

ZAKŁAD FIZYKI JĄDROWEJ
UNIwersYTET WARSZAWSKI

Specjalne seminarium
z okazji
 $_{90}\text{Th}$ (orowej) rocznicy
Jana Żylicza



Plan

- Poszukiwanie Ununennium - Krzysztof Rykaczewski,
- Wstrząśnięte, czy zmieszane? - Robert Grzywacz,
- Stan jednocząstkowy $\nu i_{13/2}$ - Agnieszka Korgul,
- Nadsubtelności ^{229}Th - Marek Pfützner.

Poszukiwanie Ununennium

Krzysztof Rykaczewski (ORNL)

KR od ponad 45 lat korzystający ze wskazówek naukowych Janka Żylicza, od wykładu “Fizyka jądrowa” dla studentów III roku w 1976 do zaakceptowanych pomiarów rozpadu ^{78}Ni z MTAS-FRIB w 2021.

un-un-ennium – nowy pierwiastek chemiczny 119

współpraca Japonia - USA (ORNL-UTK) - Francja

Układ Okresowy Pierwiastków (grudzień 2016)

IUPAC Periodic Table of the Elements

1 H hydrogen 1.008 (1.0078, 1.0082)																	18 He helium 4.0026						
3 Li lithium 6.94 (6.938, 6.967)	4 Be beryllium 9.0122	Key: atomic number Symbol name isotopic atomic weight standard atomic weight																13 B boron 10.81 (10.806, 10.821)	14 C carbon 12.011 (12.009, 12.012)	15 N nitrogen 14.007 (14.006, 14.008)	16 O oxygen 15.999 (15.999, 16.003)	17 F fluorine 18.998	10 Ne neon 20.180
11 Na sodium 22.990	12 Mg magnesium 24.305 (24.304, 24.307)																	13 Al aluminum 26.982	14 Si silicon 28.086 (28.084, 28.089)	15 P phosphorus 30.974	16 S sulfur 32.06 (32.059, 32.076)	17 Cl chlorine 35.45 (35.446, 35.457)	18 Ar argon 39.948
19 K potassium 39.098	20 Ca calcium 40.078(4)	21 Sc scandium 44.956	22 Ti titanium 47.867	23 V vanadium 50.942	24 Cr chromium 51.996	25 Mn manganese 54.938	26 Fe iron 55.845(2)	27 Co cobalt 58.933	28 Ni nickel 58.693	29 Cu copper 63.546(3)	30 Zn zinc 65.38(2)	31 Ga gallium 69.723	32 Ge germanium 72.630(8)	33 As arsenic 74.922	34 Se selenium 78.971(8)	35 Br bromine 79.904 (79.901, 79.907)	36 Kr krypton 83.796(2)						
37 Rb rubidium 85.468	38 Sr strontium 87.62	39 Y yttrium 88.906	40 Zr zirconium 91.224(2)	41 Nb niobium 92.906	42 Mo molybdenum 95.95	43 Tc technetium	44 Ru ruthenium 101.07(2)	45 Rh rhodium 102.91	46 Pd palladium 106.42	47 Ag silver 107.87	48 Cd cadmium 112.41	49 In indium 114.82	50 Sn tin 118.71	51 Sb antimony 121.76	52 Te tellurium 127.60(3)	53 I iodine 126.90	54 Xe xenon 131.29						
55 Cs caesium 132.91	56 Ba barium 137.33	57-71 lanthanoids	72 Hf hafnium 178.49(2)	73 Ta tantalum 180.95	74 W tungsten 183.84	75 Re rhenium 186.21	76 Os osmium 190.23(3)	77 Ir iridium 192.22	78 Pt platinum 195.08	79 Au gold 196.97	80 Hg mercury 200.59	81 Tl thallium 204.38, 204.39	82 Pb lead 207.2	83 Bi bismuth 208.98	84 Po polonium	85 At astatine	86 Rn radon						
87 Fr francium	88 Ra radium	89-103 actinoids	104 Rf rutherfordium	105 Db dubnium	106 Sg seaborgium	107 Bh bohrium	108 Hs hassium	109 Mt meitnerium	110 Ds darmstadtium	111 Rg roentgenium	112 Cn copernicium	113 Nh nihonium	114 Fl flerovium	115 Mc moscovium	116 Lv livermorium	117 Ts tennessine	118 Og oganesson						

119 **120**

New elements 119 and 120 to be discovered with ORNL-made targets and digital detection

57 La lanthanum 138.91	58 Ce cerium 140.12	59 Pr praseodymium 140.91	60 Nd neodymium 144.24	61 Pm promethium	62 Sm samarium 150.36(2)	63 Eu europium 151.96	64 Gd gadolinium 157.25(3)	65 Tb terbium 158.93	66 Dy dysprosium 162.50	67 Ho holmium 164.93	68 Er erbium 167.26	69 Tm thulium 168.93	70 Yb ytterbium 173.05	71 Lu lutetium 174.97
89 Ac actinium	90 Th thorium 232.04	91 Pa protactinium 231.04	92 U uranium 238.03	93 Np neptunium	94 Pu plutonium	95 Am americium	96 Cm curium	97 Bk berkelium	98 Cf californium	99 Es einsteinium	100 Fm fermium	101 Md mendelevium	102 No nobelium	103 Lr lawrencium

122

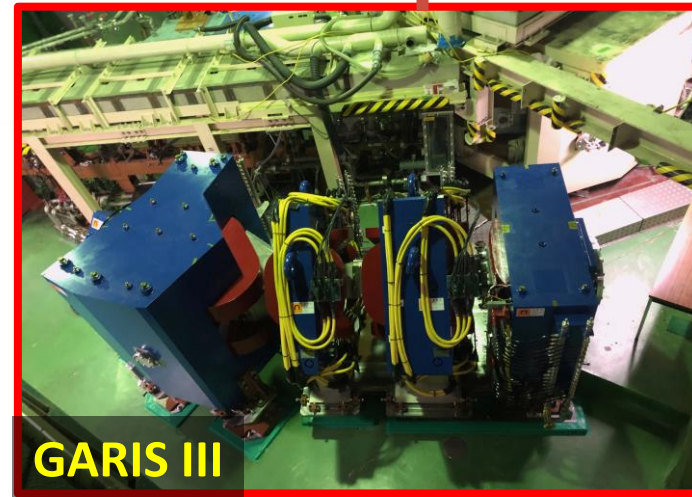
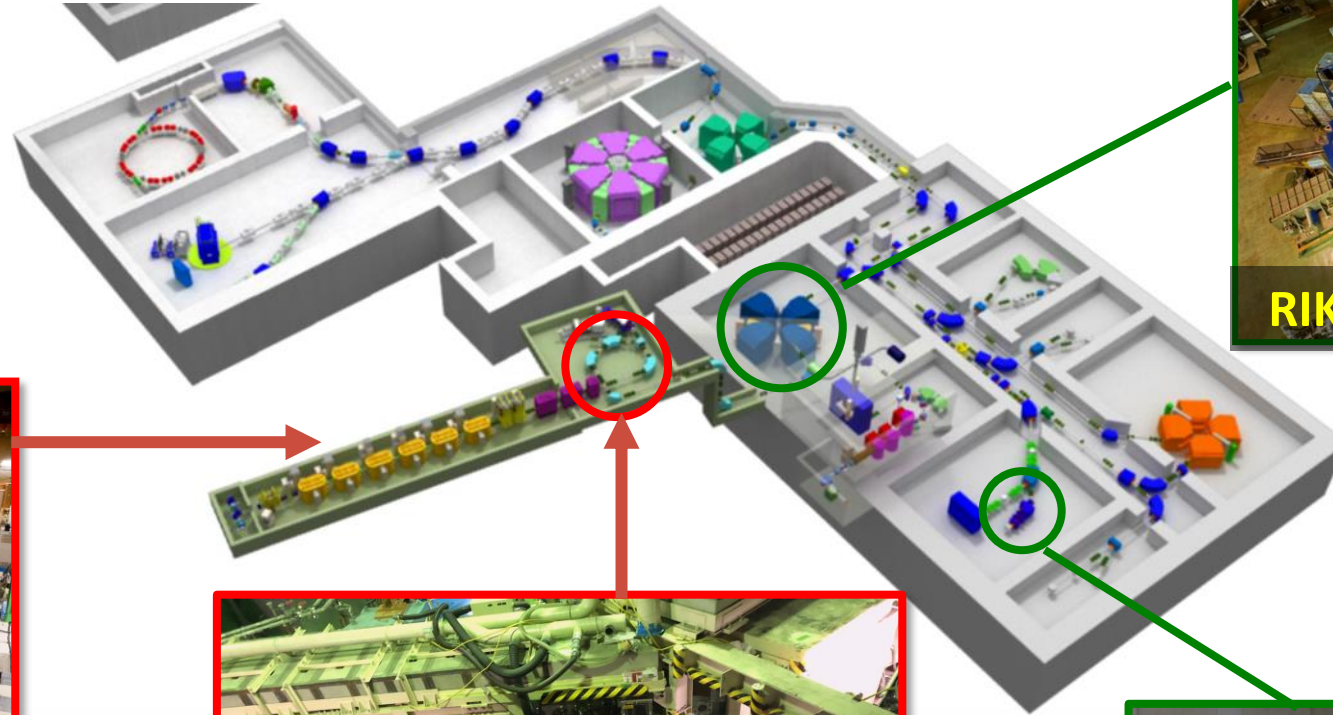
124

"121-nides" from $^{251}\text{Cf} + ^{58}\text{Fe}$ reaction

Motywacje badań najcięższych pierwiastków i nuklidów

- Gdzie są granice Układu Okresowego Pierwiastków i Tablicy Nuklidów (ile protonów oraz neutronów możemy złożyć razem w jądro atomowe ?)
- Wyspa Stabilności (A. Sobiczewski) z nowymi liczbami magicznymi czy wzmocniona stabilność jądrowa bez dużych przerw energetycznych (W. Nazarewicz, J. Dobaczewski i inni)
- Wytwarzanie nowych najcięższych pierwiastków i jąder atomowych (K. Wilczyńska, M. Kowal, J. Skalski, T. Cap ...)
- Konkurencja rozszczepienia i rozpadu alfa, struktura i własności jąder w obecności najsilniejszych oddziaływań Coulombowskich (W. Nazarewicz "Coulomb frustration")
- Własności chemiczne nowych pierwiastków (Z=118 Oganesson najprawdopodobniej nie jest gazem w temperaturze pokojowej)
- Nukleosynteza i najcięższe jądra

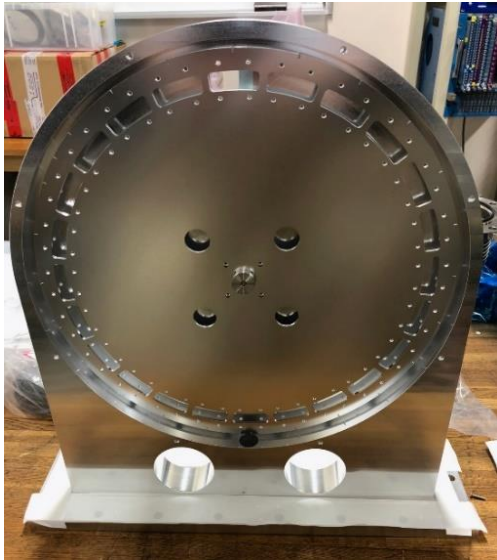
Dwa niezależne układy do badań SHE w RIKEN



Stan poszukiwań 119 (RIKEN-ORNL-Kyushu-UTK-IPHC-JAEA ..)

Eksperyment trwa

- Od 2018 tarcza $Z=96$ ^{248}Cm z ORNL jest naświetlana wiązka $Z=23$ ^{51}V ($\sim 10^{13}$ pps)
- Chcemy wytworzyć i zidentyfikować izotopy $^{295,296}\text{119}$ czyli produkty reakcji fuzji z emisją 4n i 3n
- SRILAC, GARIS-III separator z pełną cyfrową akwizycją UTK/ORNL rozpoczęły pomiary w 2021. Pomiary mają trwać do odkrycia nowego pierwiastka 119 (2022 +)
- Około 30 tygodni “wiązki na tarczy”, ponad 10^{20} pocisków, niedaleko przewidywanego p. czynnego



Koło z tarczami ^{248}Cm (30 mg),
obracające się 2000/min,
naświetlane wiązką ^{51}V $\sim \text{part} \cdot \mu\text{A}'\text{s}$



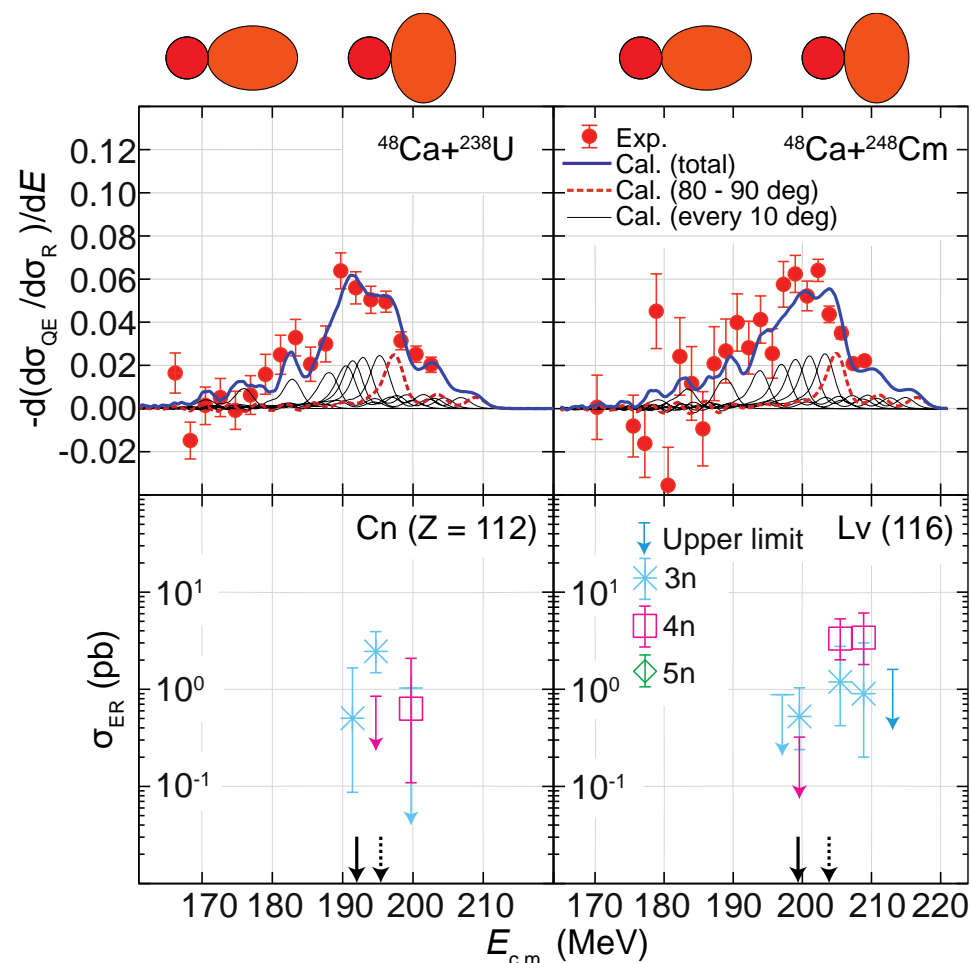
Fizycy z ORNL, RIKEN i UTK przy
separatorze GARIS-II w RIKEN
2019



Cyfrowe zbieranie danych (UTK/ORNL)
obsługujące eksperyment $Z=119$ w RIKEN.
Nowe moduły 16-bit Pixie z ORNL w 2020

Optymalna energia wiązki ^{51}V

Określiłiśmy eksperymentalnie energię wiązki dla produktów fuzji mierząc funkcję wzbudzenia dla rozproszenia quasi-elastycznego/elastycznego w reakcjach ^{22}Ne , ^{26}Mg , $^{48}\text{Ca} + ^{238}\text{U}$, ^{248}Cm i porównując z tak samo zbadaną reakcją $^{51}\text{V} + ^{248}\text{Cm}$.

