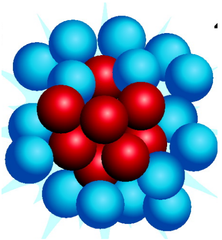
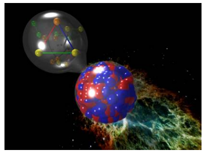
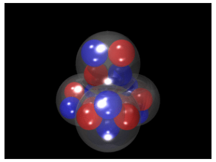
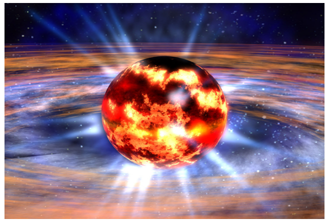
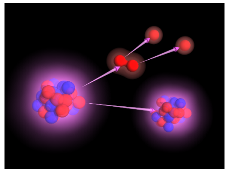
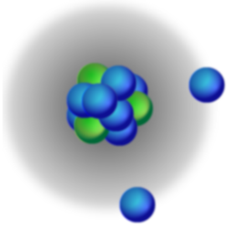
Particle Spectroscopy

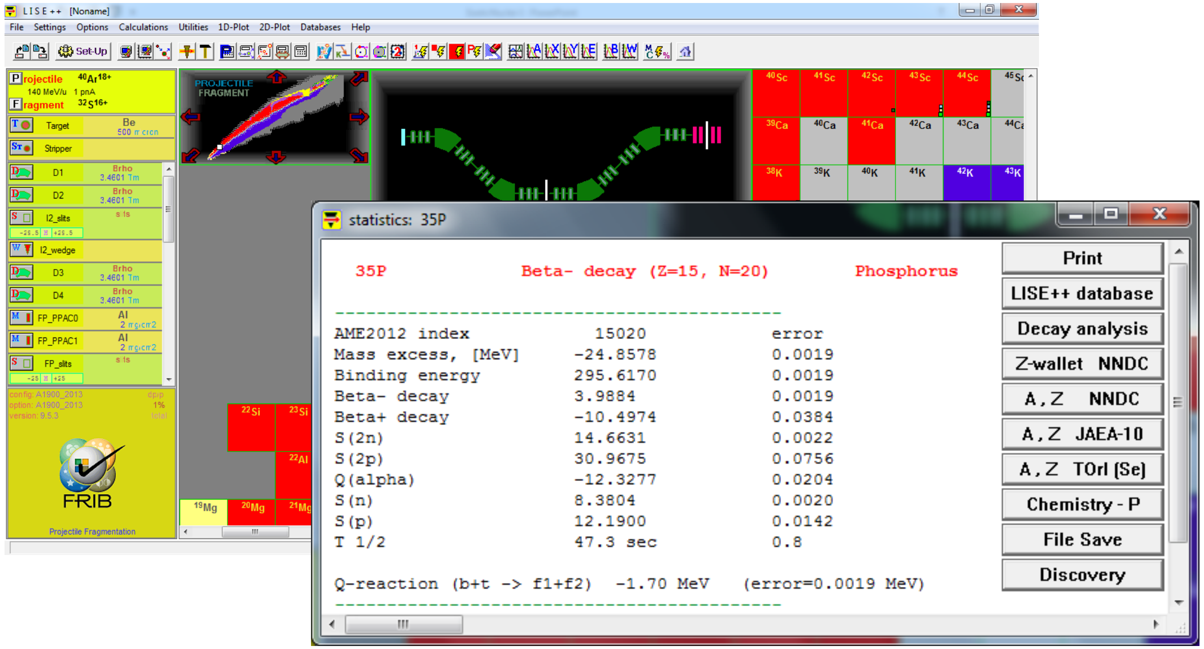





Michael Thoennessen
FRIB/NSCL
Michigan State University

Great Tool: LISE++



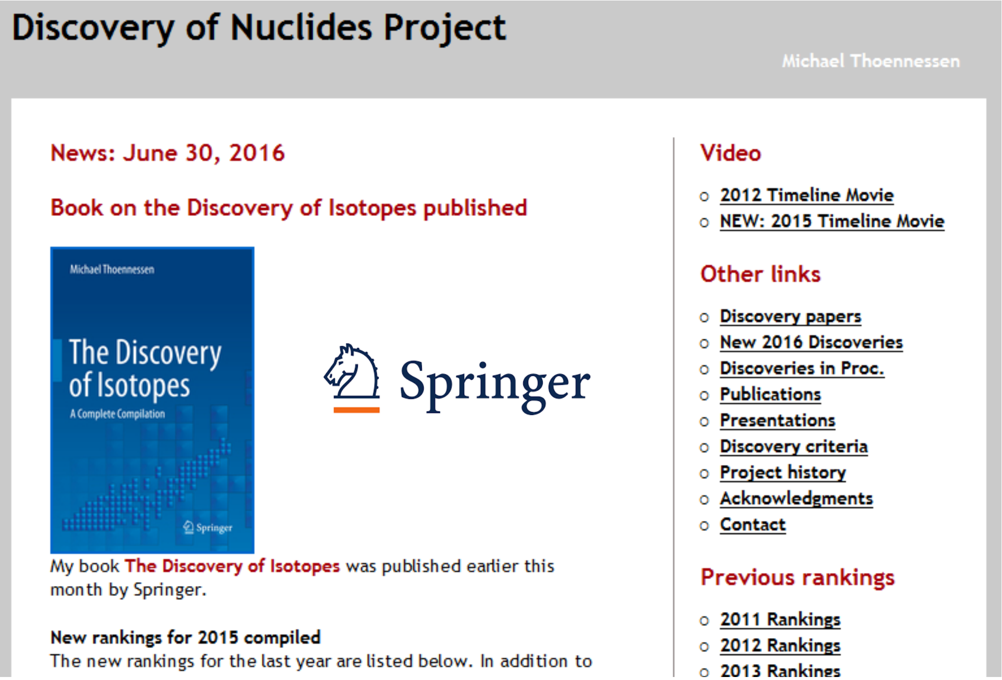
```
  35P            Beta- decay (Z=15, N=20)          Phosphorus

-------------------------------------------
AME2012 index           15020              error
Mass excess, [MeV]     -24.8578            0.0019
Binding energy         295.6170            0.0019
Beta- decay            3.9884              0.0019
Beta+ decay            -10.4974            0.0384
S(2n)                  14.6631             0.0022
S(2p)                  30.9675             0.0756
Q(alpha)               -12.3277            0.0204
S(n)                   8.3804              0.0020
S(p)                   12.1900             0.0142
T 1/2                  47.3 sec            0.8

Q-reaction (b+t -> f1+f2)  -1.70 MeV   (error=0.0019 MeV)
-------------------------------------------
```

O. Tarasov, http://lise.nscl.msu.edu

Discovery of Isotopes



Discovery of Nuclides Project

Michael Thoennessen

News: June 30, 2016

Book on the Discovery of Isotopes published

Michael Thoennessen

The Discovery of Isotopes

A Complete Compilation

Springer

Springer

My book **The Discovery of Isotopes** was published earlier this month by Springer.

New rankings for 2015 compiled

The new rankings for the last year are listed below. In addition to

Video

- 2012 Timeline Movie
- NEW: 2015 Timeline Movie

Other links

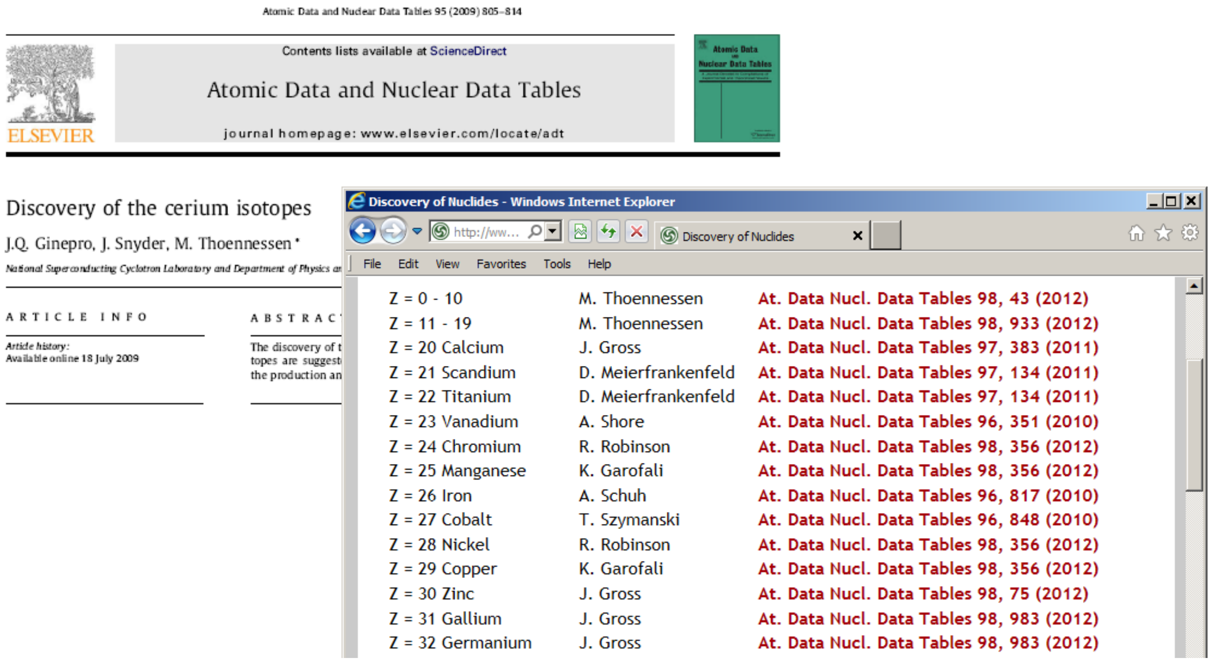
- Discovery papers
- New 2016 Discoveries
- Discoveries in Proc.
- Publications
- Presentations
- Discovery criteria
- Project history
- Acknowledgments
- Contact

Previous rankings

- 2011 Rankings
- 2012 Rankings
- 2013 Rankings

https://people.nscl.msu.edu/~thoennes/isotopes/

Papers on discovery



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

Contents lists available at ScienceDirect

Atomic Data and Nuclear Data Tables

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

Discovery of the cerium isotopes

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

National Superconducting Cyclotron Laboratory and Department of Physics an

ARTICLE INFO

Article history:
Available online 18 July 2009

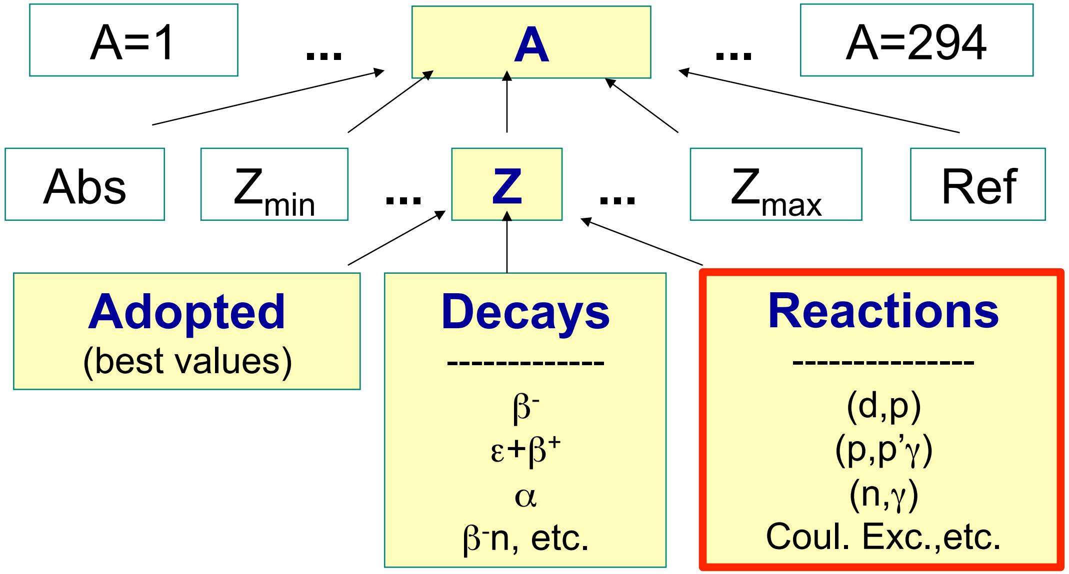
ABSTRACT

The discovery of t
topes are suggest
the production an

Z = 0 - 10	M. Thoennessen	At. Data Nucl. Data Tables 98, 43 (2012)
Z = 11 - 19	M. Thoennessen	At. Data Nucl. Data Tables 98, 933 (2012)
Z = 20 Calcium	J. Gross	At. Data Nucl. Data Tables 97, 383 (2011)
Z = 21 Scandium	D. Meierfrankenfeld	At. Data Nucl. Data Tables 97, 134 (2011)
Z = 22 Titanium	D. Meierfrankenfeld	At. Data Nucl. Data Tables 97, 134 (2011)
Z = 23 Vanadium	A. Shore	At. Data Nucl. Data Tables 96, 351 (2010)
Z = 24 Chromium	R. Robinson	At. Data Nucl. Data Tables 98, 356 (2012)
Z = 25 Manganese	K. Garofali	At. Data Nucl. Data Tables 98, 356 (2012)
Z = 26 Iron	A. Schuh	At. Data Nucl. Data Tables 96, 817 (2010)
Z = 27 Cobalt	T. Szymanski	At. Data Nucl. Data Tables 96, 848 (2010)
Z = 28 Nickel	R. Robinson	At. Data Nucl. Data Tables 98, 356 (2012)
Z = 29 Copper	K. Garofali	At. Data Nucl. Data Tables 98, 356 (2012)
Z = 30 Zinc	J. Gross	At. Data Nucl. Data Tables 98, 75 (2012)
Z = 31 Gallium	J. Gross	At. Data Nucl. Data Tables 98, 983 (2012)
Z = 32 Germanium	J. Gross	At. Data Nucl. Data Tables 98, 983 (2012)

https://people.nscl.msu.edu/~thoennes/isotopes/

ENSDF Schematic



A=1 … **A** … A=294

Abs Z_{min} … **Z** … Z_{max} Ref

Adopted
(best values)

Decays

β^-
$\varepsilon+\beta^+$
α
β^-n, etc.

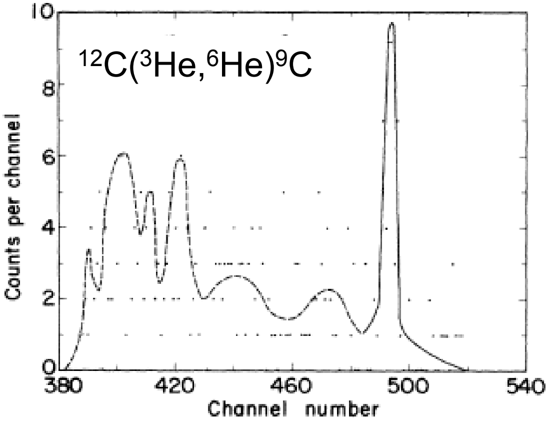
Reactions

(d,p)
(p,p'γ)
(n,γ)
Coul. Exc.,etc.

Missing Mass Spectra

^{9}C excitation energy (Q-value)

Ejectile (^{6}He) energy



Position in spectrometer focal plane

Most transfer reactions (d,p, p,t, etc.) with spectrometers are basically missing mass measurements.

Ejectile energy – Excited states energy (Calibration)

Angular distr. – Level spin (Optical model)

Intensity – Spectroscopic factor (reaction dependent)

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

Application to “exotic nuclei”?

