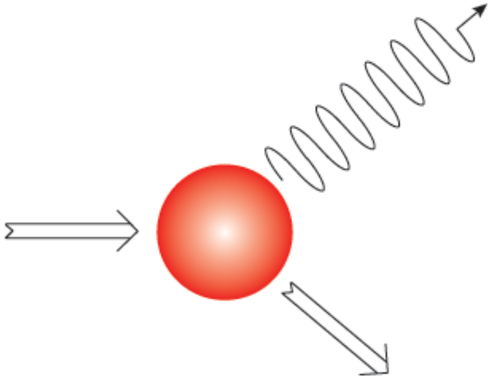
β-delayed neutrons for nuclear technologies



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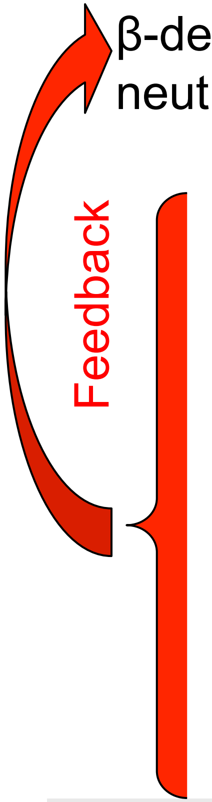
A brief introduction of CIEMAT’s Nuclear Innovation Group

CIEMAT is a public research institution dedicated to the R&D of energy sources and associated technologies. Our group belongs to the the Dpt. Energy / Nuclear Fission Division and its research activities are focussed on:

I. NUCLEAR DATA FOR TRANSMUTATION AND ADVANCED REACTORS

Neutron cross section measurements (n_TOF facility at CERN).

β-delayed neutron measurements at Jyvaskyla and other facilities (BELEN 4π neutron counter and the MONSTER neutron spectrometer)



II. INTEGRAL EXPERIMENTS IN SUBCRITICAL REACTORS

Exiperiments in Cadarache, Minsk and Mol.

III. ADVANCED NUCLEAR FUEL CYCLES

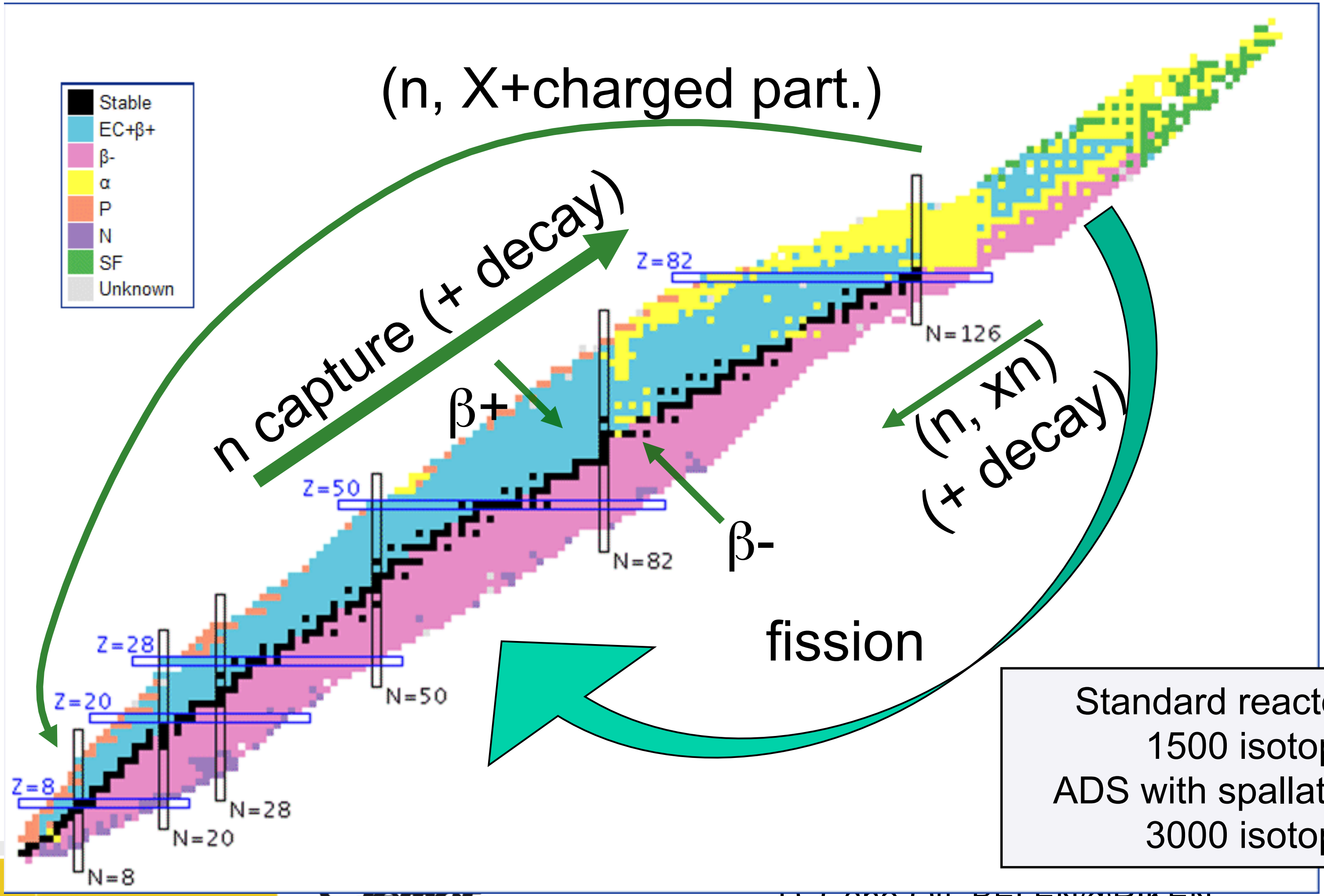
Detailed simulation of complex fuel cycles over large periods of time (100 years)

IV. CRITICAL AND SUBCRITICAL REACTORS

Design of criticial (Na-cooled, Pb-cooled) fast reactors and Accelerator Driven Systems (MYRRHA project)

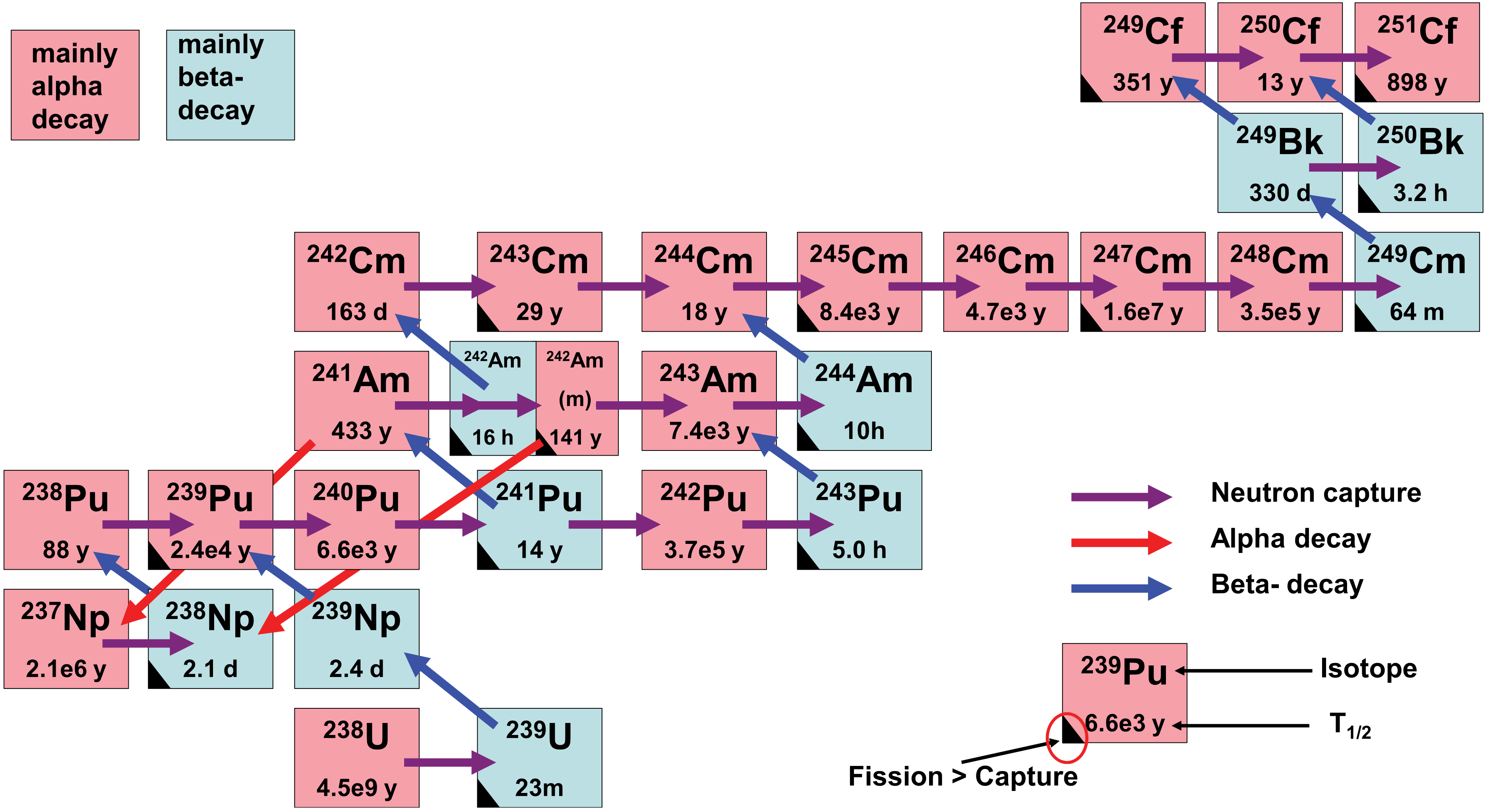
Artificial nucleosynthesis

- n- induced fission (energy + wastes)
- neutron capture (activation + breeding)
- elastic and inelastic neutron scattering
- radioactive decay
- (n,xn), (n, charged particle), …



Standard reactor
1500 isotopes
ADS with spallation
3000 isotopes

The nucleosynthesis path inside a light water reactor



mainly alpha decay

mainly beta- decay

^{249}Cf 351 y
^{250}Cf 13 y
^{251}Cf 898 y

^{249}Bk 330 d
^{250}Bk 3.2 h

^{242}Cm 163 d
^{243}Cm 29 y
^{244}Cm 18 y
^{245}Cm 8.4e3 y
^{246}Cm 4.7e3 y
^{247}Cm 1.6e7 y
^{248}Cm 3.5e5 y
^{249}Cm 64 m

^{241}Am 433 y
^{242}Am 16 h
^{242}Am (m) 141 y
^{243}Am 7.4e3 y
^{244}Am 10h

^{238}Pu 88 y
^{239}Pu 2.4e4 y
^{240}Pu 6.6e3 y
^{241}Pu 14 y
^{242}Pu 3.7e5 y
^{243}Pu 5.0 h