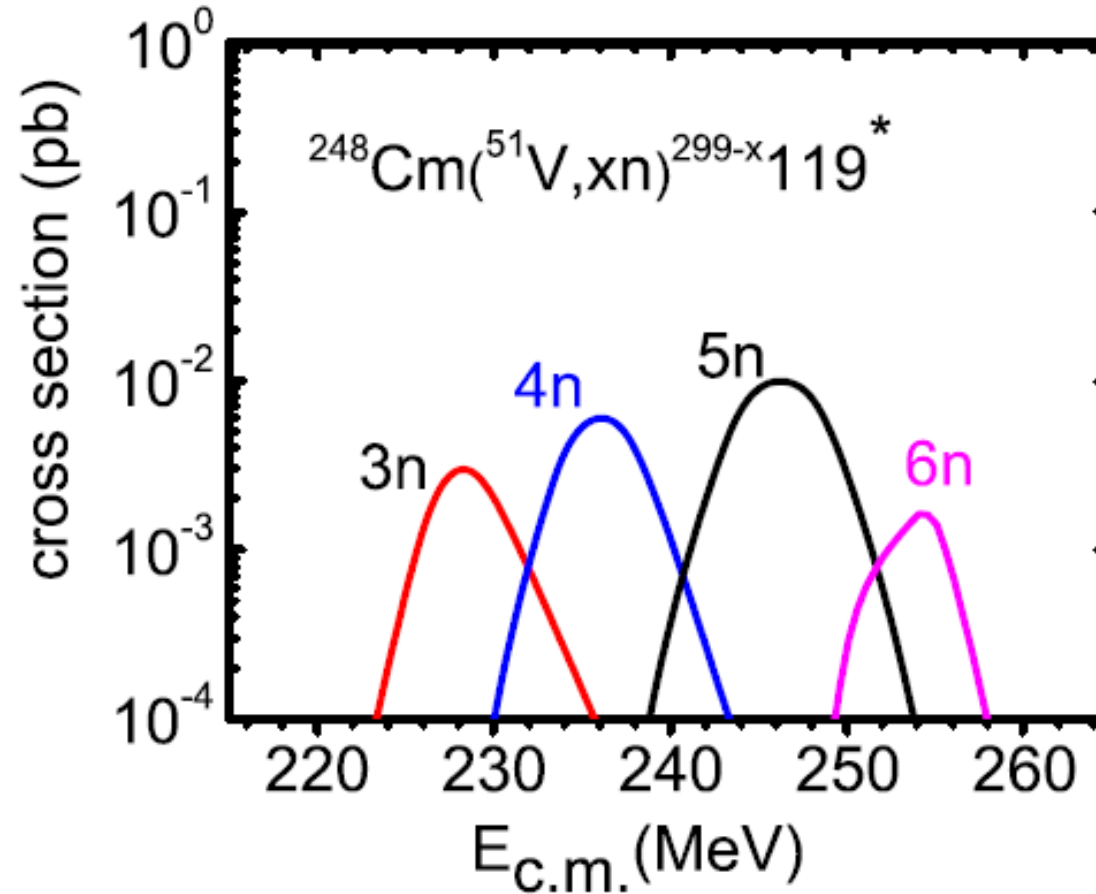


Tanaka et al, PRL 124, 052502, 2020

Optymalna energia wiązki ^{51}V

K. Wilczyńska, T. Cap, M. Kowal, PR C 99, 054603, 2019

3n – 3 fb
4n – 6 fb
5n – 10 fb



“three-humped camel”

Przewidywania A. Adamian’a oraz N. Antonenki (Dubna) również wskazują na maksimum przekroju czynnego dla kanału 5n !
(private comm. Oct 2021)

Drogi Janku !

Twoi wychowankowie dostarczali Ci w czasie dekad badań wielu pozytywnych emocji naukowych.

Pamiętamy, że często były to badania inicjowane przez Ciebie !

Obiecujemy, że będziemy dalej rozwijać fizykę jądrową i dzielić się z Tobą emocjami nowych wyników.

ps. Tarczę $Z=98$ Cf do poszukiwań nowego pierwiastka un-bi-nilium w reakcji fuzji $^{50}\text{Ti} + ^{249-251}\text{Cf}$ planujemy dostarczyć do Dubnej w tym roku. Zaczniemy od poszukiwań nowych izotopów $Z=118$ Og.

Wstrząśnięte czy zmieszane?

Badanie hipotezy jądra złożonego w rozpadzie β_n ?

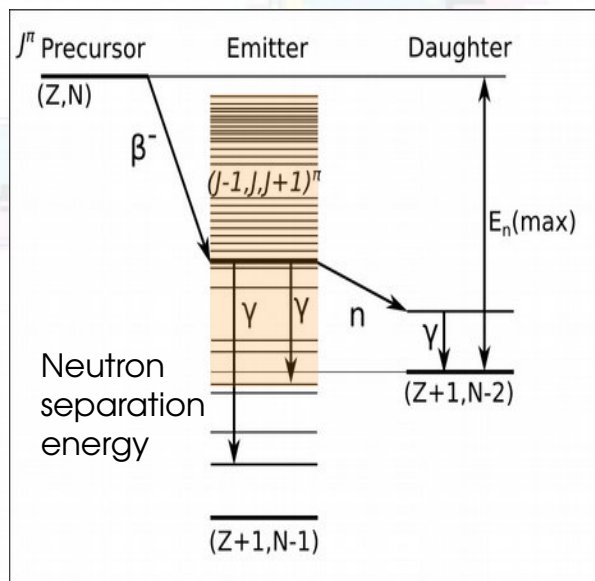
Robert Grzywacz (UTK/ORNL)



Models of beta-delayed particle emission postulate the intermediate compound nucleus stage post beta decay !

Bohr hypothesis:

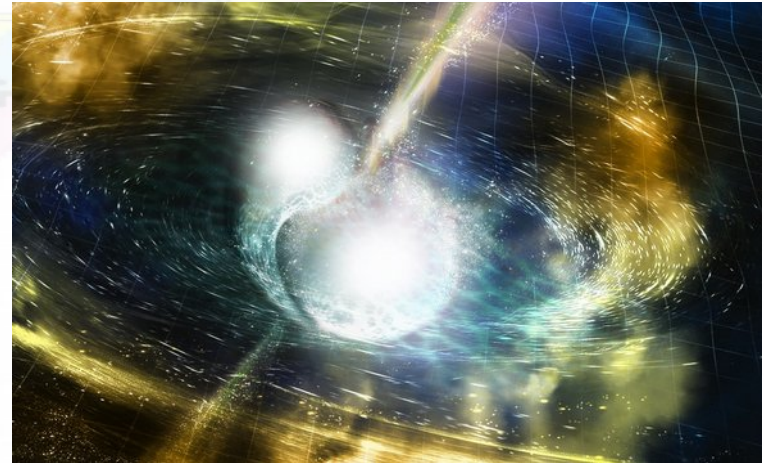
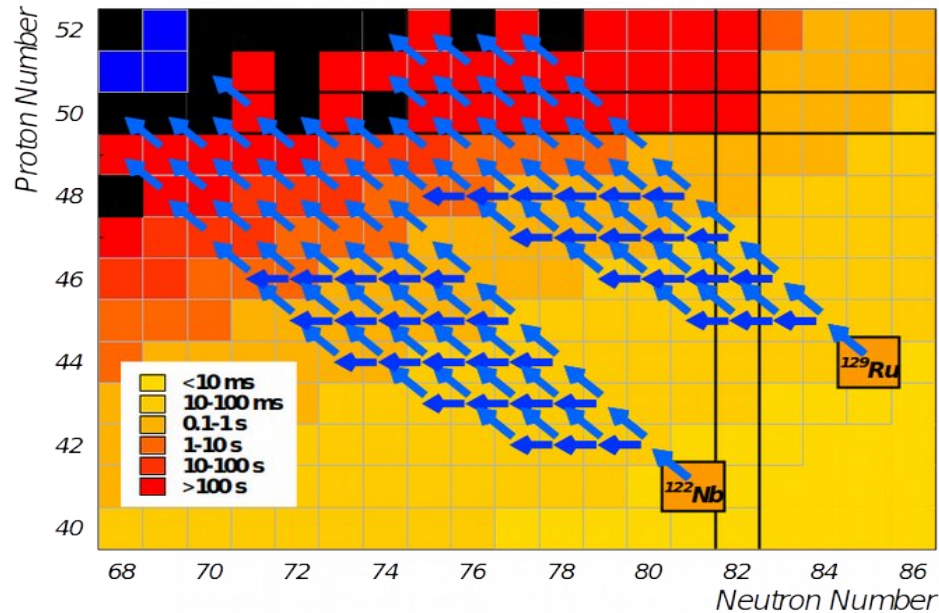
"The properties of the C. N. do not depend upon the detailed way of formation."



Inspiracja:
W ZSJ (1992)
Srodowe wykłady i seminaria w ZSJ
Praca magisterska:
Emisja protonow opoznionych w rozpadzie 101Sn

Beta delayed multi-neutron emission relevant for astrophysics

Delayed neutron emission probabilities influence the decay to stability for the r-process nuclei. Final isotopic abundances depend on P_{xn} distribution.

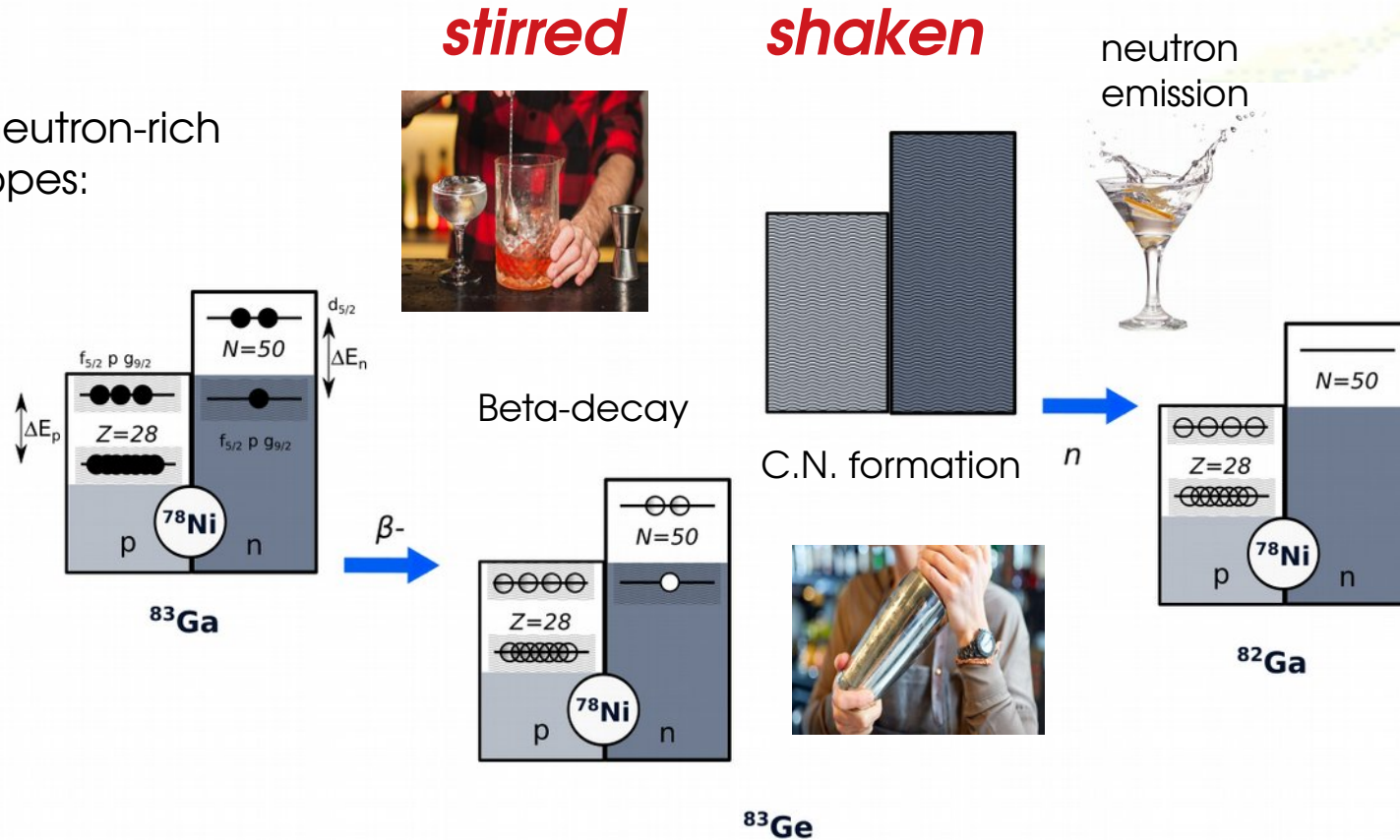


<https://aasnova.org/2017/10/16/neutron-star-merger-detected-by-many-eyes-and-ears/>

“Compound nucleus” stage in beta decay ?

Particle-hole configurations populated in GT decays of exotic nuclei must dampen to C.N.