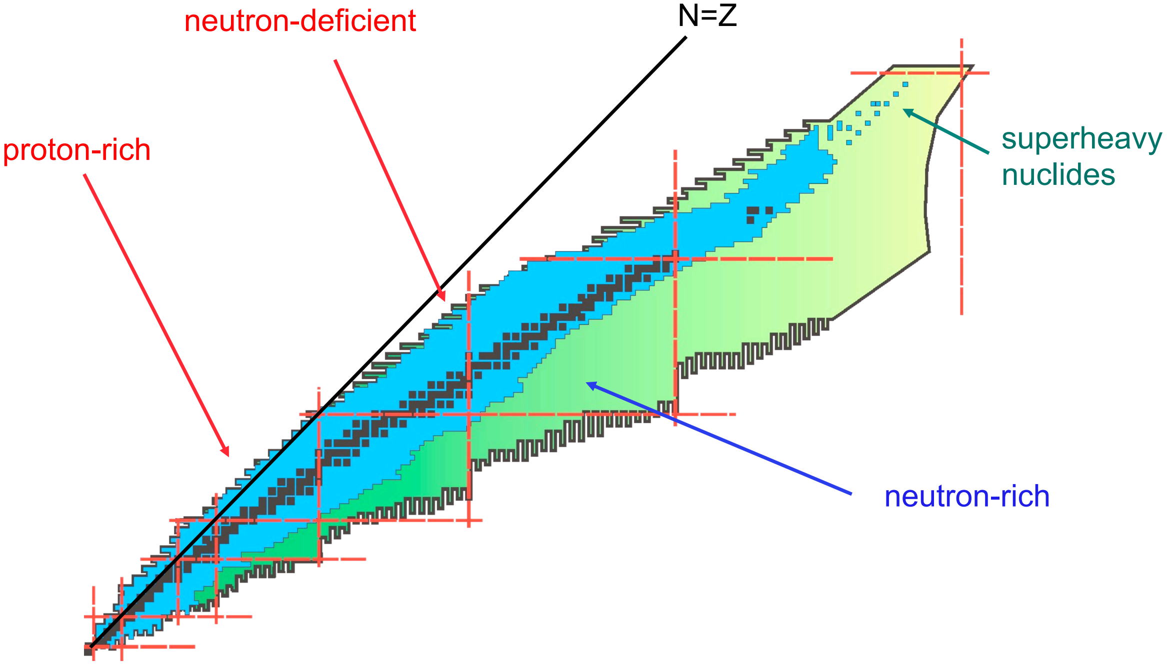
“Nuclei with ratios of neutron number *N* to proton number *Z* much larger or much smaller than those of nuclei found in nature.”

McGraw-Hill Concise Encyclopedia of Physics. (2002). Retrieved August 5 2015 from http://encyclopedia2.thefreedictionary.com/Exotic+nuclei

Terminology:

- Exotic nuclei?
- Rare isotopes?
- Radioactive nuclei?
- Nuclei/Nuclides/Isotopes

Reaching the extremes



neutron-deficient

N=Z

proton-rich

superheavy
nuclides

neutron-rich

Nucleus - Nuclide - Isotope

Nucleus: The nucleus is the small, dense region consisting of protons and neutrons at the center of an atom.

Nuclide: A nuclide is an atomic species characterized by the specific constitution of its nucleus, i.e., by its number of protons Z, its number of neutrons N, and its nuclear energy state.

Isotopes: Different nuclides having the same atomic number are called isotopes.

A species of atoms identical as regards atomic number (proton number) and mass number (nucleon number) should be indicated by the word ‘nuclide’, not by the word ‘isotope’.

https://en.wikipedia.org/wiki/Nuclide
E.R. Cohen and P. Giacomo,
Document I.U.P.A.P.-25 (SUNAMCO 87-1)

Different types of nuclides?

Stable: Nuclides which do not decay

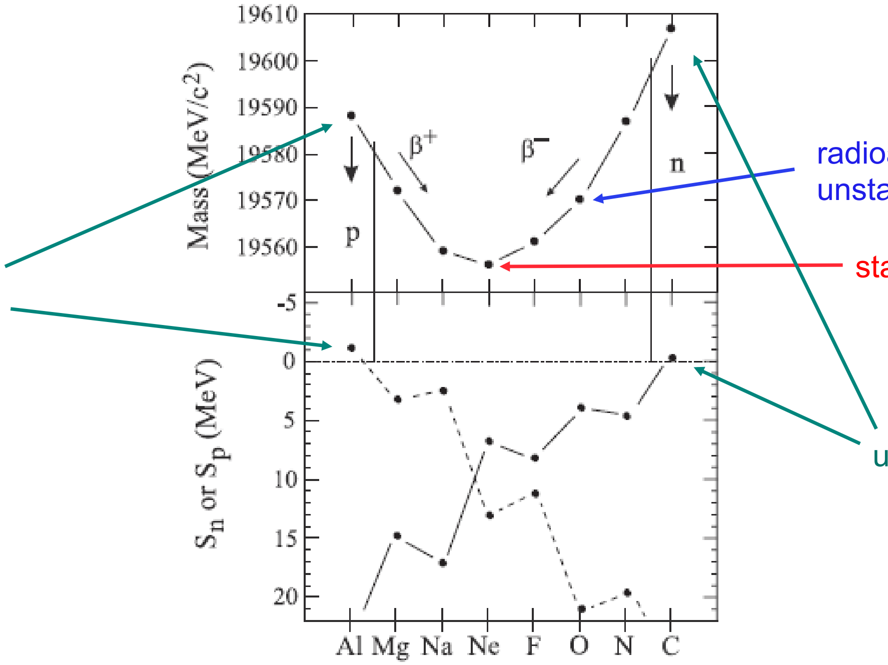
(What about ^{128}Te: $T_{1/2} = 2.2\cdot10^{24}$ years)

Radioactive: Nuclides which decay with a half-life longer than about 10^{-12}s

(^{8}Be is unstable:
$T_{1/2}$ = 82 as ($8.2\cdot10^{-17}$ s)

Bound: With respect to neutron or proton emission

A = 21 isobars



radioactive/
unstable

stable

unbound

unbound

Decay of proton-rich nuclei

Unbound nuclides can still be radioactive:

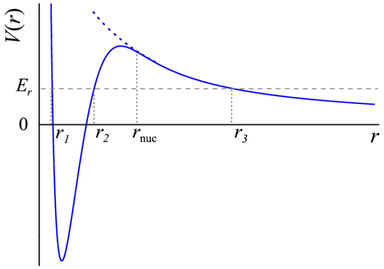
^{121}Pr: $T_{1/2}$ = 12 ms (proton emitter)

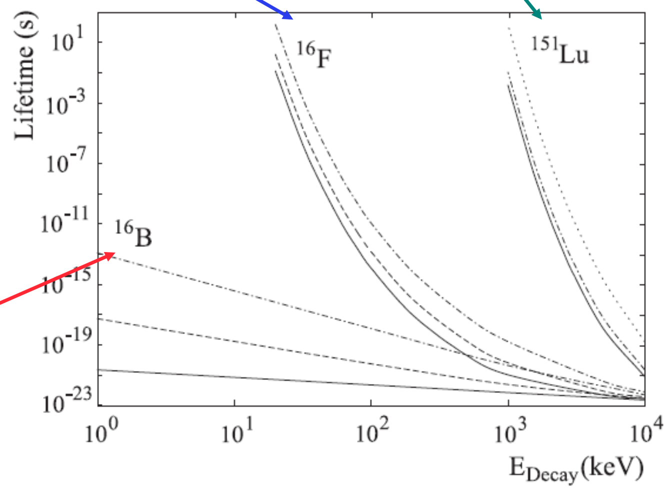
121PR
ONE-TO-ONE PUBLIC RELATIONS

Unbound nuclides do not have to decay by proton emission:

^{135}Tb: $T_{1/2}$ = 1 ms
S_p = –1.19 MeV - β^+ emitter

Coulomb/angular momentum barrier





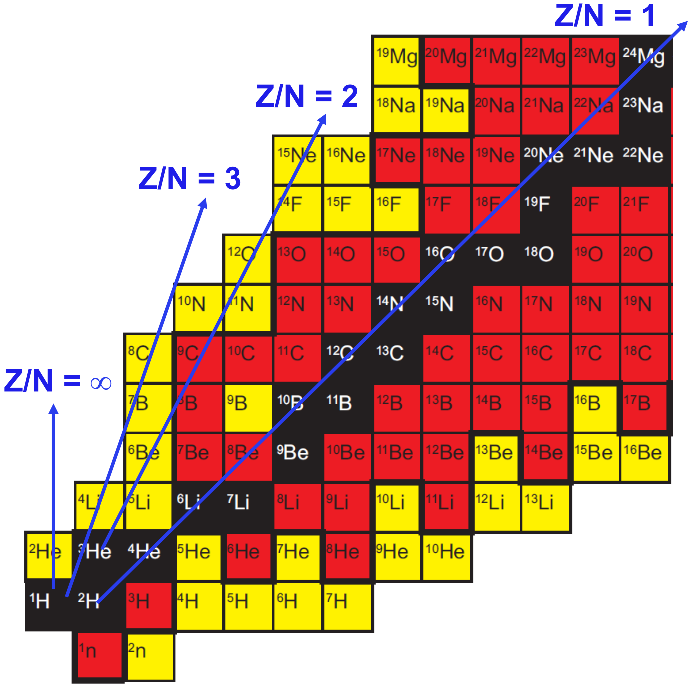
proton unbound

proton radioactive

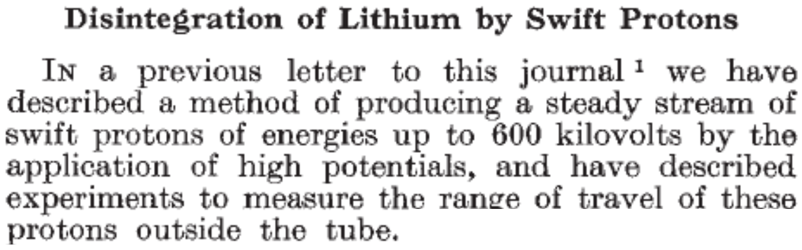
neutron unbound

Unbound proton-rich exotic nuclides

Z/N = 3 : ^{4}Li,^{8}C



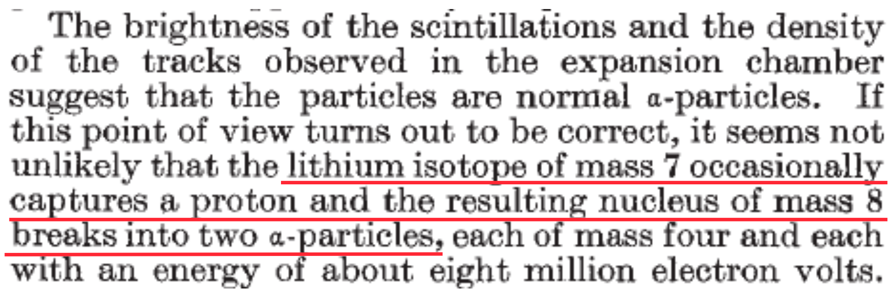
First new isotope produced with an accelerator



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.

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

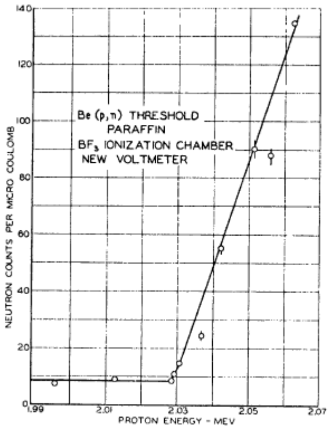


The brightness of the scintillations and the density of the tracks observed in the expansion chamber suggest that the particles are normal α-particles. If this point of view turns out to be correct, it seems not unlikely that the lithium isotope of mass 7 occasionally captures a proton and the resulting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

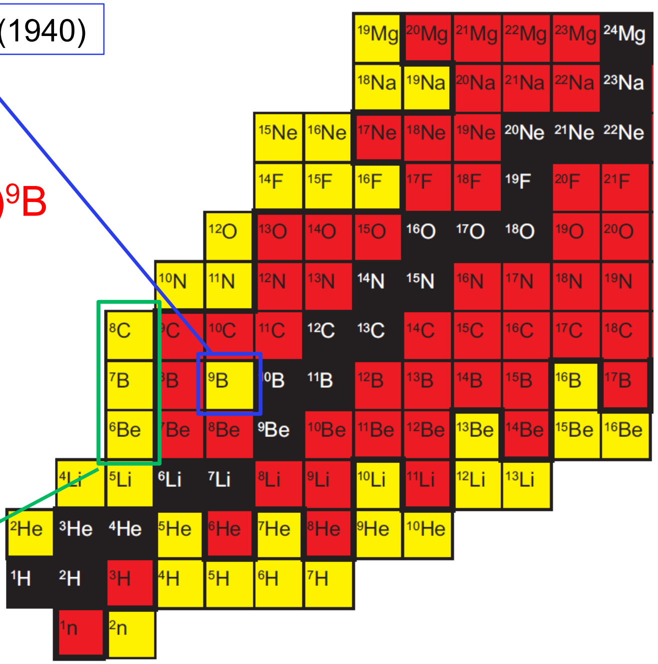
J.D. Cockcroft and E.T.S. Walton, Nature 129 (1932) 649

Proton-unbound nuclei

^{9}B: First proton unbound isotope (1940)



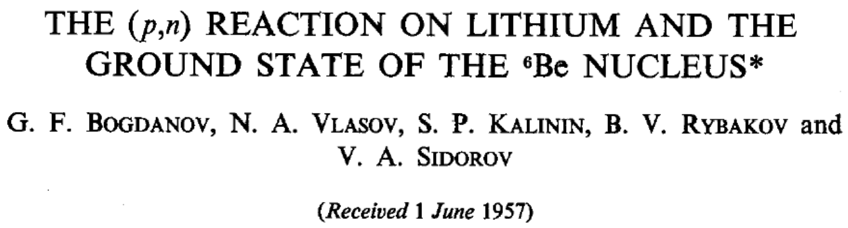
^{9}Be(p,n)^{9}B



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

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

Two-proton unbound nucleus: ^{6}Be

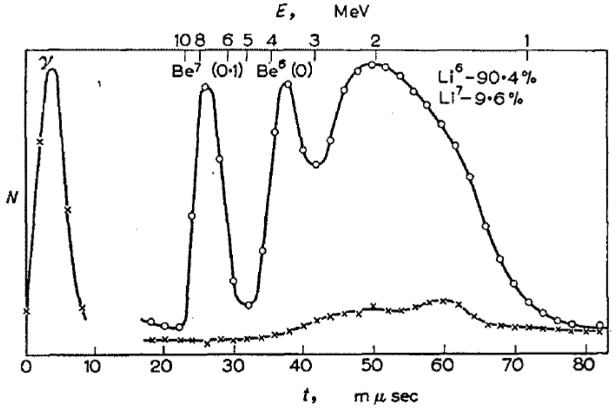


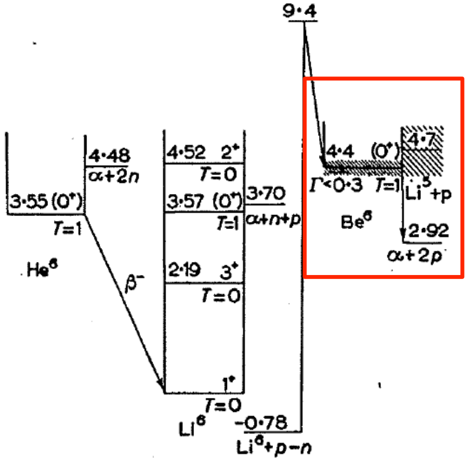
THE (p,n) REACTION ON LITHIUM AND THE GROUND STATE OF THE ^{6}Be NUCLEUS*

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

(*Received* 1 *June* 1957)

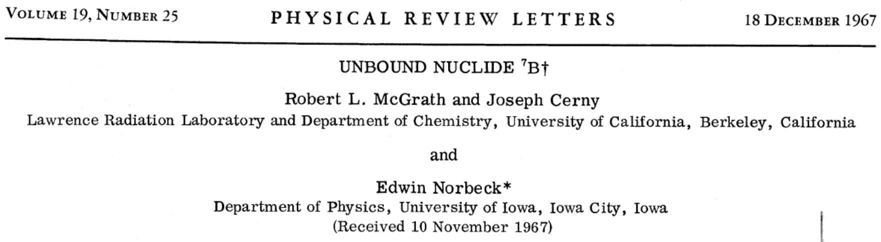
^{6}Li(p,n)^{6}Be





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

Three-proton unbound nucleus: ^{7}B



Volume 19, Number 25 PHYSICAL REVIEW LETTERS 18 December 1967

UNBOUND NUCLIDE ^{7}B†

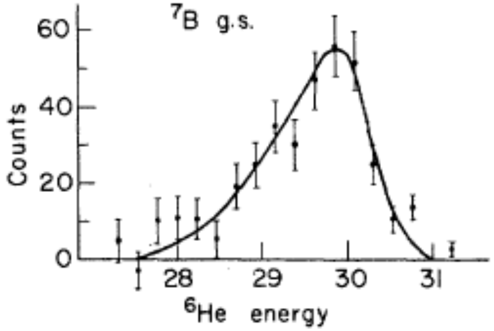
Robert L. McGrath and Joseph Cerny
Lawrence Radiation Laboratory and Department of Chemistry, University of California, Berkeley, California