^{237}Np 2.1e6 y
^{238}Np 2.1 d
^{239}Np 2.4 d

^{238}U 4.5e9 y
^{239}U 23m

Neutron capture
Alpha decay
Beta- decay

^{239}Pu ← Isotope
6.6e3 y ← $T_{1/2}$
Fission > Capture

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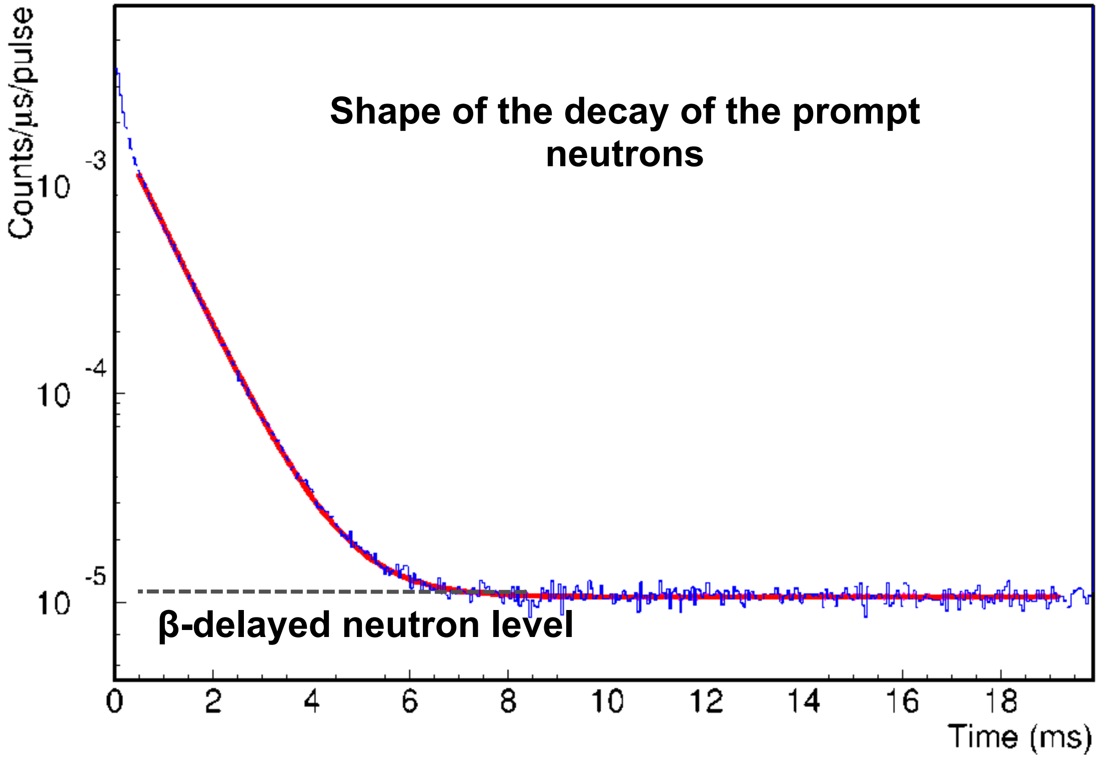
In order to model in time and space a nuclear reactor, it is mandatory to have reliable evaluated nuclear data for al the isotopes involved on the following quantities:

- Reaction cross sections: fission, capture, elastic, inelastic, neutron multiplication…
- Residual products produced in the reactions: fission fragments, minor actinides.
- Secondary particles produced in the reactions: number of prompt neutrons per fission, γ-rays produced in the different reactions (fission, capture, inelastic), **β-delayed γ-rays and neutrons emitted by the fission fragments**…

Even though the delayed neutrons represent a small fraction of the total neutron balance (< 1%), the are produced at much longer times, allowing to control the reactors at reasonable time scales (of seconds and tens of seconds).

Pulsed neutron source experiments (PNS)



From point kinetics equations

$$N(t) = N(0)\exp\left(\frac{k_{eff}-1}{\Lambda}t\right)$$

k_{eff} = 1.001 (i.e., a reactivity ≅ 1 mk) and Λ = 1 ms = 10^{-3} s,

$$N(t) = N(0)\exp\left(\frac{1.001-1}{0.001s}t\right) = N(0)\exp(t)$$

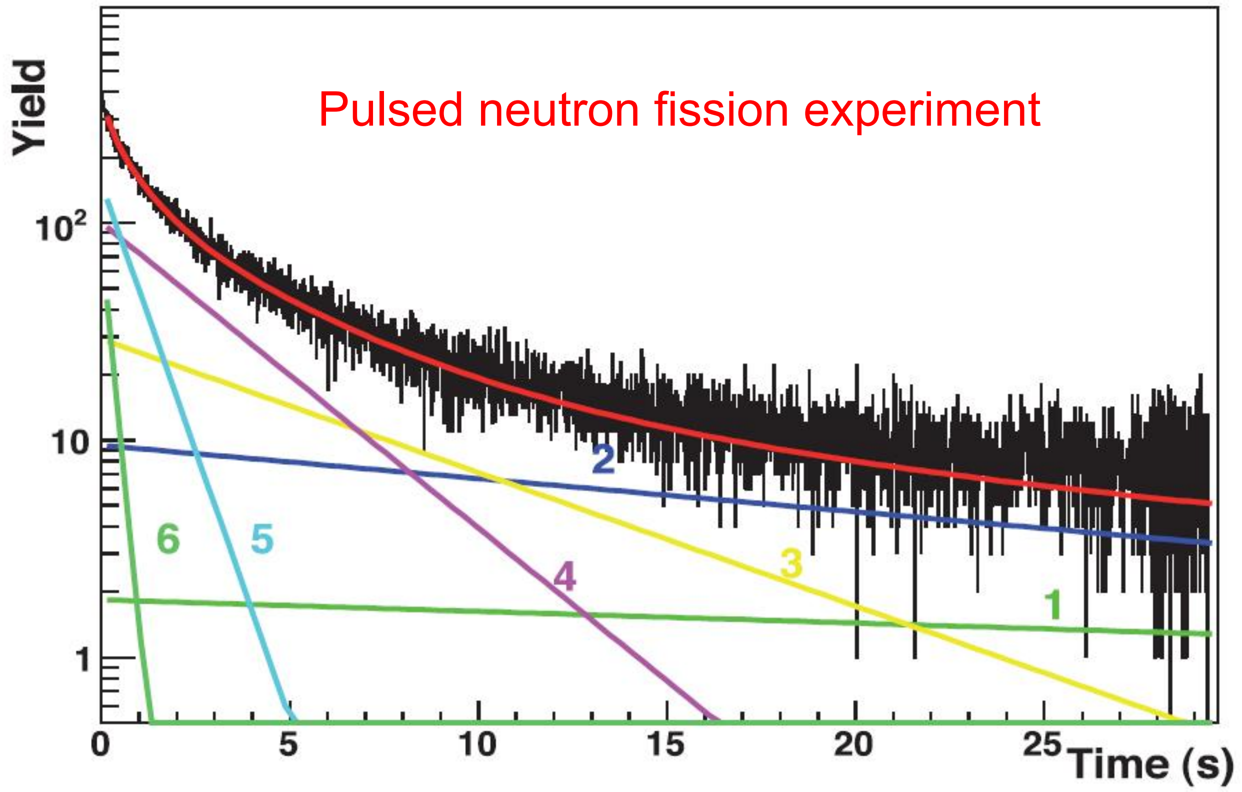
by a factor exp(1) = 2.718 in 1 s

by a factor exp(2) = 2.718^2 = 7.389 in 2 s

by a factor exp(3) = 2.718^3 = 20.1 in 3 s!

This is a very fast rate of increase in the fission power, and it would be **impossible to control such a fast power increase** with mechanical shutdown systems.

The Keepin formula (six-group representation)



$$n(t) = \sum_i a_i e^{-\lambda_i t}$$

Group #→	1	2	3	4	5	6
$T_{1/2}$	54.51	21.84	6.0	2.23	0.496	0.179
λ_I	0.0127	0.031	0.1155	0.310	1.397	3.871
β_i/β	.038	0.213	0.188	0.407	0.128	0.026
β_I	0.0002641	0.00148035	0.0013066	0.00282865	0.0008896	0.0001807

Table 1 Typical precursor coefficients.

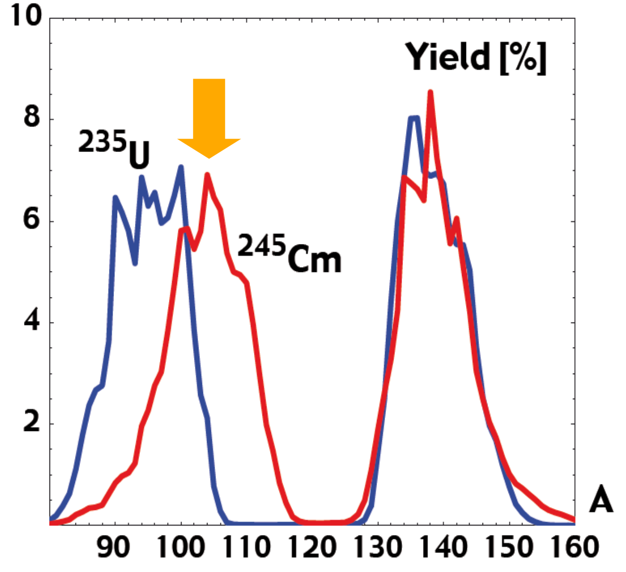
For the values in table 1, $\beta \equiv \sum_{i=1}^{6} \beta_i$ =0.0065. So the delayed precursors only account for 0.65%

Summation calculations

Alternatively, the number of delayed neutrons per fission can be obtained by summing the neutron production of all the fission fragments. It is necessary to know **for every fissioning system** the **fission yields** and **decay data** (half-lives, neutron emission probabilities…) of tens to hundred of isotopes with a good accuracy.