β n-decays of neutron-rich Ga ($Z=31$) isotopes:



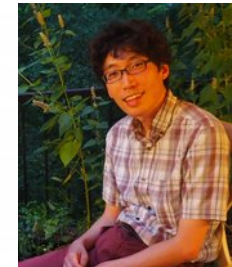
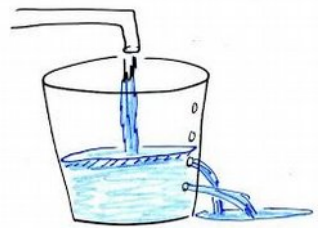
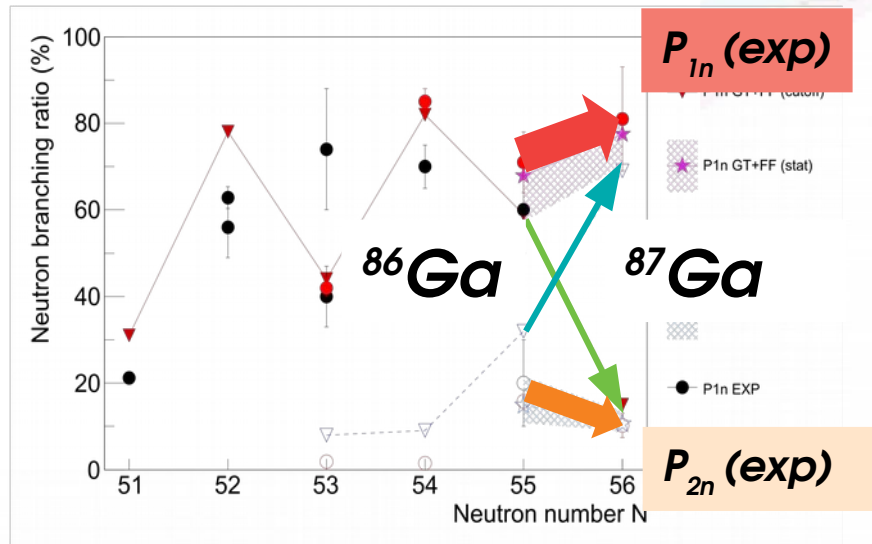
“Compound nucleus” essential to model 1n/2n/.../xn competition

Unexpectedly, 1n dominates over 2n in beta-delayed neutron emission of ^{87}Ga .

Result explained, if statistical neutron emission is considered.

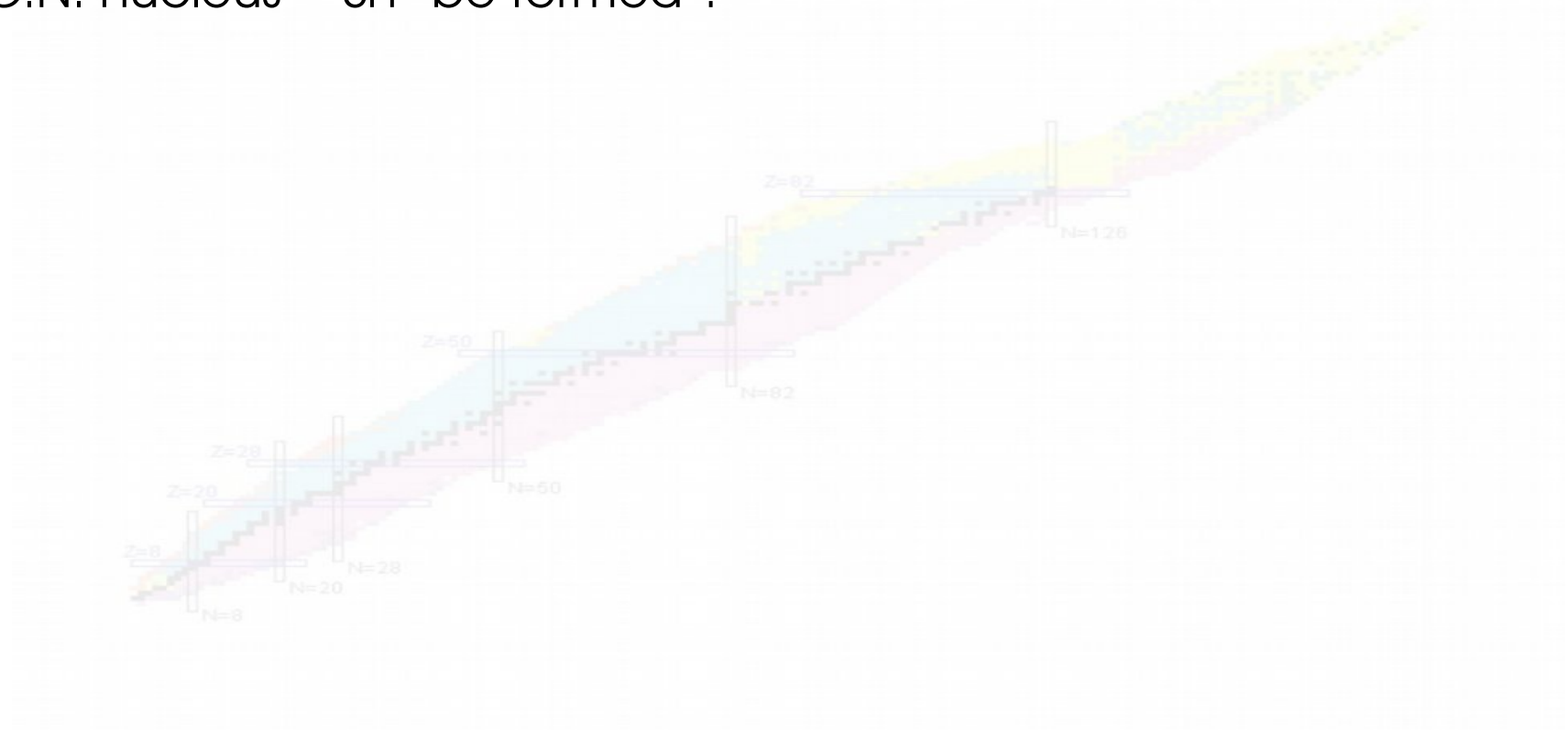


BRIKEN



Decay of $^{134,134}\text{In}$ - very selective population of GT resonances in $^{133,134}\text{Sn}$

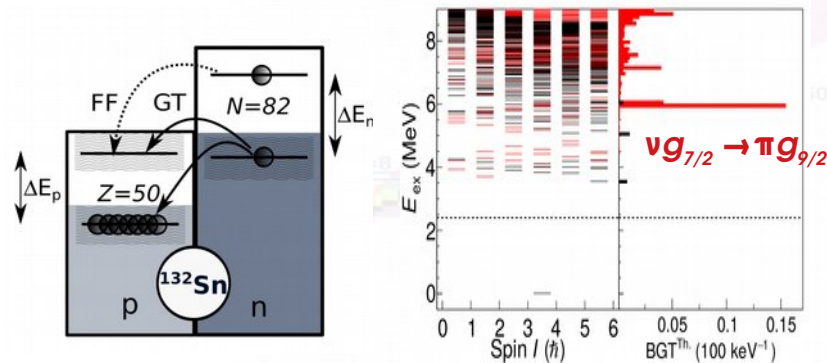
Decays in close proximity to doubly magic ^{132}Sn !
Will the C.N. nucleus $^{134}\text{Sn}^*$ be formed ?



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GT decay of $^{133,134}\text{In}$ is dominated by the $\nu g_{7/2} \rightarrow \pi g_{9/2}$ transformation.
 Localized group of unbound resonances in $^{133/134}\text{Sn}$.



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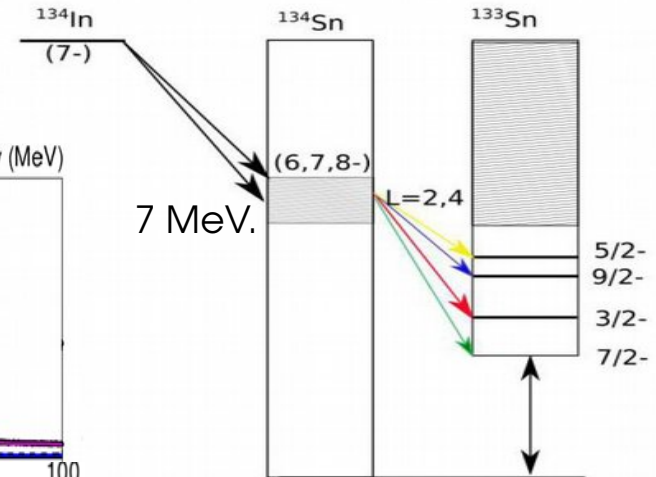
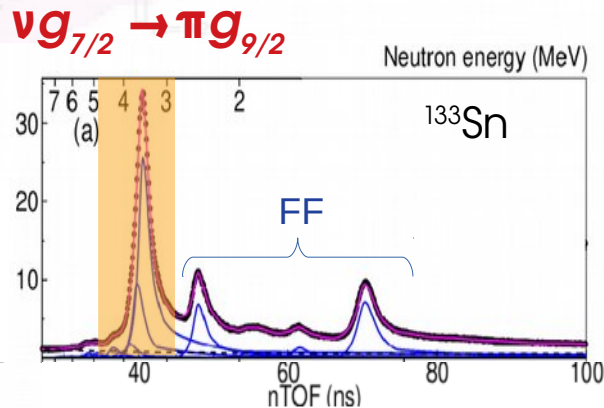
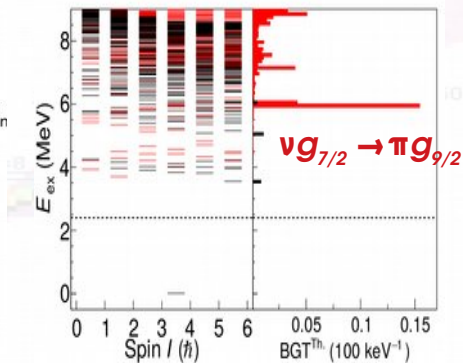
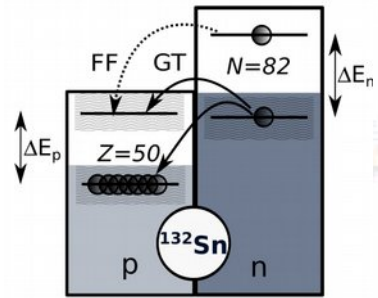
Decays in close proximity to doubly magic ^{132}Sn !
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GT decay of $^{133,134}\text{In}$ is dominated by the $\nu g_{7/2} \rightarrow \pi g_{9/2}$ transformation.
 Localized group of unbound resonances in $^{133/134}\text{Sn}$.

The neutrons emitted from $^{134}\text{Sn}^*$ feed single particle states in ^{133}Sn .

Neutron-gamma coincidences !

Experiment performed at ISOLDE with neutron time-of-flight array.

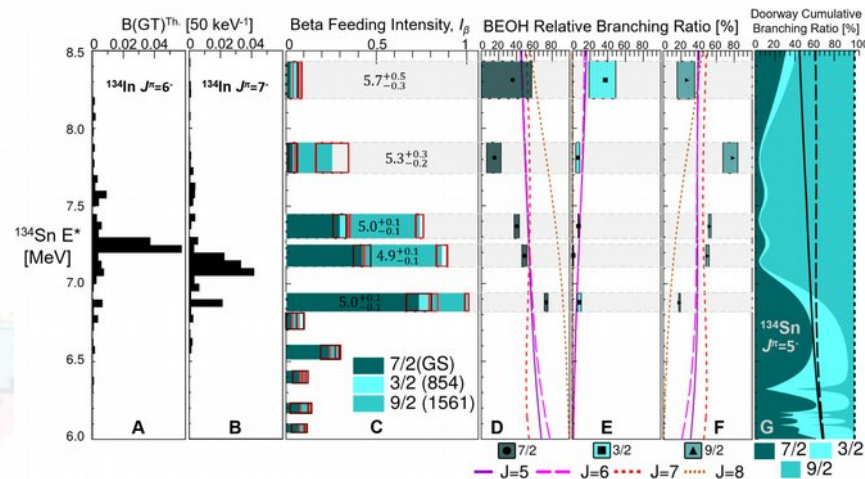
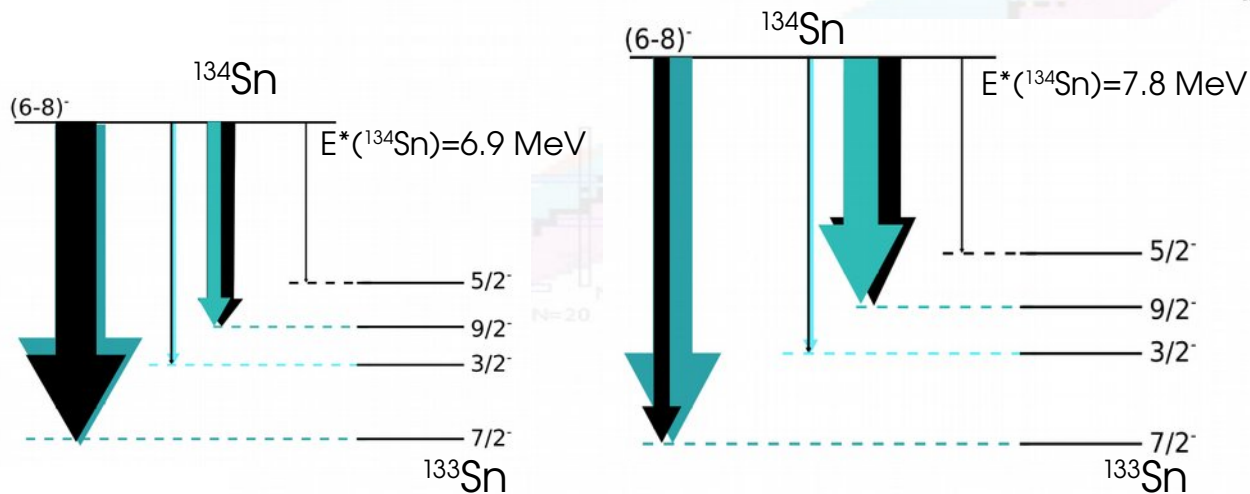


Is the decay of ^{134}In “statistical”?

The statistical model predicts neutron intensities to excited states in ^{133}Sn as a function of E^* and J^π of states in ^{134}Sn .

Measured intensity pattern disagree with the C.N. predictions for five strongest neutron emitting states.

