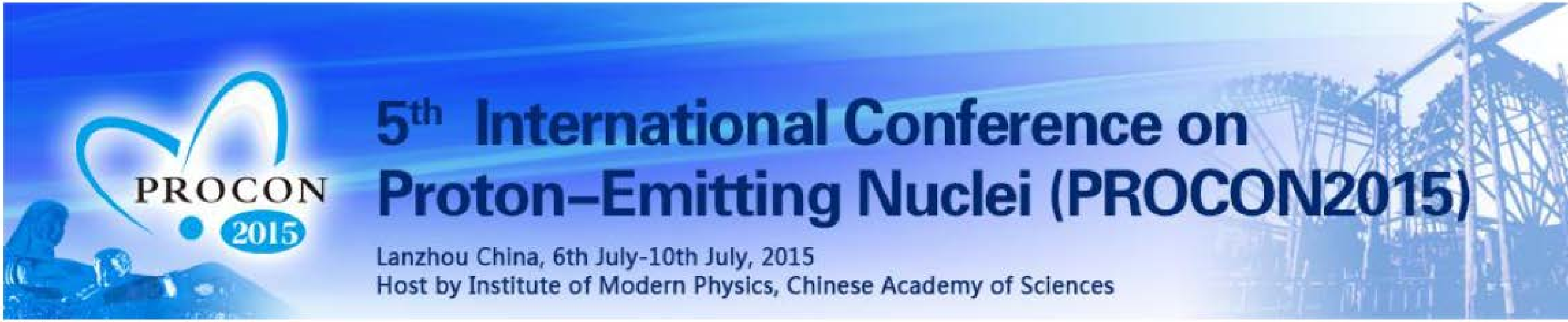
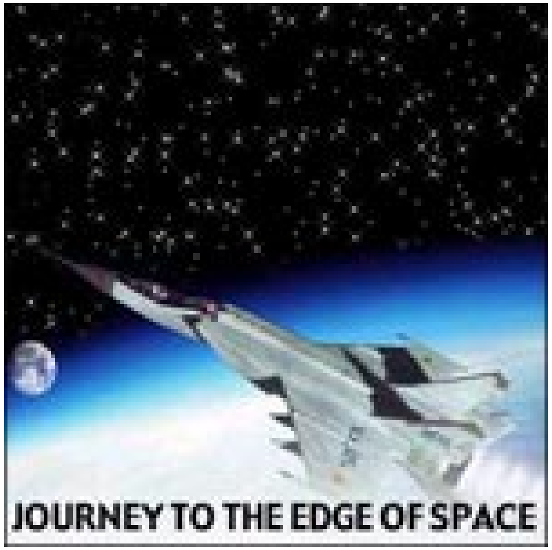


Discovery of Nuclei at and beyond the proton dripline

Michael Thoennessen
FRIB/NSCL
Michigan State University

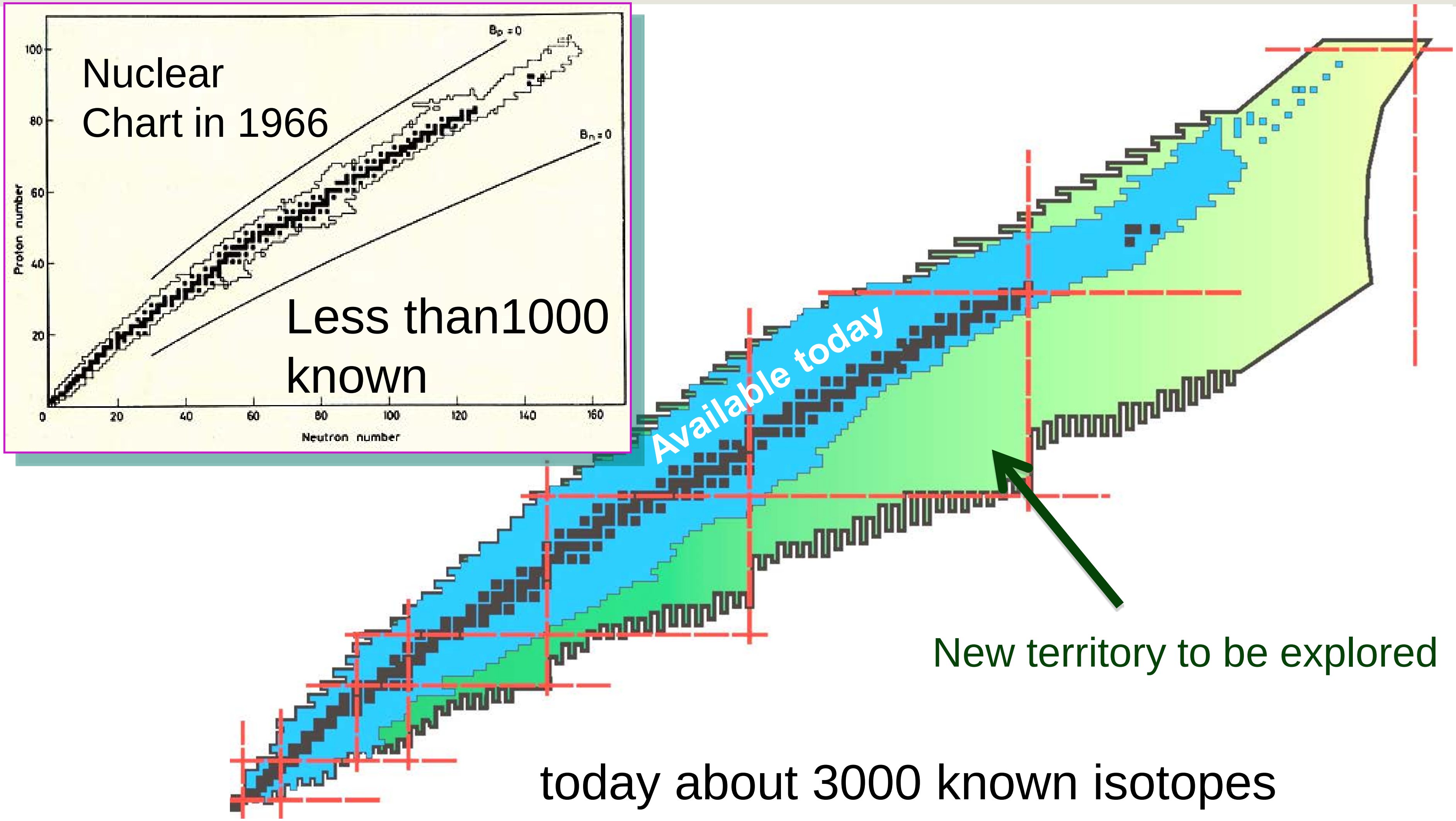
Why search for new isotopes?

- 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

Discovery potential

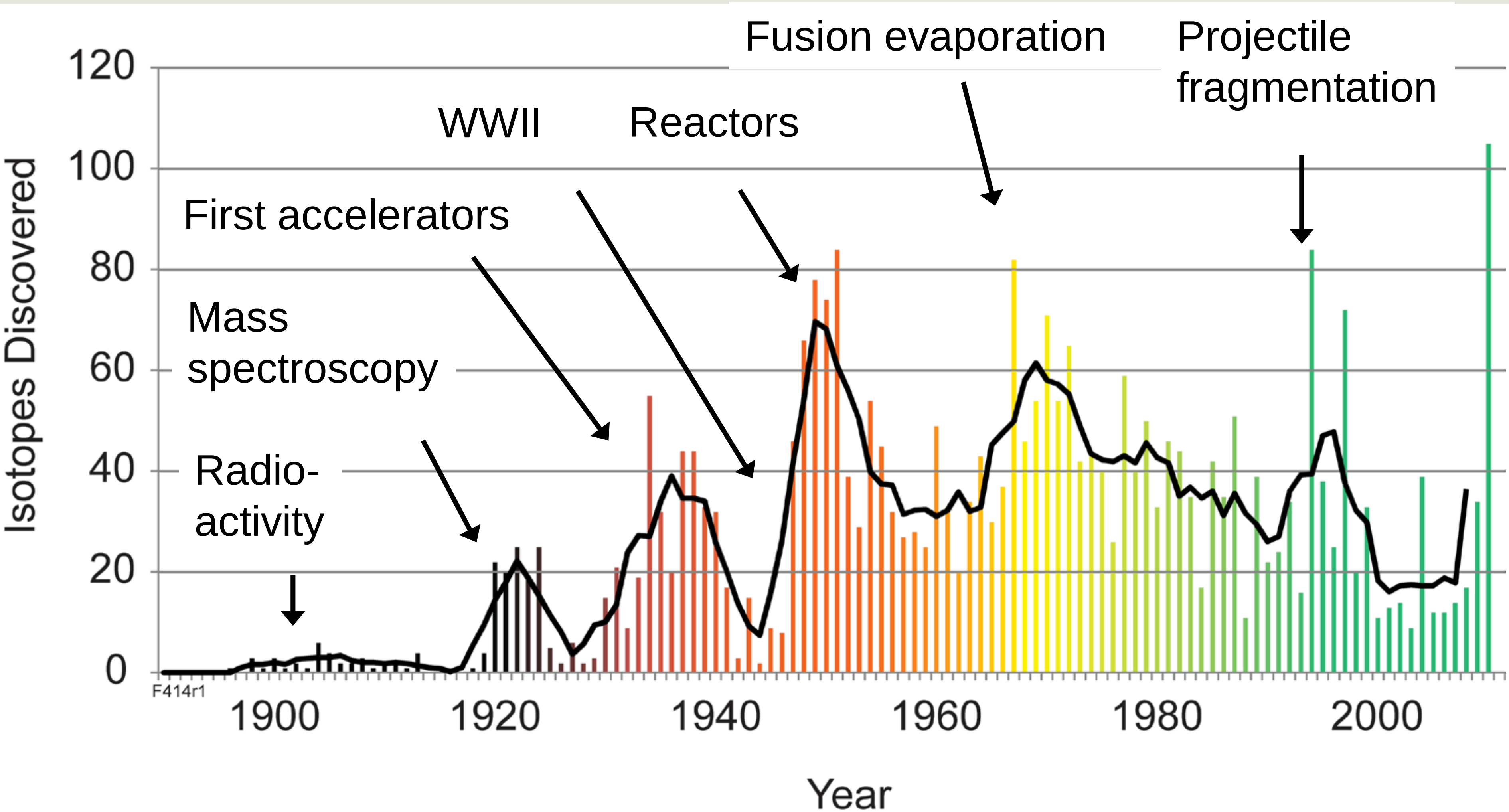


Renaissance of the discovery of isotopes

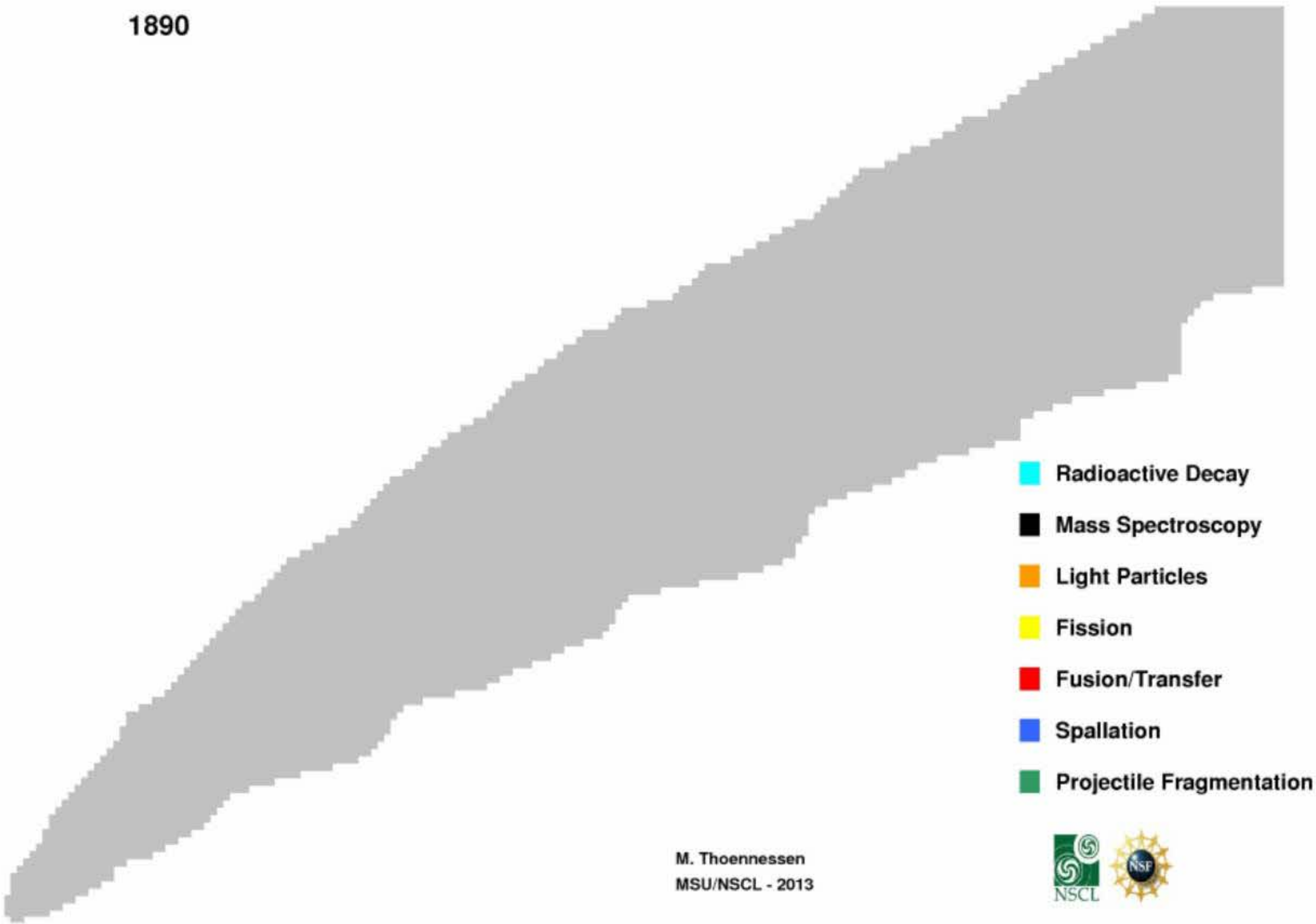
"Owing to the rapid advance in research on disintegration and the theory of nuclear structure, the existence or non-existence of rare isotopes has acquired an entirely unexpected importance and calls for a short review of their present situation."