$$\bar{\nu}_d = \sum_i P_{ni} \cdot c_i$$

FF distribution: depends on the fissioning system and neutron energy



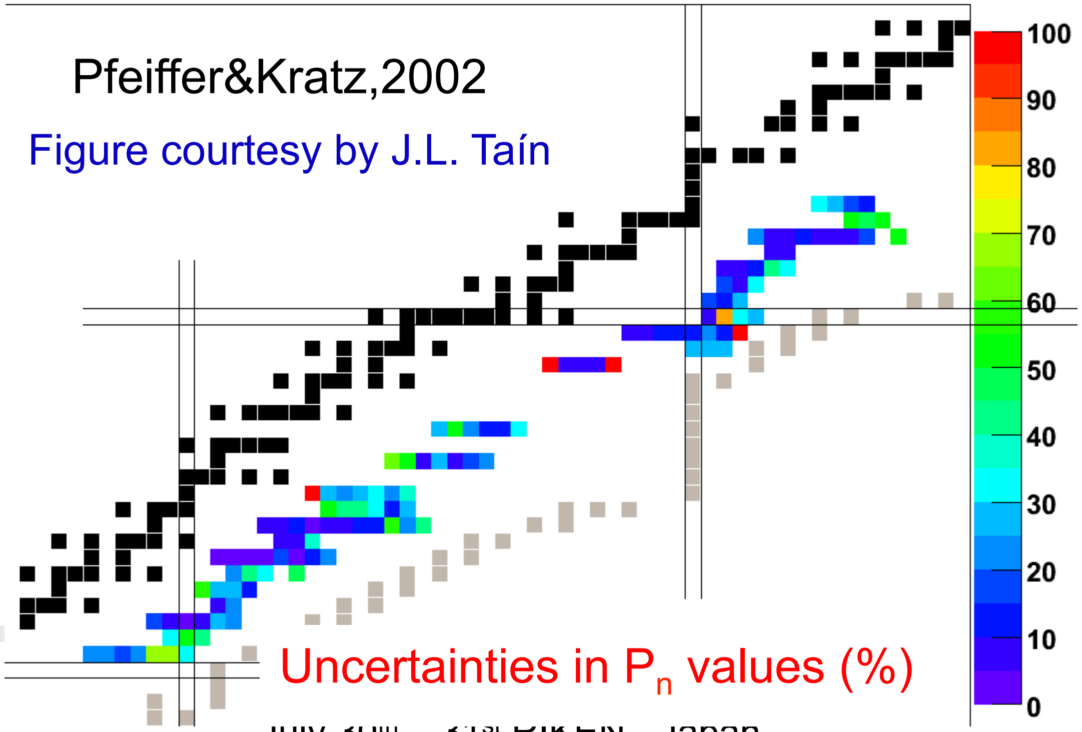

Pfeiffer&Kratz,2002

Figure courtesy by J.L. Taín

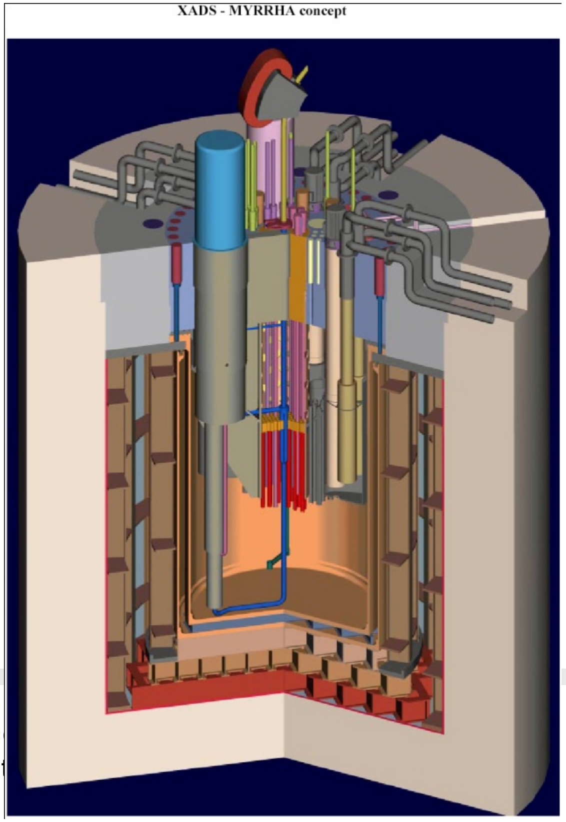
Uncertainties in P_n values (%)

Nuclear data are necessary for recent nuclear technologies

New nuclear data needs have been triggered by following reasons:

-Higher burnup (how to use nuclear fuels more efficiently).
-Life extension (how to exploit existing nuclear power plants for longer periods than initially expected).
-Design of new **fast critical reactors** (Gen IV): liquid metal Na-cooled reactor, Pb-cooled reactor and gas cooled reactor.
-Design of Accelerator Driven Systems (ADS) for the **transmutation of the nuclear waste** (MYRRHA project, demonstrator of ESNII European Sustainable Nuclear Industrial Initiative).
-Characteristics of fuels with high Minor Actinide enrichment (heavy fissioning systems)

An ADS is a subcritical nuclear system (K_{eff} = 0.95-0.98) whose power is sustained by a external high intensity neutron source. Usually the neutrons are produced by spallation in heavy nuclides (Pb) by high energy neutrons (~1 GeV)



Which data need to be improved?

A software tool has been developed to test the present status of Evaluated Decay Data and Fission Yield data libraries to predict (UPM – CIEMAT collaboration):

- the neutron emission rate
- average neutron energy and neutron delayed spectra

A systematic comparison of these values with *Keepin* formula with values taken from the JEFF 3.1 and ENDFB B-VII.1 evaluated cross section data libraries (MT455) has been performed for the case of ^{235}U thermal fission (one of the best known cases). Additional libraries and fissioning systems are in progress, as part of the IAEA Collaborative Research Project to be started this year (August 2013).

Summary of the data available in the JEFF-3.1.1 and ENDF/B-VII.1libraries (experimental data + calculations):

- JEFF 3.1.1: 241 βn-emitters, 18 β2n-emitters and only 4 β3n-emitters (^{11}Li, ^{14}Be, ^{17}B, ^{31}Na)
- ENDF/B-VII.1 : 390 βn-emitters, 111 β2n-emitters, 14 β 3n-emitter and 2 β4n-emitters

Prediction of “uncertainties” due to the current uncertainties in these Nuclear Data Libraries

The total delayed neutron emission per fission can be calculated as follows:

$$\bar{\nu}_d = \sum_i P_{ni} \cdot c_i$$

where:

c_i is the cumulative yields of isotope-i, taken from "*Evaluated Fission Yield Data Library*"

P_{ni} is the probability of a nuclide-i emitting a neutron as a result of a beta decay "*Evaluated Fission Decay Data Library*"

The uncertainty in the calculated $\bar{\nu}_d$ can be estimated assuming c_i and P_{ni} are independent:

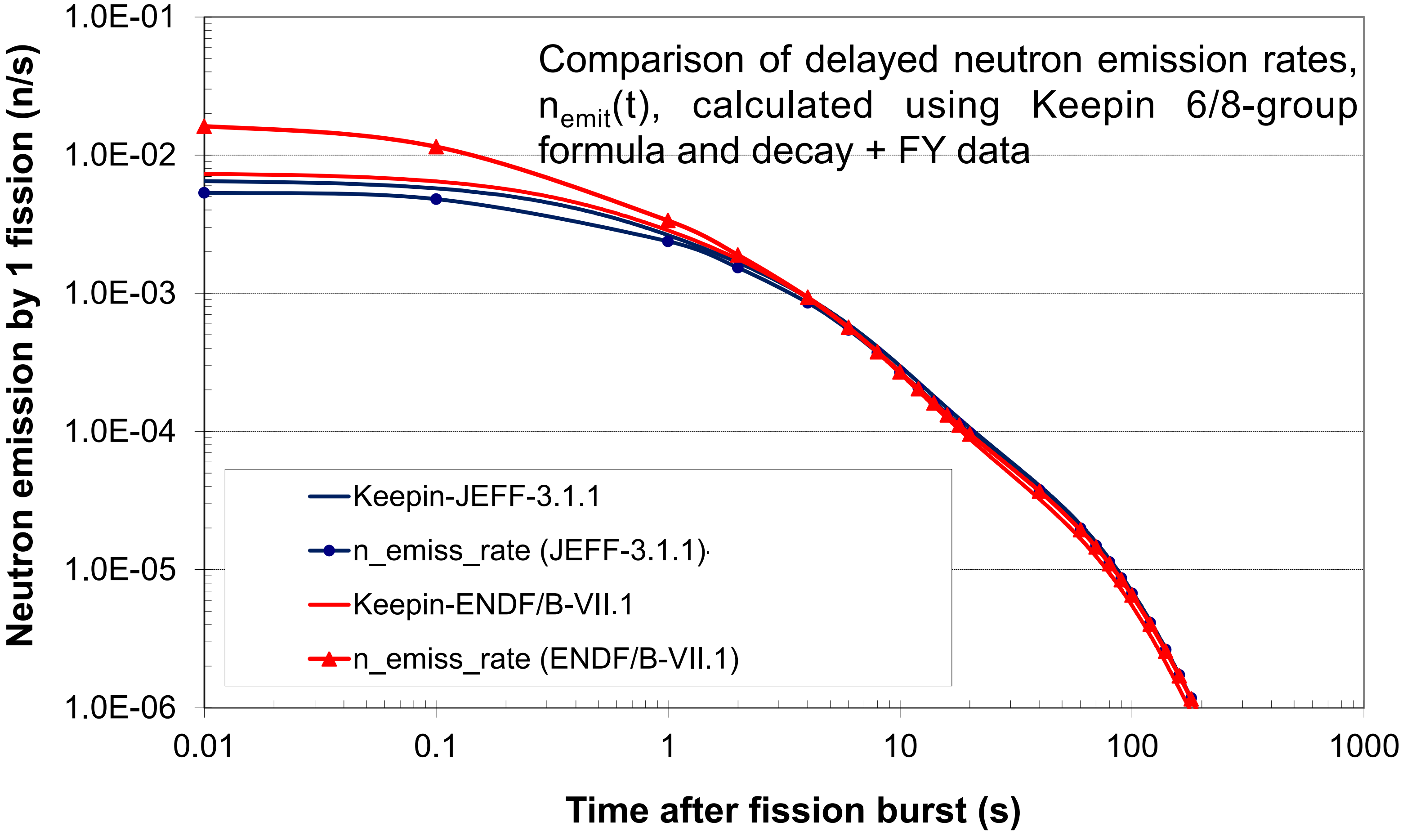
$$\mathrm{var}(\bar{\nu}_d) = \sum_i P_{ni}^2 \cdot \mathrm{var}(c_i) + \mathrm{var}(P_{ni}) \cdot c_i^2$$

