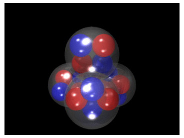
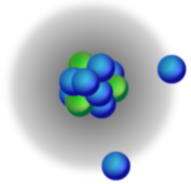
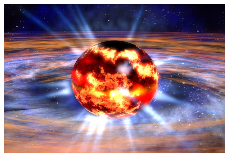
Nuclear Experiments: Introduction

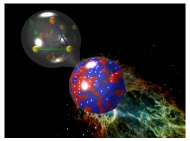
Major open questions in current nuclear structure physics:

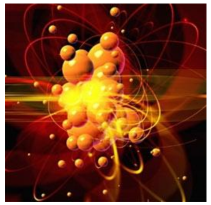


- What is the nature of the nuclear force that binds protons and neutrons into stable nuclei and rare isotopes?
- What is the origin of simple patterns in complex nuclei?
- What is the origin of the element in the cosmos?



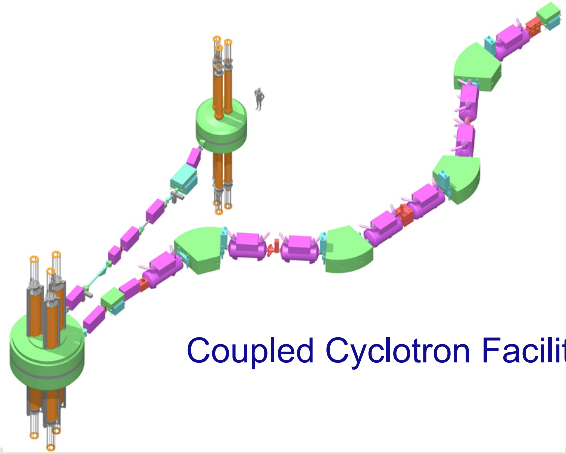






National Superconducting Cyclotron Laboratory

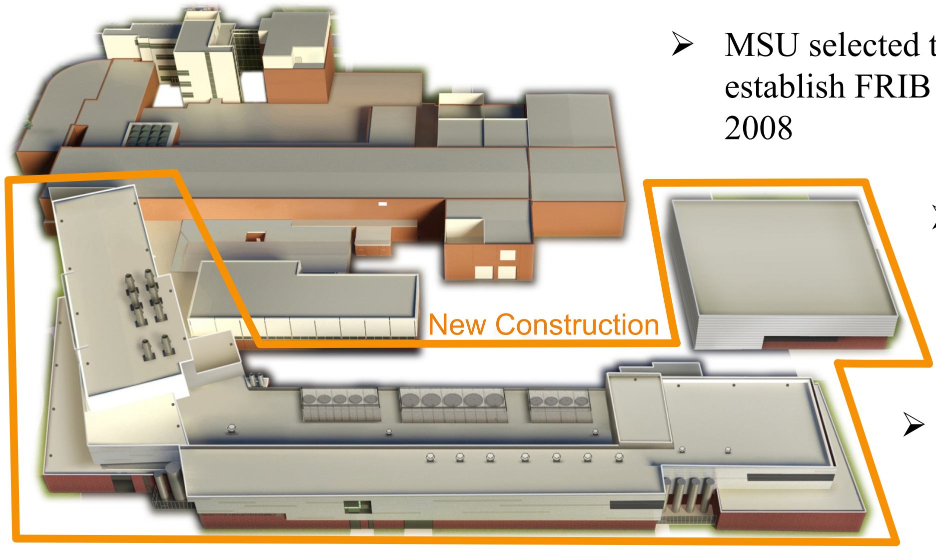
131 Undergrad. students
85 Graduate students
43 Postdocs
44 Faculty



Coupled Cyclotron Facility

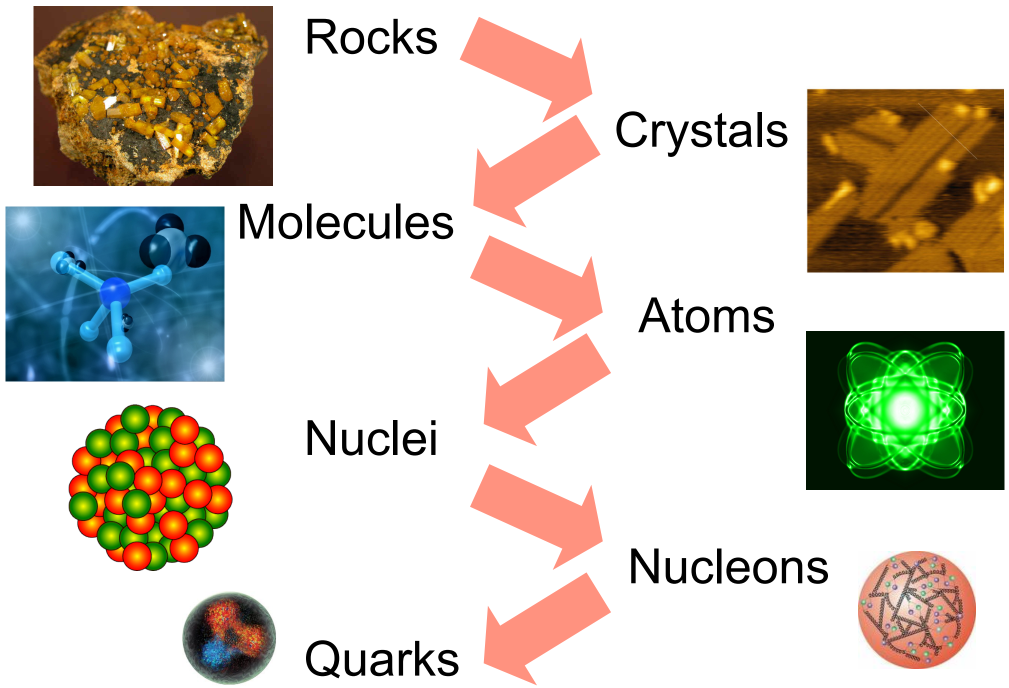
FRIB: Facility for Rare Isotope Beams

- FRIB is located on the campus of Michigan State University and funded by the U.S. Department of Energy



- MSU selected to design and establish FRIB in December 2008
- Project started in June 2009
- Expected completion 2022

Fundamental physics



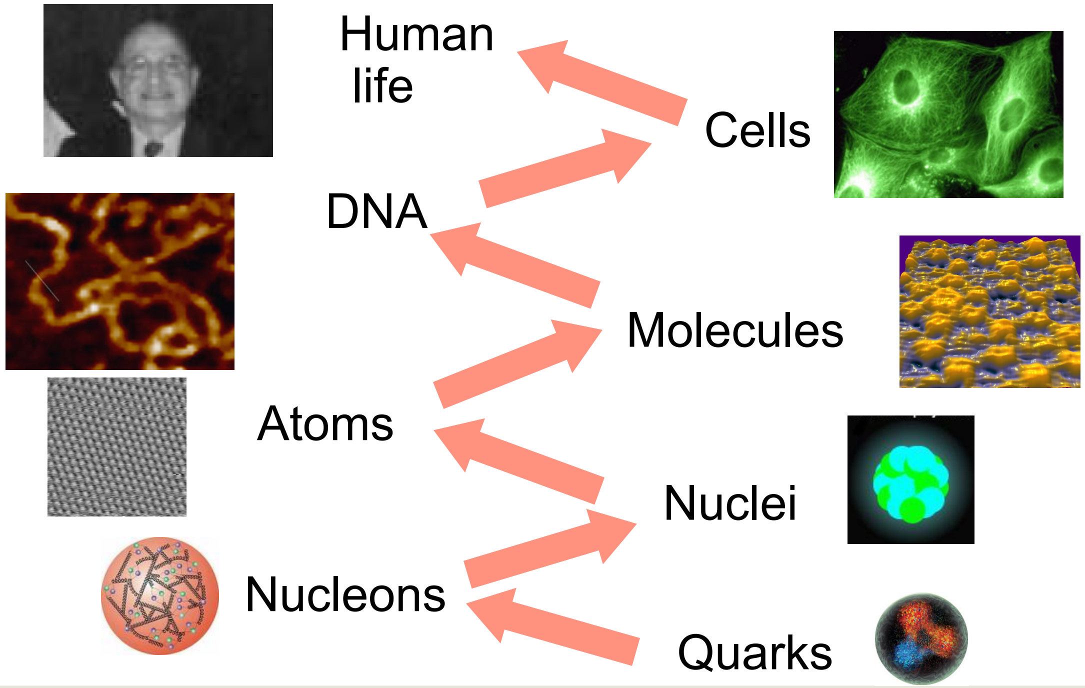
There is more than fundamental physics

I would like to describe a field, in which little has been done, but in which an enormous amount can be done in principle. This field is not quite the same as the others in that it will not tell us much of fundamental physics (in the sense of, “What are the strange particles?”) but it is more like solid-state physics in the sense that it might tell us much of great interest about the strange phenomena that occur in complex situations.

Richard Feynman

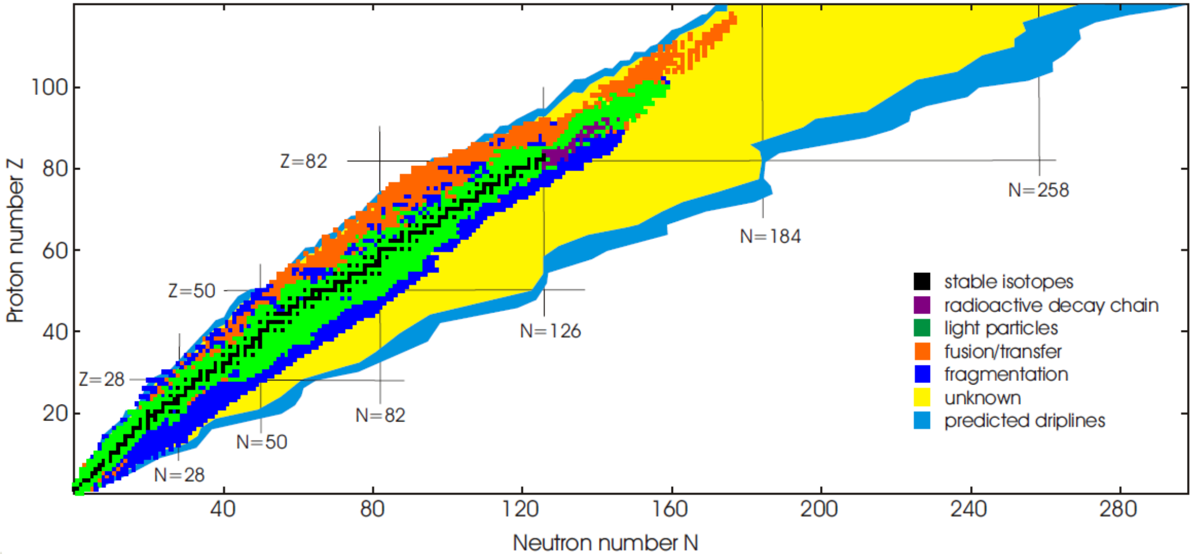
APS Meeting 1959, *Engineering and Science*, February 1960

From simplicity to complexity



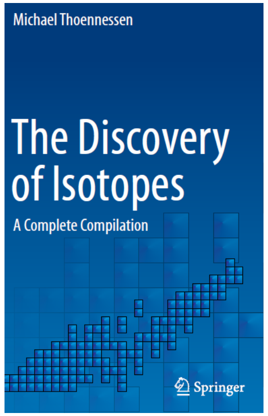
Nuclear chart

In order to answer the main questions one has to measure the properties of nuclides as a function of N and Z