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

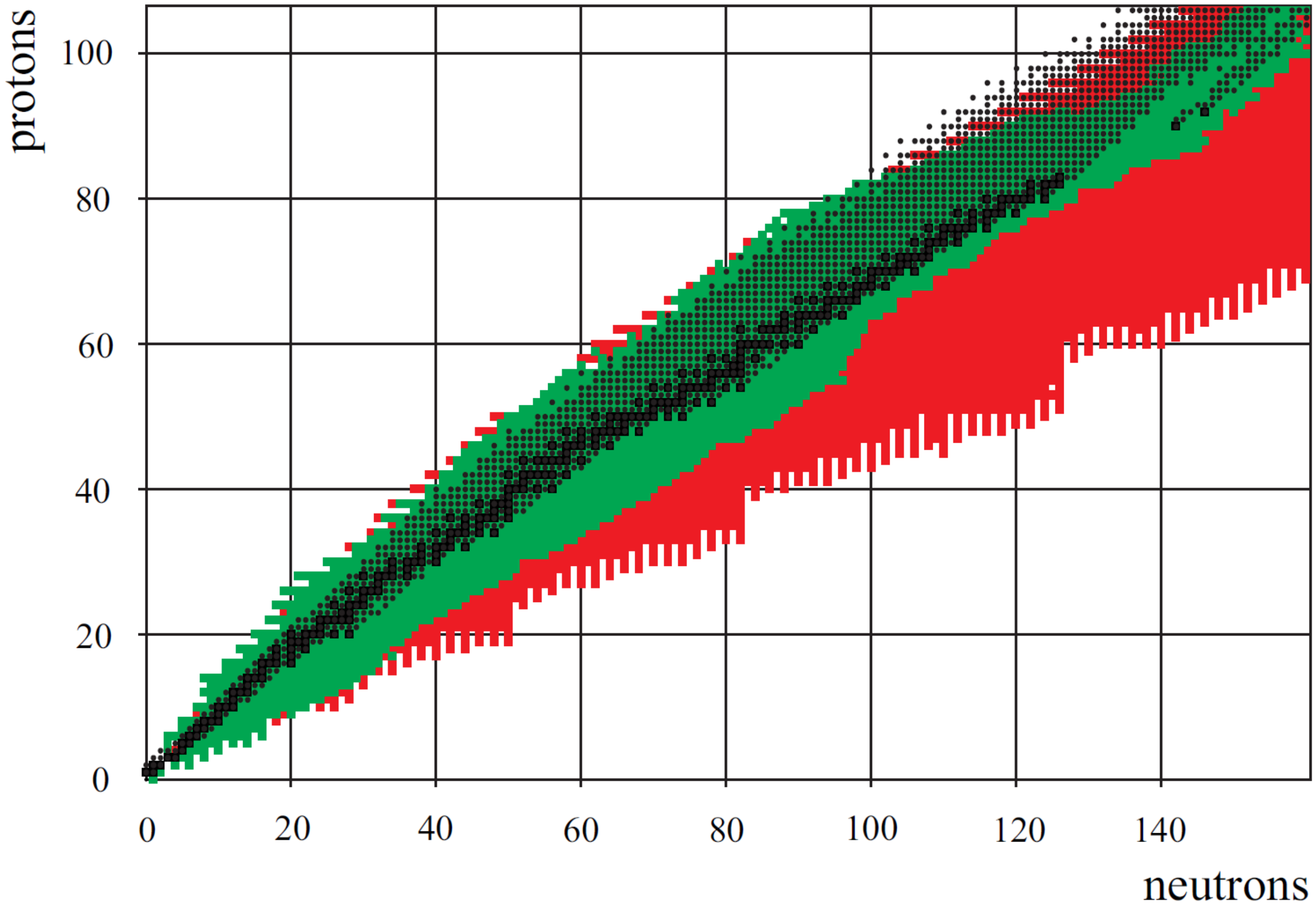
Discoveries are driven by new technologies



M. T. and B.M. Sherrill, Nature 473 (2011) 25 http://www.nscl.msu.edu/~thoennes/isotopes



Fusion evaporation reactions



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

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

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.

Phys. Rev. 80 (1950) 486

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.

Phys. Rev. 81 (1951) 154

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

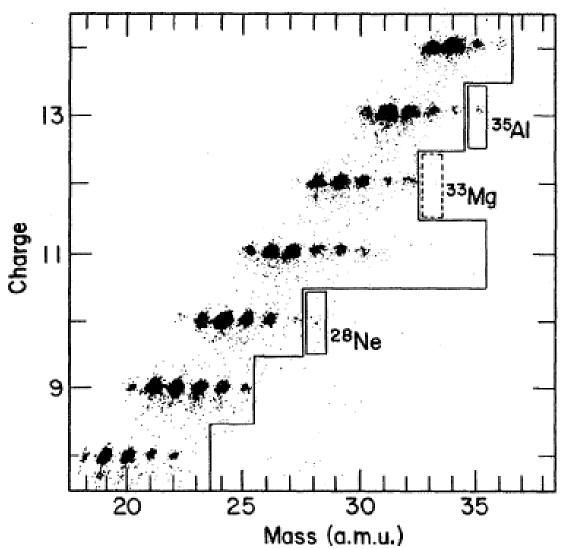
Projectile fragmentation

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

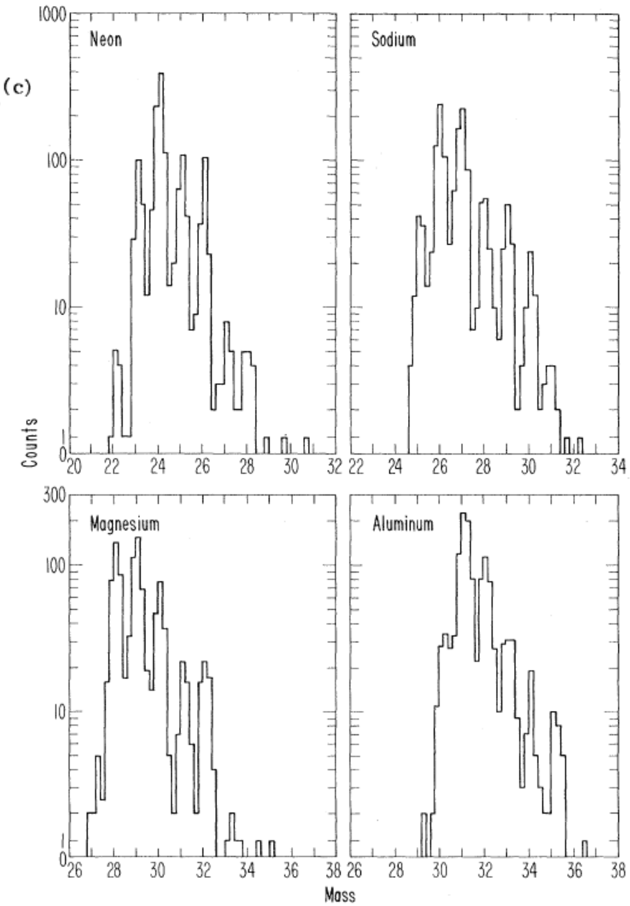
T. J. M. Symons, Y. P. Viyogi,[a] G. D. Westfall, P. Doll,[b] D. E. Greiner, H. Faraggi,[c] P. J. Lindstrom, and D. K. Scott
Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720

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

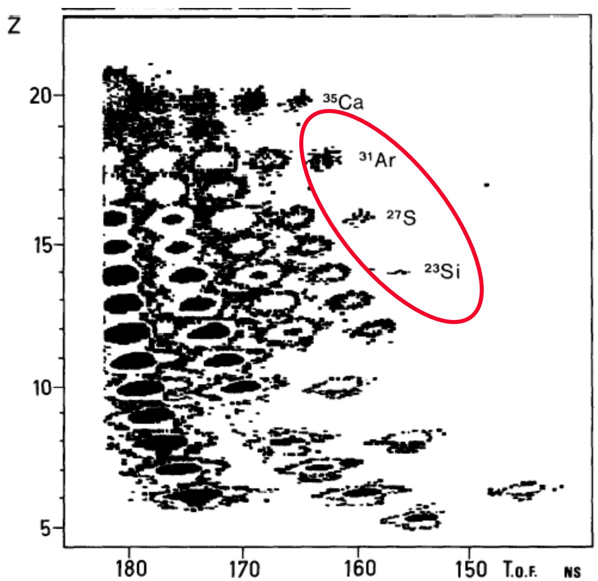


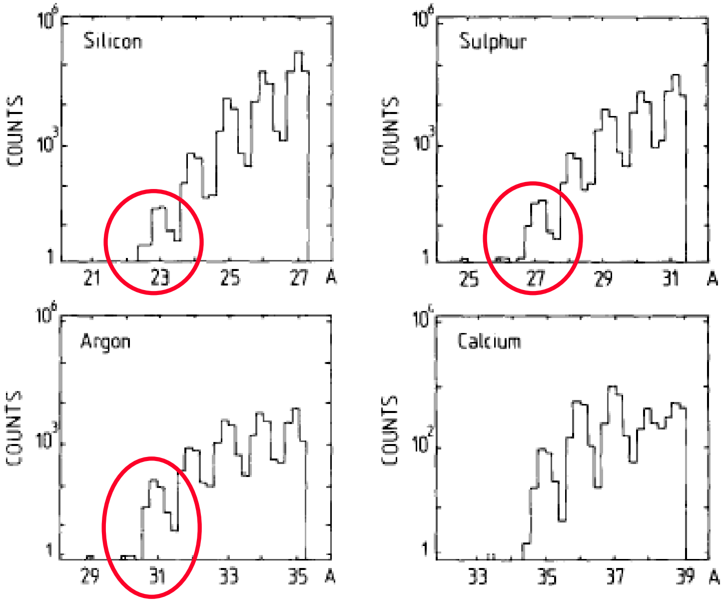
Phys. Rev. Lett. 42 (1979) 40

Projectile fragmentation at the proton dripline

MAPPING OF THE PROTON DRIP-LINE UP TO $Z = 20$: OBSERVATION OF THE $T_z = -\frac{5}{2}$ SERIES ^{23}Si, ^{27}S, ^{31}Ar AND ^{35}Ca*

M. LANGEVIN†[1], A. C. MUELLER[2], D. GUILLEMAUD-MUELLER[2], M.G. SAINT-LAURENT[2], R. ANNE[2], M. BERNAS[1], J. GALIN[1], D. GUERREAU[2], J.C. JACMART[1], S.D. HOATH[1,3], F. NAULIN[1], F. POUGHEON[1], E. QUINIOU[1] and C. DÉTRAZ[2]





M. Langevin et al., Nucl. Phys. A455 (1986) 149

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.