A well known case: the thermal fission of ^{235}U

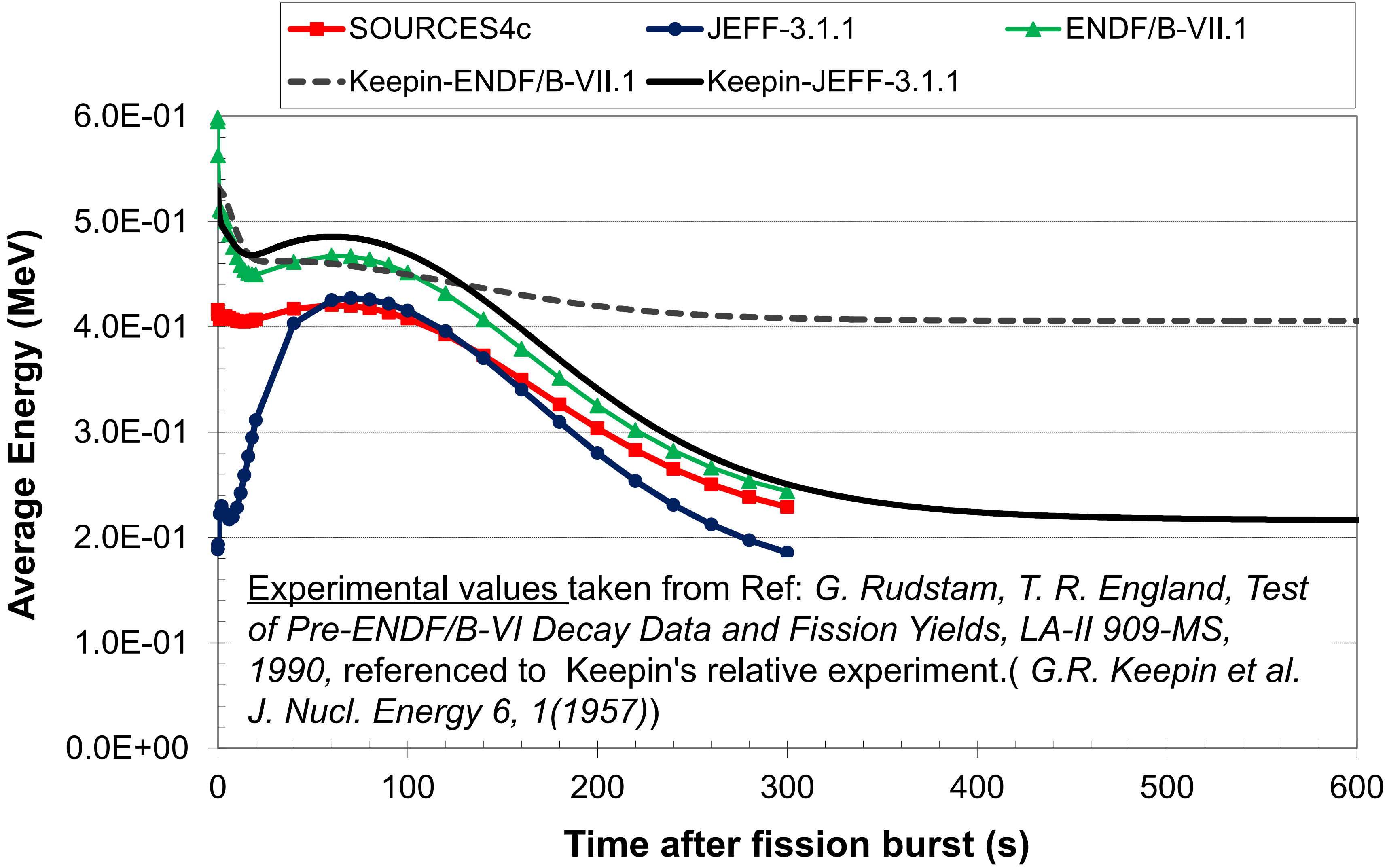
$$S_d(t) = n_f \sum_{i=1}^{6} \nu_{di} \lambda_{di} e^{-\lambda_{di} t}$$

ν_{di} : is the yield of the i-th delayed-neutron group
λ_{di} : is the decay constant of the i-th neutron group
n_f : number of fissions

For ENDF/B-VII.1, at t=0s there are differences of ~128% between the Keepin formula and decay FY data. The neutron emission rates calculated with decay + FY data overestimate Keepin formula

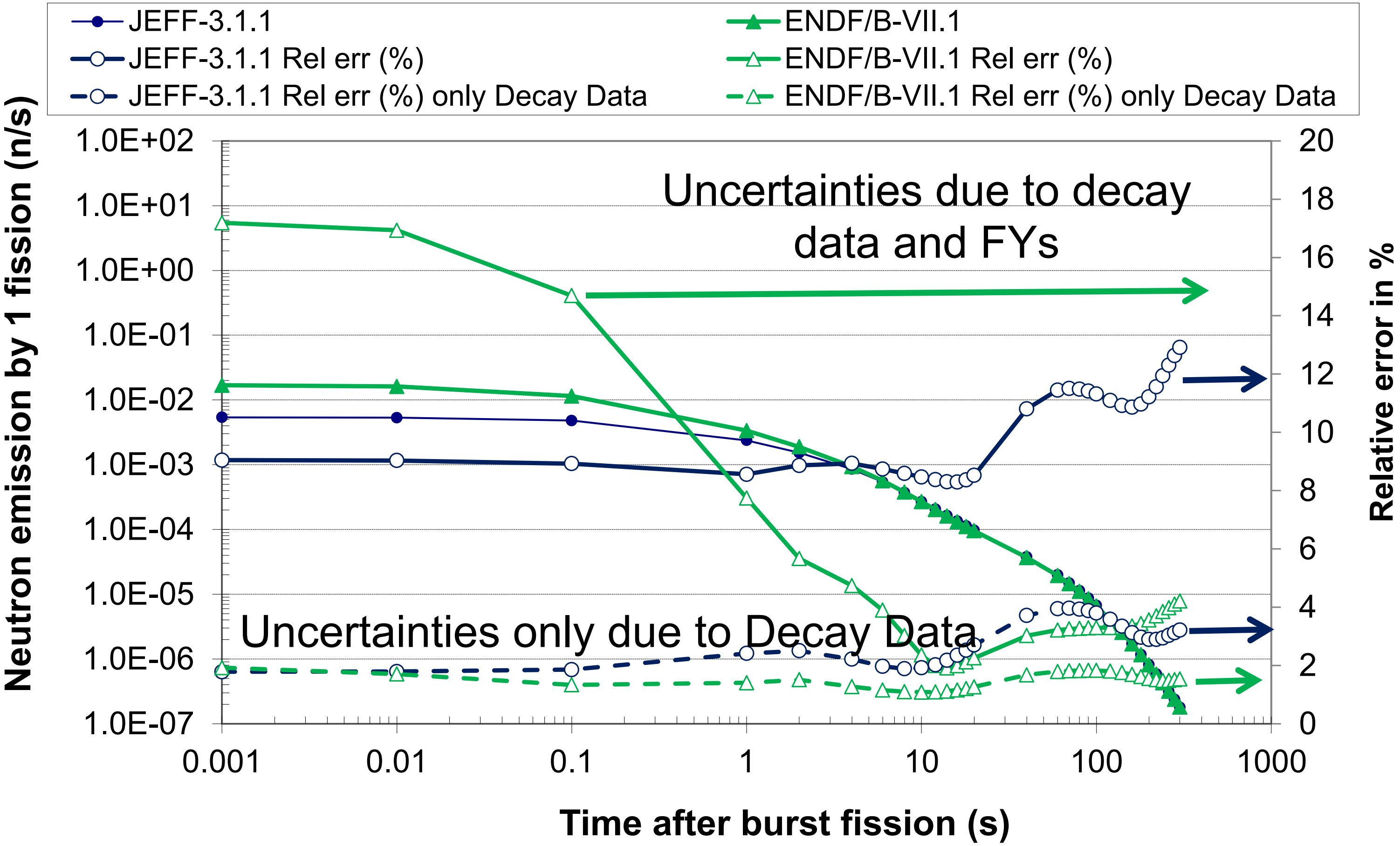


Delayed neutron average energy calculated with JEFF-3.1.1, ENDF/B-VII.1 and SOURCES4C (LANL) code.



Experimental values taken from Ref: *G. Rudstam, T. R. England, Test of Pre-ENDF/B-VI Decay Data and Fission Yields, LA-II 909-MS, 1990,* referenced to Keepin's relative experiment.(*G.R. Keepin et al. J. Nucl. Energy 6, 1(1957)*)

Calculated relative uncertainties in the neutron emission due to uncertainties in Decay Data and Independent Fission Yields.



Conclusion: the main contribution at low times to the total uncertainty in the $n_{emit}(t)$ are the uncertainties in the fission yields. **BUT, can the uncertainties be trusted?**

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July 30th – 31st RIKEN - Japan

List of the most important contributor (>1%) to the neutron emission rate: JEFF-3.1.1 vs ENDF/B-VII.1 at “t=0.0 seconds”, just after the “fission pulse”.

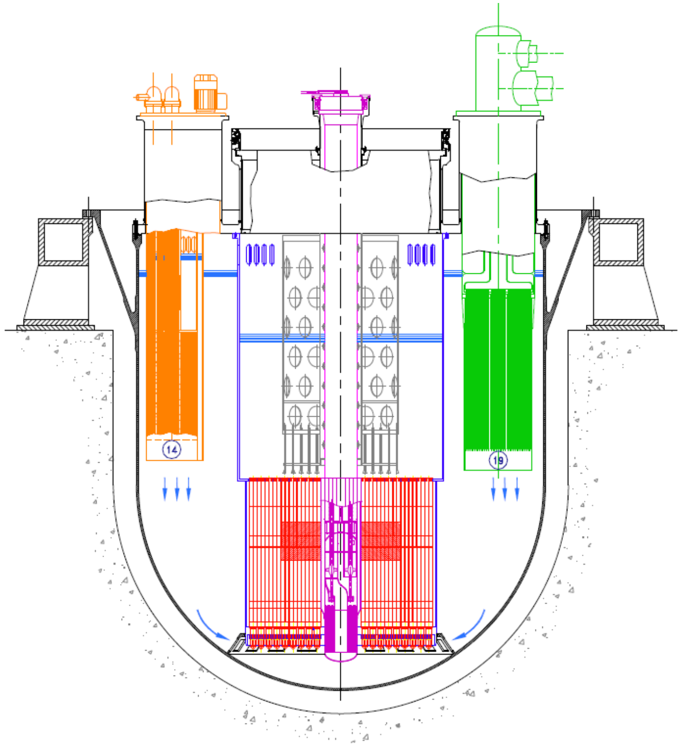
JEFF-3.1.1, nemit=5.40E-03					ENDF/B-VII.1, nemit=1.69E-02				
Isotope	Relative Contribution (RC) in %	P_{ni}	$T_{1/2}$(s)	Ni(0)=g_i	Isotope	Relative Contribution (RC) in %	P_{ni}	$T_{1/2}$(s)	Ni(0)=g_i
Ge-86					Ge-86	14.10	0.05	0.09	6.29E-03
As-85	1.95	0.22	2.04	1.41E-03	As-85	1.46	0.59	2.02	1.21E-03
As-86	1.98	**0.33**	0.95	**4.42E-04**	As-86	0.11	0.13	0.95	1.99E-04
As-87					As-87	1.47	0.40	0.56	5.05E-04
As-88					As-88	18.70	0.41	0.11	1.24E-03
Se-89	1.68	0.08	0.41	6.87E-04	Se-89	0.38	0.08	0.41	4.85E-04
Br-89	5.36	0.14	4.37	1.29E-02	Br-89	1.34	0.14	4.40	1.04E-02
Br-90	7.91	0.25	1.90	4.76E-03	Br-90	2.97	0.25	1.92	5.53E-03
Br-91	7.21	0.20	0.54	1.51E-03	Br-91	3.39	0.20	0.54	2.24E-03
Br-92	2.47	0.33	0.34	2.00E-04	Br-92	0.43	0.14	0.34	2.68E-04
Br-93	1.65	0.68	0.10	1.93E-05	Br-93	0.33	0.27	0.10	3.08E-05
Rb-94	6.71	0.10	2.70	1.40E-02	Rb-94	2.50	0.11	2.70	1.57E-02
Rb-95	18.80	0.09	0.38	6.48E-03	Rb-95	7.22	0.09	0.38	7.64E-03
Rb-96	5.80	0.13	0.20	6.71E-04	Rb-96	4.53	0.13	0.20	1.68E-03
Rb-97	4.74	0.25	0.17	2.50E-04	Rb-97	2.35	0.26	0.17	3.79E-04
Rb-100	0.006	0.06	0.05	**3.95E-08**	Rb-100	9.06	0.32	0.05	**3.48E-04**
Y-98m	4.36	**0.03**	2.00	1.97E-02	Y-98m	0.08	**0.003**	2.00	1.11E-02
Y-99	2.62	0.02	1.48	1.77E-02	Y-99	0.93	0.02	1.47	1.95E-02
Y-102	0.24	0.05	0.30	1.13E-04	Y-102	1.50	0.05	0.36	2.68E-03
Cd-131	0.003	0.04	0.07	5.01E-07	Cd-131	5.67	0.68	0.07	**1.38E-04**
Sb-135	2.06	0.16	1.74	1.78E-03	Sb-135	0.78	0.22	1.68	1.45E-03
Sb-137	0.26	**0.49**	0.45	1.87E-05	Sb-137	6.77	**1.00**	0.45	7.43E-04
I-137	1.05	0.07	24.50	3.10E-02	I-137	0.31	0.07	24.50	2.62E-02
I-138	1.46	0.05	6.46	1.38E-02	I-138	0.52	0.06	6.23	1.42E-02
I-139	3.22	0.10	2.30	5.89E-03	I-139	1.39	0.10	2.28	7.71E-03
I-140	1.66	0.09	0.86	1.20E-03	I-140	0.64	0.10	0.86	1.37E-03
I-141	1.29	0.21	0.43	2.06E-04	I-141	0.82	0.21	0.43	4.07E-04
Cs-143	1.84	0.02	1.79	1.57E-02	Cs-143	0.53	0.02	1.79	1.40E-02
Cs-145	2.78	0.14	0.59	8.98E-04	Cs-145	0.78	0.15	0.59	7.56E-04