C.N. vs. **EXP**



Experiment performed at Isolde Decay Station (CERN) analyzed by Joe Heideman:



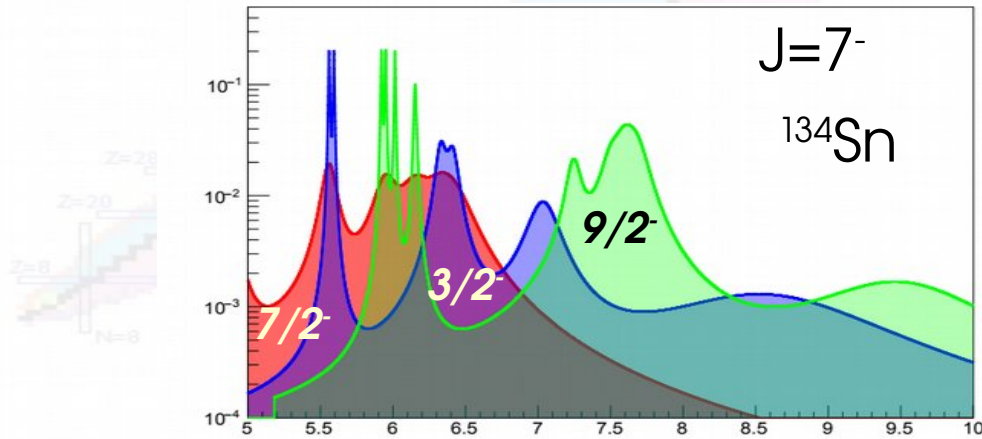
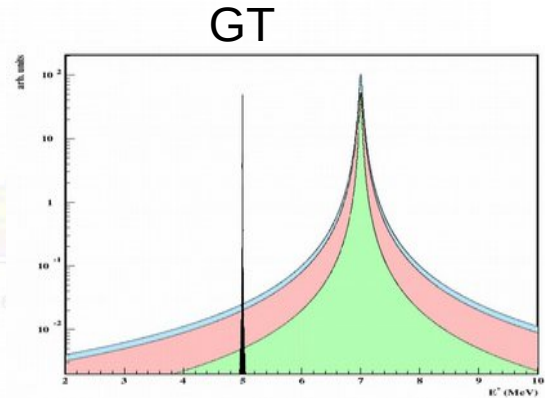
Doorway states decay hypothesis for βn

“Bucket hole” model

Direct neutron emission proceeds through the tails of broad resonances in ^{134}Sn , with strong overlap with excited states in ^{133}Sn .

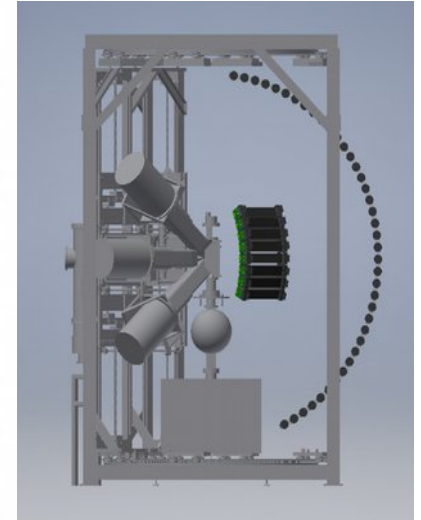
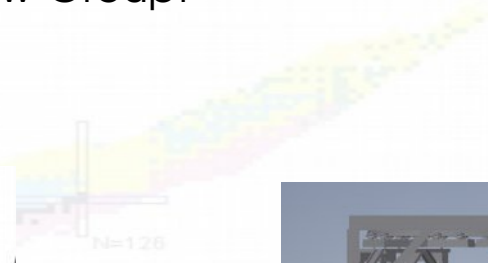
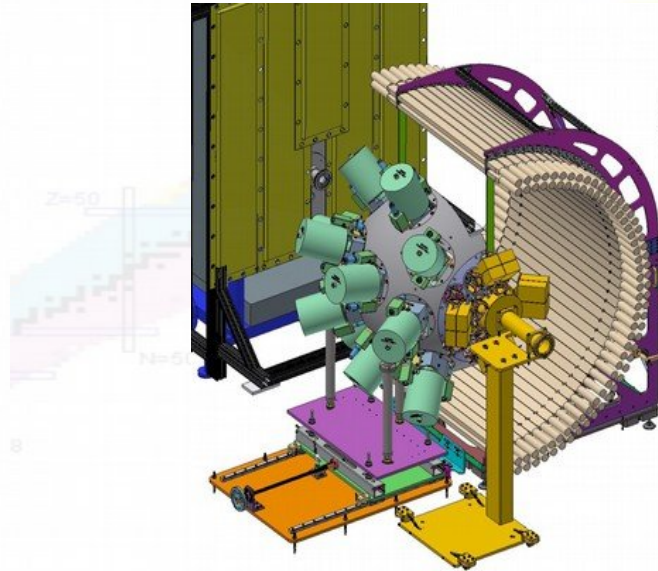
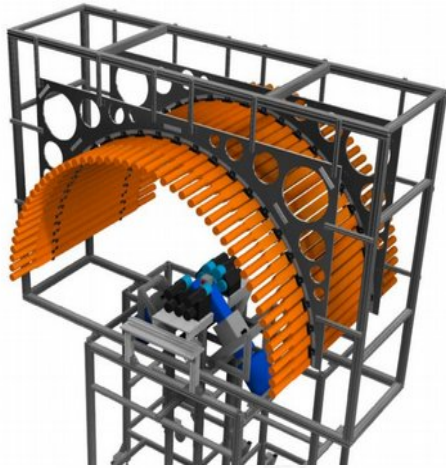
The decay model uses shell-model spectroscopic factors and particle emission probabilities from optical model.

The fluctuating nature of neutron emission intensities is related to the distribution of resonances in ^{134}Sn .



Is this effect valid only for ^{134}In ? Close to magic numbers ?

Experimental search for the non-statistical effect in other nuclei at RIKEN, FRIB Decay Station and Isolde Decay Station with strong involvement of the Warsaw Group.



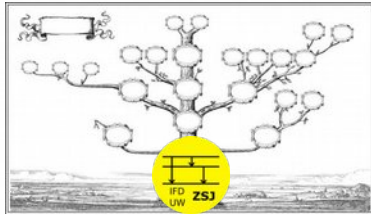
Happy Bir(Th)day !

ca 1994



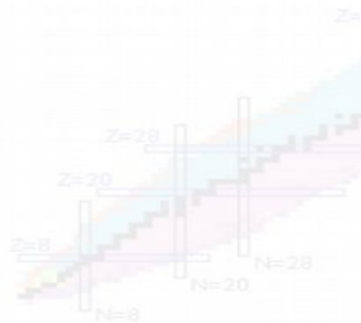
.. from the scientific great-grandchildren of Prof. Jan Żylicz !

The Knoxville branch:

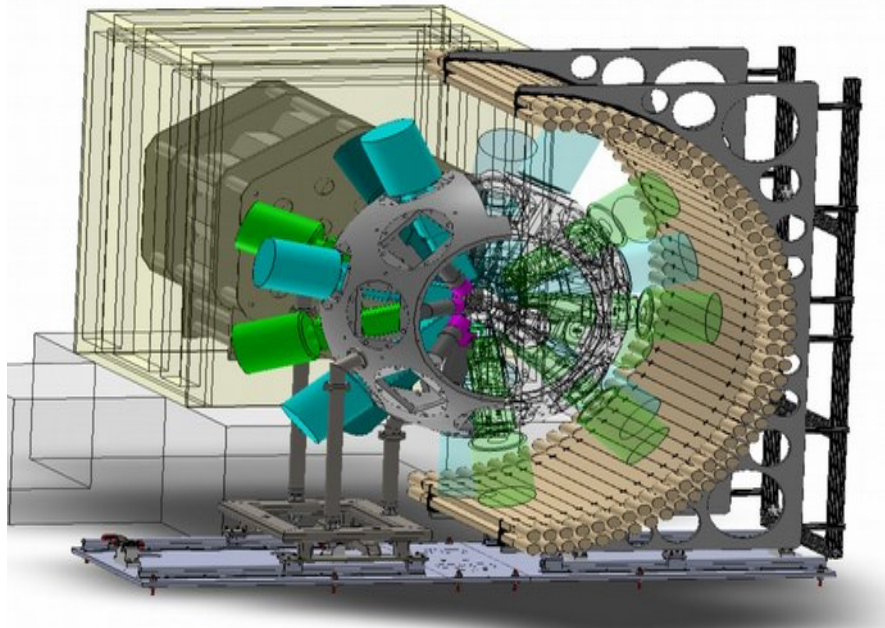


2022

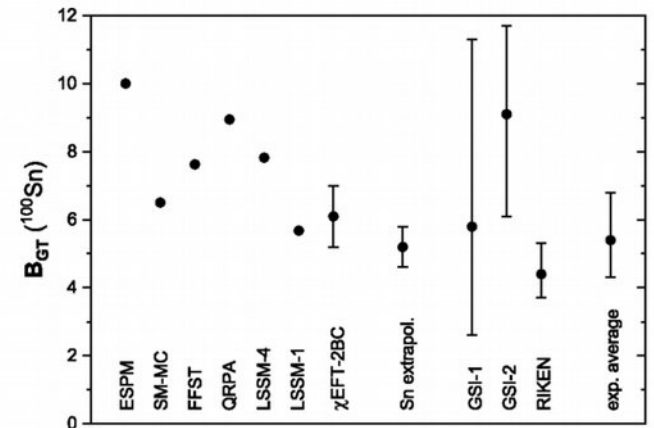
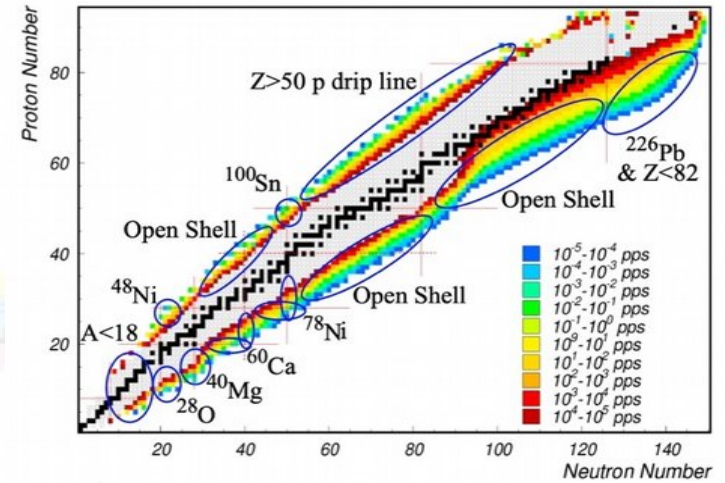
... and the Grzywacz family !



We hope to meet everyone at FRIB
for the MTAS ^{100}Sn experiment and more ...

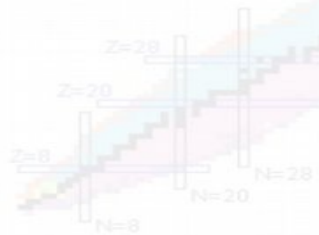


FRIB Decay Station Initiator



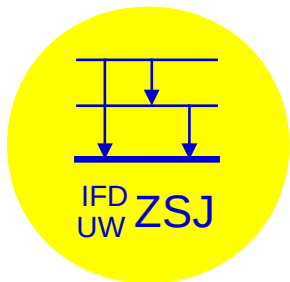
First experimental studies of ^{100}Sn required a strong international and multi-institutional collaborative effort using advanced detection systems

^{100}Sn experiment
preparation,
30 years ago...



Stan jednocząstkowy $\nu_{13/2}$

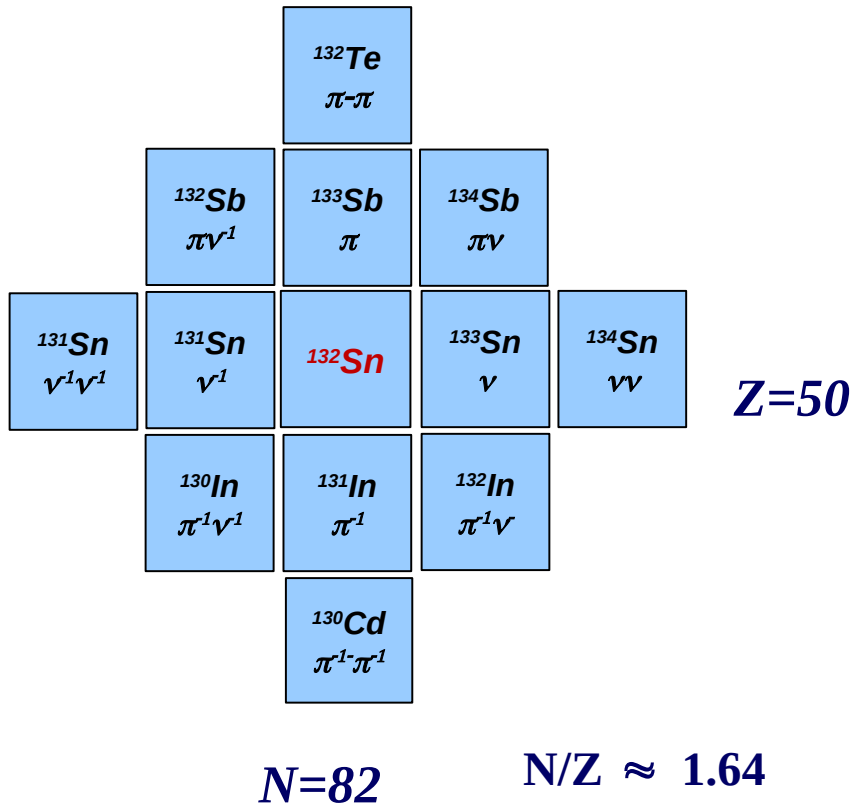
Agnieszka Korgul



ZAKŁAD FIZYKI JĄDROWEJ
UNIwersytet WARSZAWSKI

Obszar podwójnie magicznej ^{132}Sn

^{130}Te
 ^{123}Sb
 ^{124}Sn
 ^{115}In
 ^{116}Cd



Rozszczepienie:

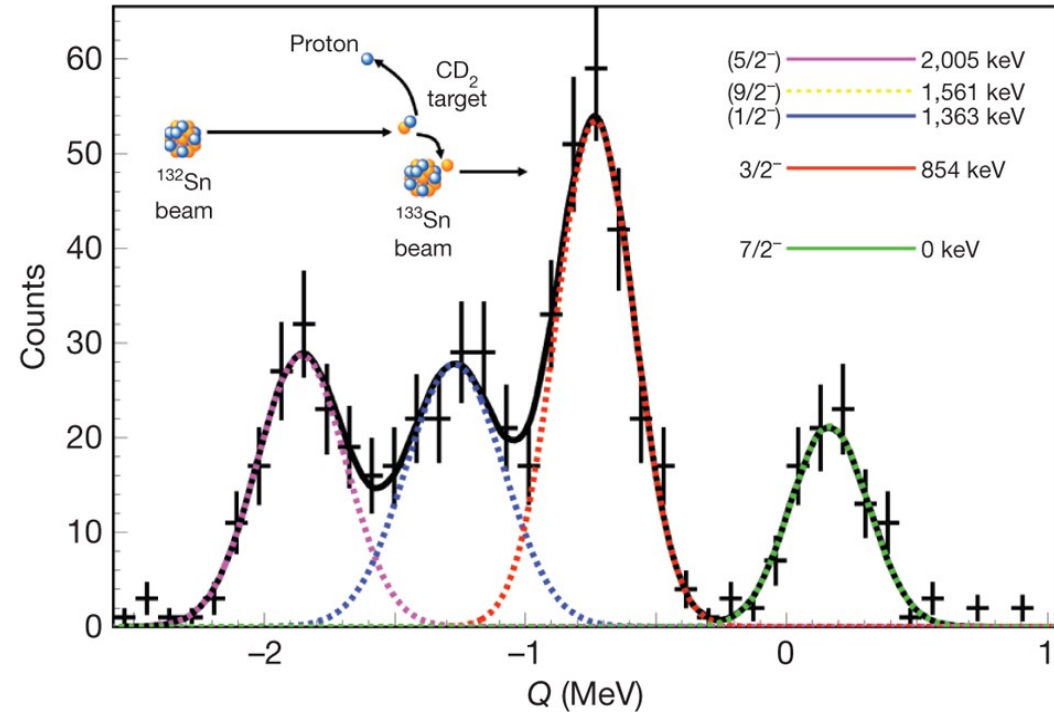
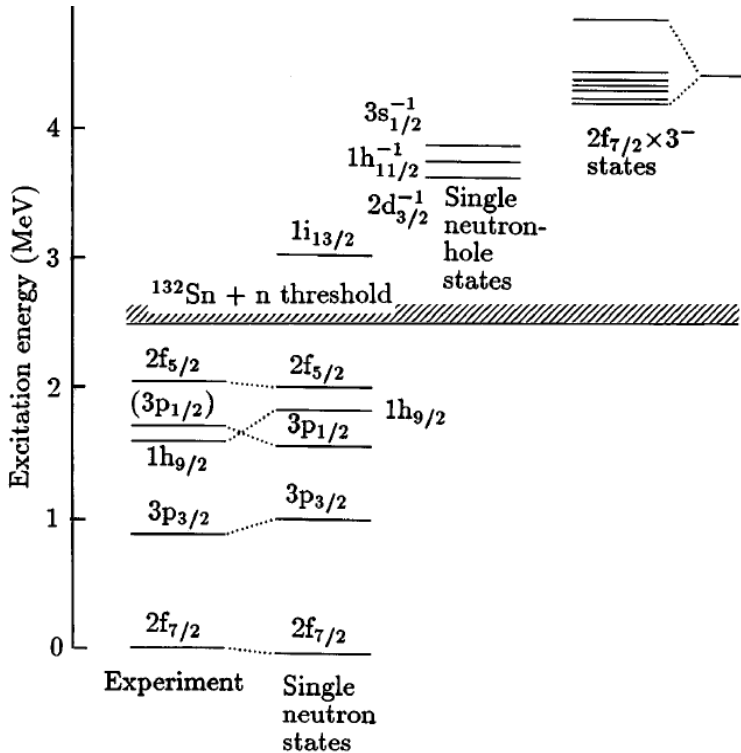
^{248}Cm , ^{252}Cf , ^{238}U

Przemiana β^-

		Q_β (keV)
^{135}In :	$(50) - 1, (82) + 4$	14100(400)
^{134}In :	$(50) - 1, (82) + 3$	14770(300)
^{133}In :	$(50) - 1, (82) + 2$	13410(200)

M. Wang *et al.*, Chin. Phys. C 41, 030003 (2017).

Stany jednocząstkowe w ^{133}Sn – status badań



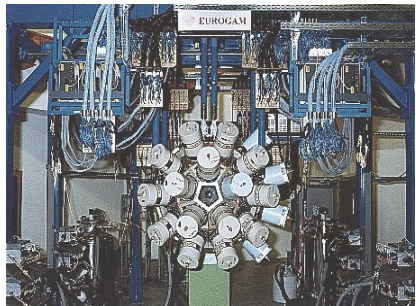
P. Hoff *et al.* PRL 77, 1020 (1996)

K. Jones *et al.* Nature 465, 454-457 (2010)

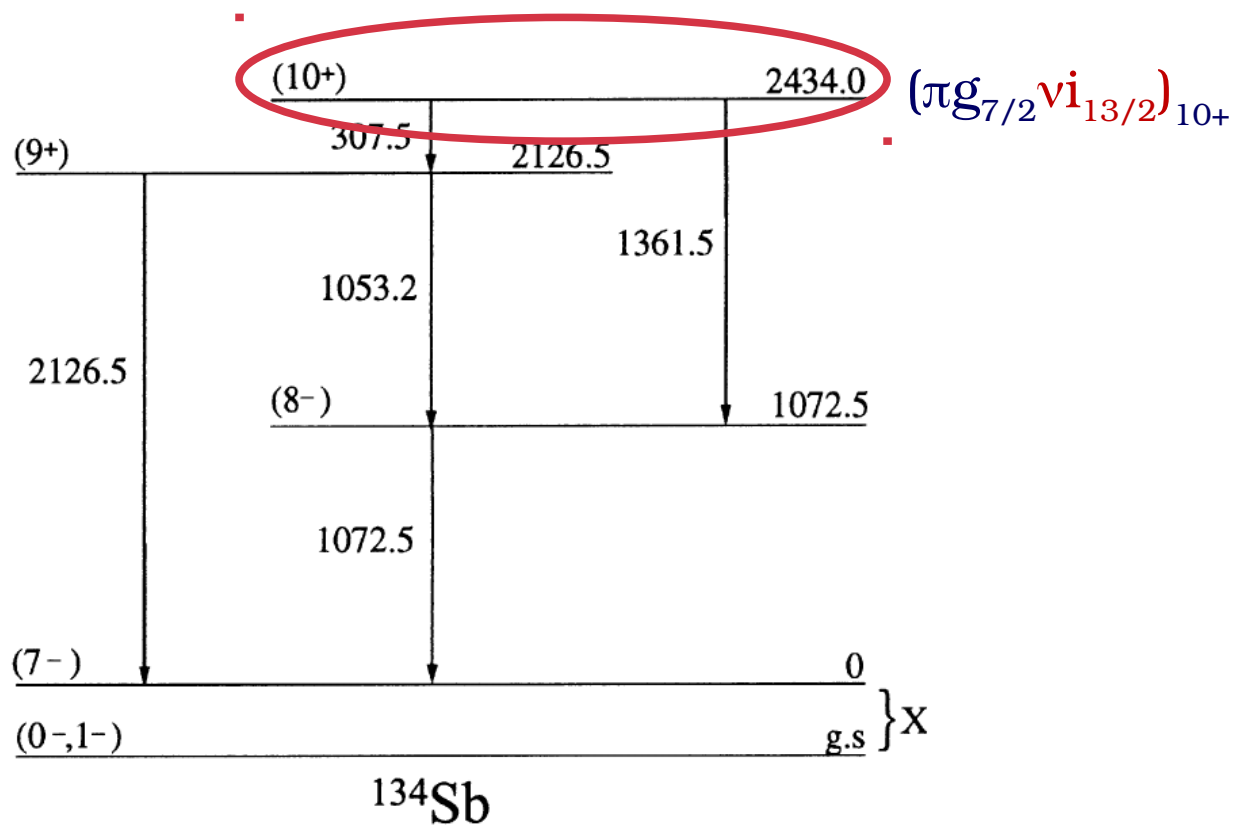


energia $\nu_{i_{13/2}}$ - nieznana

^{134}Sb – neutron + proton walencyjny



rozszczerzenie ^{248}Cm

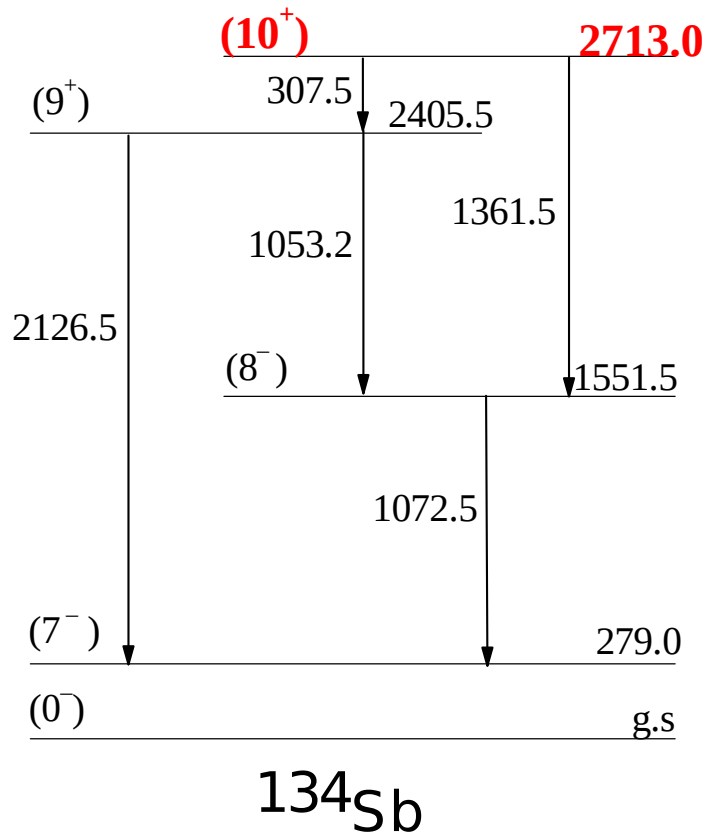


$$E(10^+) = E(\pi g_{7/2}) + E(\nu i_{13/2}) + E_{\text{int}}$$

$$E(\nu i_{13/2}) = 2700(200) \text{ keV}$$

W. Urban, W. Kurcewicz, A. Nowak *et al.* EPJ A 5, 239 (1999)

^{134}Sb – neutron + proton walencyjny

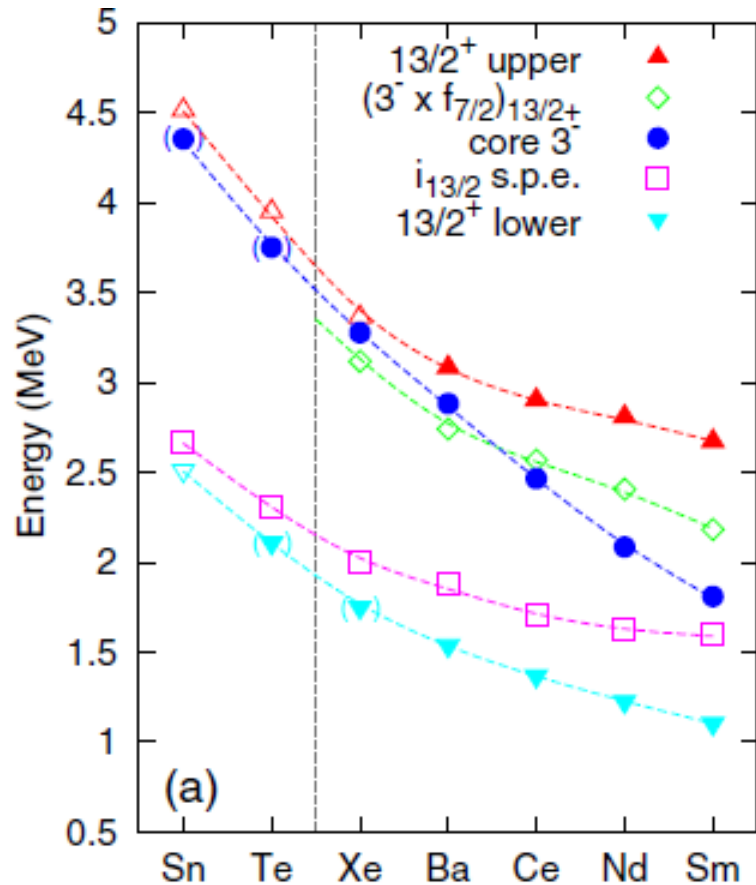


$$(\pi g_{7/2} \nu i_{13/2})_{10^+}$$

$$E(10^+) = E(\pi g_{7/2}) + E(\nu i_{13/2}) + E_{\text{int}}$$

$^{208}\text{Pb} \rightarrow ^{132}\text{Sn}$			^{132}Sn		
Configuration	V_0	V_1	Configuration	V_2	ΔV
$(\pi h_{9/2} \nu j_{15/2})_{12^+}$	-621	-723	$(\pi g_{7/2} \nu i_{13/2})_{10^+}$		
$(\pi h_{9/2} \nu g_{9/2})_{9^-}$	-396	-461	$(\pi g_{7/2} \nu f_{7/2})_{7^-}$	-488	-27
$(\pi h_{9/2} \nu i_{11/2})_{10^-}$	-776	-903	$(\pi g_{7/2} \nu h_{9/2})_{8^-}$	-976	-73
$(\pi i_{13/2} \nu g_{9/2})_{11^+}$	-960	-1117	$(\pi h_{11/2} \nu f_{7/2})_{9^+}$	-1154	-37
$(\nu g_{9/2} \nu i_{11/2})_{10^+}$	-221	-257	$(\nu f_{7/2} \nu h_{9/2})_{8^+}$	-280	-23
$(\pi h_{9/2} \pi f_{7/2})_{8^+}$	+107	+125	$(\pi g_{7/2} \pi d_{5/2})_{6^+}$	+201	+76