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

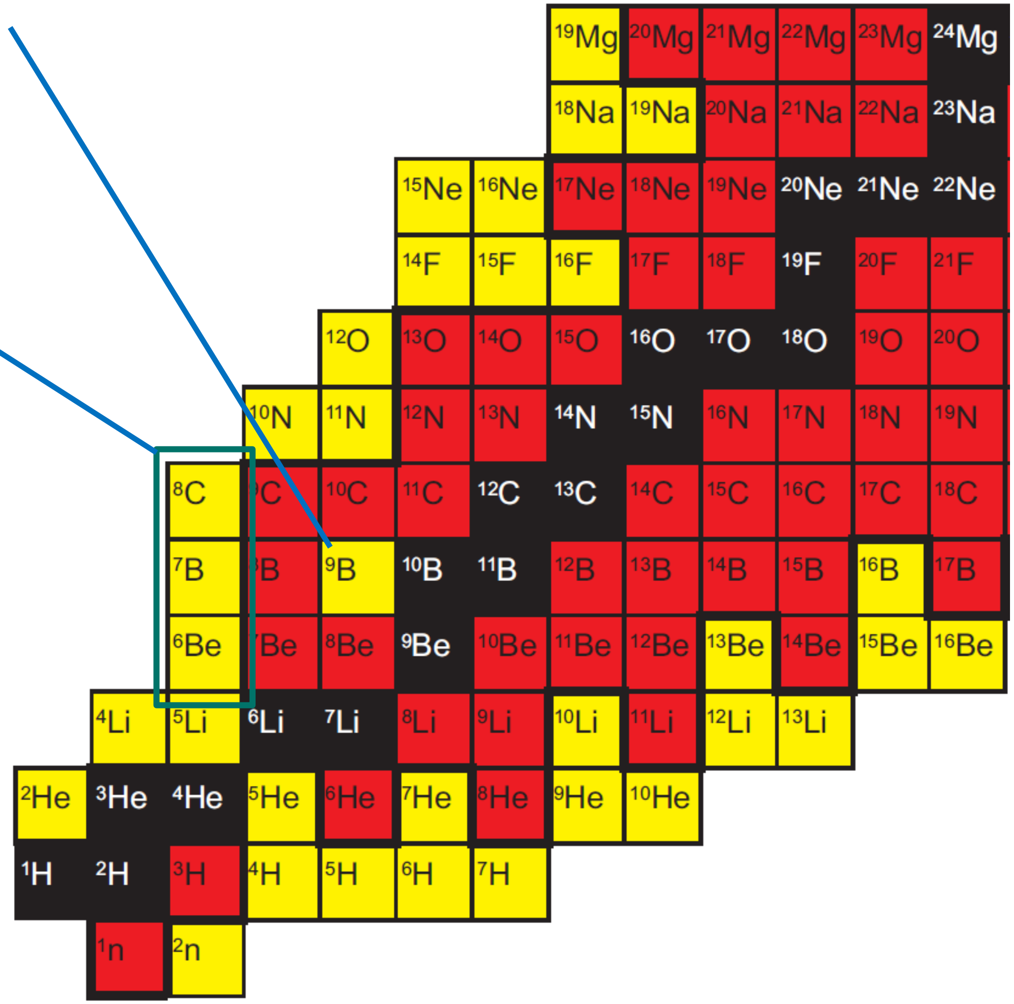
The brightness of the scintillations and the density of the tracks observed in the expansion chamber suggest that the particles are normal α-particles. If this point of view turns out to be correct, it seems not unlikely that the lithium isotope of mass 7 occasionally captures a proton and the resulting 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

Unbound nuclei

^{9}B: First proton unbound isotope

^{6}Be, ^{7}B, and ^{8}C:
2,3, and 4-proton
unbound isotopes



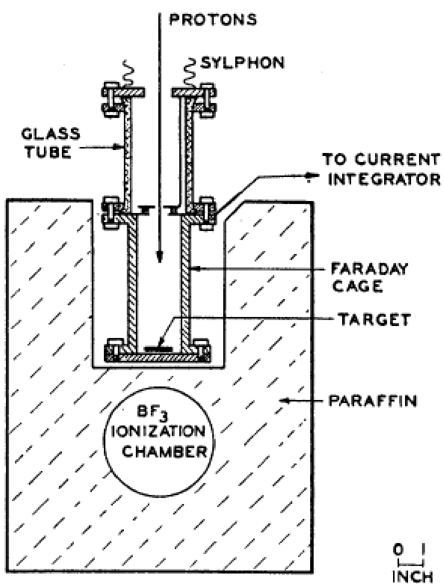
1940: First proton unbound nucleus: ^{9}B

DECEMBER 15, 1940 PHYSICAL REVIEW VOLUME 58

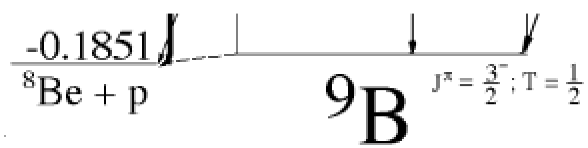
Thresholds for the Proton-Neutron Reactions of Lithium, Beryllium, Boron, and Carbon

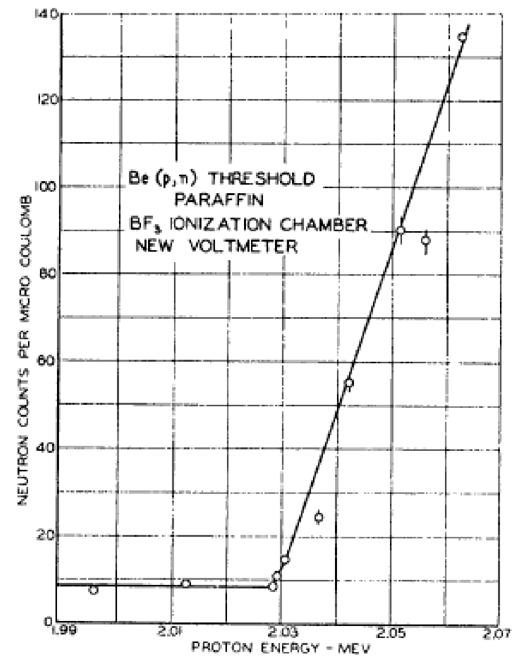
R. O. HAXBY,† W. E. SHOUPP,* W. E. STEPHENS‡ AND W. H. WELLS
Westinghouse Research Laboratories, East Pittsburgh, Pennsylvania

(Received August 30, 1940)



$^{9}Be(p,n)^{9}B$





R.O. Haxby et al., Phys. Rev. 58 (1940) 1035

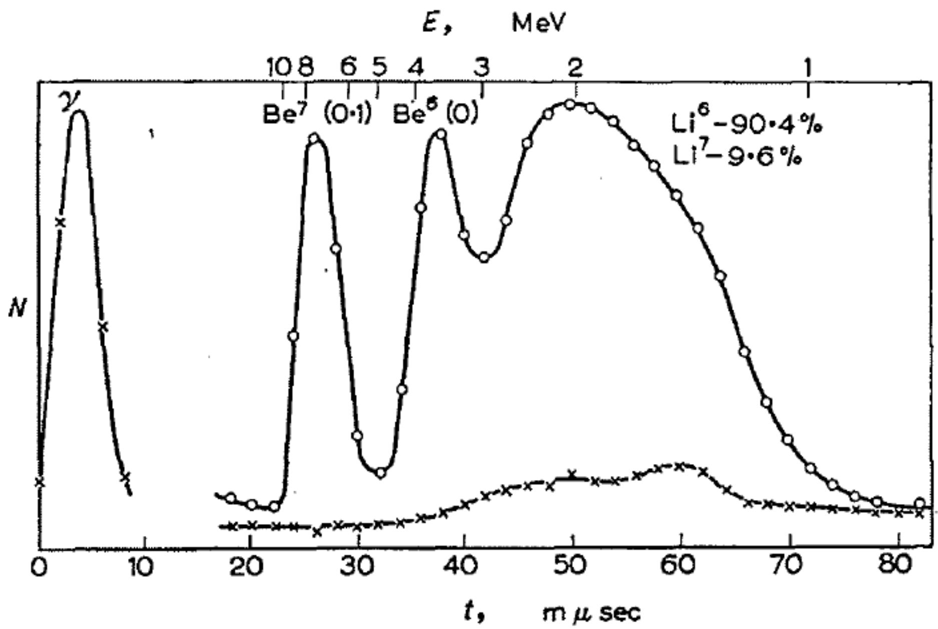
1957: Two-proton unbound nucleus: ^{6}Be

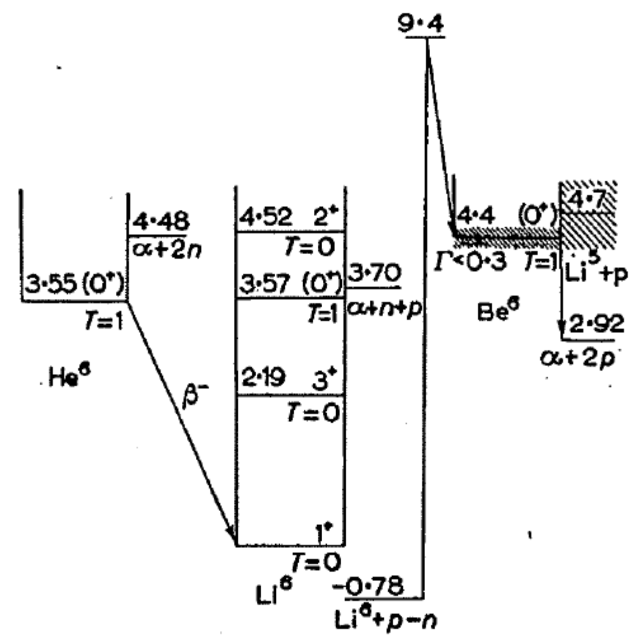
THE (*p*,*n*) REACTION ON LITHIUM AND THE GROUND STATE OF THE ^{6}Be NUCLEUS*

G. F. Bogdanov, N. A. Vlasov, S. P. Kalinin, B. V. Rybakov and V. A. Sidorov

(*Received* 1 *June* 1957)

^{6}Li(p,n)^{6}Be





G.F. Bogdanov et al., J. Nucl. Ener. 8 (1958) 148

1967: Three-proton unbound nucleus: ^{7}B

VOLUME 19, NUMBER 25 PHYSICAL REVIEW LETTERS 18 DECEMBER 1967

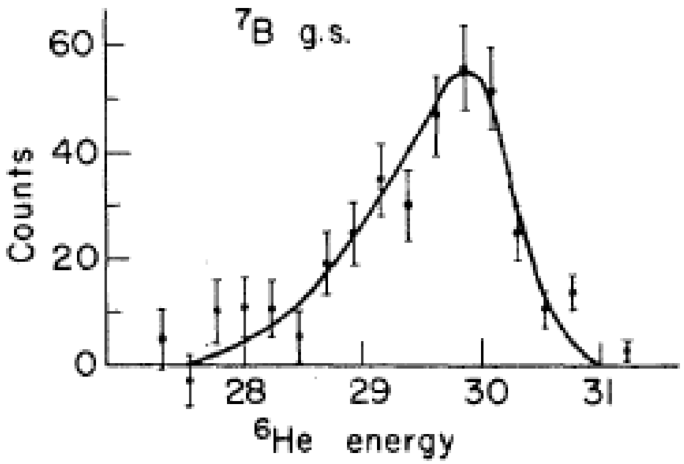
UNBOUND NUCLIDE ^{7}B†

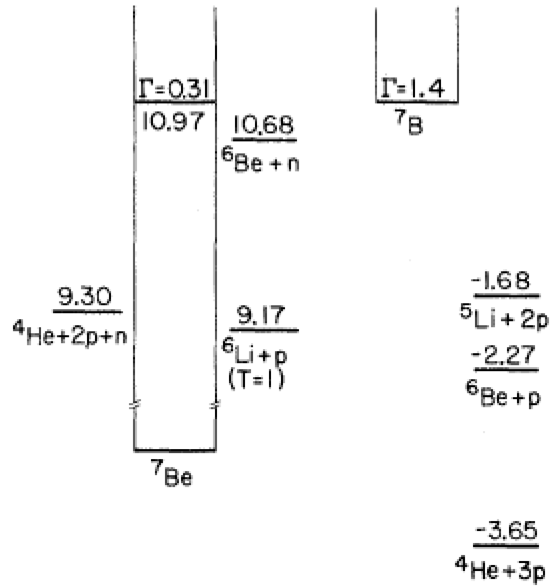
Robert L. McGrath and Joseph Cerny
Lawrence Radiation Laboratory and Department of Chemistry, University of California, Berkeley, California

and

Edwin Norbeck*
Department of Physics, University of Iowa, Iowa City, Iowa
(Received 10 November 1967)

