Beta-delayed neutron emission for very neutron-rich nuclei

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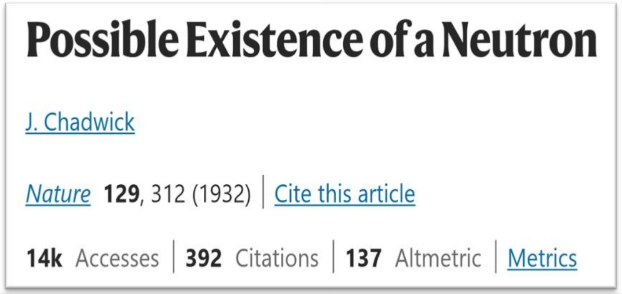
HIAF Collaboration Meeting, Huizhou
Sept. 5, 2025

Contents

Neutron and neutron induced fission

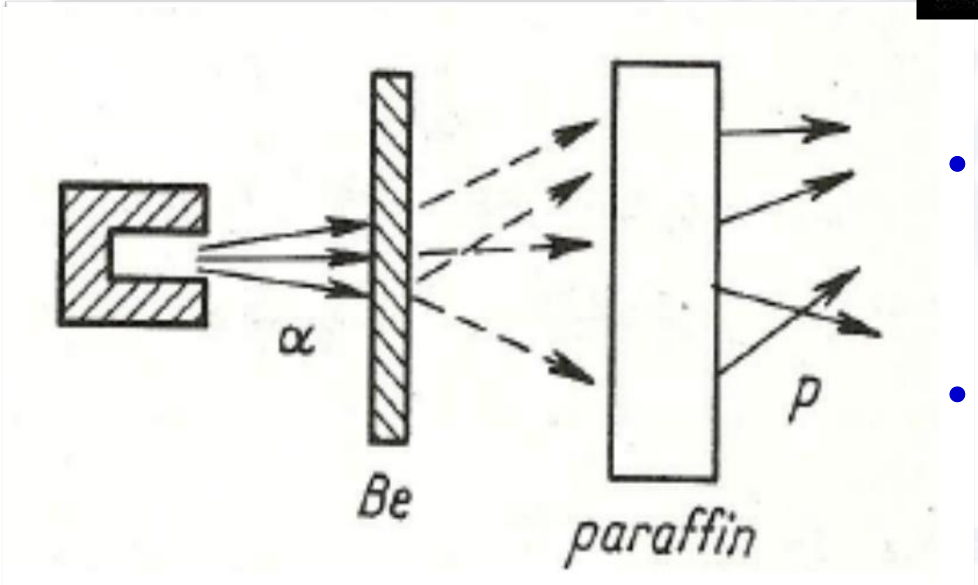


Possible Existence of a Neutron

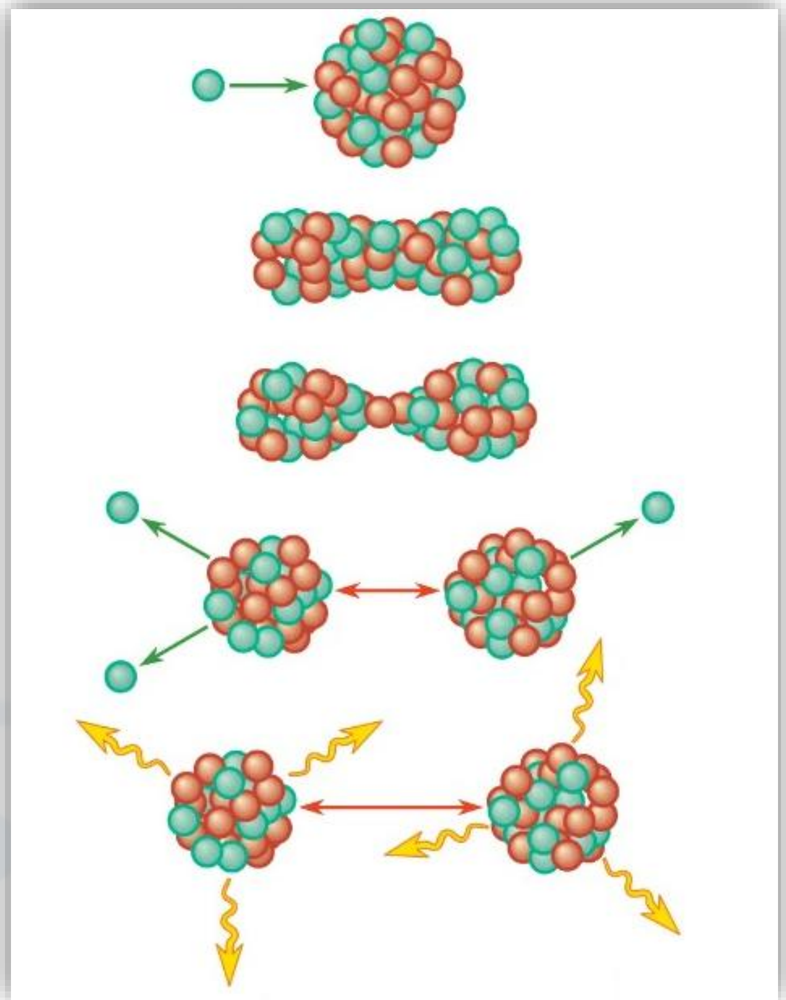
J. Chadwick

Nature **129**, 312 (1932) | Cite this article

14k Accesses | **392** Citations | **137** Altmetric | Metrics



- Marks the modelling of nucleus in proton-neutron constitution
- Provides a powerful tool to new discoveries and significant applications
- Such as fission in 1938



Delayed Neutron emission in fission

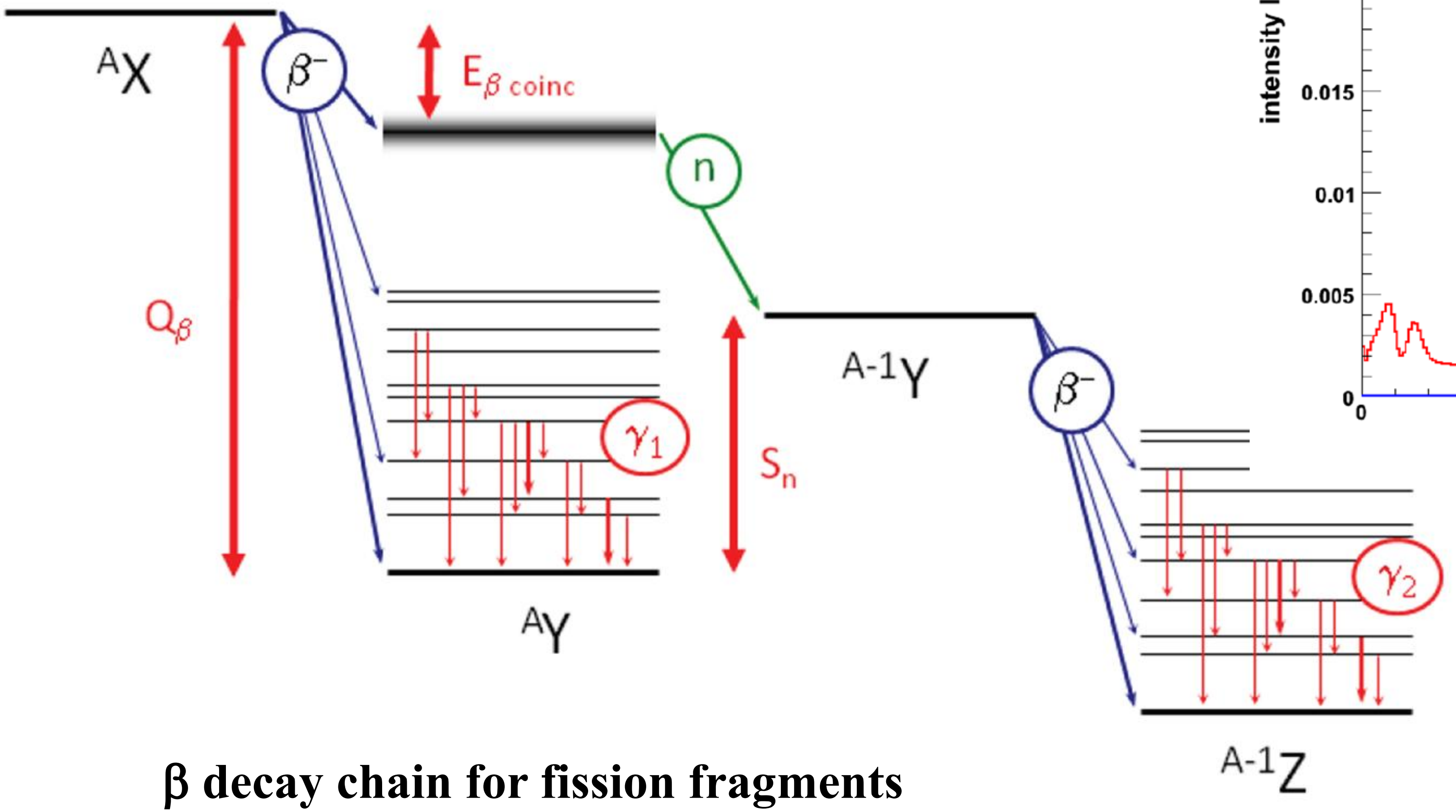
664 LETTERS TO

The Delayed Neutron Emission which Accompanies Fission of Uranium and Thorium

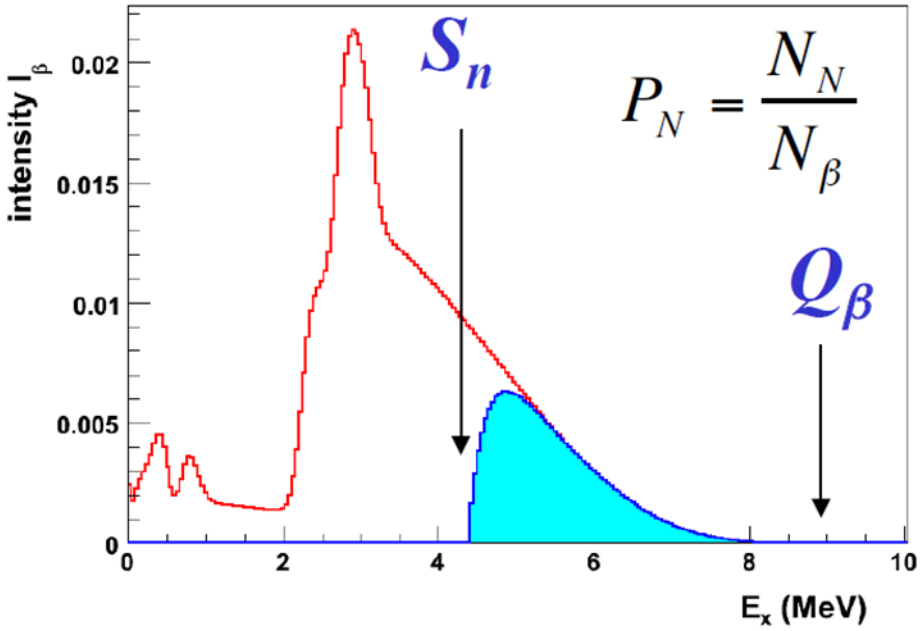
In our previous letter[1] we suggested that the delayed neutrons produced by neutron bombardment of uranium might originate either in direct neutron emission (by one of the disintegration products), or in a photodisintegration process. Further evidence has now been obtained which indicates that direct neutron emission is responsible for the delayed neutrons which we observed.

R.B. Roberts, L.R. Hafstad, R.C. Meyer, P. Wang, The Delayed Neutron Emission which Accompanies Fission of Uranium and Thorium, Phys. Rev. 55 (1939) 664.

Beta delayed neutron emission probability Pn



β decay chain for fission fragments



$Q_{\beta} > S_n$ of the daughter nucleus

Beta delayed neutron in fission

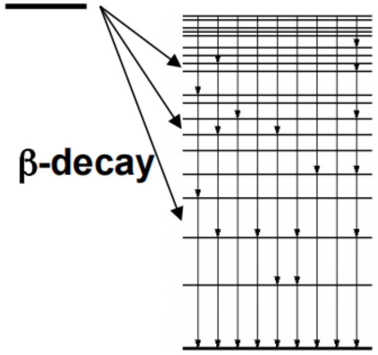
Average number of delayed neutrons per fission → $<\nu_d> = \sum_i Y_i \times P_{ni}$

- Y_i: **cumulative fission fragment yield**
- P_{ni}: **Delayed neutron emission probability**

Fissioning system	^{233}U(n$_t$,f)	^{235}U(n$_{th}$,f)	^{239}Pu(n$_{th}$,f)	^{241}Pu(n$_{th}$,f)
$<\nu_d>$ (Integral)	6.73E-03	1.62E-02	6.50E-03	1.60E-02
$<\nu_d>$ (Sum)	7.24E-03	1.48E-02	6.05E-03	1.23E-02
Diff. (S–I)/I	+8%	-9%	-7%	-23%
Fissioning system	^{242m}Am(n$_{th}$,f)	^{243}Cm(n$_{th}$,f)	^{245}Cm(n$_{th}$,f)	
$<\nu_d>$ (Integral)	6.50E-03	3.01E-03	6.40E-03	
$<\nu_d>$ (Sum)	5.82E-03	2.21E-03	5.26E-03	
Diff. (S–I)/I	-11%	-27%	-18%	

M.A. Kellett et al. JEFF Report 20, NEA No. 6287 , 2009

Basics of beta decay from experiment



Fermi / Gamow-Teller:

$$B_{i\to f} = \left| \left\langle \Psi_f \middle| \tau^{\pm} \ or\ \sigma\tau^{\pm} \middle| \Psi_i \right\rangle \right|^2$$

Strength function

Beta feeding

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

Fermi function

Half life of parent

Relationship

$$S_\beta = \frac{1}{6147 \pm 7}\left(\frac{g_A}{g_V}\right)^2 \sum_{E_f \in \Delta E} \frac{1}{\Delta E} B_{i\to f}$$

Basics of beta decay from Pn values

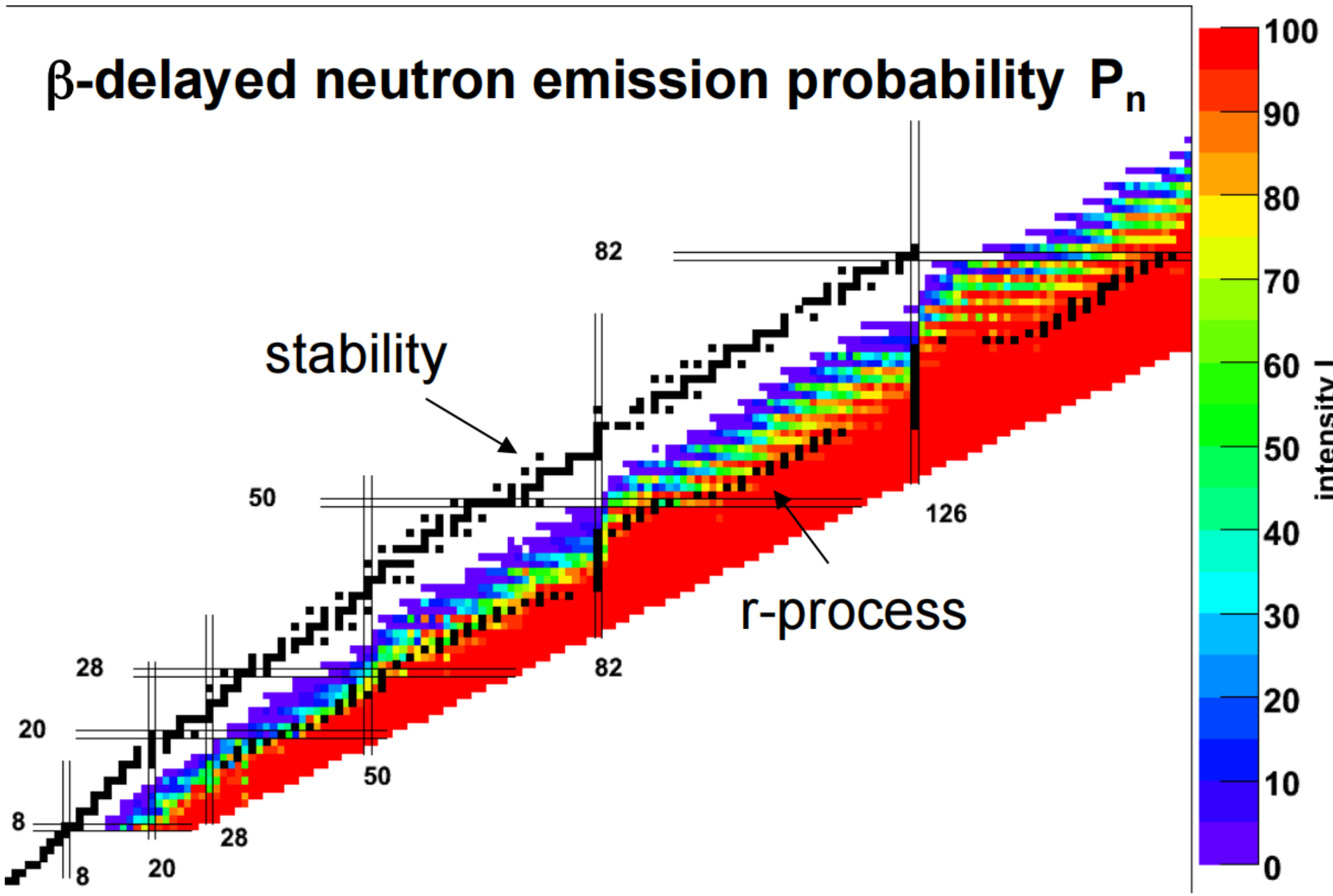
The (inverse of the) half-life $T_{1/2}$ is a weighted average of the β-strength S_β