^{133}Sn – energia poziomu $\nu i_{13/2}$

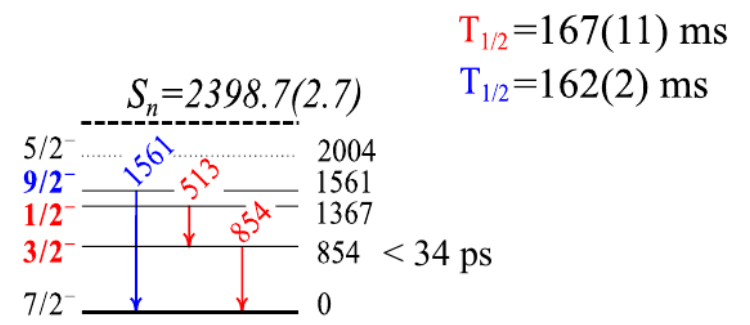
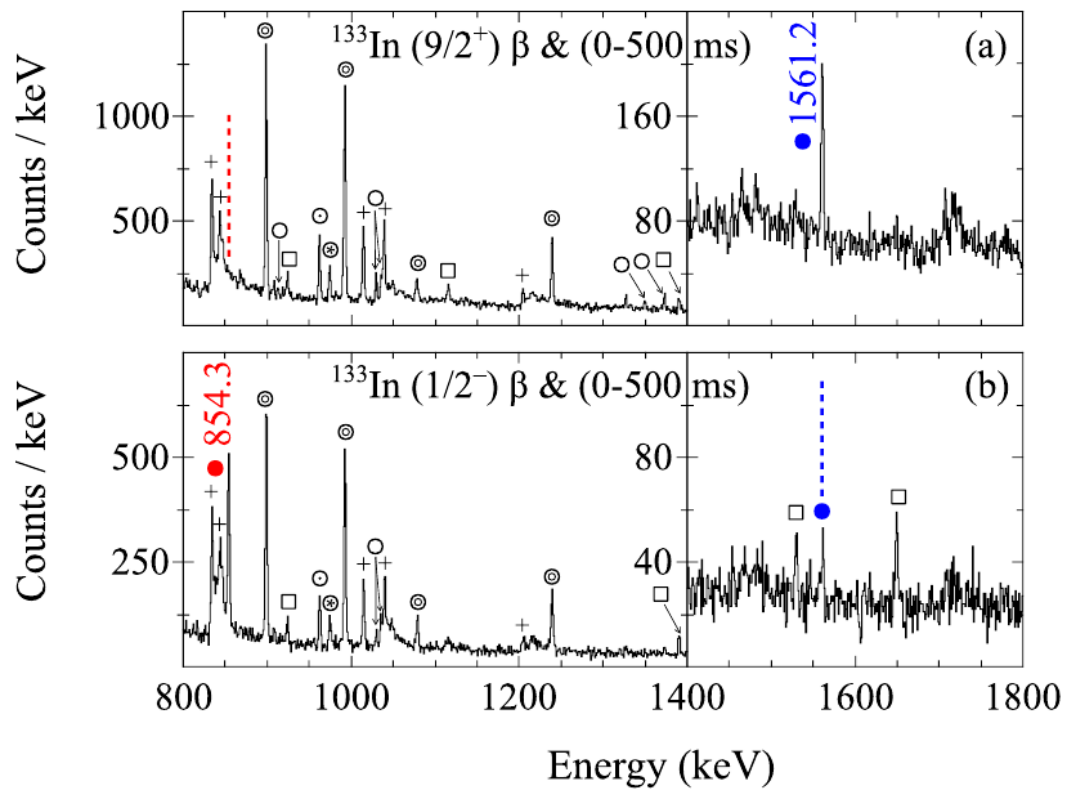
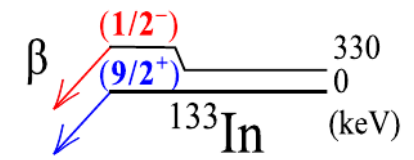


$$\frac{13/2^+}{\text{---}} \quad 3^- \times 2f_{7/2}$$

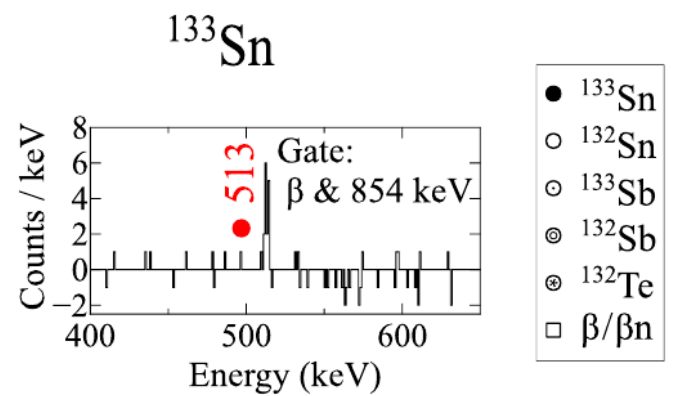
$$\frac{13/2^+}{\text{---}} \quad i_{13/2}$$

$$E_{13/2^+} = 2511(80) \text{ keV}$$

Eksperyment ISOLDE: rozpad β ^{133}In



$T_{1/2} = 167(11)$ ms
 $T_{1/2} = 162(2)$ ms



M. Piersa, A.K. *et al.* PRC 99, 024304 (2019)

Eksperyment ISOLDE: rozpad β ^{134}In

Energia poziomu $13/2^+$ vi $_{13/2}^+$:

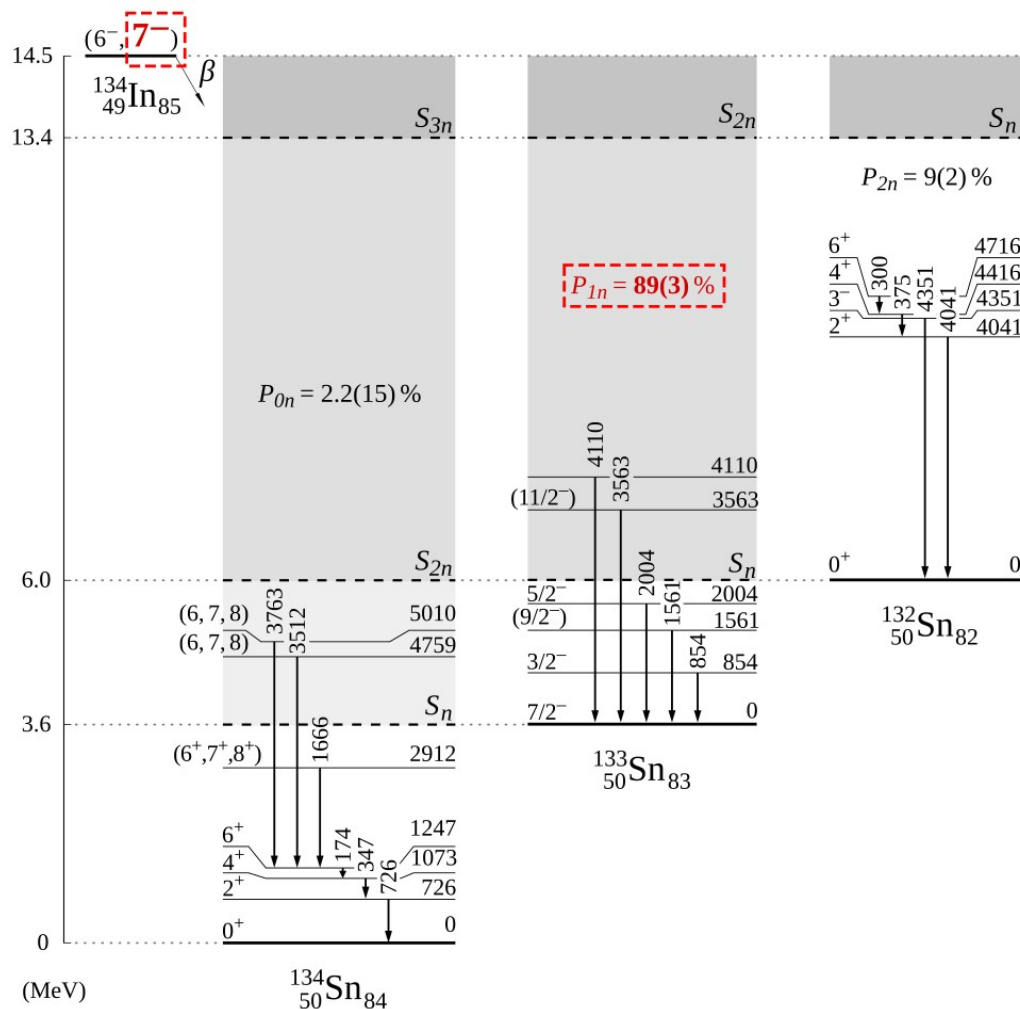
2511(80) keV

A.K. et al. PRC 91, 027303 (2015)

2360 – 2600 keV

$N=83$ ^{137}Xe ($13/2^+_1$, $13/2^+_2$)

W. Reviol et al. PRC 94,034309 (2016)



M. Piersa-Siłkowska, A.K. et al. PRC 104, 044328 (2021)

Eksperyment ISOLDE: rozpad β ^{134}In i ^{135}In

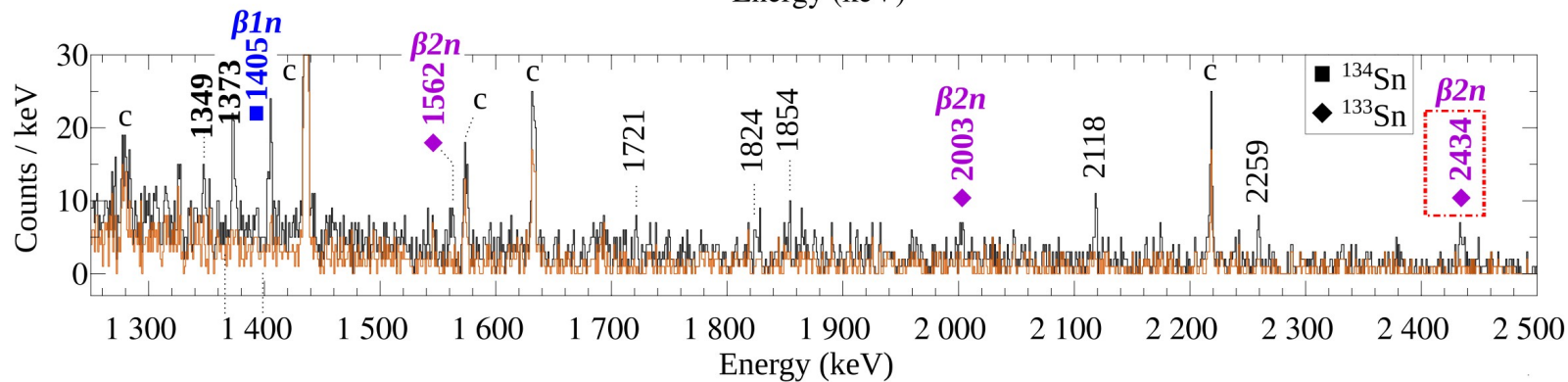
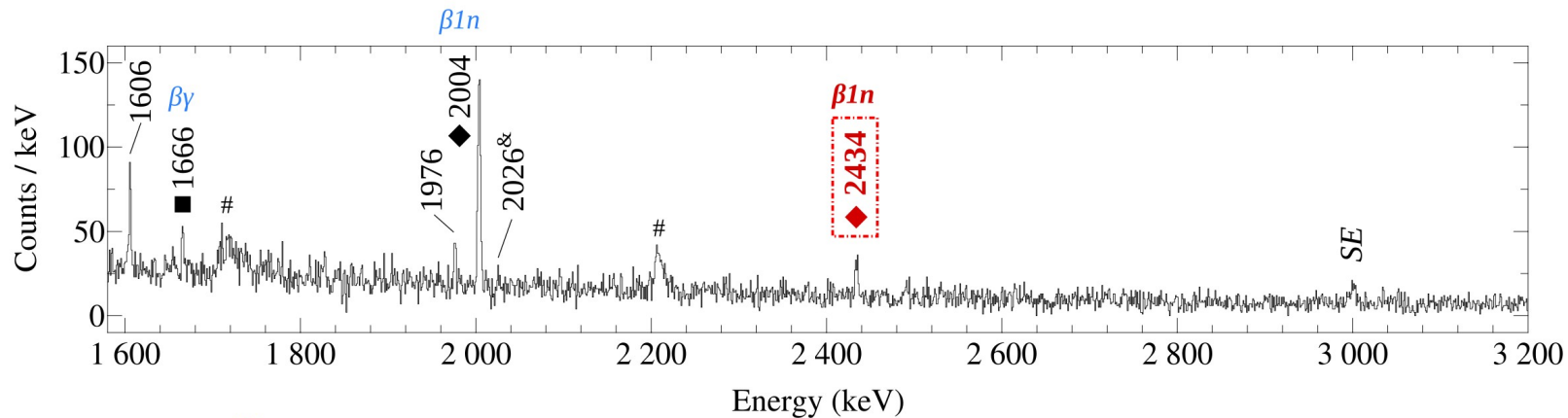
Energia poziomu $13/2^+$ $\nu_{i13/2}$

- 2511(80) keV

A.K. *et al.* PRC 91, 027303 (2015)

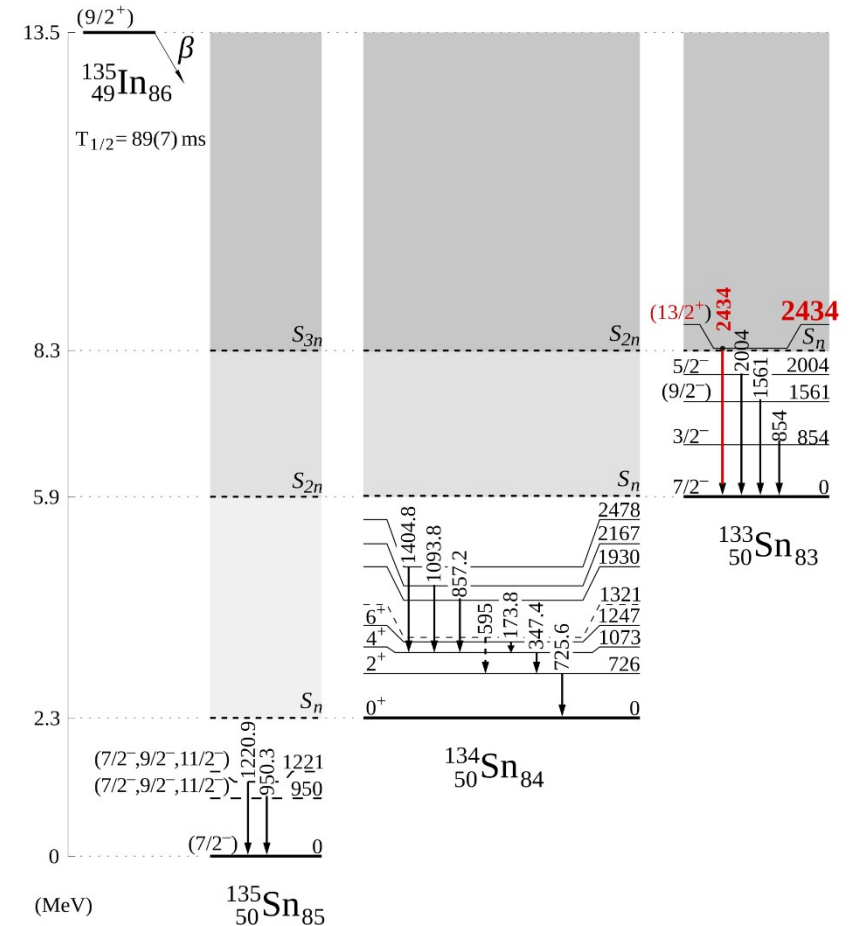
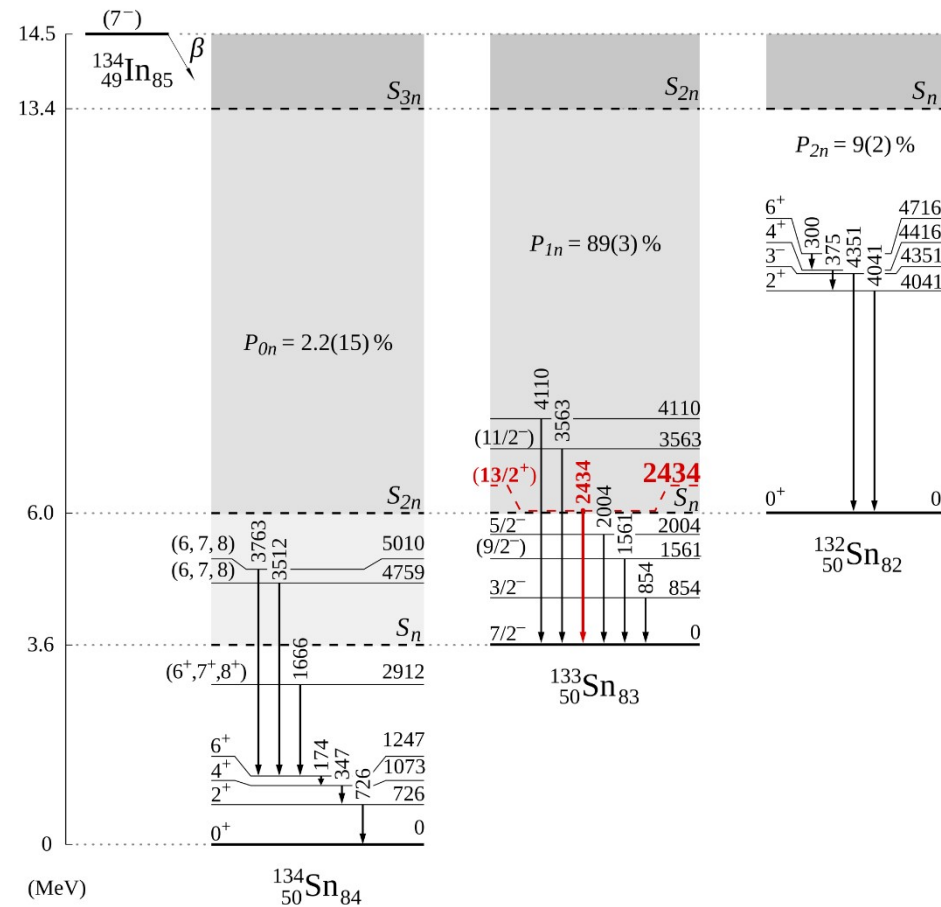
- 2360 – 2600 keV