$^{10}B(^{3}He,^{6}He)^{7}B$





R.L. McGrath et al., Phys. Rev. Lett. 19 (1967) 1442

1974: Four-proton unbound nucleus: ^{9}C

VOLUME 32, NUMBER 21 PHYSICAL REVIEW LETTERS 27 MAY 1974

Highly Proton-Rich $T_z = -2$ Nuclides: ^{8}C and ^{20}Mg

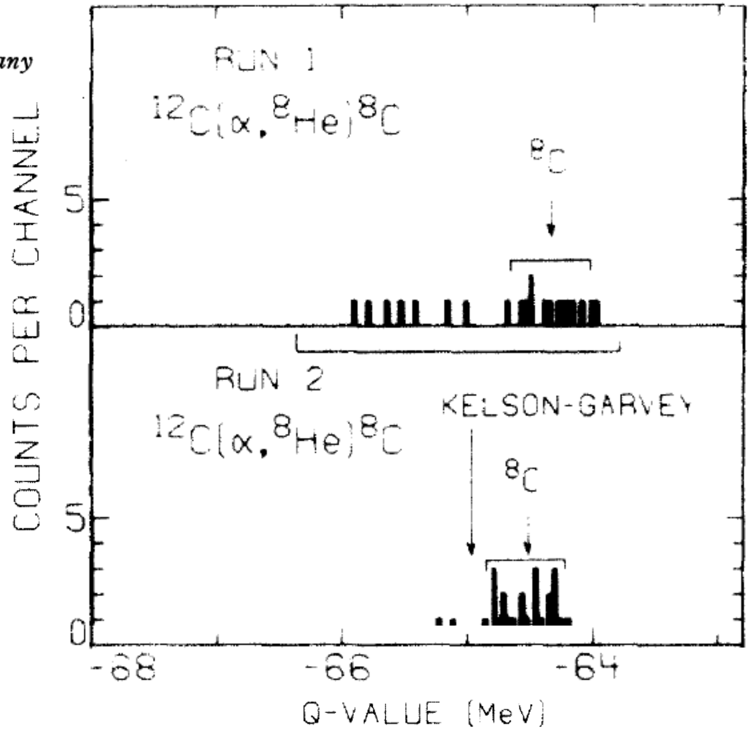
R. G. H. Robertson
Cyclotron Laboratory and Physics Department, Michigan State University, East Lansing, Michigan 48824*

and

S. Martin, W. R. Falk,† D. Ingham, and A. Djaloeis
Institut für Kernphysik, Kernforschungsanlage, 517 Jülich, West Germany

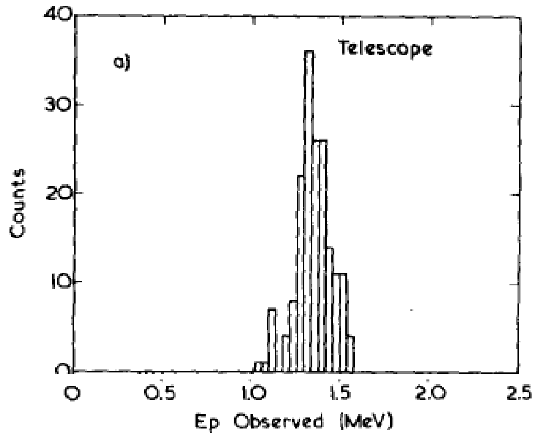
(Received 8 April 1974)

$^{12}C(\alpha,^{8}He)^{8}C$



R.G.H. Robertson et al., Phys. Rev. Lett. 32 (1974) 1207

1970: Proton radioactivity



$^{16}O(^{40}Ca,p2n)^{53}Co$

$^{53}Co^{m}$: A PROTON-UNSTABLE ISOMER†

K. P. JACKSON *, C. U. CARDINAL **, H. C. EVANS ‡ and N. A. JELLEY
Nuclear Physics Laboratory, University of Oxford, England

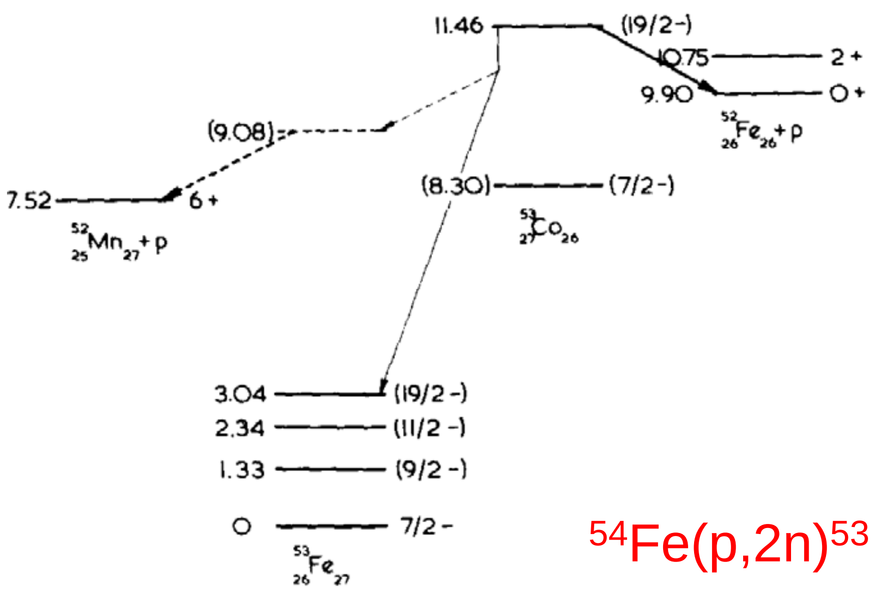
J. CERNY ‡‡
Nuclear Physics Laboratory, University of Oxford, England: and Lawrence Radiation Laboratory and Department of Chemistry, University of California, Berkeley, California 94720, USA.

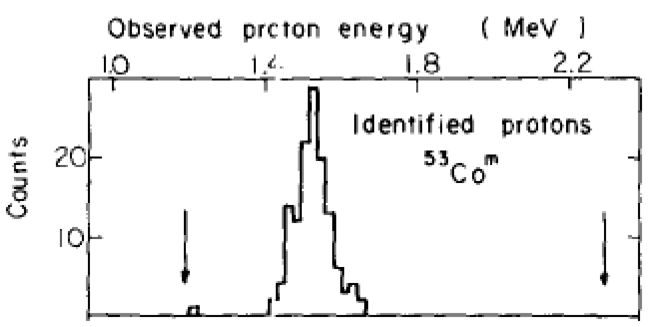
Received 23 September 1970

CONFIRMED PROTON RADIOACTIVITY‡ OF $^{53}Co^{m}$

J. CERNY, J. E. ESTERL, R. A. GOUGH* and R. G. SEXTRO
Department of Chemistry and Lawrence Radiation Laboratory
University of California, Berkeley, California 94720, USA

Received 23 September 1970





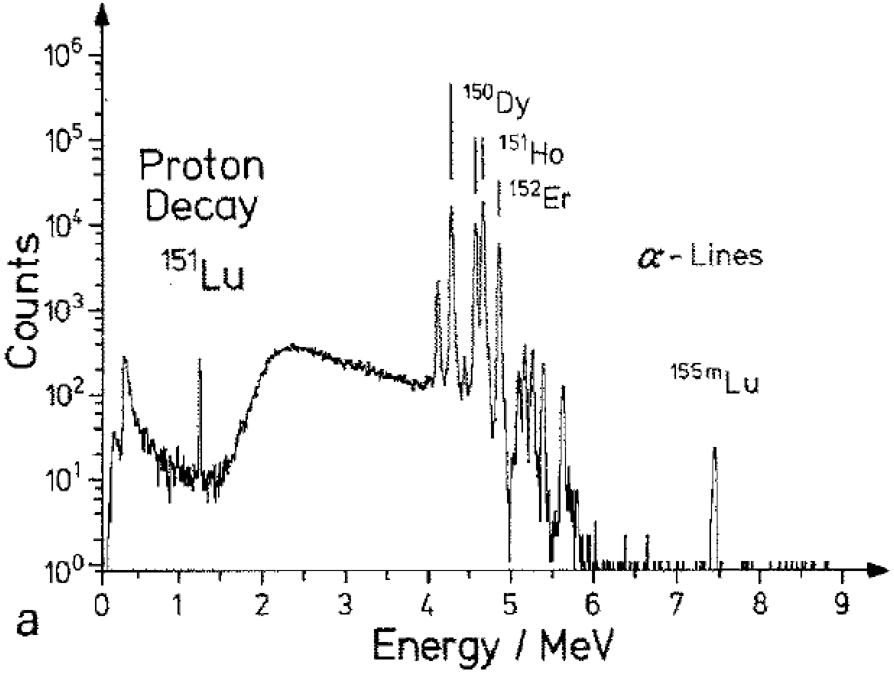
$^{54}Fe(p,2n)^{53}Co$

K.P. Jackson et al., Phys. Lett. 33B (1970) 281
J. Cerny et al., Phys. Lett. 33B (1970) 284

1982: Ground-state proton radioactivity

Proton Radioactivity of ^{151}Lu

S. Hofmann, W. Reisdorf, G. Münzenberg, F.P. Heßberger, J.R.H. Schneider, and P. Armbruster
Gesellschaft für Schwerionenforschung mbH, Darmstadt, Federal Republic of Germany



^{96}Ru(^{58}Ni,p2n)^{151}Lu

S. Hofmann et al., Z. Phys. A 305 (1982) 111

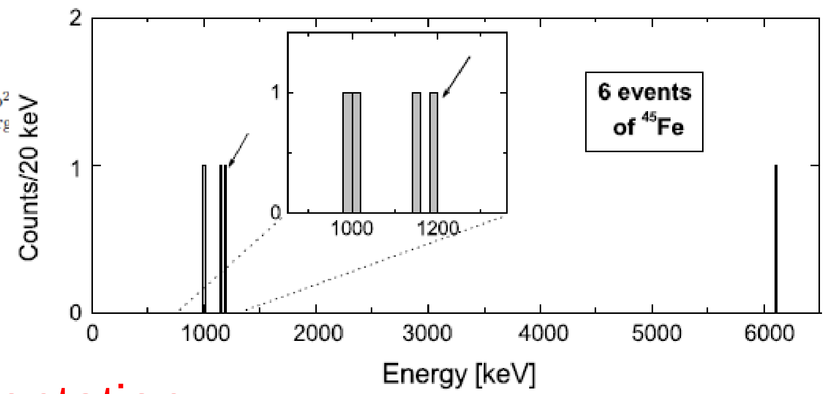
2002: Two-proton radioactivity

First evidence for the two-proton decay of ^{45}Fe

M. Pfützner[1,a], E. Badura[2], C. Bingham[3], B. Blank[4], M. Chartier[5], H. Geissel[2], J. Giovinazzo[4], L.V. Grigorenko[2], R. Grzywacz[1], M. Hellström[2], Z. Janas[1], J. Kurcewicz[1], A.S. Lalleman[4], C. Mazzocchi[2], I. Mukha[2], G. Münzenberg, C. Plettner[2], E. Roeckl[2], K.P. Rykaczewski[6,1], K. Schmidt[7], R.S. Simon[2], M. Stanoiu[8], and J.-C. Thomas[4]

[1] Institute of Experimental Physics, Warsaw University, PL-00-681 Warszawa, Poland
[2] GSI, Planckstrasse 1, D-64291 Darmstadt, Germany
[3] Department of Physics and Astronomy, University of Tennessee, Knoxville 37996 TN, USA
[4] CEN Bordeaux-Gradignan, F-33175 Gradignan Cedex, France
[5] Oliver Lodge Laboratory, Department of Physics, University of Liverpool, Liverpool, L69 3BX, UK
[6] Physics Division, ORNL, Oak Ridge, TN 37831-6371, USA
[7] Department of Physics and Astronomy, University of Edinburgh, Edinburgh EH9 3JZ, UK
[8] GANIL, BP 5027, F-14021 Caen Cedex, France

Received: 17 May 2002
Communicated by J. Äystö



600 MeV/A ^{58}Ni fragmentation

VOLUME 89, NUMBER 10 PHYSICAL REVIEW LETTERS 2 SEPTEMBER 2002

Two-Proton Radioactivity of ^{45}Fe

J. Giovinazzo, B. Blank, M. Chartier,* S. Czajkowski, A. Fleury, M. J. Lopez Jimenez,† M. S. Pravikoff, and J.-C. Thomas
CEN Bordeaux-Gradignan, Le Haut-Vigneau, F-33175 Gradignan Cedex, France

F. de Oliveira Santos, M. Lewitowicz, V. Maslov,‡ and M. Stanoiu
Grand Accélérateur National d'Ions Lourds, B.P. 5027, F-14076 Caen Cedex, France

R. Grzywacz§ and M. Pfützner
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C. Borcea
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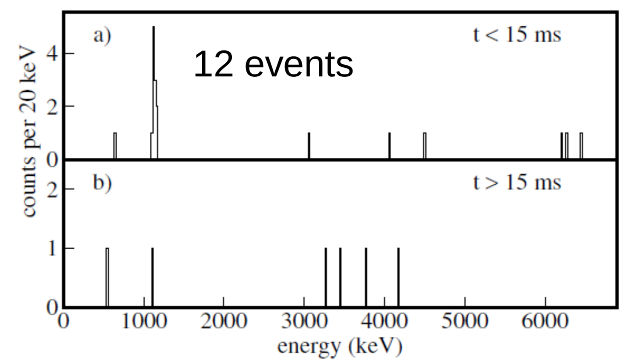
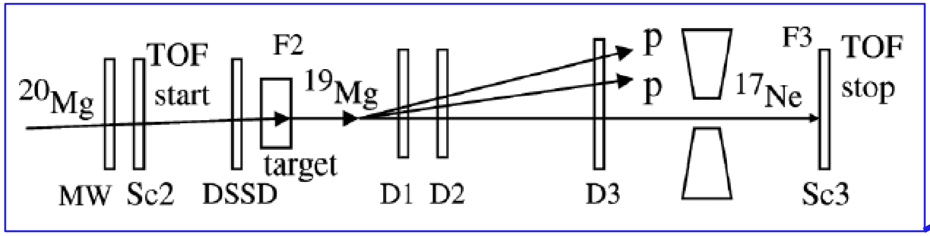
B. A. Brown
Department of Physics and Astronomy and National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824-1321
(Received 21 May 2002; published 19 August 2002)