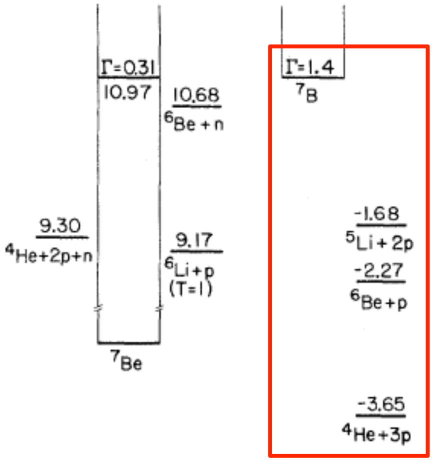
and

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

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

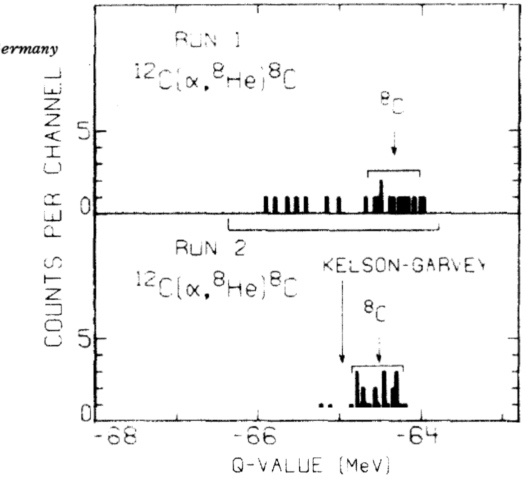
R. G. H. Robertson
Cyclotron Laboratory and Physics Department, Michigan State University, East Lansing, Michigan 48824*

and

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

(Received 8 April 1974)

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



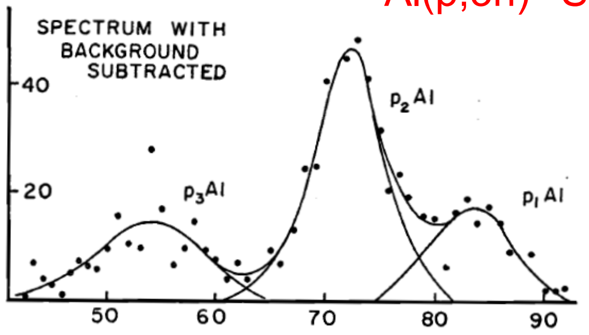
R.G.H. Robertson et al., Phys. Rev. Lett. 32 (1974) 1207

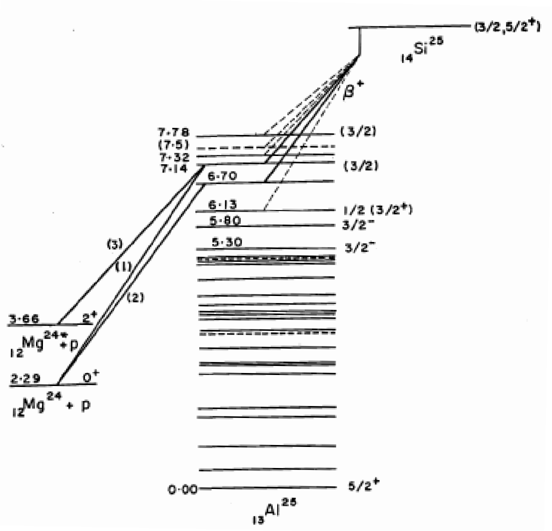
Beta-delayed protons

OBSERVATION OF DELAYED PROTON RADIOACTIVITY

R. BARTON,* R. MCPHERSON, R. E. BELL, W. R. FRISKEN,
W. T. LINK, AND R. B. MOORE
Radiation Laboratory, McGill University, Montreal
Received August 14, 1963

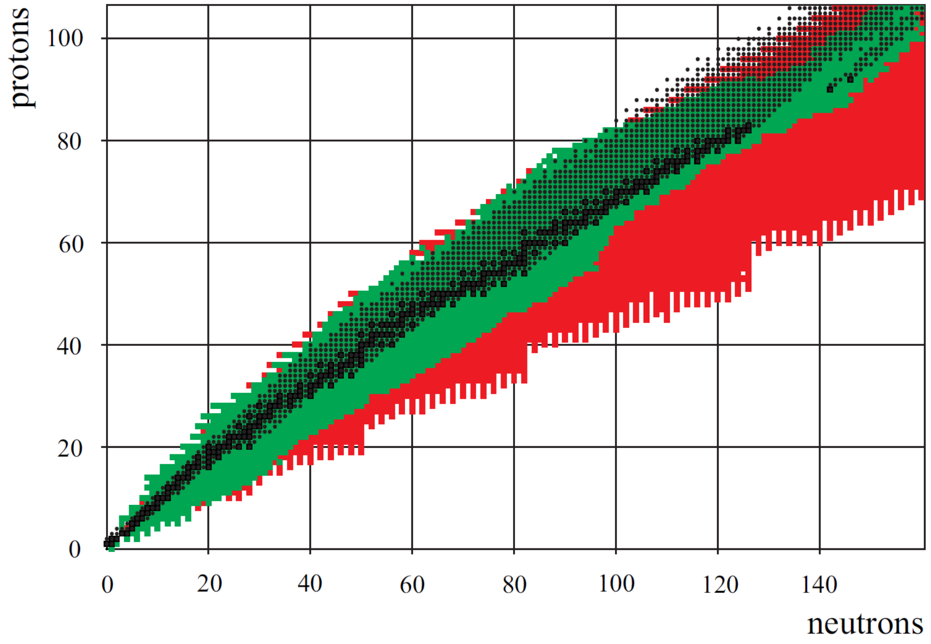
^{27}Al(p,3n)^{25}Si





R. Barton et al., Can. J. Phys. 31 (1963) 2007

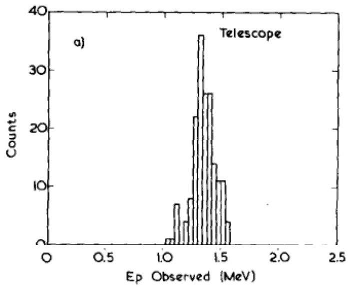
Fusion evaporation reactions



National Science Foundation
Michigan State University

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

1970: Proton radioactivity



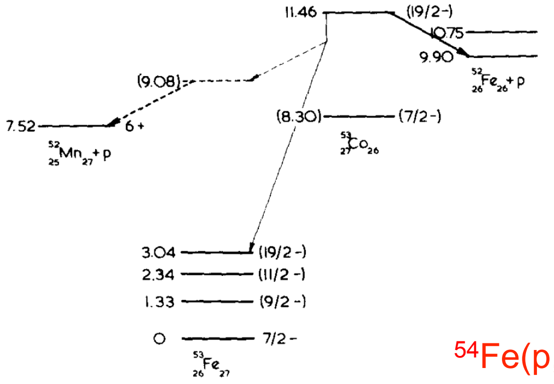
$^{16}O(^{40}Ca,p2n)^{53}Co$

$^{53}Co^{m}$: 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.*

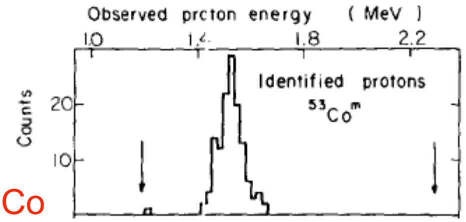
Received 23 September 1970



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

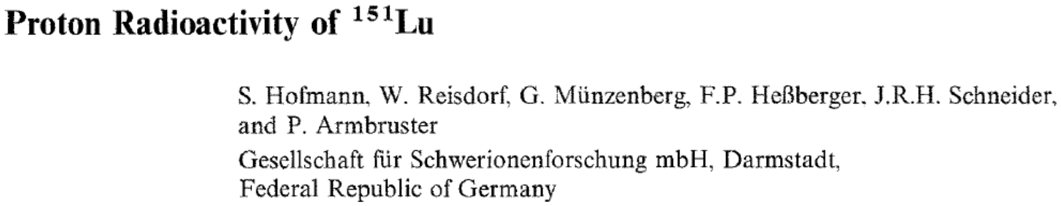


$^{54}Fe(p,2n)^{53}Co$

National Science Foundation
Michigan State University

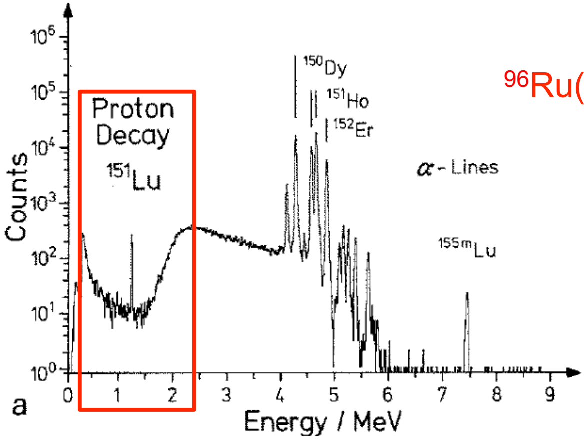
K.P. Jackson et al., Phys. Lett. 33B (1970) 281
J. Cerny et al., Phys. Lett. 33B (1970) 284

Ground-state proton radioactivity



Proton Radioactivity of ^{151}Lu

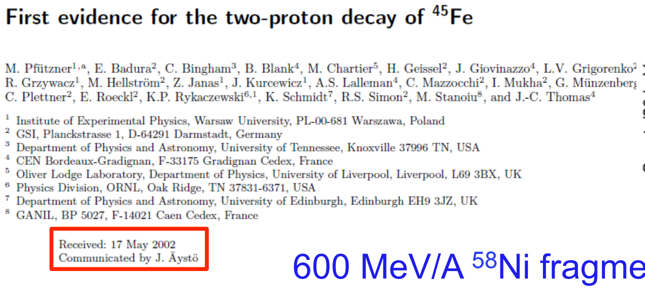
S. Hofmann, W. Reisdorf, G. Münzenberg, F.P. Heßberger, J.R.H. Schneider,
and P. Armbruster
Gesellschaft für Schwerionenforschung mbH, Darmstadt,
Federal Republic of Germany



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

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

Two-proton radioactivity

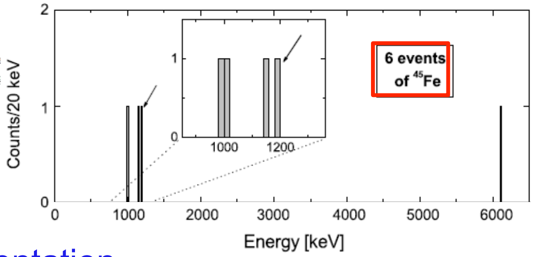


First evidence for the two-proton decay of ^{45}Fe

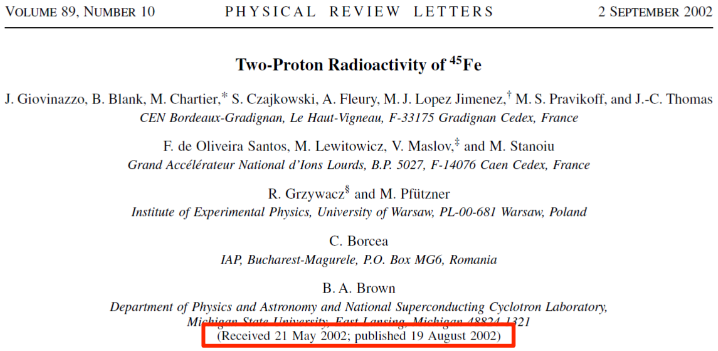
M. Pfützner[1,a], E. Badura[2], C. Bingham[3], B. Blank[4], M. Chartier[5], H. Geissel[2], J. Giovinazzo[4], L.V. Grigorenko[2], R. Grzywacz[1], M. Hellström[2], Z. Janas[1], J. Kurcewicz[1], A.S. Lalleman[4], C. Mazzocchi[2], I. Mukha[2], G. Münzenberg[2], C. Plettner[2], E. Roeckl[2], K.P. Rykaczewski[6,1],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

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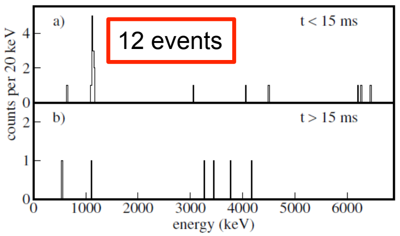
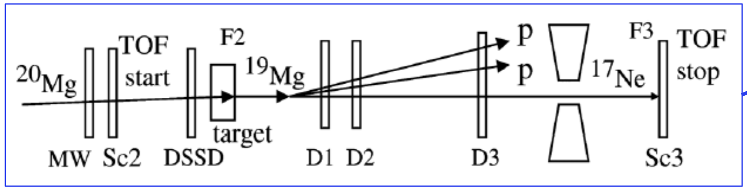
(Received 21 May 2002; published 19 August 2002)

