Compilation of beta-delayed neutron emission data

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IAEA

International Atomic Energy Agency

Outlook

- EXFOR compilation of beta-delayed neutron (βdn) data in the past
- Motivation for the compilation of the βdn data from individual precursors
- Main parameters of the βdn emission
- LEXFOR update (**Memo CP-C/429** 23 May 2014)
- Experimental techniques for the measurement of βdn emission probabilities and spectra

Compilation of β*dn* data in the past

- **Total Average Delayed Fission Neutron Yield** ((…(N,F),DL,NU)): extensively compiled
- **Partial (Group) Delayed Fission Neutron Yields** (relative ((…(N,F),DL/GRP,NU)/(…(N,F),DL,NU)) and absolute (…(N,F),DL/GRP,NU)): extensively compiled
- **Delayed-Neutron Energy Spectrum for a Given Neutron Group** ((…(N,F),DL/GRP,NU/DE)): mainly evaluated data
- **Delayed-Neutron Emission Probability (P_n value)** ((Z-S-A(0,B-)Z'-S'-A',,PN) for a single fragment; (ELEM/MASS(0,B-),,PN) for a series of fragments) : no completeness in some cases compiled as (Z-S-A(X,F) ELEM/MASS(,DL,NU).
- **Energy spectrum** of the neutrons emitted by a **specific precursor**: not compiled

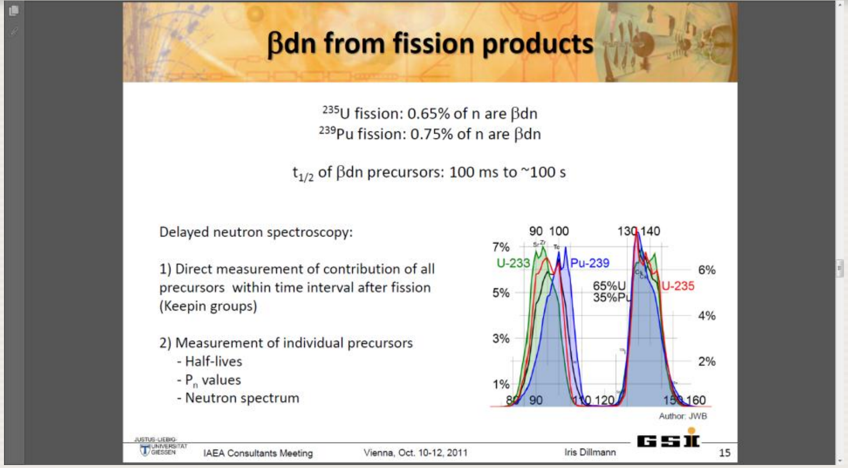
Motivation for the compilation of βdn data from individual precursors

- Nuclear technologies (reactor kinetics, decay heat calculations etc.)
- Nuclear astrophysics
- Nuclear model calculations
- Nuclear structure

Motivation for the compilation of β*dn* data from individual precursors – nuclear technologies -I

- The β*dn* are essential for **reactor kinetics**, **safety and decay heat** calculations. Critical assemblies are sensitive to the β*dn* data.
- The new developments of advanced reactors, ADS etc., considerably extend the type of the targets, projectiles and excitation energies involved in the nuclear fission or fragmentation processes, as well as the nuclear composition and its dynamics during the fuel cycle.

Motivation for the compilation of *βdn* data from individual precursors – nuclear technologies -II



βdn from fission products

^{235}U fission: 0.65% of n are βdn
^{239}Pu fission: 0.75% of n are βdn

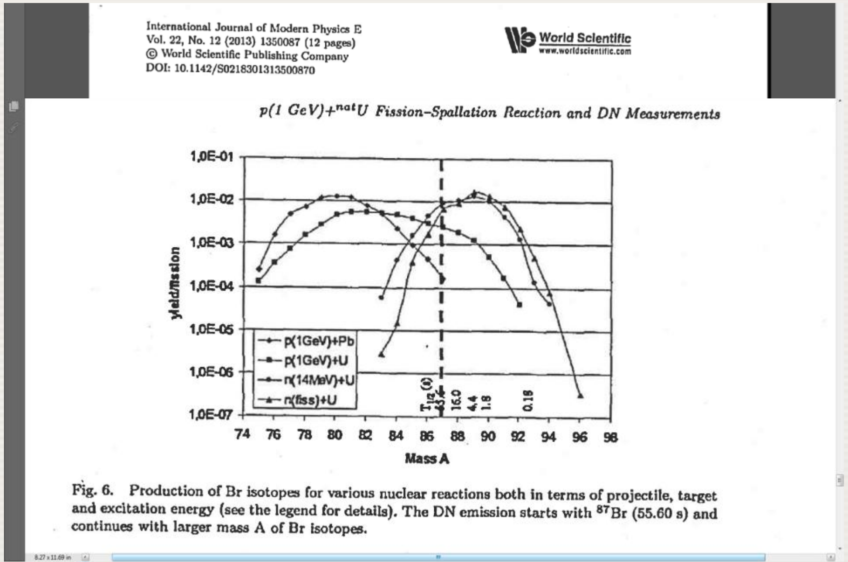
$t_{1/2}$ of βdn precursors: 100 ms to ~100 s

Delayed neutron spectroscopy:

1) Direct measurement of contribution of all precursors within time interval after fission (Keepin groups)

2) Measurement of individual precursors
   - Half-lives
   - P_n values
   - Neutron spectrum

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN IAEA Consultants Meeting Vienna, Oct. 10-12, 2011 Iris Dillmann GSI 15



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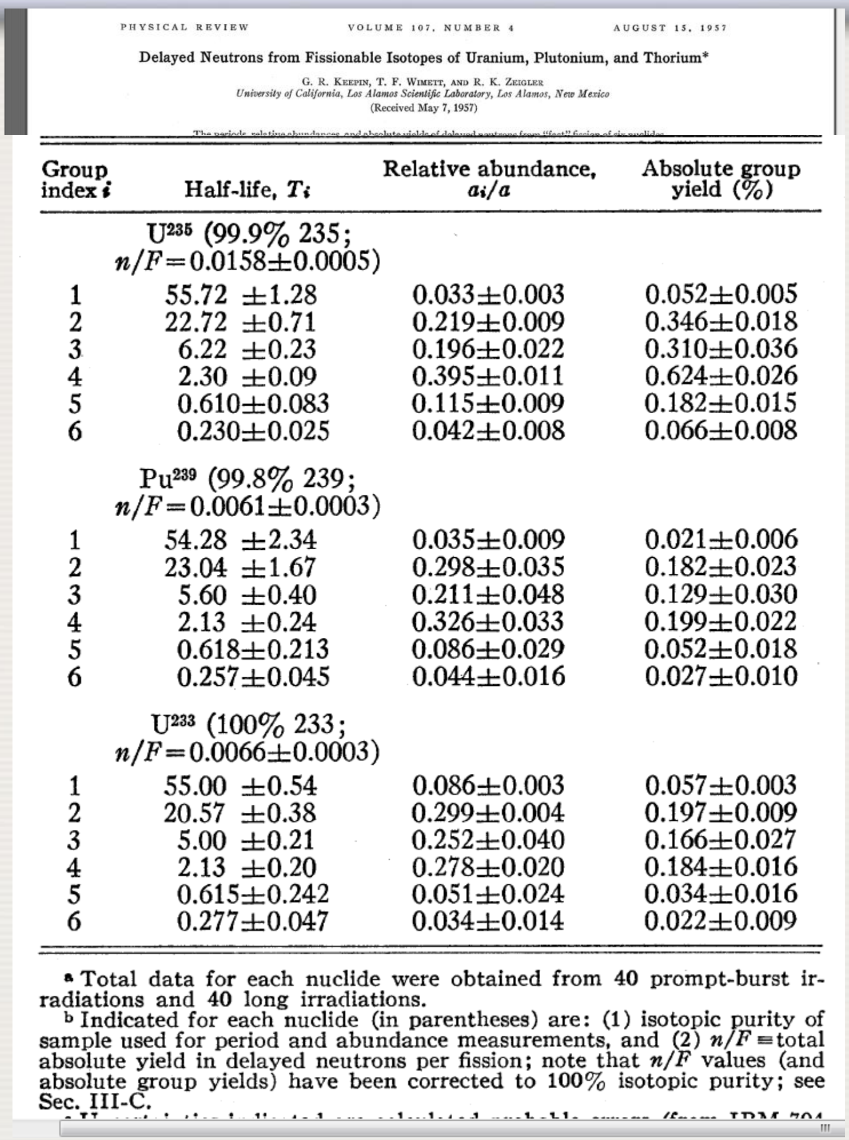
p(1 GeV)+^{nat}U Fission–Spallation Reaction and DN Measurements

Fig. 6. Production of Br isotopes for various nuclear reactions both in terms of projectile, target and excitation energy (see the legend for details). The DN emission starts with ^{87}Br (55.60 s) and continues with larger mass A of Br isotopes.