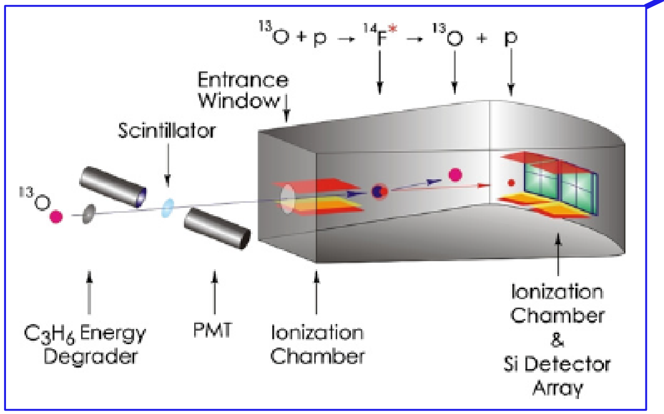


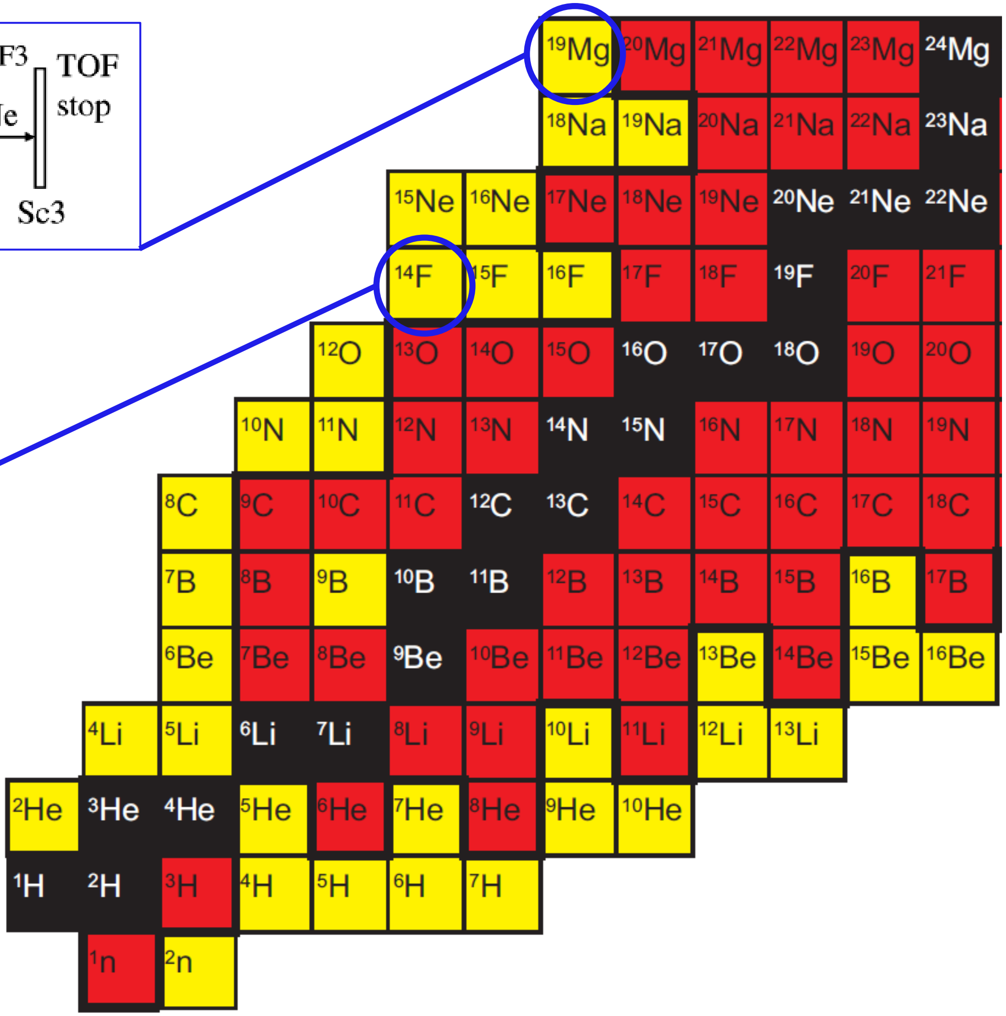
75 MeV/A ^{58}Ni fragmentation

M. Pfuetzner et al., Eur. Phys. J. A 14 (2002) 279
J. Giovinazzo et al., Phys. Rev. Lett. 89 (2002) 102501

Mapping the proton dripline: Z<13

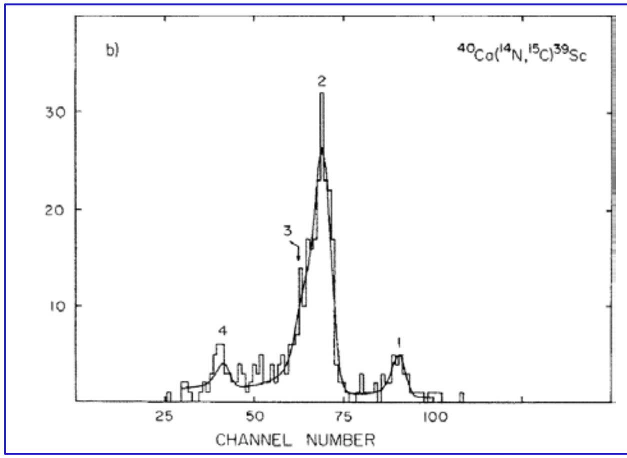






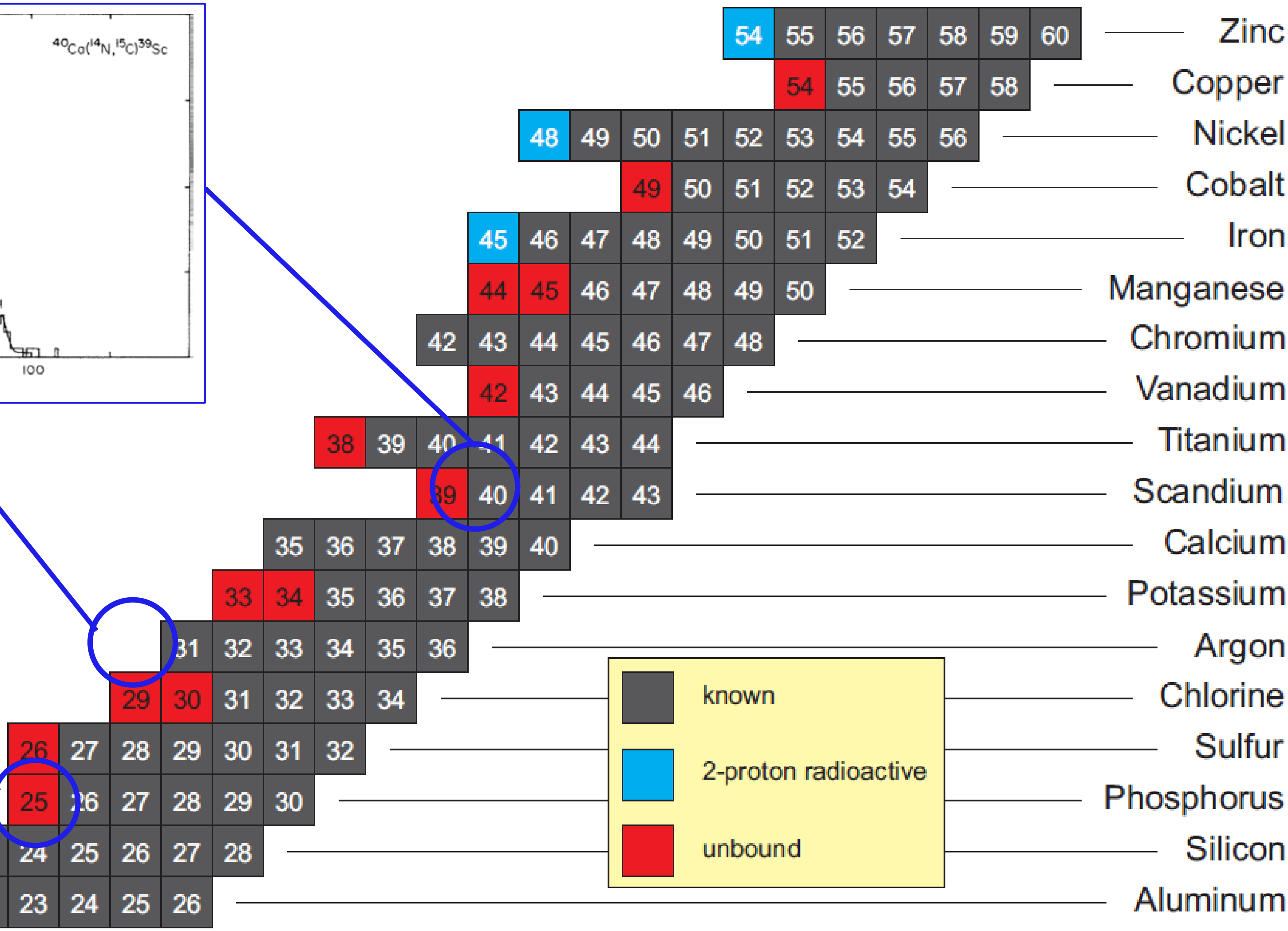
I. Mukha et al., Phys. Rev. Lett. 99 (2007) 182501
V.Z. Goldberg et al., Phys. Lett. B692 (2010) 307