W. Reviol *et al.* PRC 94,034309 (2016)



M. Piersa-Siłkowska, A.K. *et al.* PRC 104, 044328 (2021)

Eksperyment ISOLDE: rozpad β ^{134}In oraz ^{135}In



M. Piersa-Siłkowska, A.K. *et al.* PRC 104, 044328 (2021)

Podsumowanie oraz plany

Przewidywana energia poziomu $13/2^+$ $\nu i_{13/2}$

2511(80) keV *A.K. et al. PRC 91, 027303 (2015)* 2360 – 2600 keV *W. Reviol et al. PRC 94,034309 (2016)*

Obserwacja $E_\nu = 2434$ keV: ^{134}In (βn) oraz ^{135}In ($\beta 2n$)

- poziom $13/2^+$ w ^{133}Sn

Zaakceptowane 3 eksperymenty ISOLDE

A. Fijałkowska, R. Grzywacz, Z. Janas, M. Karny, A. Korgul, C. Mazzocchi, K. Miernik, M. Piersa-Siłkowska, K. P. Rykaczewski

- *Total absorption spectroscopy of neutron-rich indium isotopes beyond $N=82$*
- *Beta-delay neutron emission of ^{134}In and search for $i_{13/2}$ single particle neutron state in ^{133}Sn*
- *Neutron emission from unbound states in ^{135}Sn*

Dziękujemy i ...



Nadsubtelności ^{229}Th

PHYSICAL REVIEW C

VOLUME 57, NUMBER 6

JUNE 1998

Rates of transitions between the hyperfine-splitting components of the ground-state and the 3.5 eV isomer in $^{229}\text{Th}^{89+}$

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(Received 14 January 1998)

PHYSICAL REVIEW C, VOLUME 64, 064301

Nuclear-spin mixing oscillations in $^{229}\text{Th}^{89+}$

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J. Żylicz and M. Pfützner

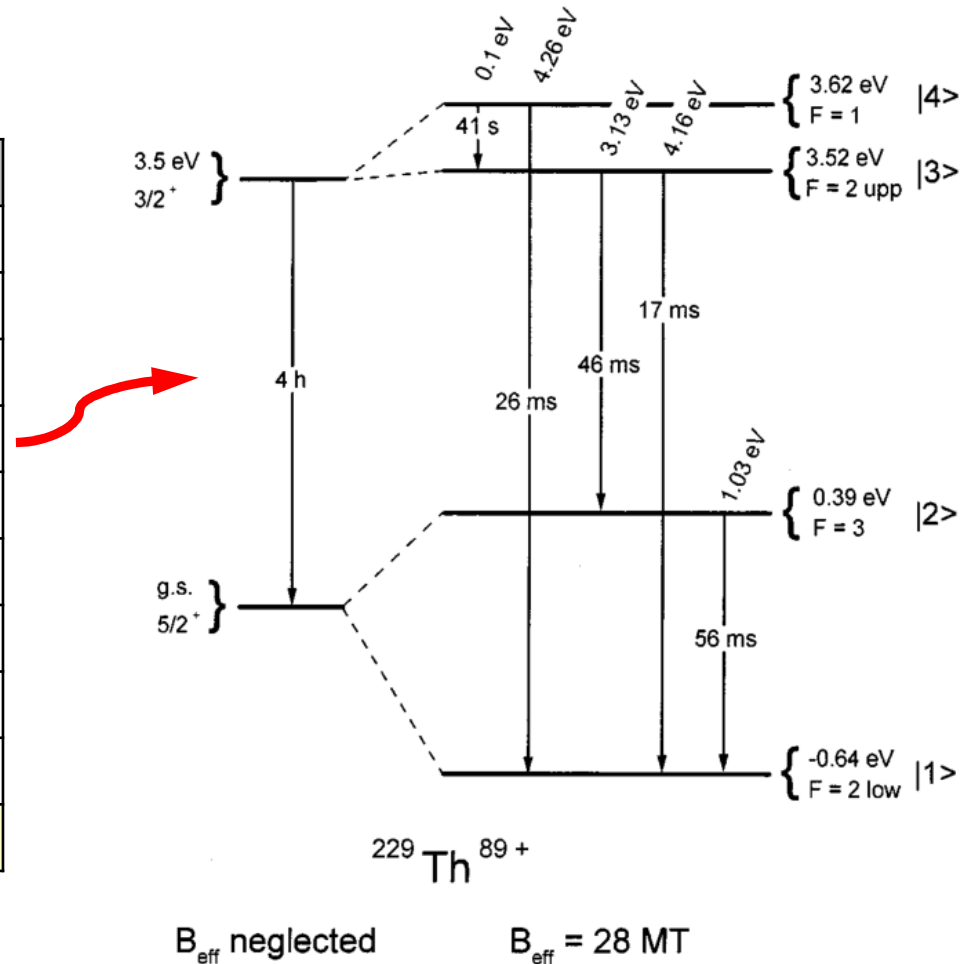
Institute of Experimental Physics, Warsaw University, 00-681 Warszawa, Poland

(Received 12 February 2001; published 5 November 2001)

Izomer w ^{229}Th

Energia izomeru ^{229m}Th

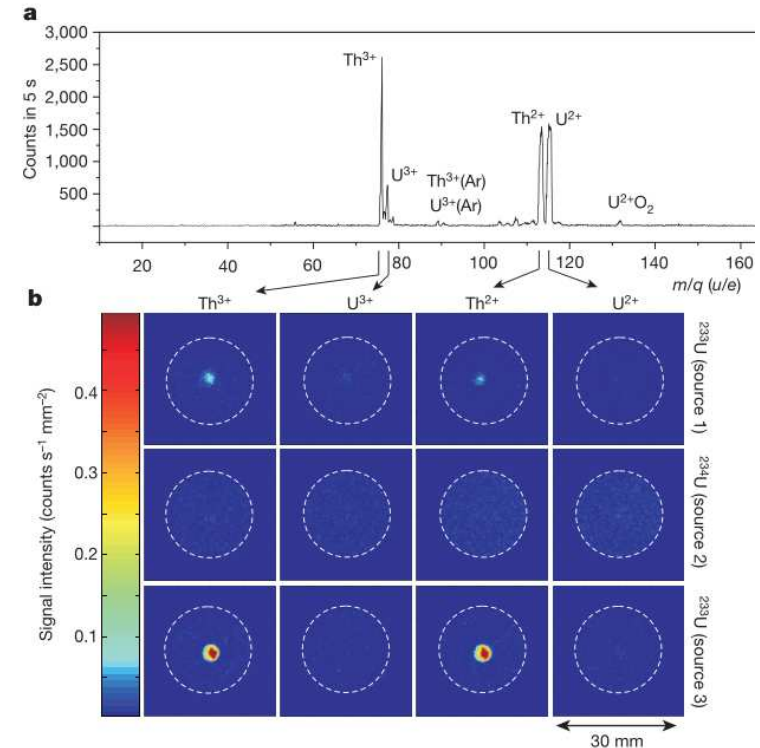
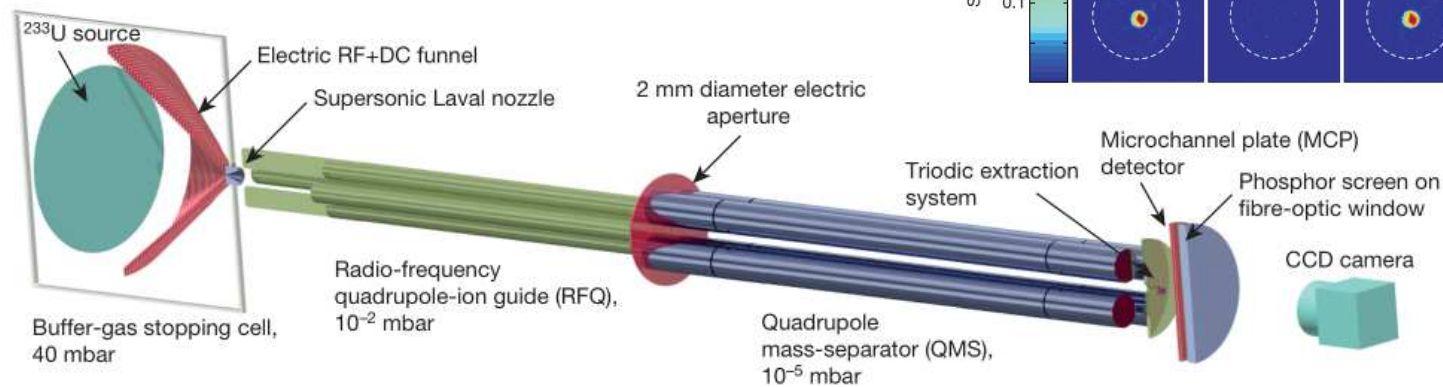
Rok	$E(3/2^+)$ [eV]	Autorzy
1976	< 100	Kroger, Reich
1990	-1 ± 4	Reich, Helmer
1993	4.5 ± 1	Reich, Helmer
1994	3.5 ± 1	Helmer, Reich
2007	7.6 ± 0.5	Beck et al.
2009	7.8 ± 0.5	Beck et al.
2016	$(6.3 - 18.3)$	V.d. Wense et al.
2019	8.28 ± 0.17	Seiferle et al.
2020	8.10 ± 0.17	Sikorsky et al.
2020	8.12 ± 0.11	Wense, Seiferle



Pierwsza obserwacja

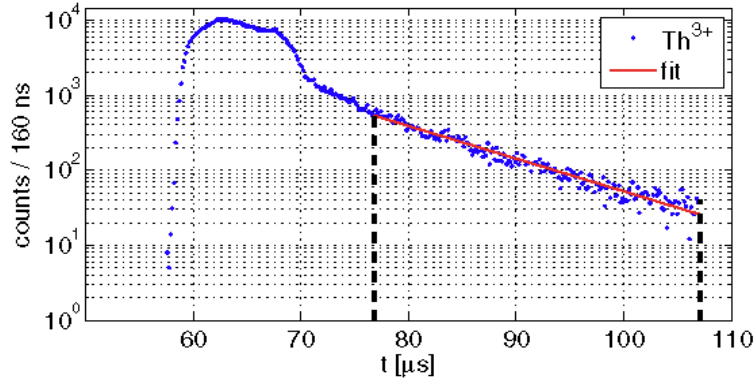
Bezpośrednia obserwacja rozpadu izomeru w ^{229}Th poprzez pomiar elektronów konwersji

- Energia izomeru jest między pierwszym a trzecim potencjałem jonizacyjnym toru:
 - ➔ $6.3 \text{ eV} < E < 18.3 \text{ eV}$



v.d.Wense et al. Nature 533 (2016) 47

Czas życia i energia

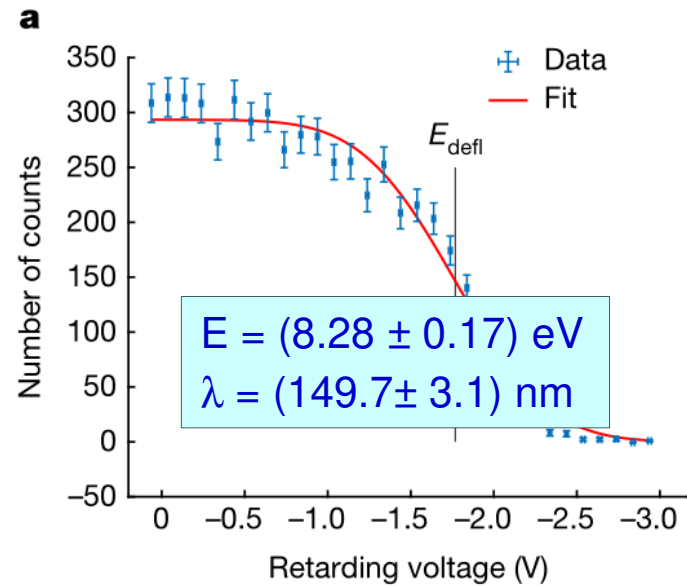
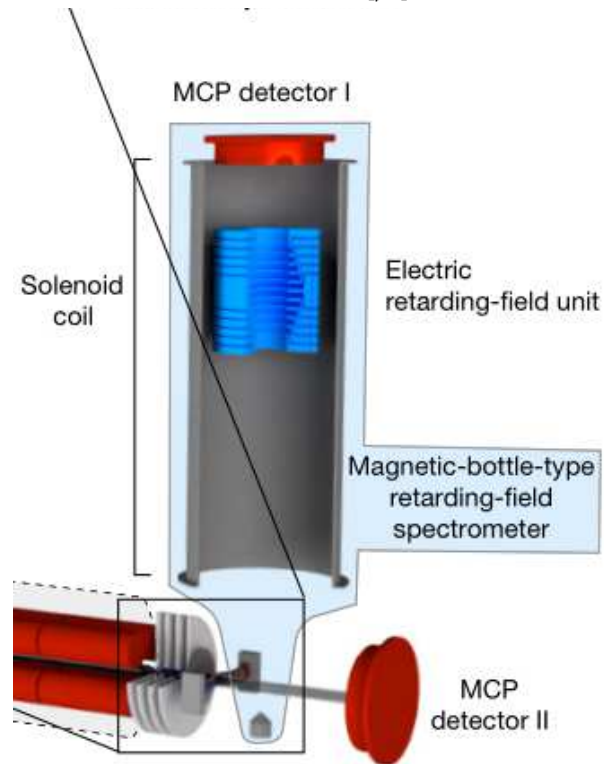