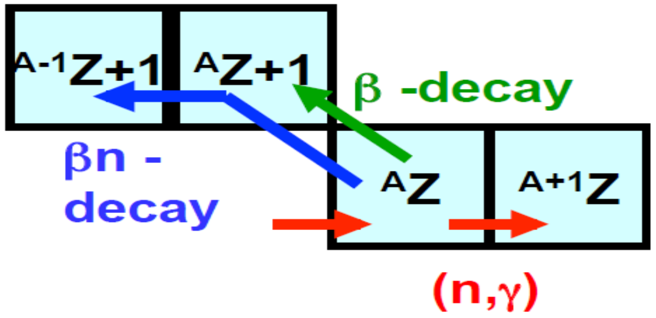
$$\frac{1}{T_{1/2}} = \int_0^{Q_\beta} S_\beta(E_x) \cdot f(Q_\beta - E_x)\, dE_x$$

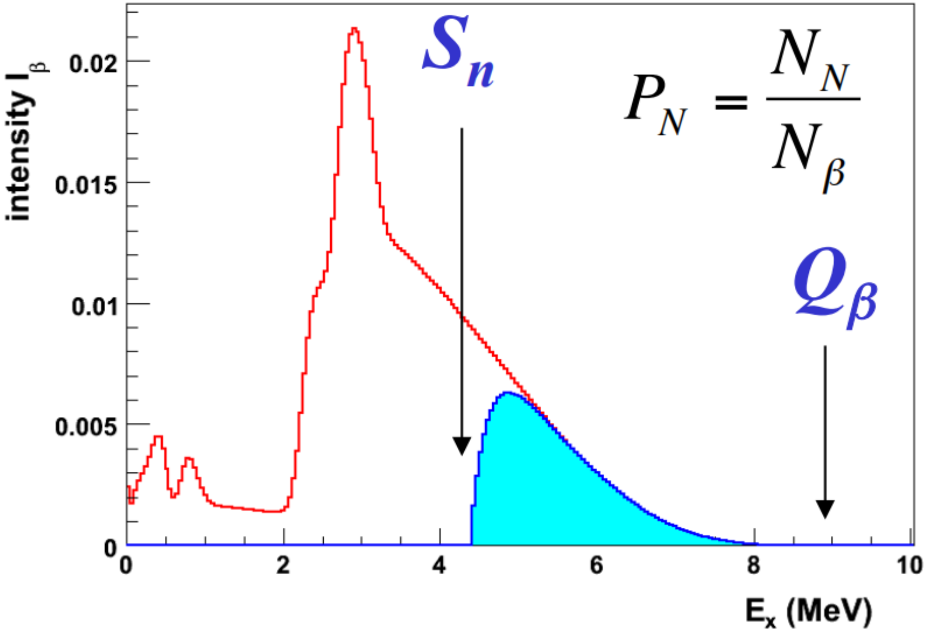
The neutron emission probability P_n measures the fraction of β-strength above the neutron separation energy S_n

$$P_n = \frac{\int_{S_n}^{Q_\beta} S_\beta(E_x) \cdot f(Q_\beta - E_x) \frac{\Gamma^n}{\Gamma^n + \Gamma^\gamma} dE_x}{\int_0^{Q_\beta} S_\beta(E_x) \cdot f(Q_\beta - E_x)\, dE_x}$$

P_n for very neutron-rich nuclei

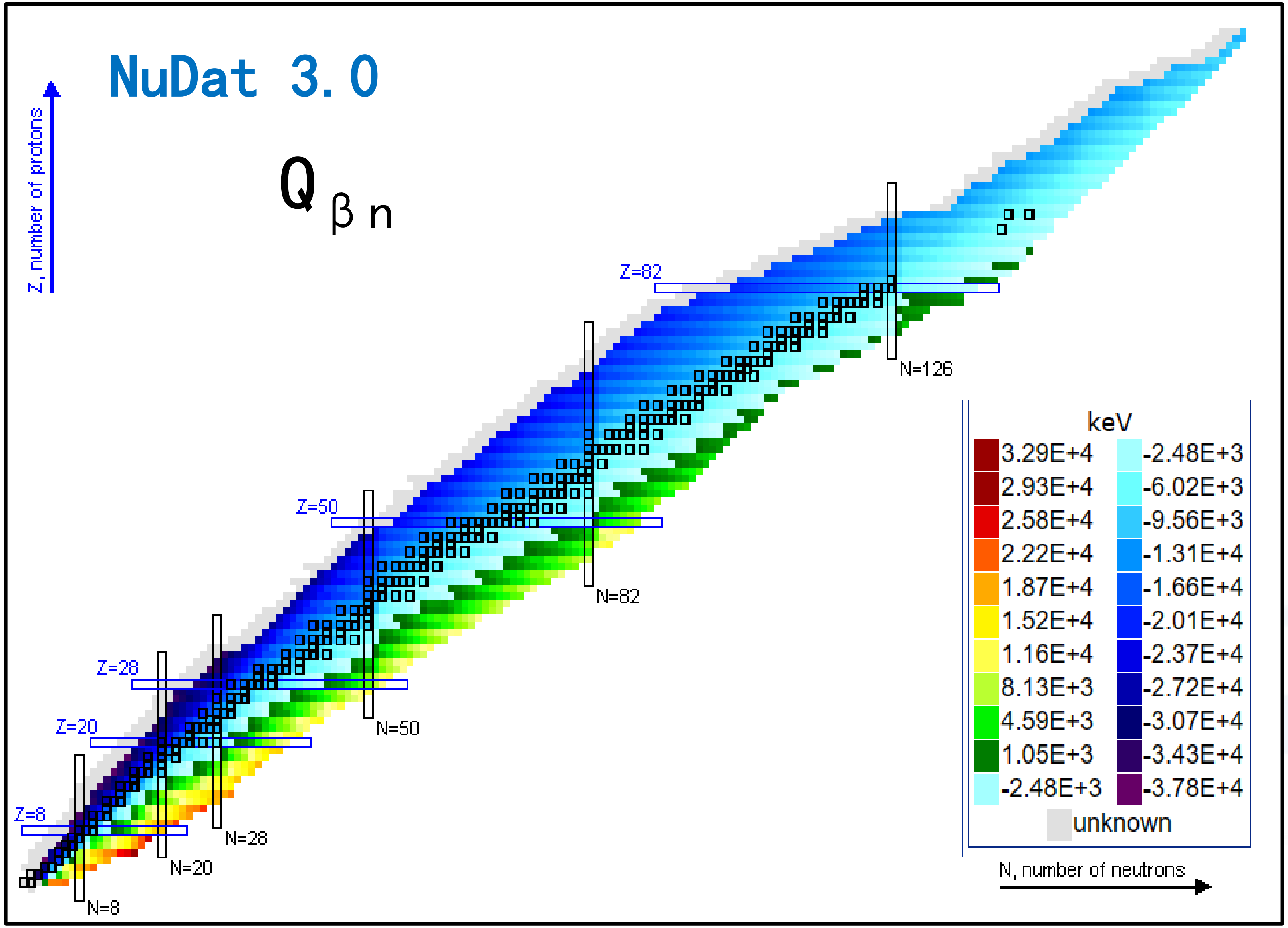






To understand nuclear structure and r-process relies on the knowledge of beta-delayed neutrons

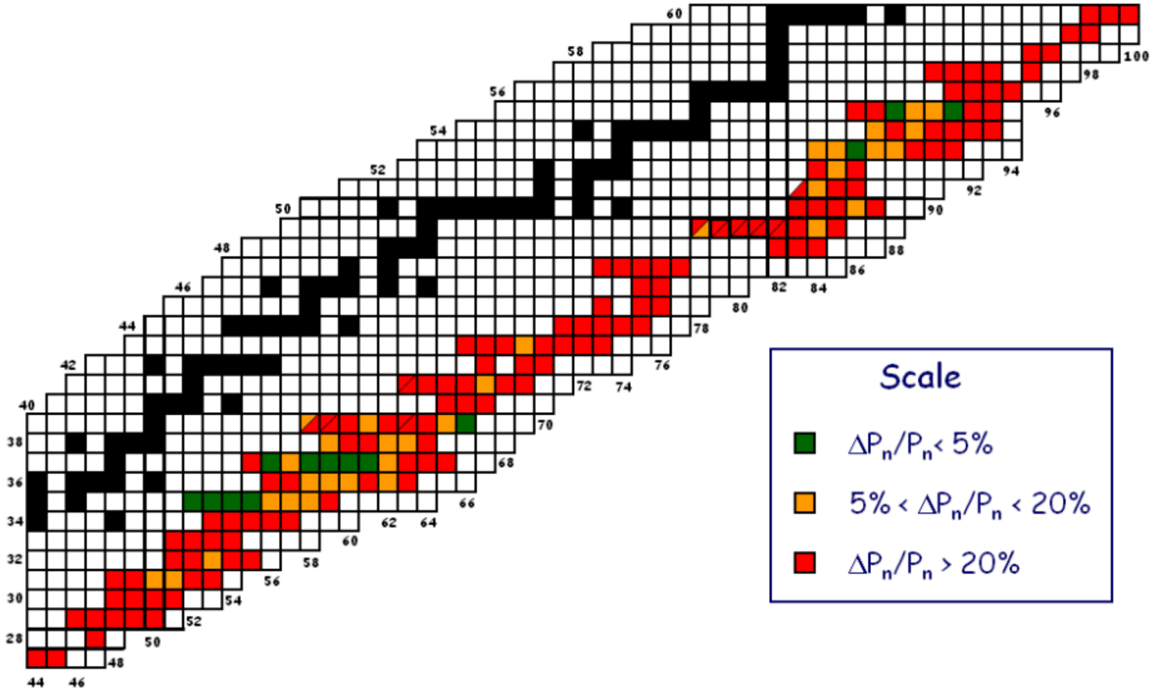
Beta delayed neutron emitters

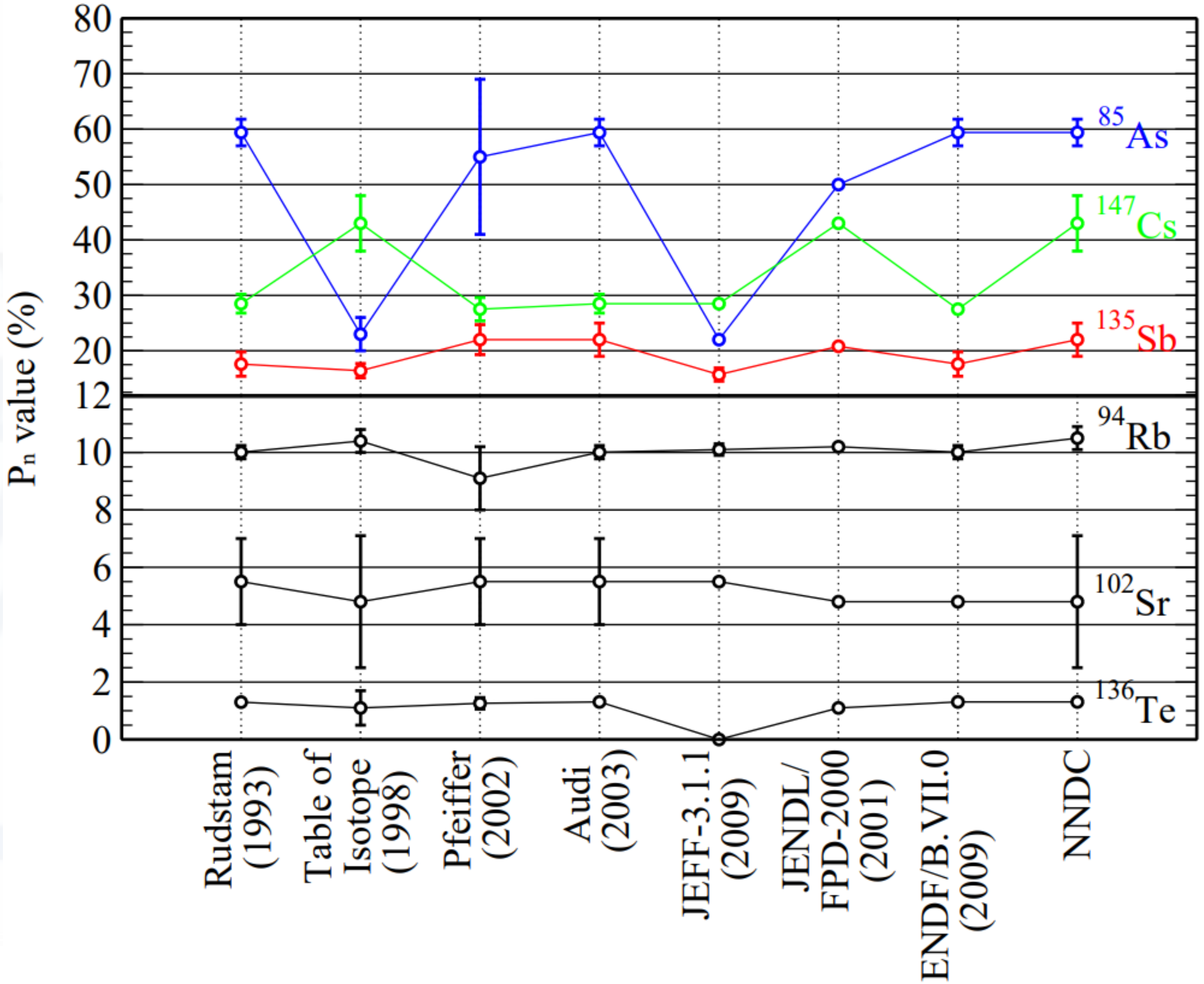


Model predicts:

- About 665 β_{1n} emitters with $Q_{\beta 1n}>0$
- About 325 β_{2n} emitters with $Q_{\beta 2n}>0$
- About 138 nuclei with $Q_{\beta 3n}>0$ and 58 nuclei with $Q_{\beta 4n}>0$

Deviation in available Pn data





- **JEFF-3.1.1** **33.3% with uncertainties**
- **ENDF/B-VII.0** **only 7%**
- **JENDL/FPD-2000** **only 1%**

IAEA CRP on a Reference Database for Beta-Delayed Neutron Emission

Code F41028; Duration 2013-2018

Participants

- Ivan Borzov
- Daniel Cano
- Satoshi Chiba
- Iris Dillmann
- Muriel Fallot
- Paul Garrett
- Robert Grzywac
- Xiaolong Huang
- Tomislav Marketin
- Robert Mills
- Futoshi Minato
- Gopal Mukherjee
- Vladimir Piksaikin
- Krzysztof Rykaczewski
- Balraj Singh
- José L. Tain
- Alejandro Algora
- Tim Johnson
- Libby McCutchan
- Alejandro Sonzogni

The CRP on beta-delayed neutron emission data

CRP Objective

The overall CRP Objective is to enhance Member States' (MS) knowledge and calculational capabilities in the fields of nuclear energy, safeguards, used fuel and waste management and nuclear sciences by creating a Reference Database for Beta-Delayed Neutron Emission that contains both a compilation of existing data, evaluated data and recommended data, which will be made readily available to the user community. The project starts in 2013 and will have a duration of 4 years.

