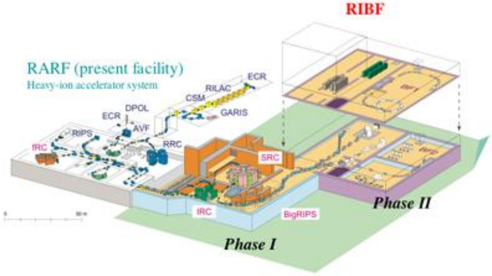
GSI

GANIL spiral2

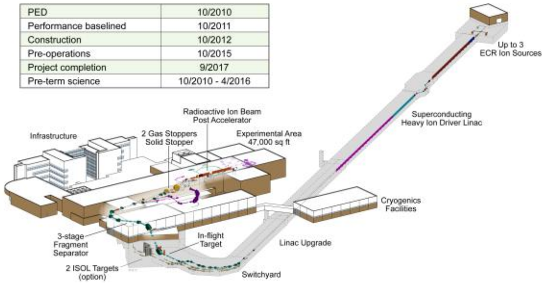
laboratoire commun CEA/DSM CNRS/IN2P3

RIKEN NiSHiNA CENTER

RIKEN Nishina Center for Accelerator-Based Science

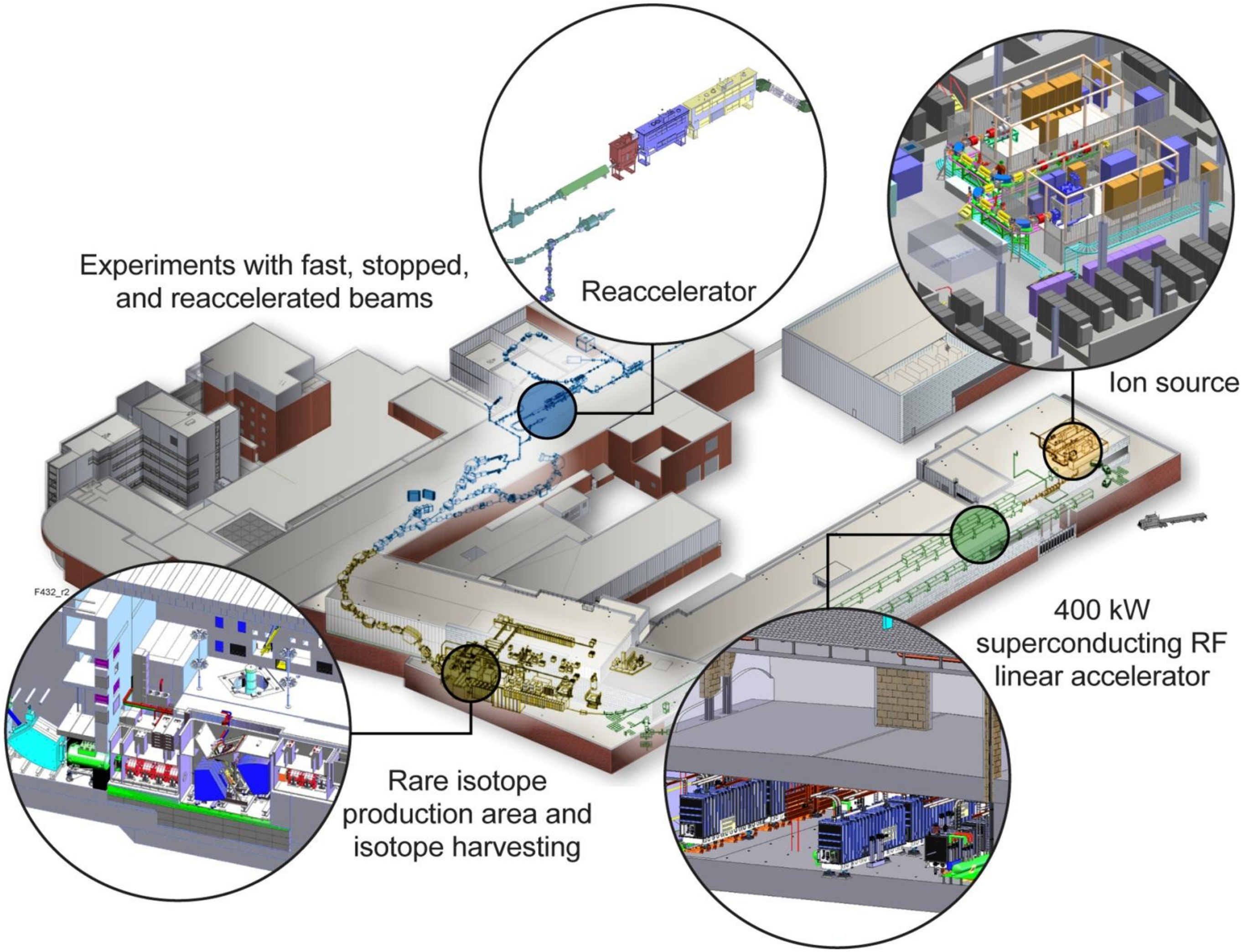


PED	10/2010
Performance baselined	10/2011
Construction	10/2012
Pre-operations	10/2015
Project completion	9/2017
Pre-term science	10/2010 - 4/2016



