ISOL FRANCE

ISOL-France Workshop V

Mar 20 – 22, 2023
ISM

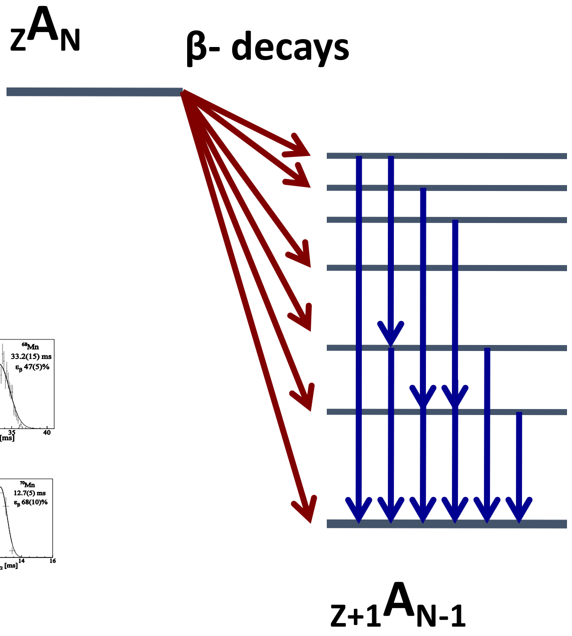
Review talk on β decay

G.Benzoni
INFN, sez. Milano (Italy)

$T_{1/2}$

$P_{n/p}$

%β, %α …

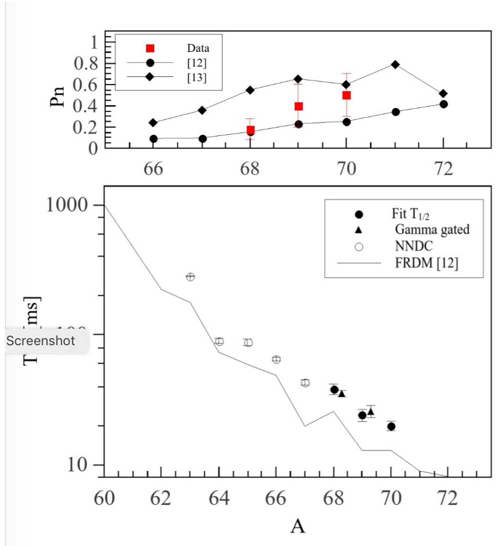


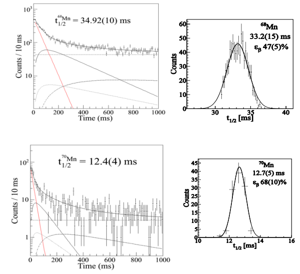
γ transitions

Possible existence of many decaying states

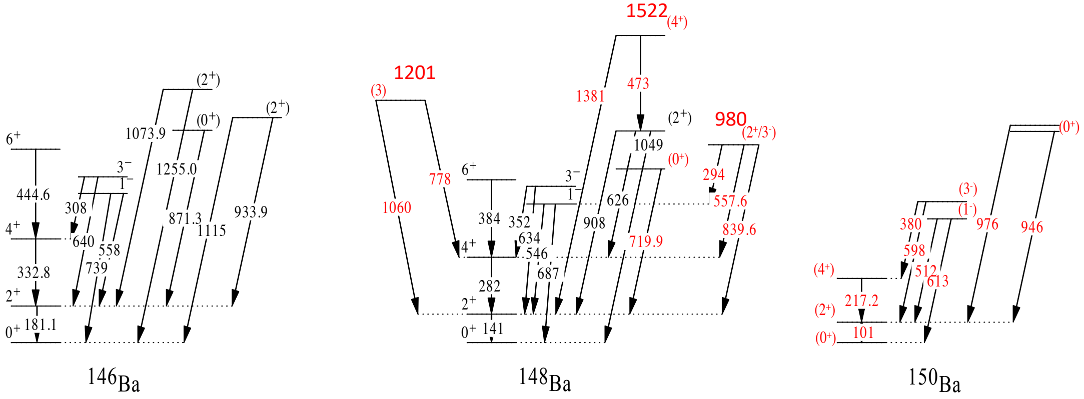
γ–γ coincidences➔ level schemes

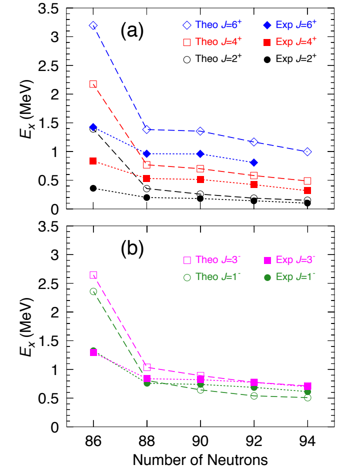
Relative intensities I_β logft

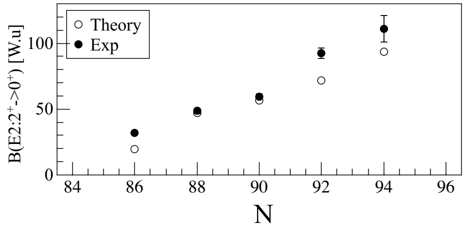




Selection rules allow to suggest/define J^π in both mother and daughter

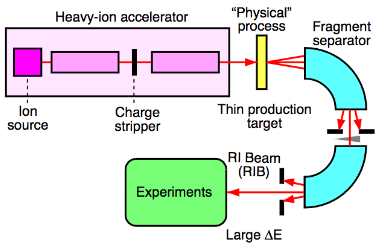






Producing radioactive beams i.e. exotic nuclei

IN-FLIGHT



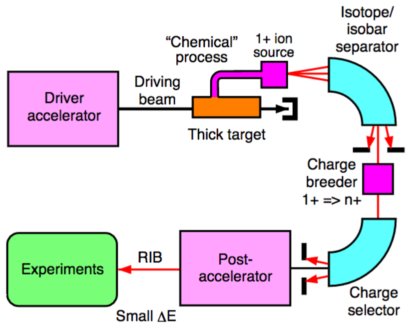
relativistic fragmentation/fission of heavy nuclei on thin targets

- > 50 MeV/u ➔ production of cocktail beams of many nuclei
- Use of spectrometers to transport/separate nuclei of interest➔ Relatively long decay paths Δt > 150-300 ns
- Nuclei are brought to rest in final focal plane and let decay

+ cocktail beam: many nuclei at once
+ both short and long-living species
+ get information already with few ions

- Low cross sections
- Limitation on rate to distinguish contribution from each species

ISOL method



spallation/fission/fragmentation on thick targets, followed by chemical/physical processes to extract desired nuclei

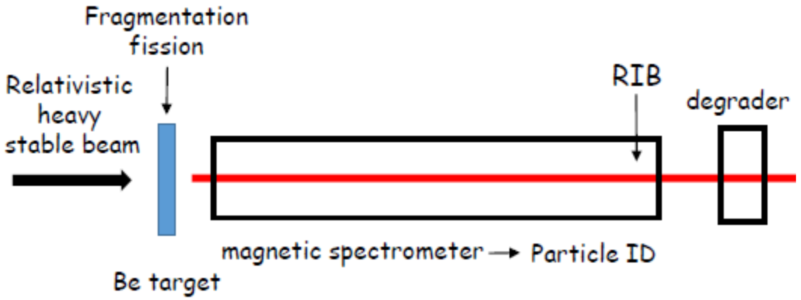
- beams produced at very low energies (~60 keV)
- Mono-isotopic beams sometimes achieved. Impurities due to few contaminant species ➔ usually long-living though

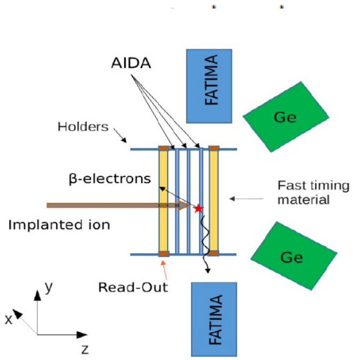
+ high cross section
+ no need to re-accelerate beams
+ high rates accepted

- short-living species might not be accessed easily
- Refractory elements
- Presence of long-living impurities

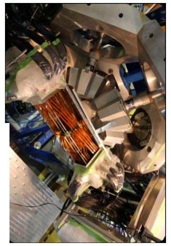
(isobaric contamination)

Measuring β decay

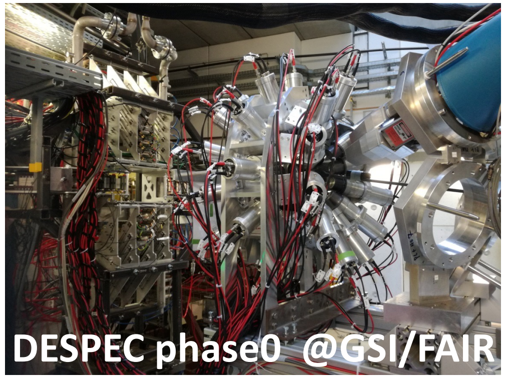




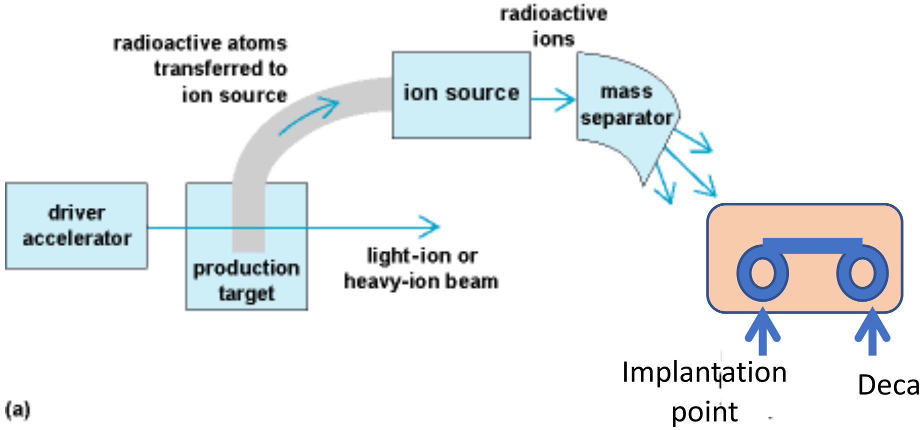
IN-Flight facility



Eurica@RIKEN



DESPEC phase0 @GSI/FAIR



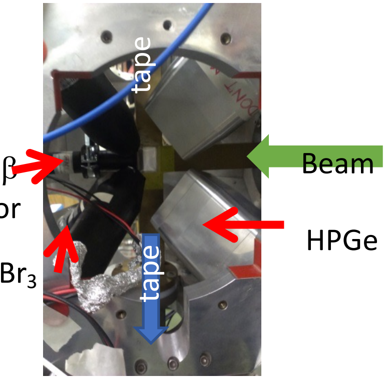
Implantation point

Decay point

ISOL facility

Tape decay stations

IDS @ CERN



tape

Plastic β detector

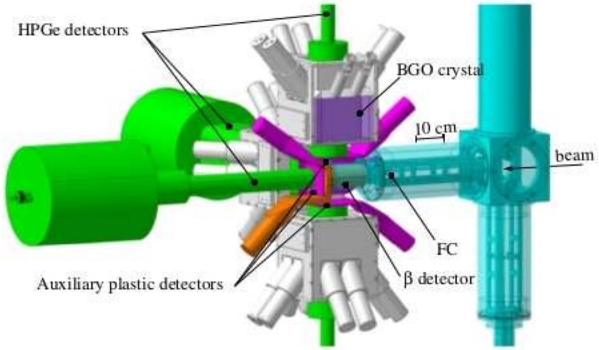
Beam

HPGe

LaBr$_3$

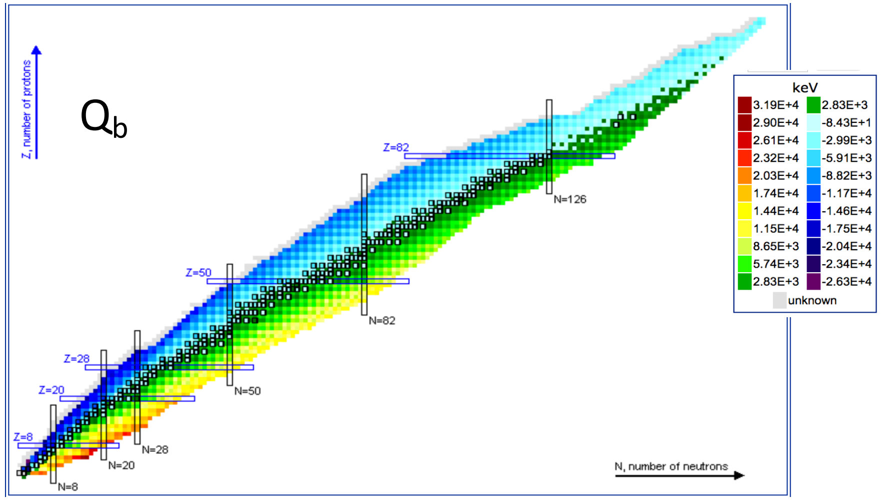
tape

BEDO @ ALTO



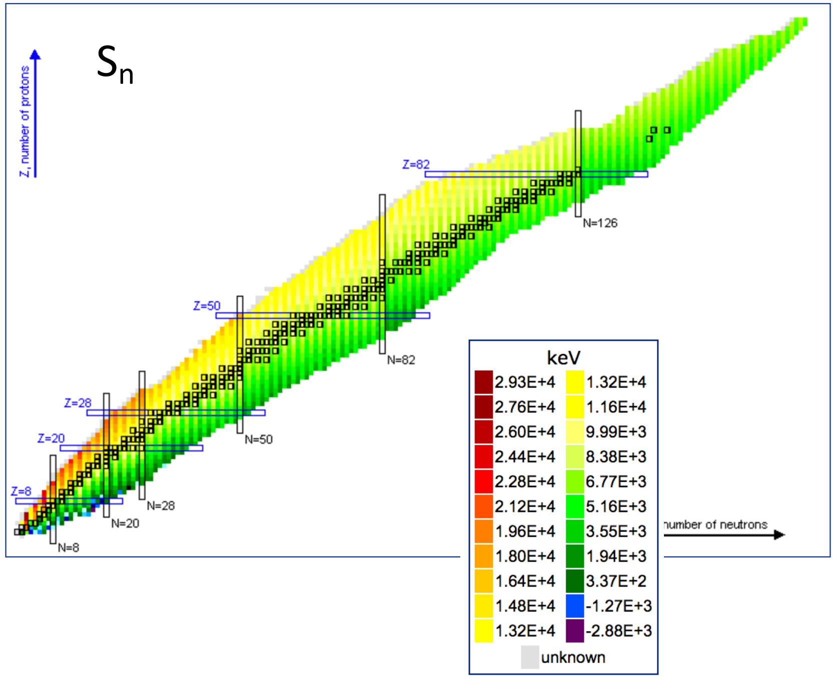
Exotic nuclei: β-decay key features

- Region in chart of nuclides difficult to access
- Increasing Q_b values (up to 15 MeV)
- Lowering of S_n
- Large range of half-lives ~ 10ms -100 s
- Possible competing modes (α decay, cluster decay, delayed fission)



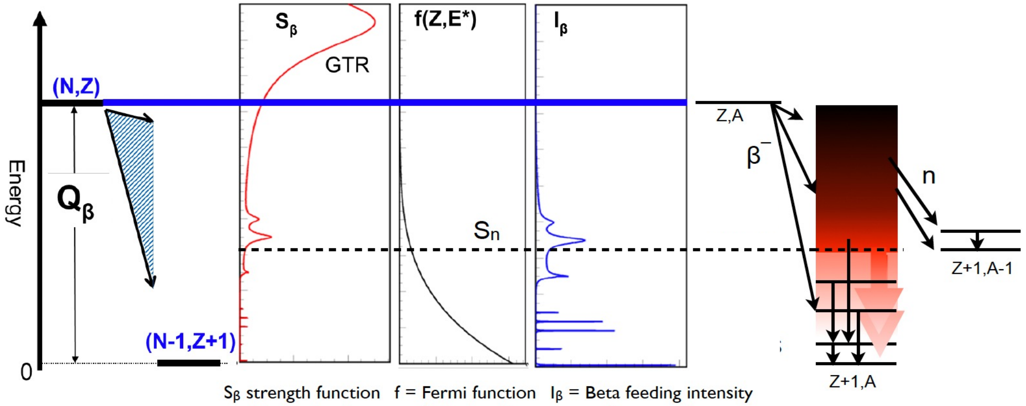
- New orbitals being occupied
- Occurrence of intruder states
- Highlighting the contribution from high-lying states and regions of increased level density

➔ Opening of competing channels
➔ Increased competition with forbidden transitions
➔ Access to large portion of GT strength



$$\frac{1}{T_{1/2}} = \sum_{E_i \geq 0}^{E_i \leq Q_\beta} S_\beta(E_i) \times f(Z, Q_\beta - E_i)$$

$\beta^- \rightarrow n = p + e^- + \bar{\nu}$

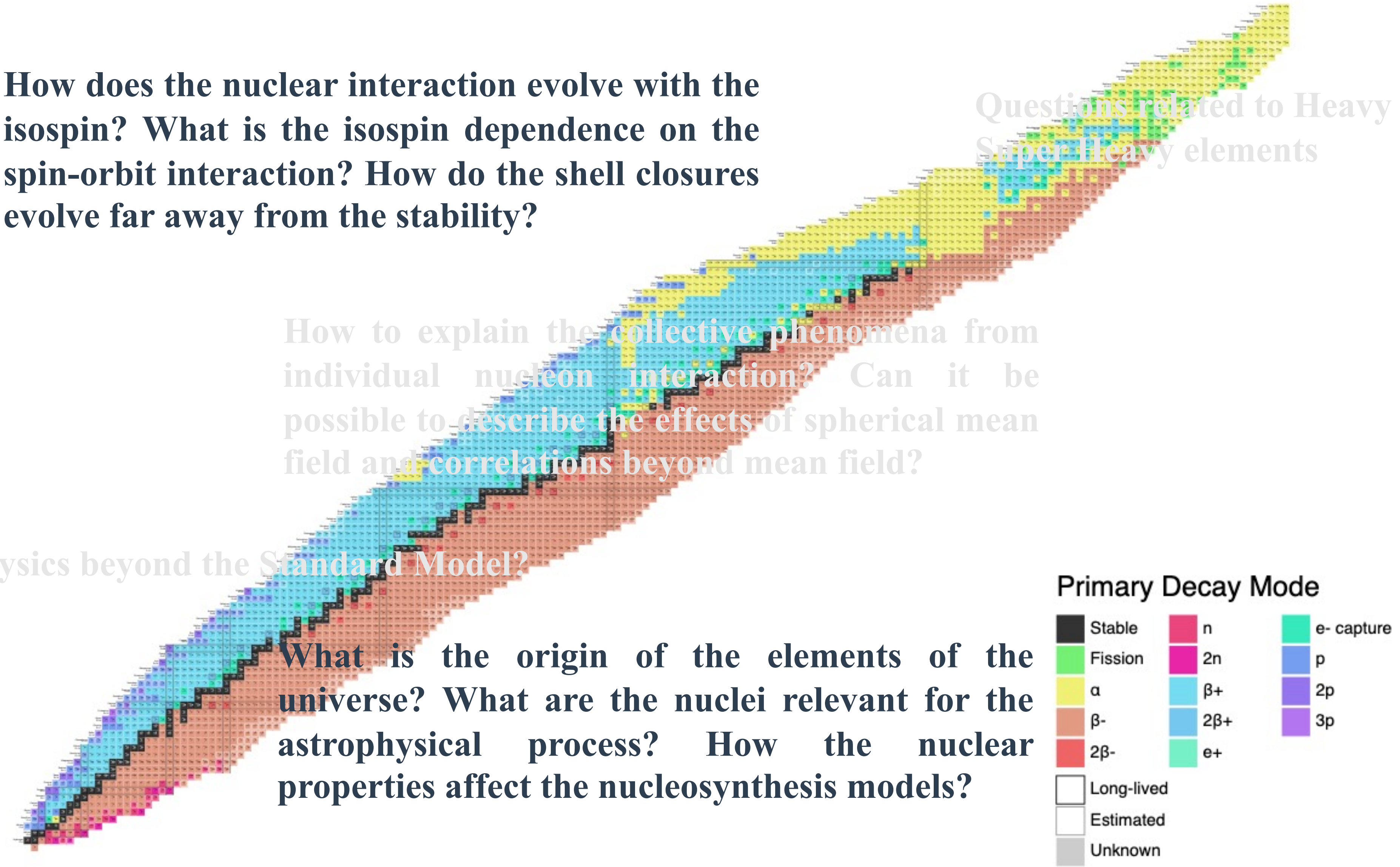


S_β strength function (determined) f = Fermi function (calculated) I_β = Beta feeding intensity (measured)

a complete picture of the β-decay process requires **high-resolution, high-efficiency studies** and **exclusive measurements**

- **high-resolution:** aiming at a detailed reconstruction of decay scheme. Exploits combination of HPGe detectors, coupled to ancillaries such as LaBr3(Ce) to enhance the sensitivity to specific observables (levels)
- **high-efficiency:** Total Absorption Spectrometry technique, requires instead the use of highly efficient scintillator detectors aiming at measuring the full decay strength
- **exclusive measurements**: aiming at studying specific quantities, such as delayed neutron emission probability and spectroscopy

https://people.physics.anu.edu.au/~ecs103/chart/



How does the nuclear interaction evolve with the isospin? What is the isospin dependence on the spin-orbit interaction? How do the shell closures evolve far away from the stability?