Compilation and Evaluation of Beta-Delayed Neutron Emission Probabilities and Half-Lives for Z > 28 Precursors. J. Liang *et al*. Nuclear Data Sheets **168**, 1–116(2020).

Progress in Pn data

Nucleus	Proportion of all DN	$\Delta P_n/P_n$
^{137}I	13 to 40%	8%
^{98m}Y	5 to 16%	30%
^{94}Rb	7 to 12%	5% [2]
^{138}I	4 to 10%	7%
^{135}Sb	0.3 to 3%	30%
^{99}Y	2 to 4%	20% [3]
^{105}Nb	0.2 to 2%	50%
^{91}Br	0.5 to 2%	15% [2]
^{136}Te	0.6 to 1.7%	100% [4]
^{140}I	0.1 to 1.3%	10% [2]
^{137}Te	0.2 to 1.5%	5% [3]
^{85}As	0.8 to 3%	60%
^{86}As	0.2 to 1%	12% [2,3]

M.A. Kellett et al. JEFF Report 20, NEA No. 6287(2009)

表1 核能应用需要精确测量的 β 延迟中子发射核。延迟中子占比取决于不同的裂变系统.

核素	半衰期 (秒) [a]	P_n [a]	$\Delta P_n/P_n$	<n_{di}>/<n_d>
^{137}I	24.59(10)	7.63(14)	1.8%	13- 40%
^{98m}Y	2.32(8)	3.44(95)	27.6%	5 - 16%
^{94}Rb	2.704(15)	10.39(22)	2.1%	7 - 12%
^{138}I	6.251(31)	5.30(21)	4.0%	4 - 10%
^{99}Y	1.478(7)	1.97(30)	15.2%	2 - 4%
^{135}Sb	1.668(10)	20.0(29)	1.5%	0.3 - 3%
^{85}As	2.023(7)	62.5(10)	0.2%	0.8 - 3%
^{105}Nb	2.91(7)	1.7(9)	52.9%	0.2-2%
^{91}Br	0.544(10)	30.4(14)	0.5%	0.5 - 2%
^{136}Te	17.67(9)	1.37(5)	3.6%	0.6 - 1.7%
^{137}Te	2.50(5)	2.91(16)	5.5%	0.2 - 1.5%
^{140}I	0.590(16)	7.88(43)	5.5%	0.1 - 1.3%
^{86}As	0.944(10)	34.5(9)	2.6%	0.2 - 1%

J. Liang *et al*. Nuclear Data Sheets **168**, 1–116(2020)

Experimental methods to measure Pn

1）Ion counting

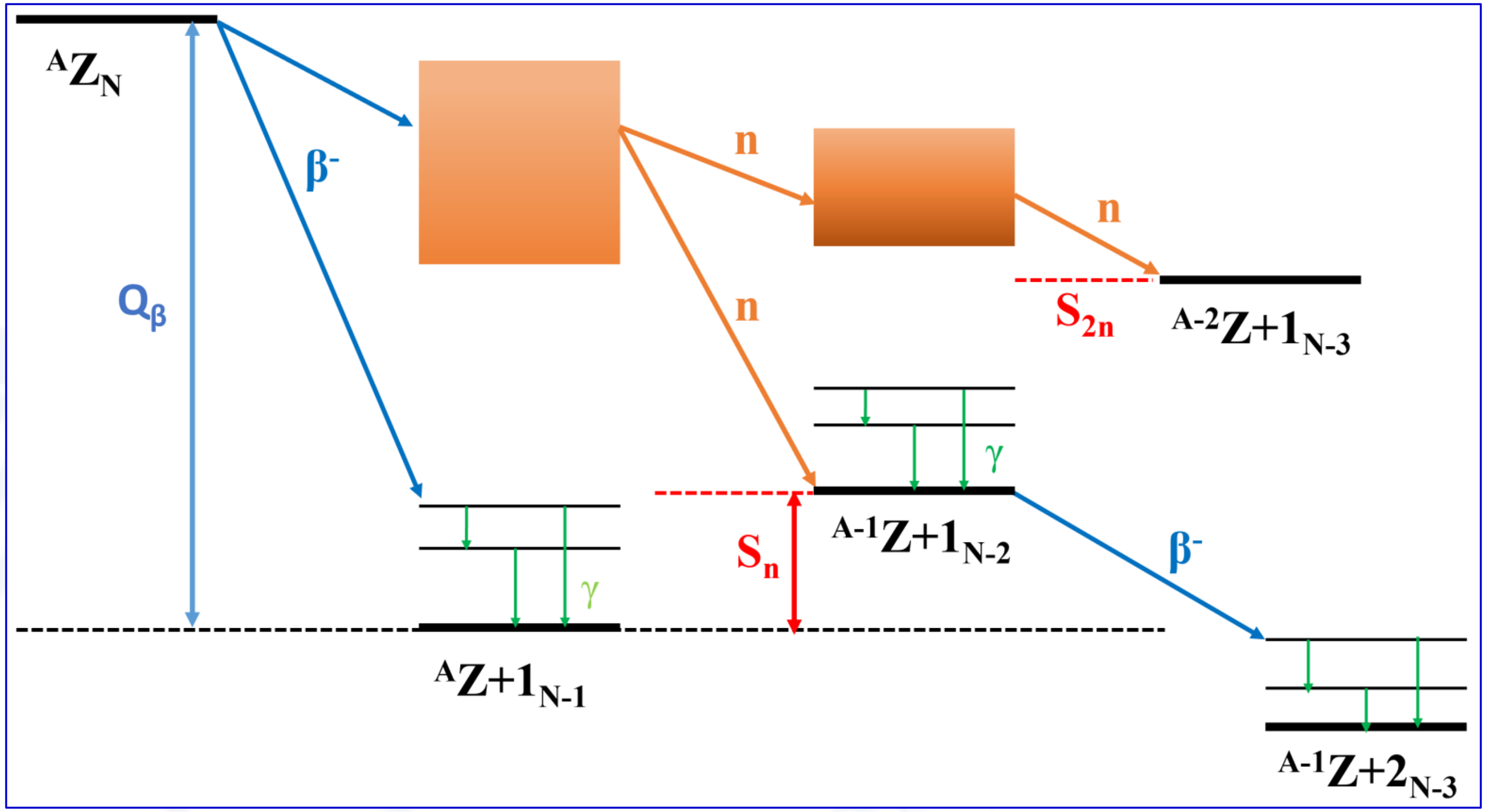
$$P_n = \frac{N_n}{N_{ion}\varepsilon_n}$$

2）Neutron-beta coincidences

$$P_n = \frac{N_{n-\beta}\varepsilon_\beta}{N_\beta \varepsilon_{n-\beta}} = \frac{N_{n-\beta}}{N_\beta \varepsilon_n}$$

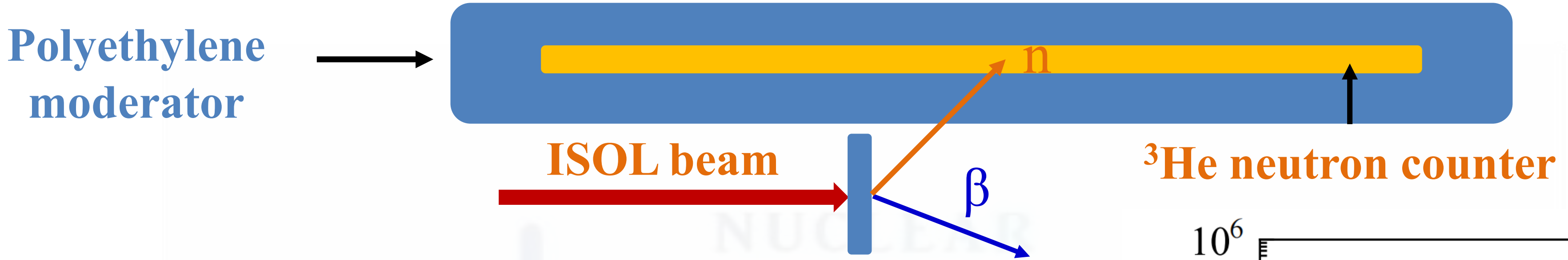
3）Combined with γ rays

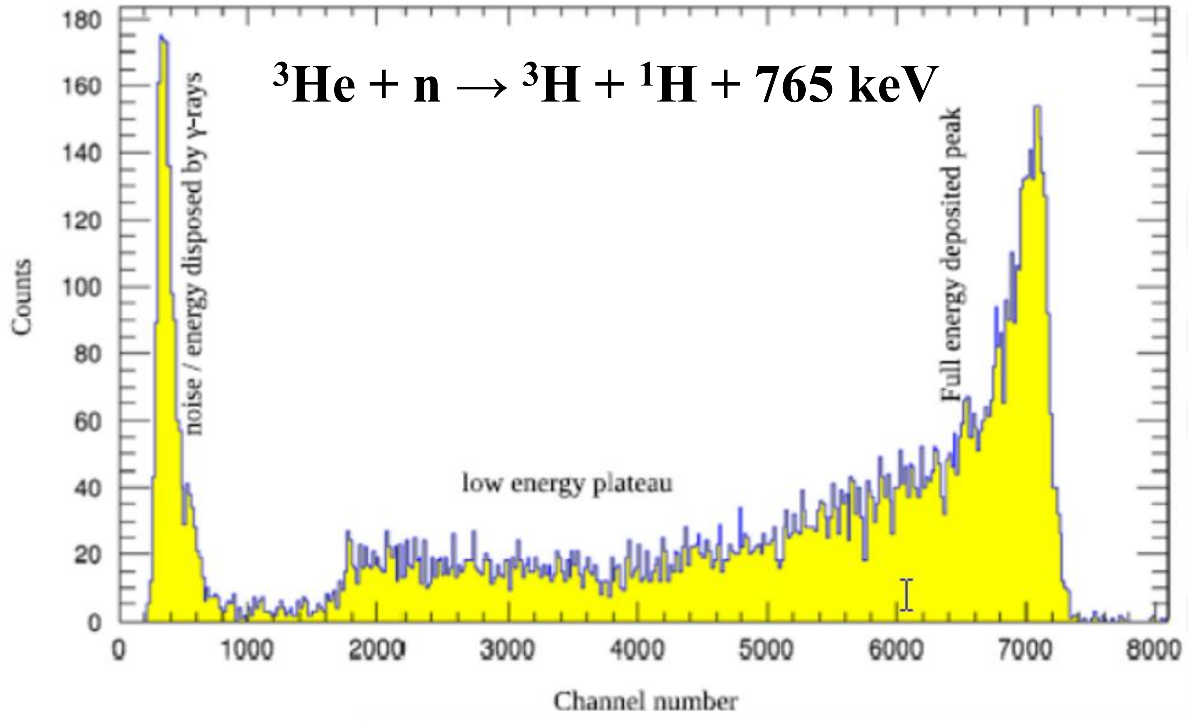
$$P_n = \frac{N_n}{N_\gamma} \cdot \frac{B_\gamma \varepsilon_\gamma}{\varepsilon_n}$$

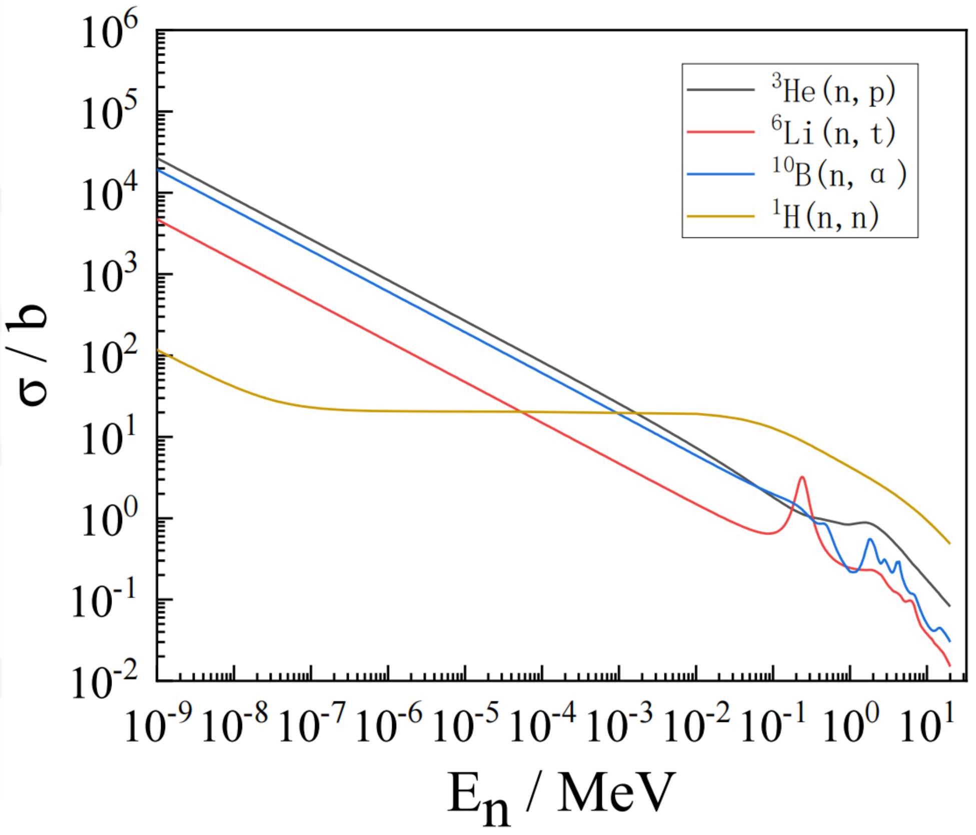


- Neutron detector are hard to calibrate
- None flat efficiency for neutron and β detectors
- Neutron and huge β background induced ambiguities

Principle of ^{3}He neutron counter







Neutron lose much of their energy and time information in the process of thermalization

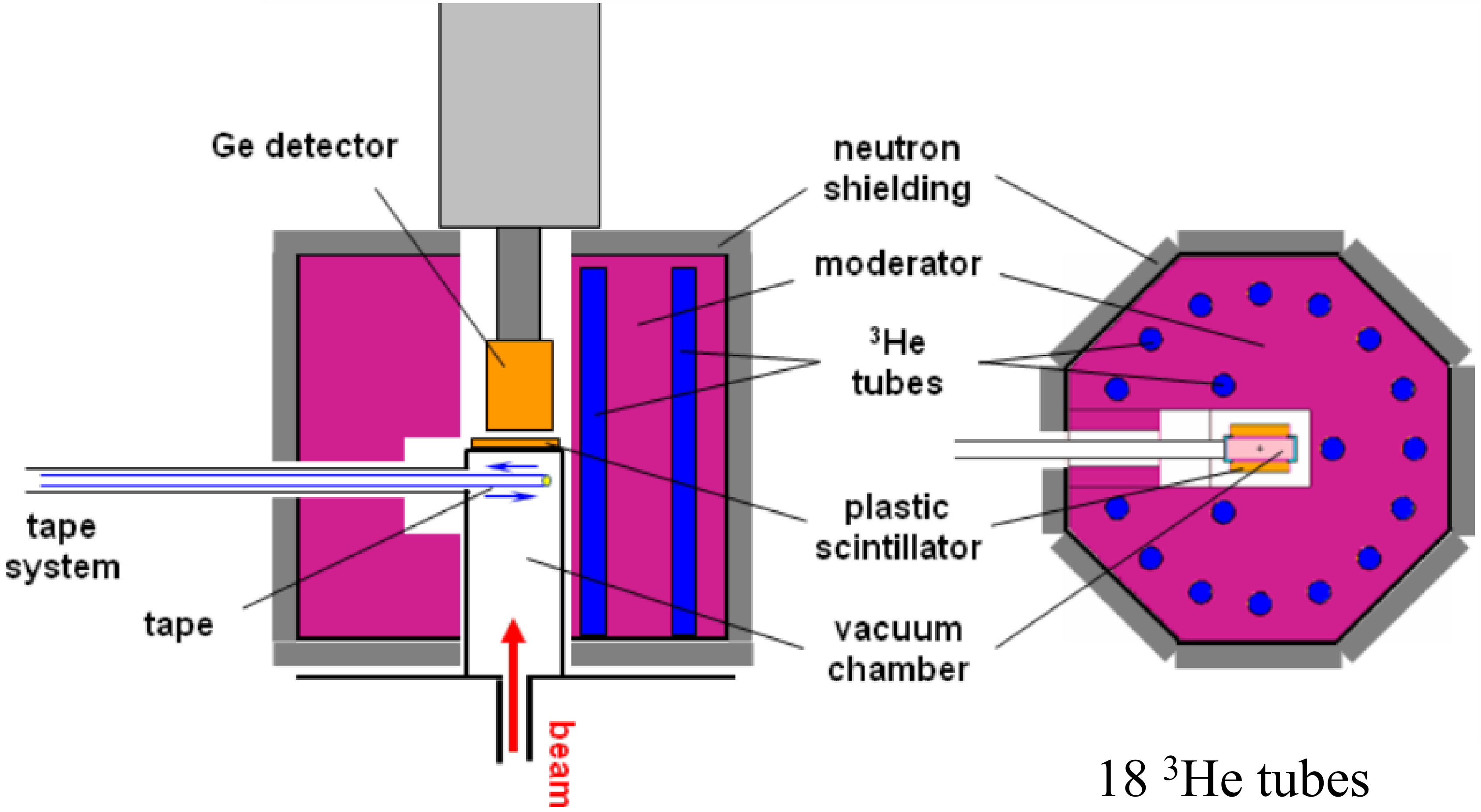
Known ^{3}He neutron arrays

Facility	RIB	Neutron array	Isotopes for example	References
LOHEN GRIN	ISOL	LOENIE	^{99}Y, ^{136}Te	*JINST* **7**(2012) P08029
ORSAY-ALTO	ISOL	TETRA	^{81,82}Ga	NIM **A815** (2016) 96
ORNL	ISOL	VANDLE	^{83,84}Ga	NIM **A836** (2016) 122 PRL **117** (2016) 092502
GSI-FRS	Projectile fragmentation	BELEN-30	^{210,211}Hg, $^{211\text{-}216}$Tl	PRL**117**(2016) 012501
BigRIPS	Projectile fragmentation	BRIKEN	$^{81,82,84\text{-}87}$Ga, ^{80}Zn	NIM **A925**(2019)133 PRC**100**(2019) 031302(R)