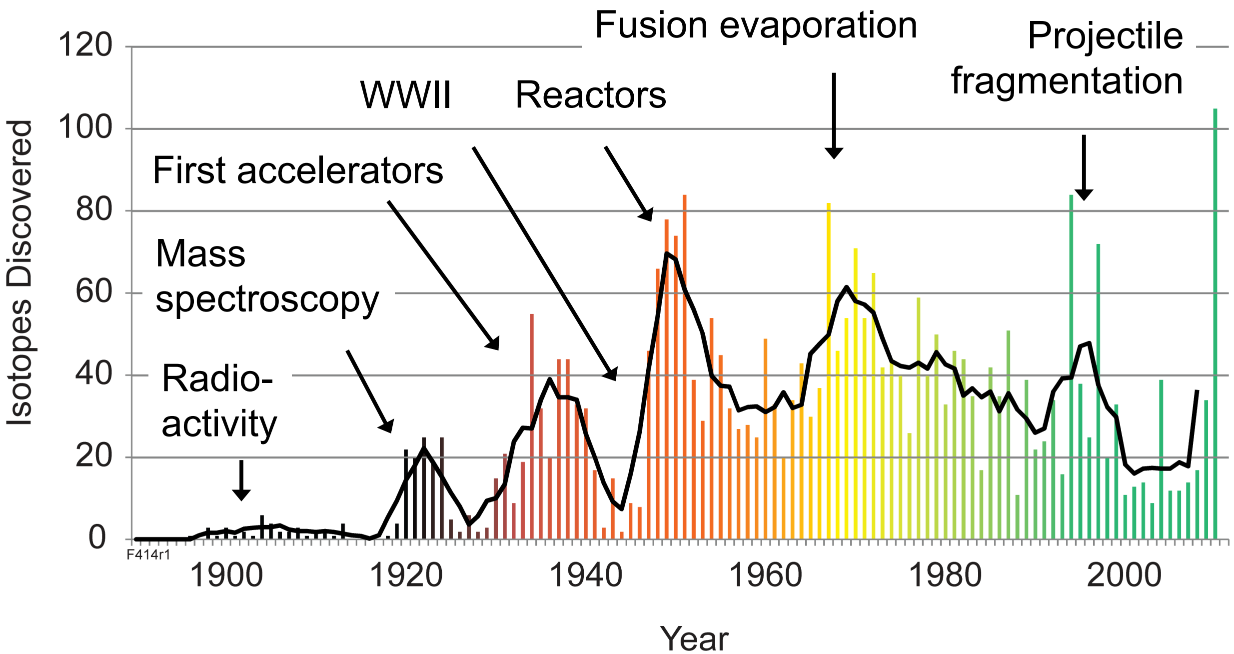
Discovery of isotopes

- 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

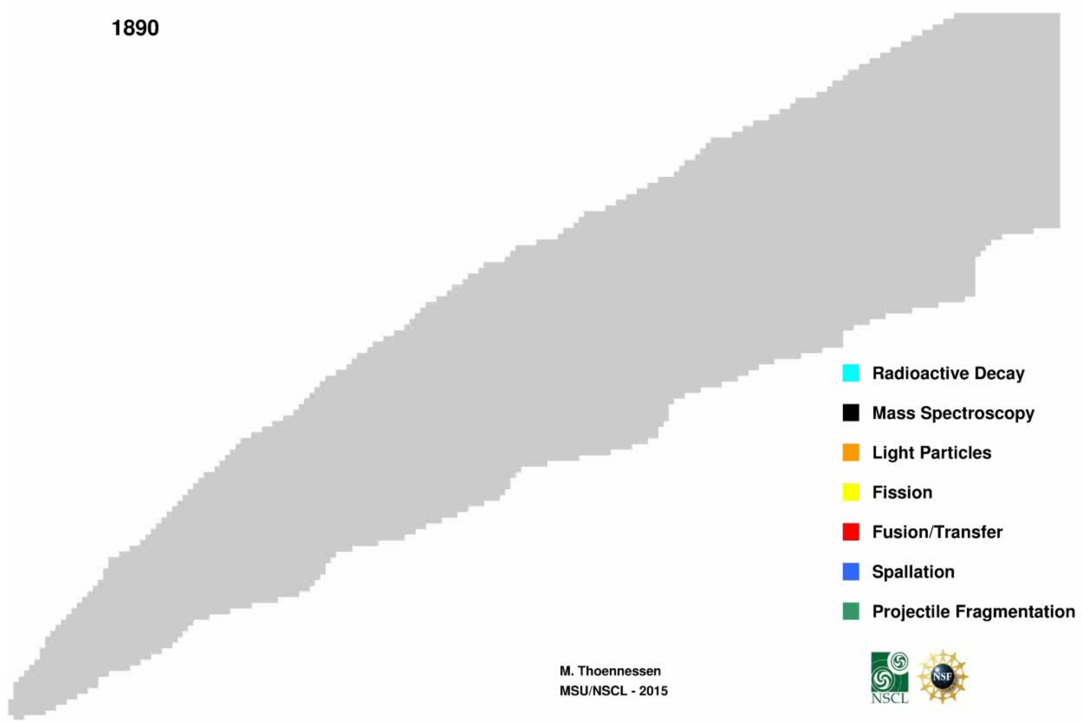


The quest for the unknown is a driving force for discovery

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

Discovery of radioactivity: ^{238}U

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.

Exponential decay I

THE

LONDON, EDINBURGH, AND DUBLIN

PHILOSOPHICAL MAGAZINE

AND

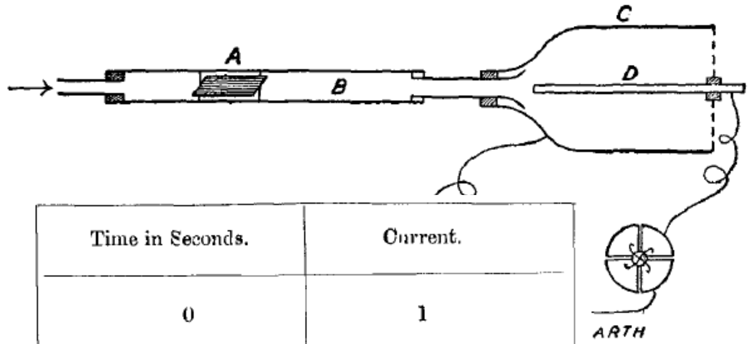
JOURNAL OF SCIENCE.

[FIFTH SERIES.]

JANUARY 1900.

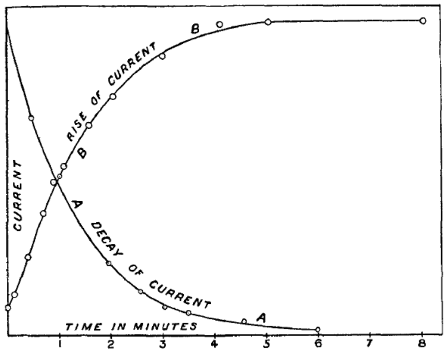
I. *A Radio-active Substance emitted from Thorium Compounds. By* E. RUTHERFORD, *M.A., B.Sc., Macdonald Professor of Physics, McGill University, Montreal* *.

McGill University, Montreal,
September 13th, 1899.



Time in Seconds.	Current.
0	1
28	·69
62	·51
118	·23
155	·14
210	·067
272	·041
360	·018

Exponential decay II



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

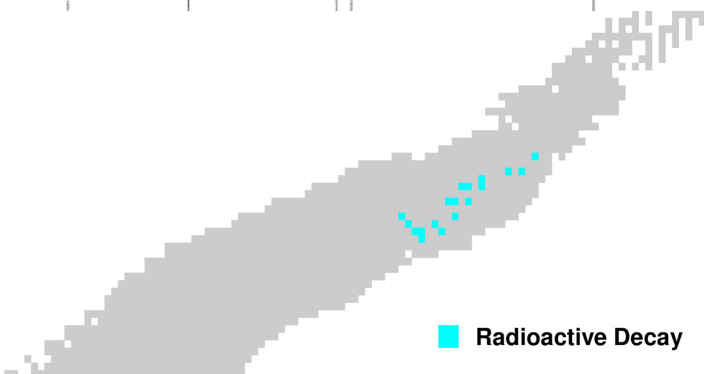
$$\frac{n}{N} = e^{-\lambda t},$$

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)	—



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.

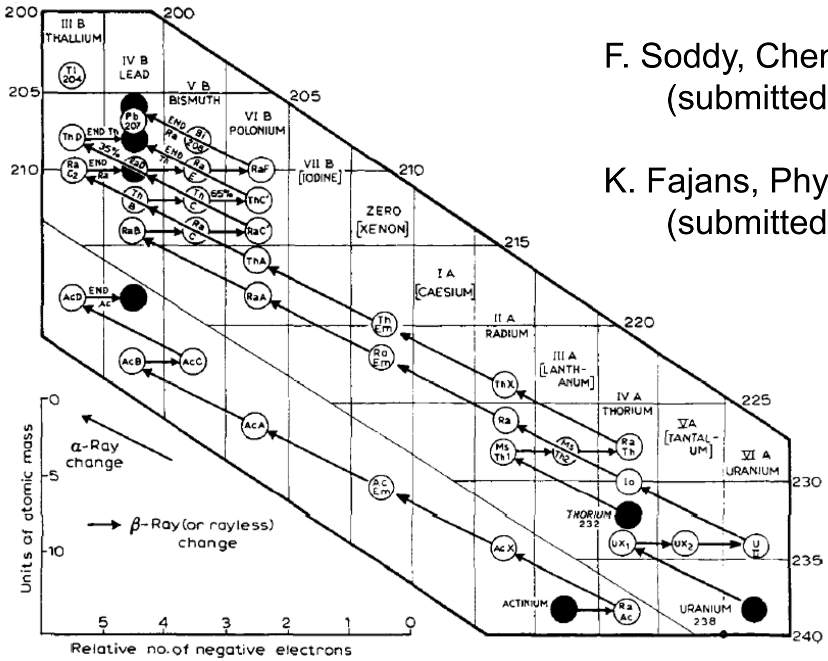
(Read June 18 ; MS. received July 17, 1908.)

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.*

M. Thoennessen
MSU/NSCL - 2011

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

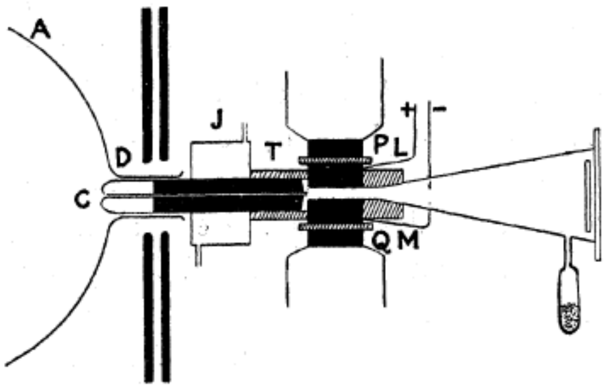
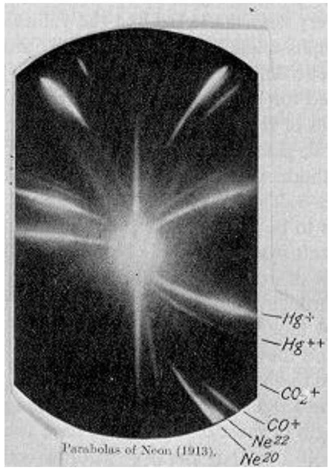


Fig. 4.



Parabolas of Neon (1913).

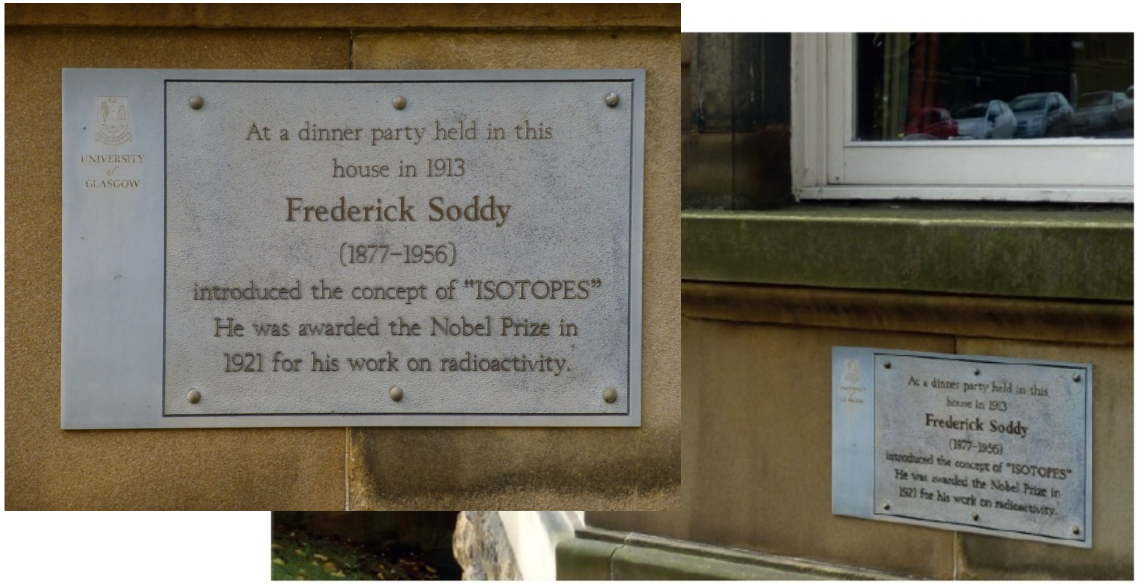
There can, therefore, I think, be little doubt that what has been called neon is not a simple gas but a mixture of two gases, one of which has an atomic weight about 20 and the other about 22.