FRIB Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science
Michigan State University

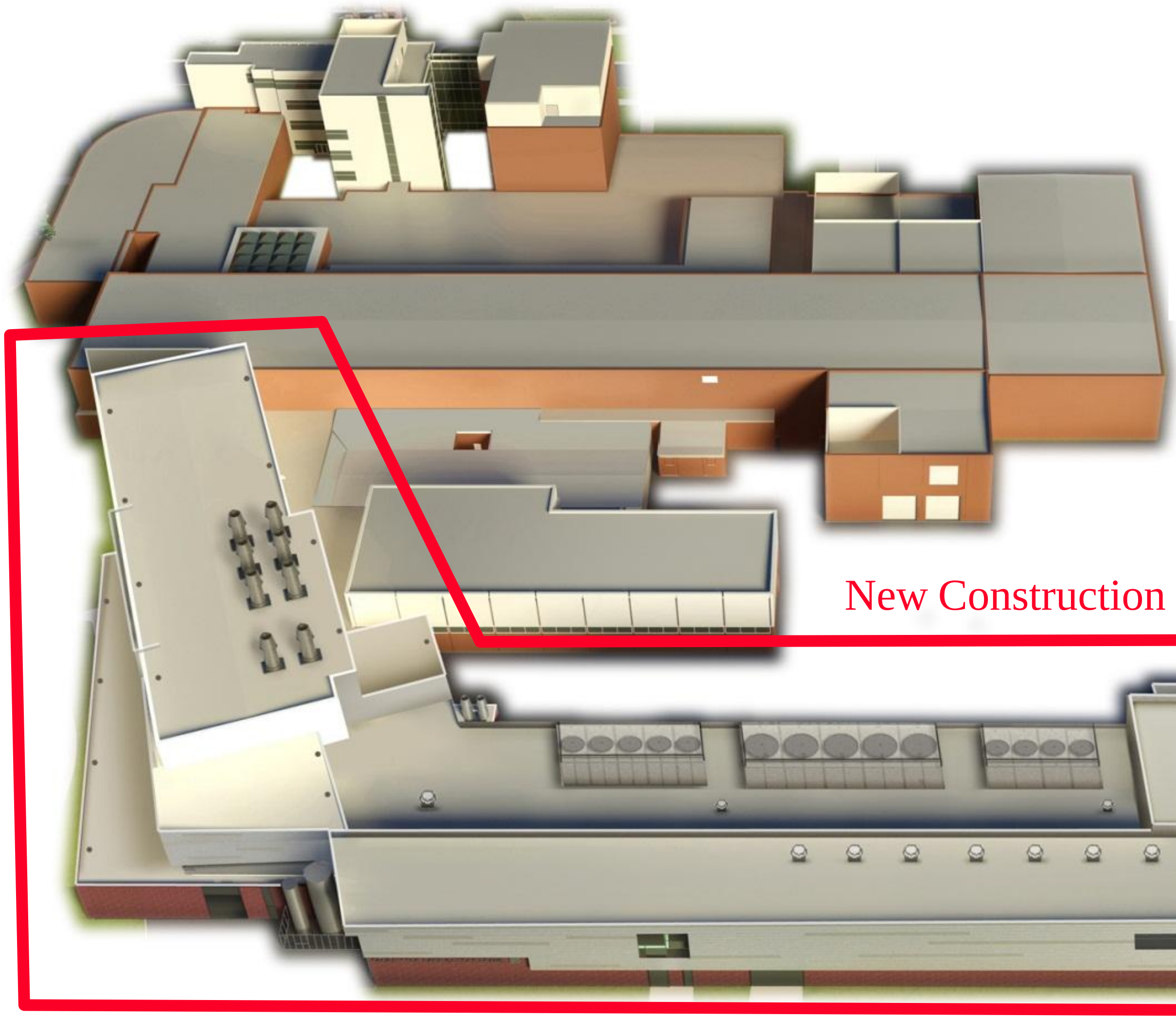
FRIB: Facility for Rare Isotope Beams



FRIB project is on track

- Project started in June 2009
  - –MSU selected to design and establish FRIB in December 2008
  - –Cooperative Agreement signed by DOE and MSU in June 2009
- Preliminary technical design, final civil design, and R&D complete
- Final technical design underway, to be completed in 2013
- NSAC Implementation Subcommittee 2013 - FRIB a priority
  - –"With FRIB, the field has a clear path to achieve its overall scientific goals"
- Early completion expected in 2019
  - –CD-4 (project completion) is 2021