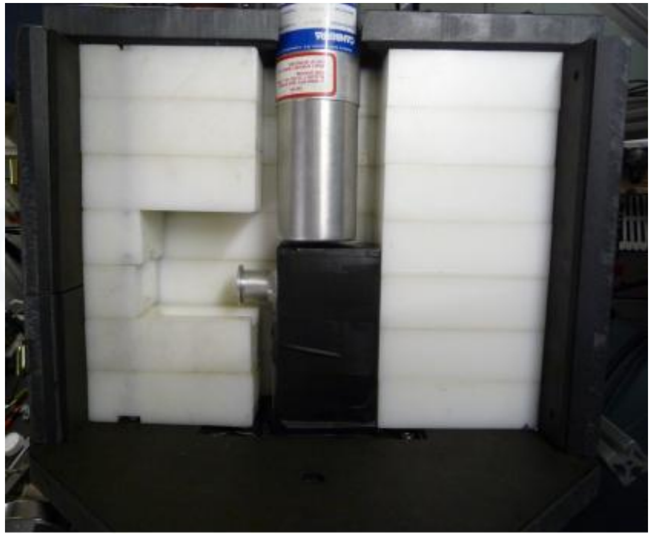
LOng-counter with ENergy Independant Effificiency (LOENIE)

Inner ring： r_1=8cm
Outer ring： r_2=17cm

^{3}He tube：
pressure： 10 atm

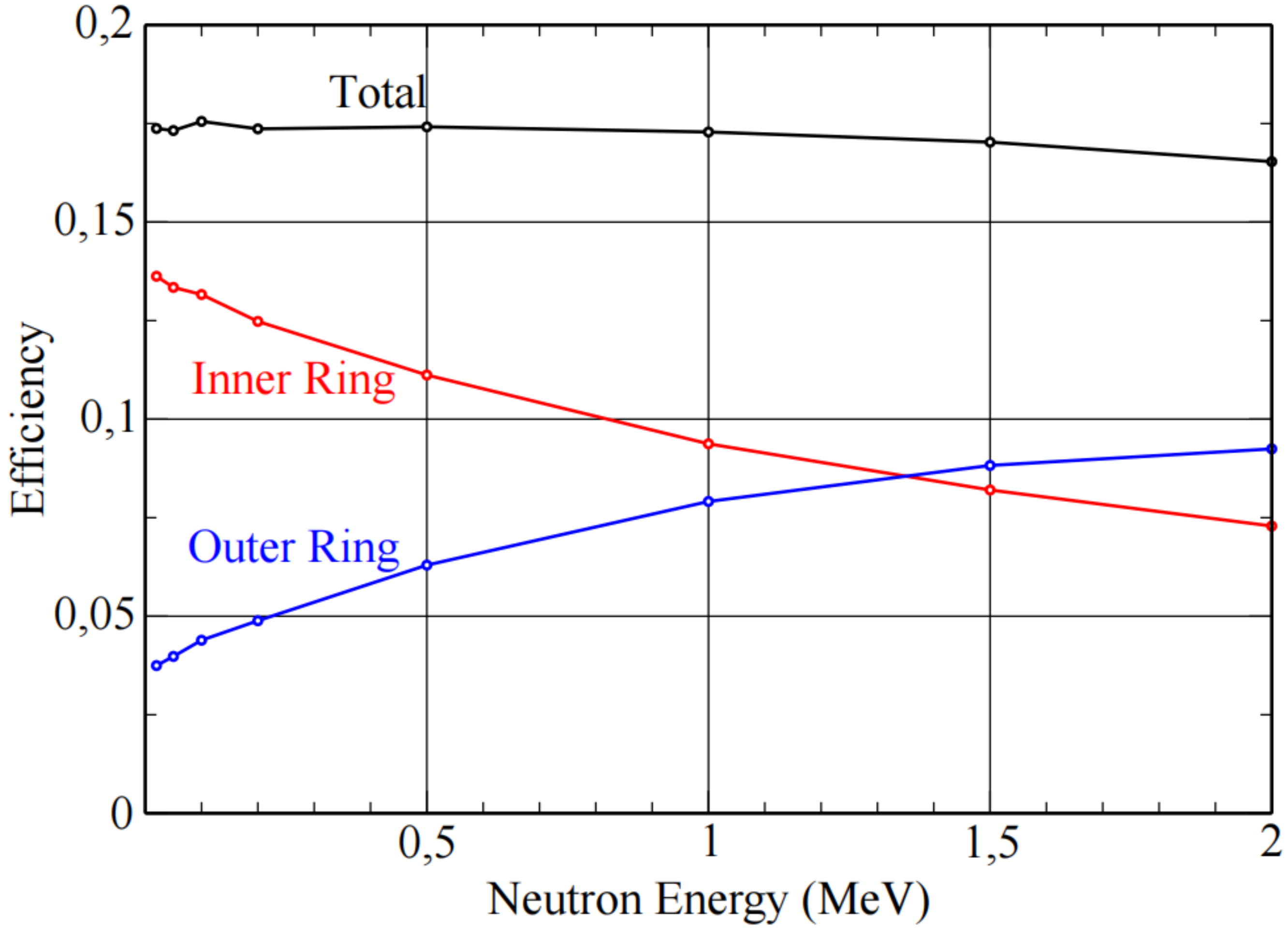


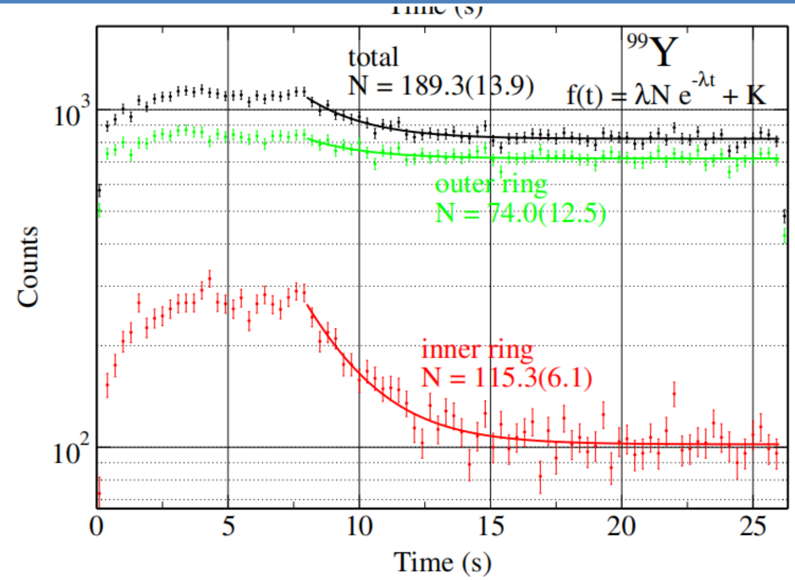
18 ^{3}He tubes

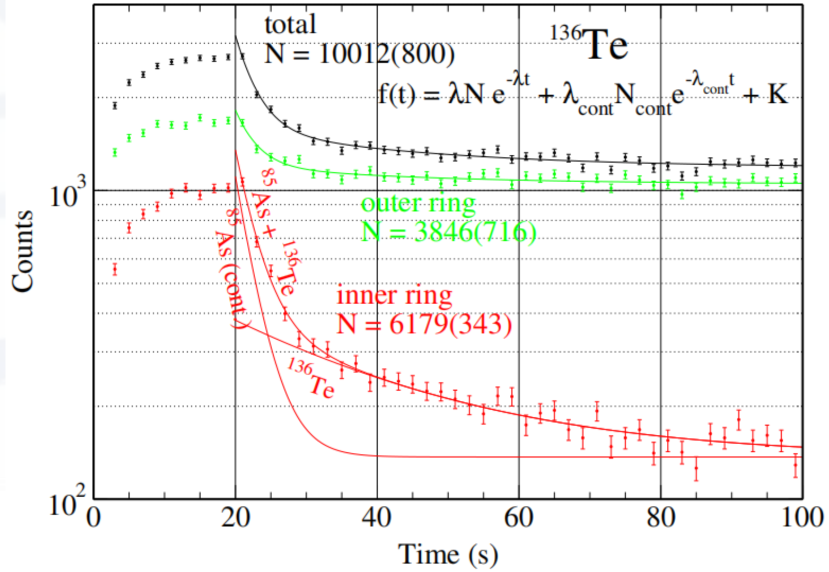


Performance of LOENIE

Calibration: constant efficiency is achieved of 23.1±0.3% for 0-1 MeV

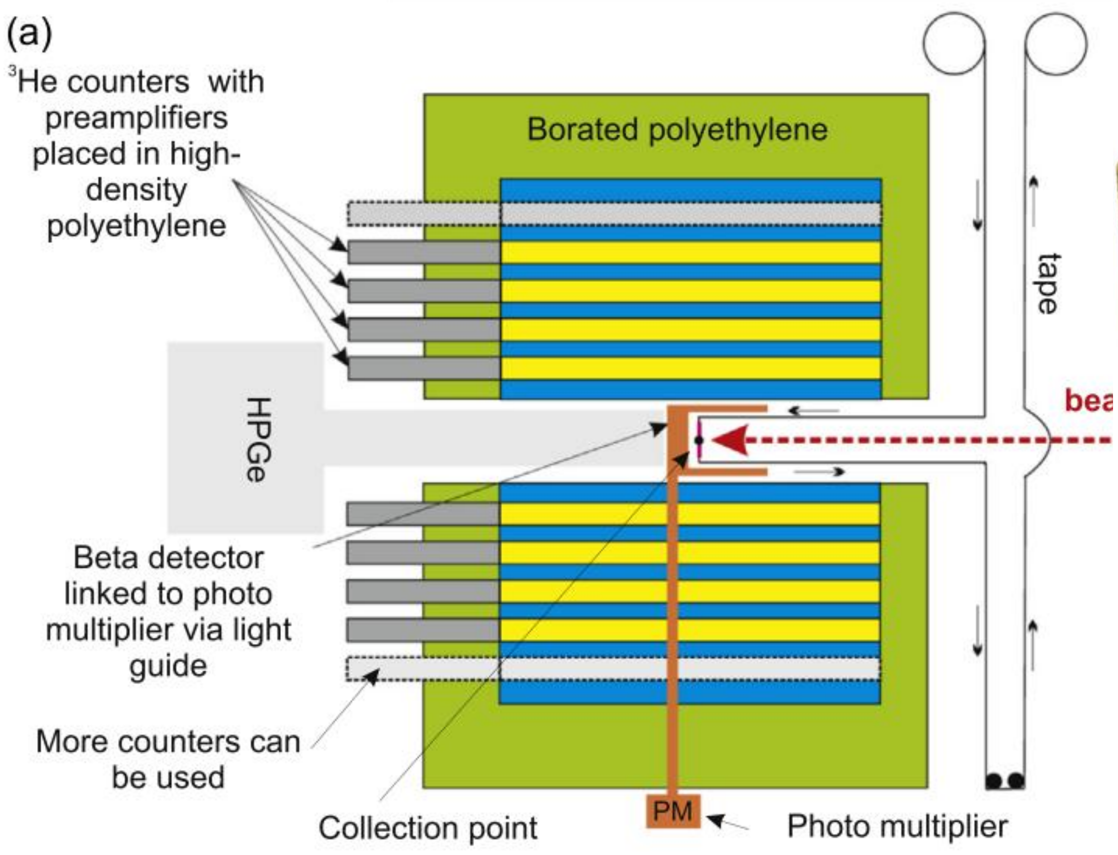




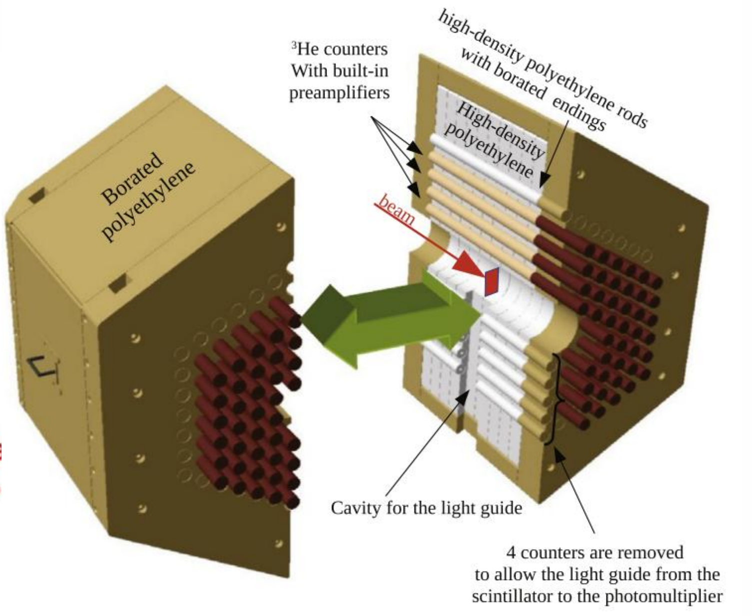


MCNP Simulation:17%, 6% difference!

The ^{3}He long-counter TETRA @ ALTO ISOL facility



Schematic view.