8.27 x 11.69 in



PHYSICAL REVIEW VOLUME 107, NUMBER 4 AUGUST 15, 1957

Delayed Neutrons from Fissionable Isotopes of Uranium, Plutonium, and Thorium*

G. R. Keepin, T. F. Wimett, and R. K. Zeigler
University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico

(Received May 7, 1957)

The periods, relative abundances, and absolute yields of delayed neutrons from "fast" fission of six nuclides.

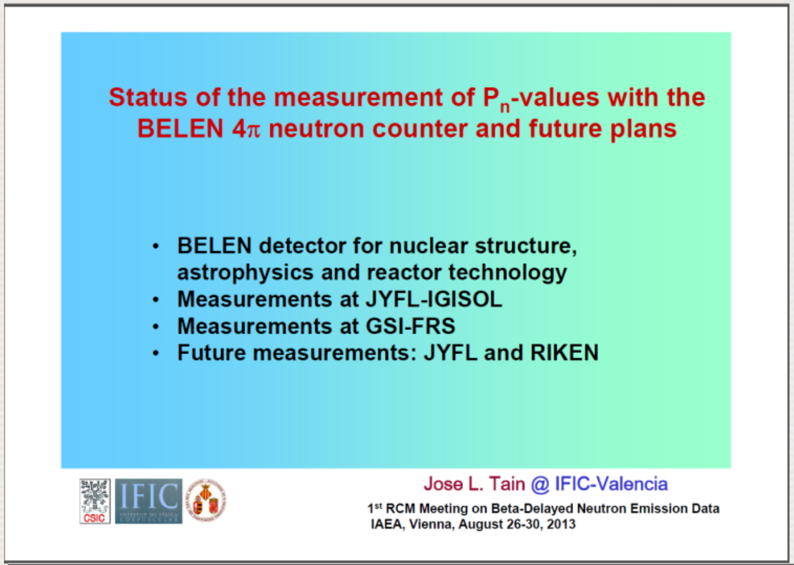
Group index i	Half-life, T_i	Relative abundance, a_i/a	Absolute group yield (%)
	U^{235} (99.9% 235; $n/F=0.0158\pm0.0005$)		
1	55.72 ± 1.28	0.033 ± 0.003	0.052 ± 0.005
2	22.72 ± 0.71	0.219 ± 0.009	0.346 ± 0.018
3	6.22 ± 0.23	0.196 ± 0.022	0.310 ± 0.036
4	2.30 ± 0.09	0.395 ± 0.011	0.624 ± 0.026
5	0.610 ± 0.083	0.115 ± 0.009	0.182 ± 0.015
6	0.230 ± 0.025	0.042 ± 0.008	0.066 ± 0.008
	Pu^{239} (99.8% 239; $n/F=0.0061\pm0.0003$)		
1	54.28 ± 2.34	0.035 ± 0.009	0.021 ± 0.006
2	23.04 ± 1.67	0.298 ± 0.035	0.182 ± 0.023
3	5.60 ± 0.40	0.211 ± 0.048	0.129 ± 0.030
4	2.13 ± 0.24	0.326 ± 0.033	0.199 ± 0.022
5	0.618 ± 0.213	0.086 ± 0.029	0.052 ± 0.018
6	0.257 ± 0.045	0.044 ± 0.016	0.027 ± 0.010
	U^{233} (100% 233; $n/F=0.0066\pm0.0003$)		
1	55.00 ± 0.54	0.086 ± 0.003	0.057 ± 0.003
2	20.57 ± 0.38	0.299 ± 0.004	0.197 ± 0.009
3	5.00 ± 0.21	0.252 ± 0.040	0.166 ± 0.027
4	2.13 ± 0.20	0.278 ± 0.020	0.184 ± 0.016
5	0.615 ± 0.242	0.051 ± 0.024	0.034 ± 0.016
6	0.277 ± 0.047	0.034 ± 0.014	0.022 ± 0.009

[a] Total data for each nuclide were obtained from 40 prompt-burst irradiations and 40 long irradiations.

[b] Indicated for each nuclide (in parentheses) are: (1) isotopic purity of sample used for period and abundance measurements, and (2) $n/F\equiv$total absolute yield in delayed neutrons per fission; note that n/F values (and absolute group yields) have been corrected to 100% isotopic purity; see Sec. III-C.

Motivation for the compilation of *βdn* data from individual precursors – nuclear astrophysics and structure

https://www-nds.iaea.org/beta-delayed-neutron/1RCM/presentations/BELEN-IAEA-Aug2013.pdf

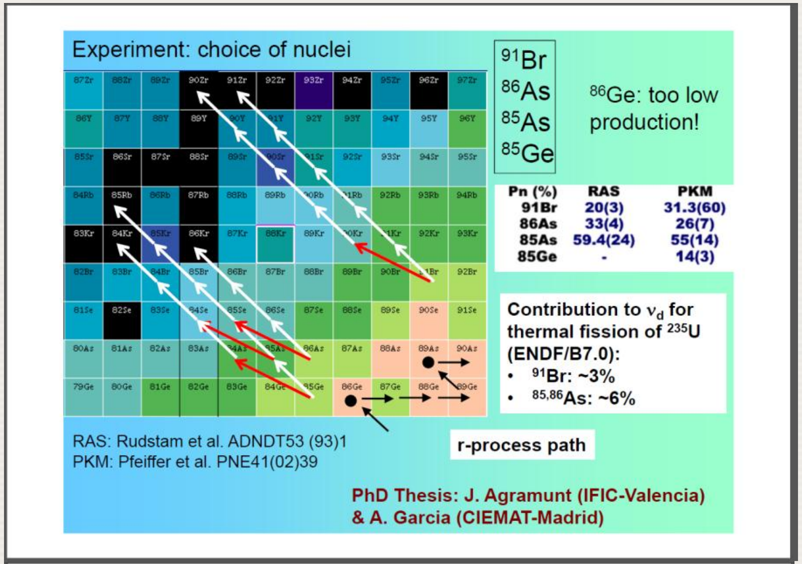


Status of the measurement of P_n-values with the BELEN 4π neutron counter and future plans

- **BELEN detector for nuclear structure, astrophysics and reactor technology**
- **Measurements at JYFL-IGISOL**
- **Measurements at GSI-FRS**
- **Future measurements: JYFL and RIKEN**

Jose L. Tain @ IFIC-Valencia

1st RCM Meeting on Beta-Delayed Neutron Emission Data
IAEA, Vienna, August 26-30, 2013



Experiment: choice of nuclei

^{91}Br
^{86}As
^{85}As
^{85}Ge

^{86}Ge: too low production!