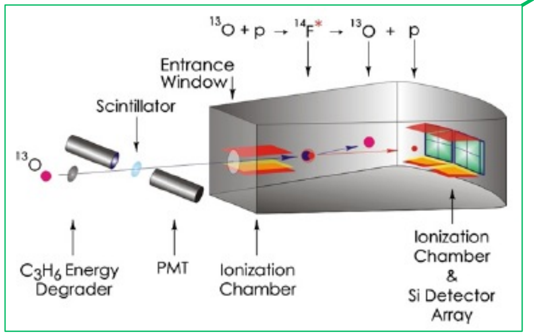


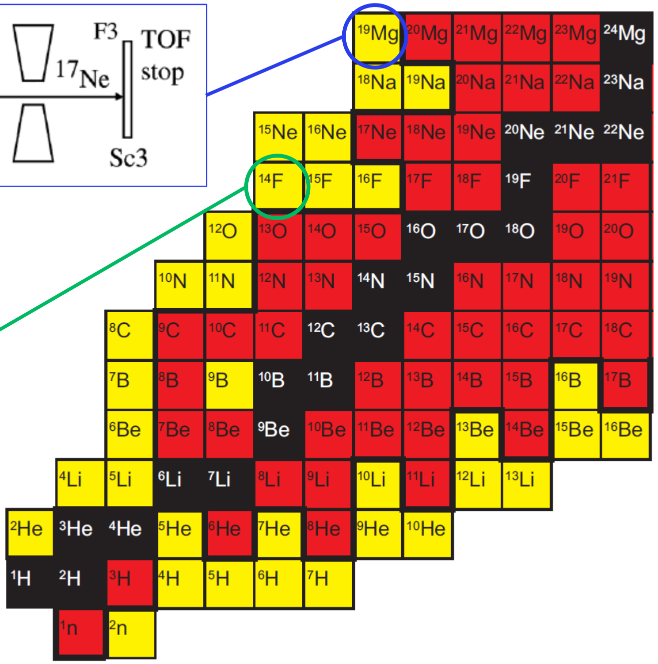
75 MeV/A ^{58}Ni fragmentation

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



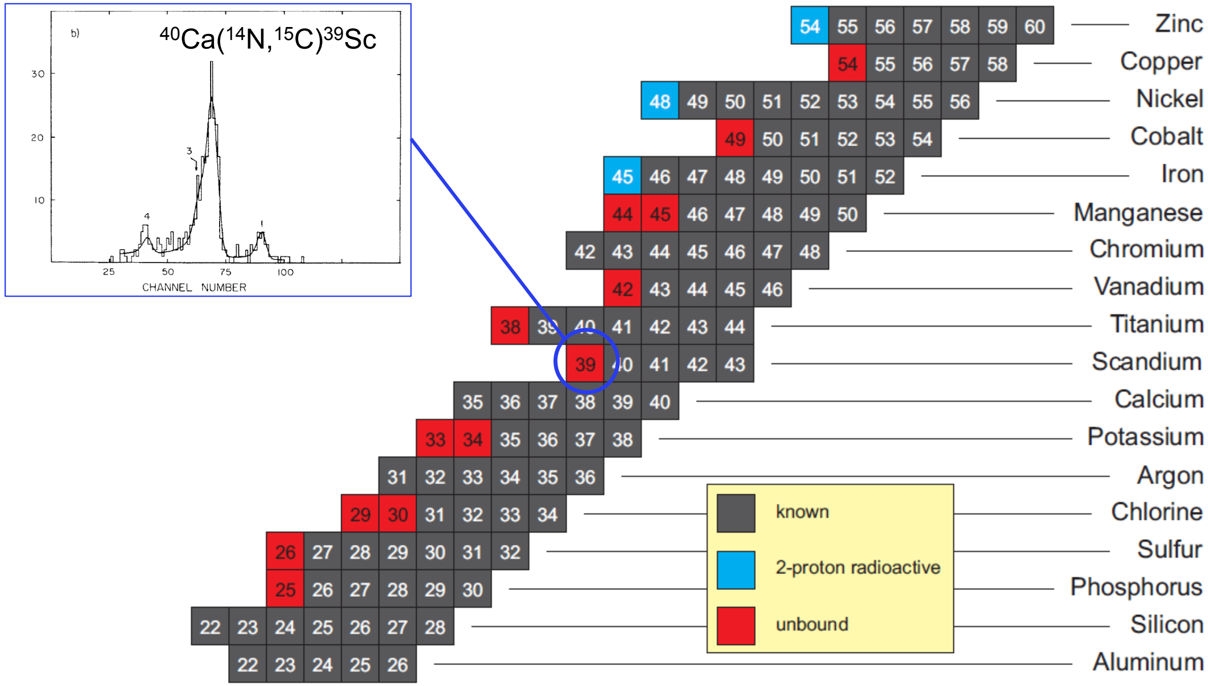




							^{19}Mg	^{20}Mg	^{21}Mg	^{22}Mg	^{23}Mg	^{24}Mg
							^{18}Na	^{19}Na	^{20}Na	^{21}Na	^{22}Na	^{23}Na
					^{15}Ne	^{16}Ne	^{17}Ne	^{18}Ne	^{19}Ne	^{20}Ne	^{21}Ne	^{22}Ne
					^{14}F	^{15}F	^{16}F	^{17}F	^{18}F	^{19}F	^{20}F	^{21}F
				^{12}O	^{13}O	^{14}O	^{15}O	^{16}O	^{17}O	^{18}O	^{19}O	^{20}O
			^{10}N	^{11}N	^{12}N	^{13}N	^{14}N	^{15}N	^{16}N	^{17}N	^{18}N	^{19}N
		^{8}C	^{9}C	^{10}C	^{11}C	^{12}C	^{13}C	^{14}C	^{15}C	^{16}C	^{17}C	^{18}C
		^{7}B	^{8}B	^{9}B	^{10}B	^{11}B	^{12}B	^{13}B	^{14}B	^{15}B	^{16}B	^{17}B
		^{6}Be	^{7}Be	^{8}Be	^{9}Be	^{10}Be	^{11}Be	^{12}Be	^{13}Be	^{14}Be	^{15}Be	^{16}Be
	^{4}Li	^{5}Li	^{6}Li	^{7}Li	^{8}Li	^{9}Li	^{10}Li	^{11}Li	^{12}Li	^{13}Li		
^{2}He	^{3}He	^{4}He	^{5}He	^{6}He	^{7}He	^{8}He	^{9}He	^{10}He				
^{1}H	^{2}H	^{3}H	^{4}H	^{5}H	^{6}H	^{7}H						
	^{1}n	^{2}n										

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

12<Z<31



Zinc: 🟦54 55 56 57 58 59 60

Copper: 🟥54 55 56 57 58

Nickel: 🟦48 49 50 51 52 53 54 55 56

Cobalt: 🟥49 50 51 52 53 54

Iron: 🟦45 46 47 48 49 50 51 52

Manganese: 🟥44 🟥45 46 47 48 49 50

Chromium: 42 43 44 45 46 47 48

Vanadium: 🟥42 43 44 45 46

Titanium: 🟥38 39 40 41 42 43 44

Scandium: 🟥39 40 41 42 43

Calcium: 35 36 37 38 39 40

Potassium: 🟥33 🟥34 35 36 37 38

Argon: 31 32 33 34 35 36

Chlorine: 🟥29 🟥30 31 32 33 34

Sulfur: 🟥26 27 28 29 30 31 32

Phosphorus: 🟥25 26 27 28 29 30

Silicon: 22 23 24 25 26 27 28

Aluminum: 22 23 24 25 26

⬛ known

🟦 2-proton radioactive

🟥 unbound

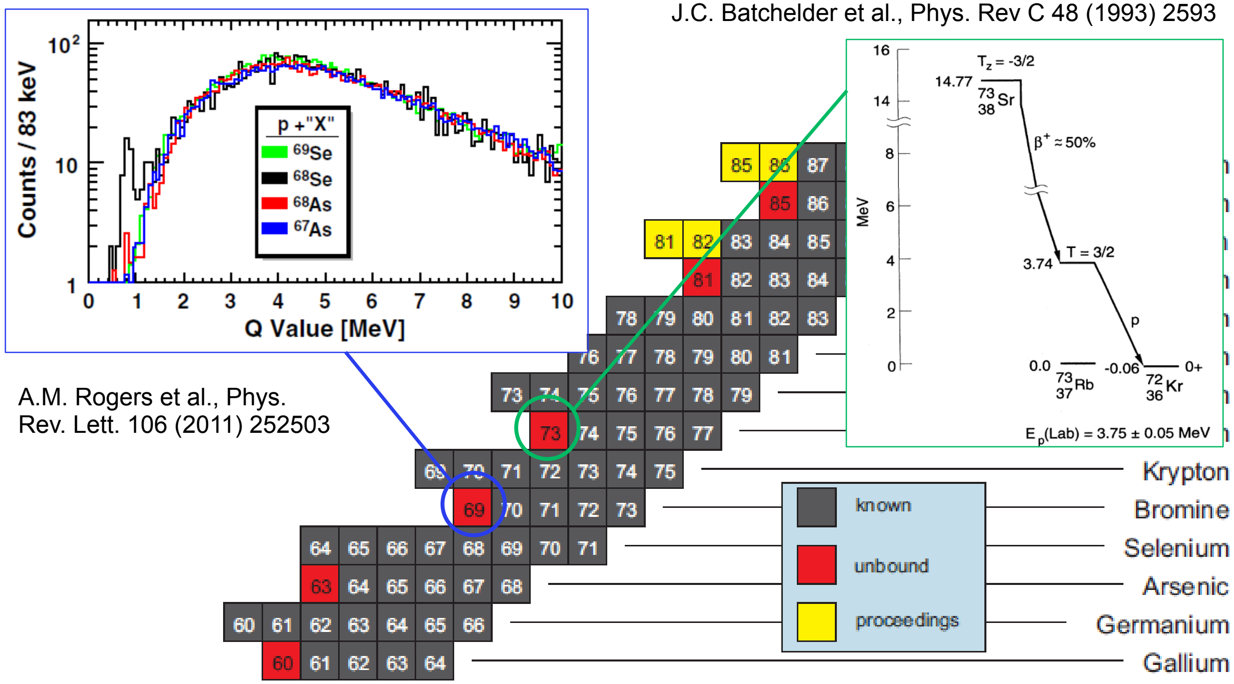
NSCL

National Science Foundation
Michigan State University

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

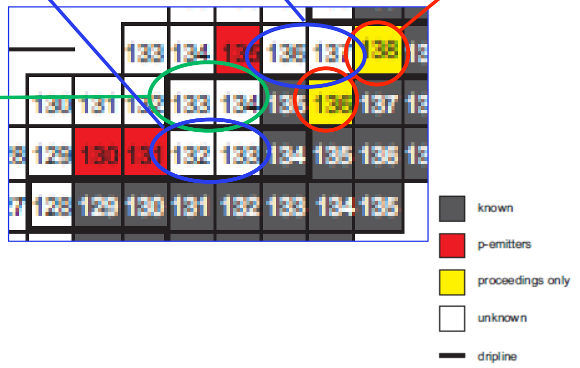
30<Z<44

J.C. Batchelder et al., Phys. Rev C 48 (1993) 2593



A.M. Rogers et al., Phys. Rev. Lett. 106 (2011) 252503

51<Z<84

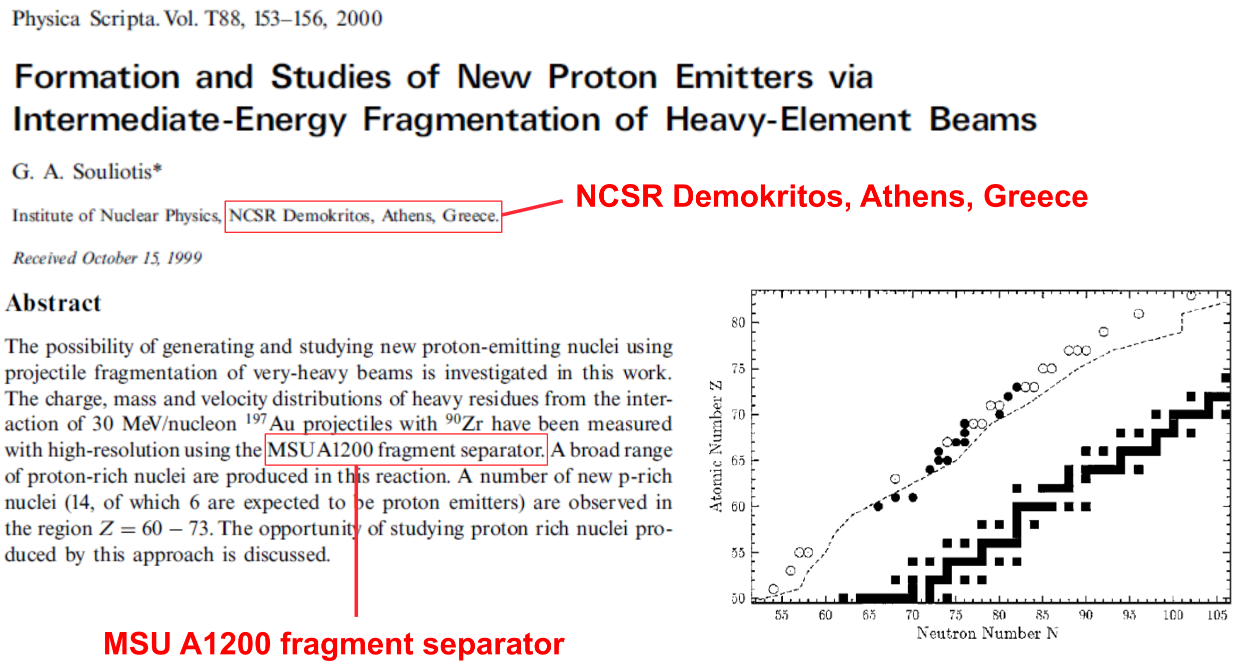


Odd-Z: Still unknown isotopes between proton and β^+ emitters

Published only in a conference proceeding

Even-Z: A few bound isotopes are still unknown

Issue with 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.

Received October 15, 1999

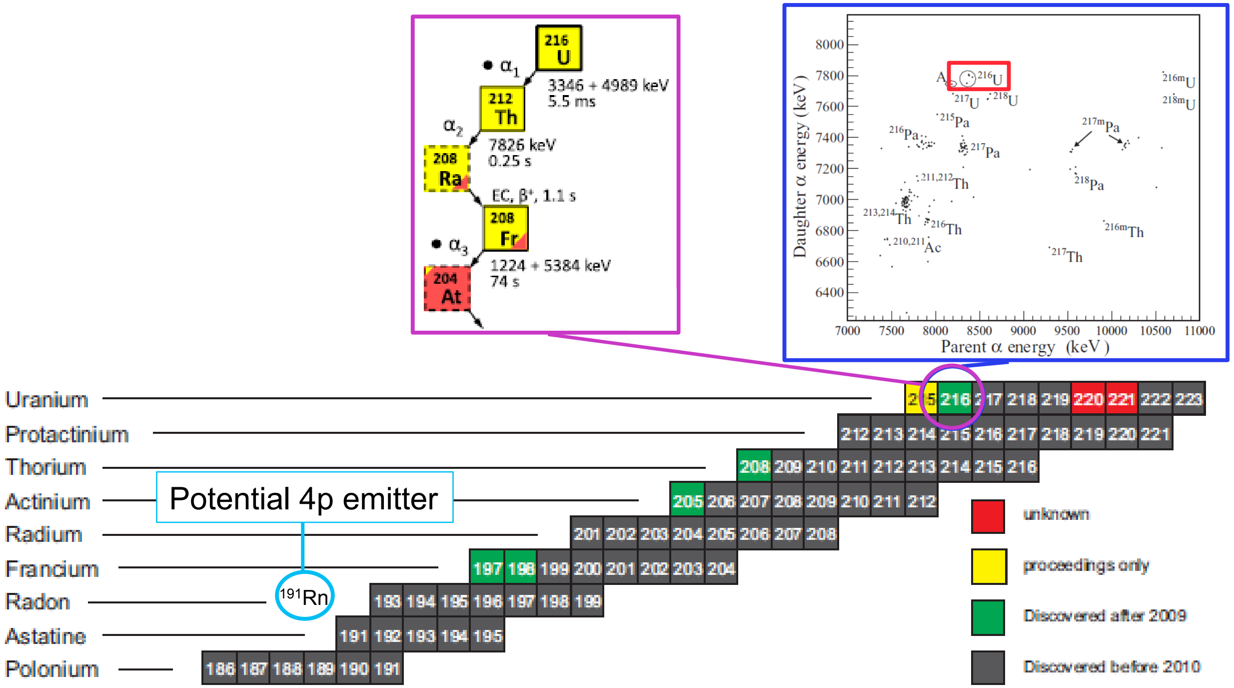
Abstract

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.