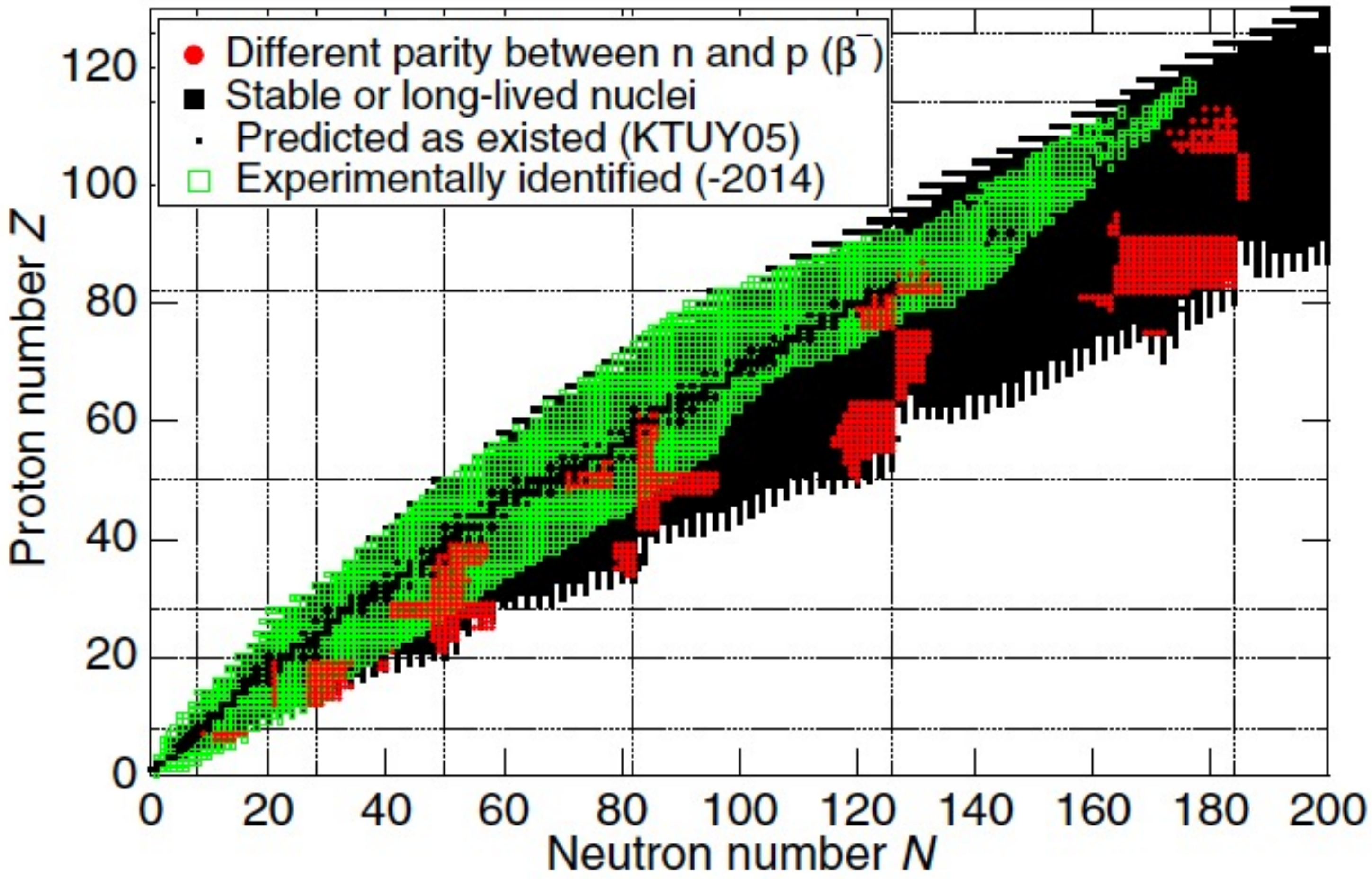
Questions related to Heavy and Super Heavy elements

How to explain the collective phenomena from individual nucleon interaction? Can it be possible to describe the effects of spherical mean field and correlations beyond mean field?

Is there physics beyond the Standard Model?

What is the origin of the elements of the universe? What are the nuclei relevant for the astrophysical process? How the nuclear properties affect the nucleosynthesis models?

Mismatching of parity btw ground-state neutron and proton levels



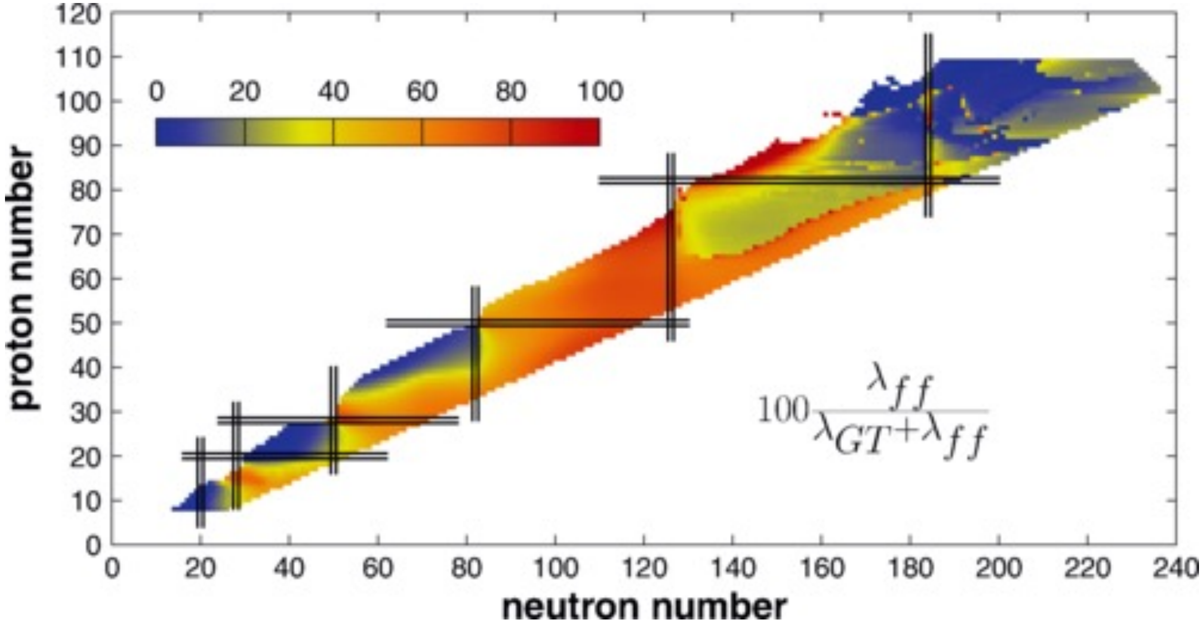
The total β-decay rate can expressed as
$\lambda_\beta = \lambda_{\text{allowed}} + \lambda_{\text{first-forbidden}}$
$= \lambda_F + \lambda_{GT} + \lambda^{(0)}{}_1 + \lambda^{(1)}{}_1 + \lambda^{(2)}{}_1$

the Fermi transition
Gamow-Teller transition
first forbidden transitions L = 0, 1, and 2

PHYSICAL REVIEW C 95, 064304 (2017)

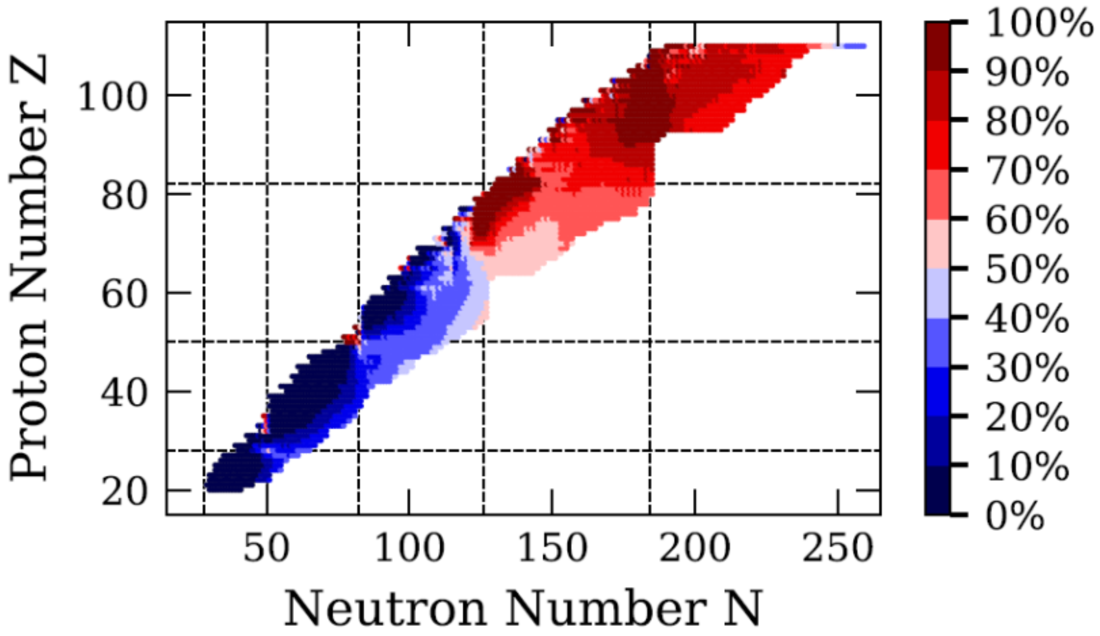
T. Marketin, L. Huther, G. Martinez-Pinedo, PRC93, 025805 (2016)

First-forbidden beta decay



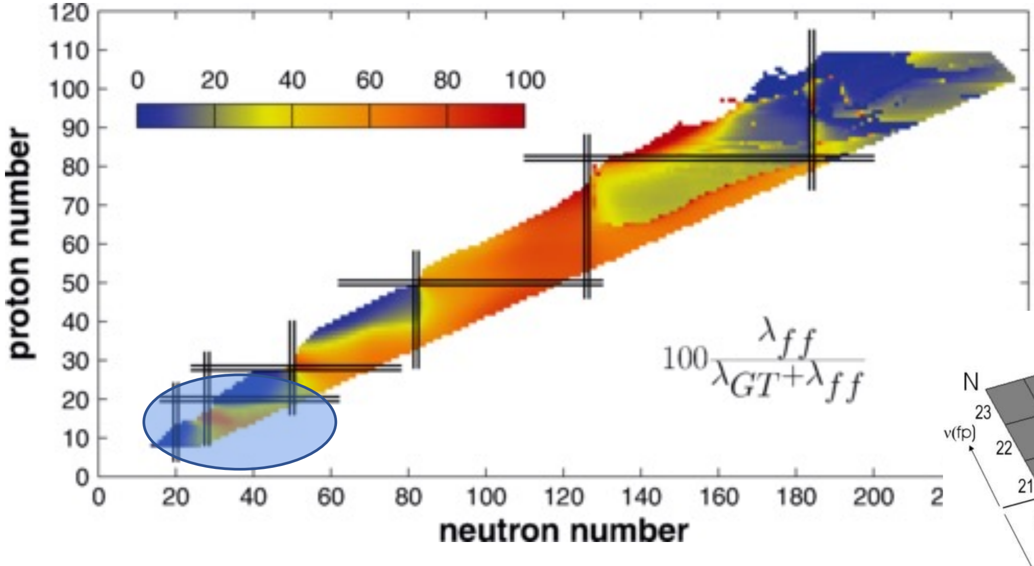
self-consistent microscopic description based on the Relativistic Hartree-Bogoliubov (RHB) model for ground state of open- and closed-shell nuclei with
the proton-neutron relativistic quasiparticle random phase approximation (pn-RQRPA)

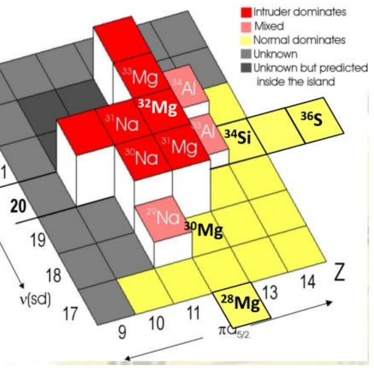
microscopic description based on Skyrme density functional, EFA applied to describe odd-A and odd-odd nuclei

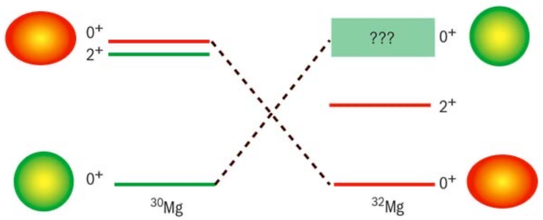


E.M. Ney, J. Engel, T.Li. N. Schunck, PRC102,034326 (2020

First-forbidden beta decay







PHYSICAL REVIEW LETTERS **129,** 212501 (2022)

Editors' Suggestion **Featured in Physics**

Crossing *N* = 28 Toward the Neutron Drip Line: First Measurement of Half-Lives at FRIB

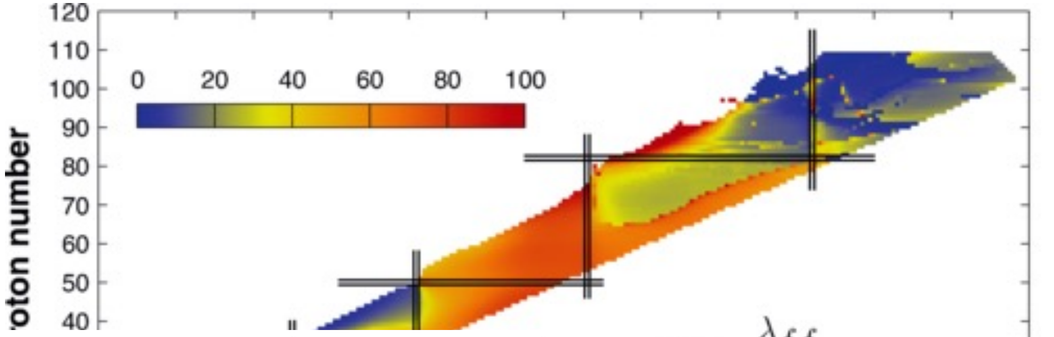
H. L. Crawford,[1,*] V. Tripathi,[2] J. M. Allmond,[3] B. P. Crider,[4] R. Grzywacz,[5] S. N. Liddick,[6,7] A. Andalib,[6,8] E. Argo,[6,8] C. Benetti,[2] S. Bhattacharya,[2] C. M. Campbell,[1] M. P. Carpenter,[9] J. Chan,[5] A. Chester,[6] J. Christie,[5] B. R. Clark,[4] I. Cox,[5] A. A. Doetsch,[6,8] J. Dopfer,[6,8] J. G. Duarte,[10] P. Fallon,[1] A. Frotscher,[1] T. Gaballah,[4] T. J. Gray,[3] J. T. Harke,[10] J. Heideman,[5] H. Heugen,[5] R. Jain,[6,8] T. T. King,[3] N. Kitamura,[5] K. Kolos,[10] F. G. Kondev,[9] A. Laminack,[3] B. Longfellow,[10] R. S. Lubna,[6] S. Luitel,[4] M. Madurga,[5] R. Mahajan,[6] M. J. Mogannam,[6,7] C. Morse,[11] S. Neupane,[5] A. Nowicki,[5] T. H. Ogunbeku,[4,6] W.-J. Ong,[10] C. Porzio,[1] C. J. Prokop,[12] B. C. Rasco,[3] E. K. Ronning,[6,7] E. Rubino,[6] T. J. Ruland,[13] K. P. Rykaczewski,[3] L. Schaedig,[6,8] D. Seweryniak,[9] K. Siegl,[5] M. Singh,[5] S. L. Tabor,[2] T. L. Tang,[2] T. Wheeler,[6,8] J. A. Winger,[4] and Z. Xu[5]

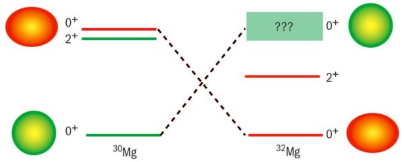
PHYSICAL REVIEW C **106**, 064314 (2022)

β^- decay of exotic P and S isotopes with neutron number near 28

Vandana Tripathi,[1,*] Soumik Bhattacharya,[1] E. Rubino,[1] C. Benetti,[1] J. F. Perello,[1] S. L. Tabor,[1] S. N. Liddick,[2,3,4] P. C. Bender,[5] M. P. Carpenter,[6] J. J. Carroll,[7] A. Chester,[2,3] C. J. Chiara,[7] K. Childers,[2,4] B. R. Clark,[8] B. P. Crider,[8] J. T. Harke,[9] B. Longfellow,[2,10] R. S. Lubna,[3] S. Luitel,[8] T. H. Ogunbeku,[8] A. L. Richard,[2,9] S. Saha,[5] N. Shimizu,[11] O. A. Shehu,[8] Y. Utsuno,[12,13] R. Unz,[8] Y. Xiao,[8] S. Yoshida,[14] and Yiyi Zhu[5]

First-forbidden beta decay





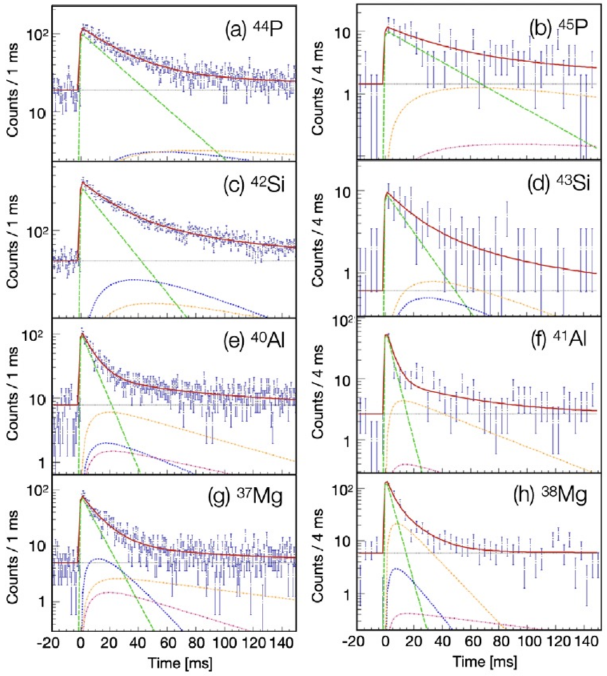
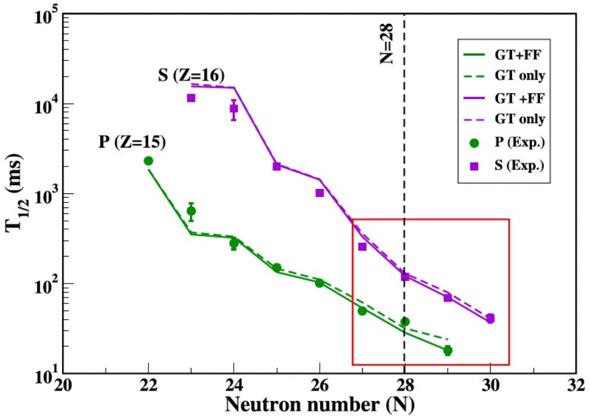
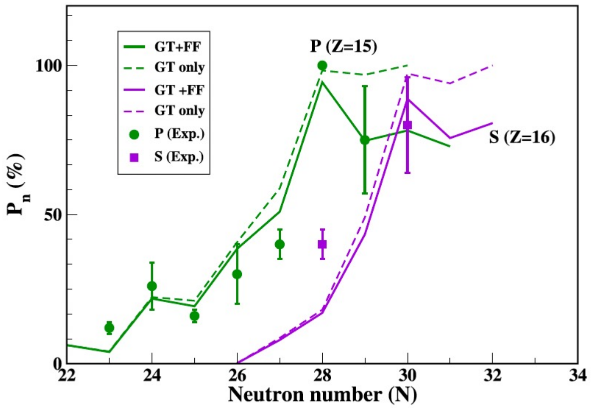
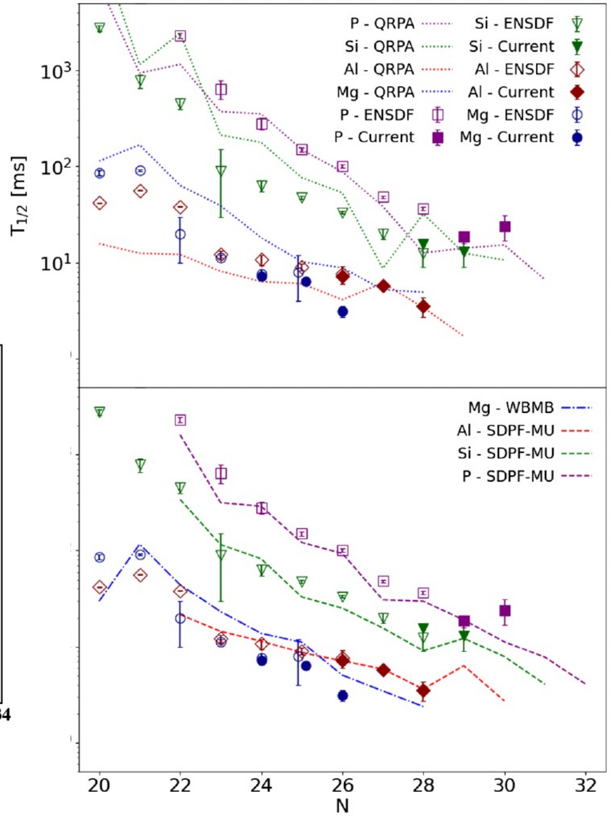


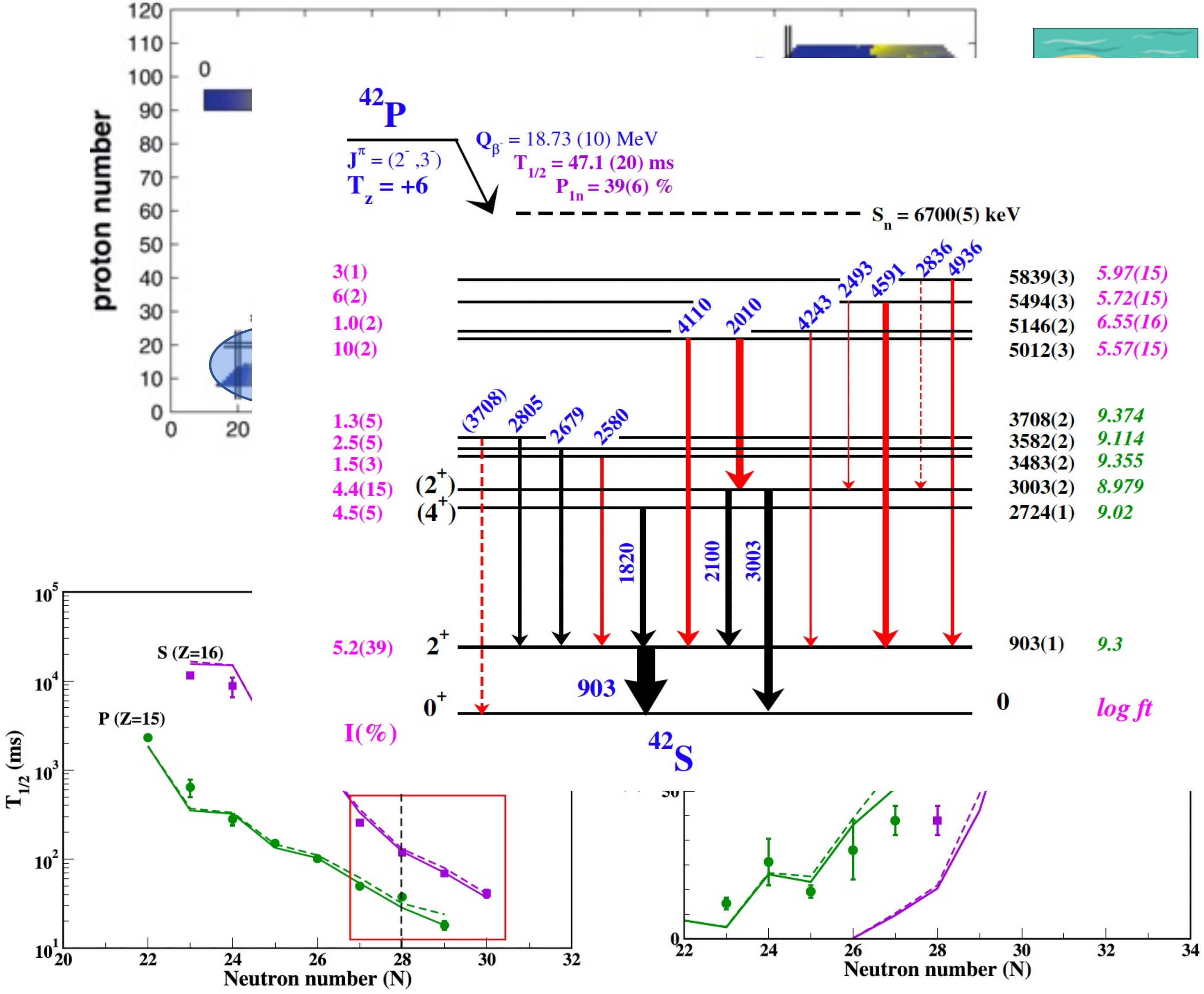
FIG. 2. Decay curves in panels (a)–(h) for ^{44,45}P, ^{42,43}Si, ^{40,41}Al, and ^{37,38}Mg respectively. The components of the fits are shown by the curves, where the solid red line is the total fit, the green dashed curve is the parent decay, the dot-dash blue line is the $\beta 0n$ daughter contribution, the dot-dot-dash orange line is the $\beta 1n$ contribution, the dot-dot-dot-dash magenta line is the $\beta 2n$ contribution, and the dotted gray line is the constant background. The derived half-lives are included in Table I.