National Science Foundation
Michigan State University
NSCL

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

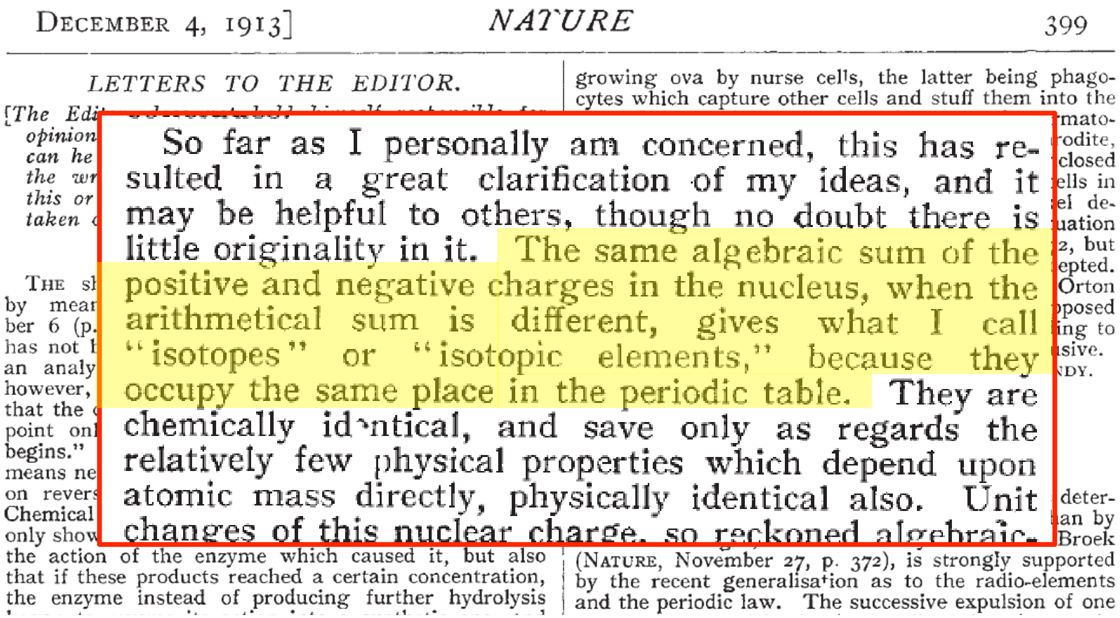
Origin of the term isotope

http://blogs.nature.com/thescepticalchymist/2013/11/isotope-day.html



B. F. Thornton and Shawn C. Burdette, Nature Chemistry **5** (2013) 979

“Iso”-”tope”: Same place



DECEMBER 4, 1913] NATURE 399

LETTERS TO THE EDITOR.

growing ova by nurse cells, the latter being phagocytes which capture other cells and stuff them into the

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-

the action of the enzyme which caused it, but also that if these products reached a certain concentration, the enzyme instead of producing further hydrolysis

(NATURE, November 27, p. 372), is strongly supported by the recent generalisation as to the radio-elements and the periodic law. The successive expulsion of one

December 4: Isotope Day

University of Glasgow | The Hunterian

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Isotope Day - 4 December 2013

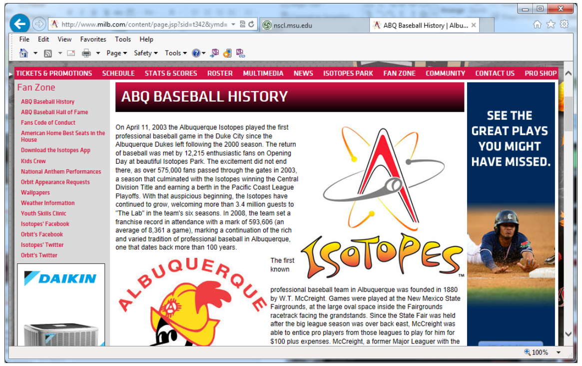
Isotopes were introduced to the world in a letter to the journal 'Nature', published on 4 December 1913 by University of Glasgow chemist Frederick Soddy.

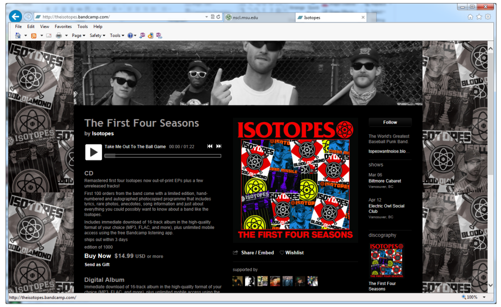
He realised that a single chemical element could occur as atoms with different atomic weights, with different nuclear properties, such as radioactive half-life. He thus reconciled the periodic table with the newly-discovered phenomena of radioactivity, and atomic transformation. He later received the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

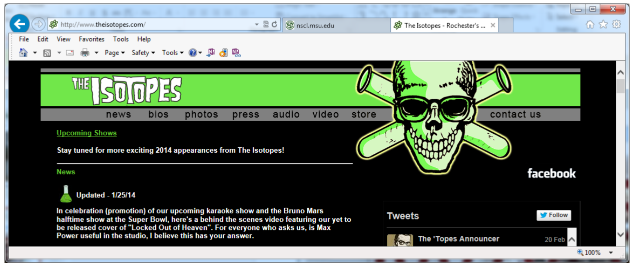
The word 'isotope' itself had been suggested to him by Margaret Todd, a Glasgow GP, during a dinner at 11 University Gardens. Isotope science was truly born at the University of Glasgow.

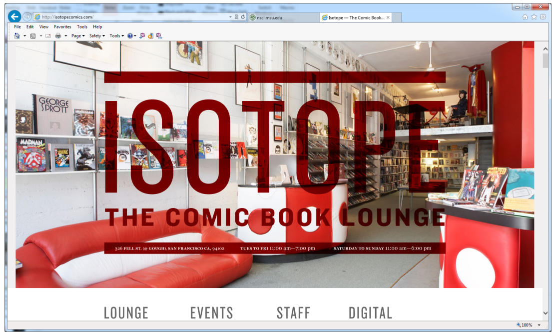
http://www.gla.ac.uk/hunterian/visit/events/headline_296351_en.html

..nothing to do with…



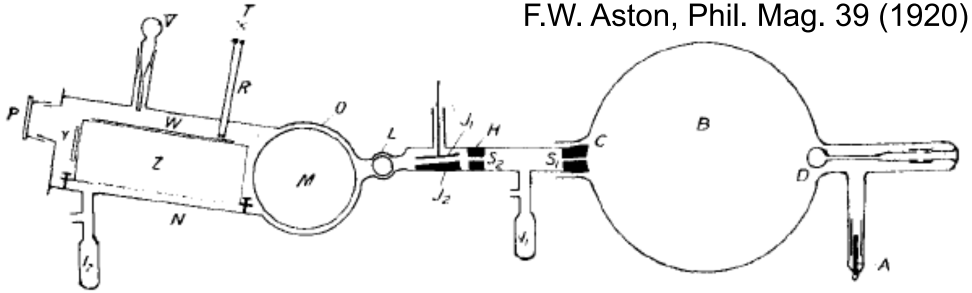


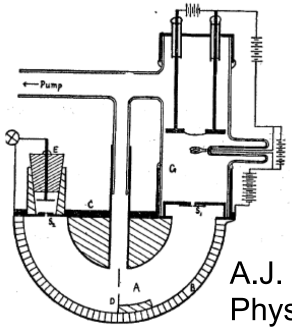




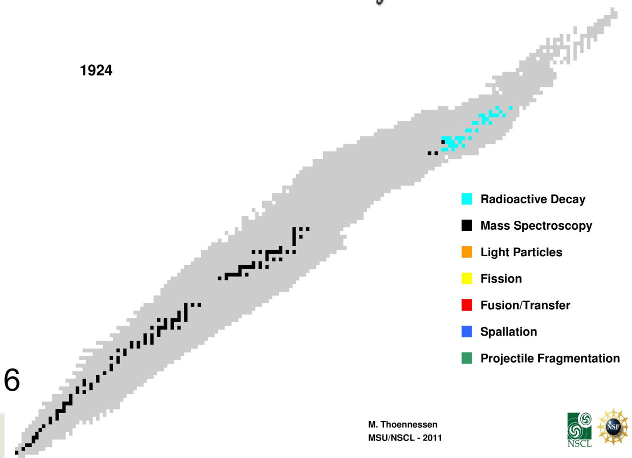
Mass spectra of chemical elements

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

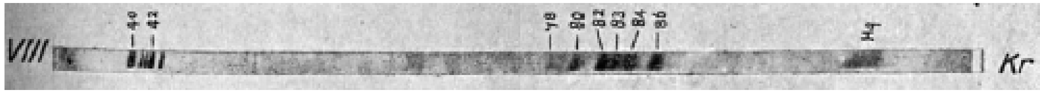




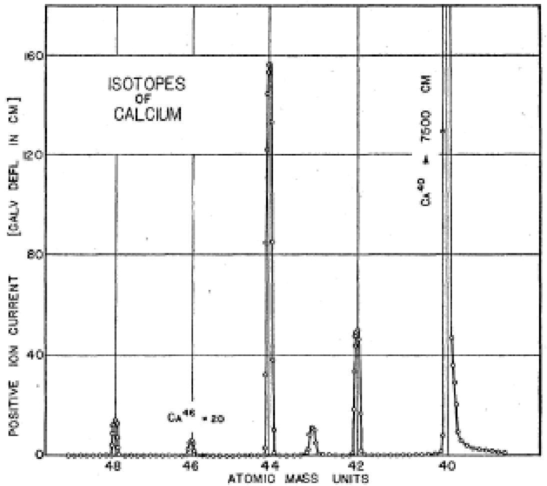
A.J. Dempster,
Phys. Rev. 11 (1918) 316



Improvement of resolution



F.W. Aston, Nature 105 (1920) 617



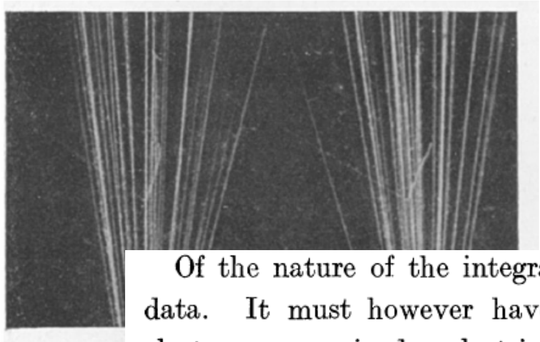
A.O. Nier,
Phys. Rev. 33 (1938) 282

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.



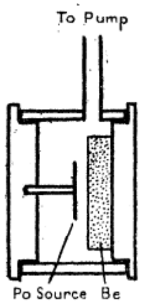
$$m_p v_p \sin \psi - m_n v_n \sin \omega = 0,$$

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

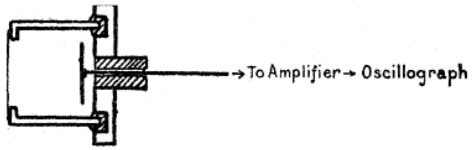
$^{14}N(\alpha,p)^{17}O$

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



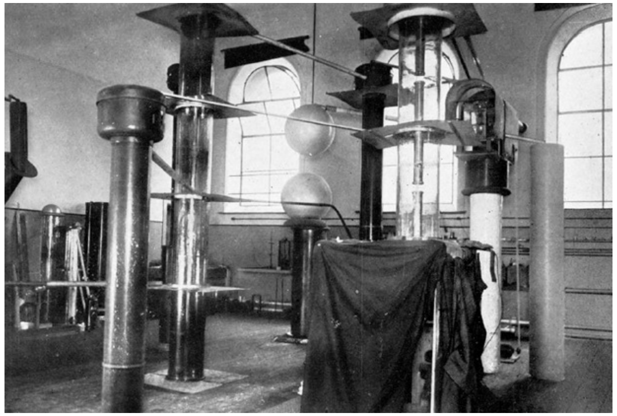
J. Chadwick, Nature 129 (1932) 312
Submitted: February 17, 1932



$^{9}Be(\alpha,n)^{12}C$

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. From the energy relations of this process

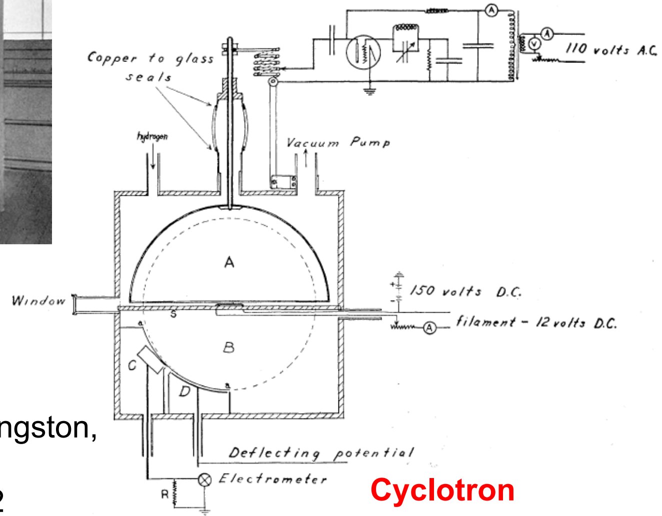
First accelerators



J.D. Cockcroft and E.T.S. Walton,
Proc. Roy. Soc. A 136 (1932) 619

Electrostatic accelerator

J.D. Cockcroft and E.T.S. Walton,
Nature 129 (1932) 242
Submitted: February 2, 1932



E.O. Lawrence and M. S. Livingston,
Phys. Rev. 40 (1932) 19
Submitted: February 20, 1932

Cyclotron

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.

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

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.

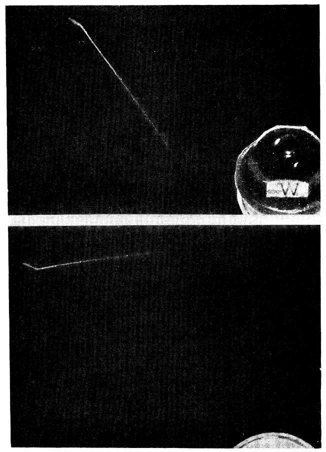
J.D. Cockcroft and E.T.S. Walton, Nature 129 (1932) 649
Submitted April 16, 1932

First new isotope produced in a neutron induced reaction

Disintegration of Fluorine Nuclei by Neutrons and the Probable Formation of a New Isotope of Nitrogen (N^{16})

$$F_1^{19} + n_1^1 \rightarrow F_2^{20} \rightarrow N_2^{16} + He_0^4$$

in which the subscripts represent the isotopic numbers and the superscripts the atomic masses.