Seiferle, Wense, Thirof,
PRL 118 (2017) 042501

Okres półrozpadu obojętnego

^{229m}Th : $T_{1/2} = 7 \pm 1 \mu\text{s}$

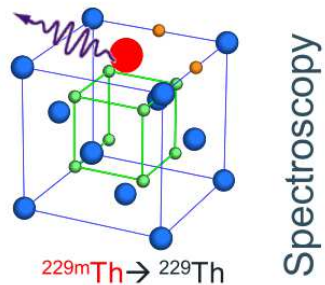
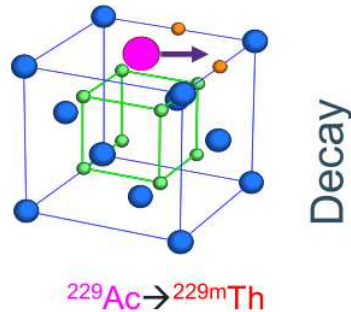
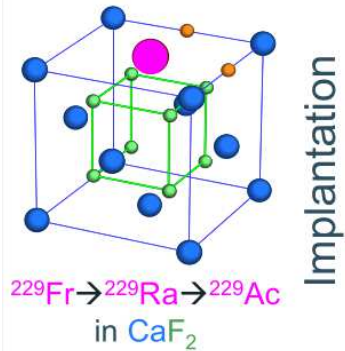
→ współczynnik konwersji
wewnętrznej $\approx 10^9$!



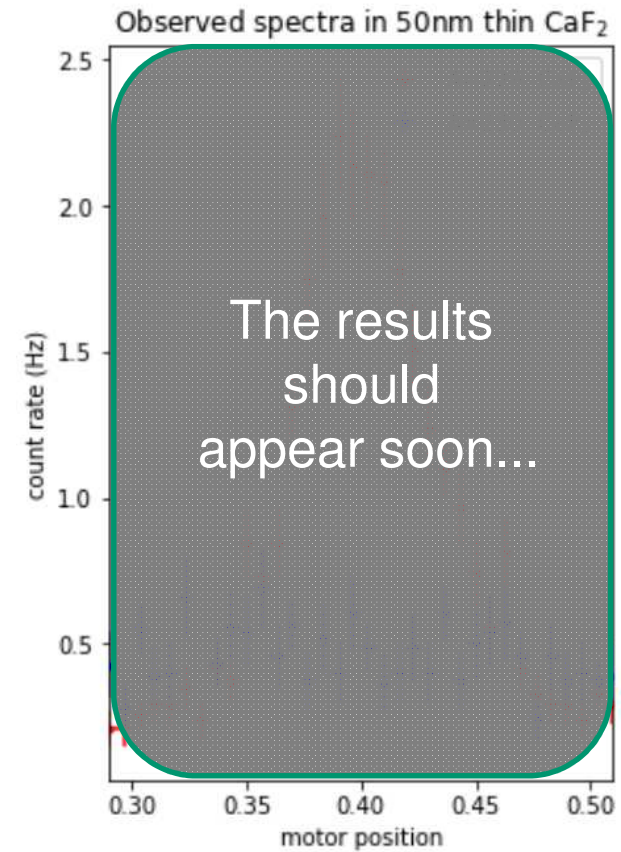
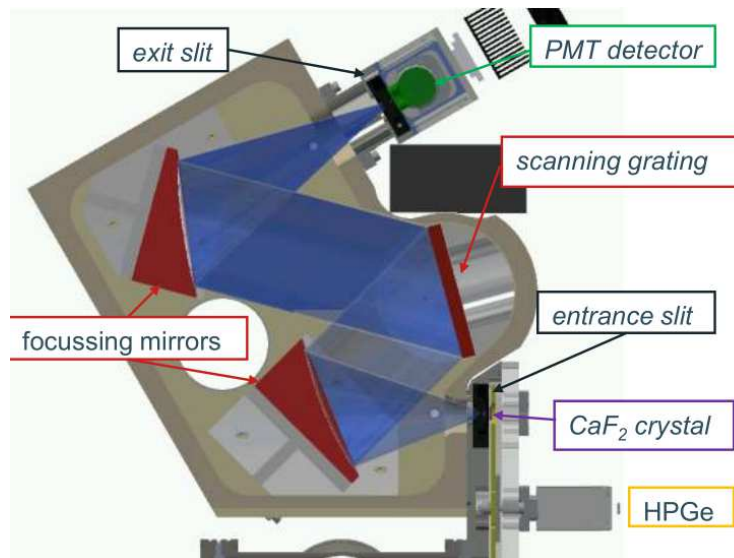
Seiferle et al. Nature 573 (2019) 243

Spektroskopia VUV w ISOLDE

Wstępne wyniki zaprezentowane na ISOLDE Workshop, 15/12/2021



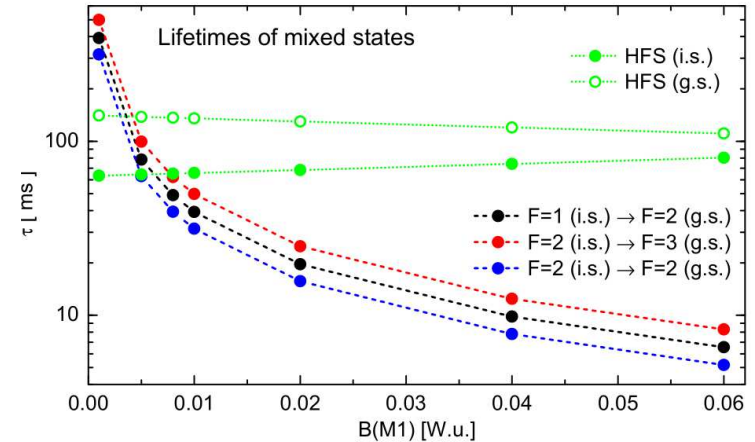
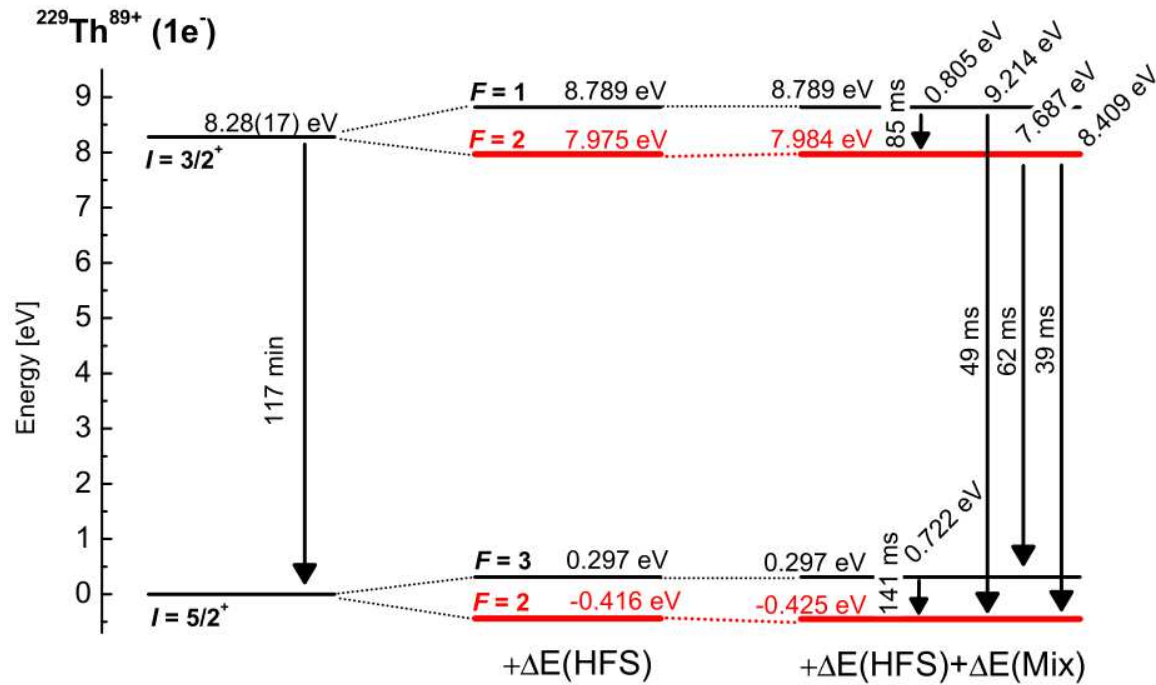
Jony $^{229}\text{Fr}/^{229}\text{Ra}$ implantowane w krysztaly CaF_2 i MgF_2



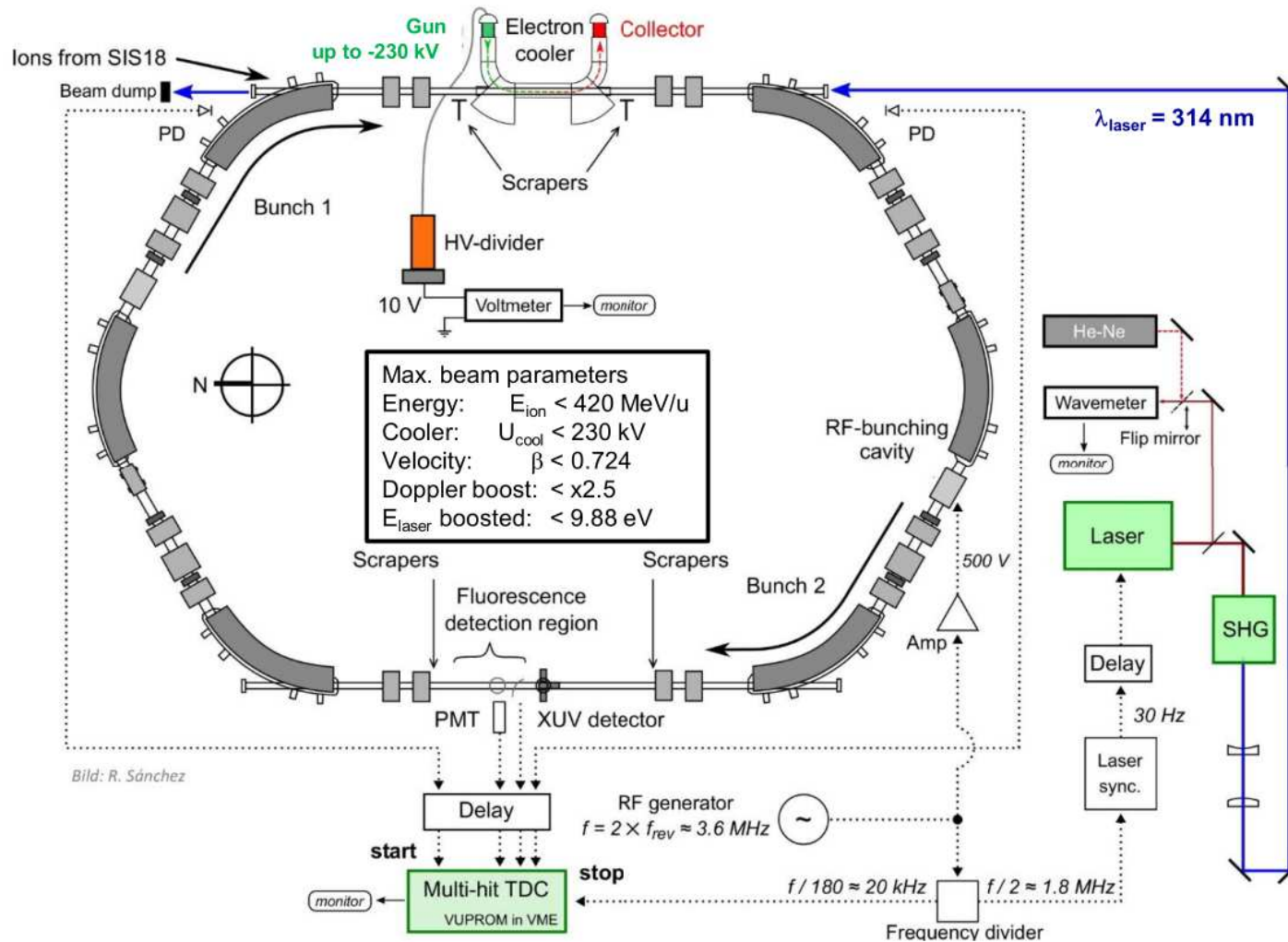
Eksperyment w GSI

Proposal: Nuclear Hyperfine Mixing in $^{229}\text{Th}^{89+}$ - Storage Ring Studies of an Orders-Of-Magnitude Accelerated Nuclear Decay

C. Brandau^{1,2*}, D. Banaś³, J. Glorius², A. Gumberidze², S. Hagmann², P.M. Hillenbrand², V. Hannen⁴, C. Heyl^{2,5,6,7}, P. Indelicato⁸, C. Kozhuharov², M. Lestinsky², Yu.A. Litvinov², I.D. Moore⁹, A. Müller¹⁰, R. Müller^{11,12}, W. Nörtershäuser^{13,14}, M. Pfützner¹⁵, R. Röhlsberger^{2,5,6}, R. Sánchez², S. Schippers¹, M. Steck², Th. Stöhlker^{2,5,6}, A. Surzhykov^{11,12}, P. Thirolf¹⁶, M. Trassinelli¹⁷, C. Weinheimer⁴, D. Winters², within the SPARC collaboration



Eksperyment w GSI



Eksperyment ma się odbyć w kwietniu 2022

Drogi Janku

życzymy Ci wielu lat
w dobrym zdrowiu!