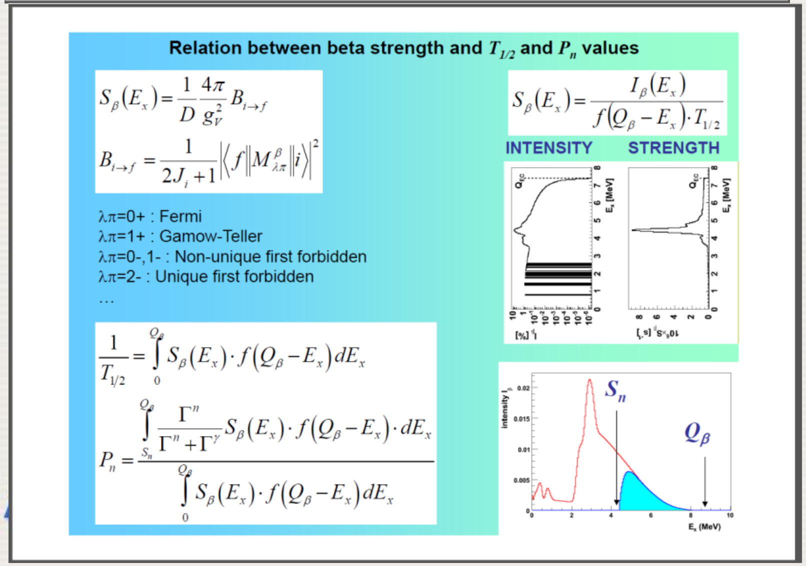
Pn (%)	RAS	PKM
91Br	20(3)	31.3(60)
86As	33(4)	26(7)
85As	59.4(24)	55(14)
85Ge	-	14(3)

Contribution to ν_d for thermal fission of ^{235}U (ENDF/B7.0):
- **^{91}Br: ~3%**
- **^{85,86}As: ~6%**

RAS: Rudstam et al. ADNDT53 (93)1
PKM: Pfeiffer et al. PNE41(02)39

r-process path

PhD Thesis: J. Agramunt (IFIC-Valencia) & A. Garcia (CIEMAT-Madrid)



Relation between beta strength and $T_{1/2}$ and P_n values

$$S_\beta(E_x) = \frac{1}{D}\frac{4\pi}{g_V^2} B_{i\to f}$$

$$B_{i\to f} = \frac{1}{2J_i+1}\left|\left\langle f \left\| M^{\beta}_{\lambda\pi} \right\| i \right\rangle\right|^2$$

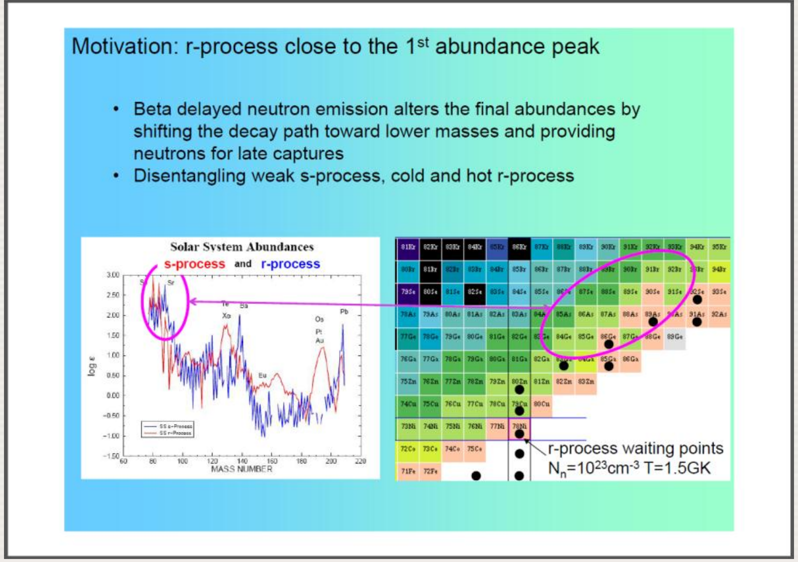
$\lambda\pi$=0+ : Fermi
$\lambda\pi$=1+ : Gamow-Teller
$\lambda\pi$=0-,1- : Non-unique first forbidden
$\lambda\pi$=2- : Unique first forbidden
…

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

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

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

INTENSITY **STRENGTH**

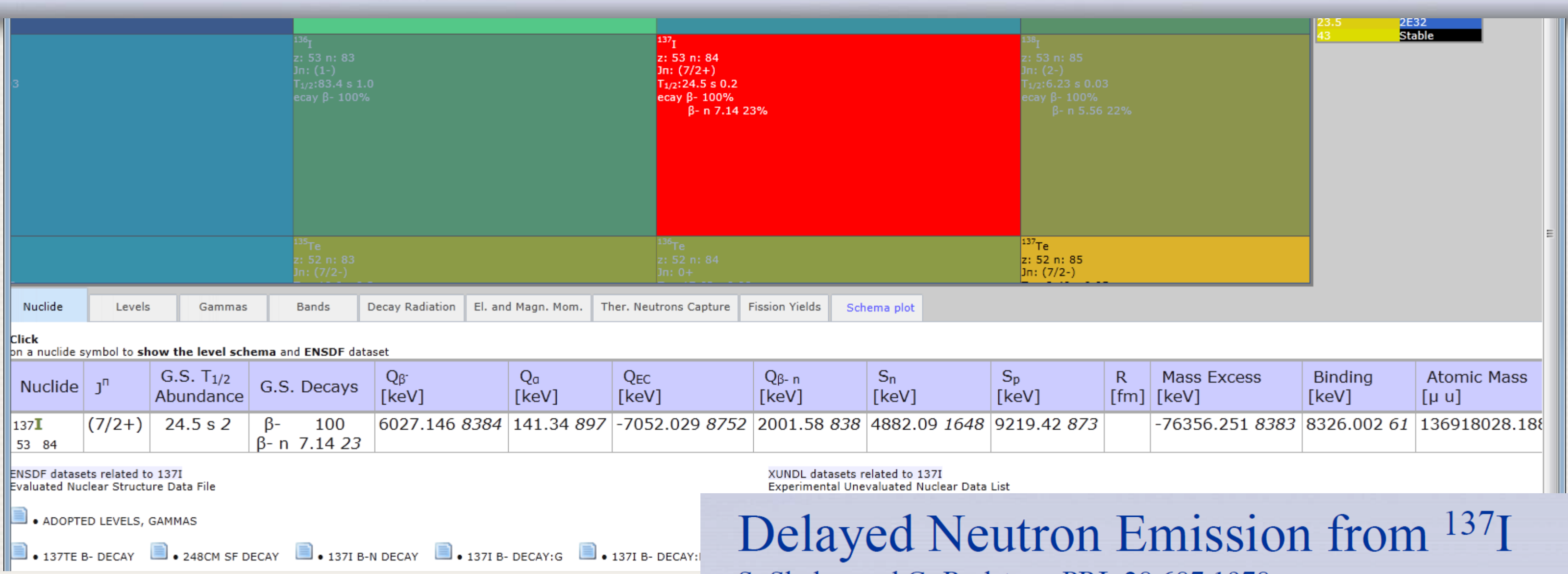


Motivation: r-process close to the 1st abundance peak

- Beta delayed neutron emission alters the final abundances by shifting the decay path toward lower masses and providing neutrons for late captures
- Disentangling weak s-process, cold and hot r-process

r-process waiting points
$N_n=10^{23}$cm^{-3} T=1.5GK

βdn spectra



3

^{136}I
z: 53 n: 83
Jπ: (1-)
$T_{1/2}$:83.4 s 1.0
ecay β- 100%

^{137}I
z: 53 n: 84
Jπ: (7/2+)
$T_{1/2}$:24.5 s 0.2
ecay β- 100%
β- n 7.14 23%

^{138}I
z: 53 n: 85
Jπ: (2-)
$T_{1/2}$:6.23 s 0.03
ecay β- 100%
β- n 5.56 22%

23.5 | 2E32
43 | Stable

^{135}Te
z: 52 n: 83
Jπ: (7/2-)

^{136}Te
z: 52 n: 84
Jπ: 0+

^{137}Te
z: 52 n: 85
Jπ: (7/2-)