NCSR Demokritos, Athens, Greece

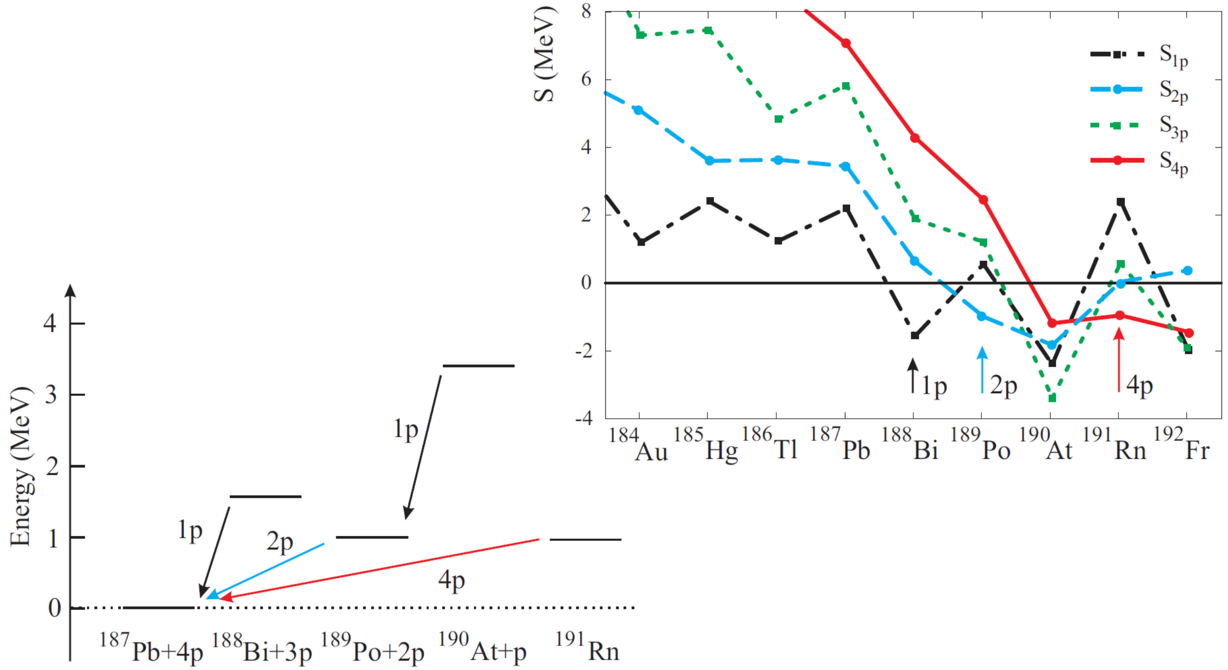
MSU A1200 fragment separator

83<Z<93



L. Ma et al., Phys. Rev. C 91 (2015) 051302(R)

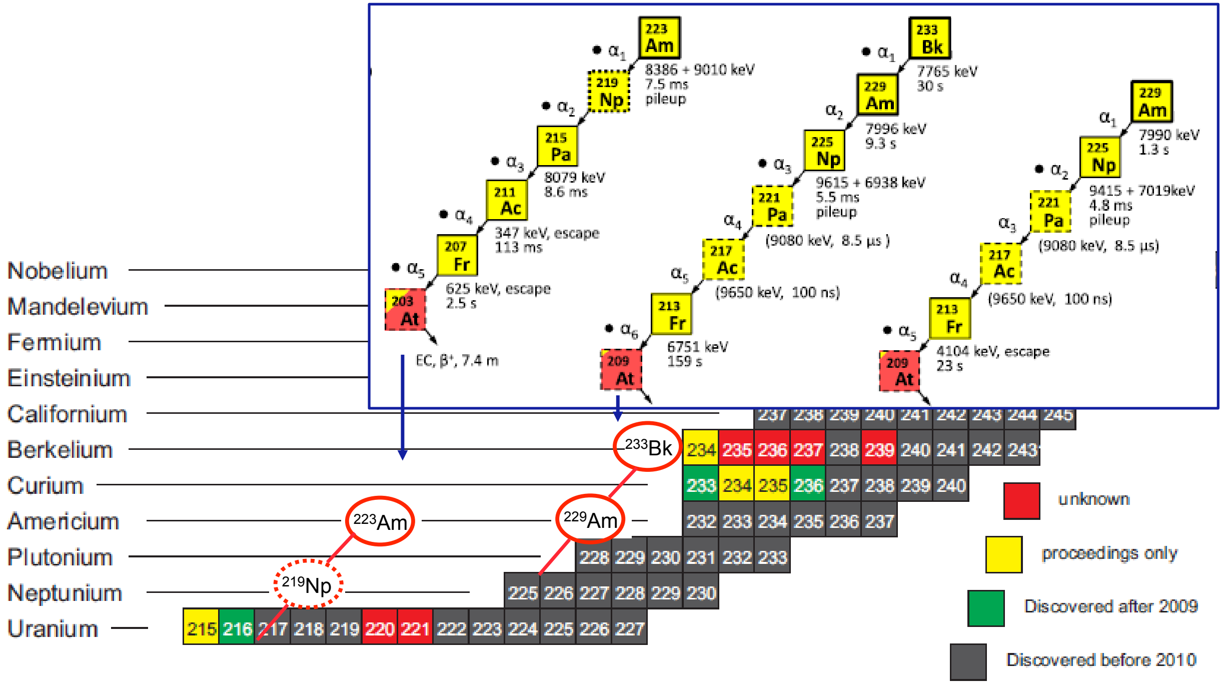
Four-proton radioactivity



National Science Foundation
Michigan State University

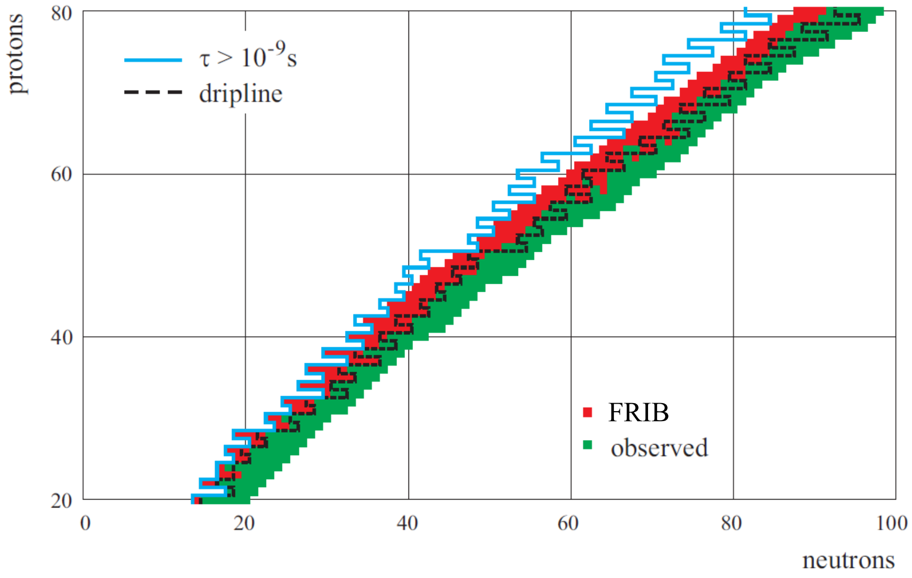
M. Thoennessen, Rep. Prog. Phys. 67 (2004) 1187

92<Z<103



H.M. Devaraja et al., Phys. Lett. B 748 (2015) 199

At and beyond the proton dripline



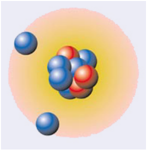
M. Thoennessen, Rep. Prog. Phys. 67 (2004) 1187

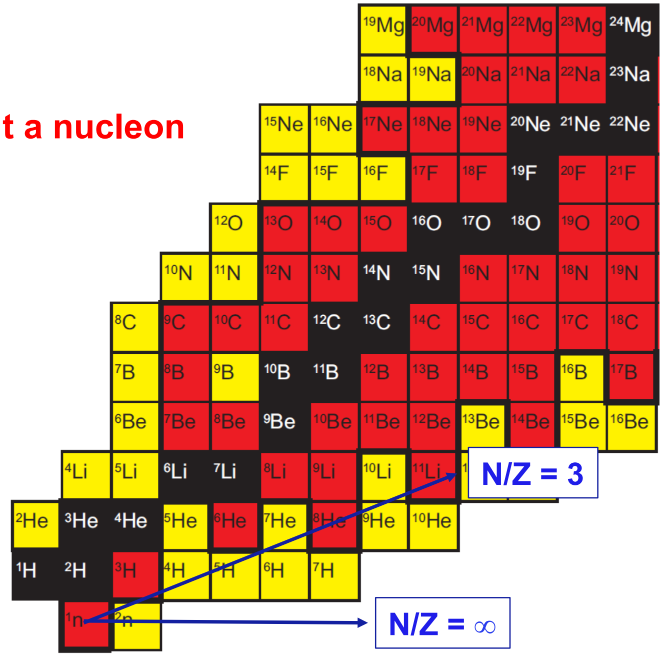
Most neutron-rich nuclides

N/Z = ∞ ~~**^{1}n**~~ **not a nuclide but a nucleon**

N/Z = 3 **^{8}He**

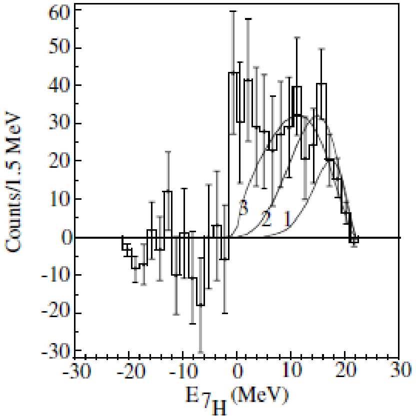
^{11}Li: N/Z = 2.67





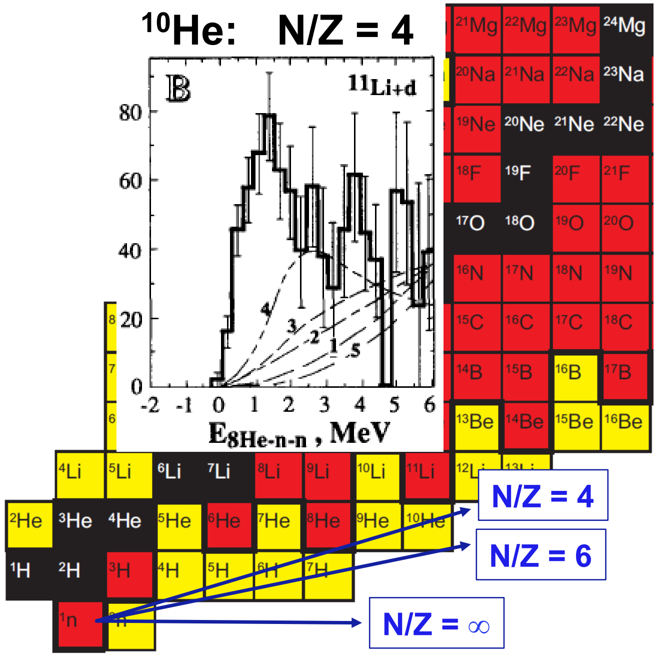
Including unbound nuclides

^{7}H: N/Z = 6



Γ ~ 5 MeV $T_{1/2} = 9 \cdot 10^{-23}$s

^{10}He: N/Z = 4



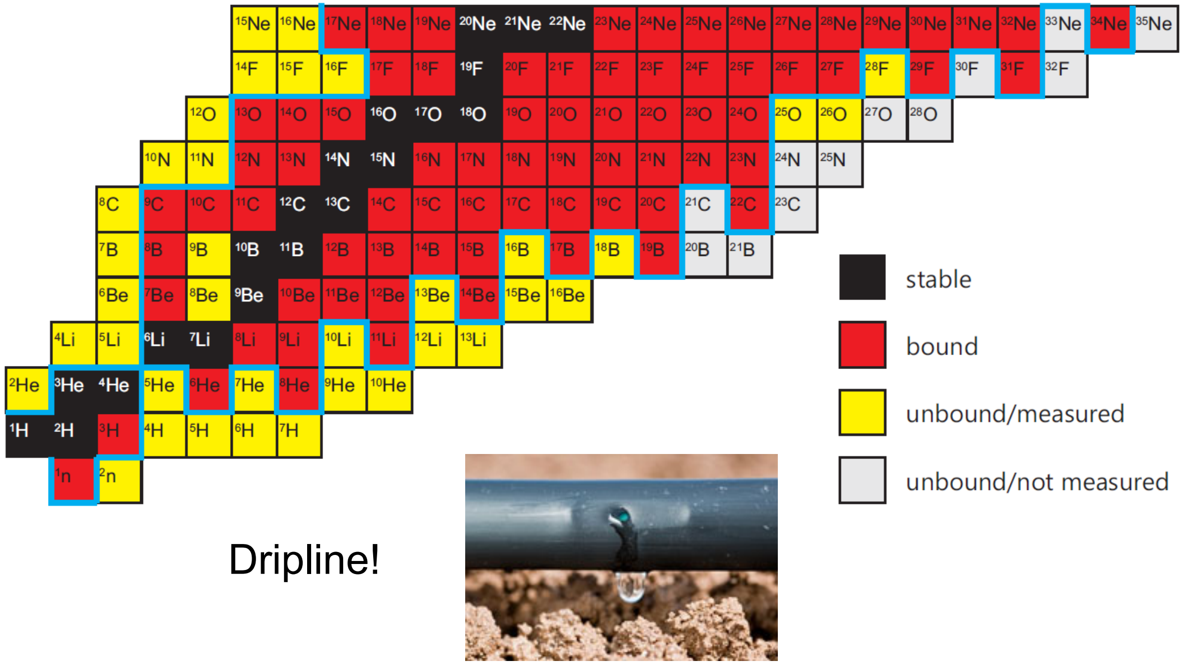
N/Z = 4

N/Z = 6

N/Z = ∞

A.A. Korsheninnikov et al., PRL 90 (2003) 082501
A.A. Korsheninnikov et al., PLB 326 (1994) 31

Neutron emitting nuclei



■ stable

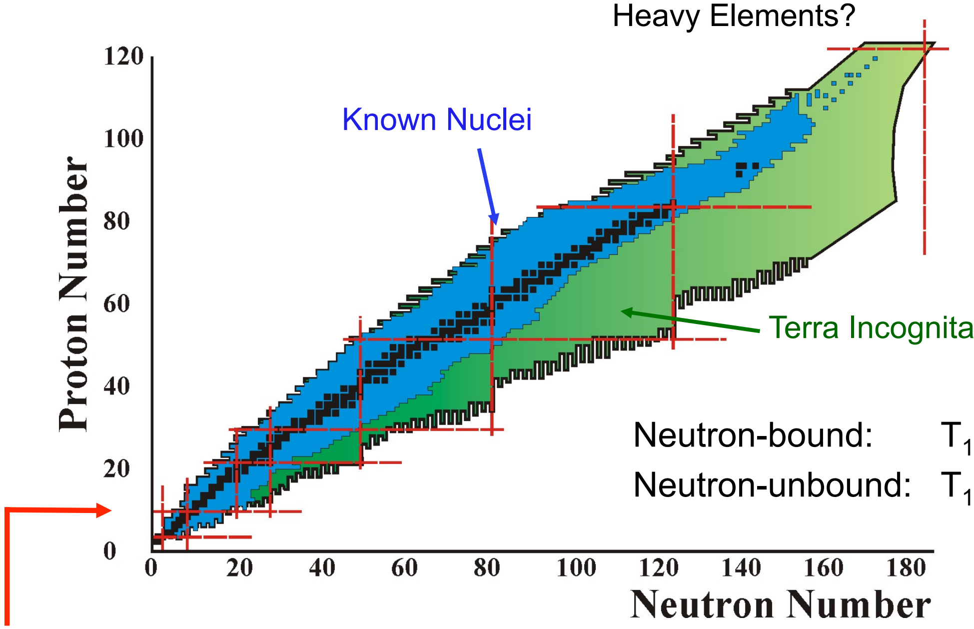
🟥 bound

🟨 unbound/measured

⬜ unbound/not measured

Dripline!

Limits of Nuclear Stability

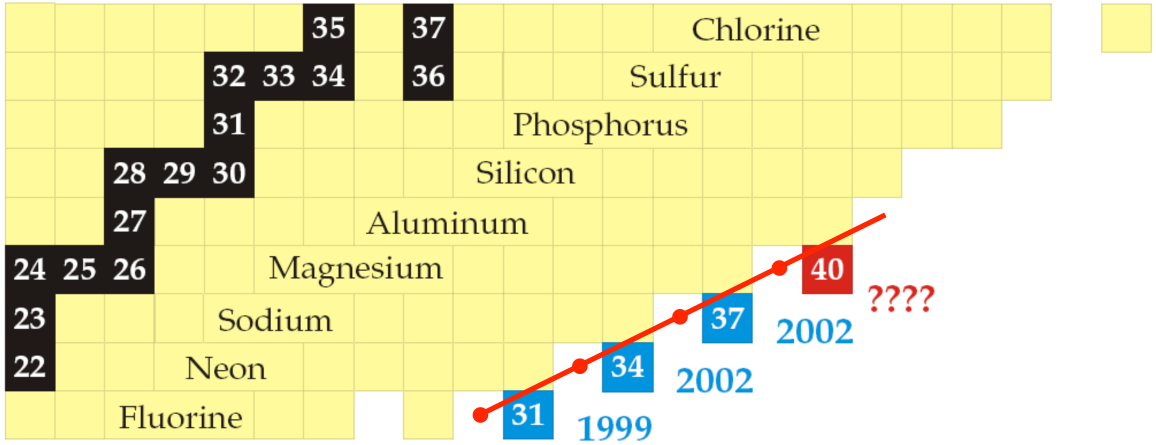


Neutron-bound: $T_{1/2} > \text{ms}$

Neutron-unbound: $T_{1/2} < 10^{-20}$ s

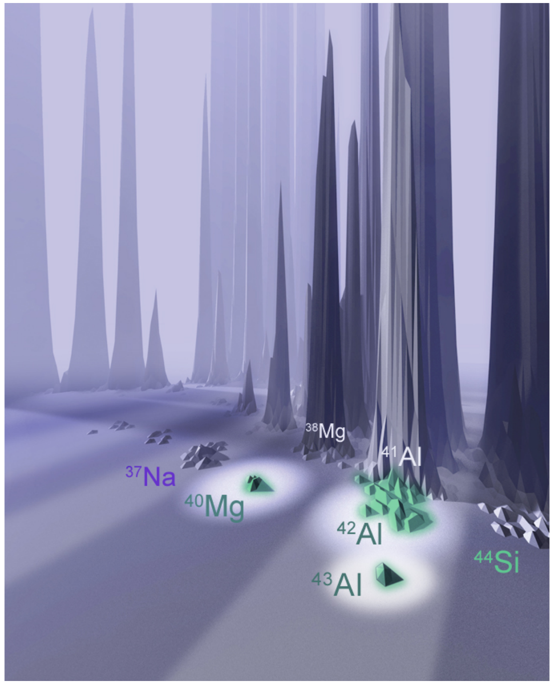
The neutron-rich limit is only known up to oxygen