Isotope (fissioning system)	Neutron energy range	Summation calculation JEFF-3.1.1 (v_dx100)		Summation calculation ENDF/B-VII.1 (v_dx100)		ENDF/B-VII.1 recommended (v_dx100)
^{233}U	Thermal	**0.72**	**± 0.06**	**0.74**	**± 0.06**	**0.74 [1]**
^{235}U	Thermal	**1.47**	**± 0.08**	**1.91**	**± 0.10**	**0.1585[2]**
^{237}Np	Thermal	**1.13**	**± 0.08**	**1.66**	**± 0.15**	**1.081[1]**
^{238}Np	Thermal	**1.41**	**± 0.14**	**-**	**-**	**1.494 [4]**
^{238}Pu	Thermal	**0.32**	**± 0.04**	**-**	**-**	**0.471[4]**
^{239}Pu	Thermal	**0.60**	**± 0.04**	**0.72**	**± 0.02**	**0.645[1]**
^{241}Pu	Thermal	**1.22**	**± 0.06**	**1.34**	**± 0.07**	**1.62 []**
^{241}Am	Thermal	**0.38**	**± 0.05**	**0.56**	**± 0.07**	**0.427 [4]**
^{242m}Am	Thermal	**0.58**	**± 0.11**	**0.77**	**± 0.09**	**0.6[]**
^{243}Am	Thermal	**0.84**	**± 0.11**	**-**	**-**	**0.7951[3]**
^{243}Cm	Thermal	**0.22**	**± 0.04**	**0.47**	**± 0.06**	**0.3[4]**
^{244}Cm	Thermal	**0.33**	**± 0.05**	**-**	**-**	**0.4451[4]**
^{245}Cm	Thermal	**0.52**	**± 0.07**	**0.71**	**± 0.08**	**0.6482[4]**

[1] summation + model + group formula
[2] group spectra
[3] Brady – England, England…
[4] from systematics (various procedures)
[5] private communication

Isotope (fissioning system)	Neutron energy range	Summation calculation JEFF-3.1.1 (ν_dx100)		Summation calculation ENDF/B-VII.1 (ν_dx100)		ENDF/B-VII.1 evaluated (ν_dx100)
^{232}Th	Fast	**5.35**	**± 0.24**	**6.22**	**± 0.48**	**5.47 []**
^{233}U	Fast	**1.04**	**± 0.08**	**0.69**	**± 0.08**	**0.74 [1]**
^{234}U	Fast	**1.34**	**± 0.17**	**0.97**	**± 0.11**	**1.29 [3]**
^{235}U	Fast	**1.69**	**± 0.09**	**1.76**	**± 0.11**	**0.1585 [2]**
^{236}U	Fast	**2.38**	**± 0.15**	**2.13**	**± 0.17**	**2.32 [3]**
^{238}U	Fast	**4.00**	**± 0.13**	**4.23**	**± 0.27**	**4.4 [1]**
^{237}Np	Fast	**1.17**	**± 0.06**	**1.22**	**± 0.12**	**1.081[1]**
^{238}Np	Fast	**1.63**	**± 0.20**	**1.84**	**± 0.16**	**1.494 [4]**
^{238}Pu	Fast	**0.48**	**± 0.07**	**0.62**	**± 0.07**	**0.471 [4]**
^{239}Pu	Fast	**0.67**	**± 0.05**	**0.63**	**± 0.06**	**0.645 [1]**
^{240}Pu	Fast	**0.92**	**± 0.06**	**0.88**	**± 0.09**	**0.9 [3]**
^{241}Pu	Fast	**1.28**	**± 0.07**	**1.37**	**± 0.11**	**1.62 [5]**
^{242}Pu	Fast	**1.67**	**± 0.08**	**1.77**	**± 0.15**	**1.53 [4]**
^{241}Am	Fast	**0.41**	**± 0.05**	**0.45**	**± 0.05**	**0.427 [4]**
^{242m}Am	Fast	**0.57**	**± 0.08**	**-**	**-**	**0.6[]**
^{243}Am	Fast	**0.81**	**± 0.10**	**0.85**	**± 0.09**	**0.7951[3]**
^{243}Cm	Fast	**0.21**	**± 0.03**	**0.29**	**± 0.04**	**0.3[4]**
^{244}Cm	Fast	**0.33**	**± 0.04**	**0.47**	**± 0.06**	**0.4451[4]**
^{245}Cm	Fast	**0.47**	**± 0.06**	**-**	**-**	**0.6482[4]**

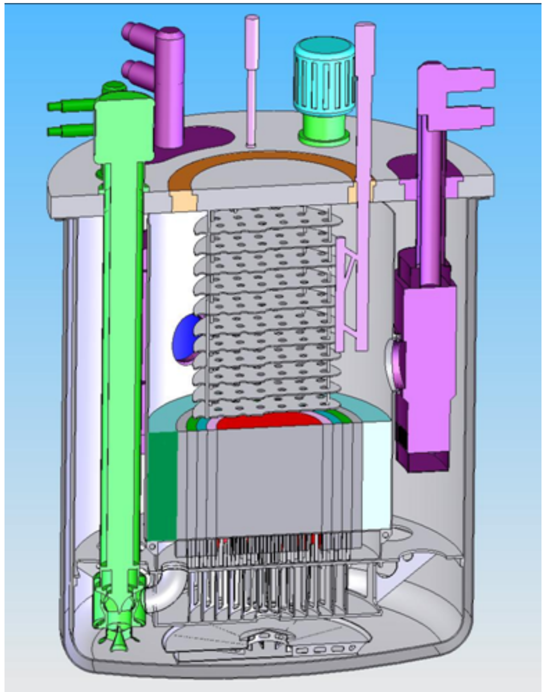
EFIT: European Facility for Industrial Transmutation

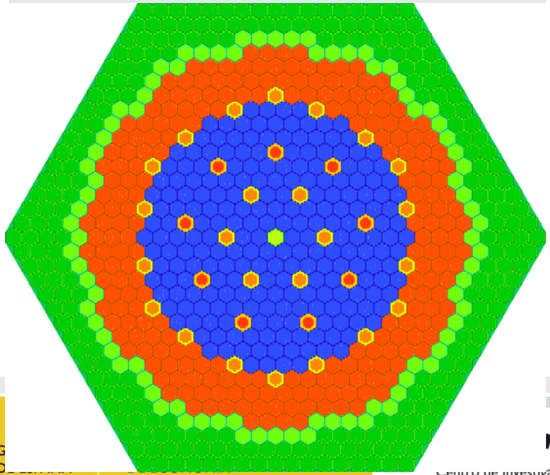


Parameter	EFIT core
Reactor power (MWth)	400
Configuration	Hexagonal pool-type
Fuel matrix	CERCER (MgO)/CERMET (Mo)
Coolant	Pure lead
Pu/MA loading (%)	40-50/60-50
Cladding material	T91 steel
Beam parameters	800 MeV, 20 mA
Burn-up (GWd/tHM)	100
Irradiation length (yr)	5
k_{eff}	~0.97

- Conceptual design of an industrial-scale accelerator-driven subcritical system
- Aimed to the analysis of the transmutation capability of the core for minor actinides streams, with uranium free fuels (50% Minor Actinide load).