Click
on a nuclide symbol to **show the level schema** and **ENSDF** dataset

Nuclide	Jπ	G.S. $T_{1/2}$ Abundance	G.S. Decays	Q_{β^-} [keV]	Q_α [keV]	Q_{EC} [keV]	$Q_{\beta^- n}$ [keV]	S_n [keV]	S_p [keV]	R [fm]	Mass Excess [keV]	Binding [keV]	Atomic Mass [μ u]
137**I** 53 84	(7/2+)	24.5 s *2*	β- 100 β- n 7.14 *23*	6027.146 *8384*	141.34 *897*	-7052.029 *8752*	2001.58 *838*	4882.09 *1648*	9219.42 *873*		-76356.251 *8383*	8326.002 *61*	136918028.18

ENSDF datasets related to 137I
Evaluated Nuclear Structure Data File

- ADOPTED LEVELS, GAMMAS
- 137TE B- DECAY
- 248CM SF DECAY
- 137I B-N DECAY
- 137I B- DECAY:G
- 137I B- DECAY:

XUNDL datasets related to 137I
Experimental Unevaluated Nuclear Data List

$B_n < Q_\beta$
Accurate mass
measurements
needed

Delayed Neutron Emission from ^{137}I

S. Shalev and G. Rudstam, PRL,28,687,1978

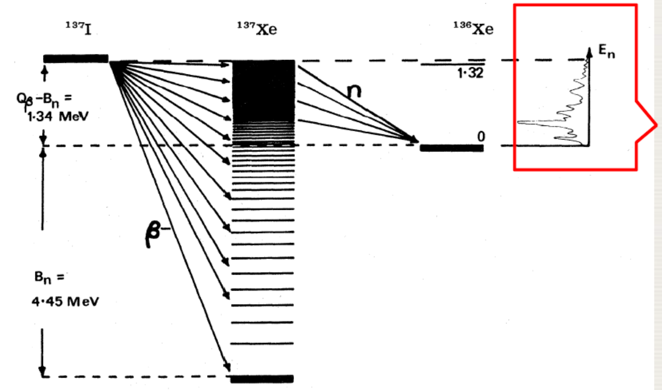


FIG. 2. Energy-level diagram for β-delayed neutron emission from ^{137}Xe.

Fine structure that reflects both decay characteristics of the precursor and the level structure of the daughter.

βdn emission probability and multiplicity

Emission probability

(et least one neutron emission)

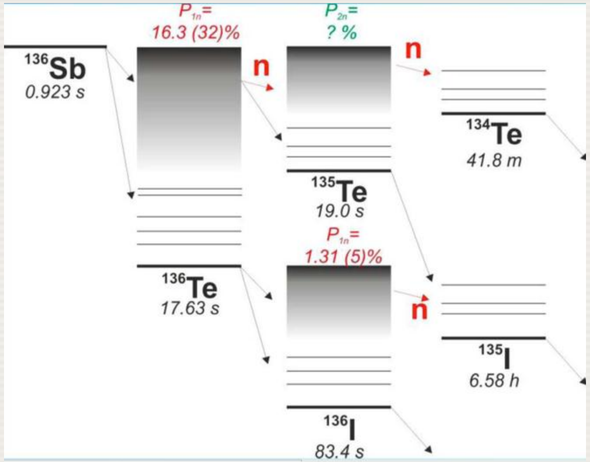
$P_n(\%)=P_{1n}+P_{2n}+P_{3n}+\ldots$

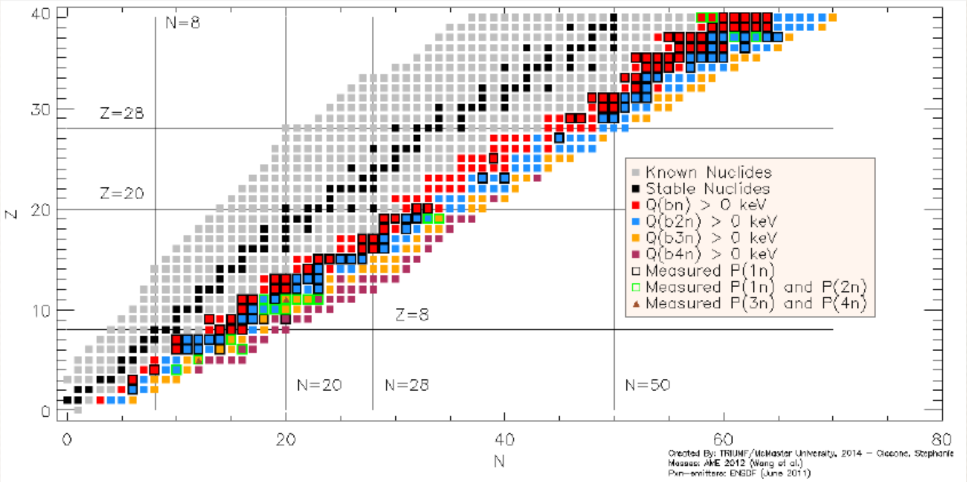
$P_{0n}=100\% - P_n$

Multiplicity

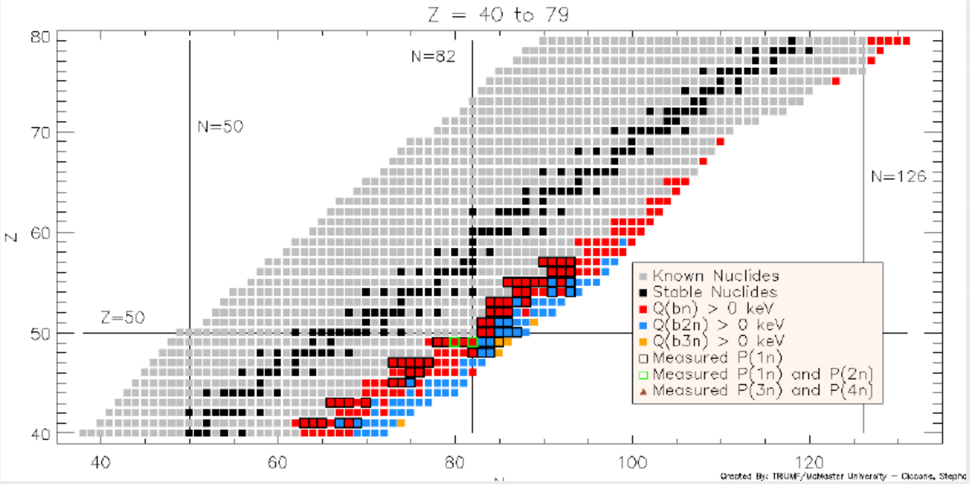
(average number of neutrons per decay)

$n_n(\%)=0.P_{0n}+1.P_{1n}+2.P_{2n}+3.P_{3n}+\ldots$





Created By: TRIUMF/McMaster University, 2014 – Ciccone, Stephanie
Masses: AME 2012 (Wang et al.)
Pxn-emitters: ENSDF (June 2011)



Created By: TRIUMF/McMaster University – Ciccone, Stepha

Memo CP-C/429

- The delayed neutron **emission probability** (=probability for emission of at least one beta-delayed neutron), **P_n** , is coded as ,**PN** with units **NO-DIM**.
- The **probability of emission of N beta-delayed** neutrons, **P_{Nn}**, is coded as **NUM,PN** with units **NO-DIM**. *(No change from 4C-3/396)*
- The **delayed-neutron emission multiplicity**, **<n>**, is coded as ,**MLT,DN** with units **PRT/DECAY** or **PC/DECAY**.
- The **energy spectrum of delayed neutrons** emitted by a specific precursor is coded as ,**PN/DE** with units of dimension **1/E**. *(Modified from CP-D/837)*

Experimental techniques for the measurement of *βdn* emission probabilities and spectra