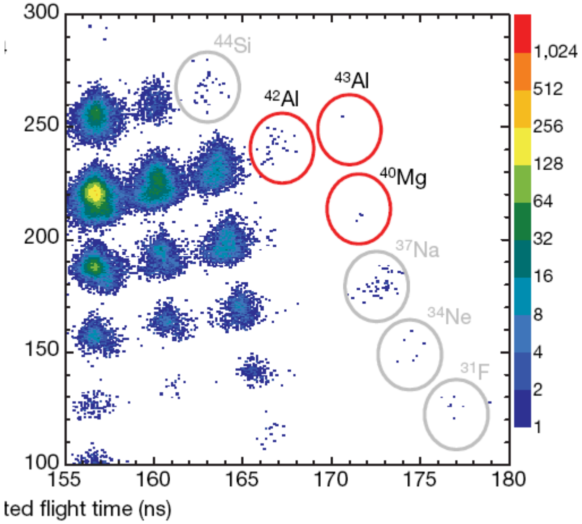
Quest for ^{40}Mg



H. Sakurai et al., PLB 448 (1999) 180
M. Notani et al., PLB 542 (2002) 49
S.M. Lukyanov et al., JPG 28 (2002) L41

First Observation of ^{40}Mg



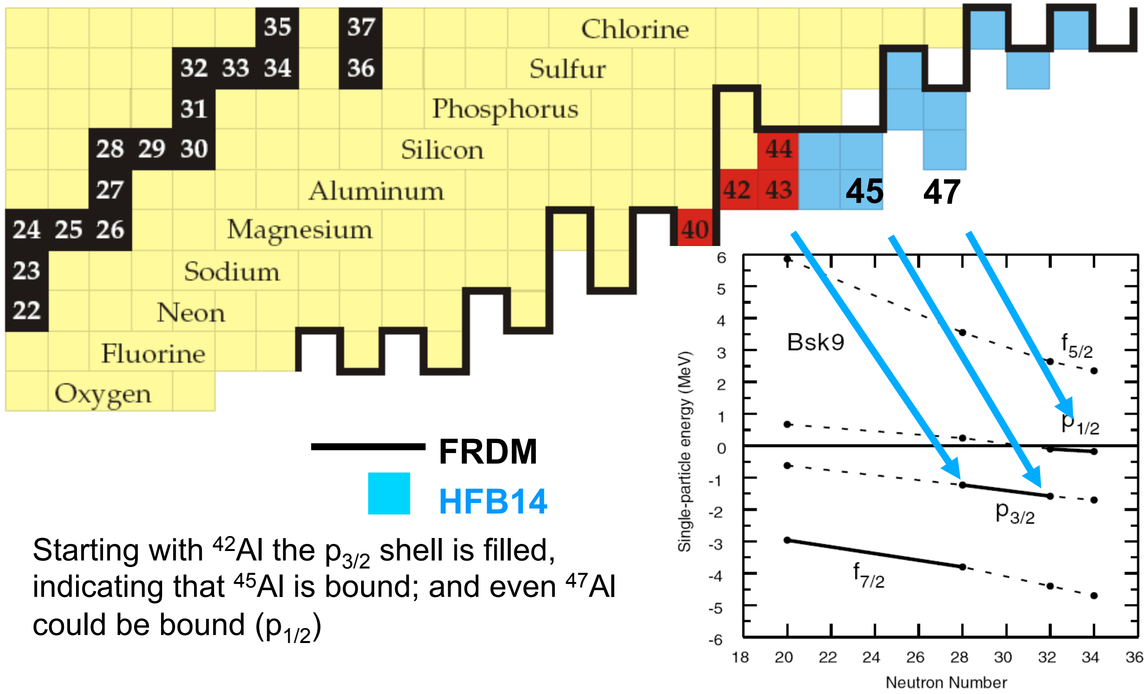


^{40}Mg production:

1 in 10^{17} ^{48}Ca beam particles !

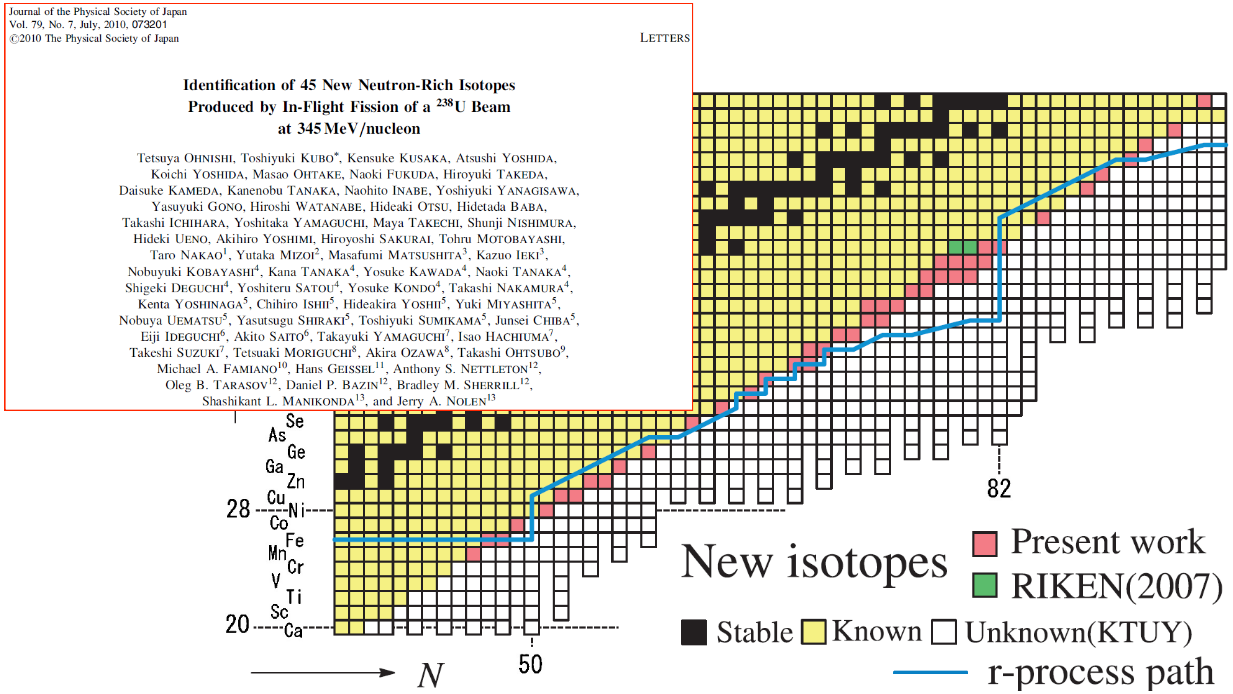
T. Baumann *et al.*, Nature **449** (2007) 1022

Dripline Extends Further than Believed



Starting with ^{42}Al the $p_{3/2}$ shell is filled, indicating that ^{45}Al is bound; and even ^{47}Al could be bound ($p_{1/2}$)

RIKEN 2010



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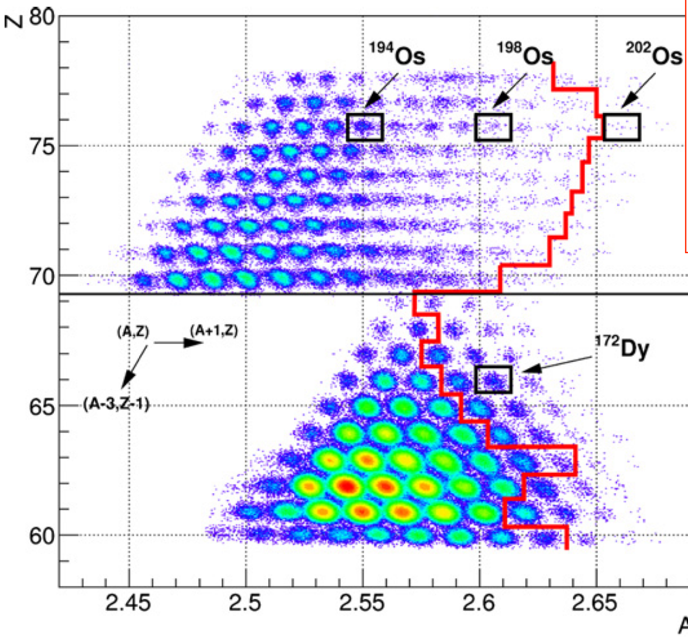
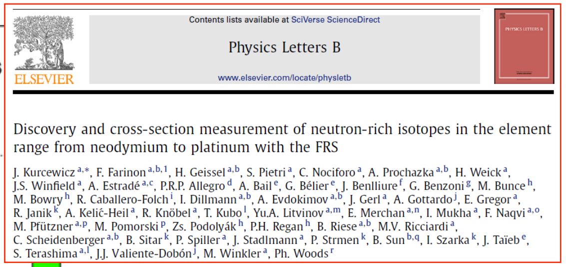
LETTERS

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

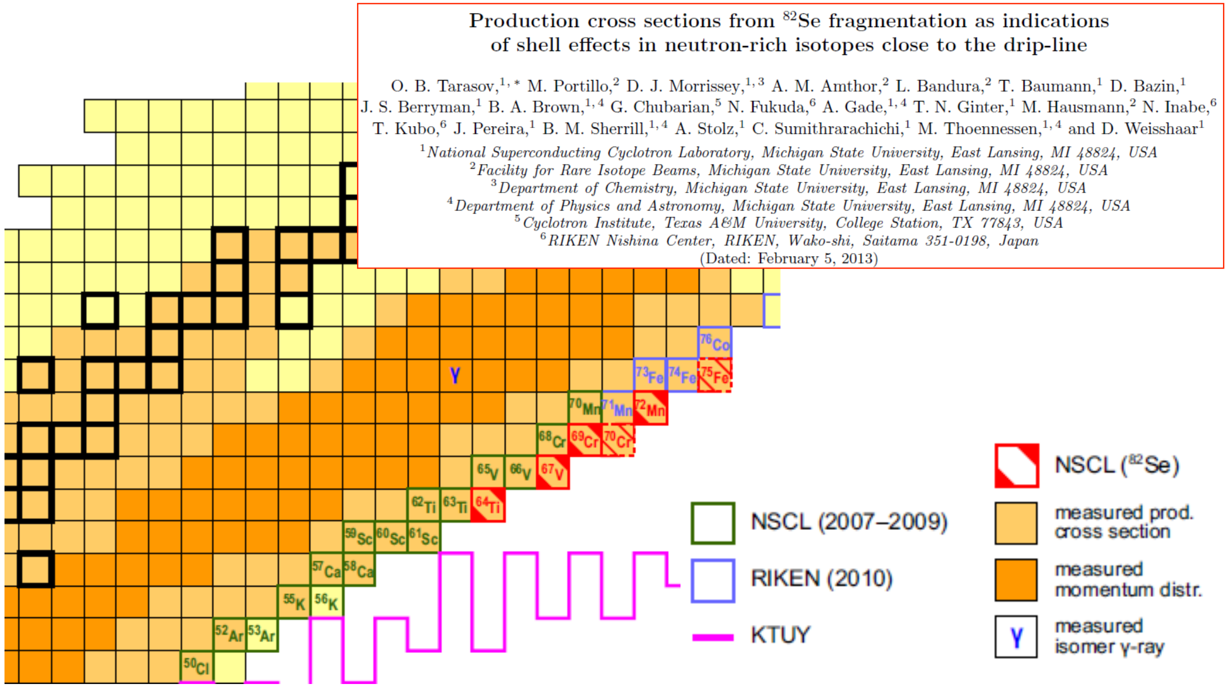
www.elsevier.com/locate/physletb

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…

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]

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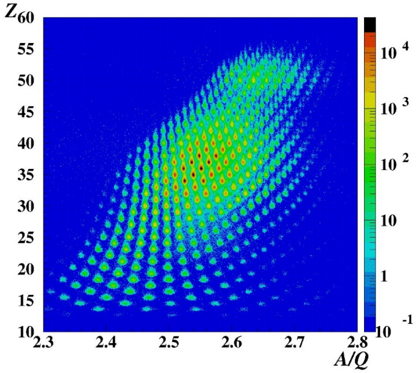
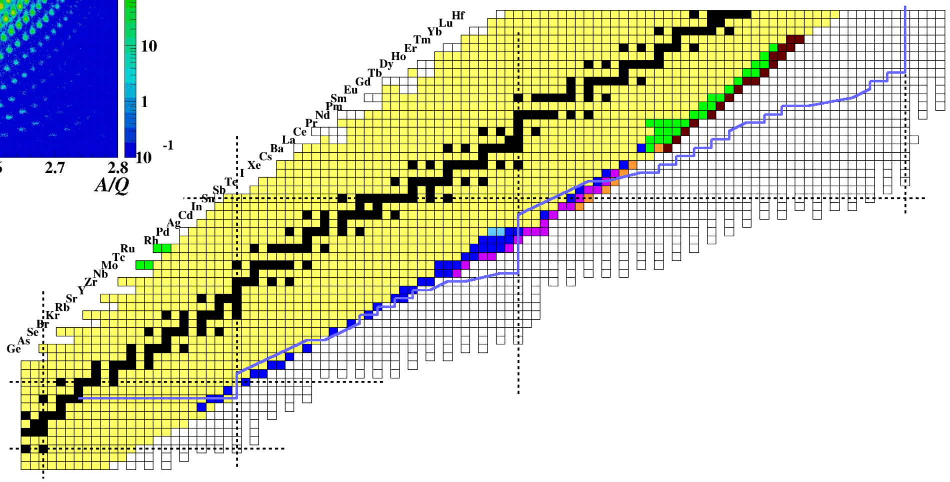
[2] Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI 48824, USA
[3] Department of Chemistry, Michigan State University, East Lansing, MI 48824, USA
[4] Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48824, USA
[5] Cyclotron Institute, Texas A&M University, College Station, TX 77843, USA
[6] RIKEN Nishina Center, RIKEN, Wako-shi, Saitama 351-0198, Japan
(Dated: February 5, 2013)

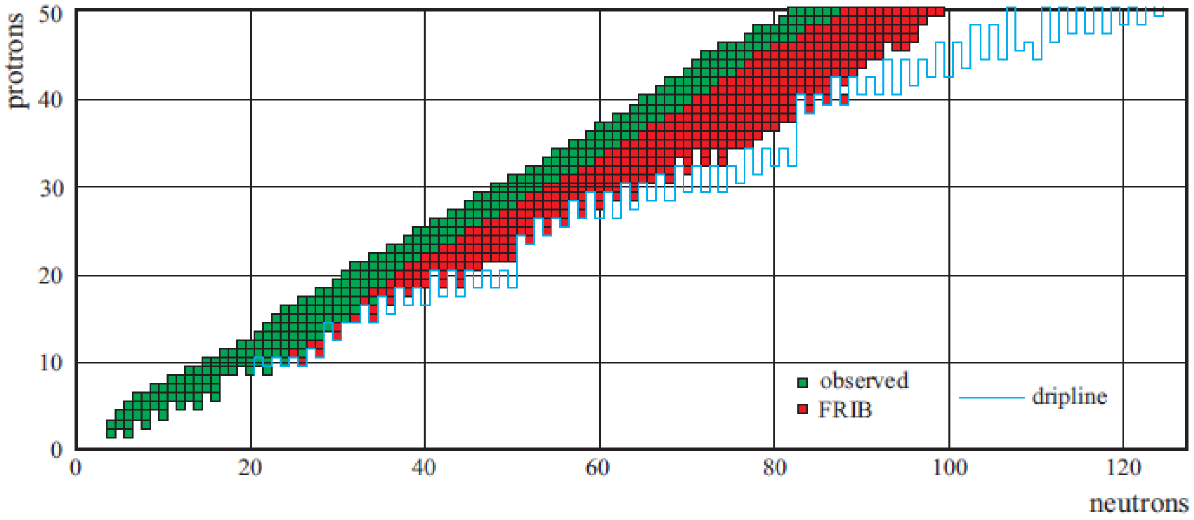
RIBF and BigRIPS: 2011-2014



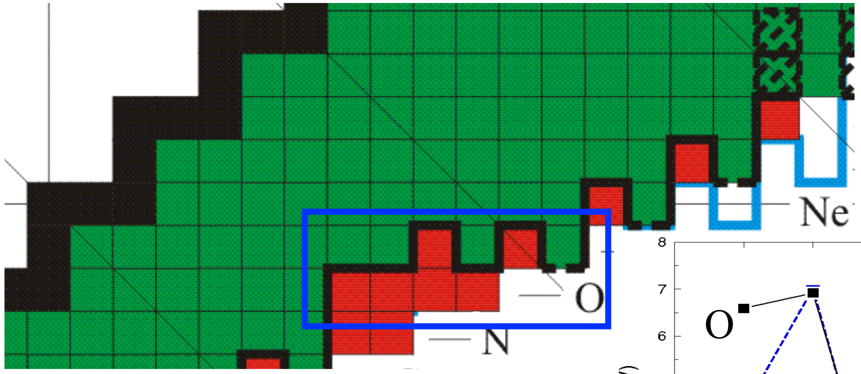
More than 70 new isotopes!