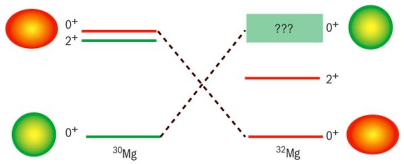






First-forbidden beta decay



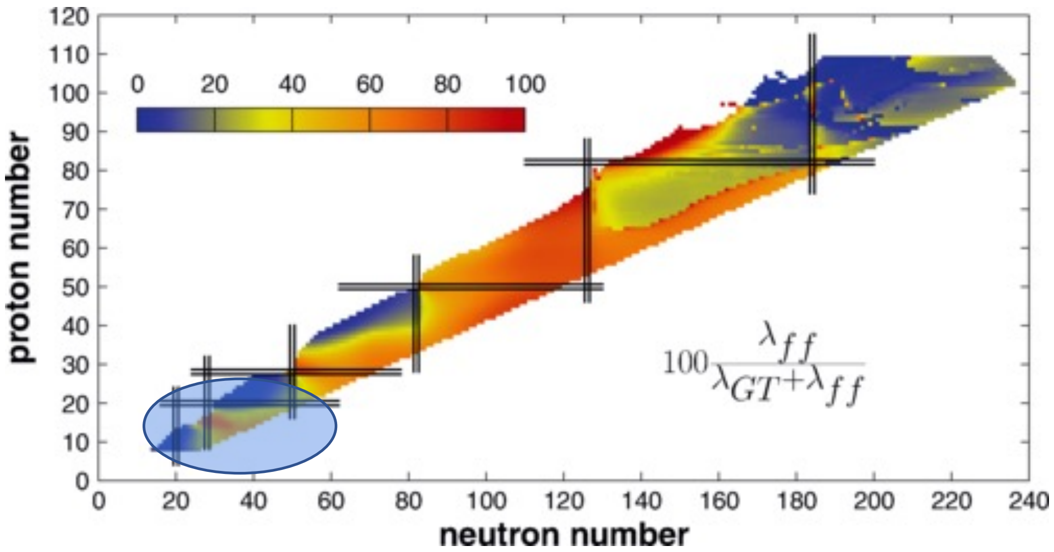


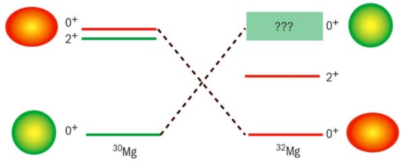
The impact of FF transitions which can be important for neutron-rich nuclei in this region with neutrons filling the 1p3/2 orbital by comparing the measured T1/2 and Pn values with SM calculations with and without FF transitions included.

- P isotopes with N = 27, 28, 29 displayed a larger contribution from FF transitions in their β decay. For the case of 42P decay there are clear indicators of states which could be populated in FF decay with log f t values consistent with the predictions of the SM calculations.
- Both the half-life and Pn value of 44P also indicate influence of FF transitions. Comparison with SM calculations of states populated in 42S in the decay of 42P both via allowed GT and FF decays suggests a Jπ of 2− or 3− for the ground state of 42P contrary to earlier suggestion of 0−.

- The Gamow-Teller (GT) strength distribution depends on the deformation and affects the half-life (T1/2) and β-delayed neutron emission probability (Pn).

First-forbidden beta decay





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- P isotopes with N = 27, 28, 29 displayed a larger contribution from FF transitions in their β decay. For the case of ^{42}P decay there are clear indicators of states which could be populated in FF decay with log f t values consistent with the predictions of the SM calculations.
- Both the half-life and Pn value of 44P also indicate influence of FF transitions. Comparison with SM calculations of states populated in 42S in the decay of 42P both via allowed GT and FF decays suggests a Jπ of 2− or 3− for the ground state of 42P contrary to earlier suggestion of 0−.
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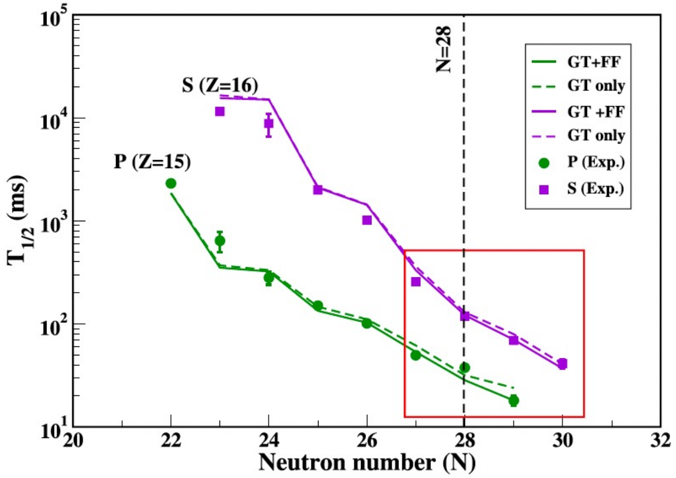
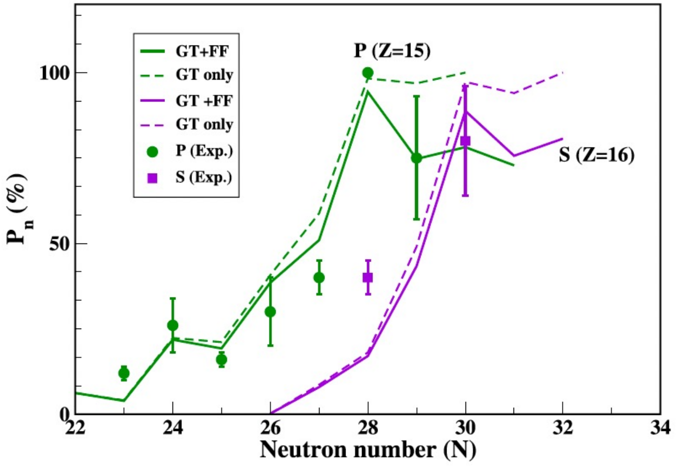
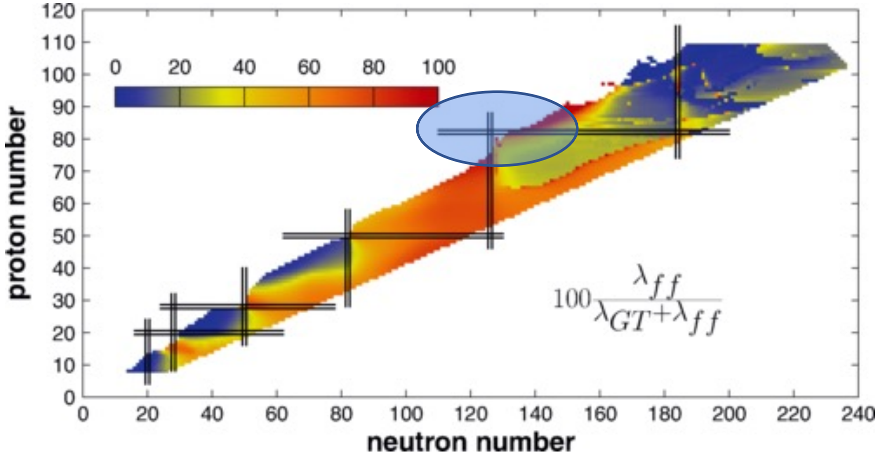
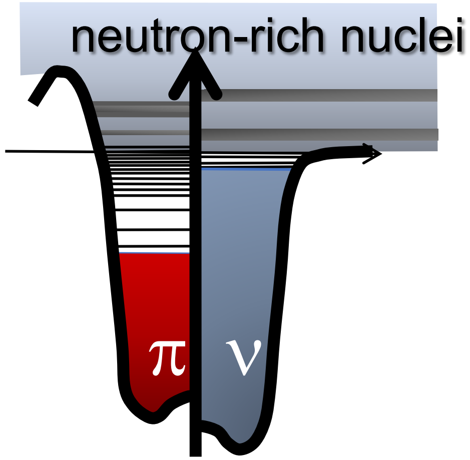




First-forbidden beta decay



Exotic nuclei with excess of neutrons have different Fermi energies for n and p
Allowed decays might not be possible owing to large mismatch in wave functions



^{208}Pb

π=- 3p1/2
π=- 3p3/2
π=- 2f5/2
π=+ 1i13/2
π=- 2f7/2
π=- 1h9/2

π=+ 3s1/2
π=+ 2d3/2

82

π

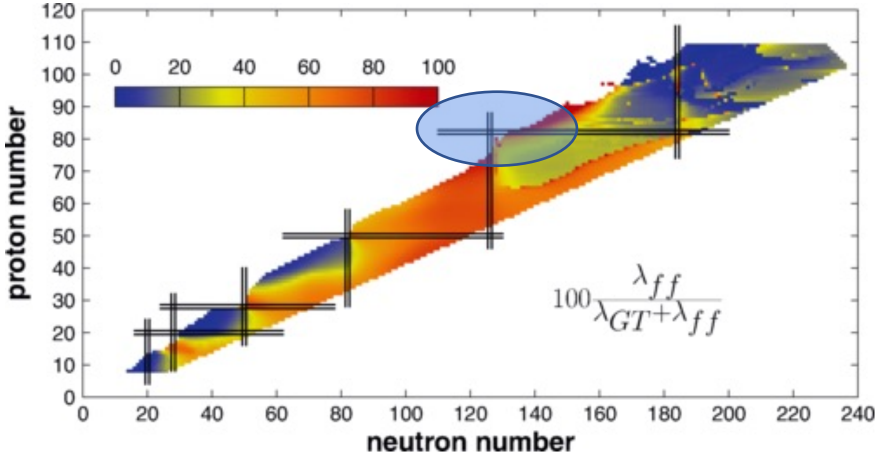
3d3/2
2g7/2 π=+
4s1/2 π=+
3d5/2 π=+
1j15/2 π=-
1i11/2 π=+
2g9/2 π=+

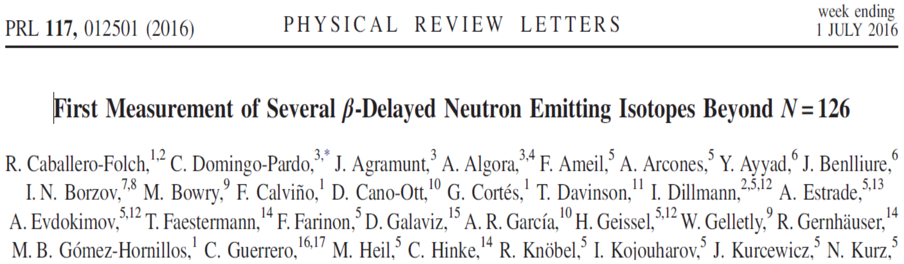
126

3d3/2

ν

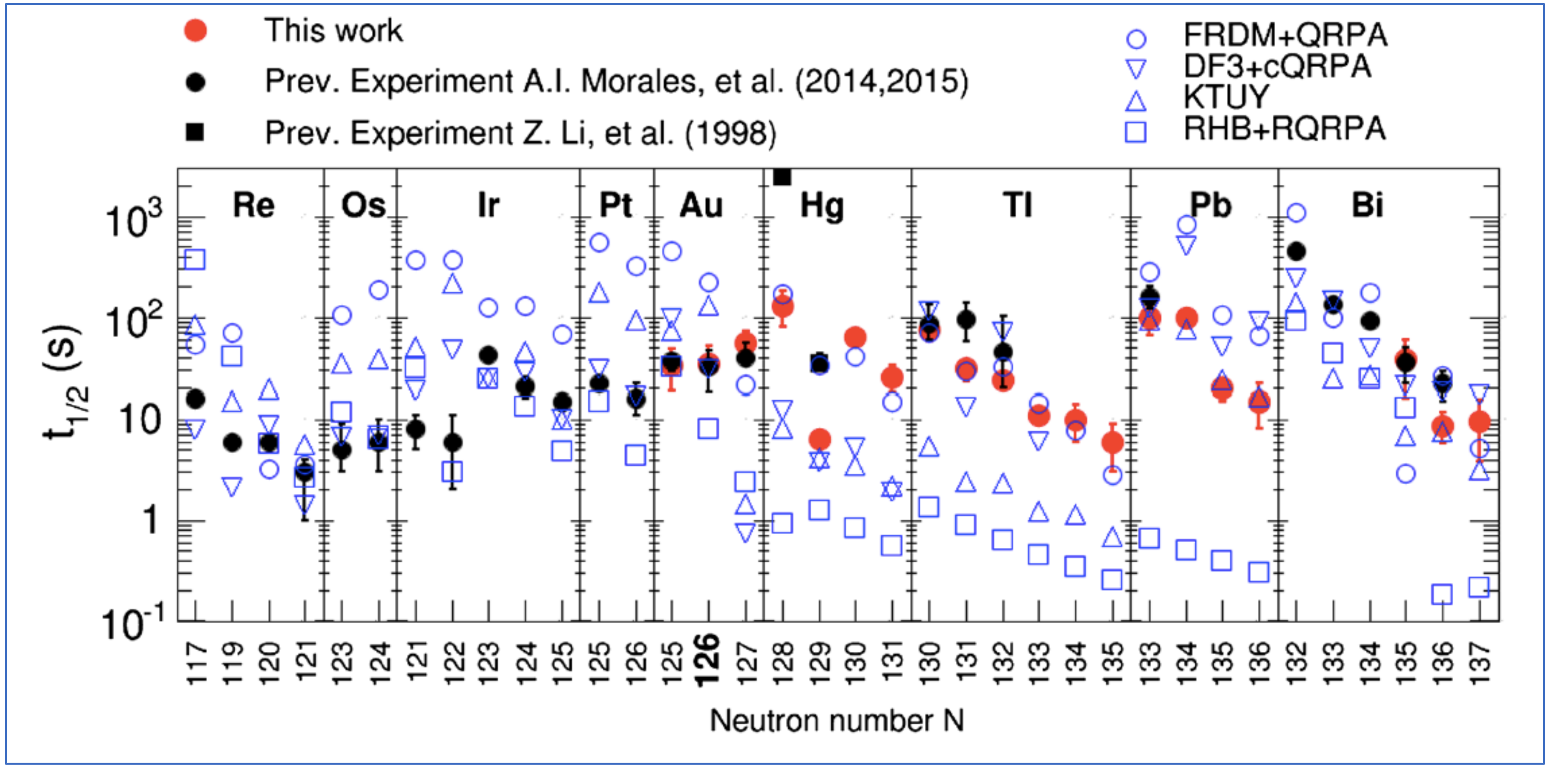
First-forbidden beta decay

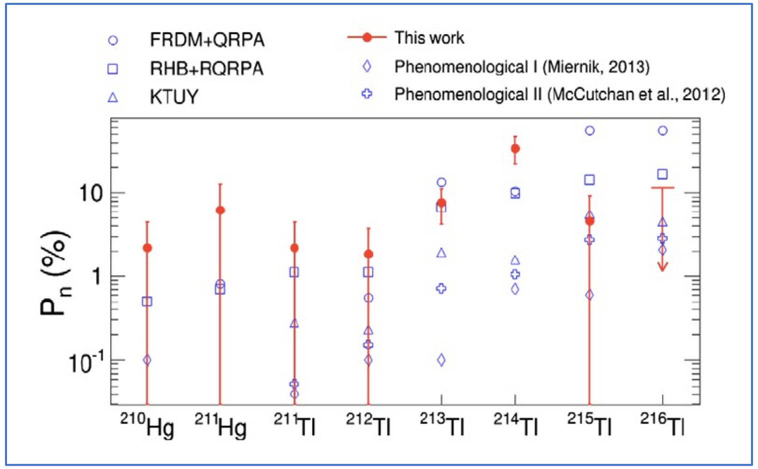



PRL **117**, 012501 (2016) PHYSICAL REVIEW LETTERS week ending 1 JULY 2016

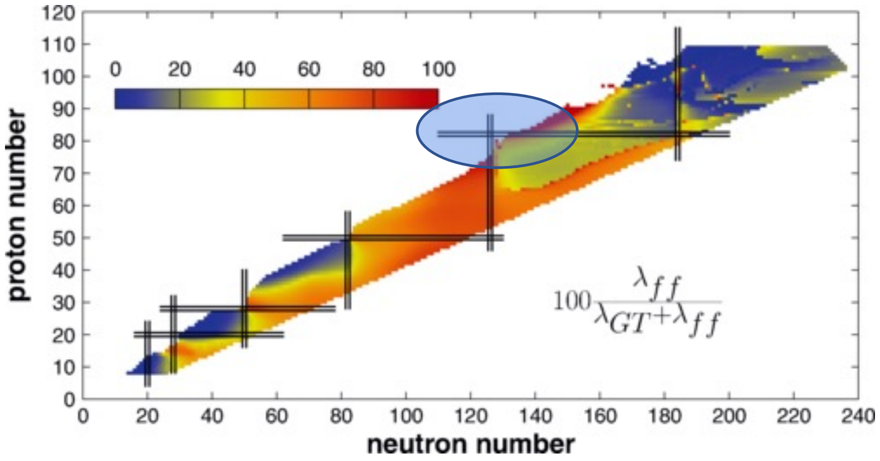
First Measurement of Several β-Delayed Neutron Emitting Isotopes Beyond $N = 126$

R. Caballero-Folch,[1,2] C. Domingo-Pardo,[3,*] J. Agramunt,[3] A. Algora,[3,4] F. Ameil,[5] A. Arcones,[5] Y. Ayyad,[6] J. Benlliure,[6] I. N. Borzov,[7,8] M. Bowry,[9] F. Calviño,[1] D. Cano-Ott,[10] G. Cortés,[1] T. Davinson,[11] I. Dillmann,[2,5,12] A. Estrade,[5,13] A. Evdokimov,[5,12] T. Faestermann,[14] F. Farinon,[5] D. Galaviz,[15] A. R. García,[10] H. Geissel,[5,12] W. Gelletly,[9] R. Gernhäuser,[14] M. B. Gómez-Hornillos,[1] C. Guerrero,[16,17] M. Heil,[5] C. Hinke,[14] R. Knöbel,[5] I. Kojouharov,[5] J. Kurcewicz,[5] N. Kurz,[5]

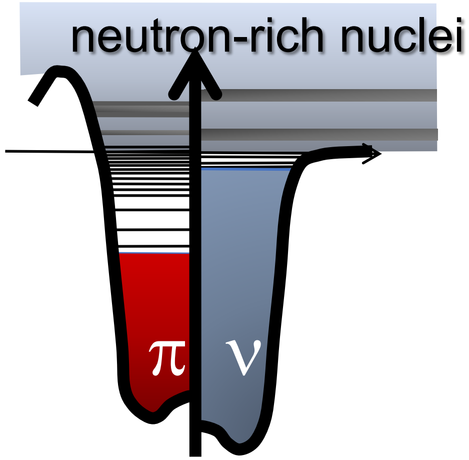




First-forbidden beta decay



Exotic nuclei with excess of neutrons have different Fermi energies for n and p
Allowed decays might not be possible owing to large mismatch in wave functions



^{208}Pb

π=-	3p1/2	3d3/2	
π=-	3p3/2	2g7/2	π=+
π=-	2f5/2	4s1/2	π=+
π=+	1i13/2	3d5/2	π=+
π=-	2f7/2	1j15/2	π=-
π=-	1h9/2	1i11/2	π=+
		2g9/2	π=+
π=+	3s1/2	3d3/2	
π=+	2d3/2		