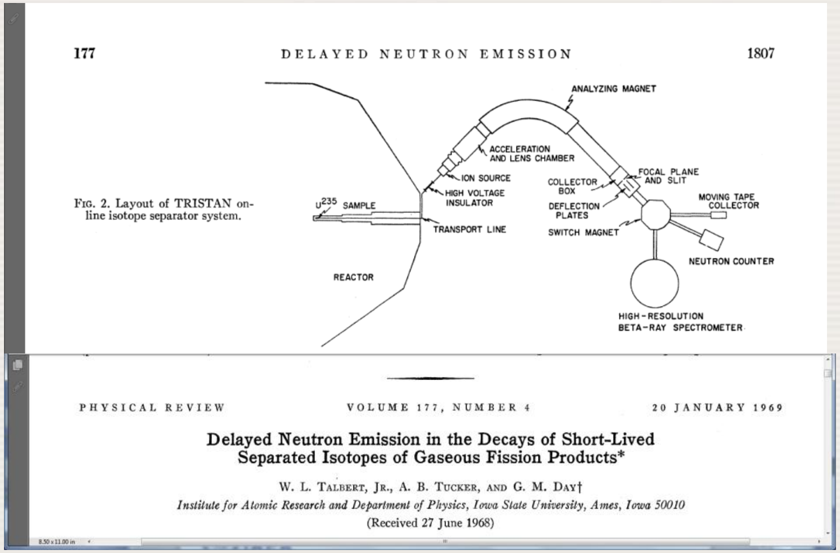
- Facilities / production of *βdn* precursors
- Methods for determination/identification/extraction of the precursors
- Measurements of the particles/radiation involved in the proses (neutrons, beta-particles, gamma-rays)
- Selection methods
- Analysis

Facilities / production of βdn precursors

Facility	βdn precursors source	βdn precursors separation	METHOD
ILL Grenoble France Univ. Mainz, Germany Studsvik, Sweden HFBR, Brookhaven Nat. Lab., USA	$n_{th} + {}^{nat}U$ $n_{th} + {}^{nat}U$ $n_{th} + {}^{nat}U$ $n_{th} + {}^{nat}U$ ${}^{56}Fe/Al$ and Sc/Ti filtered neutron beam	LOHENGRIN recoil mass sep. Chemical sep. techniques OSIRIS On-line isotope sep. TRISTAN On-line mass sep.	NIFIS
CERN	p (1GeV) + ${}^{nat}U$	ISOLDE On-line mass sep	PIFIS
GSI, Germany	${}^{238}U$ (1 GeV/u) +Be	FRB Fragment separator + (TOF+dE) isotope identification	HIIFR
Holyfield Radioactive Ion Beam Facility (HRIBF) Oak Ridge Net. Lab., USA	p (50 MeV) + ${}^{nat}U$	IRIS-1 + IRIS2 + selective laser ionization	PIFIS
Cyclotron Lab. Of Univ. of Jyvaskyla	p (25 MeV) + Th	Mass separator + penning trap	PIFIS
RIPS at RIKEN	${}^{40}Ar + {}^{nat}Ta$	Fragment separator + (TOF+dE) isotope identification	HIIFR
…..			

Methods for determination/identification/extraction of the specific precursor - I

- Very early experiments based on chemistry. No direct identification of β-decay but rather based on yield distribution of fission fragments.
- Extraction of fission fragments based on mass separation



177 DELAYED NEUTRON EMISSION 1807

FIG. 2. Layout of TRISTAN on-line isotope separator system.

PHYSICAL REVIEW VOLUME 177, NUMBER 4 20 JANUARY 1969

Delayed Neutron Emission in the Decays of Short-Lived Separated Isotopes of Gaseous Fission Products*

W. L. TALBERT, JR., A. B. TUCKER, AND G. M. DAY†

Institute for Atomic Research and Department of Physics, Iowa State University, Ames, Iowa 50010

(Received 27 June 1968)

Isotope identification and

β activity determination

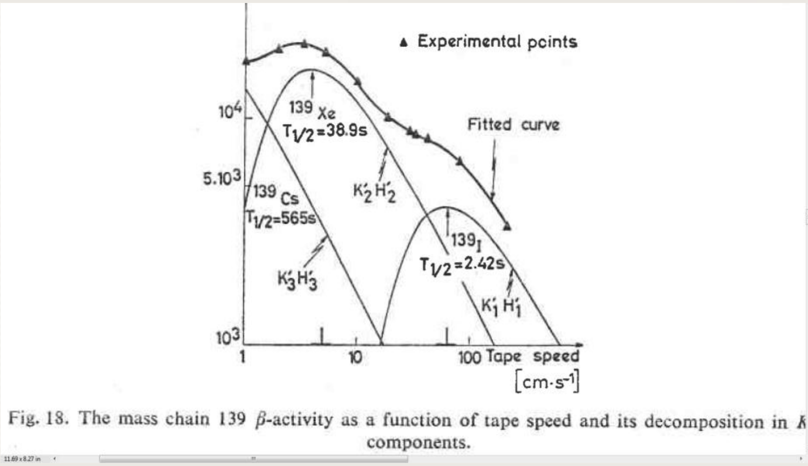
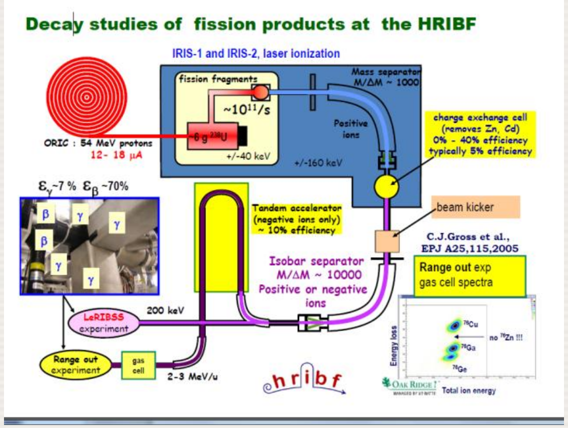


Fig. 18. The mass chain 139 β-activity as a function of tape speed and its decomposition in K components.

Methods for determination/identification/extraction of the specific precursor - II

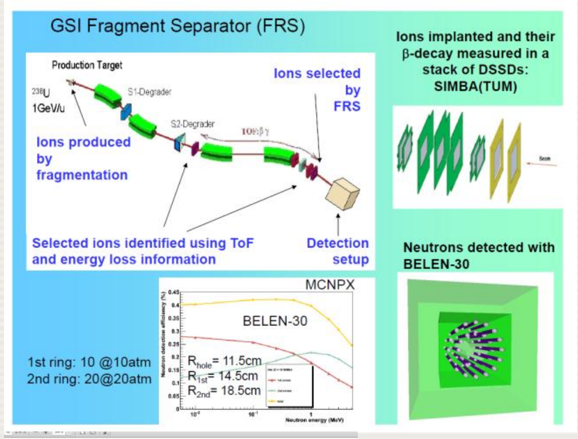
- Variety of beam purification methods:

Selective laser ionization

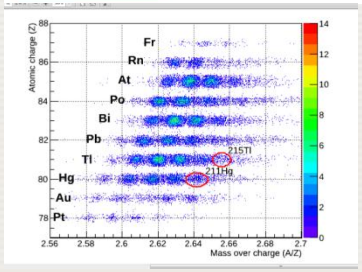


Decay studies of fission products at the HRIBF

ToF techniques

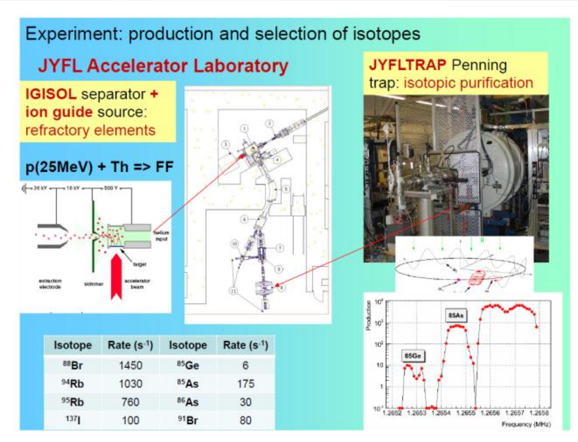


GSI Fragment Separator (FRS)