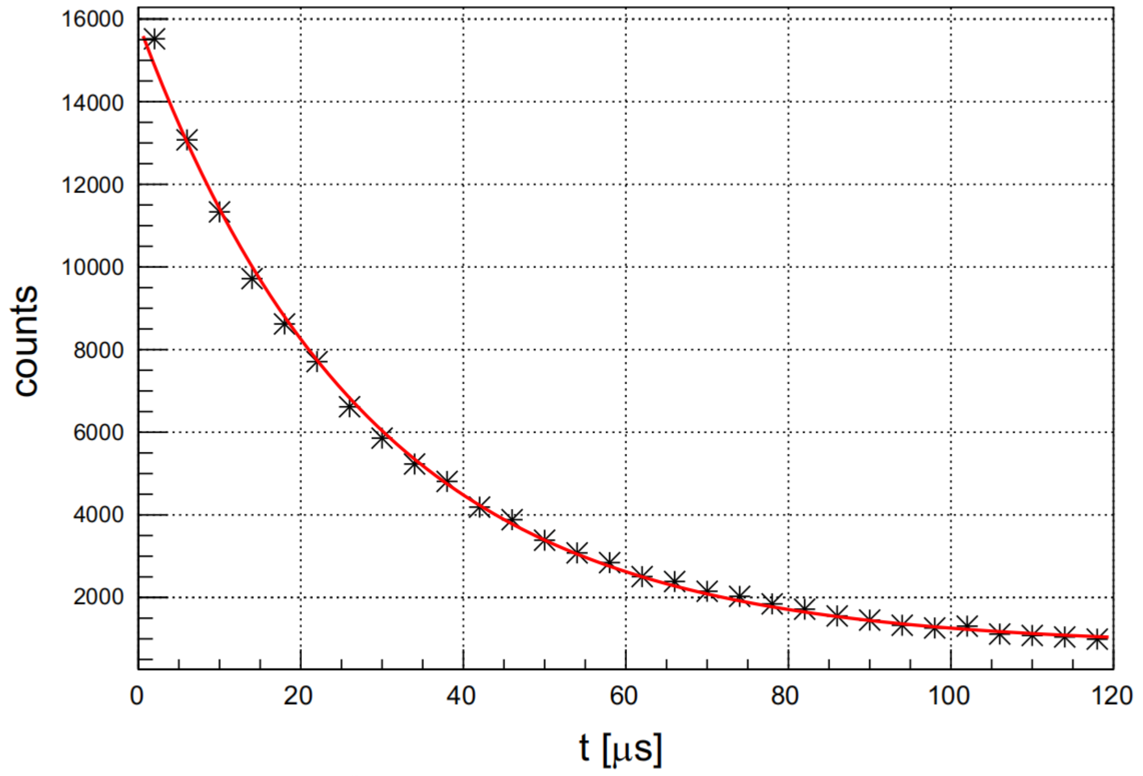


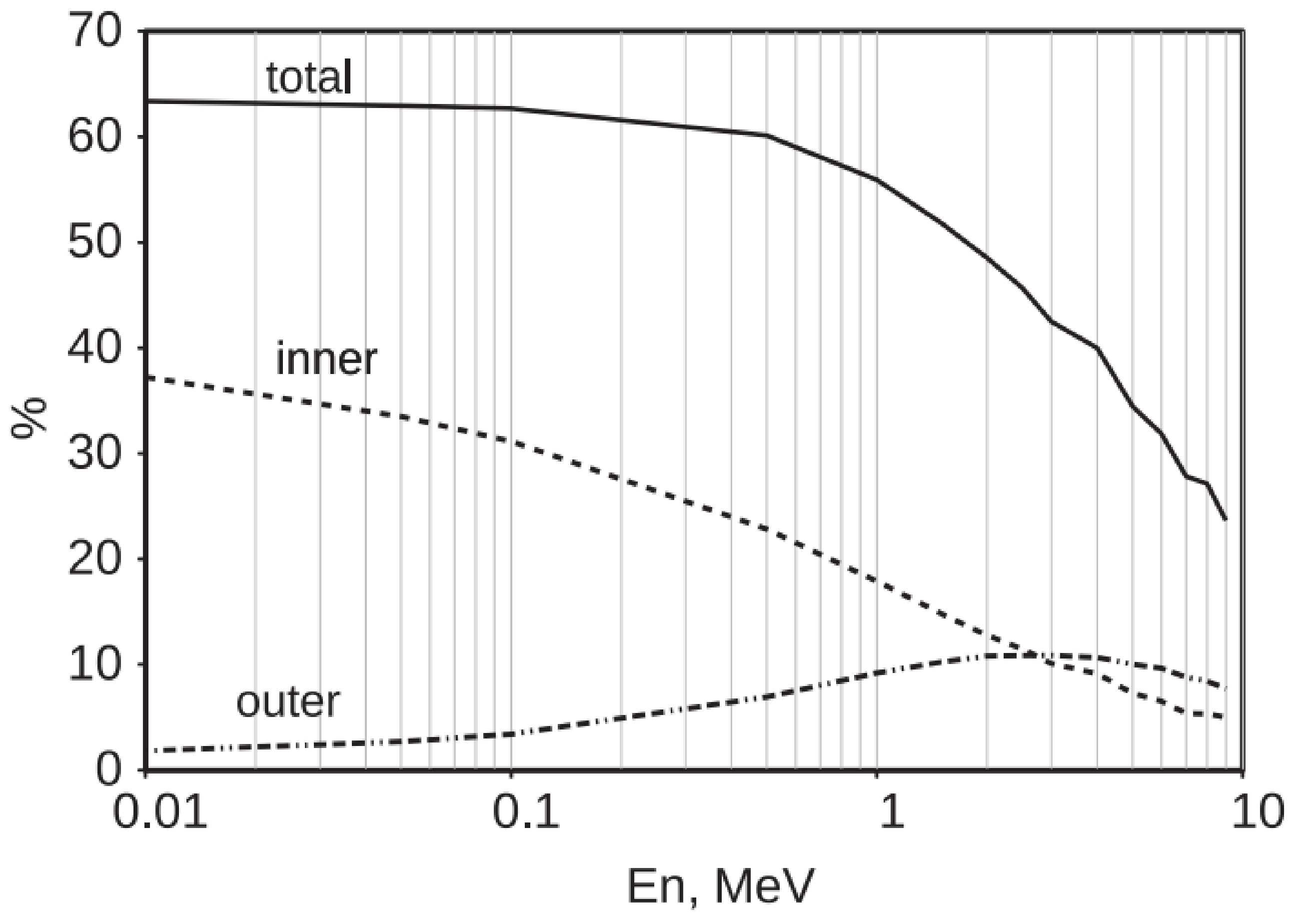
^{3}He neutron array TETRA
80 ^{3}He tubes in four rings;
500×ϕ32mm，7 atm

(b)

Overview of the setup.

Performance of TETRA





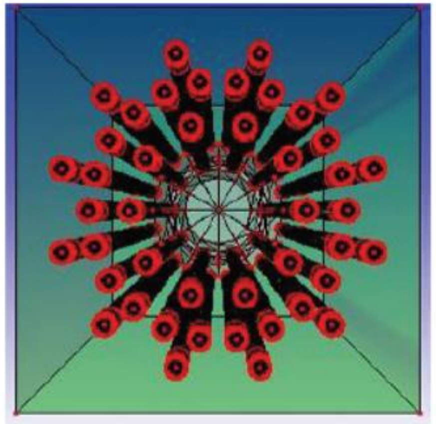
Time difference between two consecutive neutrons emitted in spontaneous fission of ^{252}Cf
Thermalization: typically less than 200 μs

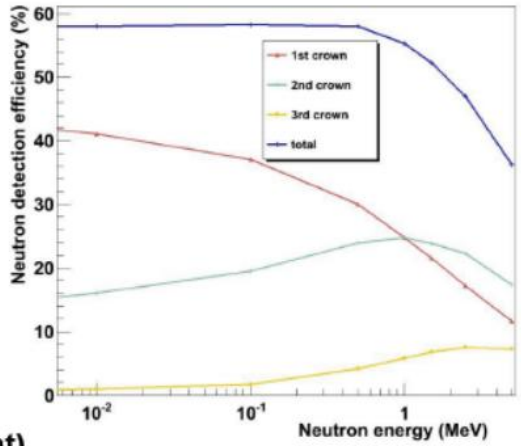
NIM A 815 (2016) 96–103

BEta deLayEd Neutron detector (**BELEN**)

BELEN progression

- The original planned neutron detector for DESPEC consists of 44 ^{3}He counters arranged in 3 crowns. To be combined with AIDA, but …





40 counters @ 10 atm UPC (refurbishment)

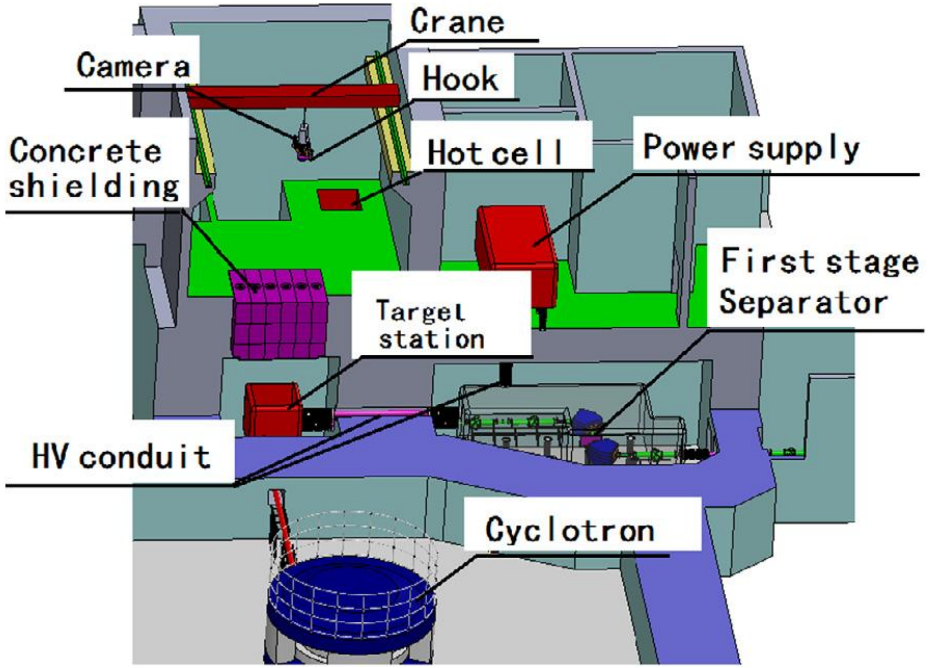
10 counters @ 10 atm GSI

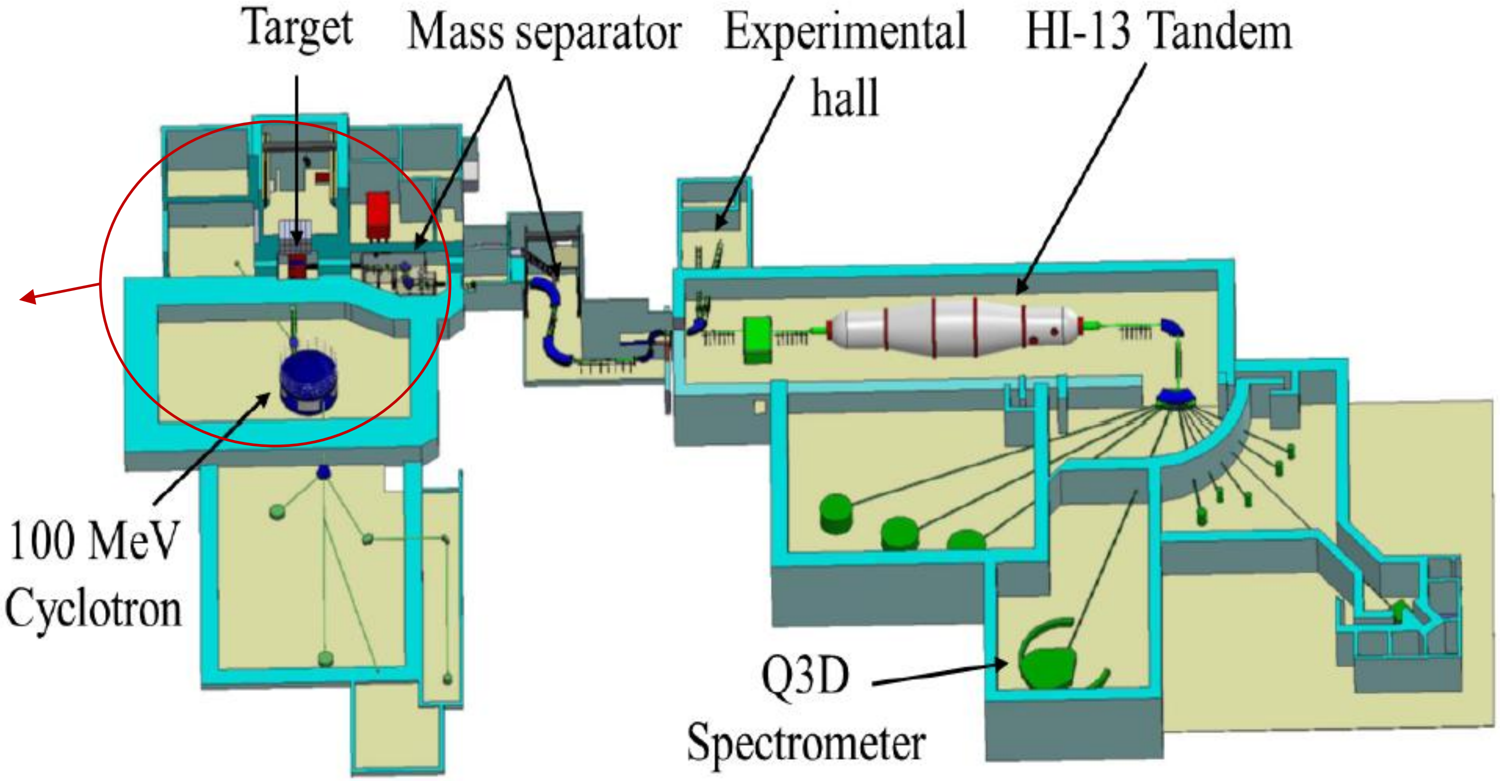
60 counters @ 4 atm JINR

	Experiment	Theory	Experiment	Theory
^{94}Kr	0.3 ± 0.1	0.44		0.55
^{99}Y	1.48 ± 0.02	0.93	2.5 ± 0.5	3.7
^{100g}Y	0.71 ± 0.03	0.29	1.8 ± 0.6	0.9
^{101}Y	0.40 ± 0.02	0.14	1.5 ± 0.5	1.4
^{102g}Y	0.29 ± 0.02	0.18	4.0 ± 1.5	1.6
^{103}Y	0.23 ± 0.02	0.08	8 ± 3	4.6
^{104}Y	0.18 ± 0.06	0.035		
^{105}Zr	0.6 ± 0.1	0.095		0
^{104g}Nb	5.0 ± 0.4	2.07	0.06 ± 0.03	0
^{105}Nb	2.8 ± 0.1	2.73	1.7 ± 0.9	0.26
^{106}Nb	0.9 ± 0.02	0.15	4.5 ± 0.3	0.27
^{107}Nb	0.30 ± 0.03	0.45	6.0 ± 1.5	3.7
^{108}Nb	0.19 ± 0.02	0.23	6.2 ± 0.5	11
^{109}Nb	0.19 ± 0.03	0.28	31 ± 5	26
^{110}Nb	0.17 ± 0.02	0.19	40 ± 8	20
^{109}Tc	0.8 ± 0.1	0.42	0.08 ± 0.02	0.02
^{110}Tc	0.78 ± 0.15	0.25	0.04 ± 0.02	0.075
^{111}Tc	0.29 ± 0.02	0.235	0.85 ± 0.2	0.53
^{112}Tc	0.29 ± 0.02	0.26	1.5 ± 0.2	1.1
^{113}Tc	0.17 ± 0.02	0.13	2.1 ± 0.3	
^{114}Tc	0.15 ± 0.03	0.08	1.3 ± 0.4	

Hyperfine Interact (2014) 223:185–194

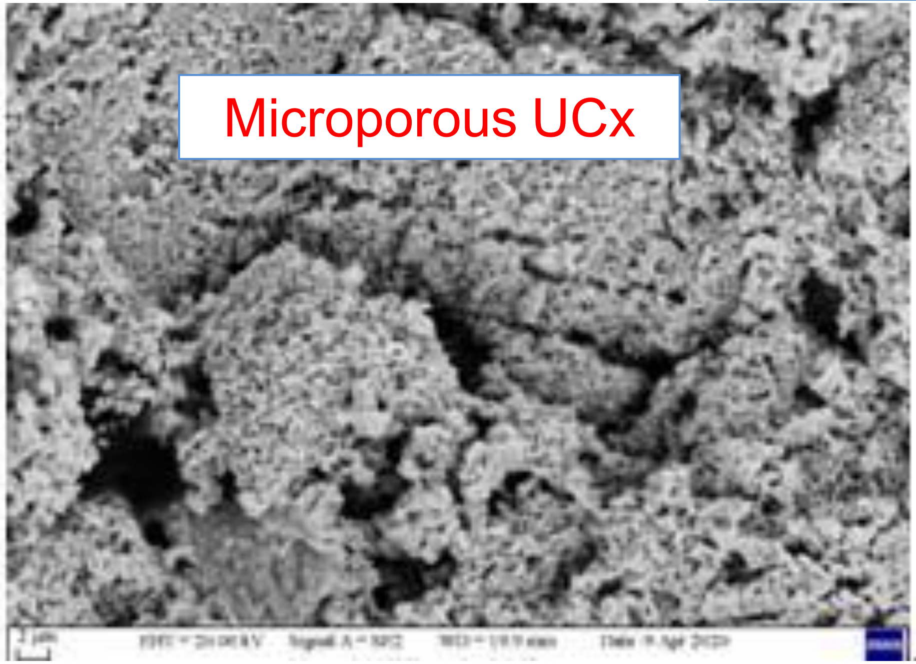
Upgrade for RIBs@CIAE





- 100 MeV proton cyclotron, Kilowatt Target-Ion Source assembly
- Charge Exchange cell + high-resolution ISOL
- HI-13 Tandem for post acceleration