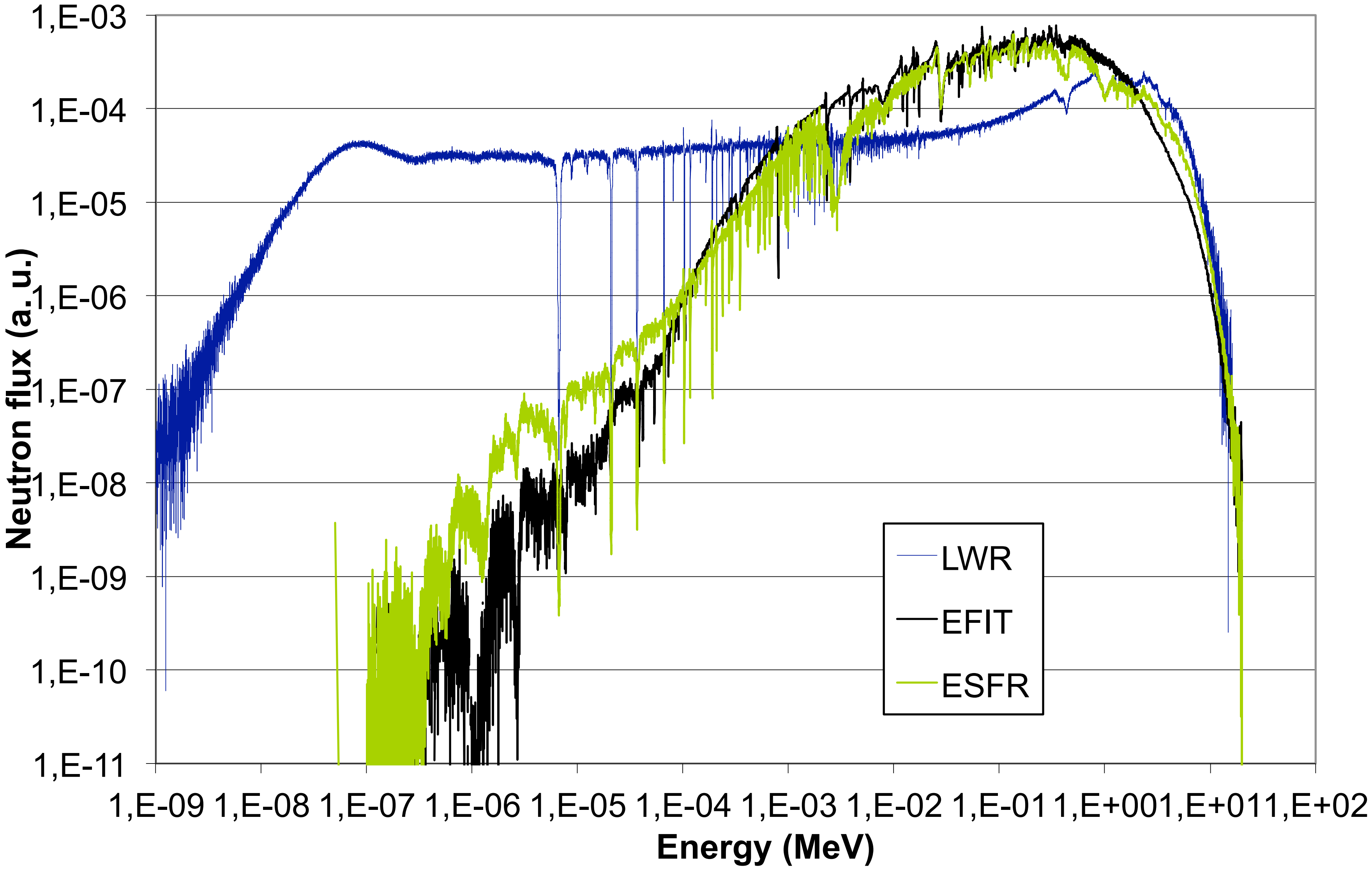
ESFR: European sodium Fast Reactor





Parameter	ESFR-OXIDE core
Reactor power (MWth)	3600
Configuration	Hexagonal pool-type
Fuel pellet material	$(U,Pu)O_2$ – ~15% Pu content
Coolant	Sodium
Cladding material	ODS steel
Burn-up (GWd/tHM)	~100
Irradiation length (d)	410 (1/5)

- Economic competitiveness for energy generation
- Optimization of the uranium resources
- Transmutation of nuclear waste: homogenous or heterogeneous loading


1,E-03
1,E-04
1,E-05
1,E-06
1,E-07
1,E-08
1,E-09
1,E-10
1,E-11
Neutron flux (a. u.)
1,E-09
1,E-08
1,E-07
1,E-06
1,E-05
1,E-04
1,E-03
1,E-02
1,E-01
1,E+00
1,E+01
1,E+02
Energy (MeV)
LWR
EFIT
ESFR

Summary and conclusions

-β-delayed neutrons are relevant for the design and safety assessment of nuclear reactors.

-Our actual knowledge is focussed on the U/Pu fuel cycle (^{235}U thermal fission). New nuclear technologies require nuclear data for additional isotopes (Pu, Minor Actinides, Th-cycle related isotopes) that have not yet been thoroughly investigated.

-The nuclear data used by the reactor physics community are compiled in evaluated libraries. Not all are up to date (regular revisions) and the recommendations made depend on the evaluator/library.

-Concerning the β-delayed neutron fraction, the largest source of uncertainty comes from the fission yields. However, even for the ^{235}U thermal fission the uncertainties in some P_n values for individual isotopes are still large (>10%).

The situation becomes worse if we consider other fissioning systems.

-We have some reasonable tools in our hands for assessing in a systematic way what are the nuclear data to be re-investigated (re-evaluated and/or re-measured) for advanced nuclear reactors.

-The goal is to provide high accuracy data.

Future work towards a proposal

Summation calculations for two advanced reactor designs:

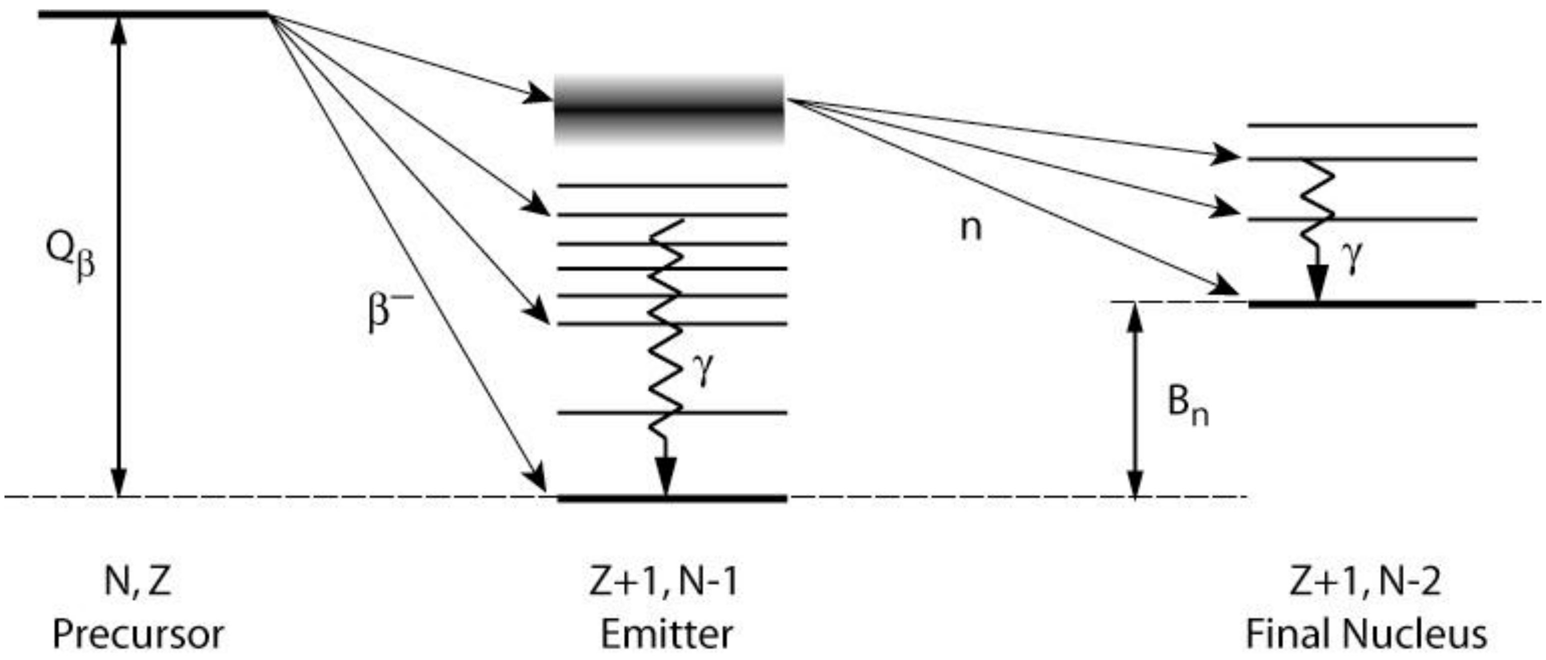
- An Accelerator Driven System (EFIT)
- A Gen-IV sodium cooled fast reactor (ESFR)

Tasks to do within the IAEA CRP on beta delayed neutrons:

- Identification of the most relevant fissioning systems at different periods of operation (changes in the fuel composition and neutron flux)
- Identification of the most relevant neutron emitters at different times for each library.
- Comparison of the results between data libraries (ENDF, JEFF and JENDL)
- Identification of isotopes that show the largest discrepancies -> proposal of new measurements for P_n values.
- Proposal for RIKEN on short lived neutron emitters OR not so short lived (less exotic) but with very high statistics (high precision measurement).

- **Mid term**: simulation of the influence of the β-delayed neutron energy spectra on the reactor parameters. Measurements with a neutron time of flight spectrometer (at RIKEN?)

Delayed neutron spectroscopy



GOAL: To measure neutron emission probabilities and energies for neutron rich isotopes with relevance to basic nuclear physics, nuclear astrophysics and nuclear technologies.

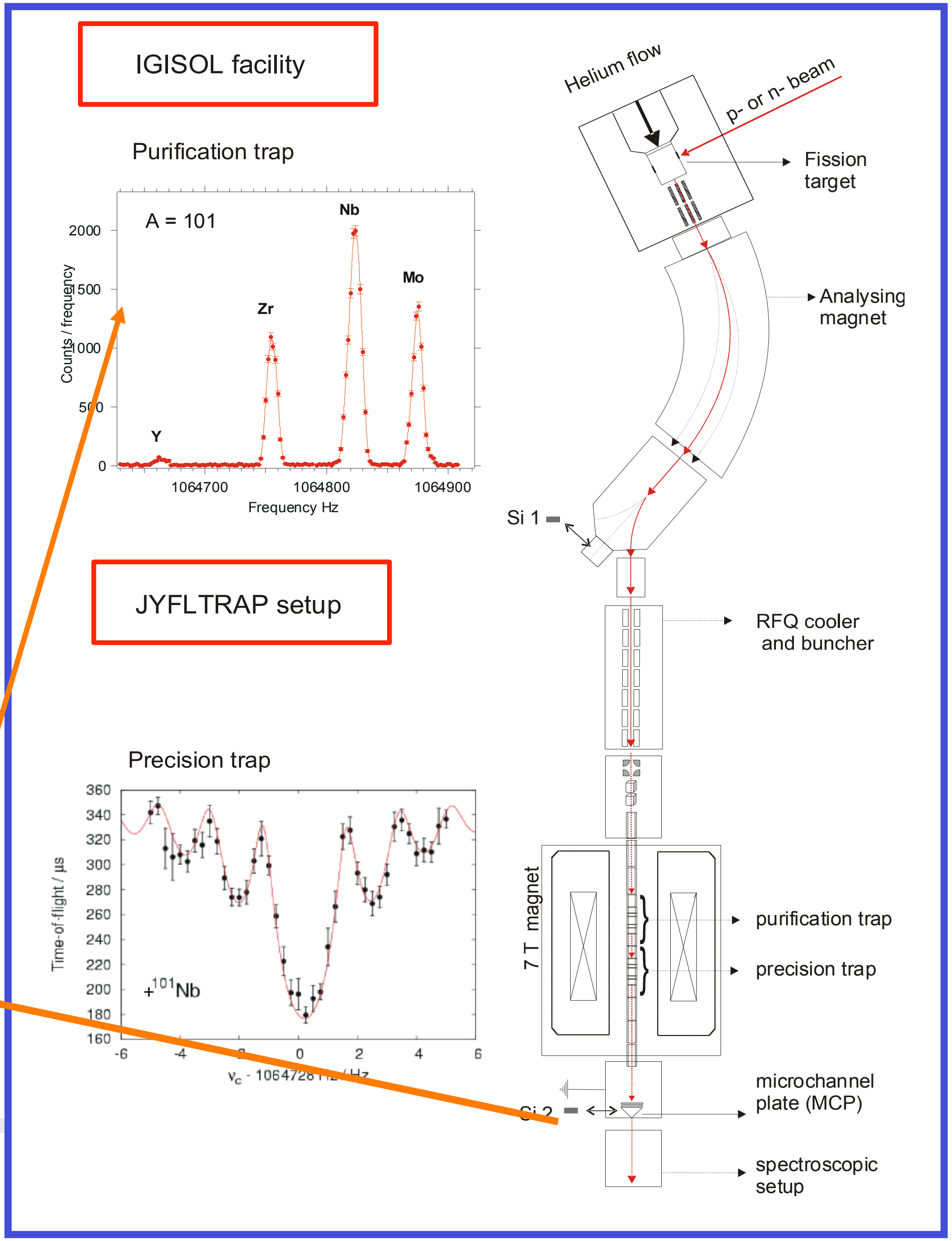
- Integral values: P_n values with BELEN

-TOF spectrometer (in combination with a dedicated gamma ray setup)

β-delayed neutron measurements at IGISOL (Cyclotron laboratory of the Univ. of Jyväskylä)

Isotopically pure fission fragment beams after a purification trap.