12<Z<31



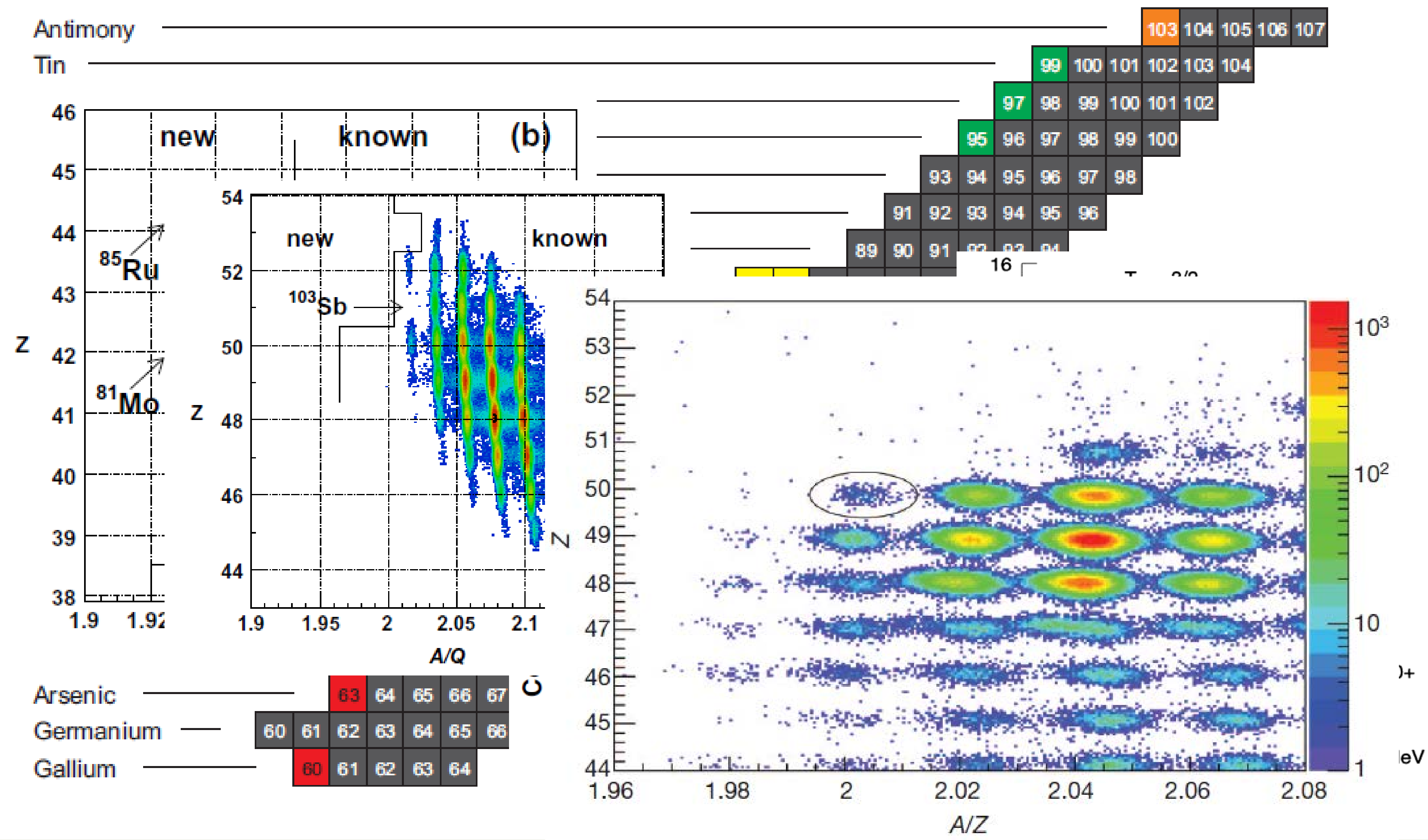
Tu 15:20
Xiaodong Xu

Mo 15:20
Beatriz Fernandez Dominguez



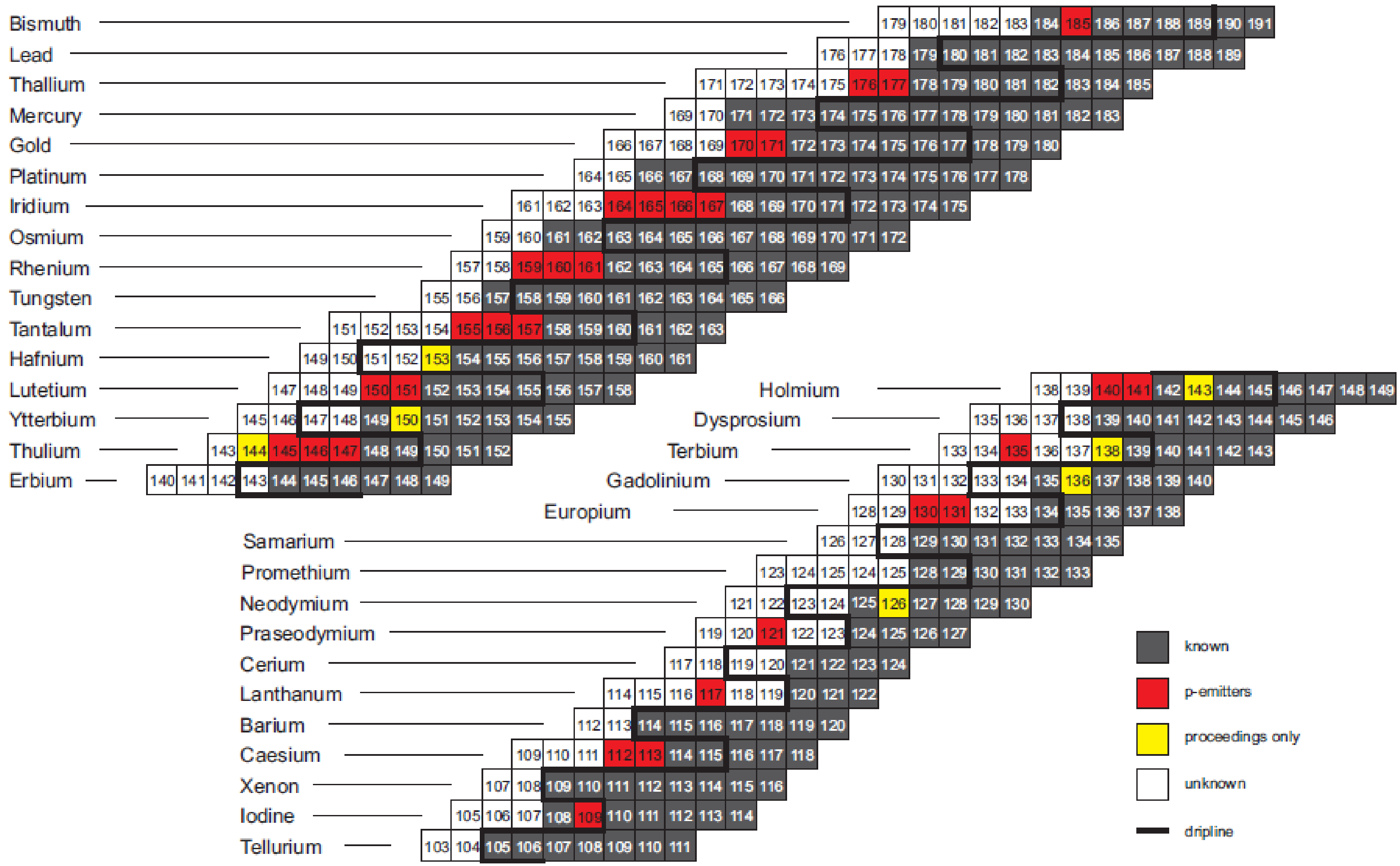
C.L. Woods et al., Nucl. Phys. A484 (1988) 145

30<Z<52



J.C. Batchelder et al., Phys. Rev C 48 (1993) 2593
A.M. Rogers et al., Phys. Rev. Lett. 106 (2011) 2525

51<Z<84



Bismuth
Lead
Thallium
Mercury
Gold
Platinum
Iridium
Osmium
Rhenium
Tungsten
Tantalum
Hafnium
Lutetium
Ytterbium
Thulium
Erbium
Holmium
Dysprosium
Terbium
Gadolinium
Europium
Samarium
Promethium
Neodymium
Praseodymium
Cerium
Lanthanum
Barium
Caesium
Xenon
Iodine
Tellurium
known
p-emitters
proceedings only
unknown
dripline

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*

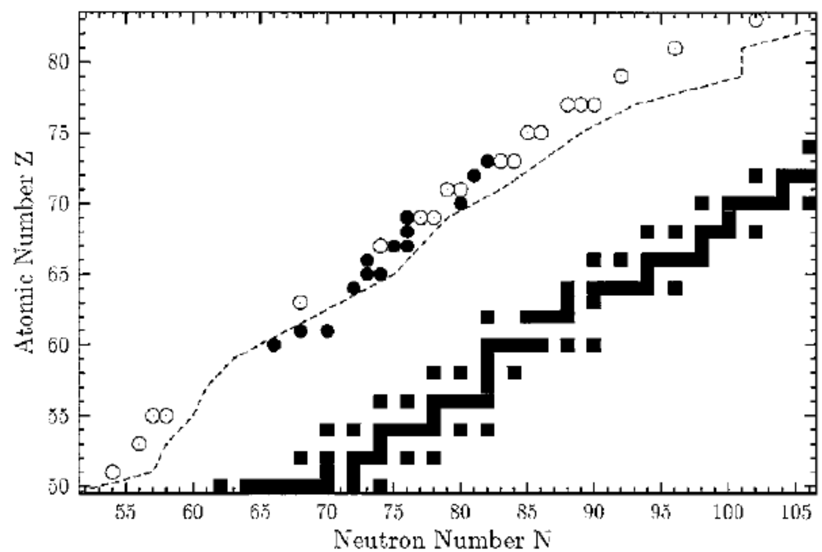
Institute of Nuclear Physics, NCSR Demokritos, Athens, Greece.

NCSR Demokritos, Athens, Greece

Received October 15, 1999

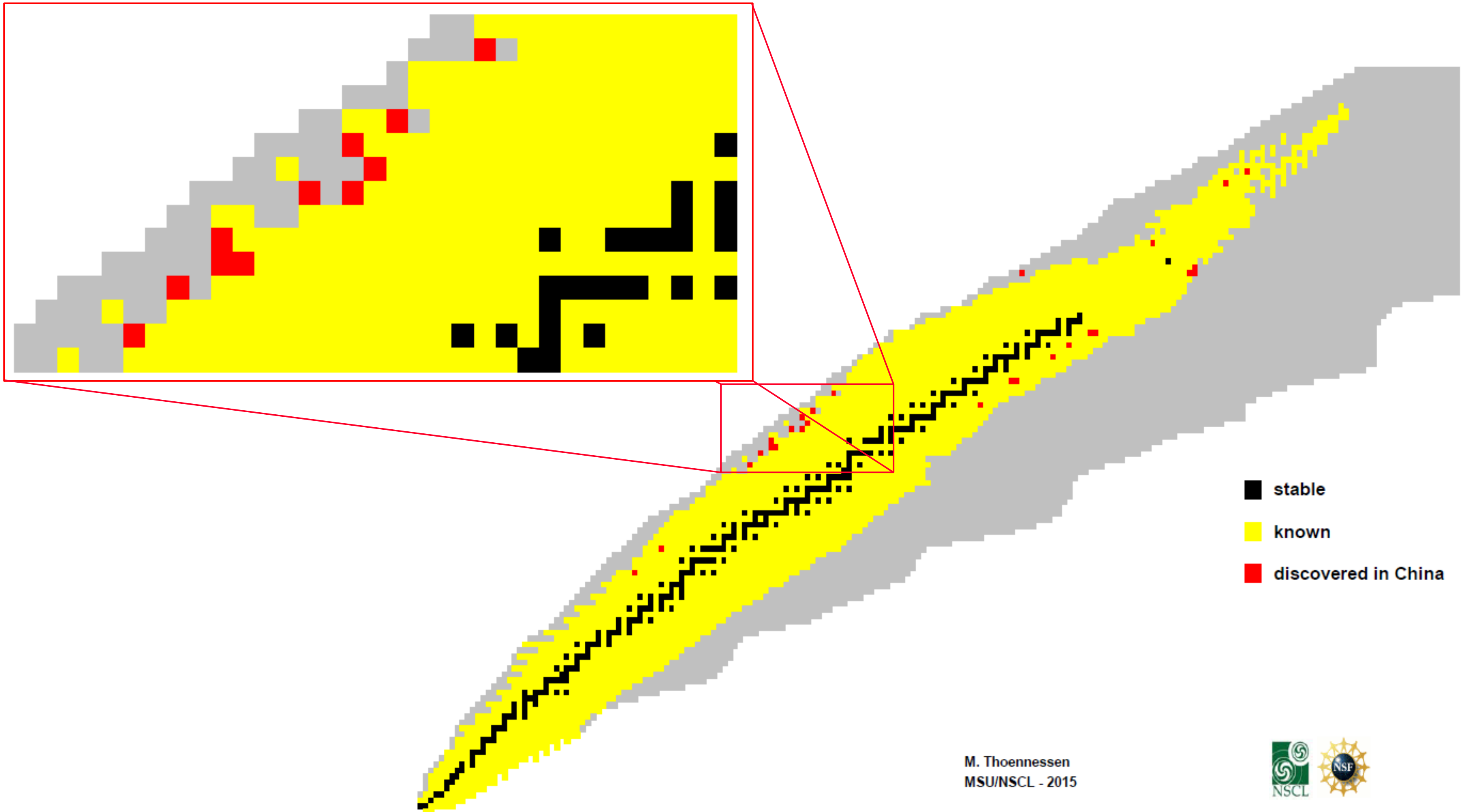
Abstract

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.