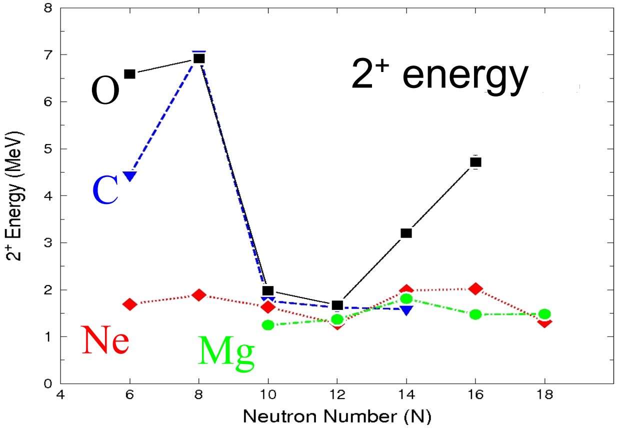
Reaching the neutron dripline



Going Beyond the Dripline

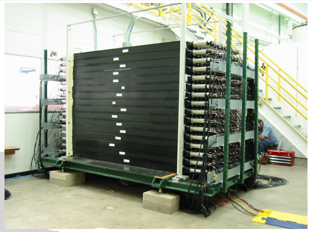


Add protons to the $0d_{5/2}$: $\nu 0d_{3/2} - \pi 0d_{5/2}$ interaction changes the N=16 shell gap

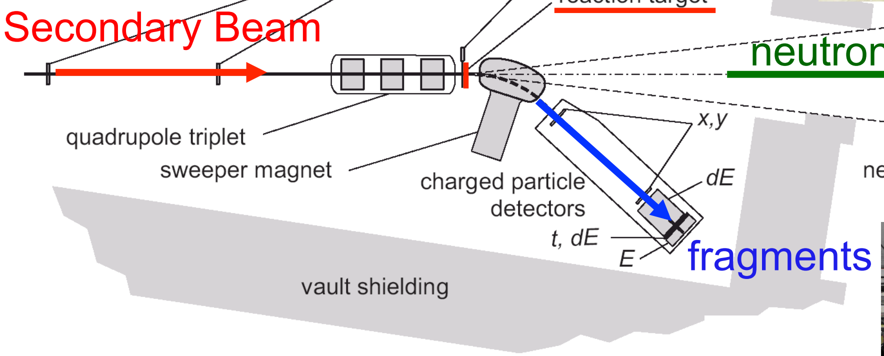


Invariant mass spectroscopy

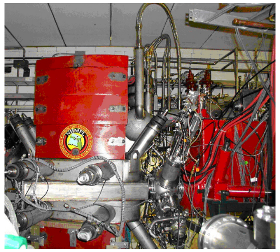
Example: ^{25}O: ^{9}Be(^{26}F,^{25}O)X



MoNA

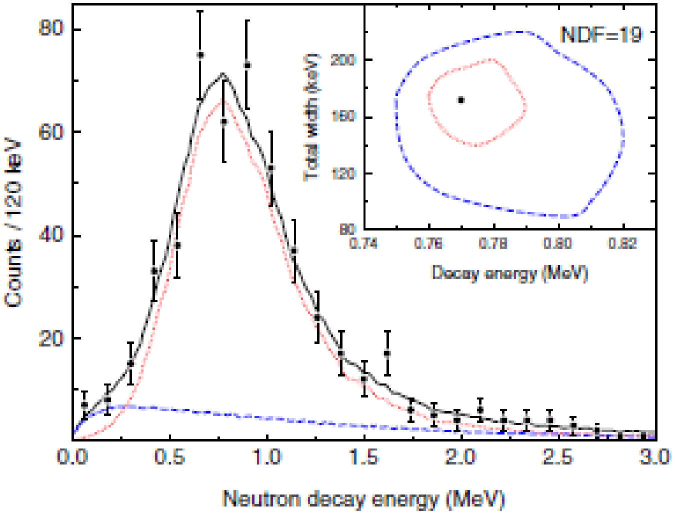


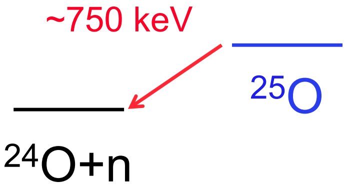
Sweeper



$$E_{\text{decay}} = \sqrt{m_{\text{f}}^2 + m_{\text{n}}^2 + 2[E_{\text{f}}E_{\text{n}} - p_{\text{f}}p_{\text{n}}\cos(\Theta_{\text{open}})]} - m_{\text{f}} - m_{\text{n}}$$

Populating ^{25}O in one-proton removal reactions from ^{26}F





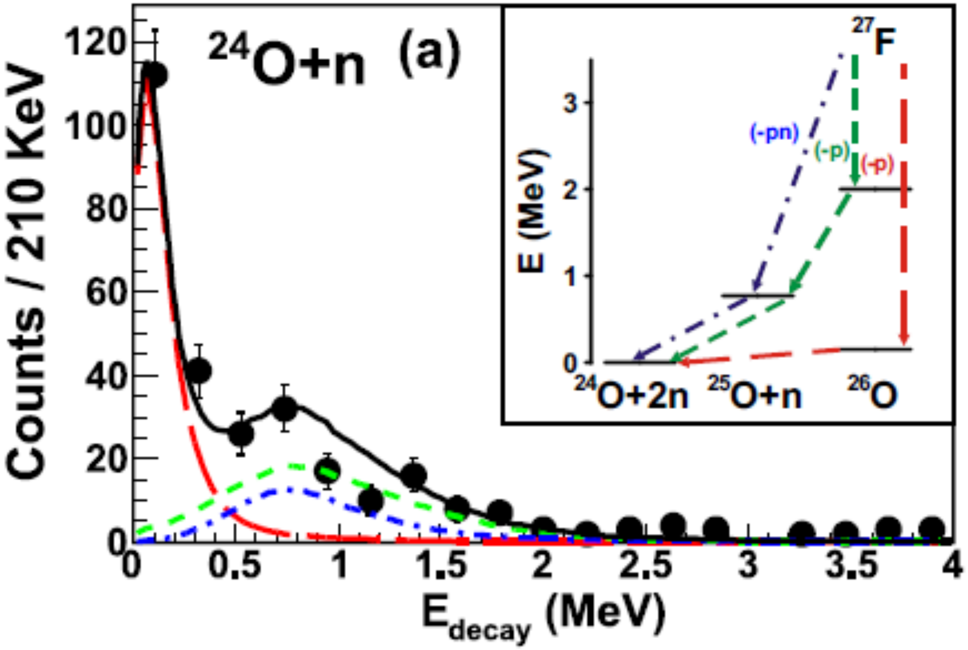
~750 keV

^{25}O

^{24}O+n

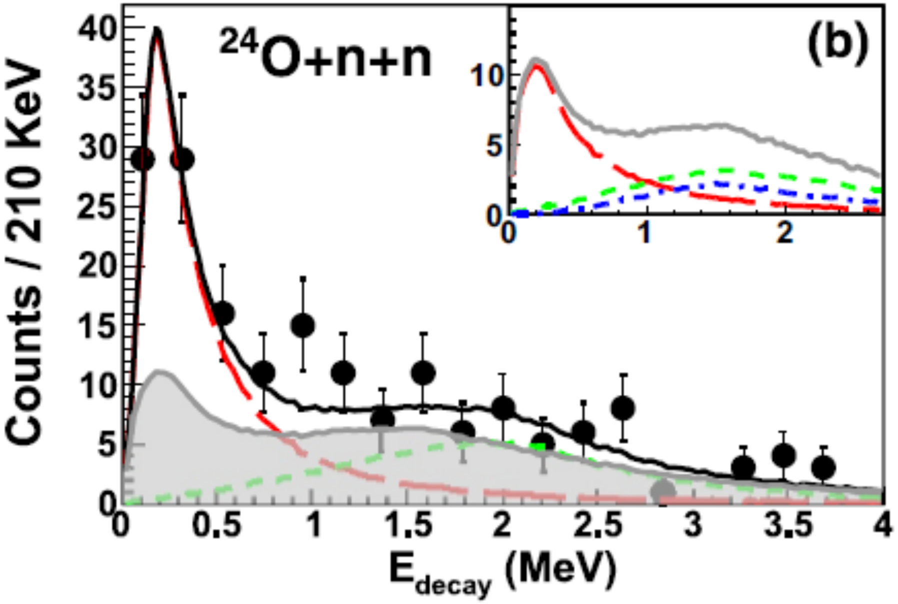
C.R. Hoffman et al., Phys. Rev. Lett. 100 (2008) 152501

Populating ^{26}O in one-proton removal reactions from ^{27}F



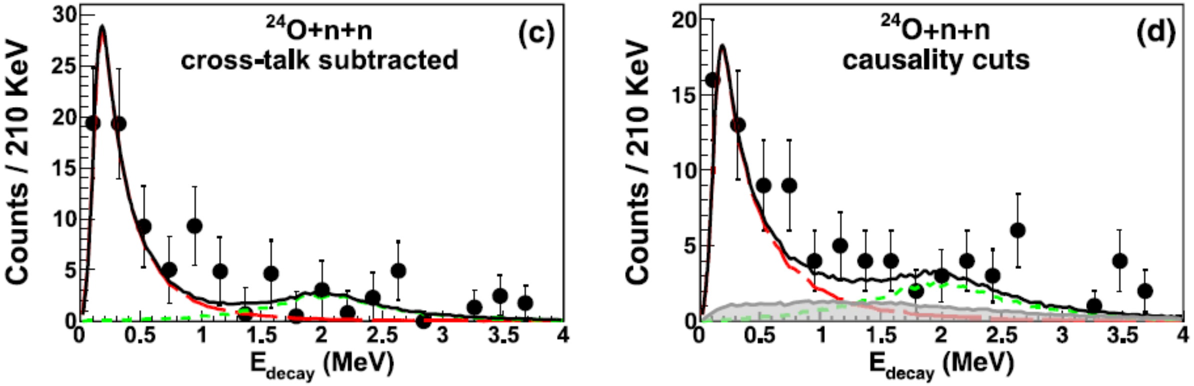
E. Lunderberg et al., Phys. Rev. Lett. **108** (2012) 142503

Reconstructing ^{26}O



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

Identifying real two-neutron events



$E_{rel} = 150^{+50}_{-150}$ keV

Causality cuts:

- Δv = 7 cm/ns
- Δ d = 25 cm

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

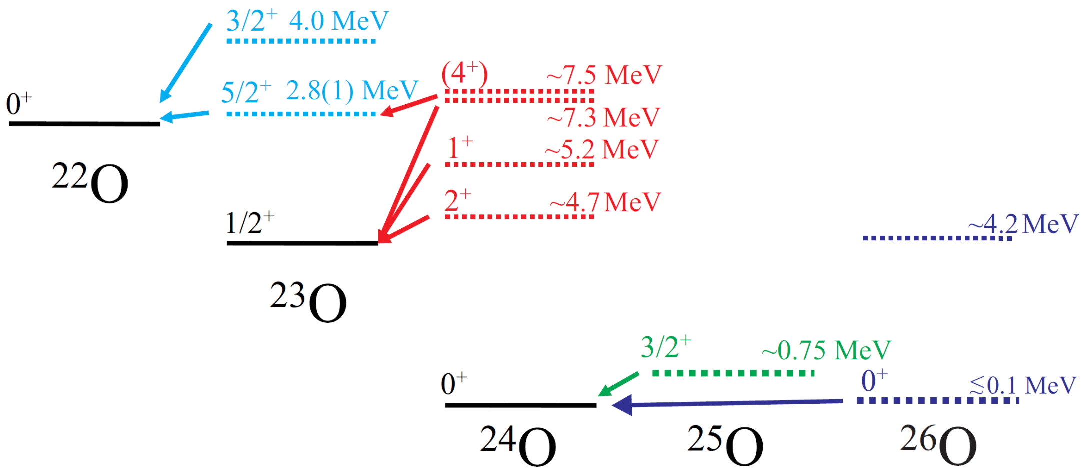
Spectroscopy of neutron-rich oxygen isotopes

Z. Elekes et al., PRL 98 (2007) 102502
A. Schiller et al., PRL 99 (2007) 112501

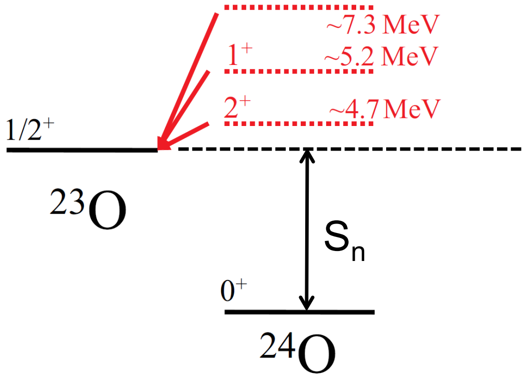
C.R. Hoffman et al., PLB 672 (2009) 17
C.R. Hoffman et al., PRC83 (2011) 031303
K. Tshoo et al., PRL 109 (2012) 022501
V. Lapoux et al., Prog. Theor. Phys. Suppl. 196 (2012) 111

C.R. Hoffman et al., PRL 100 (2008) 152501
C. Caesar et al., arXiv:1209.0156
Y, Kondo et al, COMEX4, Oct. 2012

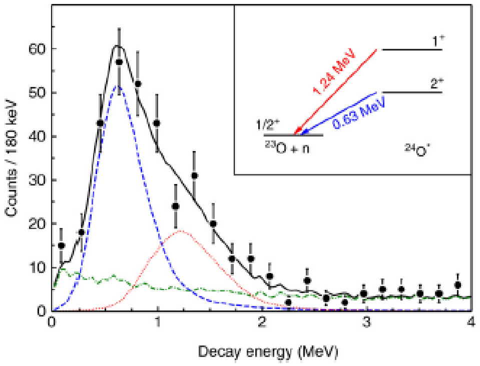
E. Lunderberg et al., PRL 108 (2012) 0142503
C. Caesar et al., arXiv:1209.0156



From decay energy to excitation energy



$E^* = E_{decay} + S_n$

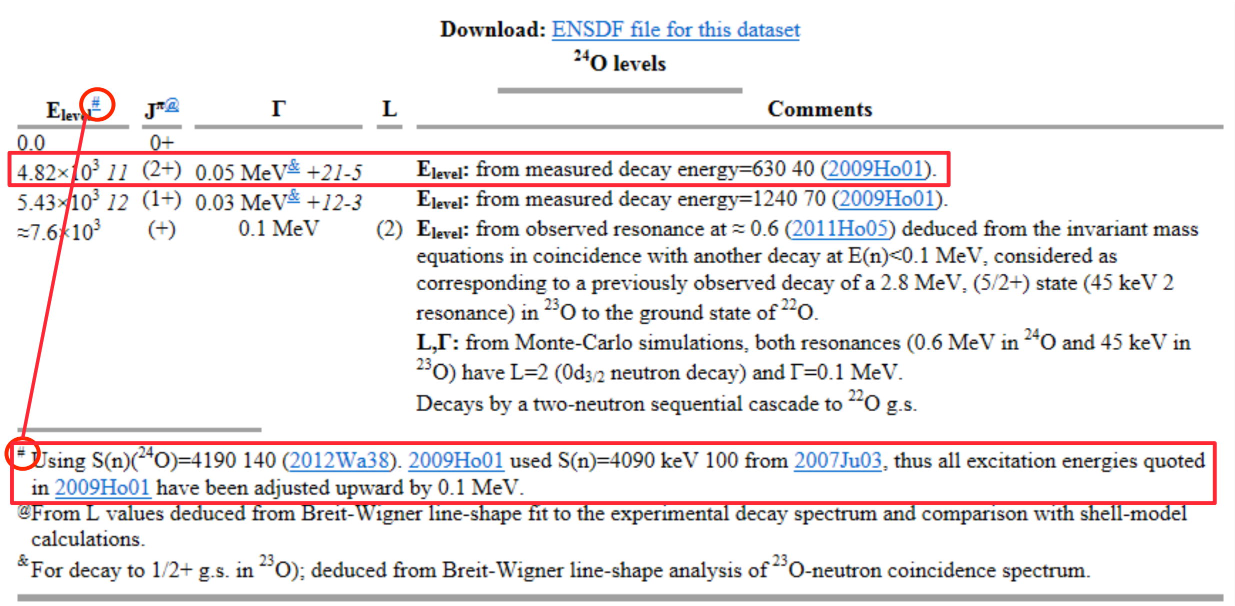


$E^*(2^+) = 4.72(11)$ MeV

However, ENSDF: $E^*(2^+) = 4.82(11)$ MeV

C.R. Hoffman et al., Phys. Lett. B 672 (2009) 17

S_n is largest source of uncertainty



Download: ENSDF file for this dataset

^{24}O levels

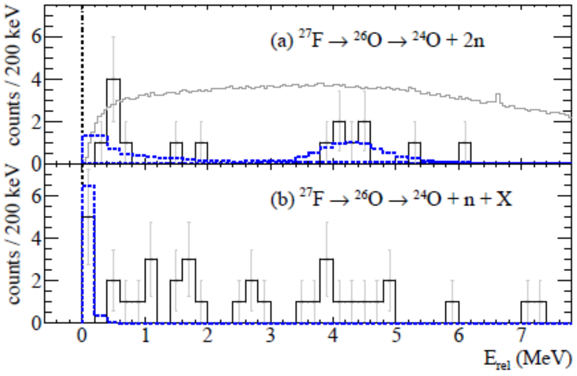
E_{level}[#]	**J^{π}**[@]	**Γ**	**L**	**Comments**
0.0	0+			
4.82×10^3 *11*	(2+)	0.05 MeV[&] *+21-5*		**E_{level}:** from measured decay energy=630 40 (2009Ho01).
5.43×10^3 *12*	(1+)	0.03 MeV[&] *+12-3*		**E_{level}:** from measured decay energy=1240 70 (2009Ho01).
≈7.6×10^3	(+)	0.1 MeV	(2)	**E_{level}:** from observed resonance at ≈ 0.6 (2011Ho05) deduced from the invariant mass equations in coincidence with another decay at E(n)<0.1 MeV, considered as corresponding to a previously observed decay of a 2.8 MeV, (5/2+) state (45 keV 2 resonance) in ^{23}O to the ground state of ^{22}O. **L,Γ:** from Monte-Carlo simulations, both resonances (0.6 MeV in ^{24}O and 45 keV in ^{23}O) have L=2 ($0d_{3/2}$ neutron decay) and Γ=0.1 MeV. Decays by a two-neutron sequential cascade to ^{22}O g.s.