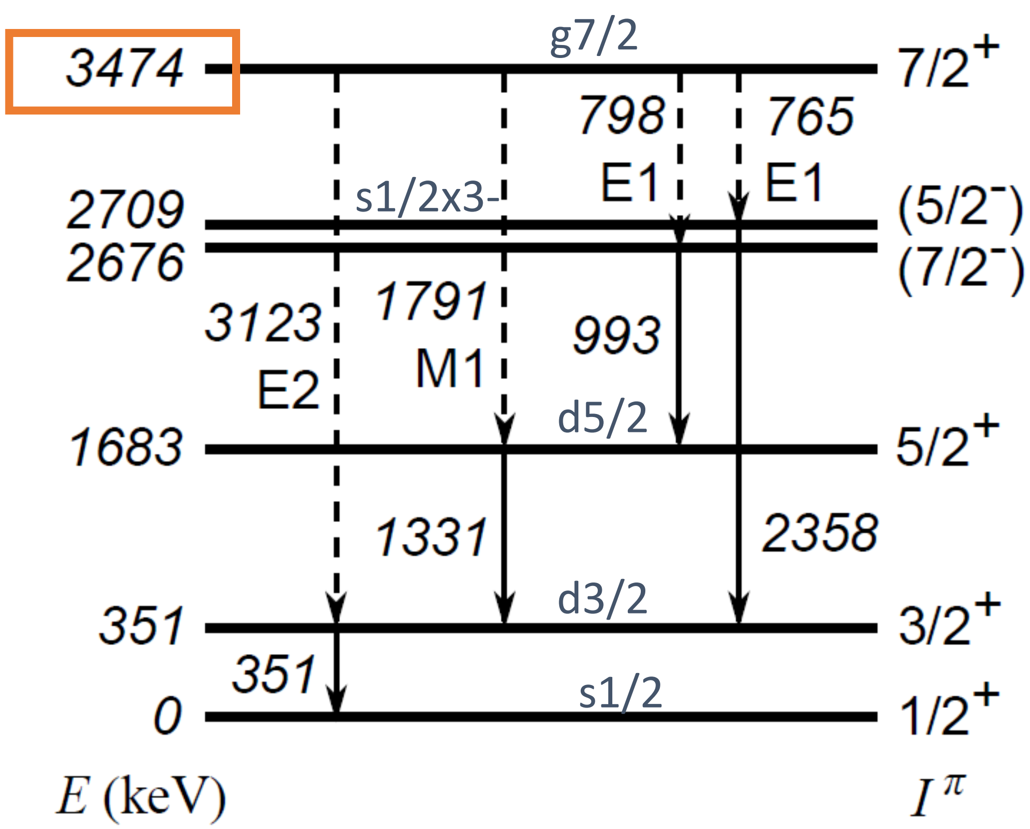
82

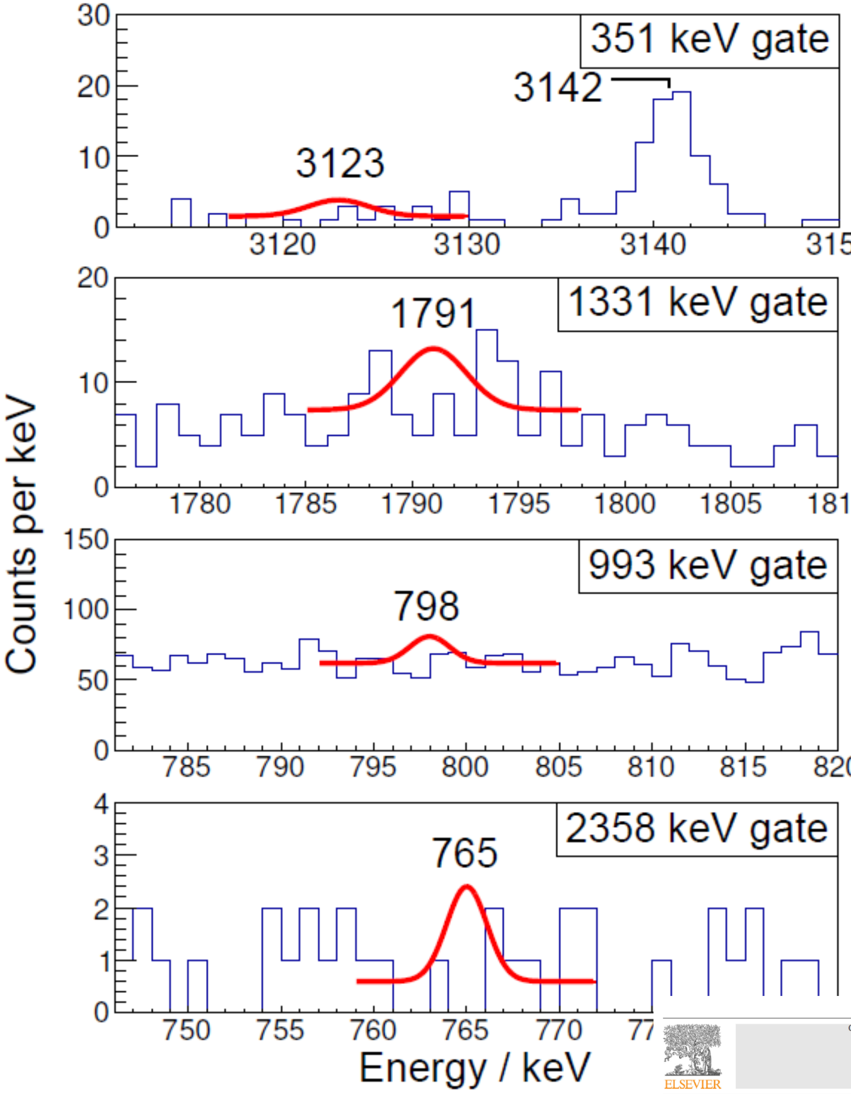
126

π

ν

The $2g_{9/2}$ -> $1g_{7/2}$ beta decay (^{207}Hg-> ^{207}Tl)

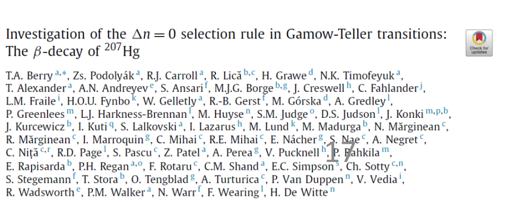




(Non-)population of the $g_{7/2}$ state <3.9×10^{-3}%

log ft > 8.8 (95% confidence limit)

(only one other, less stringent, test of Δn=0: 209Tl->209Pb)



Physics Letters B 793 (2019) 271–275

Contents lists available at ScienceDirect

Physics Letters B

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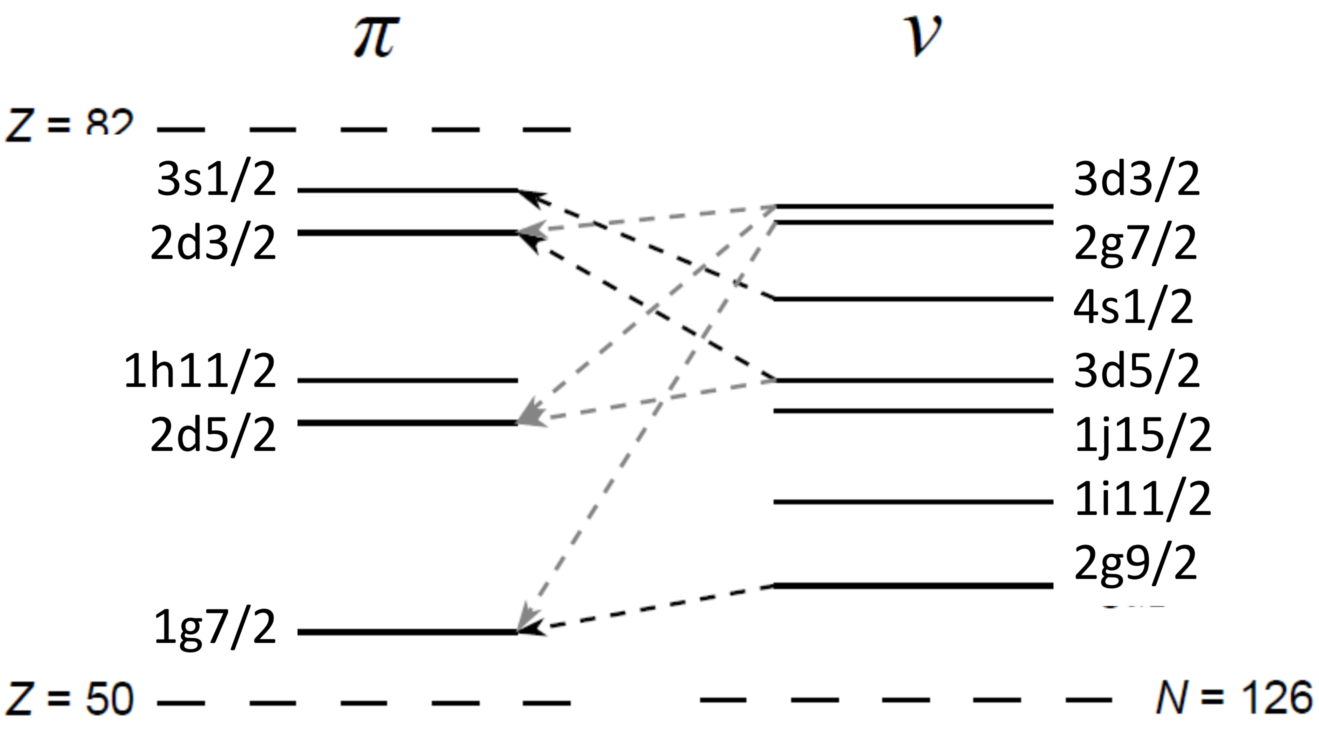
Investigation of the $\Delta n = 0$ selection rule in Gamow-Teller transitions: The β-decay of ^{207}Hg

T.A. Berry[a,*], Zs. Podolyák[a], R.J. Carroll[a], R. Lică[b,c], H. Grawe[d], N.K. Timofeyuk[a], T. Alexander[a], A.N. Andreyev[e], S. Ansari[f], M.J.G. Borge[b,g], J. Creswell[h], C. Fahlander[j], L.M. Fraile[i], H.O.U. Fynbo[k], W. Gelletly[a], R.-B. Gerst[f], M. Górska[d], A. Gredley[l], P. Greenlees[m], L.J. Harkness-Brennan[l], M. Huyse[n], S.M. Judge[o], D.S. Judson[l], J. Konki[m,p,b], J. Kurcewicz[b], I. Kuti[q], S. Lalkovski[a], I. Lazarus[h], M. Lund[k], M. Madurga[b], N. Mărginean[c], R. Mărginean[c], I. Marroquin[g], C. Mihai[c], R.E. Mihai[c], E. Nácher[g], S. Nae[c], A. Negret[c], C. Niţă[c,r], R.D. Page[l], S. Pascu[c], Z. Patel[a], A. Perea[g], V. Pucknell[h], P. Rahkila[m], E. Rapisarda[b], P.H. Regan[a,o], F. Rotaru[c], C.M. Shand[a], E.C. Simpson[s], Ch. Sotty[c,n], S. Stegemann[f], T. Stora[b], O. Tengblad[g], A. Turturica[c], P. Van Duppen[n], V. Vedia[i], R. Wadsworth[e], P.M. Walker[a], N. Warr[f], F. Wearing[l], H. De Witte[n]

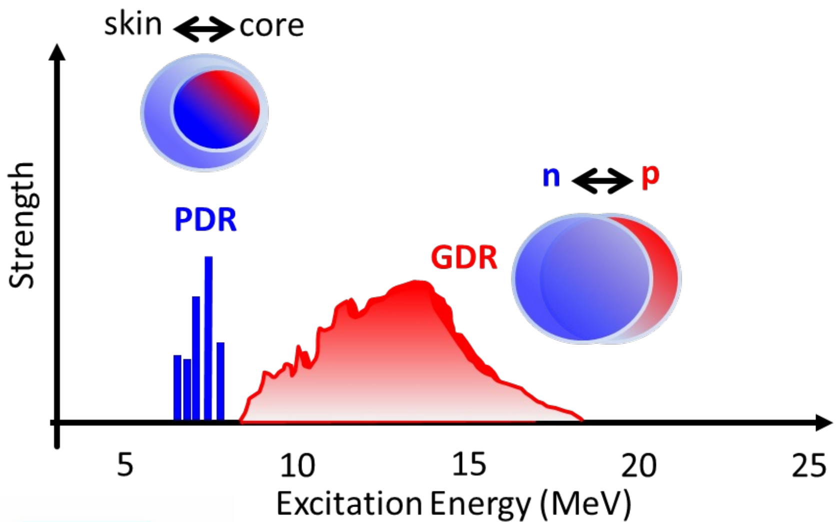


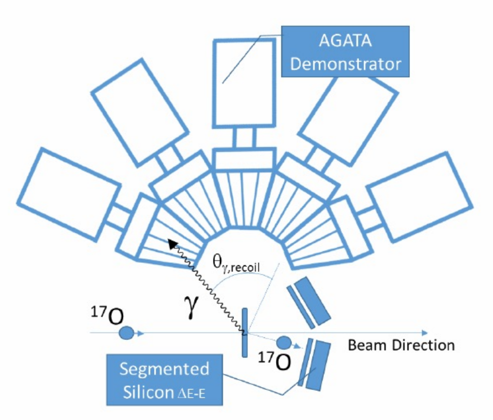
These increase dramatically for extremely neutron-rich nuclei, when either exploring deeper into the proton shell below *Z*=82 or extending further into *N*>126

lifetime of heavy neutron-rich (Z<82, N>126) nuclei strongly affected

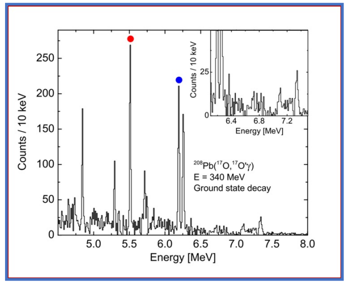
The same selection rule also affects nuclei ‘south-east’ of 132Sn due to the existence of *n* =1, *l* =0 neutron-proton orbital pairs in the region of *N*>82and *Z*<50. Experimental investigation of the forbiddenness in this mass region is an interesting possibility but remains challenging due to the large Q_β values

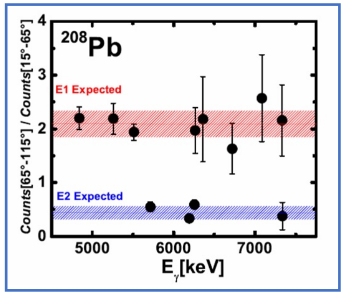
Nuclear Structure information from the E1 response in Nuclei





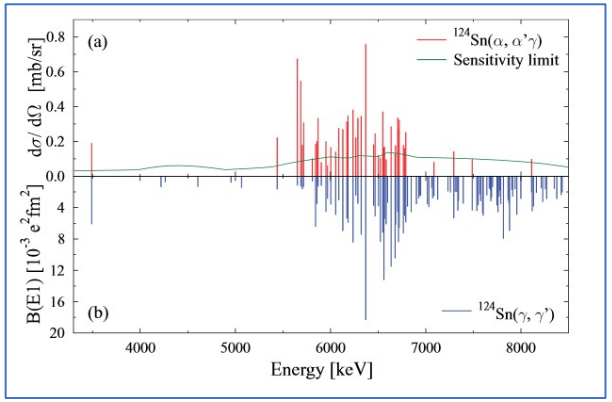
A. Bracco, F.C.L. Crespi and E.G. Lanza, EPJA (2015) 51: 99
F.C.L. Crespi, et al., PRL113 (2014) 012501





Commonly studied via:
(γ,γ'), (α,α'), Inelastic scattering of ^{17}O,^{12}C, virtual phonon scattering

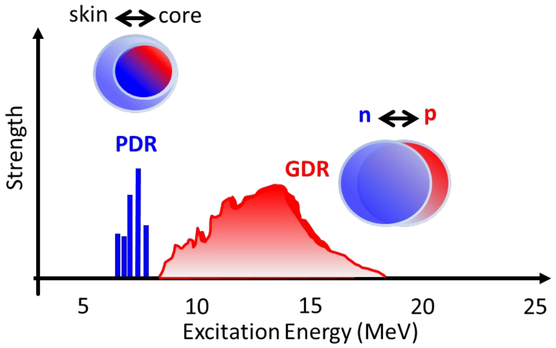
(*) figure from J. Endres et al., Phys. Rev. Lett. 105, 212503 (2010)

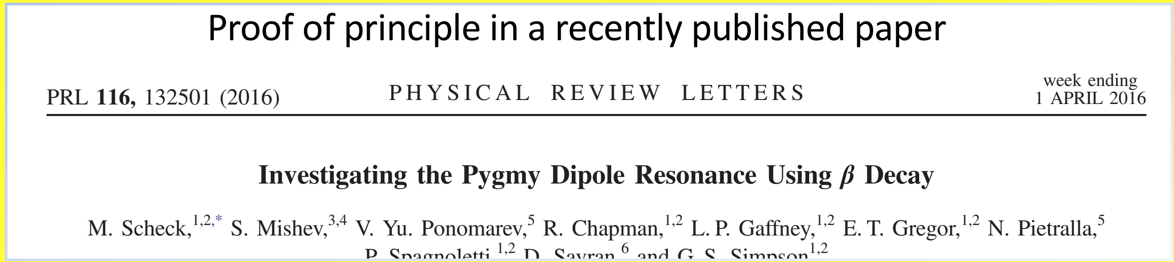


- ☐ low energy part → isoscalar character (*neutron-skin oscillations*)
- ☐ high-energy states → isovector nature (*transition towards the GDR*)

Resonances populated via β decay in n-rich nuclei

- The large Q_β-value window (> 12 MeV) allows populating at least the PDR
- The β decay could populate states which are the PDR on the IAS(R) of the mother nucleus

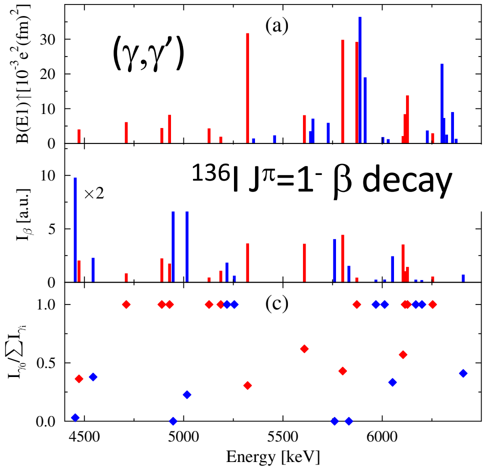



Proof of principle in a recently published paper

PRL **116,** 132501 (2016) PHYSICAL REVIEW LETTERS week ending 1 APRIL 2016

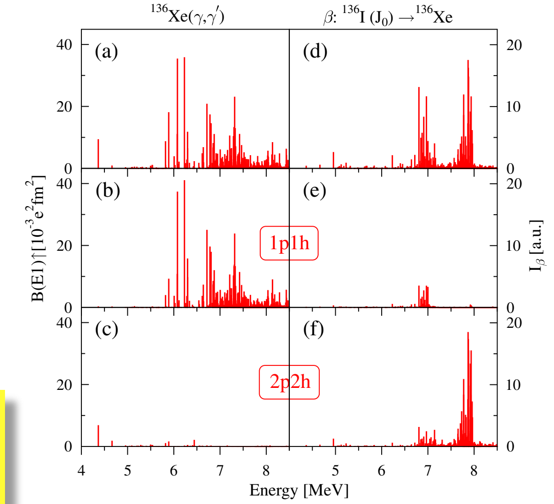
Investigating the Pygmy Dipole Resonance Using β Decay

M. Scheck,[1,2,*] S. Mishev,[3,4] V. Yu. Ponomarev,[5] R. Chapman,[1,2] L. P. Gaffney,[1,2] E. T. Gregor,[1,2] N. Pietralla,[5] P. Spagnoletti,[1,2] D. Savran,[6] and G. S. Simpson[1,2]



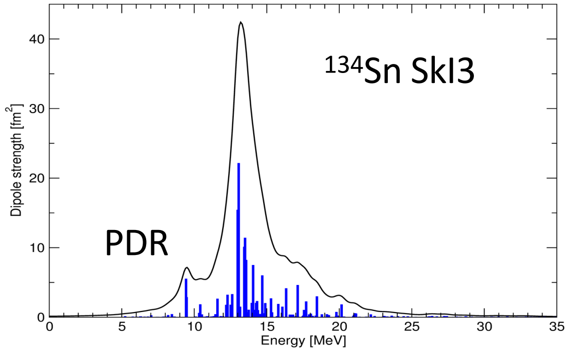
States seen in NRF are seen in β decay
β decays shows greater number of states ➔ access to 2p2h excitations

Useful tool to complement the studies BUT relies heavily on theory for the interpretation of nature of states



QPM

Resonances populated via β decay:

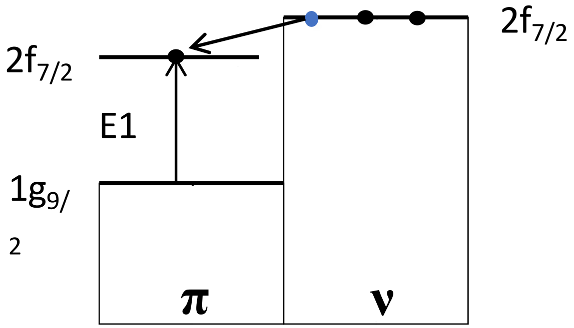


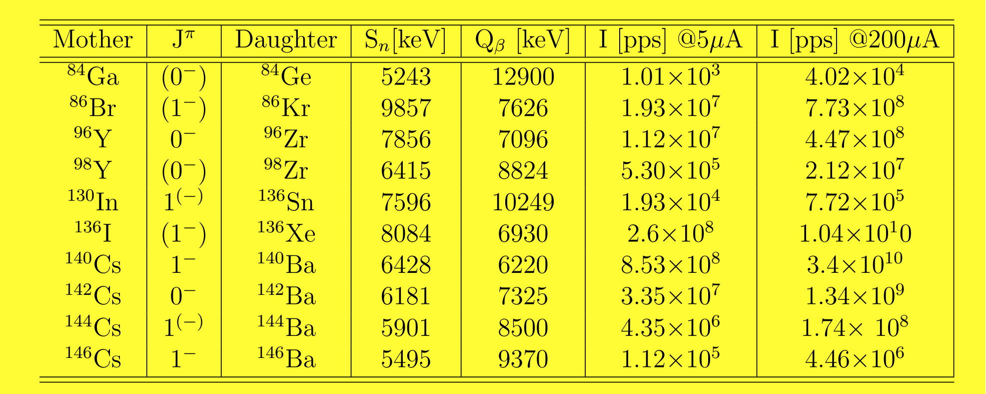
Example: ^{134}In -> ^{134}Sn (Q_β= 14.7 MeV)

$\nu f_{7/2}$ -> $\pi g_{9/2}$

β decay: $\nu 2f_{7/2}$ -> $\pi 2f_{7/2}$, $\pi 2f_{5/2}$;

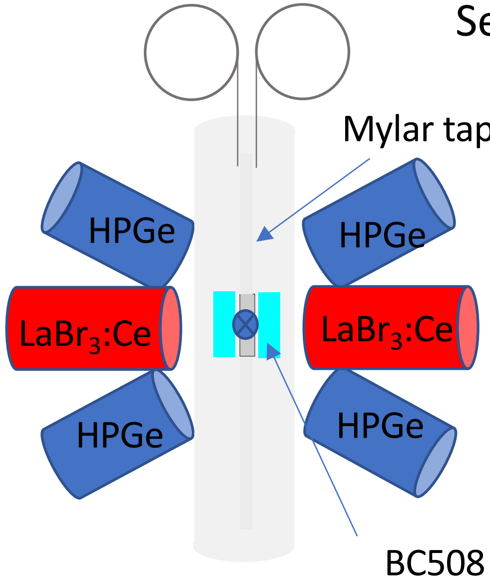
QRPA calculations with the SkI3 interaction: PDR at 10 MeV