R. Caballero-Folch,
Nucl. Data Sheets
120 (2014) 81

Penning traps



Experiment: production and selection of isotopes

JYFL Accelerator Laboratory

IGISOL separator **+ ion guide** source: refractory elements

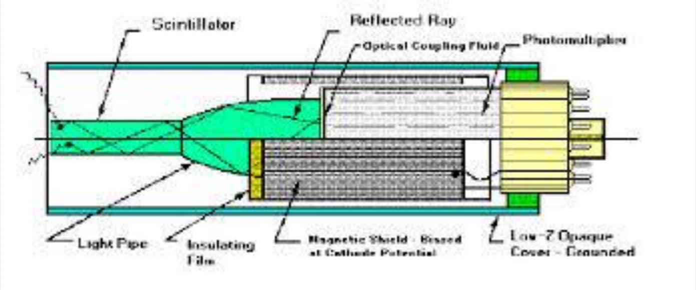
p(25MeV) + Th => FF

JYFLTRAP Penning trap: isotopic purification

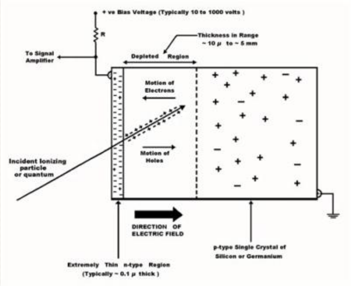
Isotope	Rate (s^{-1})	Isotope	Rate (s^{-1})
^{88}Br	1450	^{85}Ge	6
^{94}Rb	1030	^{85}As	175
^{95}Rb	760	^{86}As	30
^{137}I	100	^{91}Br	80

Beta spectroscopy

Plastic scintillators



Semiconductor Detectors

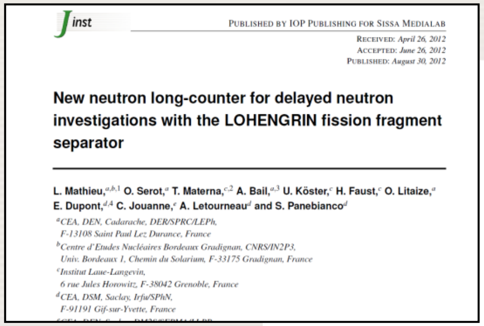


Double sided silicon detectors (DSSD), strip detectors etc.

Neutron spectroscopy /spectrometry

- **^{3}He gas** filled grid ionization chambers: extremely sensitive to thermal and epithermal neutrons, however large uncertainties at low energy part of the spectrum.
- **H_2 and CH_4 gas** filled proton recoil counters: superior energy resolution at low energies, insensitive to thermal and epithermal neutrons.
- Long counters
- Liquid scintillators

Neutron / beta/ gamma detection



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New neutron long-counter for delayed neutron investigations with the LOHENGRIN fission fragment separator

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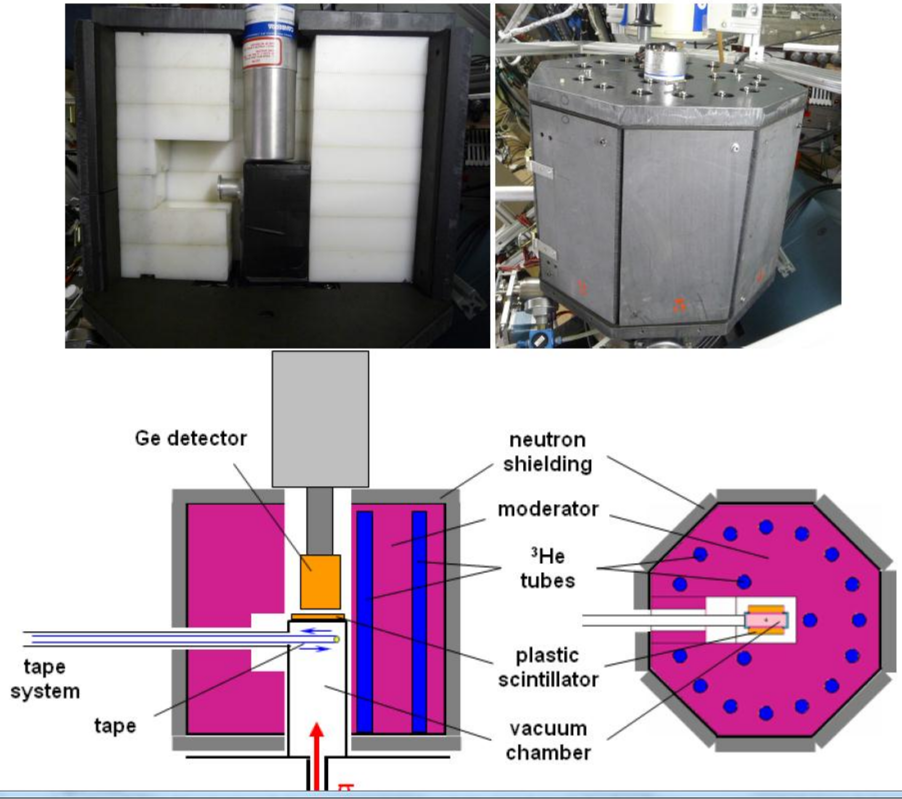
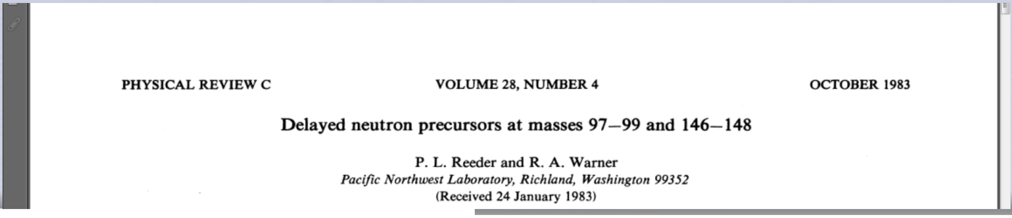
[d] *CEA, DSM, Saclay, Irfu/SPhN,*
F-91191 Gif-sur-Yvette, France





PHYSICAL REVIEW C VOLUME 28, NUMBER 4 OCTOBER 1983

Delayed neutron precursors at masses 97–99 and 146–148

P. L. Reeder and R. A. Warner
Pacific Northwest Laboratory, Richland, Washington 99352

(Received 24 January 1983)

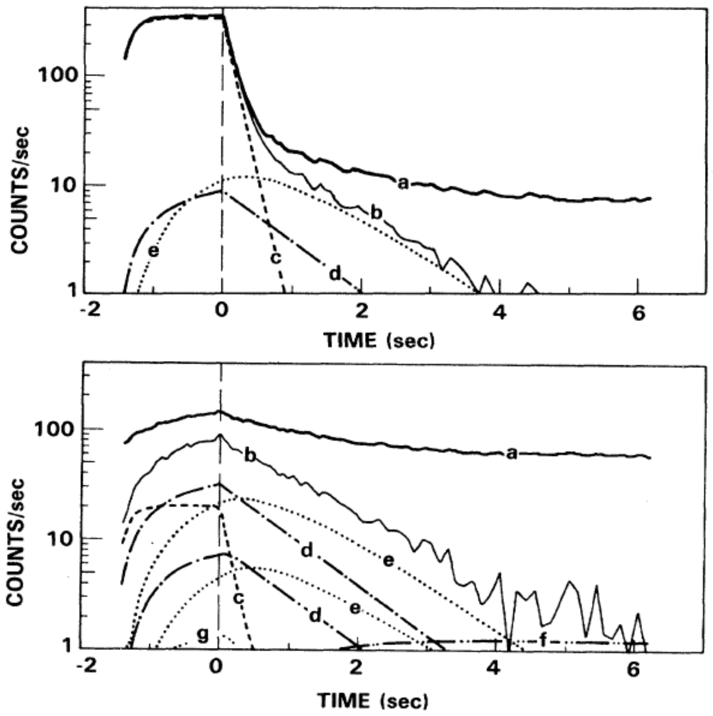


FIG. 4. Growth and decay curves at mass 98 and calculated components; the upper for the neutron, the lower for the beta. *a* denotes the experimental count rate. *b* denotes the count rate after subtraction of constant background. *c* denotes ^{98}Rb (0.108 s). *d* denotes ^{98}Sr (0.66 s). *e* denotes $^{98}Y^{g}$ (0.51 s). *f* denotes ^{98}Zr (30.7 s). *g* denotes ^{97}Sr (0.40 s). For the beta curve, ^{98}Sr and $^{98}Y^{g}$ each have two components corresponding to ^{98}Sr produced by beta decay of ^{98}Rb and by deposition from the ion beam directly.