W.D. Harkins, D.M. Gans, and H.W. Newson, Phys. Rev. 44 (1933) 945

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 :

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

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

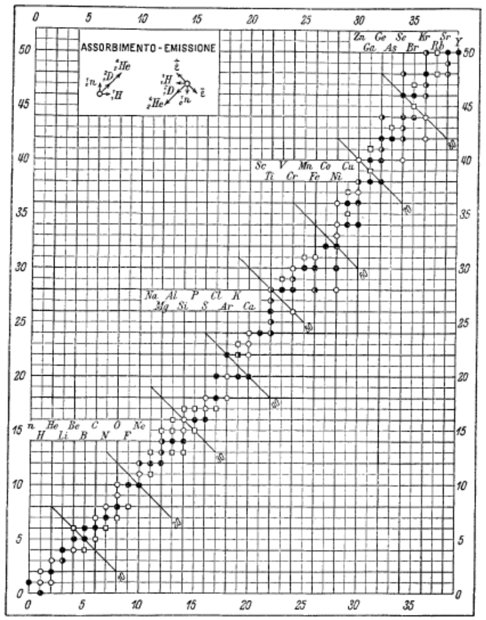
L'isotope $^{30}_{15}\mathrm{P}$ du phosphore serait radioactif avec une période de $3^{m}15^{s}$ et émettrait des électrons positifs suivant la réaction

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

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

Nature, February 10, 1934

First nuclear chart

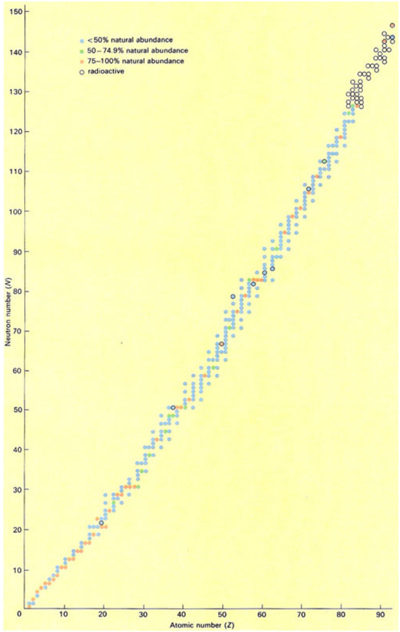


Neutrons vs Protons

G. Fea, Nuovo Cimento 12 (1935) 368

Original Segre chart

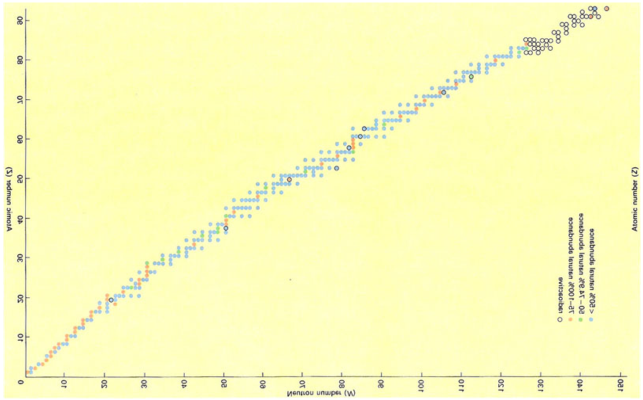
Neutrons



Protons

Emilio Segrè (1905-1989)

Protons



Neutrons

http://www.daviddarling.info/encyclopedia/I/isotope.html

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.

Early skeptics:

Über das Element 93.

Von Dr.-Ing. IDA NODDACK, Berlin.

Angew. Chemie 47 (1934) 653

Der Beweis, daß das neue Radioelement die Ordnungszahl 93 hat, ist also noch keineswegs geglückt, da *Fermi* ihn nur durch ein unvollkommen durchgeführtes Ausschlußverfahren versucht hat.

Man kann ebensogut annehmen, daß bei dieser neuartigen Kernzertrümmerung durch Neutronen erheblich andere „Kernreaktionen" stattfinden, als man sie bisher bei der Einwirkung von Protonen- und α-Strahlen auf Atomkerne beobachtet hat. Bei den letztgenannten Bestrahlungen findet man nur Kernumwandlungen unter Abgabe von Elektronen, Protonen und Heliumkernen, wodurch sich bei schweren Elementen die Masse der bestrahlten Atomkerne nur wenig ändert, da nahe benachbarte Elemente entstehen. Es wäre denkbar, daß bei der Beschießung schwerer Kerne mit Neutronen diese Kerne in mehrere g r ö ß e r e Bruchstücke zerfallen, die zwar Isotope bekannter Elemente, aber nicht Nachbarn der bestrahlten Elemente sind.

The proof that the new radioelement has Z = 93, has not been established…

It is conceivable that… these nuclei decay into several larger pieces…

Apparent confirmation, but…

Über die Umwandlungsreihen des Urans, die durch Neutronenbestrahlung erzeugt werden.

Z. Phys. 106 (1937) 249

Von **L. Meitner**, **O. Hahn** und **F. Strassmann**.

Mit 3 Abbildungen. (Eingegangen am 14. Mai 1937.)

$$1.\quad U + n \longrightarrow {}^{10''}_{92}U \xrightarrow{\beta} {}^{2,2'}_{93}\text{Eka Re} \xrightarrow{\beta} {}^{59'}_{94}\text{Eka Os} \xrightarrow{\beta} {}^{66\,h}_{95}\text{Eka Ir} \xrightarrow{\beta} {}^{2,5\,h}_{96}\text{Eka Pt} \xrightarrow{\beta} {}_{97}\text{Eka Au ?}$$

$$2.\quad U + n \longrightarrow {}^{40''}_{92}U \xrightarrow{\beta} {}^{16'}_{93}\text{Eka Re} \xrightarrow{\beta} {}^{5,7\,h}_{94}\text{Eka Os} \xrightarrow{\beta} {}_{95}\text{Eka Ir ?}$$

$$3.\quad U + n \longrightarrow {}^{23'}_{92}U \xrightarrow{\beta} {}_{93}\text{Eka Re ?}$$ ← ^{239}U

Also müssen die Prozesse Einfangprozesse des Uran 238 sein, was zu drei isomeren Kernen Uran 239 führt. Dieses Ergebnis ist mit den bisherigen Kernvorstellungen sehr schwer in Übereinstimmung zu bringen.

This result is hard to understand within the current understanding of nuclei.

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.

Reminder: Be careful!

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

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

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

World War II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Report to the Scientific Director

HEAVY NUCLIDES IN BOMB DEBRIS

Classified research

Neptunium and plutonium:

These first two transuranium elements were referred to simply as "element 93" and "element 94" or by code names, …

Throughout 1941, element 94 was referred to by the code name of "copper", which was satisfactory until it was necessary to introduce the element copper into some of the experiments. This posed the problem of distinguishing between the two.

For a while, the plutonium was referred to as "copper" and the real copper as "honest-to-God copper."

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

Classified documents

PHYSICAL REVIEW VOLUME 70, NUMBERS 7 AND 8 OCTOBER 1 AND 15, 1946

Properties of 94(239)

J. W. KENNEDY, G. T. SEABORG, E. SEGRÈ, AND A. C. WAHL
Radiation Laboratory and Department of Chemistry, University of California, Berkeley, California
(Received May 29, 1941)*

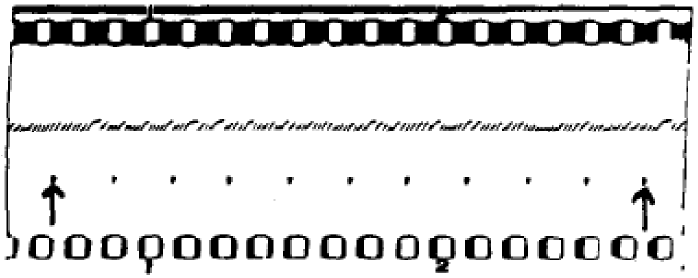
* This letter was received for publication on the date indicated but was voluntarily withheld from publication until the end of the war. The original text has been somewhat changed, by omissions, in order to conform to present declassification standards.

NATIONAL NUCLEAR ENERGY SERIES
Manhattan Project Technical Section

Division IV — Plutonium Project Record
Volume 9

New York · Toronto · London
McGRAW-HILL BOOK COMPANY, INC.
1951

New counting techniques



Photograph of an oscilloscope with an oscillograph recorder. The time interval between the arrows is 0.05 s during which 153 pulses from the decay of ^{43}Ti were counted.

$T_{1/2}$	XREF	Comments
509 ms *5*	ABCDE	%ε+%β$^+$=100; %εp=? μ=0.85 *2* (1993Ma67,2014StZZ) **μ:** β-NMR in Pt (1993Ma67,1993Ma72,1992Ma63). **J$^\pi$:** log ft=3.56 to 7/2- g.s. of ^{43}Sc (super-allowed transition). Mirror state of 7/2-, g.s. in ^{43}Sc. **$T_{1/2}$:** from β activity in 1987Ho14. Others: 0.58 s 4 (1948Sc20), 0.58 s (1954Ty33), 0.56 s 2 (1961Ja22), 0.528 s 3 (1960Ja12), 0.50 s 2 (1962Pl02), 0.40 s 5 (1963Va37), 0.49 s 1 (1967Al08).

^{43}Ti

National Science Foundation
Michigan State University

A.D. Schelberg, M.B. Sampson, and A.C.G. Mitchell, Rev. Sci. Instrum. 19, 458 (1948).

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

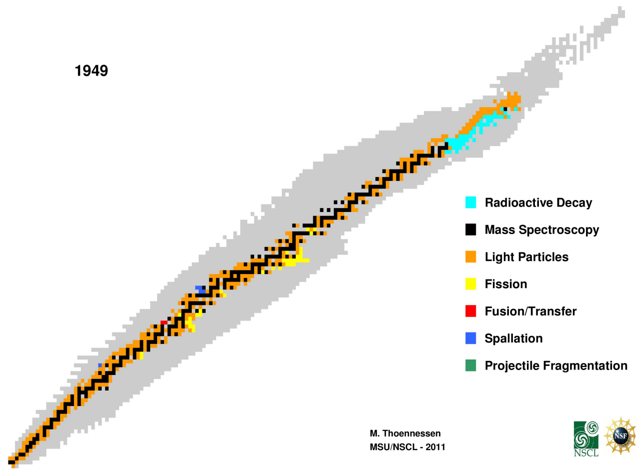
Products of High Energy Deuteron and Helium Ion Bombardments of Copper

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	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}	$\beta^+, (K)$	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}	$\beta^+, (K)$	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
$_{23}V^{48}$	$\beta^+, (K)$	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



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

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.

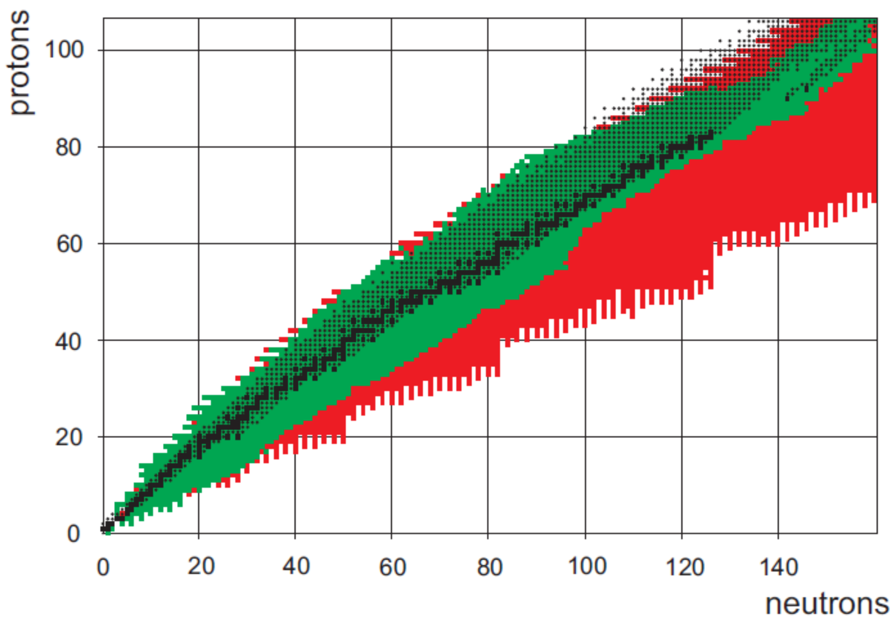
Californium Isotopes from Bombardment of Uranium with Carbon Ions*

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

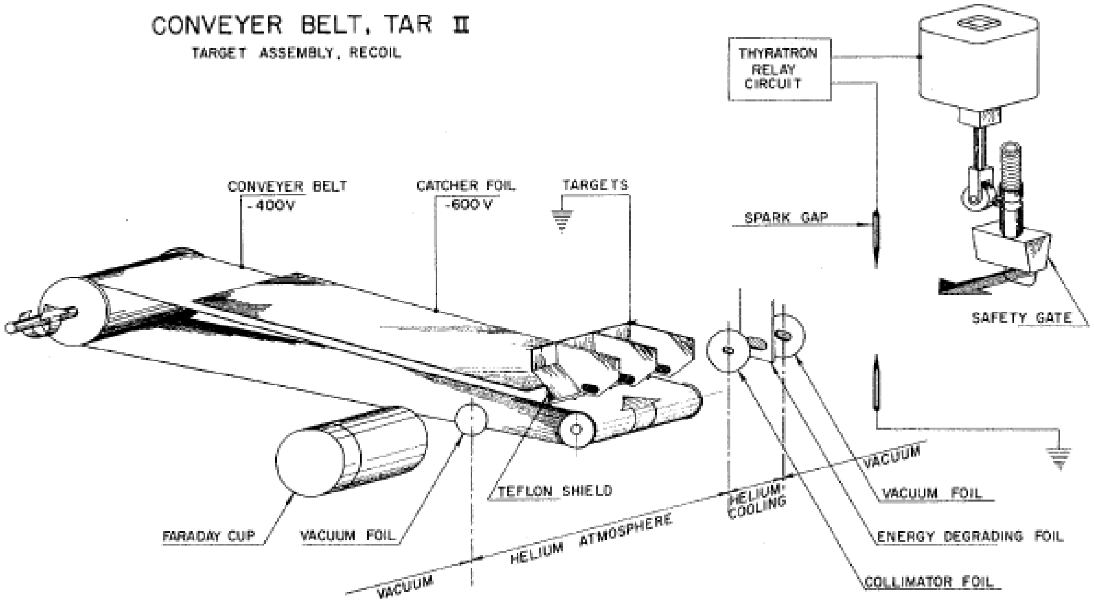
Phys. Rev. 81 (1951) 154
^{248}Cf

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.