Recent Beam development @BRIF



Target	RNB	Ion source
CaO	^{37,38,43,45,47}K	Surface IS
MgO	^{20,21,22,24,25}Na	Surface IS
SiC	^{16}N, ^{27}Al, $^{20-25}$Na	FEBIAD
UCx	^{88}Rb,^{90}Rb,^{140}Cs, ^{142}Cs	FEBIAD

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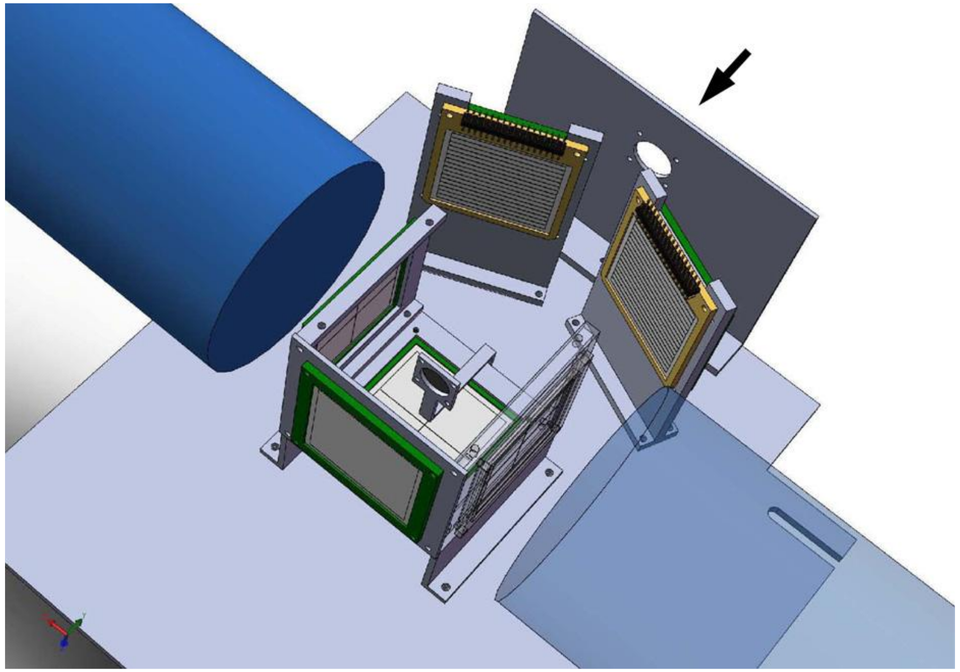
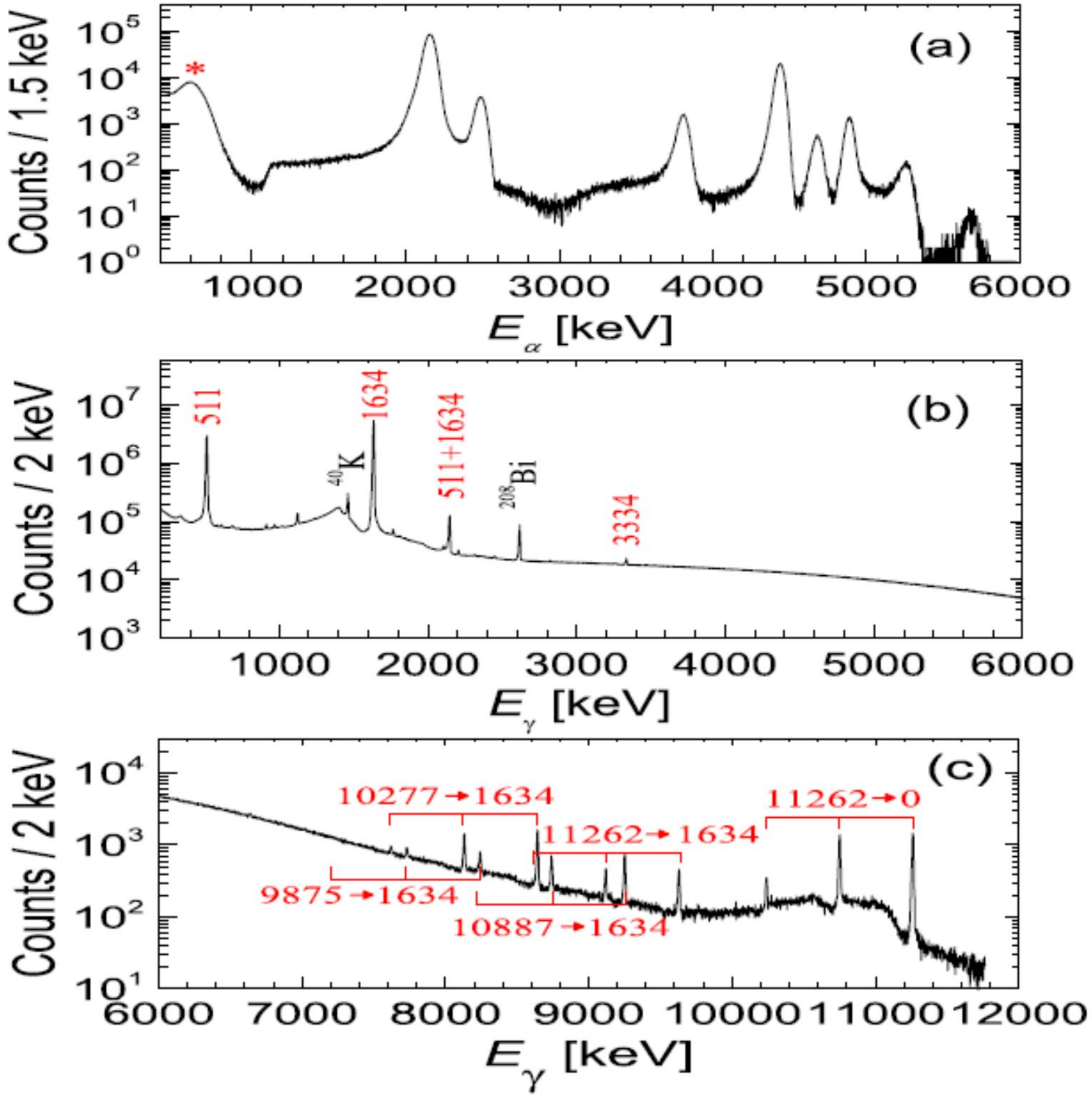
Review

Nuclear physics at BRIF

Beijing Rare Isotope Facility (BRIF)

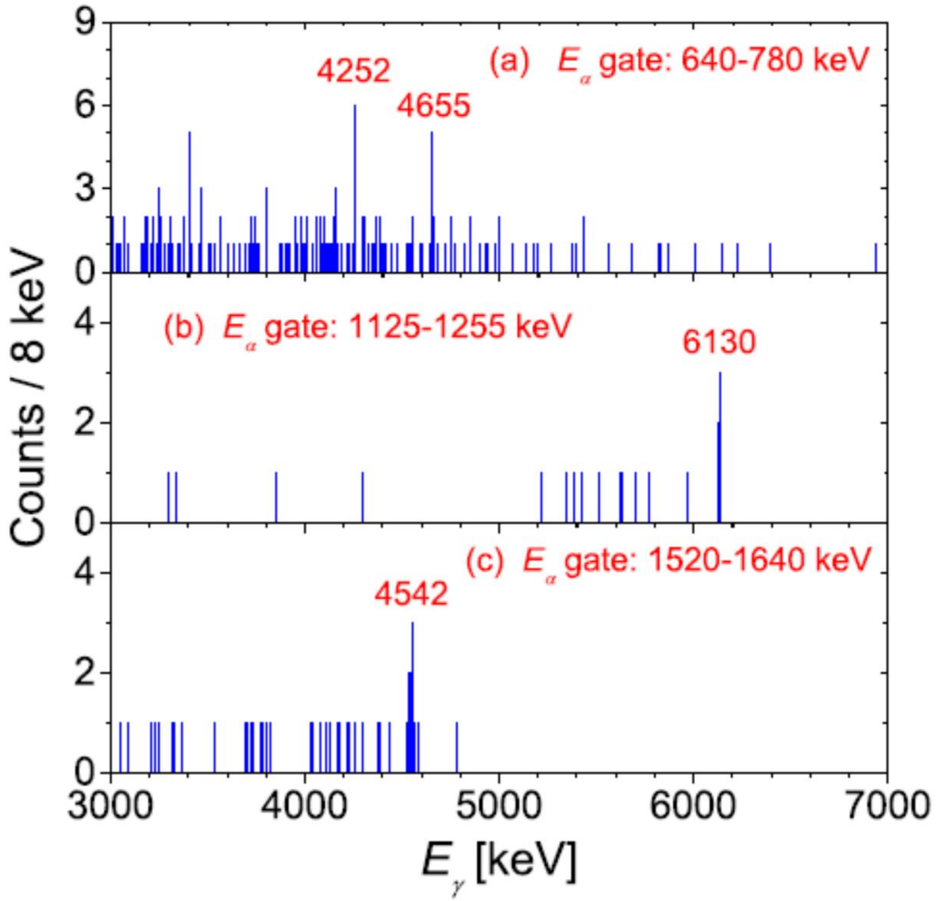
Day-1 experiment: Decay of ^{20}Na

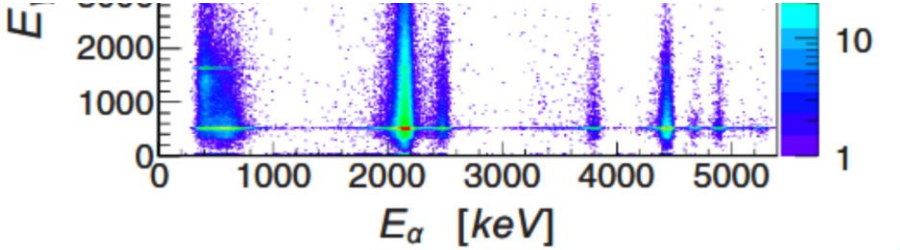




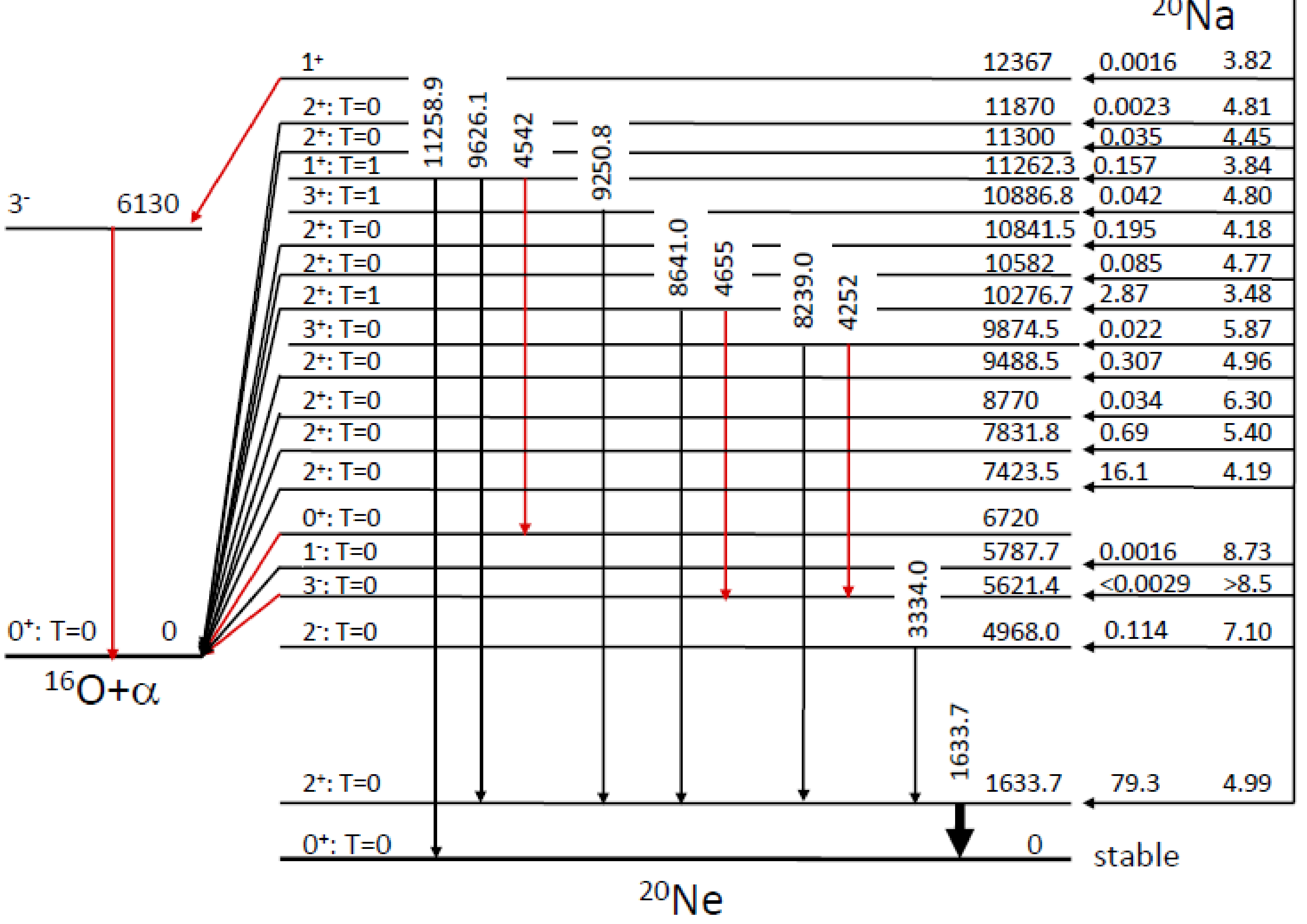
- Silicon box for β, two175% HPGe for γ
- two DSSDs for α particles
- Simultaneous measurement of β, γ and α for triple coincidence
- Implantation rate: ~1.5×10^4 pps

Direct observation of β–γ–α exotic decay mode

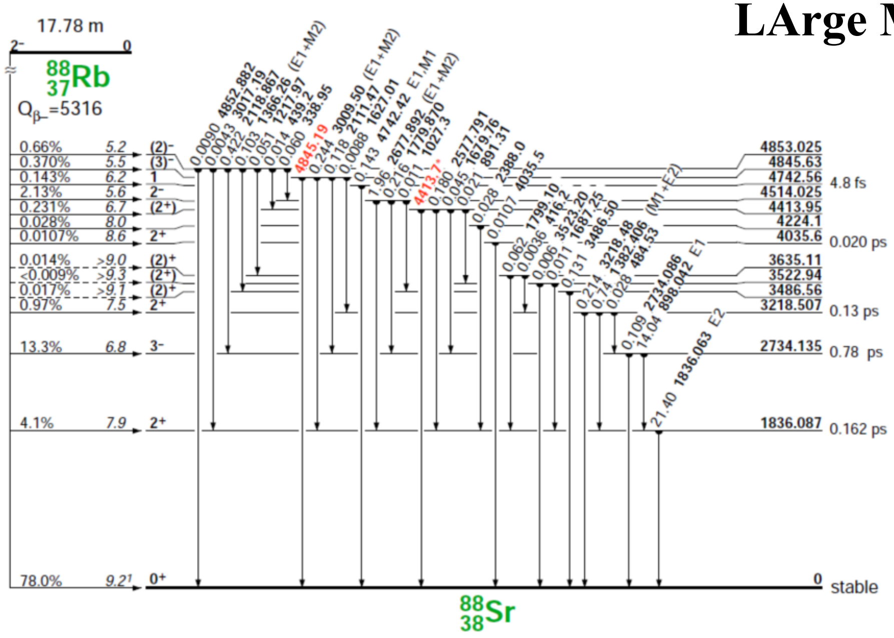




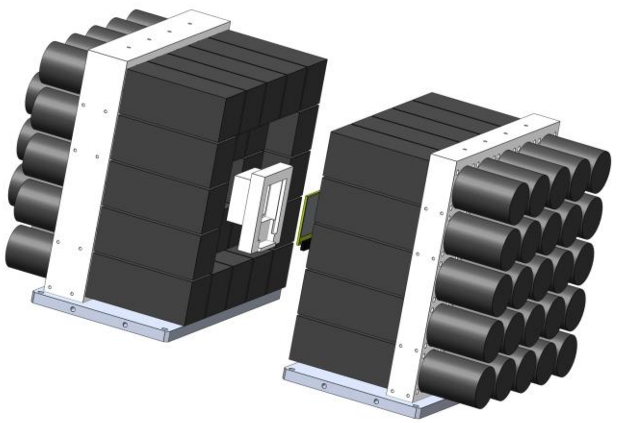
Y. B. Wang et al. PRC 103, L011301 (2021)