CIEMAT – IFIC – UPC – Jyvaskyla collaboration



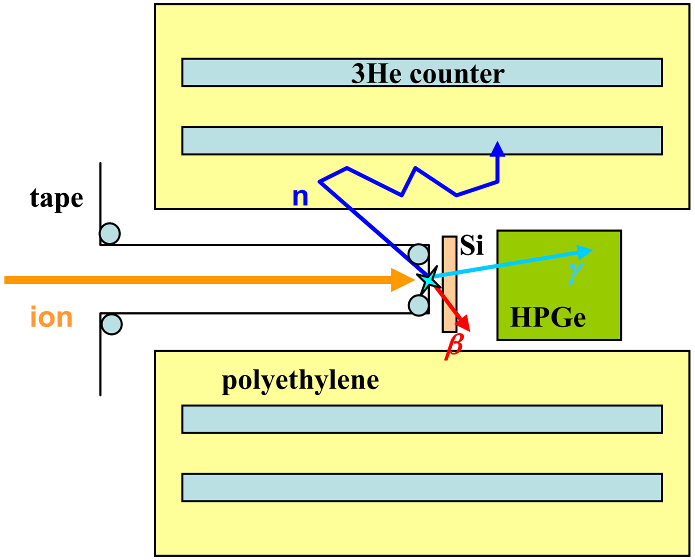
Isobar spectrum of A=101 fission products measured at spectroscopy setup

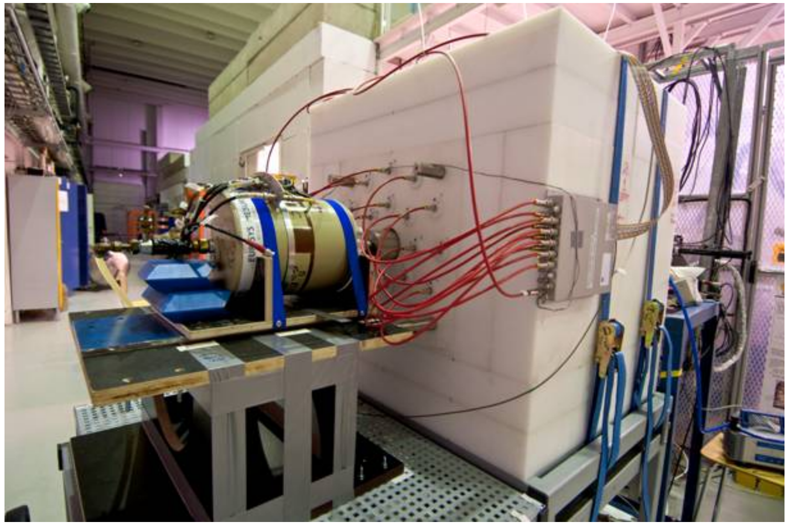
GOBIERNO DE ESPAÑA
MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD

Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

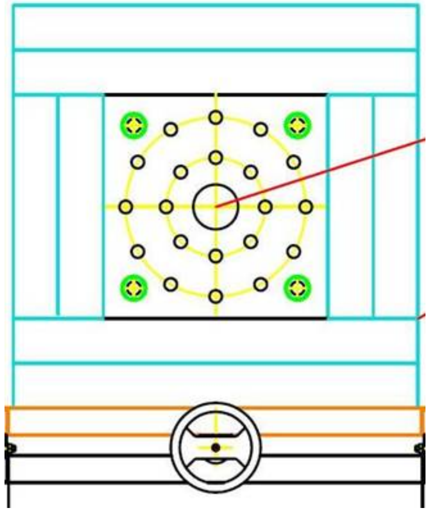
First experiment with BELEN-20 at Jyvaskyla: IGISOL+JYFLTRAP

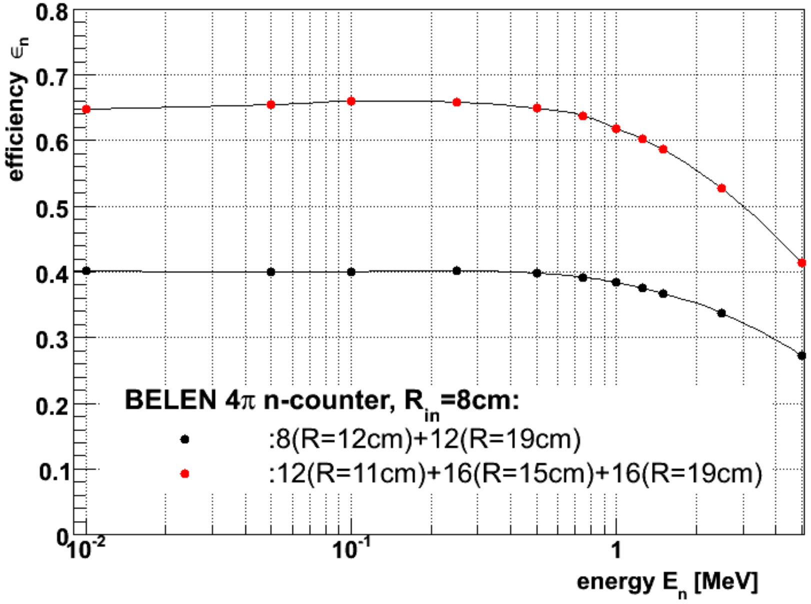
Isotopically pure beams!



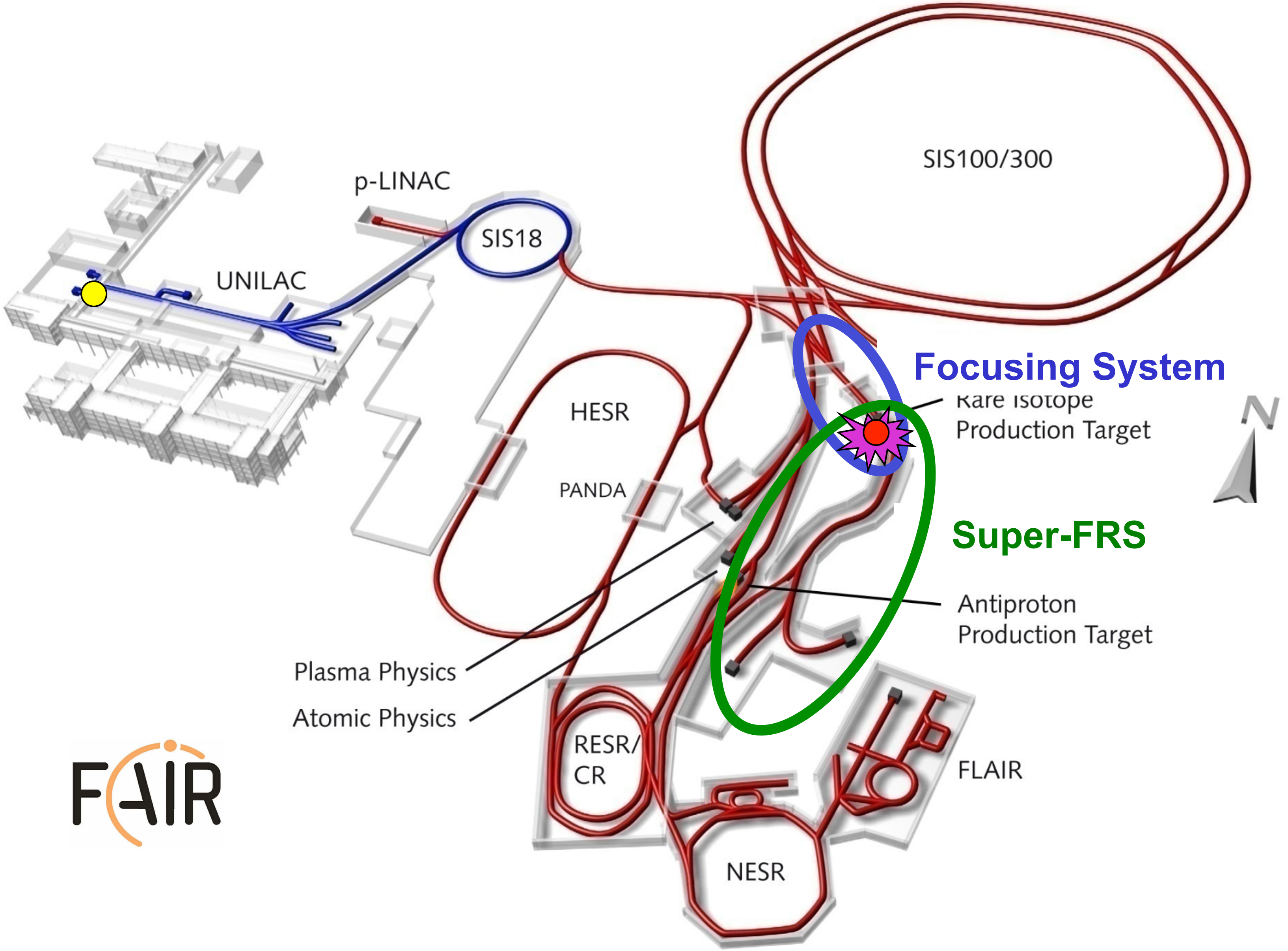


Measurement of ^{88}Br, ^{94,95}Rb, ^{138}I, ^{138}Te (UPC, IFIC, CIEMAT, Jyvaskyla collaboration)





The international FAIR facility (Darmstadt)



Design of the MOdular Neutron SpectromeTER for FAIR

The largest possible geometric effiency: 150 – 200 detectors (Consider the combined use with the Ge detectors)

A reasonable intrinsic efficiency (i.e. detector thickness)