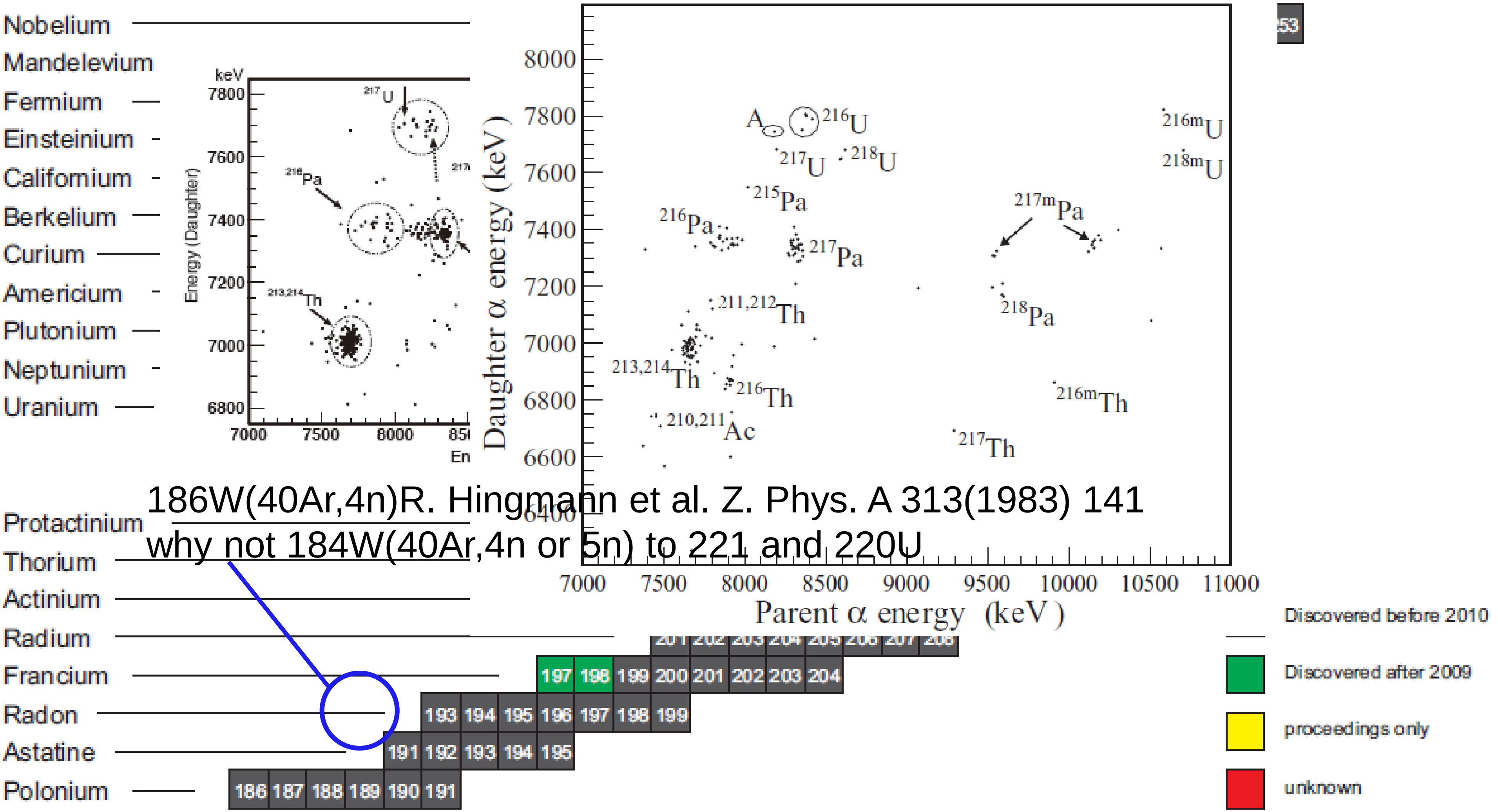


MSU A1200 fragment separator

Isotopes discovered in China



83<Z<103



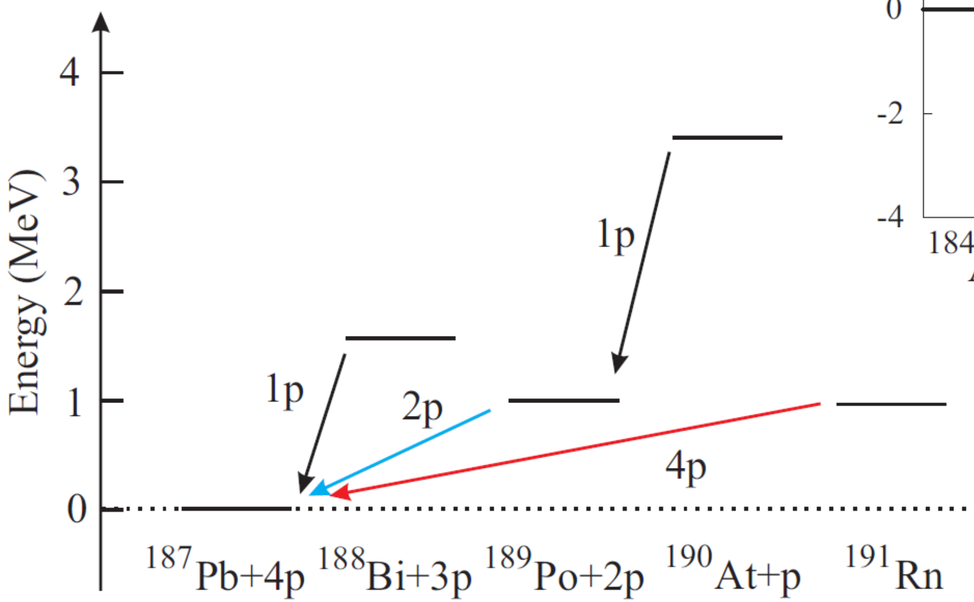
186W(40Ar,4n)R. Hingmann et al. Z. Phys. A 313(1983) 141

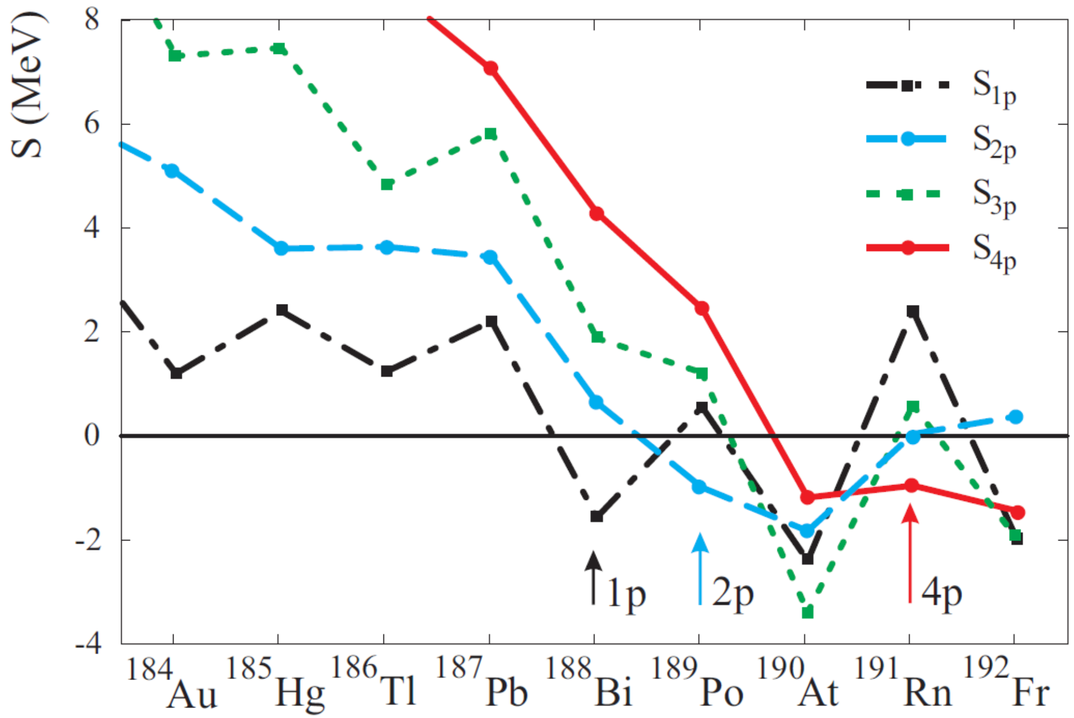
why not 184W(40Ar,4n or 5n) to 221 and 220U