Range of fusion-evaporation reactions



First detection of fusion-evaporation recoils

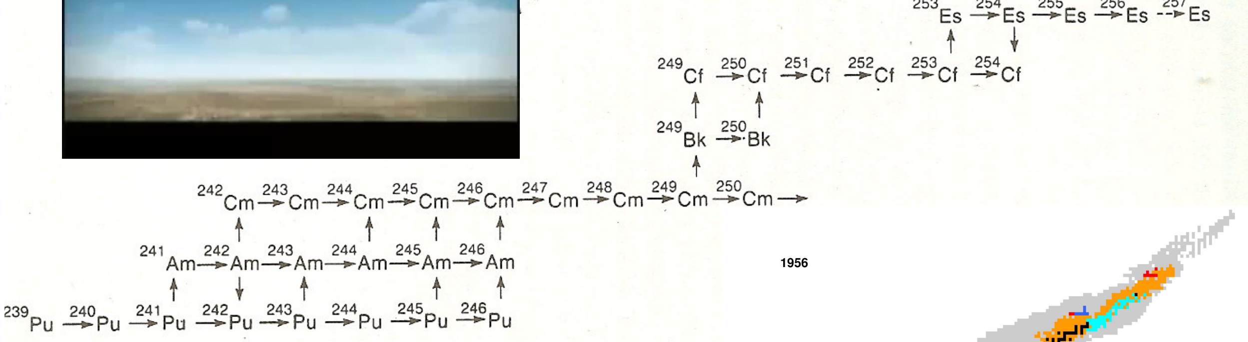


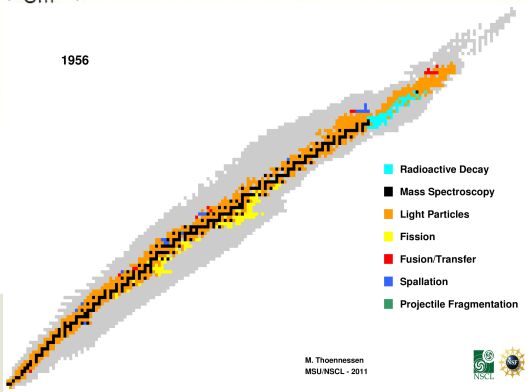
A. Ghiorso et al., Phys. Rev. Lett. 1 (1958) 1

Thermo-nuclear explosions I

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

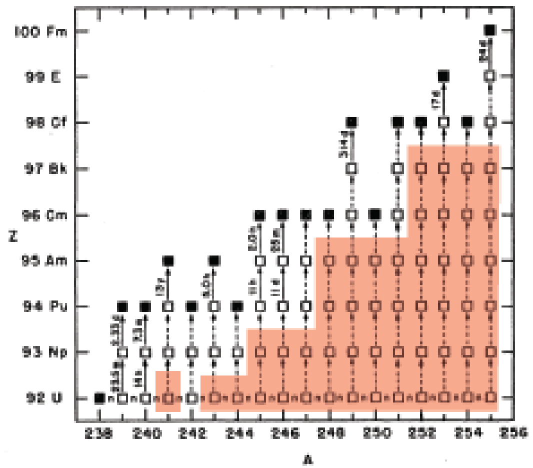
Rapid neutron capture



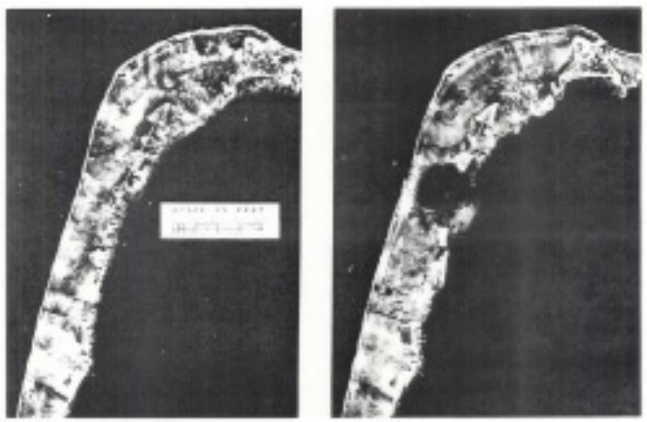


“The elements beyond uranium”,
G.T. Seaborg and W.D. Loveland (Wiley1990)

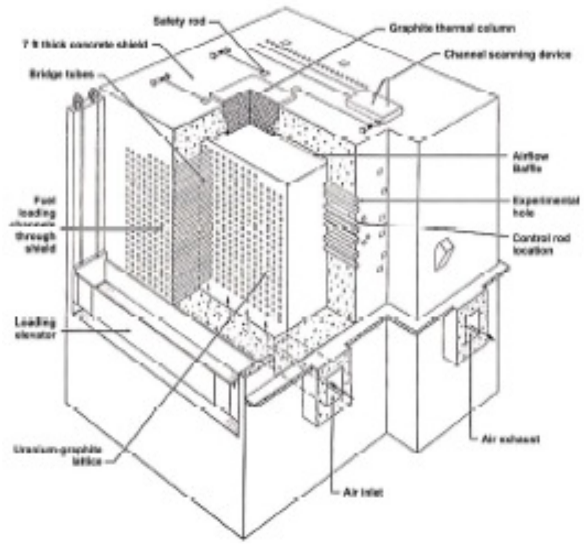
Thermo-nuclear explosions II



Successive neutron capture reactions followed by beta-decay

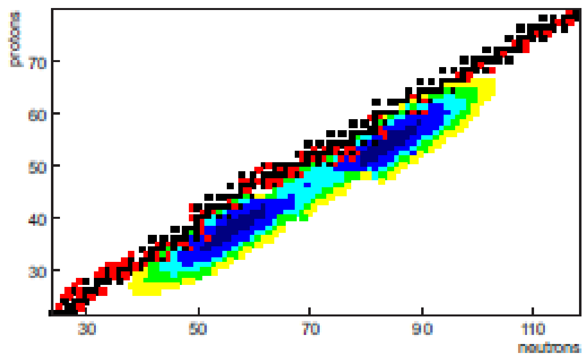


Neutron-induced reactions in reactors



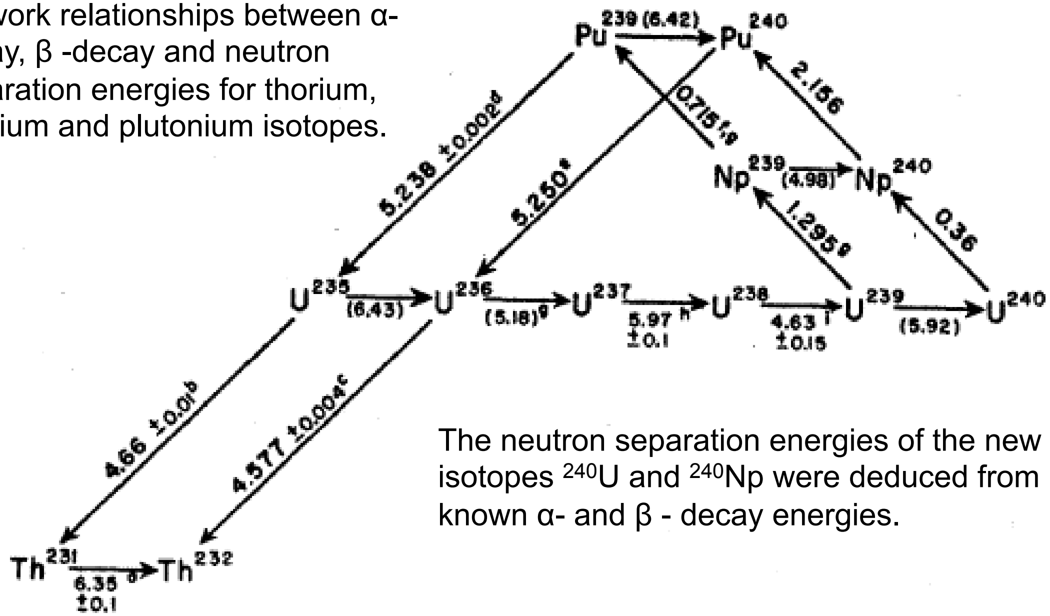
X-10 reactor in Oak Ridge

Neutron induced fission



Network relations

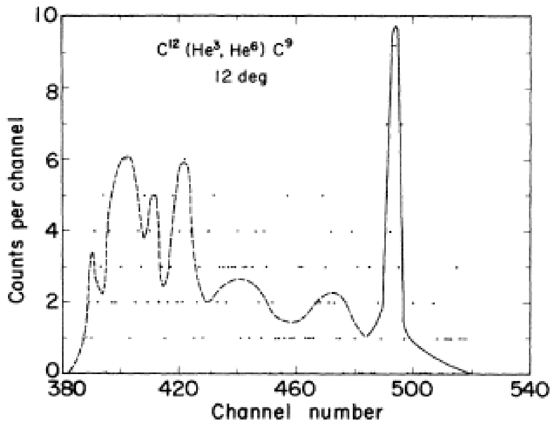
Network relationships between α-decay, β -decay and neutron separation energies for thorium, uranium and plutonium isotopes.



The neutron separation energies of the new isotopes ^{240}U and ^{240}Np were deduced from known α- and β - decay energies.

J.D. Knight et al., Phys Rev 91 (1953) 889

Missing mass spectra



$^{12}C(^{3}He,^{6}He)^{9}C$

Energy spectrum of ^{6}He ejectiles measured at 12° in a spectrograph.

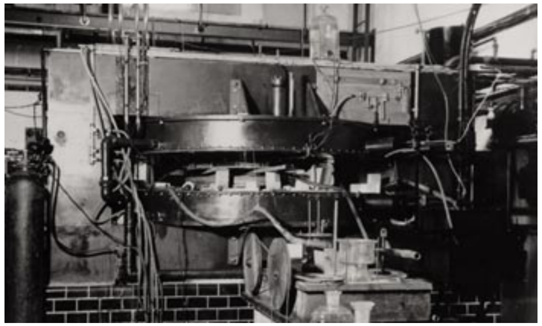
J. Cerny et al., Phys. Rev. Lett. 13 (1964) 726

First radioactive beam experiment

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)

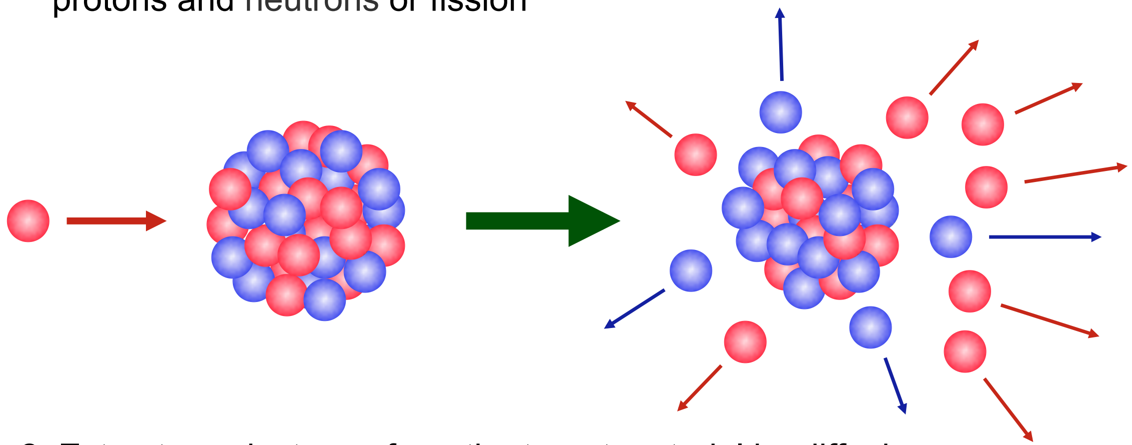
THE isotopes Kr^{89}, Kr^{90}, Kr^{91}, and their daughter substances have been investigated. Krypton formed in fission of uranium was pumped through a 10-m long tube directly from the cyclotron into the ion source of the isotope separator. The cyclotron and the isotope separator were operated simultaneously, 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