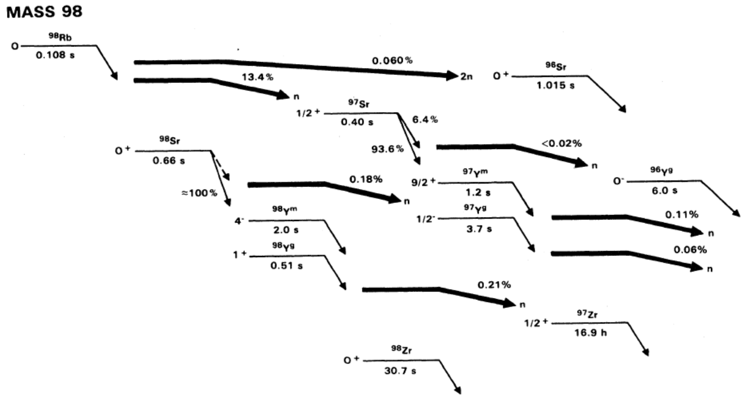
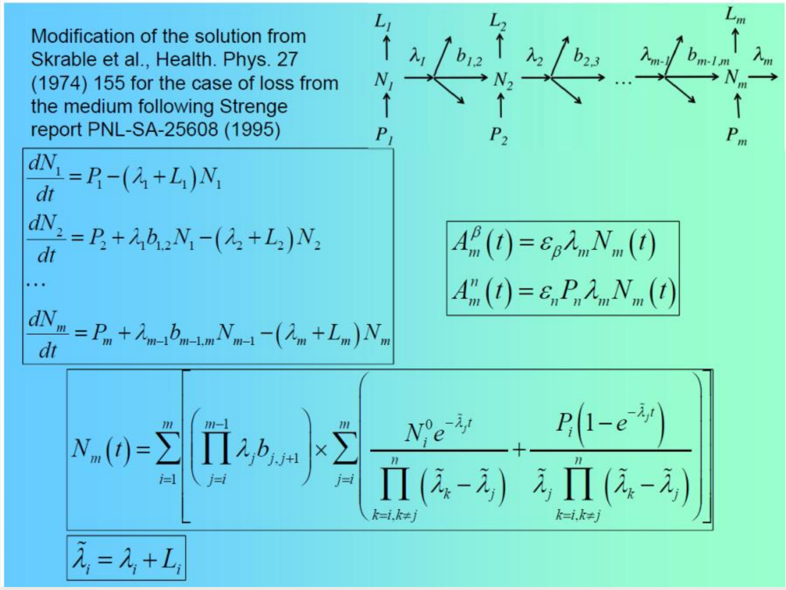


FIG. 3. The mass chain beginning with ^{98}Rb. Delayed neutron branching ratios from the present work are included.

https://www-nds.iaea.org/beta-delayed-neutron/1RCM/presentations/BELEN-IAEA-Aug2013.pdf



Modification of the solution from Skrable et al., Health. Phys. 27 (1974) 155 for the case of loss from the medium following Strenge report PNL-SA-25608 (1995)

$$\frac{dN_1}{dt} = P_1 - (\lambda_1 + L_1)N_1$$

$$\frac{dN_2}{dt} = P_2 + \lambda_1 b_{1,2} N_1 - (\lambda_2 + L_2)N_2$$

$$\cdots$$

$$\frac{dN_m}{dt} = P_m + \lambda_{m-1} b_{m-1,m} N_{m-1} - (\lambda_m + L_m)N_m$$

$$A_m^{\beta}(t) = \varepsilon_{\beta}\lambda_m N_m(t)$$

$$A_m^{n}(t) = \varepsilon_n P_n \lambda_m N_m(t)$$

$$N_m(t) = \sum_{i=1}^{m}\left[\left(\prod_{j=i}^{m-1}\lambda_j b_{j,j+1}\right)\times\sum_{j=i}^{m}\left(\frac{N_i^0 e^{-\tilde{\lambda}_j t}}{\prod_{k=i,k\neq j}^{n}\left(\tilde{\lambda}_k - \tilde{\lambda}_j\right)} + \frac{P_i\left(1-e^{-\tilde{\lambda}_j t}\right)}{\tilde{\lambda}_j \prod_{k=i,k\neq j}^{n}\left(\tilde{\lambda}_k - \tilde{\lambda}_j\right)}\right)\right]$$

$$\tilde{\lambda}_i = \lambda_i + L_i$$

Methods for *βdn data measurements*

1. “n/β”: Neutron-beta coincidences.

$$P_n = 1/\varepsilon_n * N_{\beta n}/N_\beta$$

2. “n-β”: Neutrons and betas counted separately but simultaneously.

$$P_n = \varepsilon_\beta/\varepsilon_n * N_n/N_\beta$$

3. “γ ^{A}Z+n”: Abundance of precursor determined via gamma-counting of any β-decay daughter.

$$P_n = (\varepsilon_\gamma * I_{abs,\gamma}(\,^{A}Z+n)/\,N_\gamma(\,^{A}Z+n)) * (N_n/\varepsilon_n)$$

4. “P_n ^{A}Z”: Normalization of the ratio $\varepsilon_\beta/\varepsilon_n$ with known P_n value from precursor ^{A}Z

$$P_n = P_n(\text{standard}) * (N_\beta(\text{standard})/N_n(\text{standard})) * N_n/N_\beta$$

5. “ion”: Ion counting. Counting of number of precursor M (N_{ion}).

$$P_n = N_{n\text{-}decays}/\,N_{ion}$$

6. “fiss”: Fission yields

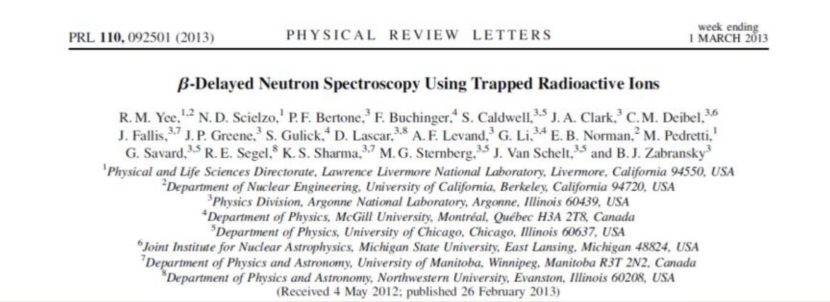
   This method used chemical separation methods and is probably the least reliable method.

$$P_n = 1/\varepsilon_n * N_n/(Y_A * P_Z) \text{ or } P_n = 1/\varepsilon_n * N_n/Y_{A,Z}$$

7. “γ-γ”: Number of neutron decays determined only via γ-counting.

$$P_n = (\varepsilon_{\gamma,daughter} * I_{abs,daughter,\gamma}/N_{daughter,\gamma})\,/\,(\,\varepsilon_{\gamma,final} * I_{abs,final,\gamma}/\,N_{final,\gamma})$$

Bdn measurements with Penning-Trap and ion recoil



PRL **110,** 092501 (2013) PHYSICAL REVIEW LETTERS week ending 1 MARCH 2013

β-Delayed Neutron Spectroscopy Using Trapped Radioactive Ions

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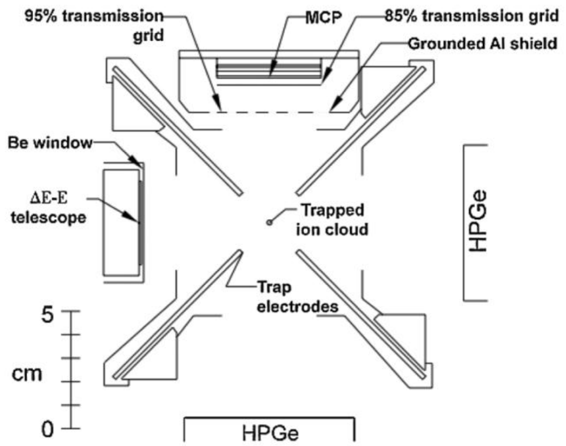

FIG. 1. End-on view of the BPT and detectors.