Y. Wakabayashi et al., RIKEN Accel. Pro

L. Ma et al., Phys. Rev. C 91 (2015) 051

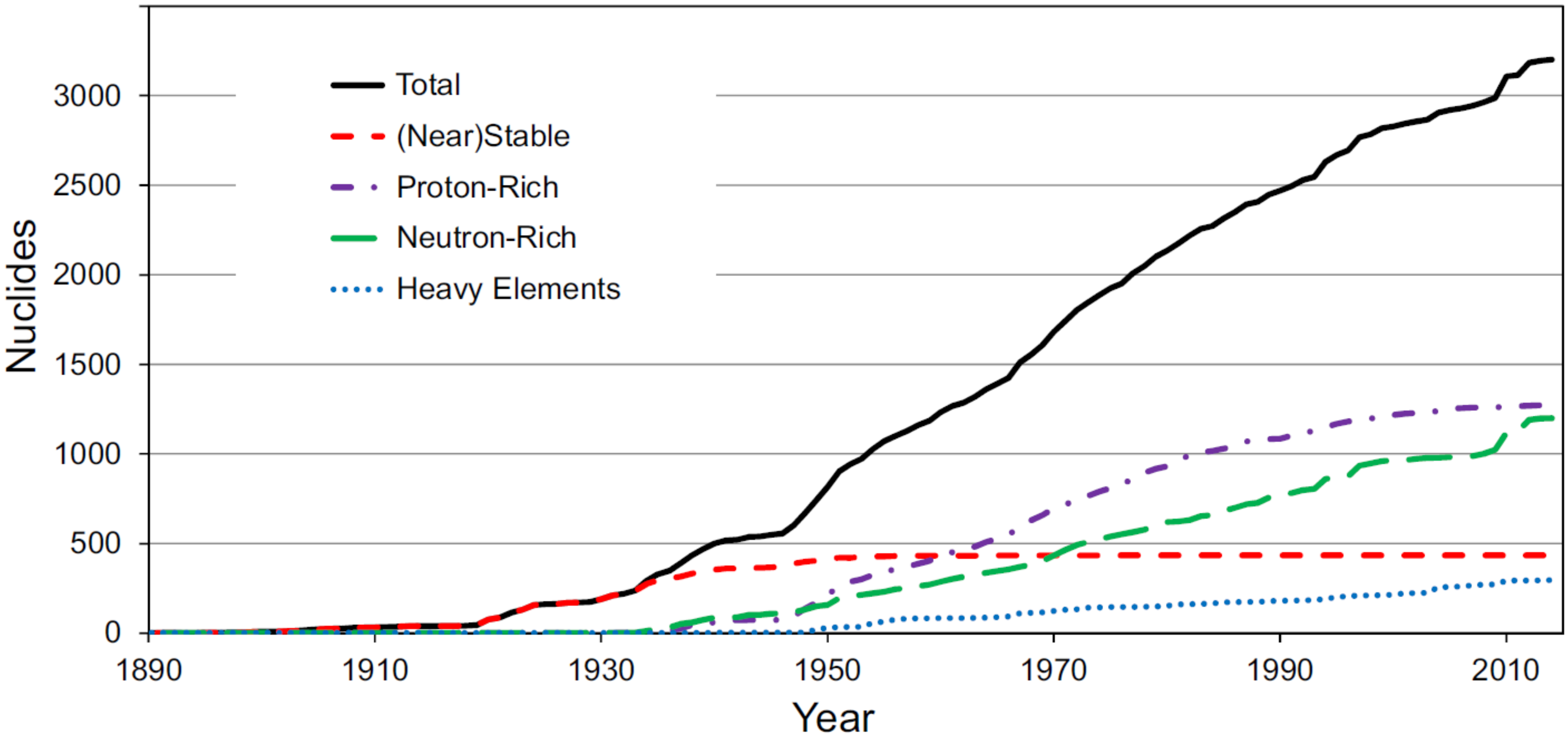
Four-proton radioactivity



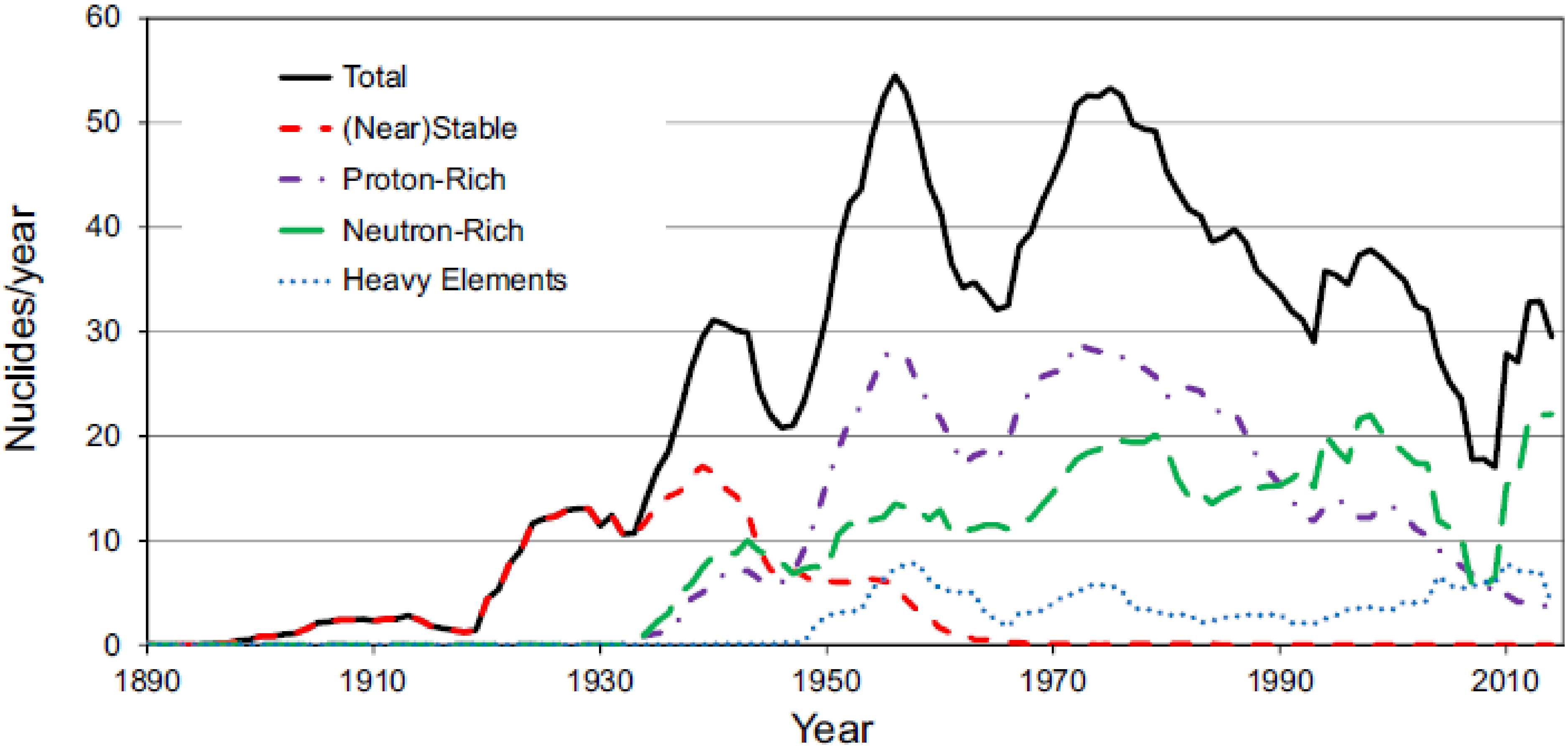


M. Thoennessen, Rep. Prog. Phys. 67 (2004) 1187

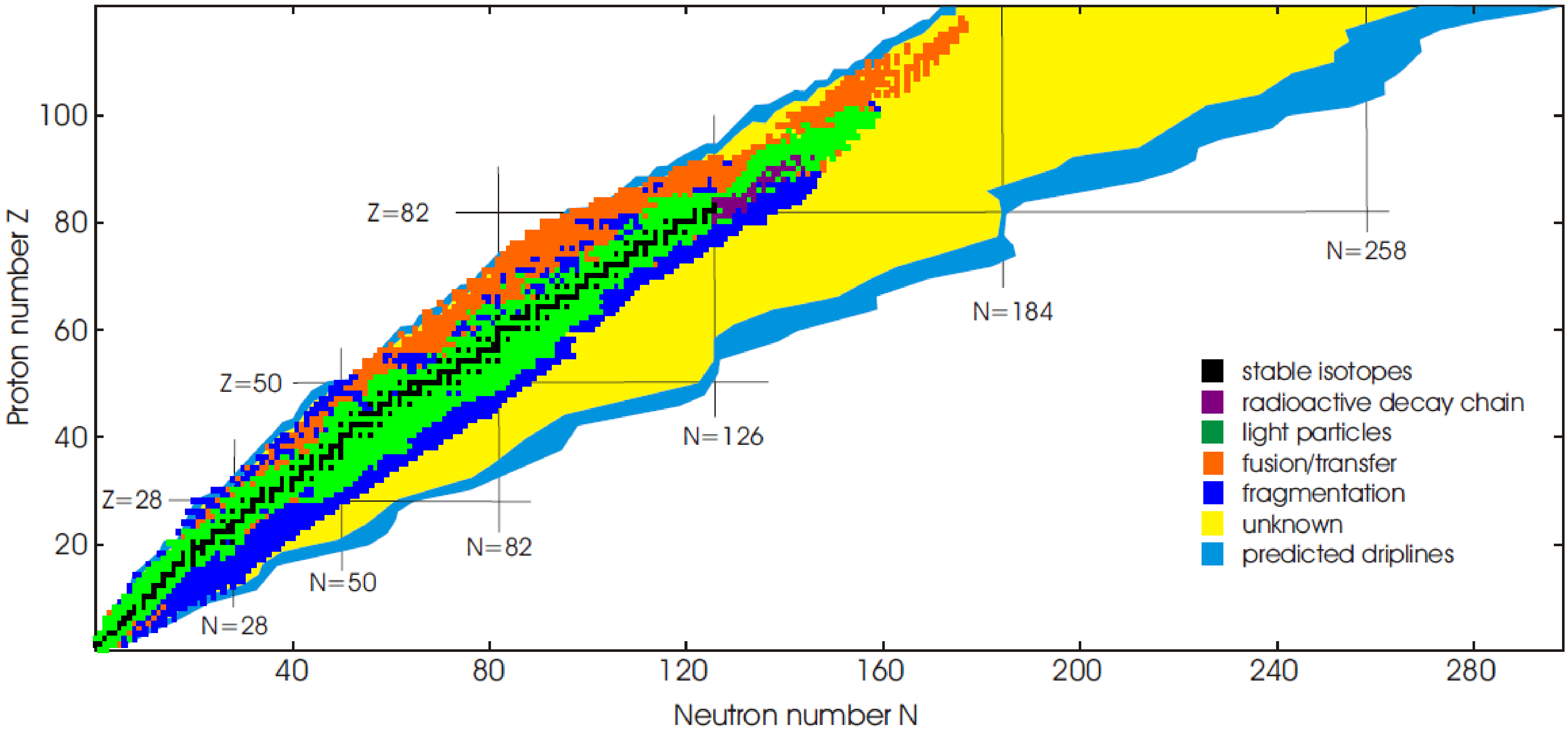
Known isotopes



Five-year running average

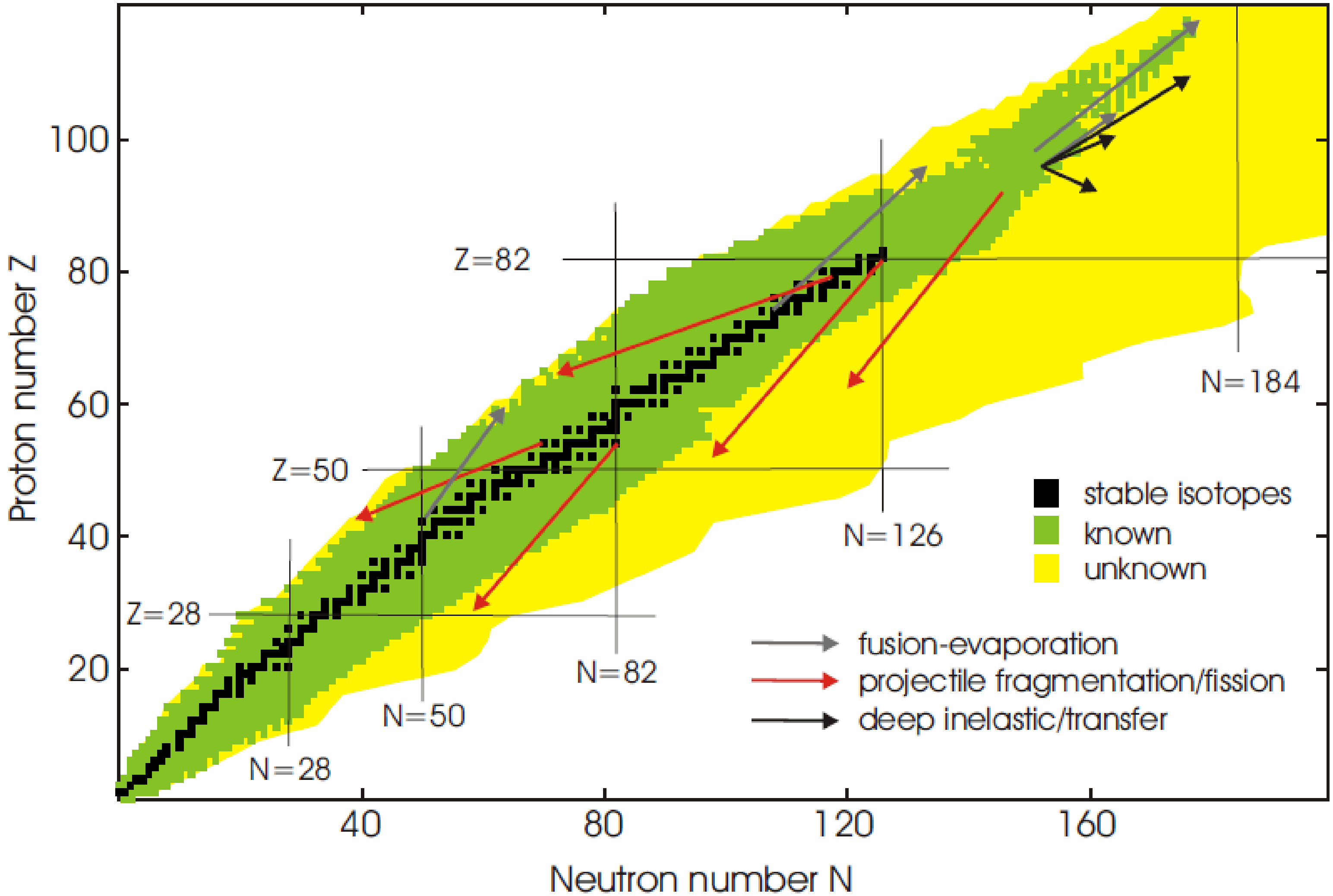


How many more nuclides are there?

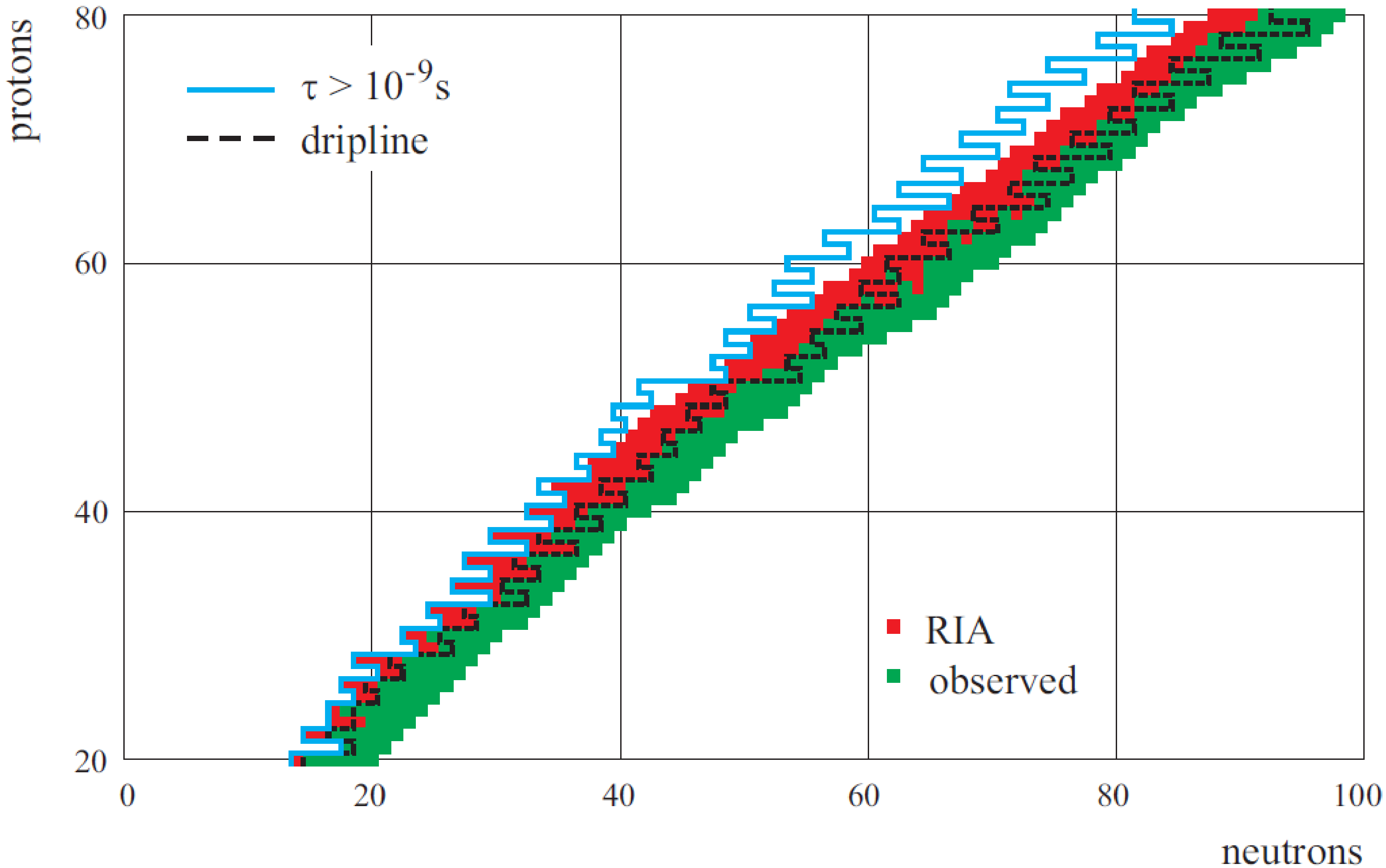


7000 bound nuclide should exist (Erler *et al.*,Nature 486 (2012) 509)

How can new nuclides be discovered?



Discovery potential



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

Summary and outlook

- FRIB construction is on schedule:
  - Project completion June 2022
  - Early completion in December 2020
- FRIB will most likely not discover new elements
- But FRIB could reach neutron-rich isotopes of superheavy elements towards N =184
- Research program is user driven
- Users are organized as part of the independent FRIB Users Organization with over 1400 members
- Please join at www.fribusers.org