Production of Rare Isotopes at Rest
(ISOL technique)

1. Bombard a thick target of heavy nuclei with energetic light particles, e.g. 1 GeV protons, to achieve random removal of protons and neutrons or fission



2. Extract rare isotopes from the target material by diffusion or effusion; ionize and accelerate them to the desired energy → beam of high quality

1 GeV p+U: Light neutron-rich isotopes

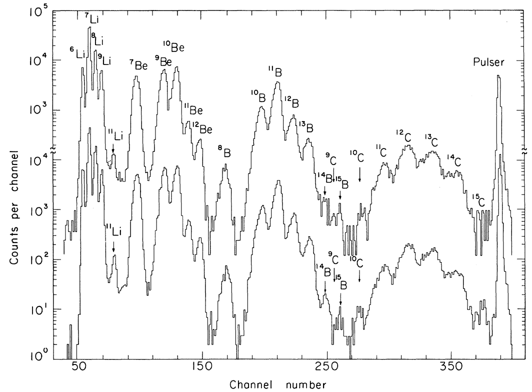
VOLUME 17, NUMBER 25 PHYSICAL REVIEW LETTERS 19 DECEMBER 1966

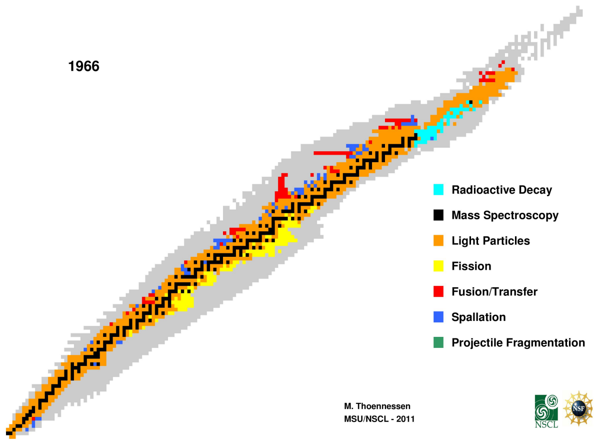
NEW ISOTOPES: ^{11}Li, ^{14}B, AND ^{15}B†

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)

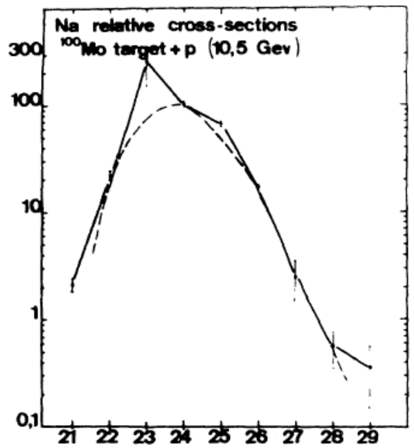


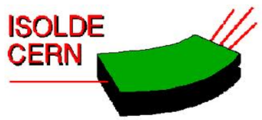


Isotope Separation On-Line (ISOL)

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)



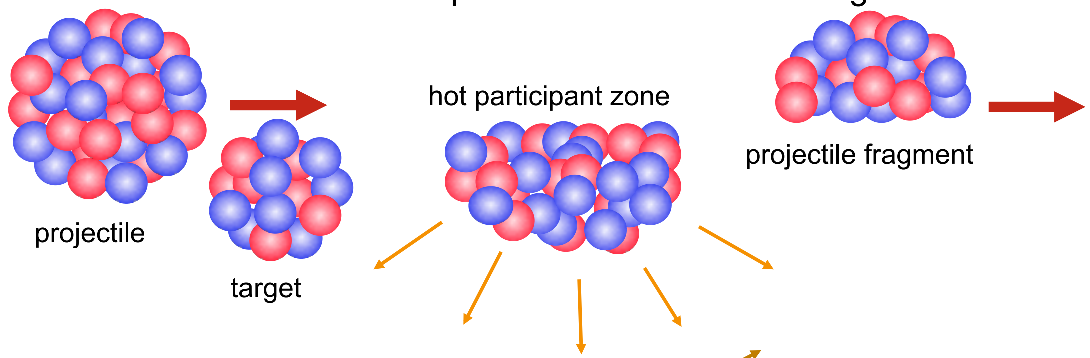


ISOLDE (Isotope Separation On-Line DEtector)

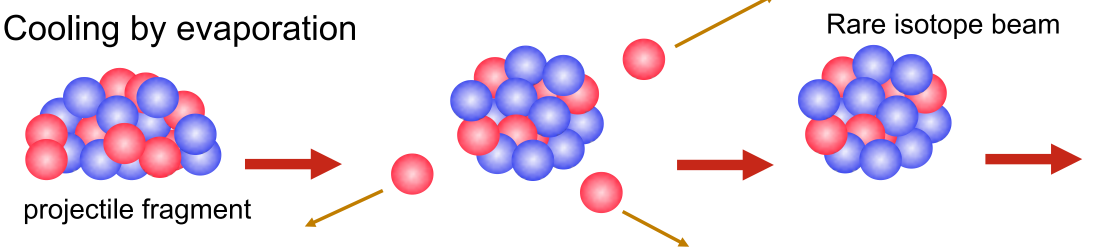
Phys. Rev. Lett. 20 (1968) 740

Production of Rare Isotopes in Flight

1. Accelerate heavy ion beam to high energy and pass through a thin target to achieve random removal of protons and neutrons in flight



2. Cooling by evaporation



Projectile fragmentation

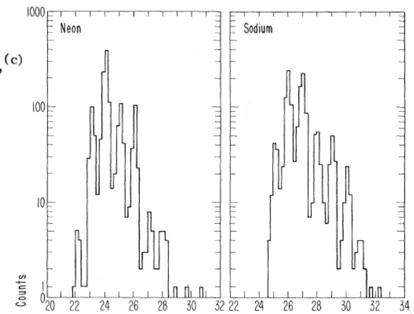
Observation of New Neutron-Rich Isotopes by Fragmentation of 205-MeV/Nucleon ^{40}Ar Ions

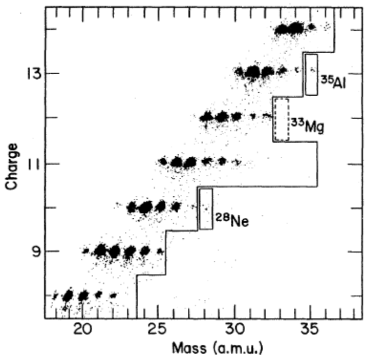
T. J. M. Symons, Y. P. Viyogi,[a] G. D. Westfall, P. Doll,[b] D. E. Greiner, H. Faraggi,[c] P. J. Lindstrom, and D. K. Scott
Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720

and

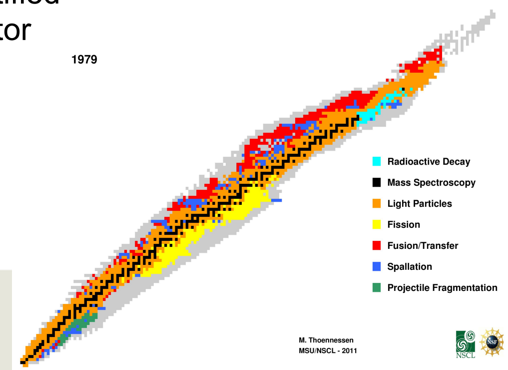
H. J. Crawford and C. McParland
Space Sciences Laboratory, University of California, Berkeley, California 94720

(Received 1 November 1978)



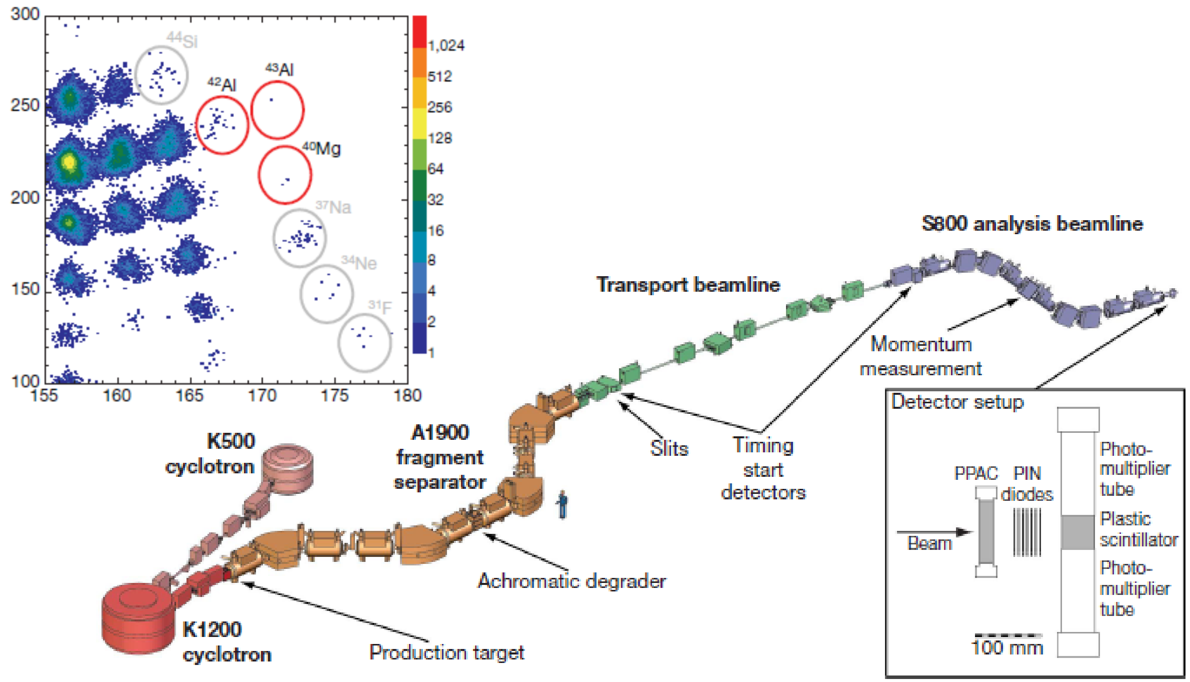


Fragments were detected in a zero-degree magnetic spectrometer and identified in a ΔE-E silicon detector telescope



Phys. Rev. Lett. 42 (1979) 40

Fragment separators (Spectrometers)



T. Baumann et al., Nature 449 (2007) 1022

Secondary beams

Observation of ^{10}He

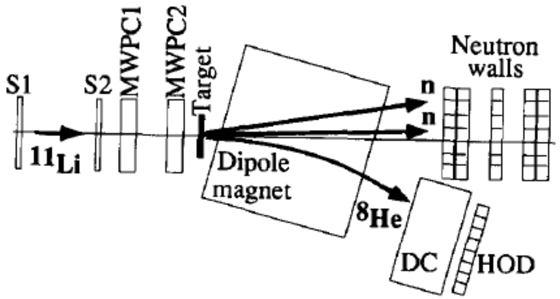
A.A. Korsheninnikov [a], K. Yoshida [b], D.V. Aleksandrov [a], N. Aoi [c], Y. Doki [c], N. Inabe [b], M. Fujimaki [b], T. Kobayashi [b], H. Kumagai [b], C.-B. Moon [d], E.Yu. Nikolskii [a], M.M. Obuti [b], A.A. Ogloblin [a], A. Ozawa [b], S. Shimoura [e], T. Suzuki [b], I. Tanihata [b], Y. Watanabe [b],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

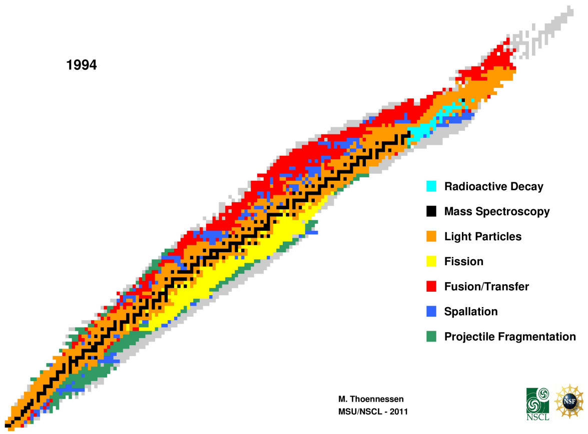
[a] *Kurchatov Institute, 123182 Moscow, Russia*
[b] *RIKEN, Hirosawa, Wako, Saitama 351-01, Japan*
[c] *Department of Physics, University of Tokyo, Hongo, Tokyo 113, Japan*
[d] *Department of Physics, Hoseo University, Chungnam 337-850, South Korea*
[e] *Department of Physics, Rikkyo University, Toshima,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