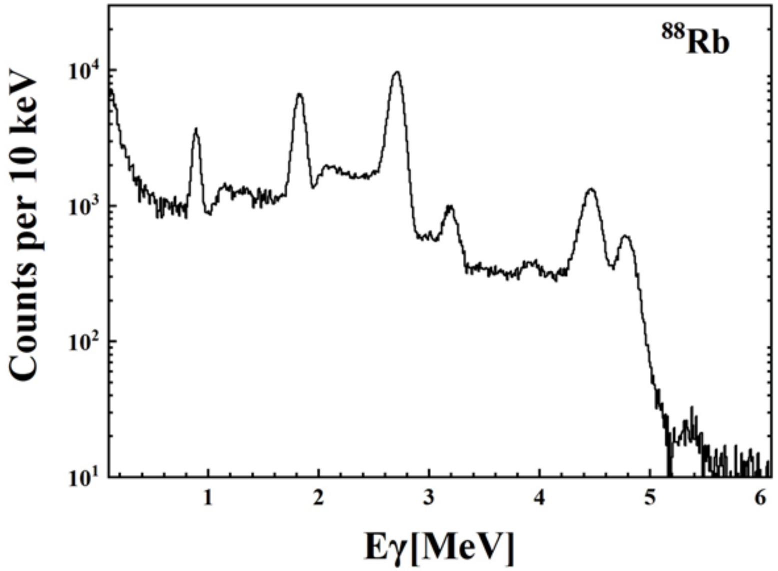


Total Absorption Gamma-ray Spectroscopy (TAGS)



LArge Module BGO Detector Array (LAMBDA)



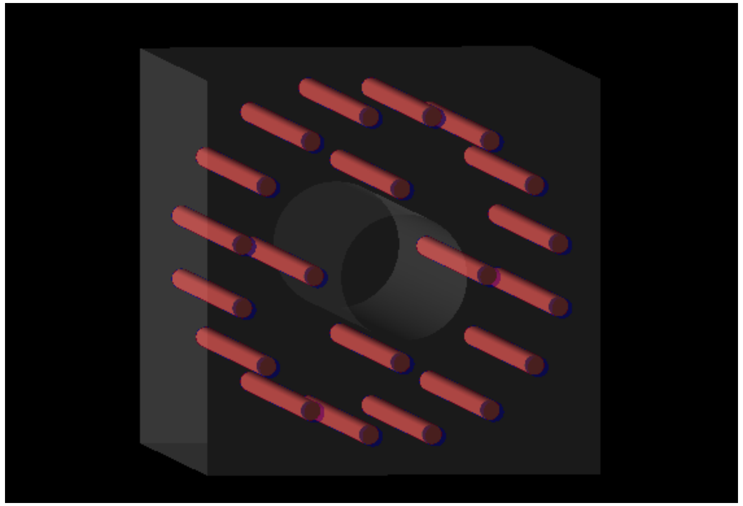


β feeding of ^{88}Rb

Ex (keV) in ^{88}Sr	Branching ratio (%)		
	LAMBDA	MTAS	ENDSF
0	77.8	78.2	76.51
1836	4.2	4.22	4.94
2734	13.0	12.8	13.59
3218	1.10	1.06	1.038
3486	0.00	0.02	0.016
3524	0.04	0.03	<0.003
3634	0.01	0.04	0.005
4035	0.02	0.014	0.0137
4224	0.10	0.008	0.03
4413	0.21	0.47	0.254
4514	2.20	1.87	2.319
4742	0.23	0.22	0.178
4845	0.41	0.59	0.401
4853	0.81	0.46	0.726

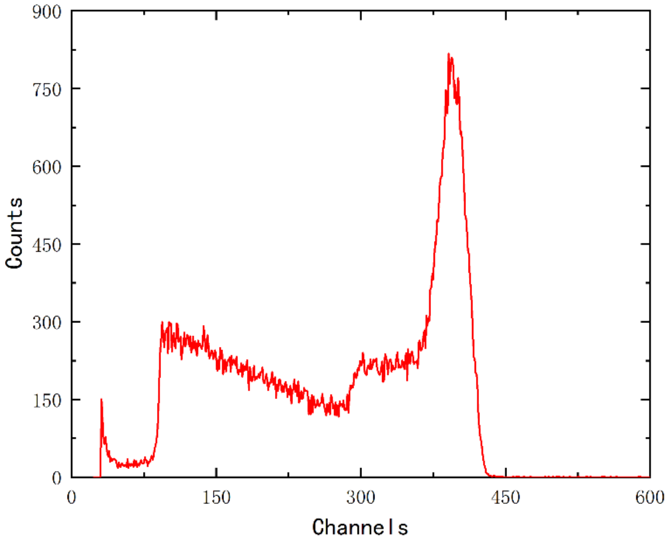
Measurements were done for ^{88}Rb, ^{90}Rb, ^{140}Cs, ^{142}Cs

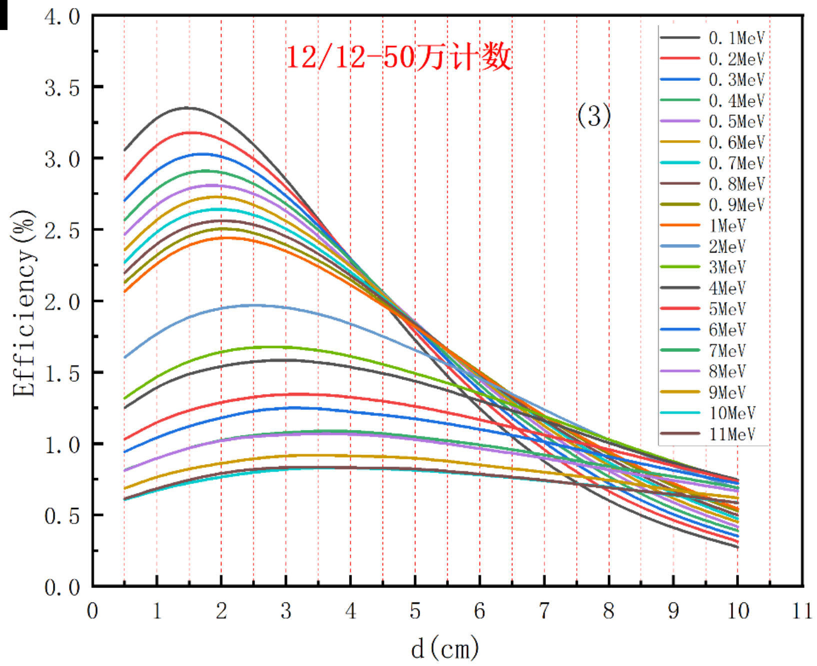
Long HElium-3 Neutron Array (LHENA)



long ^{3}He neutron array for β-delayed neutron emission probability @BRIF

- GEANT4 simulation
- ^{3}He tube testing





21 ^{3}He tubes, 800× ϕ25.4mm, 4 atm

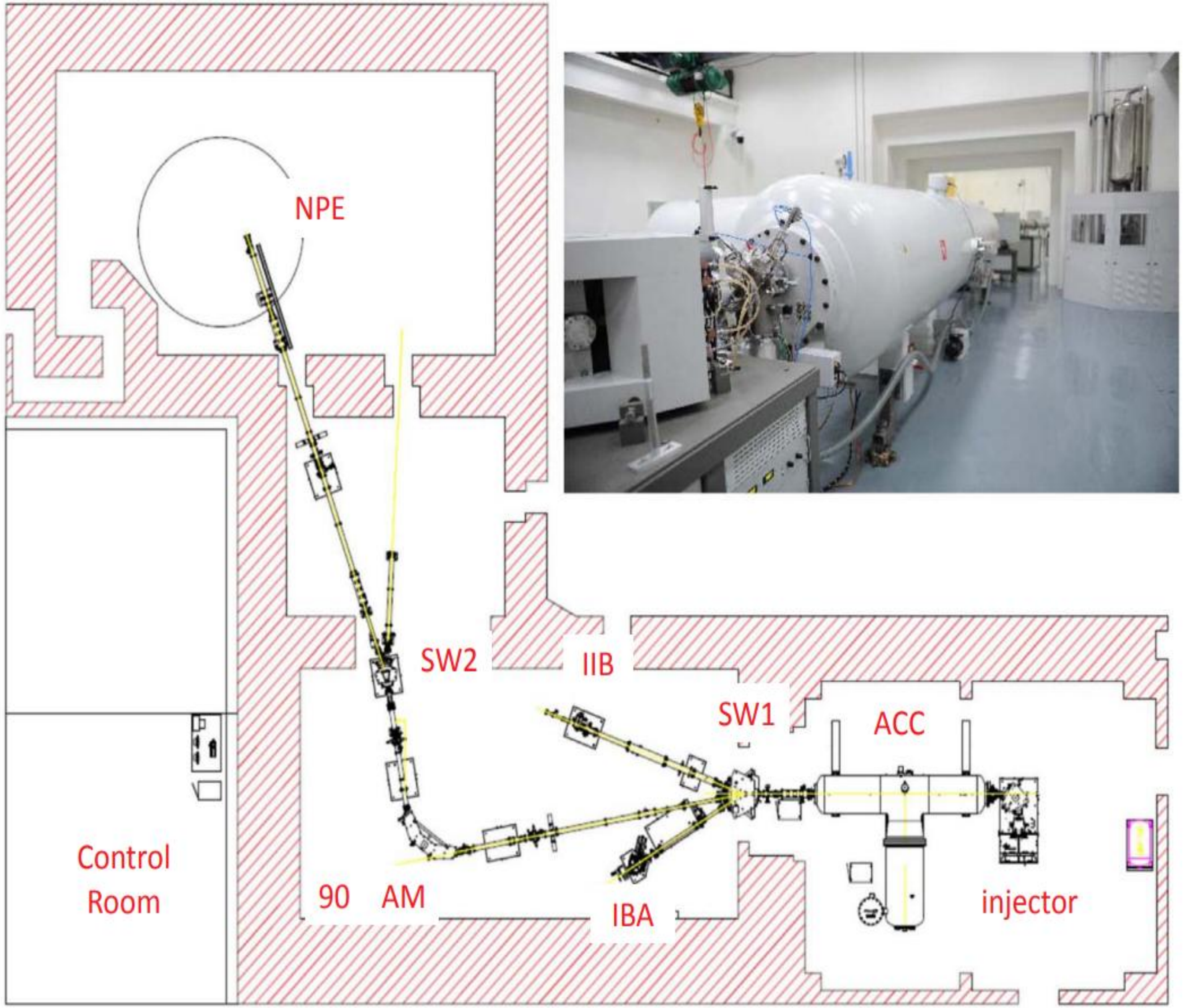
Calibration of LHENA with $^{51}V(p, n)^{51}Cr$

^{51}V： 100 μg/cm^2

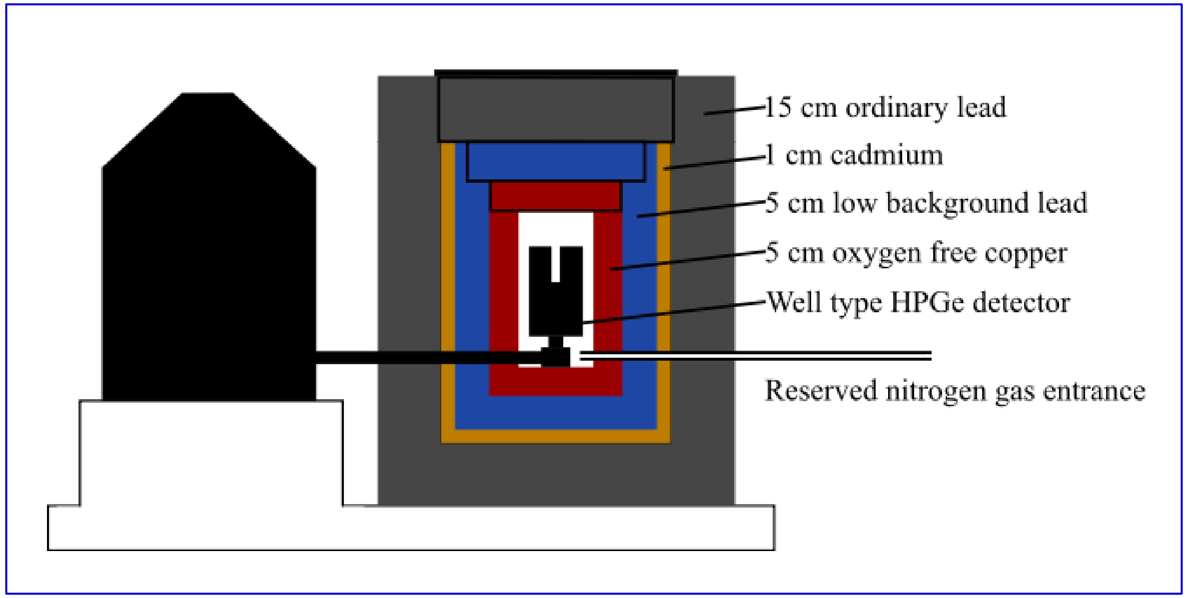
Ta backing： 1 mm in thickness

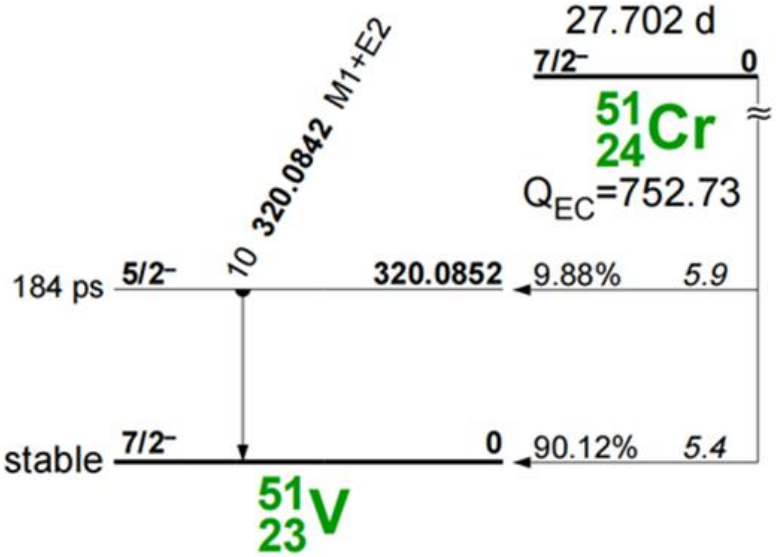
Ta backing： 15 mm in diameter

3 MV Tandem accelerator @Sichuan Univ.



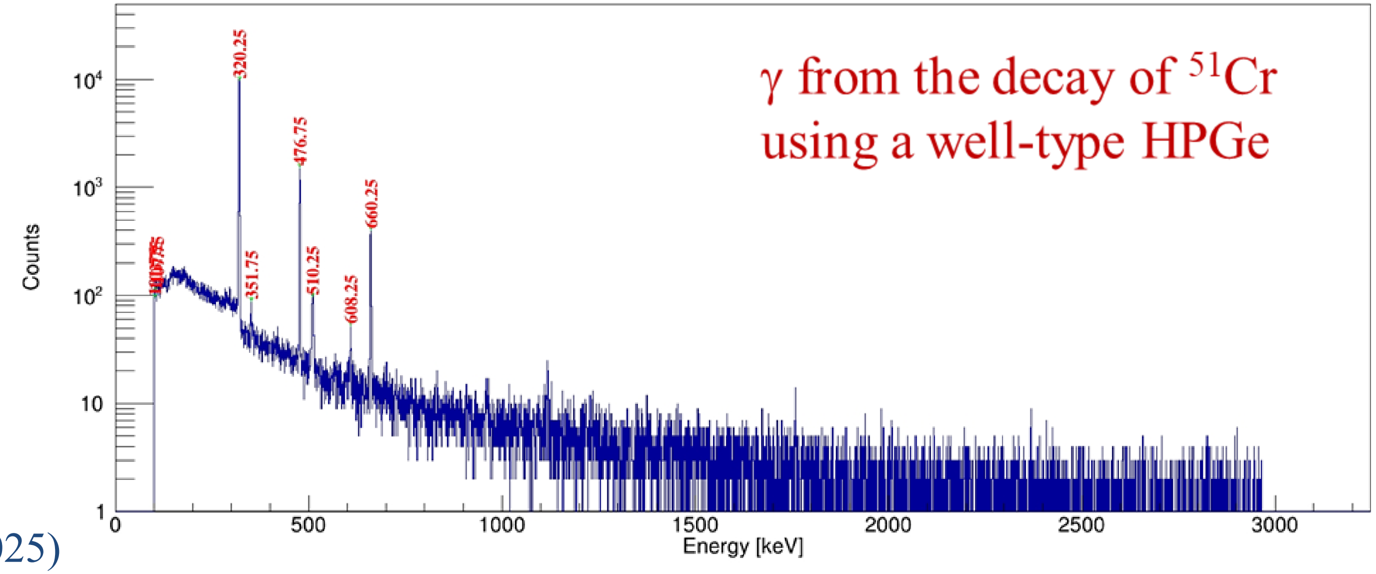
^{51}Cr by GNAS: Gamma-spectrometer for Nuclear Activation Study