[#] Using S(n)(^{24}O)=4190 140 (2012Wa38). 2009Ho01 used S(n)=4090 keV 100 from 2007Ju03, thus all excitation energies quoted in 2009Ho01 have been adjusted upward by 0.1 MeV.

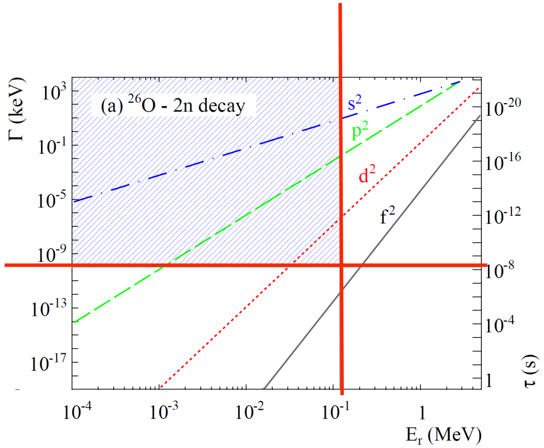
[@] From L values deduced from Breit-Wigner line-shape fit to the experimental decay spectrum and comparison with shell-model calculations.

[&] For decay to 1/2+ g.s. in ^{23}O); deduced from Breit-Wigner line-shape analysis of ^{23}O-neutron coincidence spectrum.

Results confirmed by R^3B-LAND



E_{rel} < 120 keV

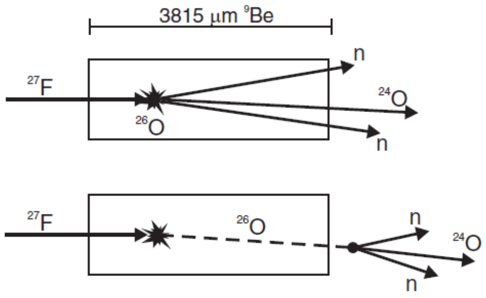


Lifetime limit: $\tau < 5.7$ ns

$E_d = 100$ keV ↔ $T_{1/2} \approx 10^{-11}$ ps
$E_d = 600$ keV ↔ $T_{1/2} \approx 10^{-16}$ ps

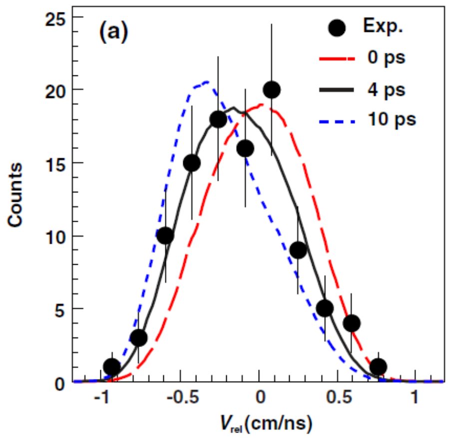
C. Caesar et al., Phys. Rev. C 88 (2013) 034313
L.V. Grigorenko et al., Phys. Rev. C 84 (2011) 021303

Lifetime measurement



improved lifetime limit: $\tau < 5.6$ ps

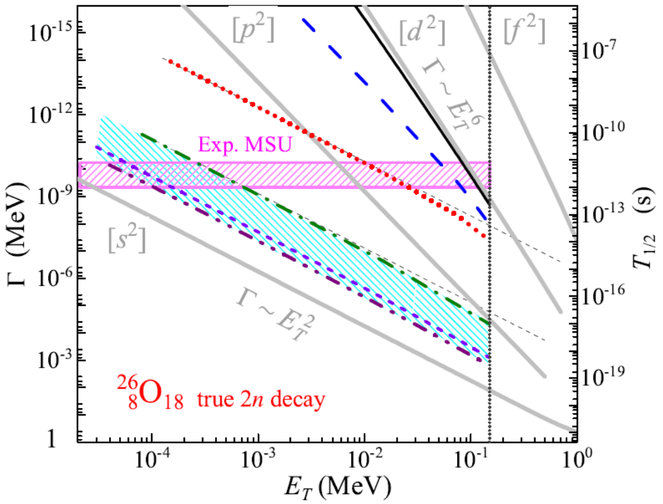
Lifetime: $\tau = 4.5^{+1.1}_{-1.5}$ (stat) ±3 (syst) ps



→ 82%C.L. for possible finite
two-neutron radioactivity lifetime

Z. Kohley et al., Phys. Rev. Lett. 110 (2012) 152501

New lifetime calculations



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“realistic theoretical limits”

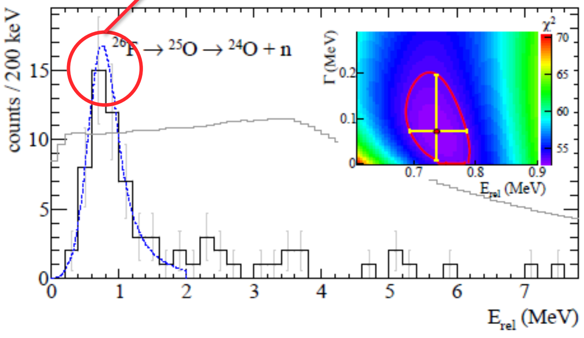
$E_T < 1$ keV

L.V. Grigorenko, I.G. Mukha, and M.V. Zhukov,
Phys. Rev. Lett. 111, 042501 (2013)

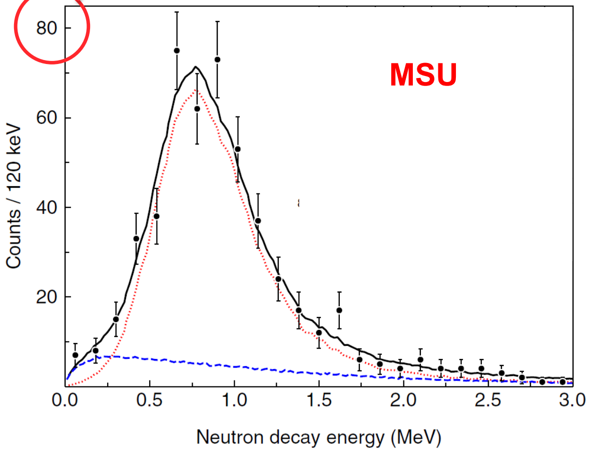
Limits of beam intensity (^{26}F to ^{25}O)

GSI

~15 counts/200keV



~80 counts/100keV

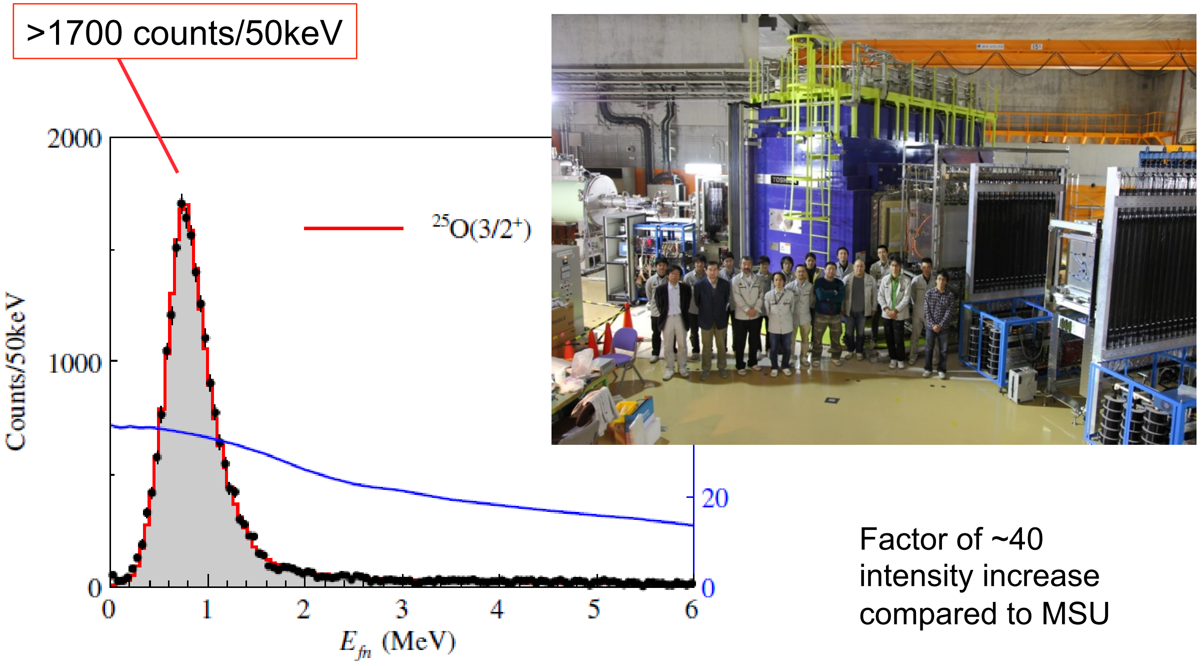


MSU

C. Caesar et al., arXiv:1209:0156v2

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

Recent results from RIBF on ^{25}O

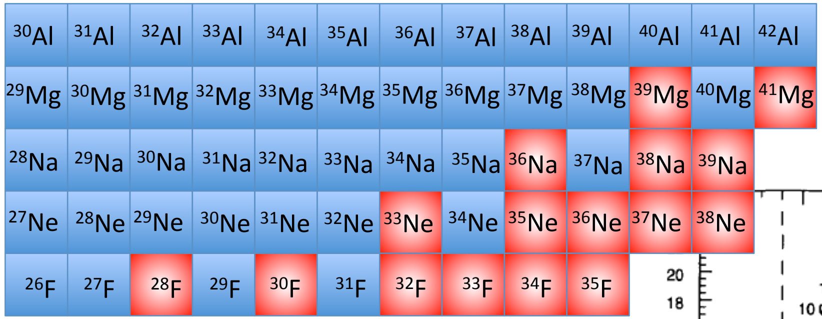


>1700 counts/50keV

Factor of ~40
intensity increase
compared to MSU

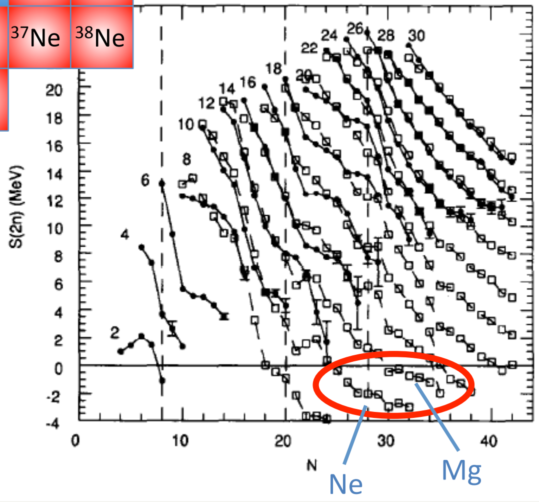
Y. Kondo et al., Phys. Rev. Lett. 116 (2016) 102503

Beyond the dripline in the *pf*-shell



^{30}Al	^{31}Al	^{32}Al	^{33}Al	^{34}Al	^{35}Al	^{36}Al	^{37}Al	^{38}Al	^{39}Al	^{40}Al	^{41}Al	^{42}Al
^{29}Mg	^{30}Mg	^{31}Mg	^{32}Mg	^{33}Mg	^{34}Mg	^{35}Mg	^{36}Mg	^{37}Mg	^{38}Mg	^{39}Mg	^{40}Mg	^{41}Mg
^{28}Na	^{29}Na	^{30}Na	^{31}Na	^{32}Na	^{33}Na	^{34}Na	^{35}Na	^{36}Na	^{37}Na	^{38}Na	^{39}Na	
^{27}Ne	^{28}Ne	^{29}Ne	^{30}Ne	^{31}Ne	^{32}Ne	^{33}Ne	^{34}Ne	^{35}Ne	^{36}Ne	^{37}Ne	^{38}Ne	
^{26}F	^{27}F	^{28}F	^{29}F	^{30}F	^{31}F	^{32}F	^{33}F	^{34}F	^{35}F			

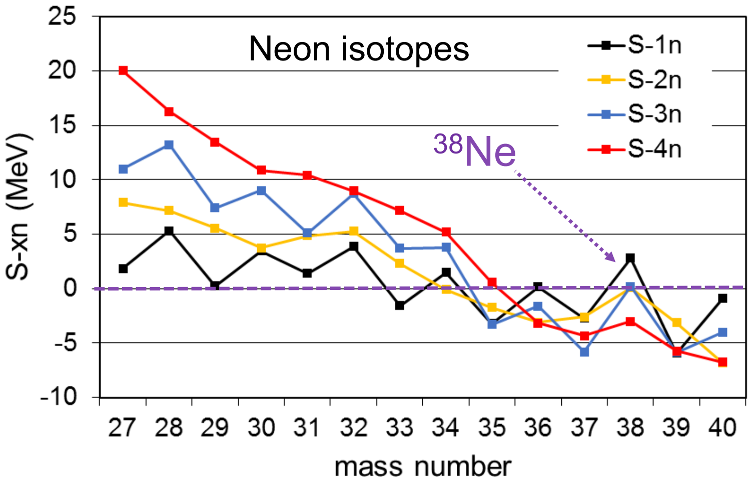
- The single particle energies within the $f_{7/2+}$ orbit change very little with increasing neutron number
- The separation energies stay almost constant
- Potential for several neutron unbound isotopes with low decay energy



B.A. Brown, Prog. Part. Nucl. Phys. 47 (2001) 517

Four-neutron emitter

- The FRDM predicts ^{38}Ne and ^{44}Mg to be direct four neutron emitters.
- They are bound with respect to 1-, 2-, and 3-neutron emission but unbound with respect 4-neutron emission.



Summary and outlook

- There are still hundreds of proton-rich isotopes left to be discovered
- On the neutron-rich side there are probably a few thousands isotopes reachable in the foreseeable future
- The driplines are not the limit. Spectroscopic information for nuclides beyond the dripline can be extracted from particle spectroscopy measurements
- The sophisticated setup require detailed simulations to extract the physical quantities
- It is important for the evaluators to understand the strengths and limitations of the various techniques