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

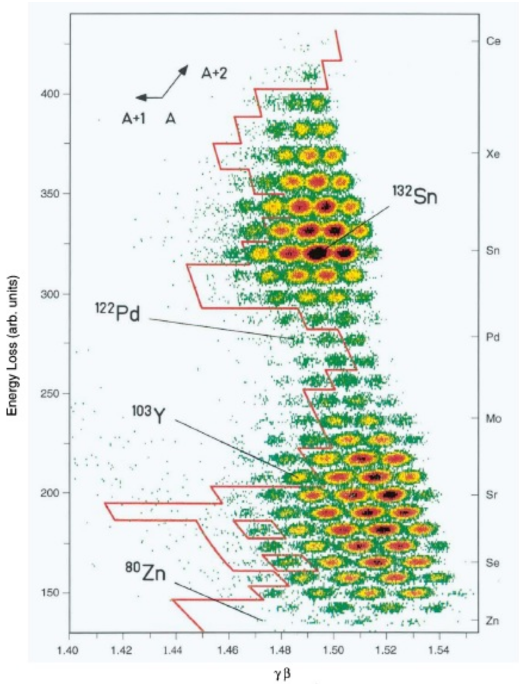
$^{18}O \longrightarrow {}^{11}Li+C \longrightarrow {}^{10}He+X$

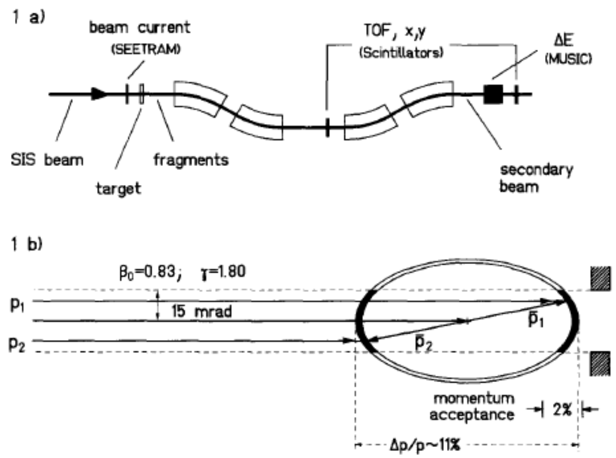
$^{10}He \longrightarrow {}^{8}He+n+n$





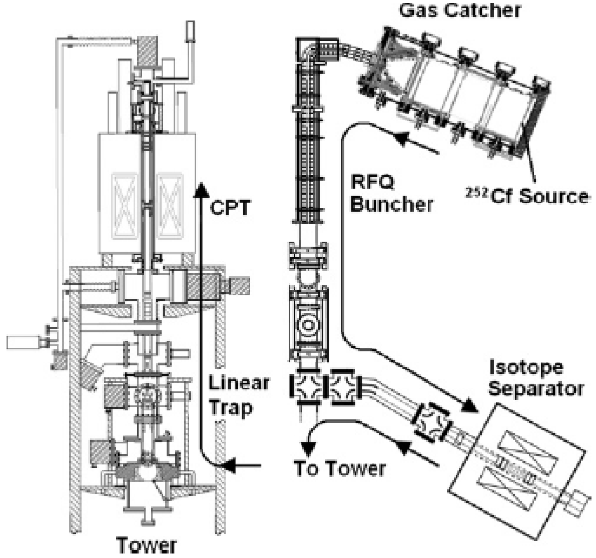
In-flight fission



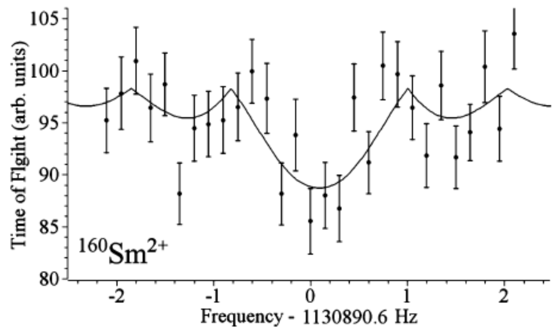


M. Bernas et al., Phys. Lett. B 331 (1994) 19

High precision mass measurements



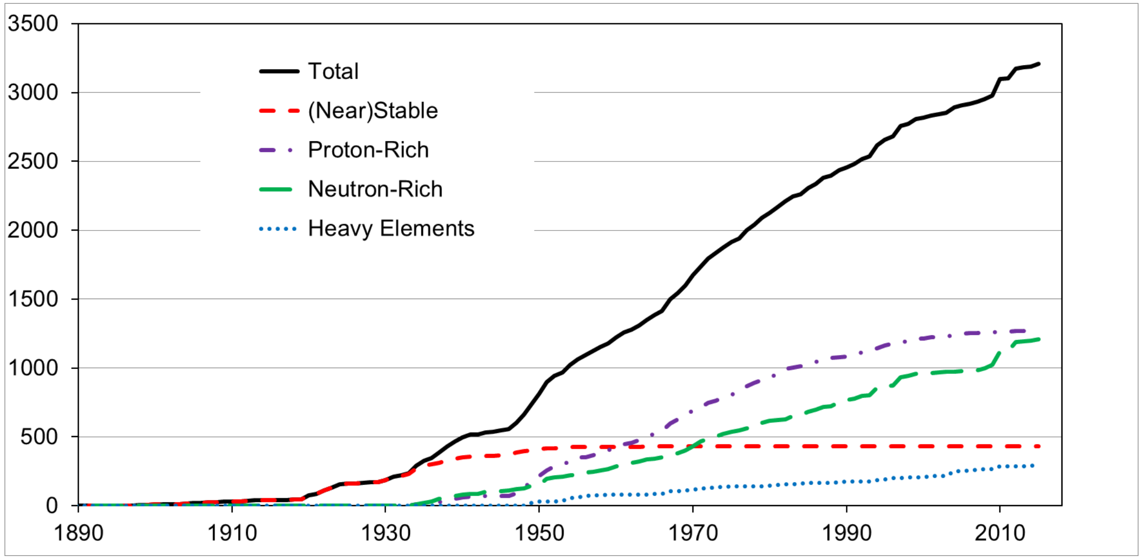
Canadian Penning Trap:
^{252}Cf fission source



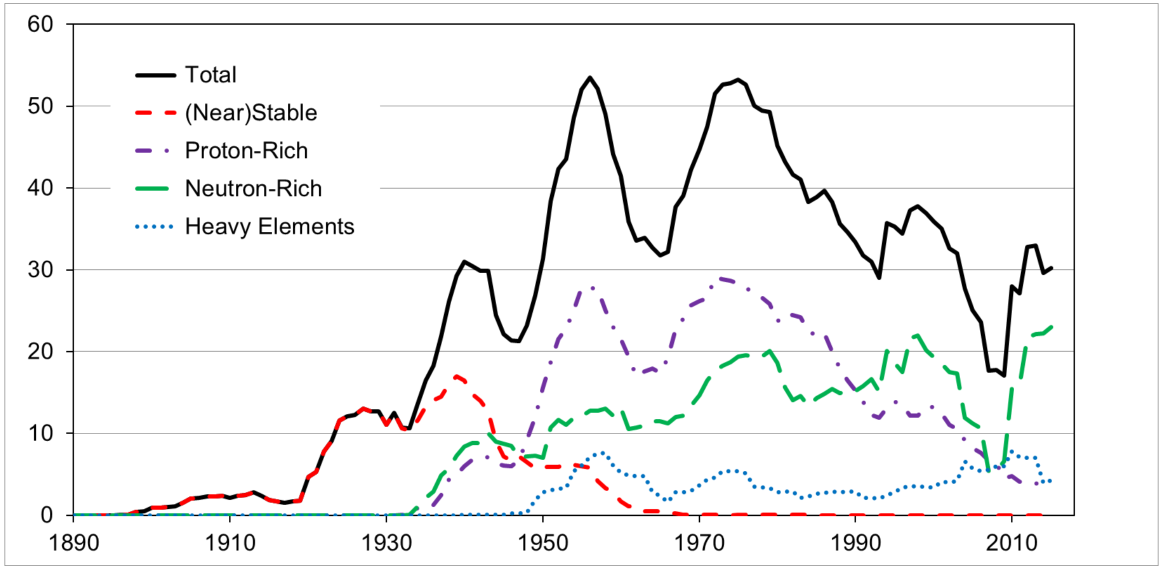
Mass excess: −60237(10) keV
AME03: −60420(200)# keV

J. Van Schelt et al., Phys. Rev. C 85 (2012) 045805

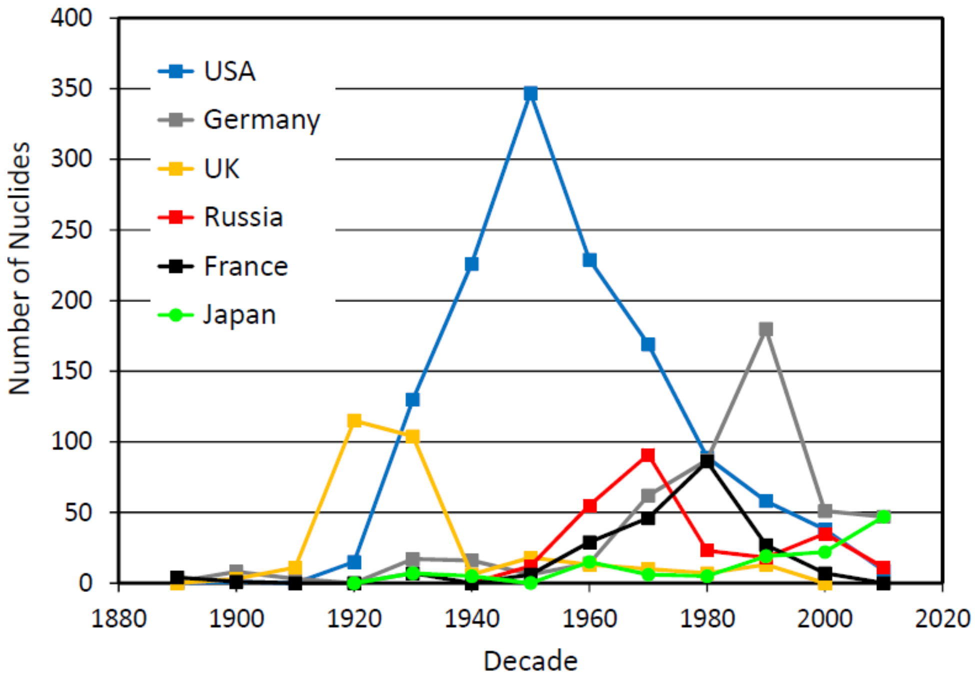
Known isotopes today



Five-year running average

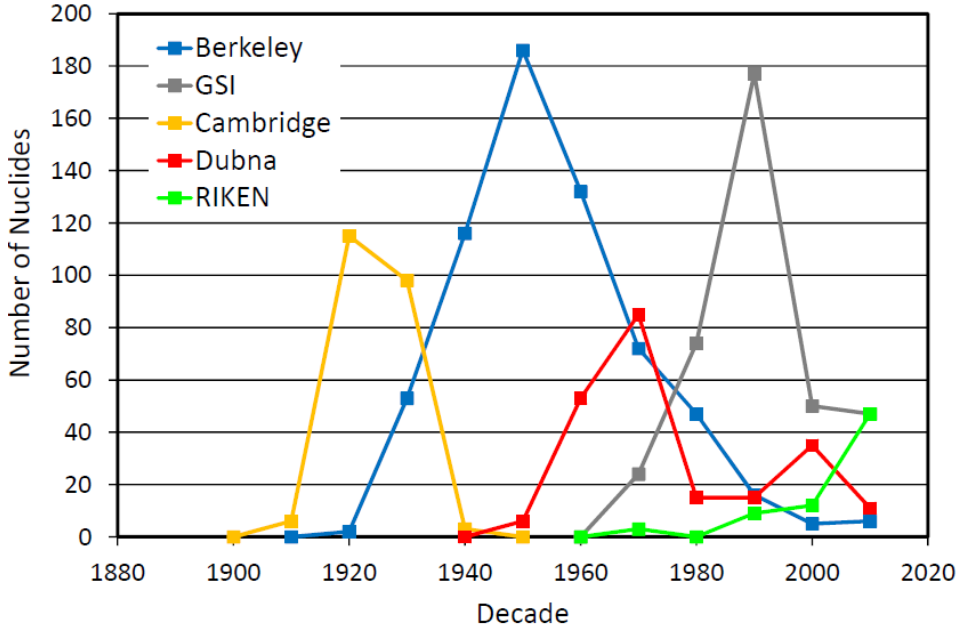


Leading countries



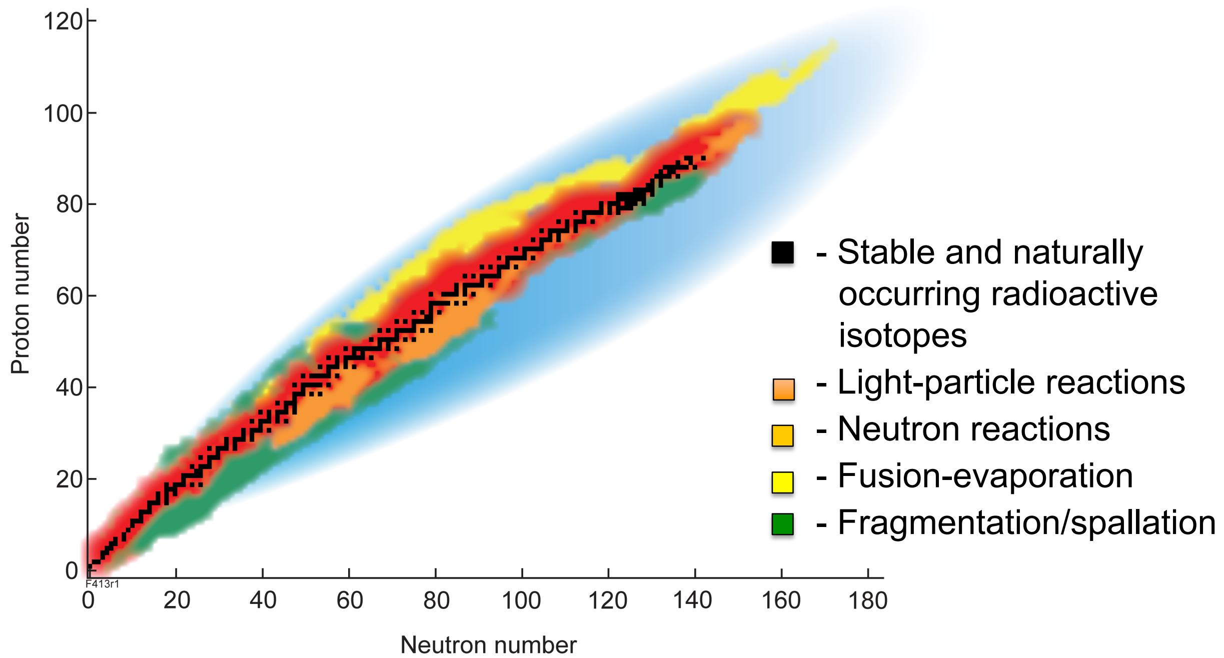
M. T., Nuclear Physics News 22, No.3, 19 (2012)