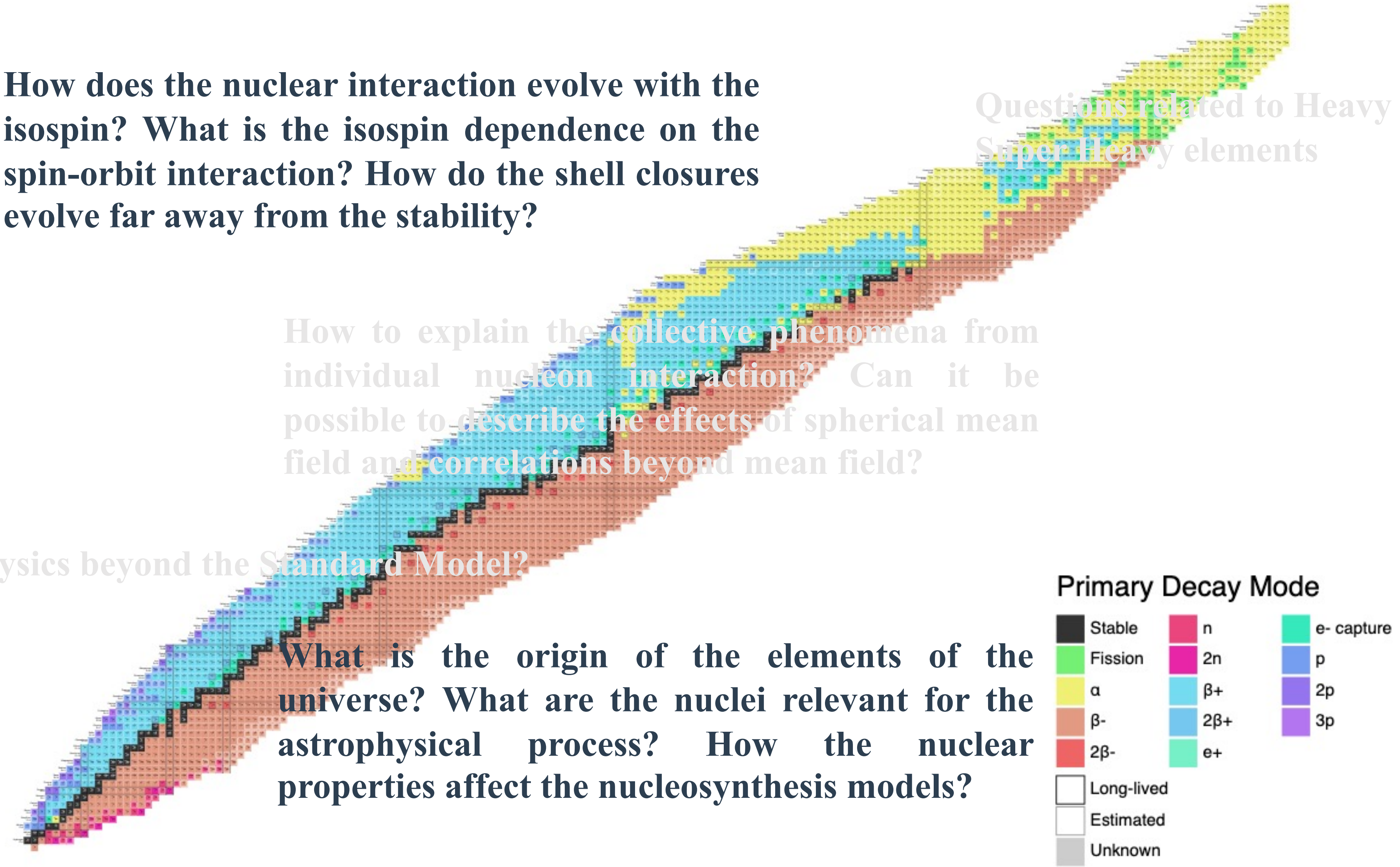
Mother	J^π	Daughter	S_n[keV]	Q_β [keV]	I [pps] @5μA	I [pps] @200μA
^{84}Ga	(0^-)	^{84}Ge	5243	12900	1.01×10^3	4.02×10^4
^{86}Br	(1^-)	^{86}Kr	9857	7626	1.93×10^7	7.73×10^8
^{96}Y	0^-	^{96}Zr	7856	7096	1.12×10^7	4.47×10^8
^{98}Y	(0^-)	^{98}Zr	6415	8824	5.30×10^5	2.12×10^7
^{130}In	$1^{(-)}$	^{136}Sn	7596	10249	1.93×10^4	7.72×10^5
^{136}I	(1^-)	^{136}Xe	8084	6930	2.6×10^8	1.04×10^10
^{140}Cs	1^-	^{140}Ba	6428	6220	8.53×10^8	3.4×10^{10}
^{142}Cs	0^-	^{142}Ba	6181	7325	3.35×10^7	1.34×10^9
^{144}Cs	$1^{(-)}$	^{144}Ba	5901	8500	4.35×10^6	1.74×10^8
^{146}Cs	1^-	^{146}Ba	5495	9370	1.12×10^5	4.46×10^6

Set-up



Large volume scintillators: PARIS etc..

https://people.physics.anu.edu.au/~ecs103/chart/



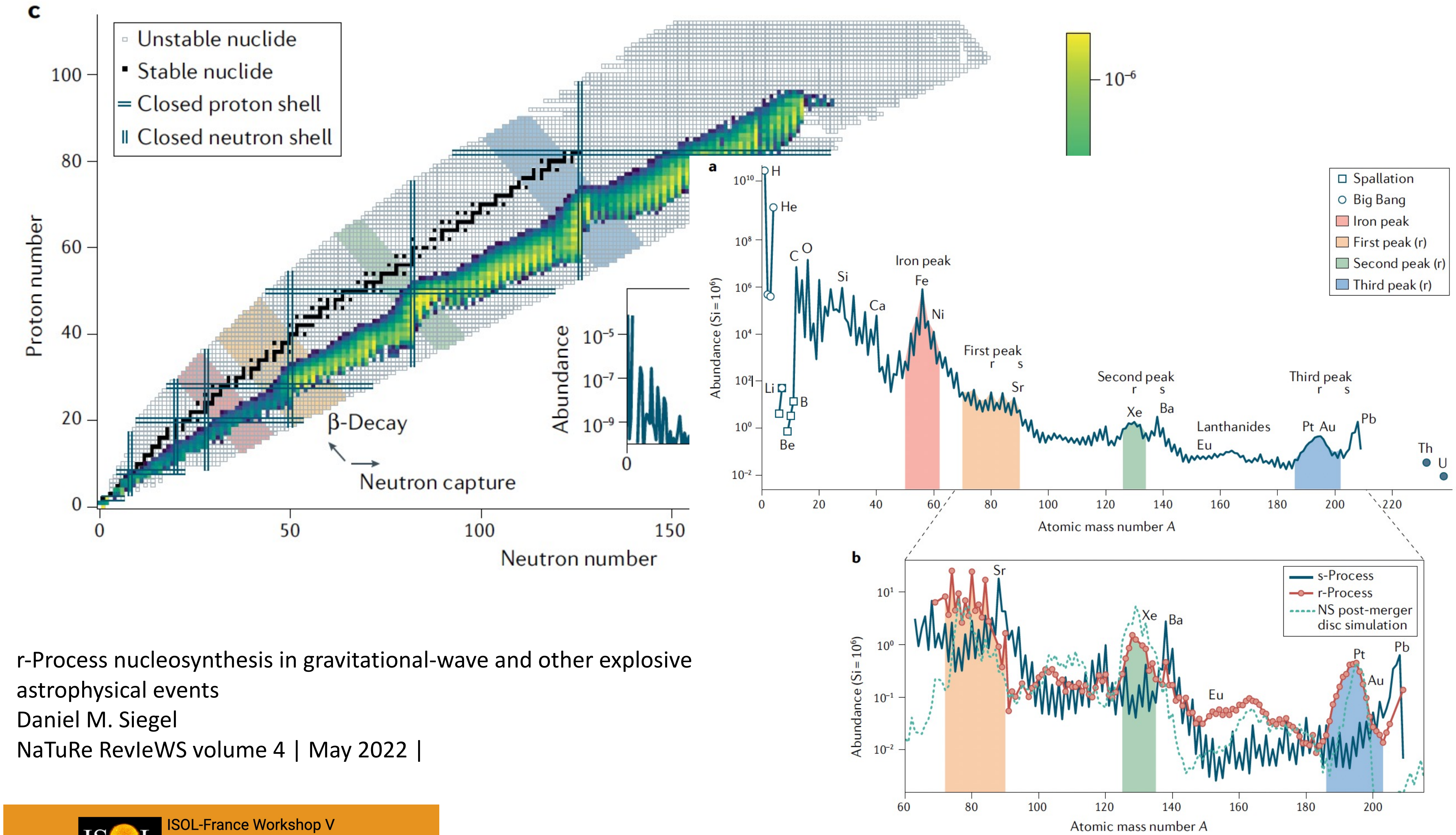
How does the nuclear interaction evolve with the isospin? What is the isospin dependence on the spin-orbit interaction? How do the shell closures evolve far away from the stability?

Questions related to Heavy and Super Heavy elements

How to explain the collective phenomena from individual nucleon interaction? Can it be possible to describe the effects of spherical mean field and correlations beyond mean field?

Is there physics beyond the Standard Model?

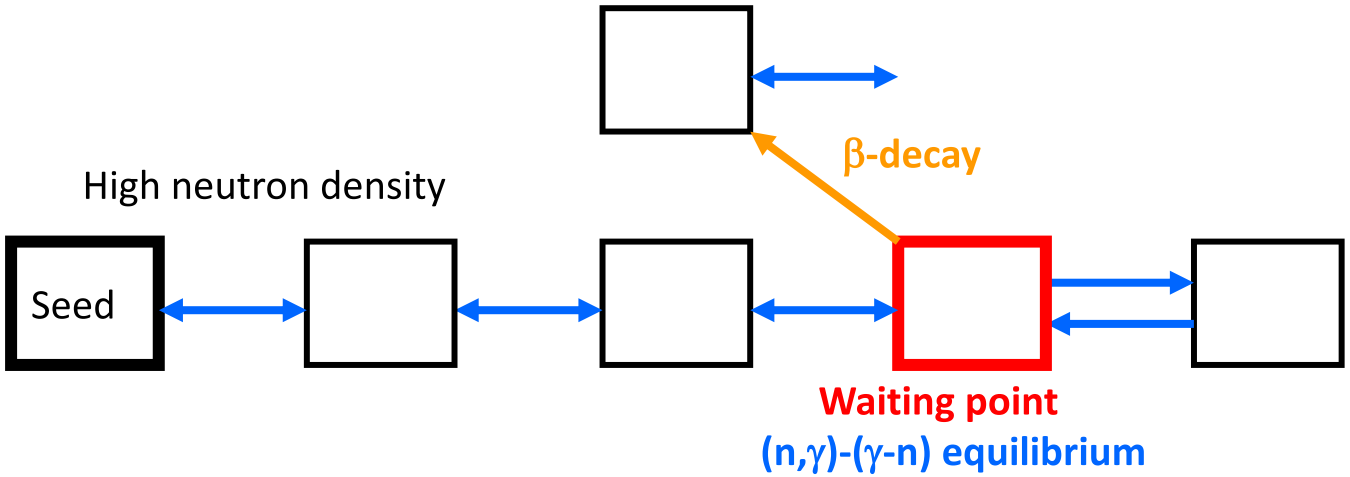
What is the origin of the elements of the universe? What are the nuclei relevant for the astrophysical process? How the nuclear properties affect the nucleosynthesis models?



r-Process nucleosynthesis in gravitational-wave and other explosive astrophysical events
Daniel M. Siegel
NaTuRe RevIeWS volume 4 | May 2022 |

β decay and nucleosynthesis

r-process basics: Element formation beyond iron involving rapid neutron capture and radioactive decay

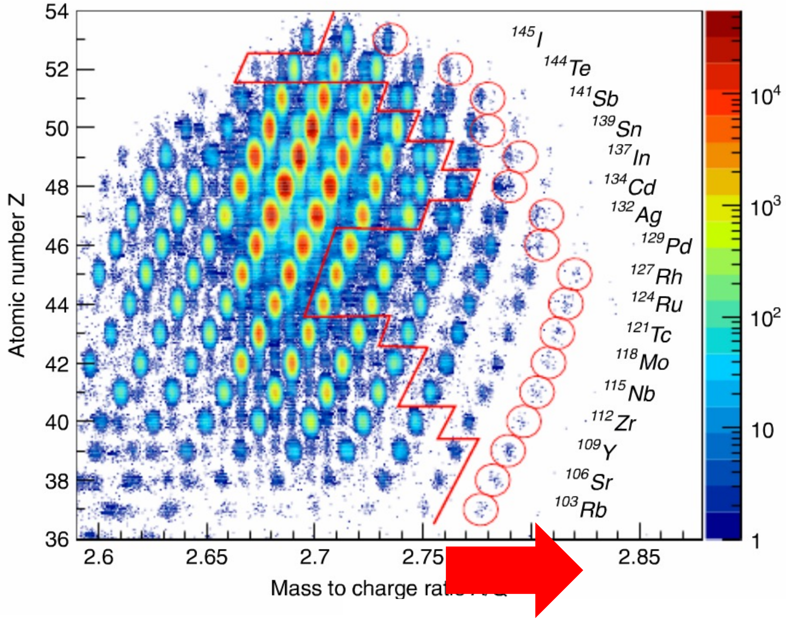


- Classical picture based on (n,γ) <-> (γ,n) equilibration interrupted at waiting points
- New approach sees r-process arising from an interplay between many processes such as
  (n, γ) <-> (γ,n) <-> β decay <-> β -n decay

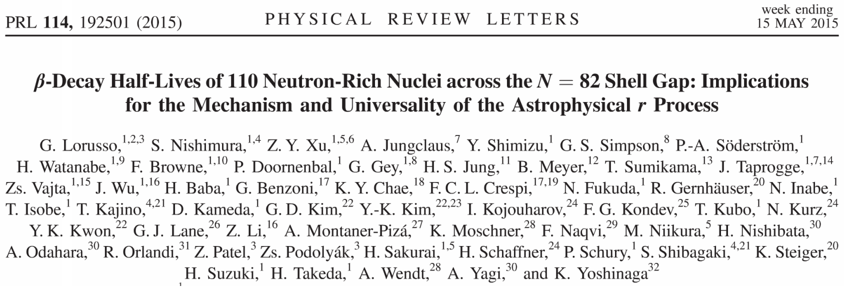
Crucial inputs from experimental nuclear physics are

- Masses
- β-decay rates
- Branching Ratios
- n-capture cross sections

Measuring half-lives for r-process

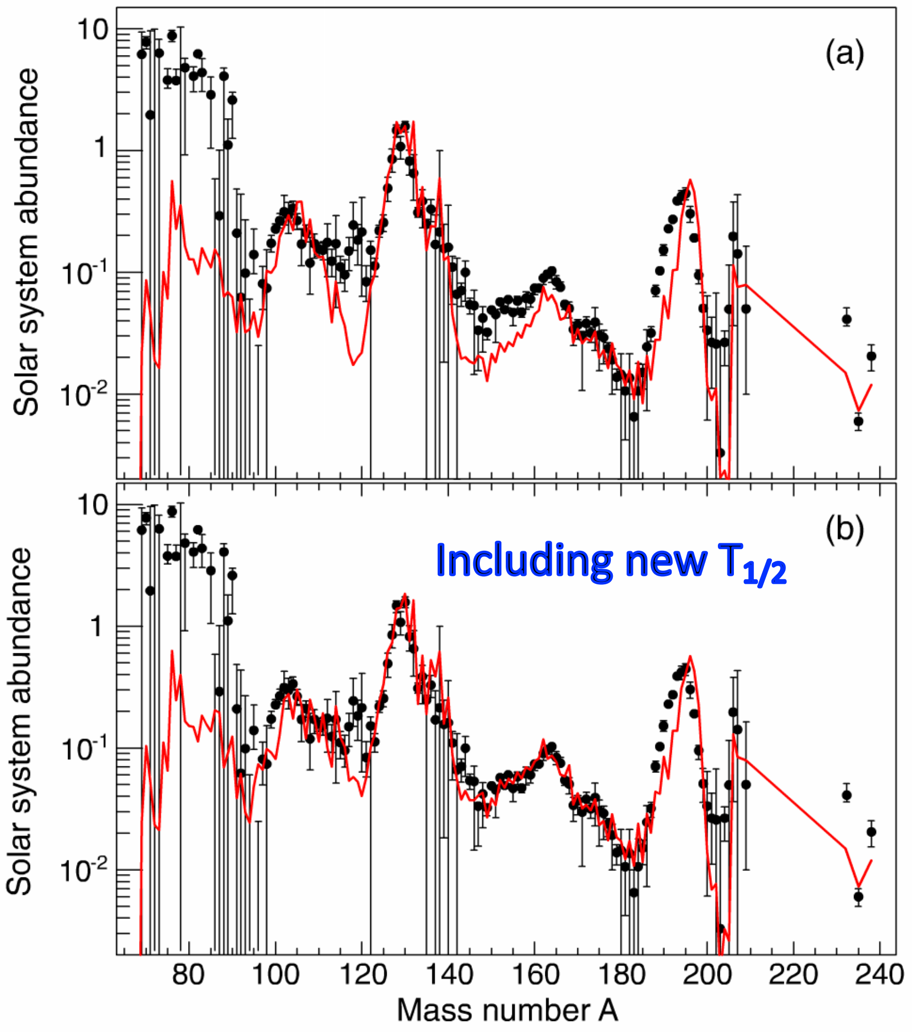


Newly measured $T_{1/2}$


PRL **114,** 192501 (2015) PHYSICAL REVIEW LETTERS week ending 15 MAY 2015

β-Decay Half-Lives of 110 Neutron-Rich Nuclei across the $N = 82$ Shell Gap: Implications for the Mechanism and Universality of the Astrophysical *r* Process

G. Lorusso,[1,2,3] S. Nishimura,[1,4] Z. Y. Xu,[1,5,6] A. Jungclaus,[7] Y. Shimizu,[1] G. S. Simpson,[8] P.-A. Söderström,[1] H. Watanabe,[1,9] F. Browne,[1,10] P. Doornenbal,[1] G. Gey,[1,8] H. S. Jung,[11] B. Meyer,[12] T. Sumikama,[13] J. Taprogge,[1,7,14] Zs. Vajta,[1,15] J. Wu,[1,16] H. Baba,[1] G. Benzoni,[17] K. Y. Chae,[18] F. C. L. Crespi,[17,19] N. Fukuda,[1] R. Gernhäuser,[20] N. Inabe,[1] T. Isobe,[1] T. Kajino,[4,21] D. Kameda,[1] G. D. Kim,[22] Y.-K. Kim,[22,23] I. Kojouharov,[24] F. G. Kondev,[25] T. Kubo,[1] N. Kurz,[24] Y. K. Kwon,[22] G. J. Lane,[26] Z. Li,[16] A. Montaner-Pizá,[27] K. Moschner,[28] F. Naqvi,[29] M. Niikura,[5] H. Nishibata,[30] A. Odahara,[30] R. Orlandi,[31] Z. Patel,[3] Zs. Podolyák,[3] H. Sakurai,[1,5] H. Schaffner,[24] P. Schury,[1] S. Shibagaki,[4,21] K. Steiger,[20] H. Suzuki,[1] H. Takeda,[1] A. Wendt,[28] A. Yagi,[30] and K. Yoshinaga[32]



Including new $T_{1/2}$

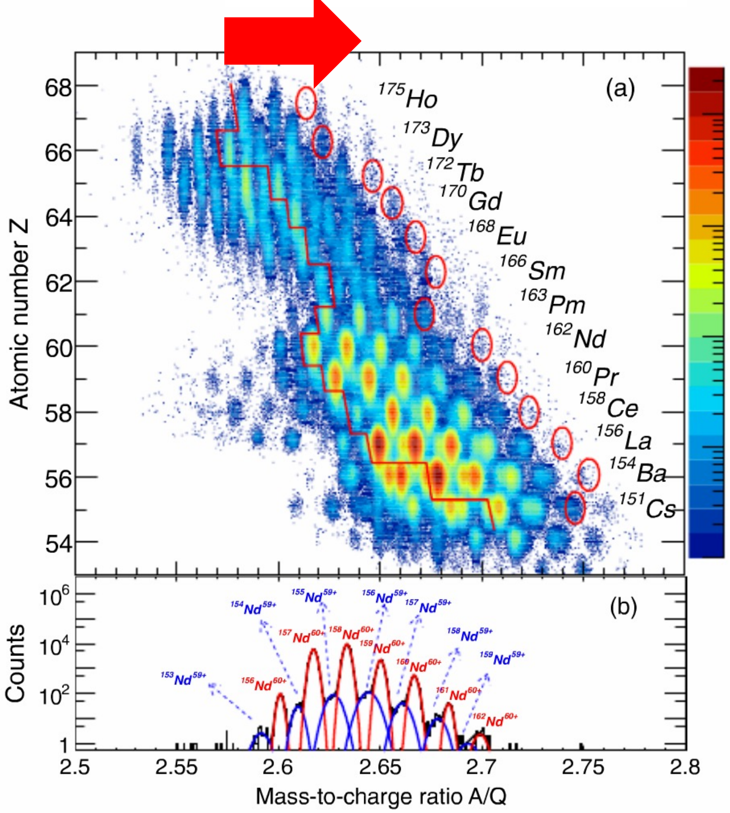
KTUY mass model

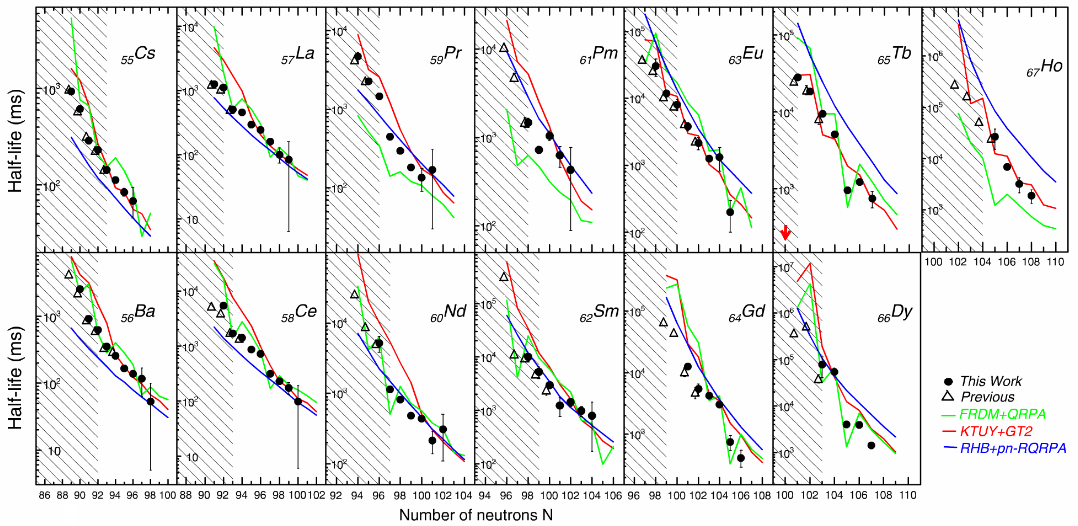
Measuring half-lives for r-process

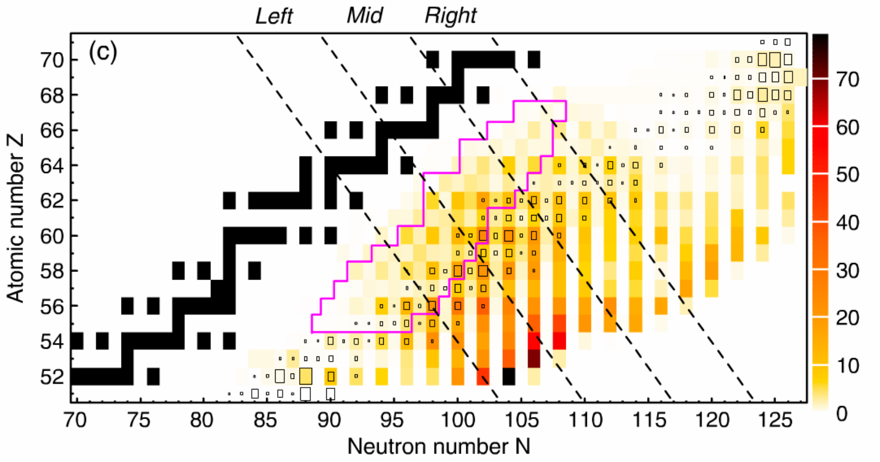
PRL **118,** 072701 (2017) PHYSICAL REVIEW LETTERS week ending 17 FEBRUARY 2017