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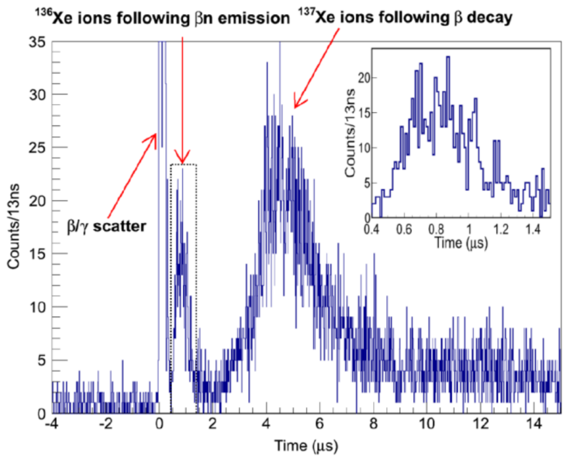
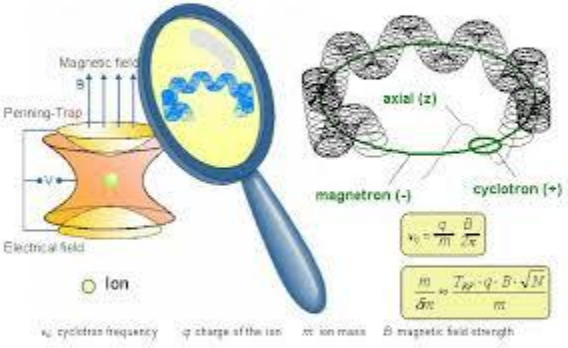


FIG. 2 (color online). Recoil-ion TOF spectrum collected with



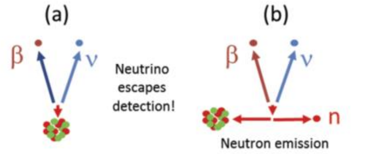
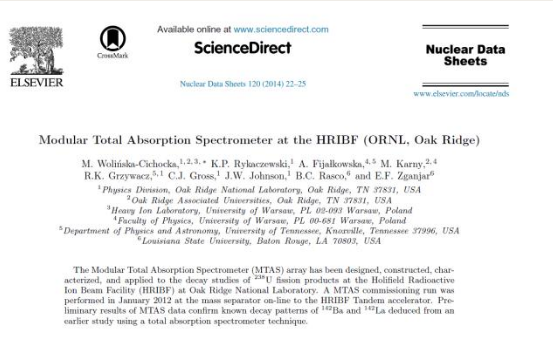


FIG. 1. (a) In β decay, the neutrino momentum and energy (and therefore entire 3-body decay kinematics) can be reconstructed from measurements of the β and recoil-ion momenta. (b) In β-delayed neutron emission, the recoil from the leptons is much smaller than the recoil from neutron emission. The neutron energy can therefore be determined solely from the nuclear recoil as this can be approximated as a 2-body decay.

New technique TAS



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Modular Total Absorption Spectrometer at the HRIBF (ORNL, Oak Ridge)

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The Modular Total Absorption Spectrometer (MTAS) array has been designed, constructed, characterized, and applied to the decay studies of ^{238}U fission products at the Holifield Radioactive Ion Beam Facility (HRIBF) at Oak Ridge National Laboratory. A MTAS commissioning run was performed in January 2012 at the mass separator on-line to the HRIBF Tandem accelerator. Preliminary results of MTAS data confirm known decay patterns of ^{142}Ba and ^{142}La deduced from an earlier study using a total absorption spectrometer technique.

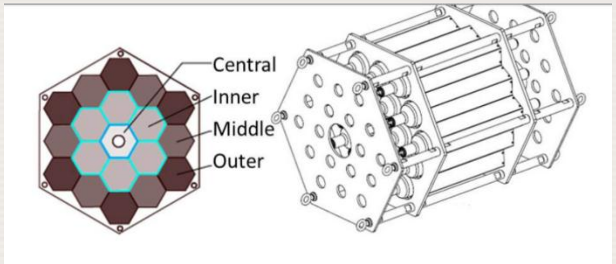


FIG. 1. A schematic view of MTAS detector array assembled from 19 NaI(Tl) modules. Four "rings" of MTAS are indicated at the left panel, the Central module and Inner, Middle, and

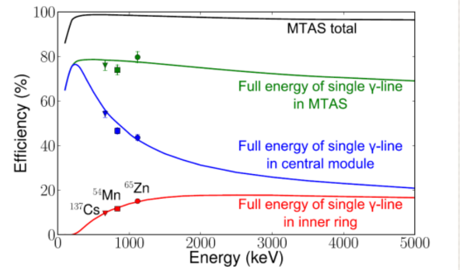
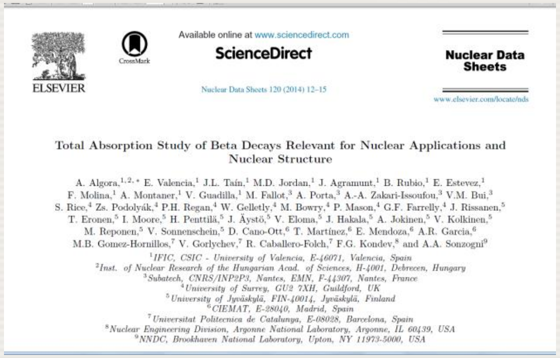


FIG. 3. The efficiencies of MTAS to detect single γ-ray transition are compared to GEANT4 simulations.



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Total Absorption Study of Beta Decays Relevant for Nuclear Applications and Nuclear Structure

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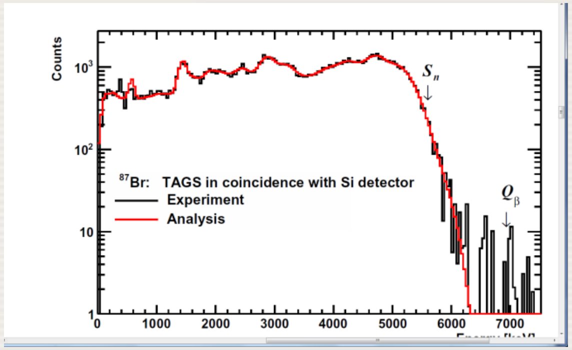

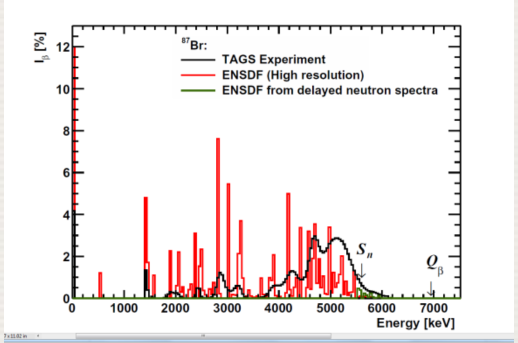

Summary

- EXFOR compilation of beta-delayed neutron (βdn) data in the past
- Motivation for the compilation of the βdn data from individual precursors
- Main parameters of the βdn emission
- LEXFOR update (**Memo CP-C/429** 23 May 2014)
- Experimental techniques for the measurement of βdn emission probabilities and spectra