Leading laboratories

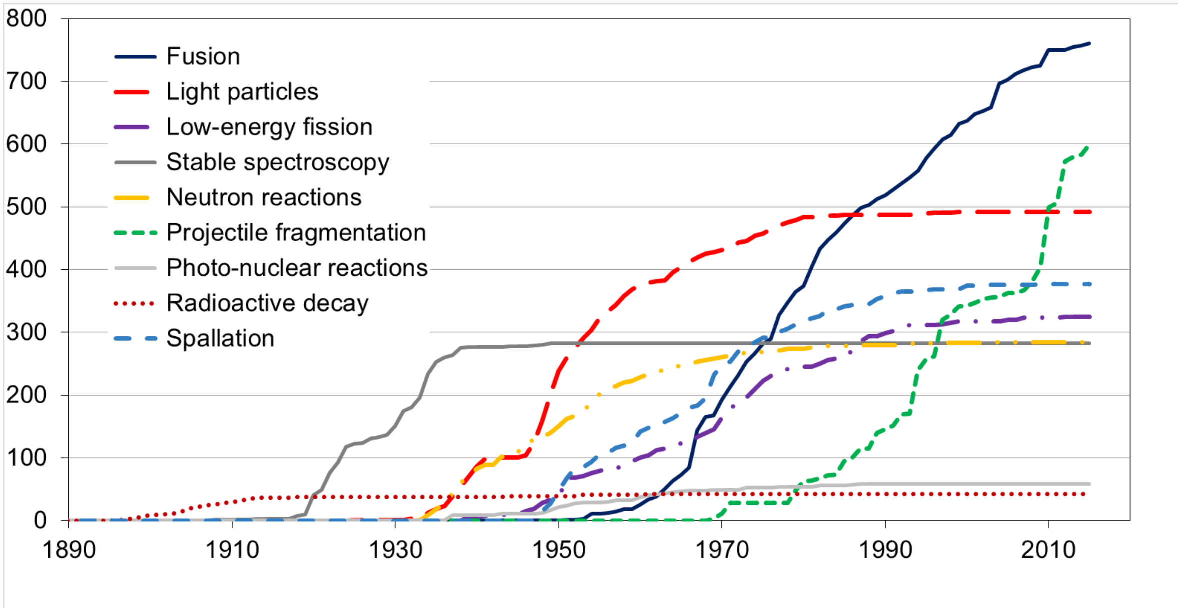


M. T., Nuclear Physics News 22, No.3, 19 (2012)

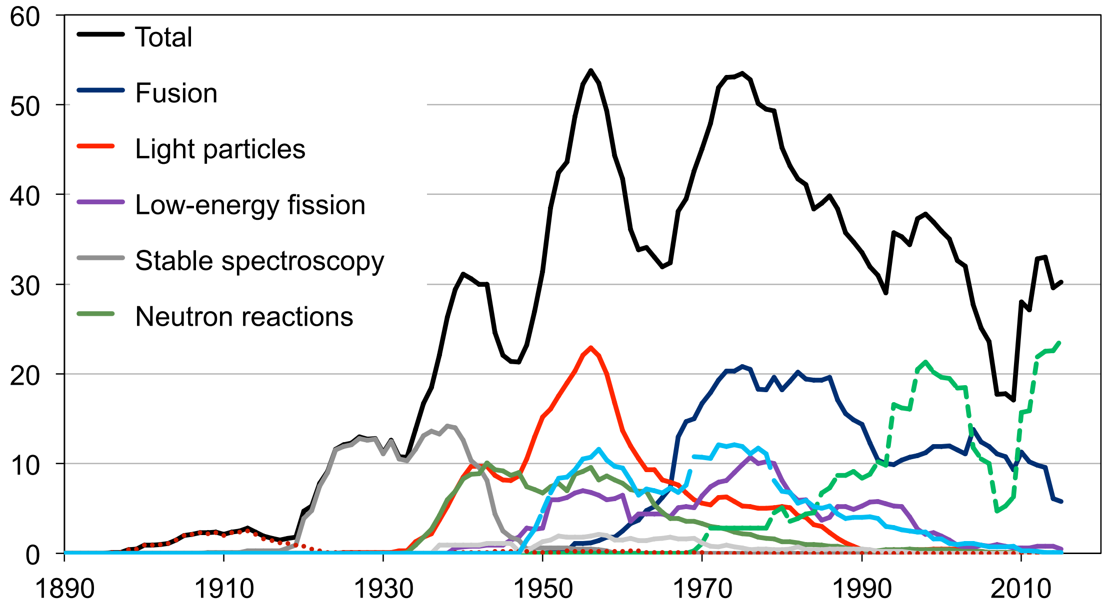
Production methods



Known isotopes by production mechanism

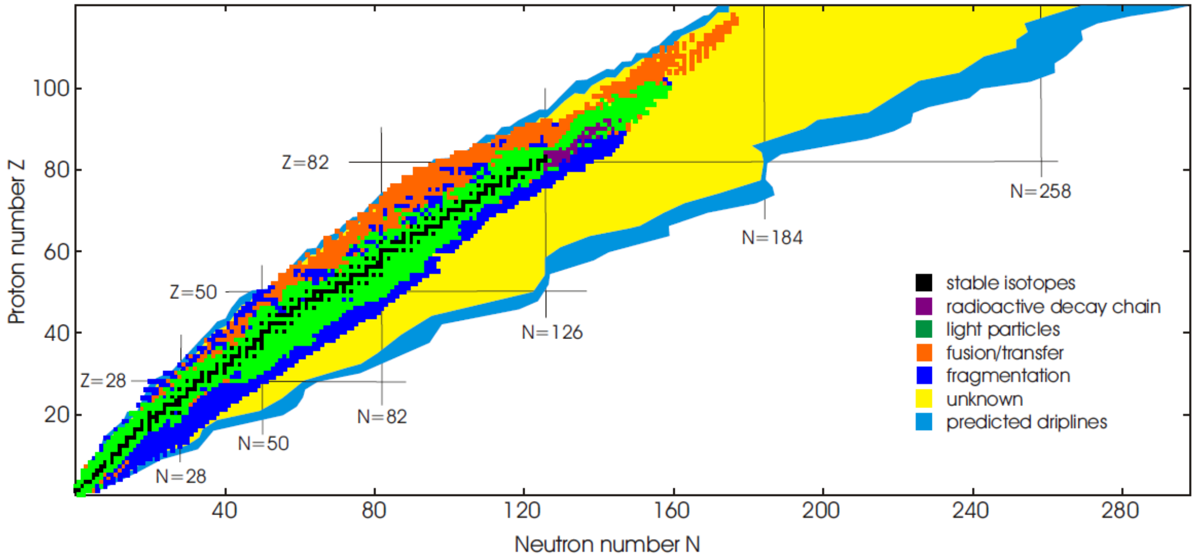


Five-year running average (production mechanism)



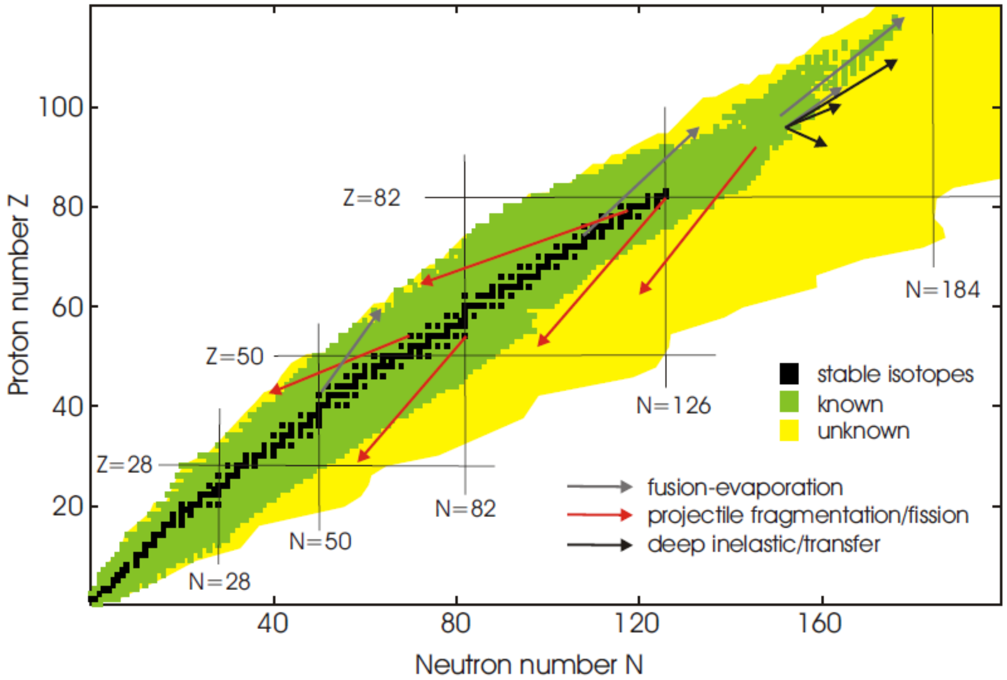
National Science Foundation
Michigan State University

How many more nuclides are there?



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

How can new nuclides be discovered?

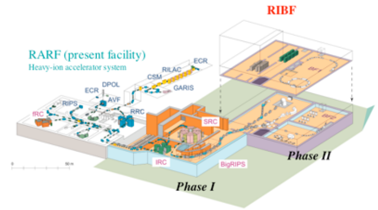


M. Thoennessen, Nucl. Data Sheets 118 (2014) 85

New fragmentation facilities

RIKEN NISHINA CENTER

RIKEN Nishina Center for Accelerator-Based Science

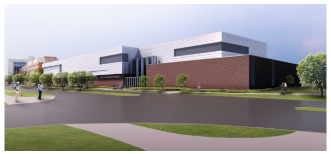


FAIR

FAIR Facility for Antiproton and Ion Research

GSI

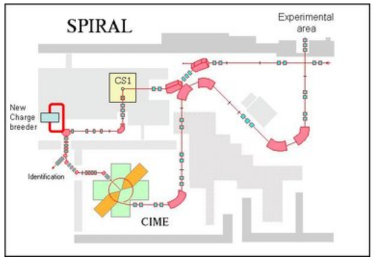
FACILITY FOR RARE ISOTOPE BEAMS



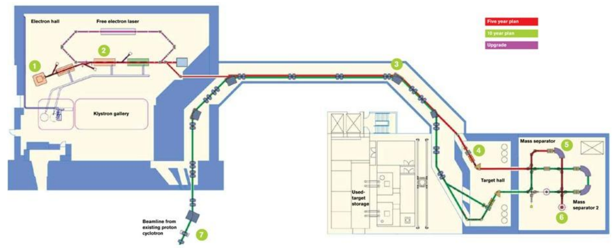
FRIB Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science
Michigan State University

ISOL facilities

GANIL
GRAND ACCELERATEUR NATIONAL D'IONS LOURDS



TRIUMF ARIEL
ADVANCED RARE ISOTOPE LABORATORY



ISOLDE

ISOLDE CERN

INFN
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Legnaro

SPES
exotic beams for science

Summary

- The quest for new discoveries pushes new technical developments
- Many of the most recent experimental techniques are based on methods developed many years ago.
- The new facilities will produce a tremendous amount of new data.
- Evaluation of these data is essential for the dissemination of the results.
- An experimental result that is not evaluated is a waste of time and money.