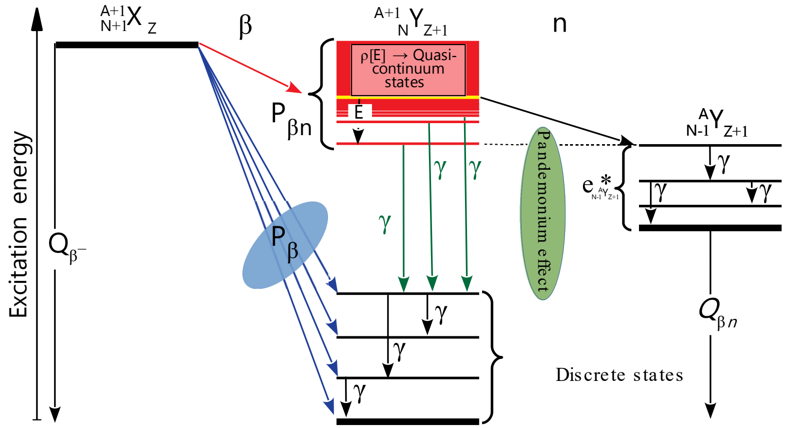
94 β-Decay Half-Lives of Neutron-Rich $_{55}$Cs to $_{67}$Ho: Experimental Feedback and Evaluation of the *r*-Process Rare-Earth Peak Formation

Newly measured $T_{1/2}$



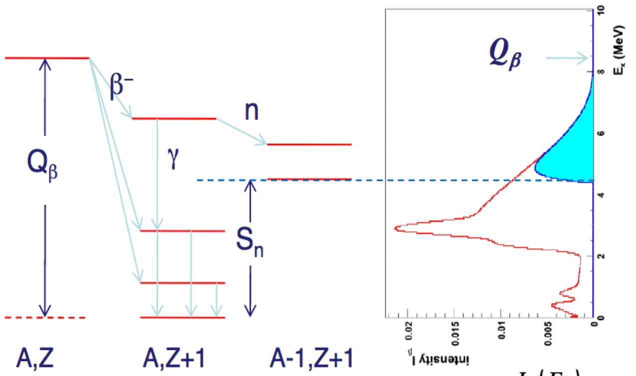






$$\frac{1}{T_{1/2}} = \sum_{0}^{Q_\beta} S_\beta(E_x)\cdot f(Q_\beta - E_x)$$

$$P_n = \frac{\sum_{S_n}^{Q_\beta} S_\beta(E_x)\cdot f(Q_\beta - E_x)}{\sum_{0}^{Q_\beta} S_\beta(E_x)\cdot f(Q_\beta - E_x)}$$



$$S_\beta(E_x) = \frac{I_\beta(E_x)}{f(Q_\beta - E_x)\cdot T_{1/2}}$$

Experimental data are needed for :

- astrophysics :
  - r process nucleosynthesis of elements heavier than Fe

- nuclear structure :
  - -properties of neutron rich nuclei
  - - nuclei at the drip line
  - - nuclei at the closed shell
  - - ...
- nuclear energy :
  - reactor design, performance and safety
    - - delayed neutron fraction
      - →Pn needed accuracy 1-5 %
    - - average energy !! → energy spectra

β-delayed neutron emission occurs when $Q_\beta > S_n$ in the daughter nucleus

$T_{1/2}$ and P_n convey information related to β feeding

$T_{1/2}$ yields information on the average β feeding
P_n yields information on β feeding above Sn

P_n are difficult to predict theoretically since the reflect the "shape" of the β strength function and fine structure on the nucleus

Relation to the Pandemonium effect

How to evaluate $P_n = \frac{N_{n-decays}}{N_{decays}}$

1- n/β: coincidences btw n-β $P_n = \frac{1}{\varepsilon_n}\frac{N_{\beta n}}{N_\beta}$

- ➔ best method. Only one absolute efficiency is needed, for the neutron detector
- ➔ the true signal has to be separated from contaminants using the decay curves, for which the proper knowledge of the different half-lives (T1/2) is needed.

2- n/β separate but simultaneous $P_n = \frac{\varepsilon_\beta}{\varepsilon_n}\frac{N_{\beta n}}{N_\beta}$

- ➔ needs two efficiencies
- ➔ this method could be advantageous in cases were the detectors cover a solid angle close to 4pi

3- Ion counting $P_n = \frac{N_{n-decays}}{N_{ions}}$

➔ The “ion” method relies on direct ion-counting. Difficult at low-energy ISOL facilities

4- γ–γ: Total counting of all γ-rays emitted by daughter and/or βn-daughter, but no counting of neutrons is carried out.

$$P_n = \frac{\varepsilon_{\gamma,daughter} * I_{abs,daughter,\gamma}}{N_{daughter.\gamma}} \Bigg/ \frac{\varepsilon_{\gamma,final} * I_{abs,final,\gamma}}{N_{final,\gamma}}$$

➔ Absolute γ-intensities are required, that means a complete knowledge the decay scheme including β’s going to the ground state or eventually competing γ-decays from levels above the neutron separation energy.

Existing arrays

- 3He counters

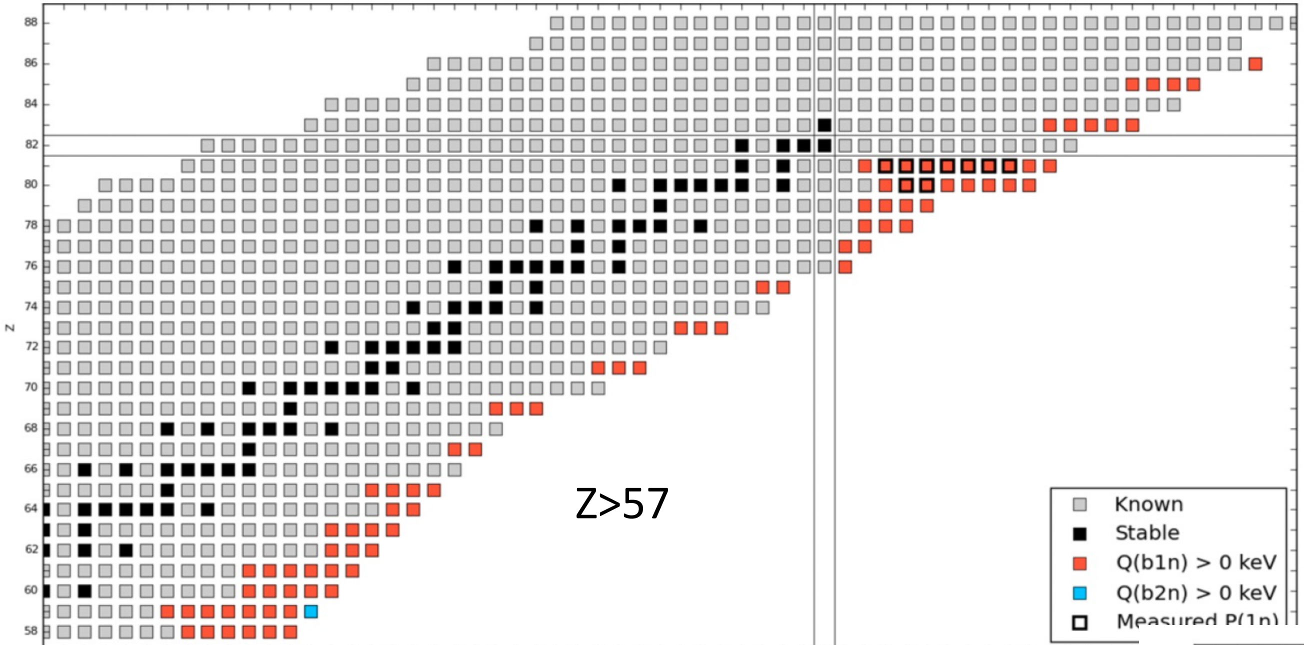
➢ B-Riken (Japan)
➢Tetra (Dubna-Orsay)
➢3Hen (Oak Ridge)
➢BELEN (GSI-FAIR)

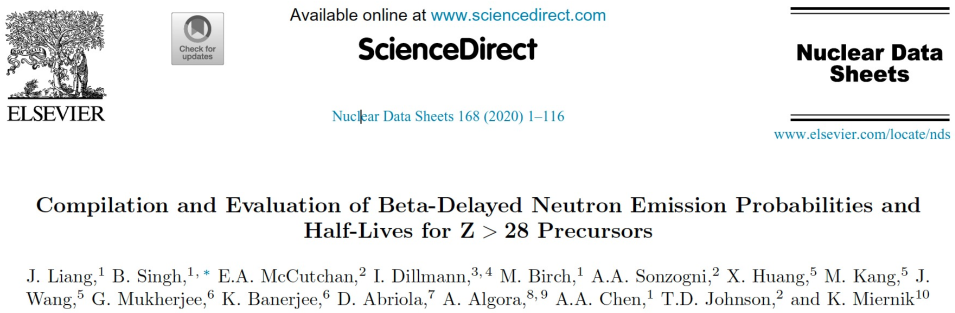
✓High angular coverage
✓High efficiency (~65 %)
~ Flat efficiency in large range of energies
X No energy information
X Difficult to disentangle 1n,2n

- TOF counters

➢ VANDLE (Oak Ridge)
➢ MONSTER (GSI-FAIR)
➢TONNERE (GANIL)
➢DESCANT (TRIUMF)

✓High angular coverage
✓ 1n – 2n discrimination
~ Good Resolution
~ Position independent eff.
X low detection threshold
X high background

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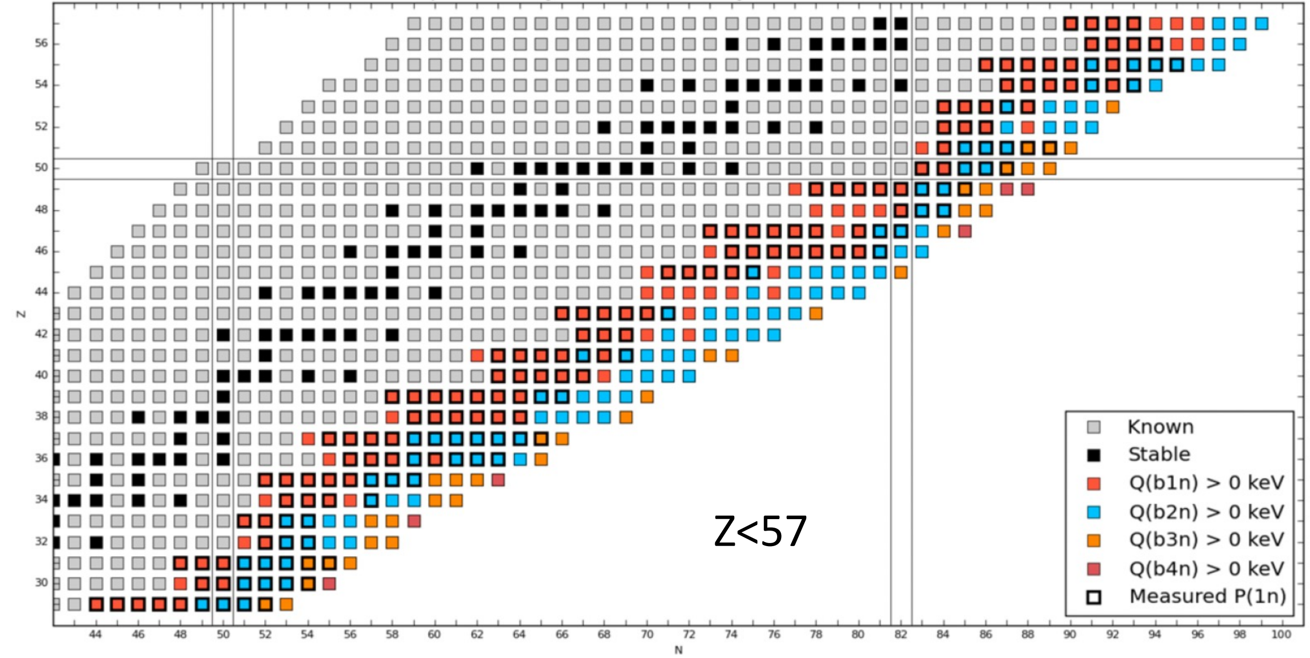
Nuclear Data Sheets 168 (2020) 1–116

Nuclear Data Sheets

www.elsevier.com/locate/nds

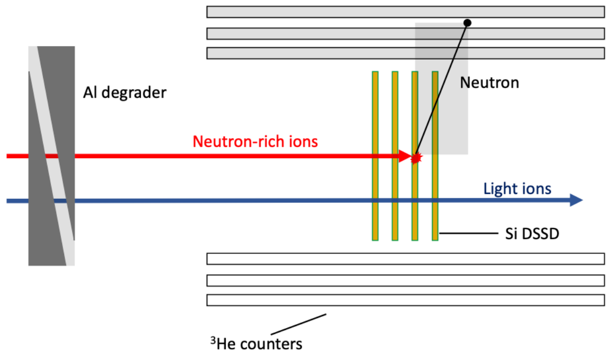
Compilation and Evaluation of Beta-Delayed Neutron Emission Probabilities and Half-Lives for Z > 28 Precursors

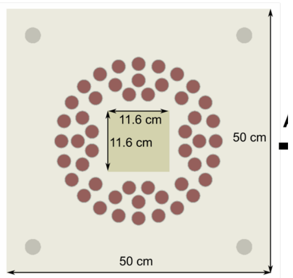
J. Liang,[1] B. Singh,[1,*] E.A. McCutchan,[2] I. Dillmann,[3,4] M. Birch,[1] A.A. Sonzogni,[2] X. Huang,[5] M. Kang,[5] J. Wang,[5] G. Mukherjee,[6] K. Banerjee,[6] D. Abriola,[7] A. Algora,[8,9] A.A. Chen,[1] T.D. Johnson,[2] and K. Miernik[10]

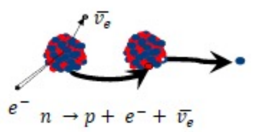


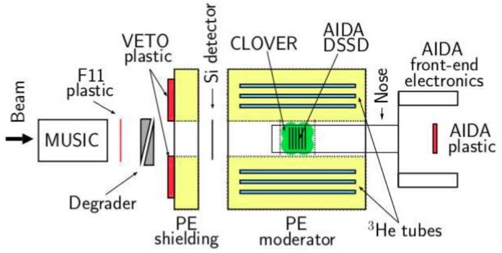
Completing the suite of detectors: n-detection arrays

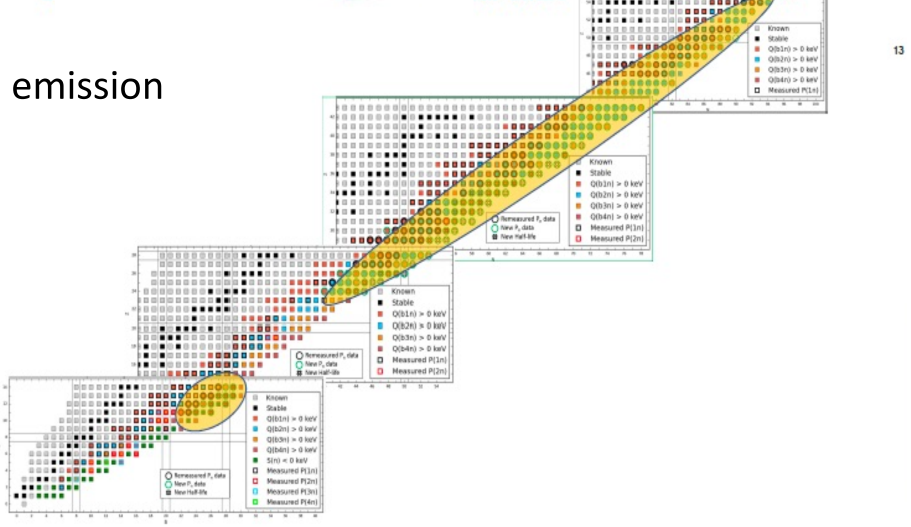
BEta-deLayEd Neutron detector (BELEN):
48 3He cylindrical counters in Polyethylene moderator



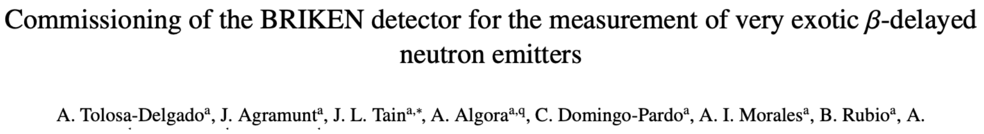








- Successful 5-years BRIKEN campaign to measure β1n and β2n emission

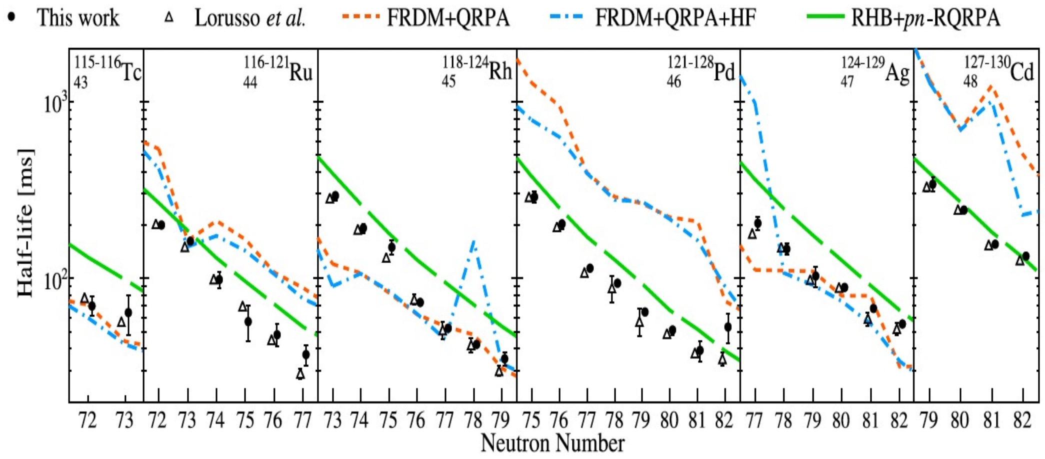


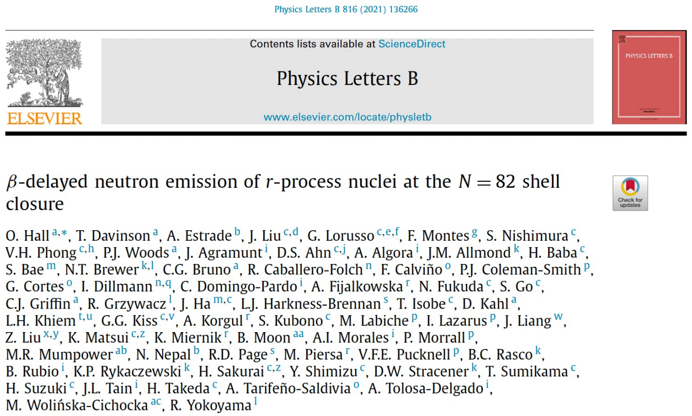
Commissioning of the BRIKEN detector for the measurement of very exotic β-delayed neutron emitters

A. Tolosa-Delgado[a], J. Agramunt[a], J. L. Tain[a,*], A. Algora[a,q], C. Domingo-Pardo[a], A. I. Morales[a], B. Rubio[a], A.

Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment
Volume 925, 1 May 2019, Pages 133-147

Courtesy of A.Tarifeño Saldiva, F.Calvino, I.Dillman,G.Cortes Rossel




Physics Letters B 816 (2021) 136266

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Physics Letters B

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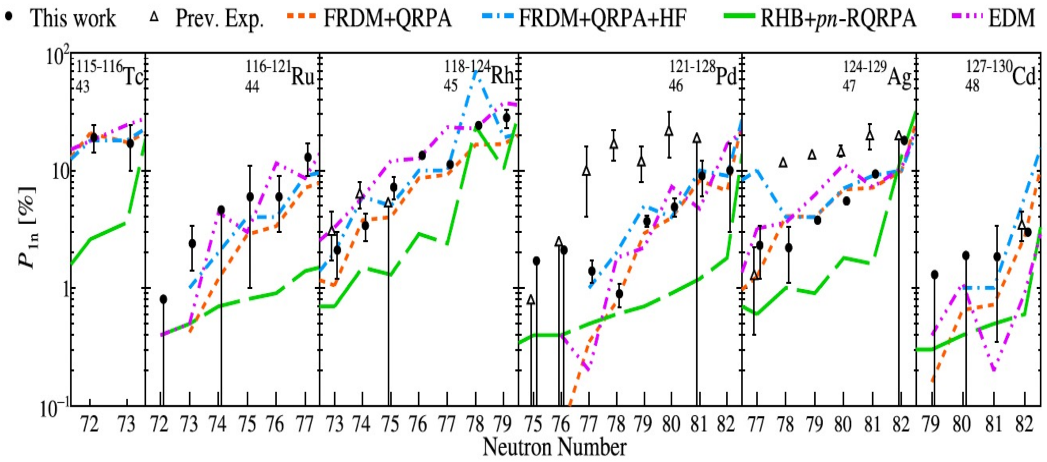
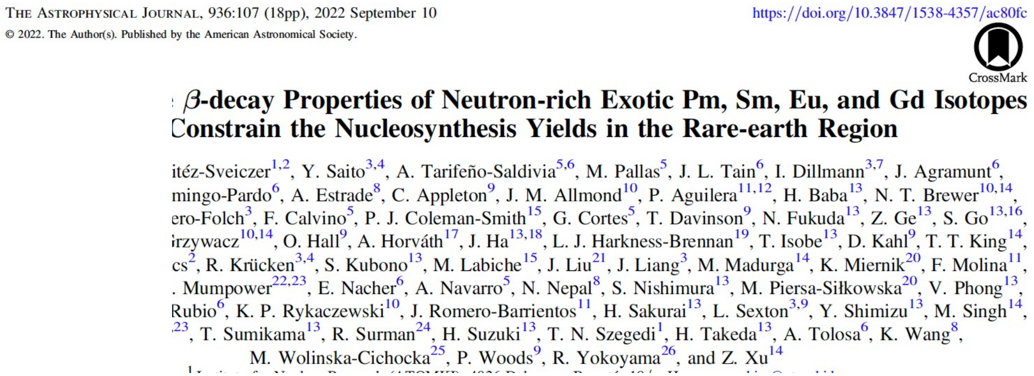
β-delayed neutron emission of r-process nuclei at the $N = 82$ shell closure

O. Hall[a,*], T. Davinson[a], A. Estrade[b], J. Liu[c,d], G. Lorusso[c,e,f], F. Montes[g], S. Nishimura[c], V.H. Phong[c,h], P.J. Woods[a], J. Agramunt[i], D.S. Ahn[c,j], A. Algora[i], J.M. Allmond[k], H. Baba[c], S. Bae[m], N.T. Brewer[k,l], C.G. Bruno[a], R. Caballero-Folch[n], F. Calviño[o], P.J. Coleman-Smith[p], G. Cortes[o], I. Dillmann[n,q], C. Domingo-Pardo[i], A. Fijalkowska[r], N. Fukuda[c], S. Go[c], C.J. Griffin[a], R. Grzywacz[l], J. Ha[m,c], L.J. Harkness-Brennan[s], T. Isobe[c], D. Kahl[a], L.H. Khiem[t,u], G.G. Kiss[c,v], A. Korgul[r], S. Kubono[c], M. Labiche[p], I. Lazarus[p], J. Liang[w], Z. Liu[x,y], K. Matsui[c,z], K. Miernik[r], B. Moon[aa], A.I. Morales[i], P. Morrall[p], M.R. Mumpower[ab], N. Nepal[b], R.D. Page[s], M. Piersa[r], V.F.E. Pucknell[p], B.C. Rasco[k], B. Rubio[i], K.P. Rykaczewski[k], H. Sakurai[c,z], Y. Shimizu[c], D.W. Stracener[k], T. Sumikama[c], H. Suzuki[c], J.L. Tain[i], H. Takeda[c], A. Tarifeño-Saldivia[o], A. Tolosa-Delgado[i], M. Wolińska-Cichocka[ac], R. Yokoyama[l]



FRDM+QRPA= cut-off approach: above Sn a neutron is emitted
FRDM+QRPA+HF = statistical decay and γ-ray emission explicitly at every stage
EDM = semiempirical effective density model

The P_{1n} values reported in this work show a regular trend for most elements, of increasing neutron emission probability as neutron number increases. Some odd-even staggering in the P1nvalues is observed for the lighter elements, such as Tc, Ru and Rh, though this is seen to diminish for nuclei close to Z=50where a smoother increase is observed.
The predictions of the FRDM+QRPA and FRDM+QRPA+HF calculations reproduce this trend well across all isotopic chains, matching much of the stagger-ing that is observed in the experimental values
BUT models who work for $T_{1/2}$ do not reproduce P_{1n}



THE ASTROPHYSICAL JOURNAL, 936:107 (18pp), 2022 September 10 https://doi.org/10.3847/1538-4357/ac80fc

β-decay Properties of Neutron-rich Exotic Pm, Sm, Eu, and Gd Isotopes Constrain the Nucleosynthesis Yields in the Rare-earth Region

itéz-Sveiczer[1,2], Y. Saito[3,4], A. Tarifeño-Saldivia[5,6], M. Pallas[5], J. L. Tain[6], I. Dillmann[3,7], J. Agramunt[6],
mingo-Pardo[6], A. Estrade[8], C. Appleton[9], J. M. Allmond[10], P. Aguilera[11,12], H. Baba[13], N. T. Brewer[10,14],
ero-Folch[3], F. Calvino[5], P. J. Coleman-Smith[15], G. Cortes[5], T. Davinson[9], N. Fukuda[13], Z. Ge[13], S. Go[13,16],
rzywacz[10,14], O. Hall[9], A. Horváth[17], J. Ha[13,18], L. J. Harkness-Brennan[19], T. Isobe[13], D. Kahl[9], T. T. King[14],
cs[2], R. Krücken[3,4], S. Kubono[13], M. Labiche[15], J. Liu[21], J. Liang[3], M. Madurga[14], K. Miernik[20], F. Molina[11],
. Mumpower[22,23], E. Nacher[6], A. Navarro[5], N. Nepal[8], S. Nishimura[13], M. Piersa-Siłkowska[20], V. Phong[13],
Rubio[6], K. P. Rykaczewski[10], J. Romero-Barrientos[11], H. Sakurai[13], L. Sexton[3,9], Y. Shimizu[13], M. Singh[14],
23, T. Sumikama[13], R. Surman[24], H. Suzuki[13], T. N. Szegedi[1], H. Takeda[13], A. Tolosa[6], K. Wang[8],
M. Wolinska-Cichocka[25], P. Woods[9], R. Yokoyama[26], and Z. Xu[14]

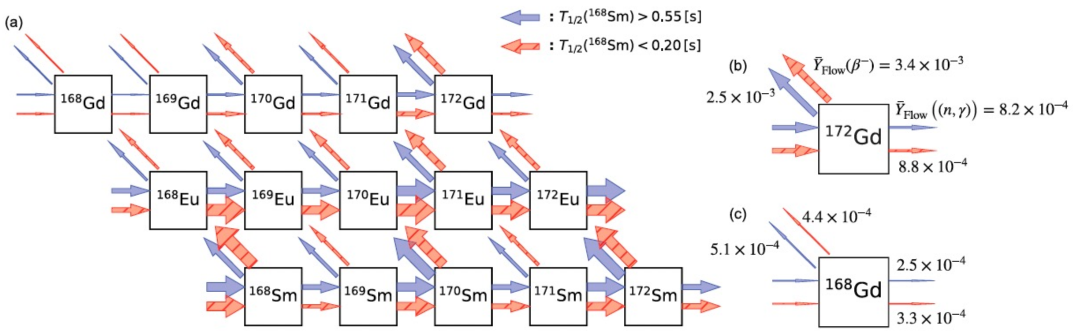
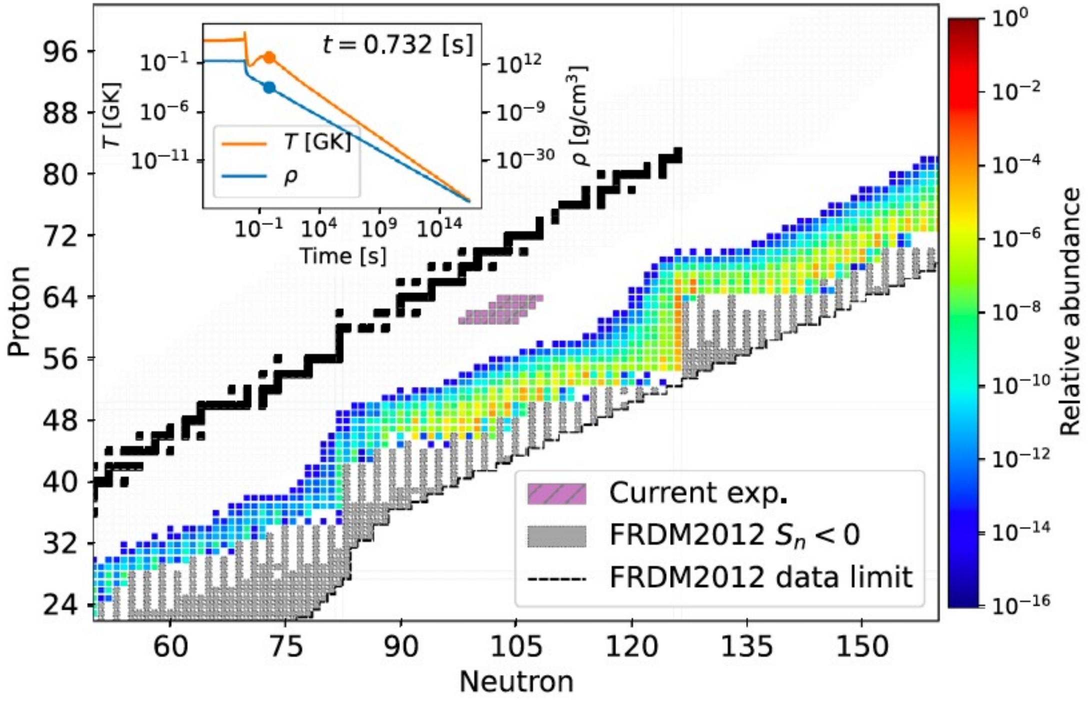
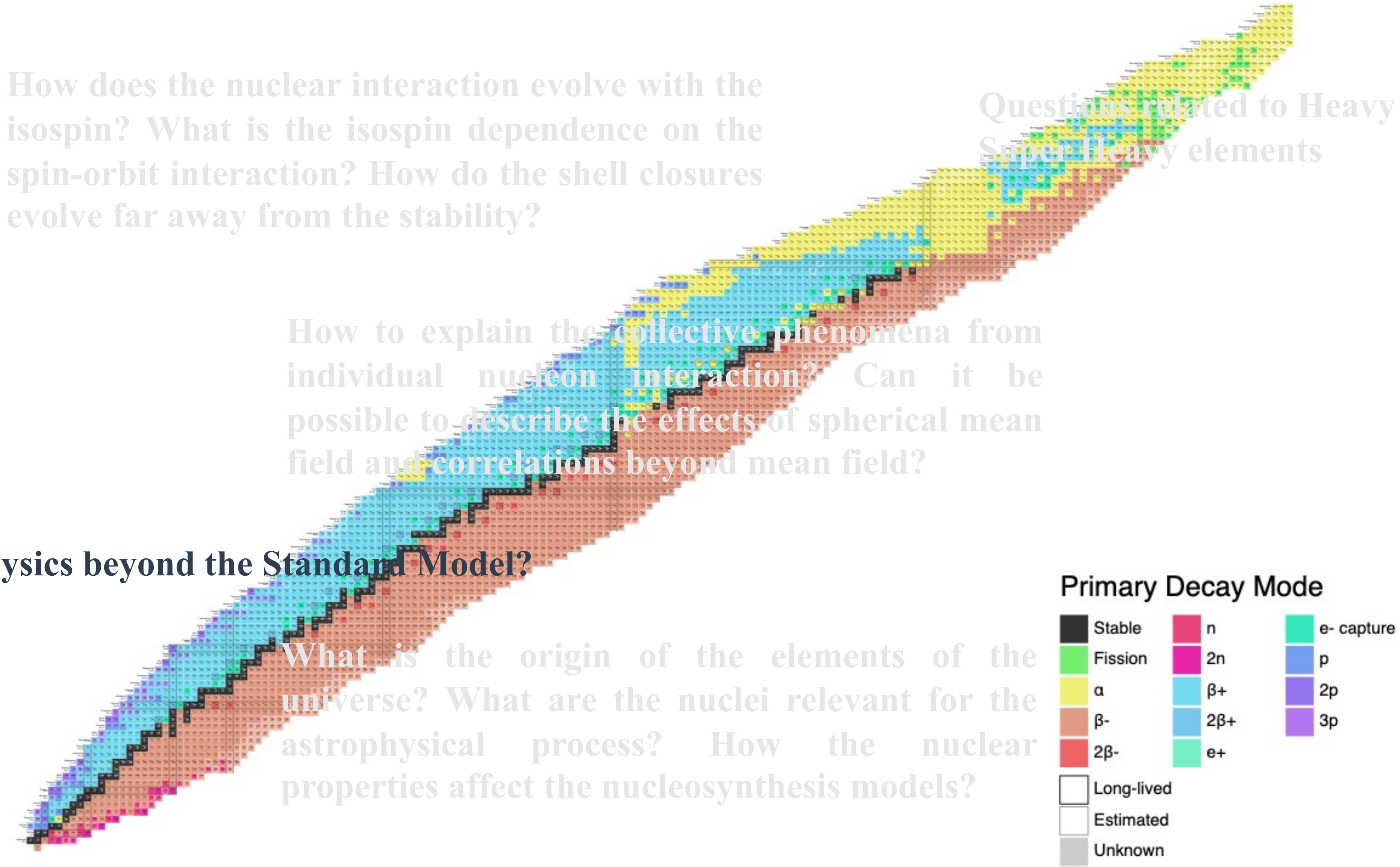


Figure 12. The arrows show the total abundance flow (same quantity as in panels (g)–(i) in Figure 11), averaged over the generated samples in the neutron-star merger scenario. Red corresponds to the case where the half-life of ^{168}Sm is shorter than 0.20 [s], and blue shows a half-live longer than 0.55 [s]. Panels (b) and (c) focus on the flows from ^{172}Gd and ^{168}Gd, respectively. The propagated influence of the half-life of ^{168}Sm is visible, which results in affecting the final abundances.

The new data not only constrain the theoretical predictions of half-lives and β-delayed neutron-emission probabilities, but also allow for probing the mechanisms of formation of the high-mass wing of the rare-earth peak located at A ≈ 160 in the r-process abundance distribution through astrophysical reaction network calculations



https://people.physics.anu.edu.au/~ecs103/chart/



How does the nuclear interaction evolve with the isospin? What is the isospin dependence on the spin-orbit interaction? How do the shell closures evolve far away from the stability?

Questions related to Heavy and SuperHeavy elements

How to explain the collective phenomena from individual nucleon interaction? Can it be possible to describe the effects of spherical mean field and correlations beyond mean field?

Is there physics beyond the Standard Model?

What is the origin of the elements of the universe? What are the nuclei relevant for the astrophysical process? How the nuclear properties affect the nucleosynthesis models?

Is there physics beyond the Standard Model?
Superallowed decays

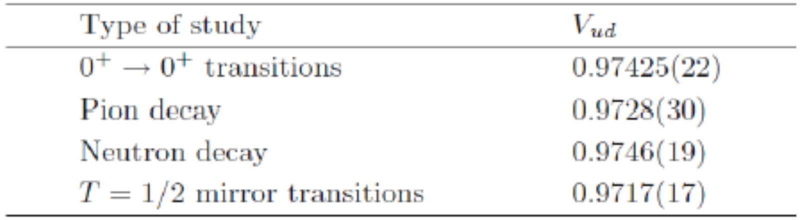
Standard model description of the mixing btw quark flavours:
CKM (Cabibbo Kobayashi Maskawa) mixing matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} \boxed{V_{ud} \quad V_{us} \quad V_{ub}} \\ V_{cd} \quad V_{cs} \quad V_{cb} \\ V_{td} \quad V_{ts} \quad V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Quark
Weak
states

Quark
Mass
states

CKM is a unitary matrix. If not there is physics beyond SM
To test this we concentrate to the first line, which is known with greater precision



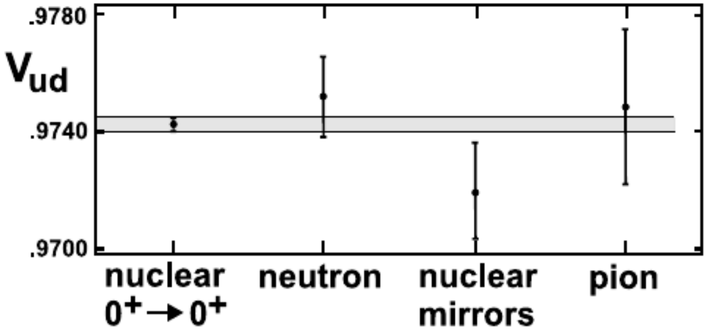
Type of study	V_{ud}
$0^+ \rightarrow 0^+$ transitions	0.97425(22)
Pion decay	0.9728(30)
Neutron decay	0.9746(19)
$T = 1/2$ mirror transitions	0.9717(17)

$$\sum_i V_{ui}^{\,2} = V_{ud}^{\,2} + V_{us}^{\,2} + V_{ub}^{\,2} = 1$$

Vud from β decay
Known with highest precision
Leading term

Vus from K meson decay:
$K^+ \rightarrow \pi^0 e^+ \nu$

Vub B meson decay
small contributions



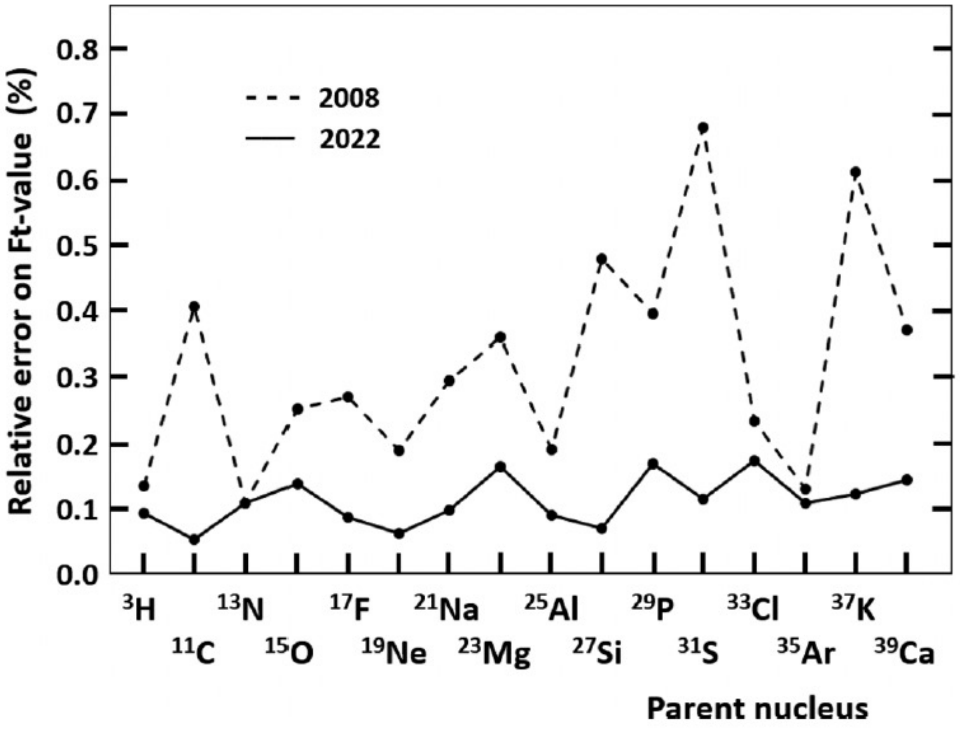
ISOL-France Workshop V
Mar 20 – 22, 2023
ISM

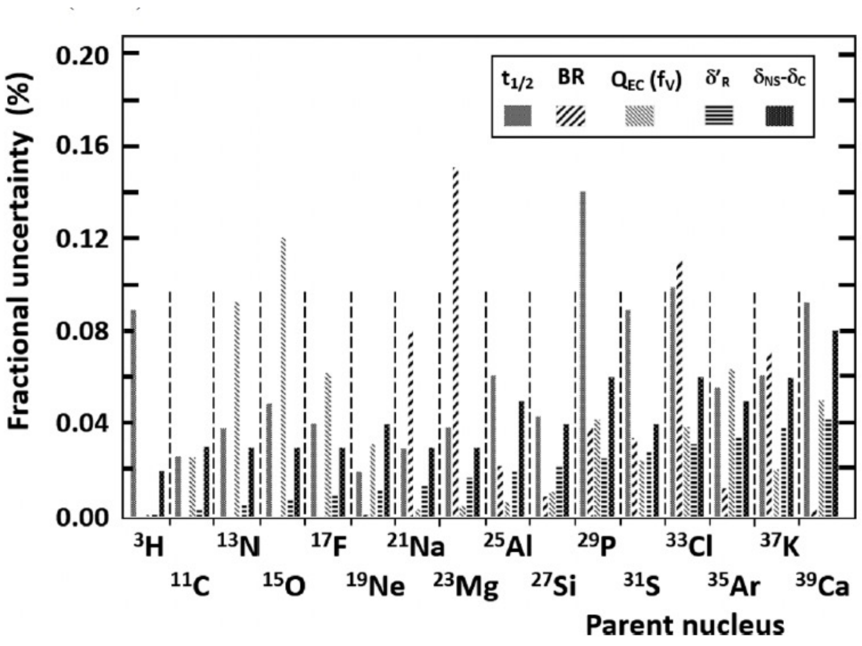
Is there physics beyond the Standard Model?
Superallowed decays

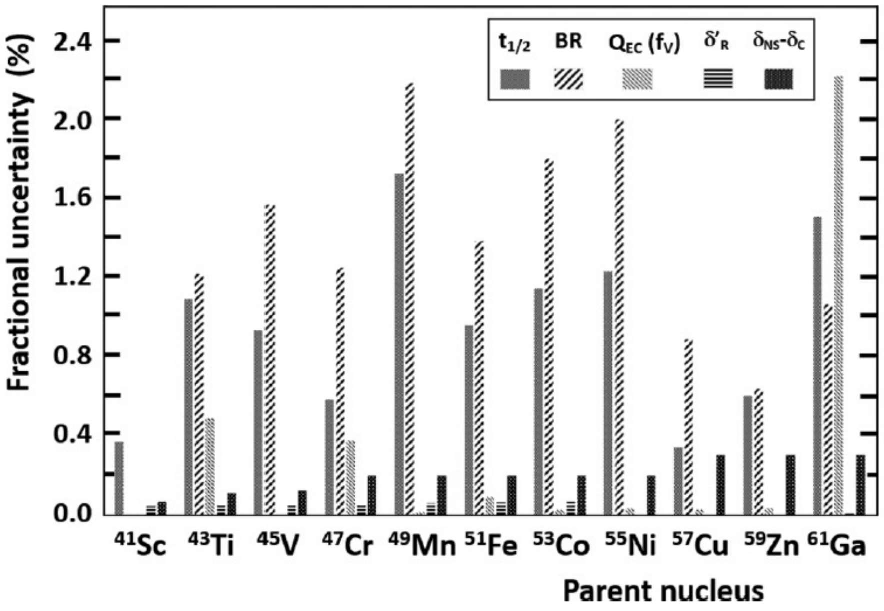
Ft values of the mirror β transitions and the weak-magnetism-induced current in allowed nuclear β decay, N. Severijns et al., PHYSICAL REVIEW C 107, 015502 (2023)

$$\mathcal{F}t = ft\left(1+\delta'_R\right)\left(1+\delta_{NS}-\delta_C\right) = \frac{K}{2G^2\left(1+\Delta_R\right)}$$

δ'_R, δ_{NS} and Δ_R are radiative corrections,
δ_C is an isospin-symmetry breaking term