Final civil design is complete

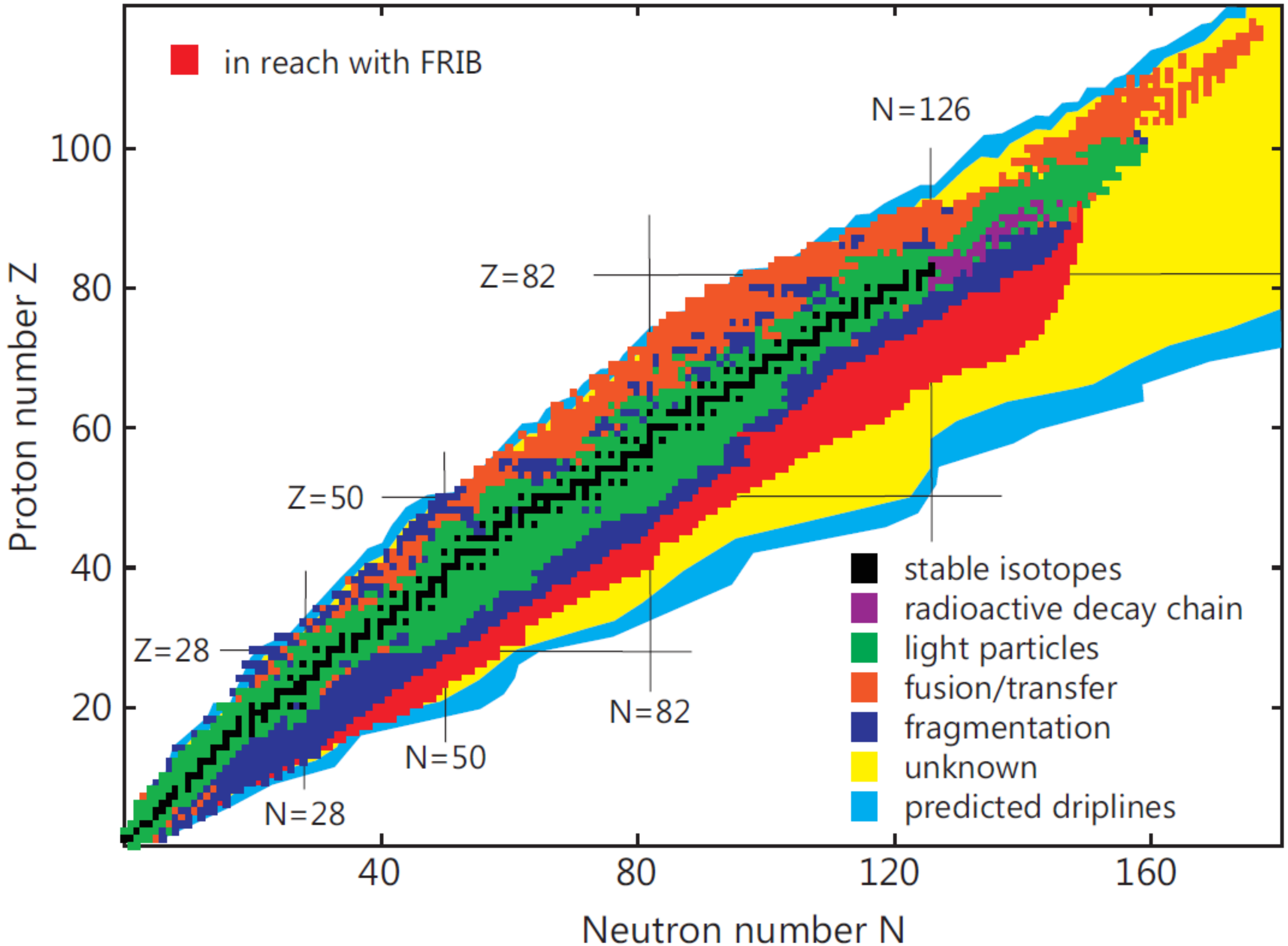


Ready for civil construction to begin

- Installation of pilings for earth retention system completed on schedule
- Site preparation activities complete; ready for start of civil construction upon approval from DOE-SC

Web cams at
www.frib.msu.edu

New nuclides with FRIB



Summary

- Discovery is the first necessary step to study new isotopes
- Search for new nuclides is a major driving force for developing new technologies and methods
- Over 3000 nuclides are known, another ~1500 nuclides should be possible to produce and identify

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