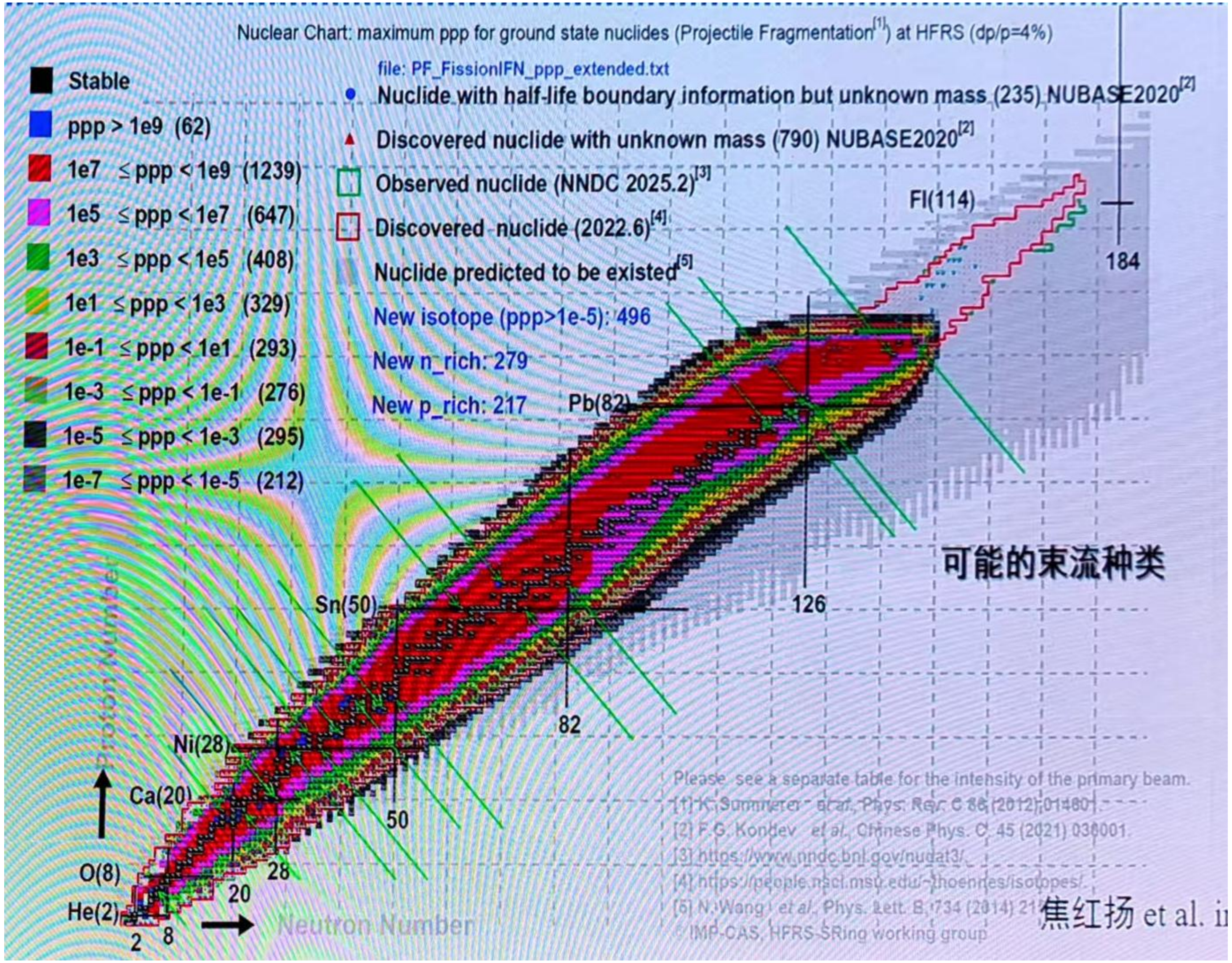
$$\varepsilon_n = n'/n$$

$$N_R = \frac{N_\gamma}{B \cdot \eta_{320}} \cdot \frac{e^{\lambda t_w}}{1 - e^{-\lambda t_c}} \cdot \frac{\lambda \cdot t_i}{1 - e^{-\lambda t_i}}$$



Min-Hao Zhu, You-Bao Wang* et al. Nucl. Sci. Tech. 36:182 (2025)

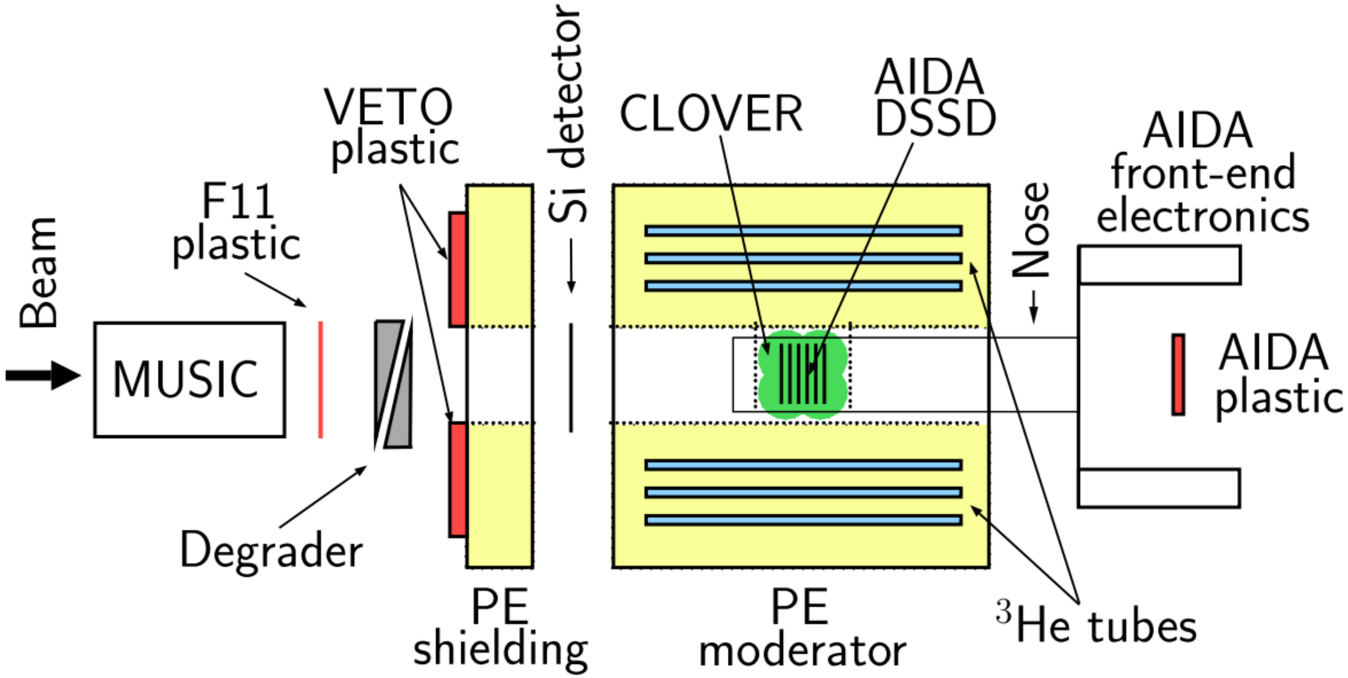
Very neutron rich isotopes at HIAF

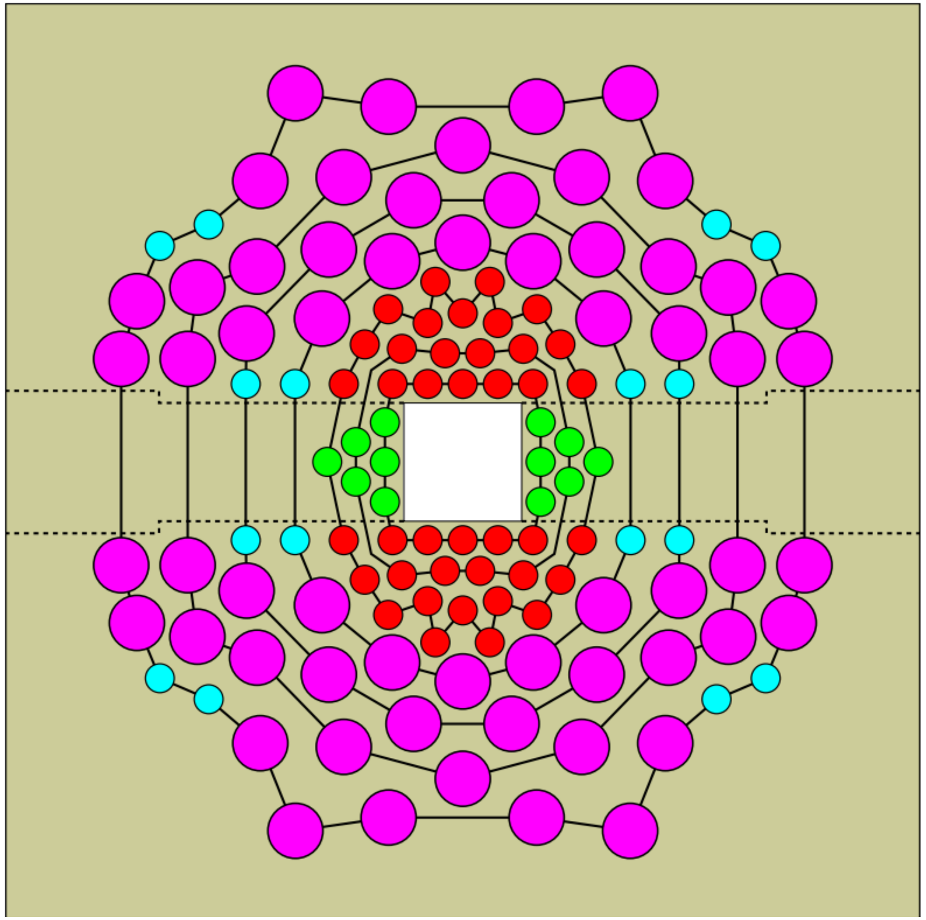


BRIKEN @BIGRIPS

Main characteristics (gas volume and pressure) and number of the different types of ^{3}He tubes used in the BRIKEN neutron counter.

Type	Length (mm)	Diameter (mm)	Pressure (atm)	Number
RIKEN	300	25.4	5	24
UPC	600	25.4	8	40
ORNL1	609.6	25.4	10	16
ORNL2	609.6	50.8	10	60





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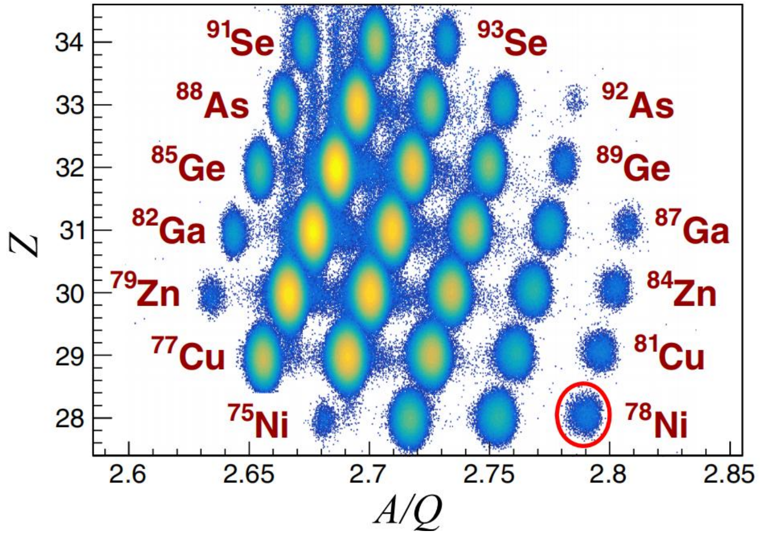
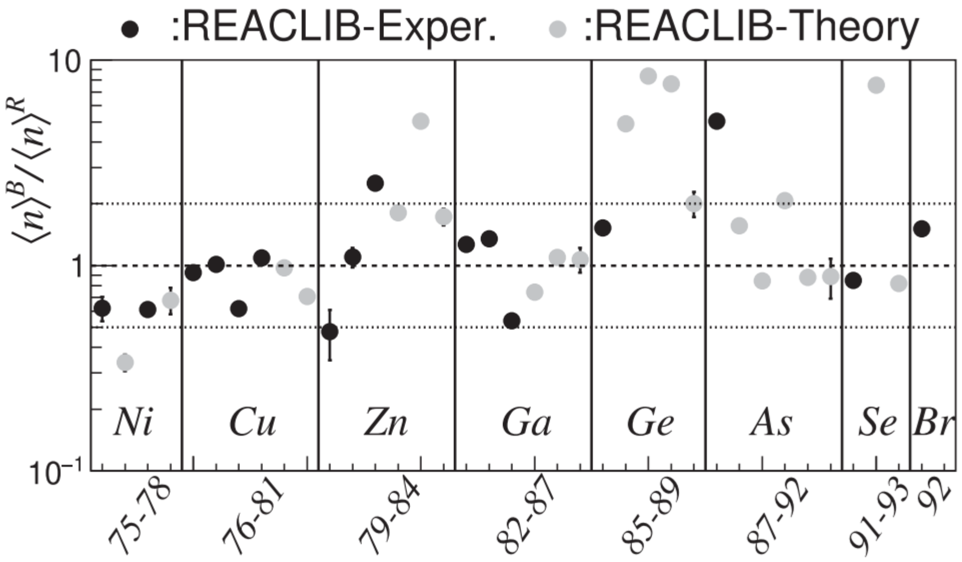


Neutron emission probabilities and half-lives of 37 β-delayed neutron emitters from ^{75}Ni to ^{92}Br were measured at the RIKEN Nishina Center in Japan, including 11 one-neutron and 13 two-neutron emission probabilities and six half-lives for the first time that supersede theoretical estimates



Nucleus	$T_{1/2}$ (ms)	P_{1n} (%)	P_{2n} (%)
^{75}Ni	331.8(32)†	6.20(83)	...
^{76}Ni	234.7(27)†	8.78(82)	...
^{77}Ni	158.4(44)†	18.4(15)	...
^{78}Ni	122.2(51)†	25.8(38)	...
^{76}Cu	637.5(80)†	6.65(55)	...
^{77}Cu	469.8(20)†	30.8(13)	...
^{78}Cu	331.7(20)†	40.2(15)	...
^{79}Cu	241.3(21)†	59.9(24)	...
^{80}Cu	114.0(24)	56.5(28)	< 0.55
^{81}Cu	75.8(38)	71.1(57)	2.2(13)
^{79}Zn	839.1(75)	0.62(17)	...
^{80}Zn	562.0(30)†	1.10(12)	...
^{81}Zn	303.7(31)†	18.88(73)	...
^{82}Zn	177.9(25)†	61.4(25)	...
^{83}Zn	99.7(30)†	57.4(29)	2.17(44)
^{84}Zn	53.6(81)†	64.0(59)	< 2
^{82}Ga	600.9(20)†	25.2(11)	...
^{83}Ga	308.4(10)†	84.7(44)	...
^{84}Ga	92.70(70)†	37.3(22)	1.61(13)
^{85}Ga	91.9(12)†	71.2(25)	1.90(16)

(Table continued)

Summary

- HIAF provides exciting opportunities for the study of β-delayed neutron emission for very neutron-rich nuclei of nuclear astrophysics significance.
- In some cases, BRIF could provide benchmark measurement and cross-check.
- Need to learn from BRIKEN experiments and start the collaboration at HIAF in time.

Thank you for your attention!