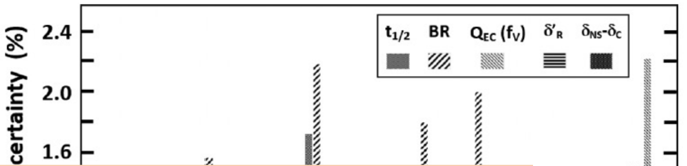






Is there physics beyond the Standard Model?
Superallowed decays

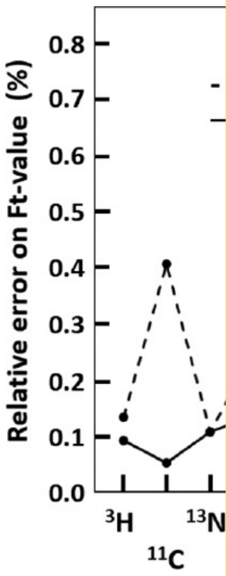
Ft values of the mirror β transitions and the weak-magnetism-induced current in allowed nuclear β decay, N. Severijns et al.,
PHYSICAL REVIEW C 107, 015502 (2023)



Ni ^{57}Cu ^{59}Zn ^{61}Ga

nt nucleus

mental and theoreti-
rror β transitions in
n vertical scale with



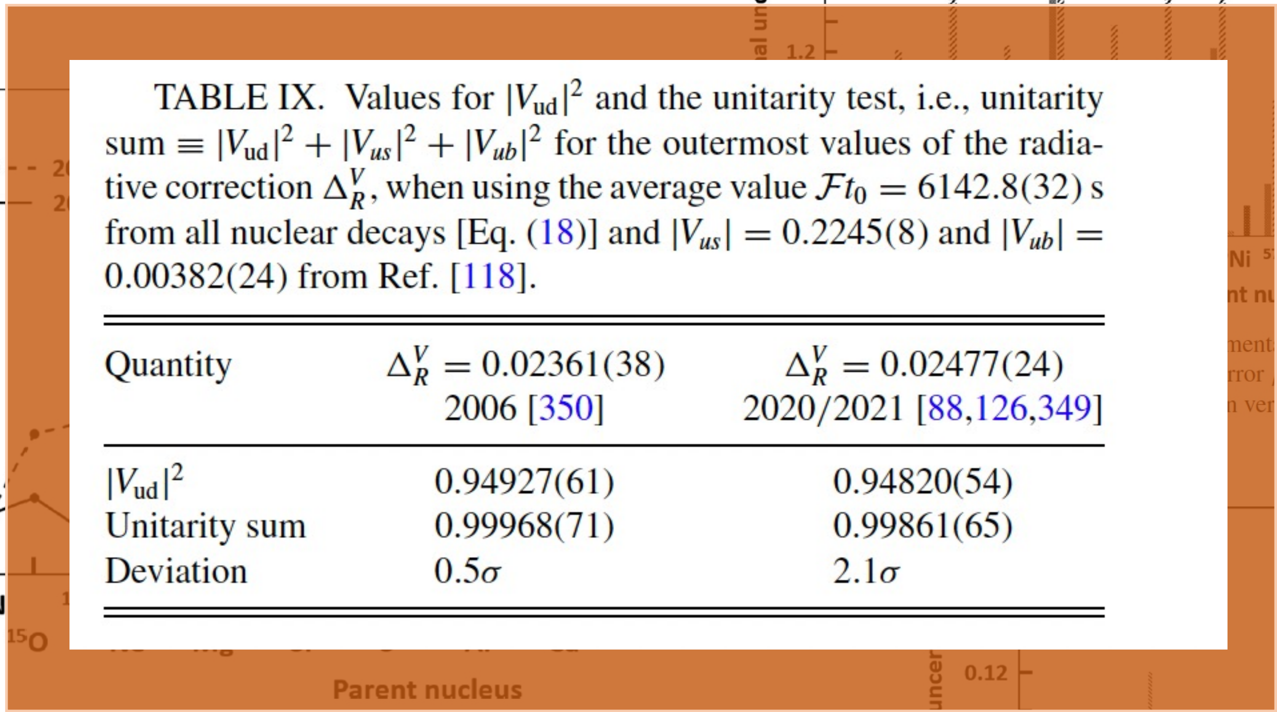


TABLE IX. Values for $|V_{ud}|^2$ and the unitarity test, i.e., unitarity sum $\equiv |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2$ for the outermost values of the radiative correction Δ_R^V, when using the average value $\mathcal{F}t_0 = 6142.8(32)$ s from all nuclear decays [Eq. (18)] and $|V_{us}| = 0.2245(8)$ and $|V_{ub}| = 0.00382(24)$ from Ref. [118].

Quantity	$\Delta_R^V = 0.02361(38)$ 2006 [350]	$\Delta_R^V = 0.02477(24)$ 2020/2021 [88,126,349]
$\lvert V_{ud}\rvert^2$	0.94927(61)	0.94820(54)
Unitarity sum	0.99968(71)	0.99861(65)
Deviation	0.5σ	2.1σ

Parent nucleus

FIG. 1. Progress in the relative uncertainties of the $\mathcal{F}t^{\text{mirror}}$ values for the mirror β transitions up to $A = 39$ from 2008 [89] (dashed) till now (solid).

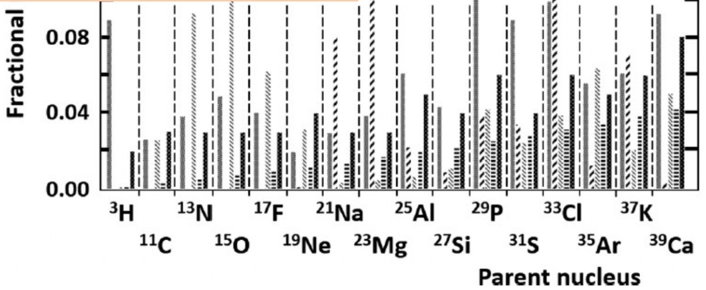
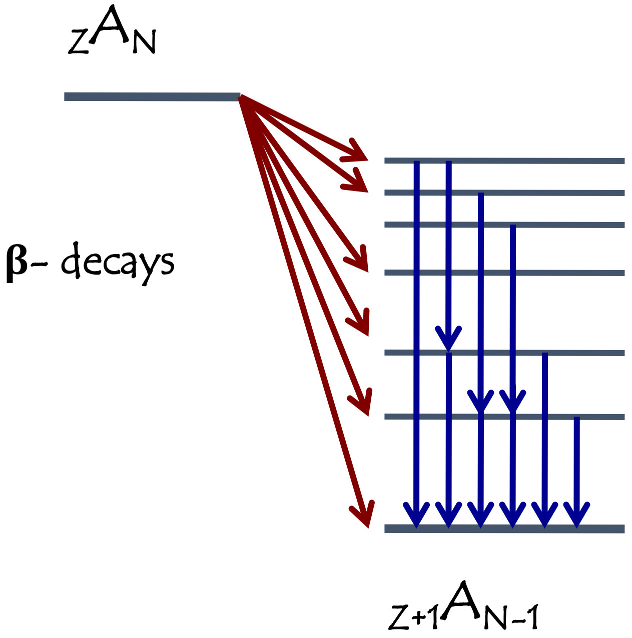
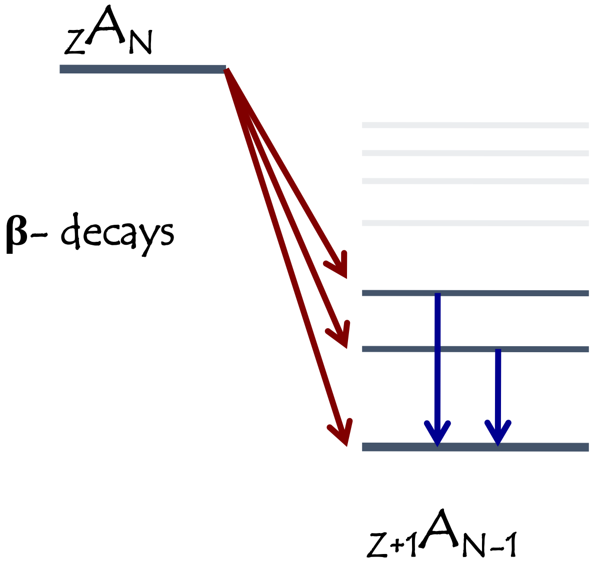


FIG. 2. Fractional contribution of the experimental and theoretical input factors to the $\mathcal{F}t^{\text{mirror}}$ values for the mirror β transitions up to $A = 39$.

General Properties of β decay





- HPGe detectors are conventionally used to construct the level scheme populated in the decay

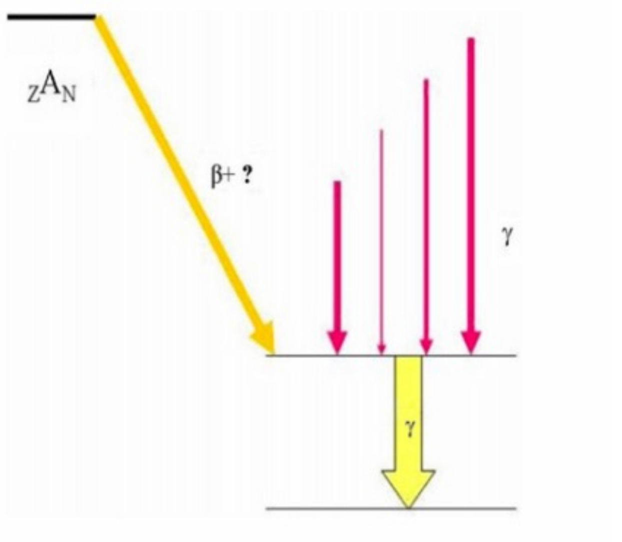
➔ Higher Qvalue higher possibility of missing feeding

- From the γ intensity balance we deduce the β-feeding

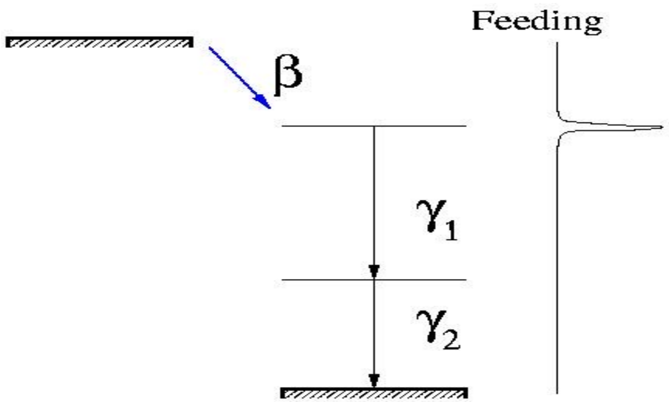
Pandemonium effect implies

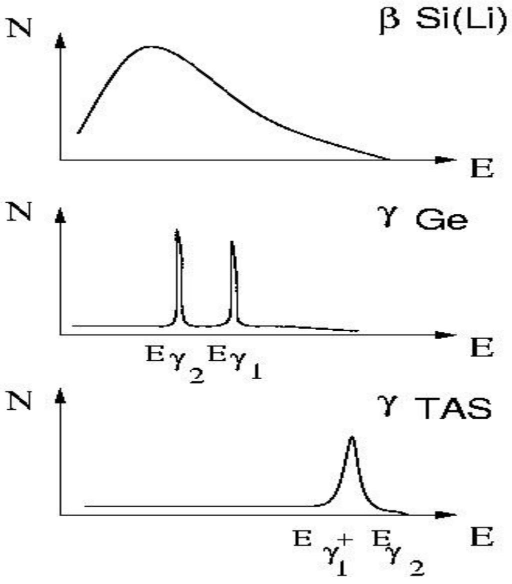
➔ Wrong definition of gamma feeding and branching ratios

I_b and logft



TAGS measurements





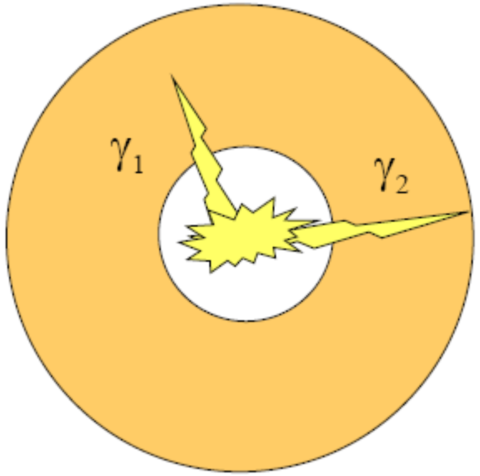
Since the gamma detection is the only reasonable way to solve the problem, we need a highly efficient device:

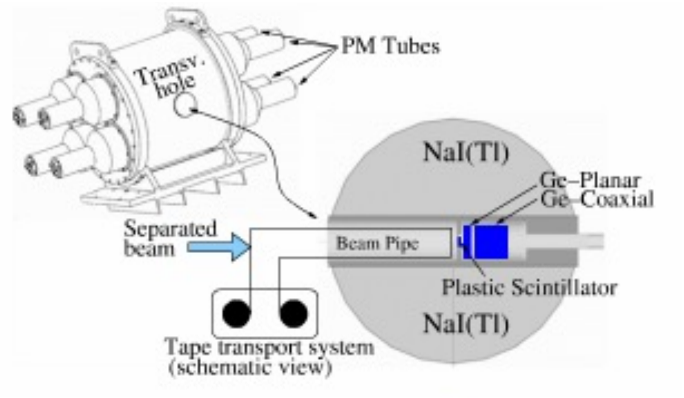
A TOTAL ABSORPTION SPECTROMETER

But there is a change in philosophy. Instead of detecting the individual gamma rays we sum the energy deposited by the gamma cascades in the detector.

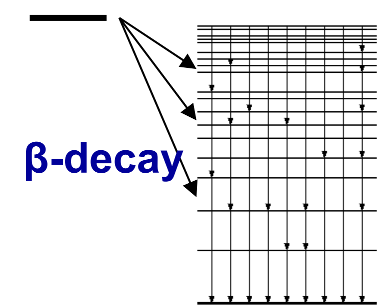
A TAS is like a calorimeter!

Big crystal, 4π (BaF_2/NaI/HPGe)





TAGS analysis



$$d_i = \sum_{j=1}^{j_{max}} R_{ij} I(E_j)$$

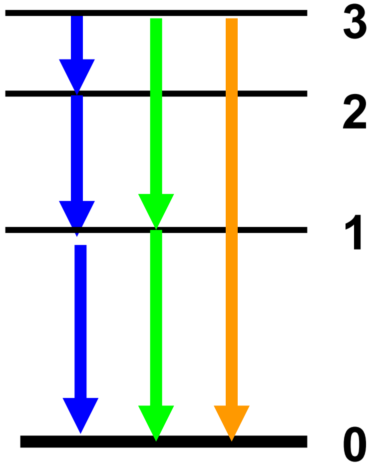
d_j = exp. data in channel I
$I(E_j)$ = beta feeding of j state

R is the response function of the spectrometer, ***R**$_{ij}$* means the probability that feeding at a level ***j*** gives counts in data channel ***i** of the spectrum*

The response matrix $\mathbf{R}$ can be constructed by recursive convolution:

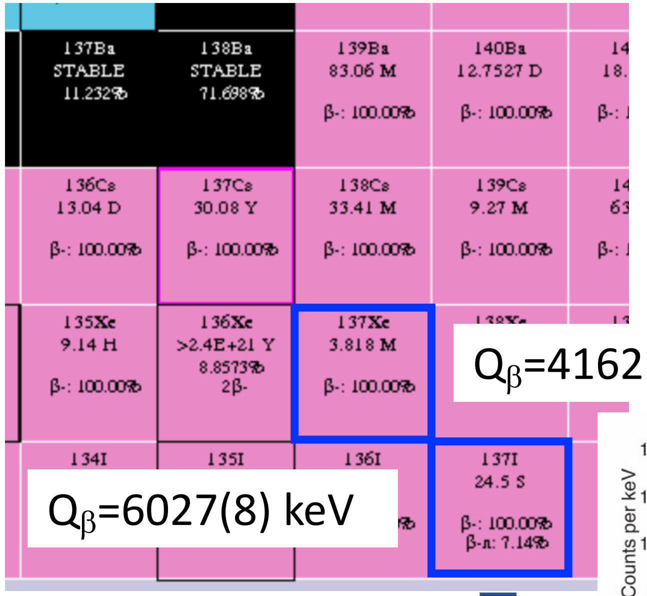
$$\mathbf{R_j} = \sum_{k=0}^{j-1} b_{jk} \mathbf{g_{jk}} \otimes \mathbf{R_k}$$

$\mathbf{g_{jk}}$: γ-response for *j* (*k* transition
$\mathbf{R_k}$: response for level *k*
b_{jk}: branching ratio for *j* (*k* transition



Mathematical formalization by Tain, Cano, et al.

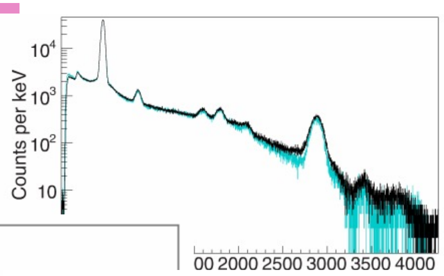
TAS measurement for decay heat evaluation

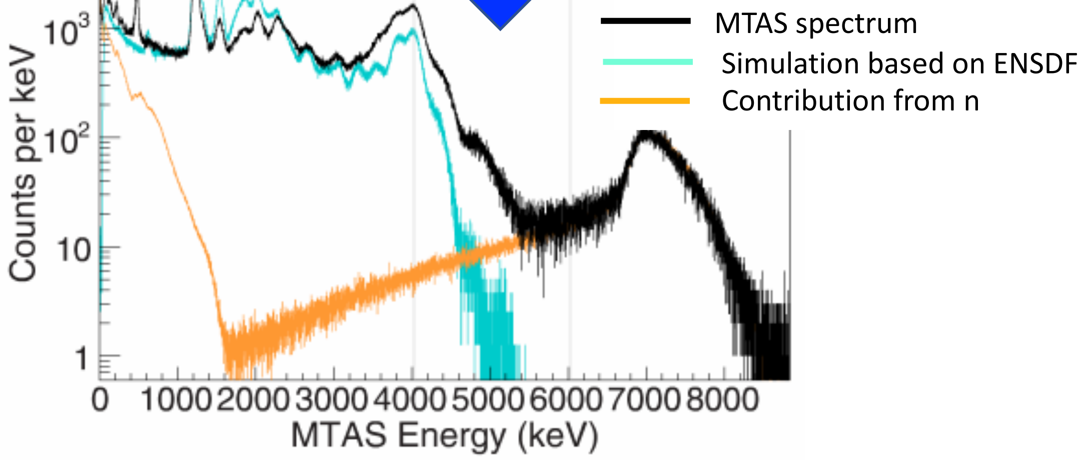


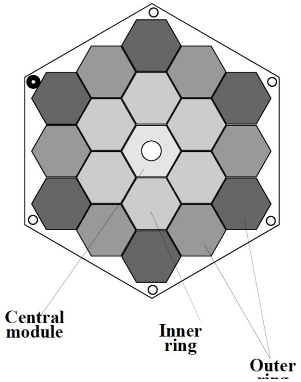
137Ba STABLE 11.232%	138Ba STABLE 71.698%	139Ba 83.06 M β-: 100.00%	140Ba 12.7527 D β-: 100.00%	14 18. β-:
136Cs 13.04 D β-: 100.00%	137Cs 30.08 Y β-: 100.00%	138Cs 33.41 M β-: 100.00%	139Cs 9.27 M β-: 100.00%	14 63 β-:
135Xe 9.14 H β-: 100.00%	136Xe >2.4E+21 Y 8.8573% 2β-	137Xe 3.818 M β-: 100.00%		13
134I	135I	136I	137I 24.5 S β-: 100.00% β-n: 7.14%	

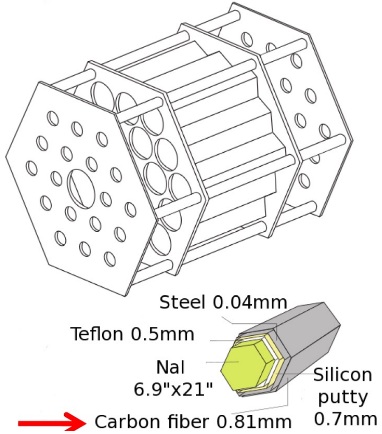
Q_β=4162(3) keV

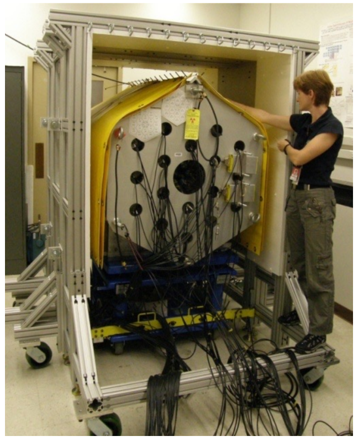
Q_β=6027(8) keV











2200 pounds of NaI(Tl) - Modular Total Absorption Spectrometer (MTAS) and its 12,000 pound shielding

Compared to the ENSDF β-feeding data there are many more γ rays measured by MTAS in the continuously binned region above Sn energy than previously reported

The average γ energy for ^{137}I decay measured with MTAS increases by 19% compared to the ENSDF data

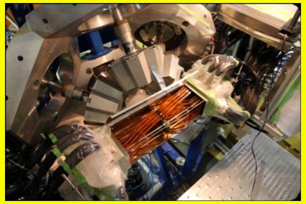
G.s. feeding increases from 45.2±0.7% to 49±1%.

Rasco et al. PRC95 (2017) 054328

Conclusions

- ➢ Broad field of application:
  - Inputs for stellar nucleosynthesis
  - Nuclear structure studies
  - Inputs for Nuclear Energy

- ➢ Simple equipment
- ➢ Versatile flexible and modular:
  - ➢ Minimal setup to extract $T_{1/2}$, P_n, β–γ coincidences
  - ➢ γ detectors to construct level schemes
  - ➢ Fast-timing setup: lifetimes ~ns range
  - ➢ E0 measurements and long-living activity
  - ➢ Complete spectroscopy using TAS

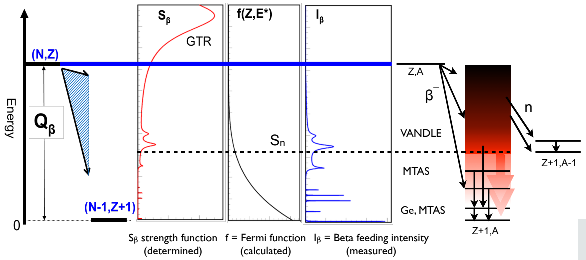


- ➢ Strong complementarity with in-beam spectroscopy
- ➢ Access to structure information already with few pps beams
- ➢ No need for post-acceleration
- ➢ Need for purified beams, even though known contribution from strong contaminants can be removed by off-line analysis

  ➔ **HRMS & RILIS & TRAPS**

$$\frac{1}{T_{1/2}} = \sum_{E_i \geq 0}^{E_i \leq Q_\beta} S_\beta(E_i) \times f(Z, Q_\beta - E_i)$$

$$\beta^- \rightarrow n = p + e^- + \overline{\nu}$$



S_β strength function (determined) f = Fermi function (calculated) I_β = Beta feeding intensity (measured)