Reasonable energy resolution < 10% up to 5

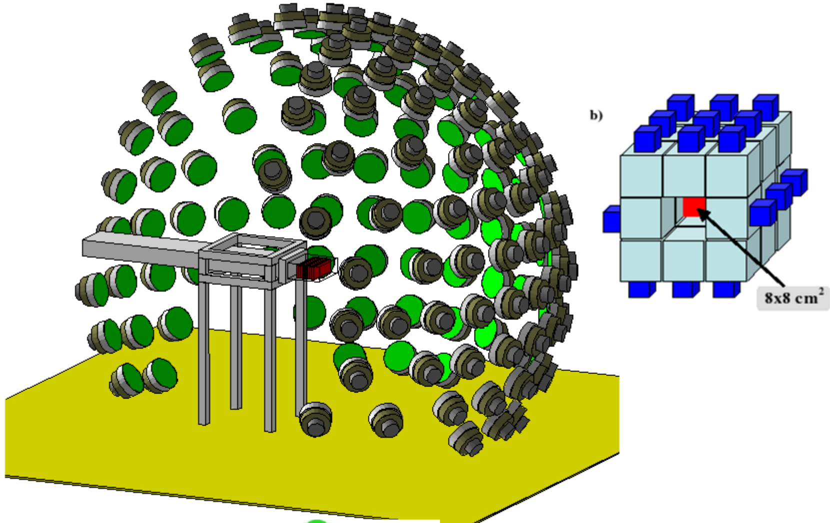
Good neutron timing ~1ns

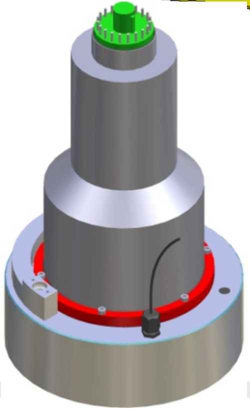
Good β timing: <1ns

Resonable flight path 2-3 m TOF

Energy threshold ~ 100 keV E_n (10 keV_{ee})

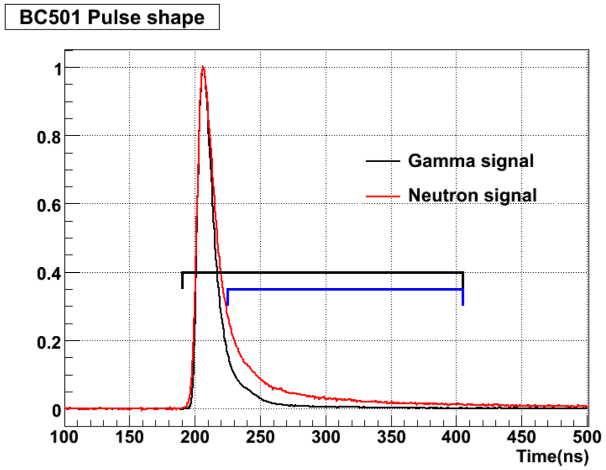
200 detectors, 10cm radius		ΔE/E @ 1 MeV	
TOF distance (m)	Geometric efficiency	1ns	5ns
2	**12.5%**	**4.6%**	**16.4%**
2.5	8.0%	3.7%	13.2%
3	**5.6%**	**3.1%**	**11%**
3.5	4.1%	2.7%	9.4%
4	3.1%	2.3%	8.2%
4.5	2.5%	2.1%	7.3%
5	2.0%	1.9%	6.6%

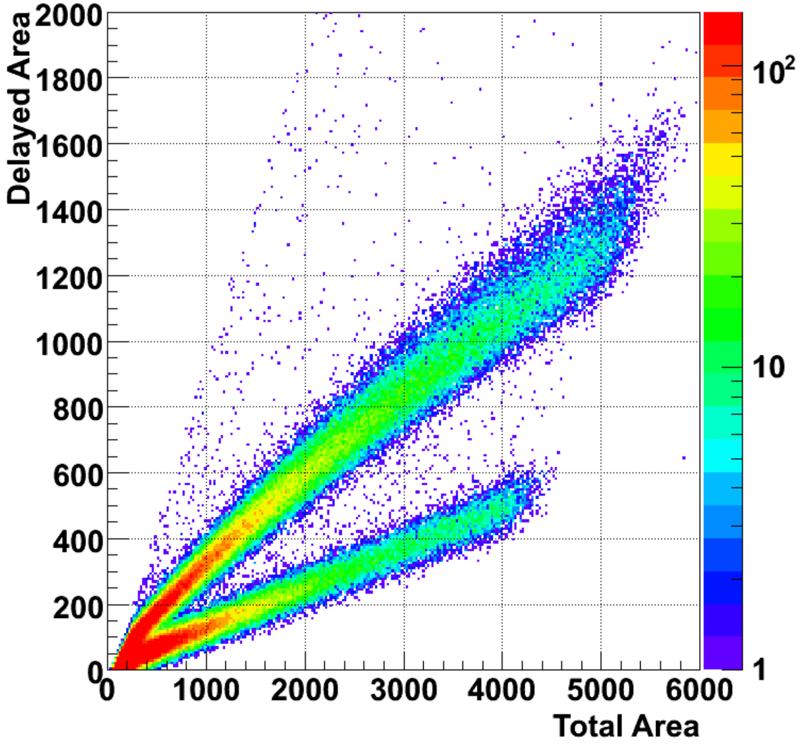




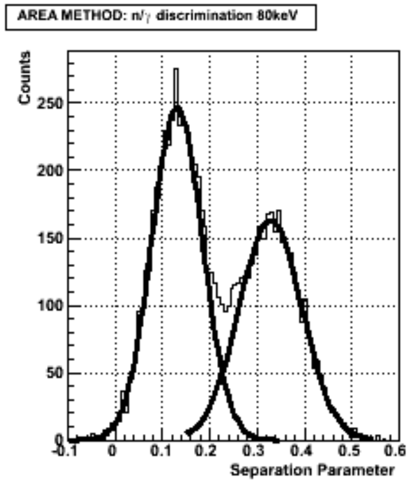
Ø=20cm
L=5cm

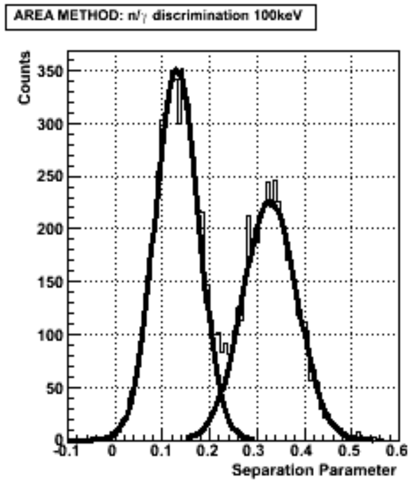
n/γ separation properties of BC501A

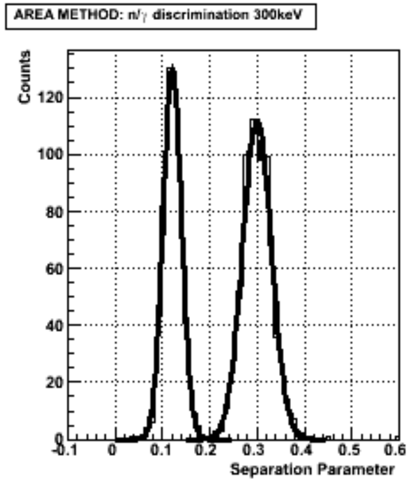


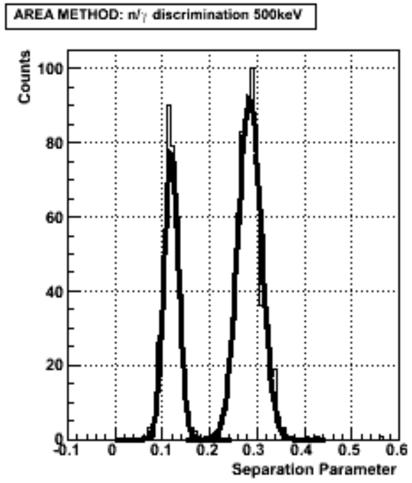


Reasonable to excellent n/γ separation for E_n > 100 MeV









The MONSTER collaboration

- CIEMAT (Madrid, Spain) - coordinators
- Instituto de Física Corpuscular (Valencia, Spain)
- University of Jyvaskyla
- VECC (India)

nTOF array @ DESIR/SPIRAL-II

- LPC (Caen, France)

Neutron ancillary detector for EXOGAM/AGATA

- Laboratori Nazionali di Legnaro (Italy) – NEDA project
- University of Uppsala (Sweden) – NEDA project

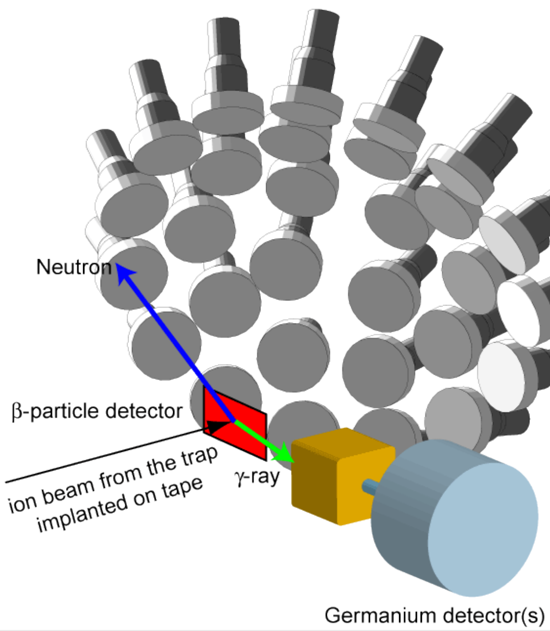
Acknowledgements:
Ministry of Science and Innovation, Spanish Government
EFNUDAT program, PTB staff
ENSAR FP7 project
Empresa Nacional de los REsiduos Radiactivos SA (ENRESA)

Various accepted proposals:

- Rb, I, Br isotopes at Jyväskyla (part of the EC FP7 project ANDES)
- ^{11}Li at ISOLDE
- PRESPEC umbrella proposal (tests)

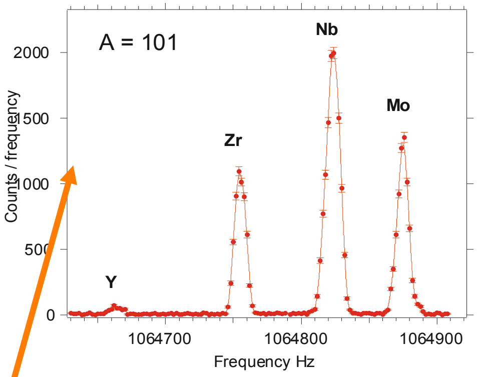
It is getting more a more difficult to have beam time.

Neutron Time Of Flight Spectrometer



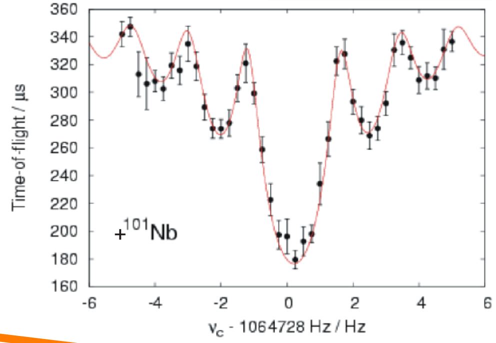
IGISOL facility

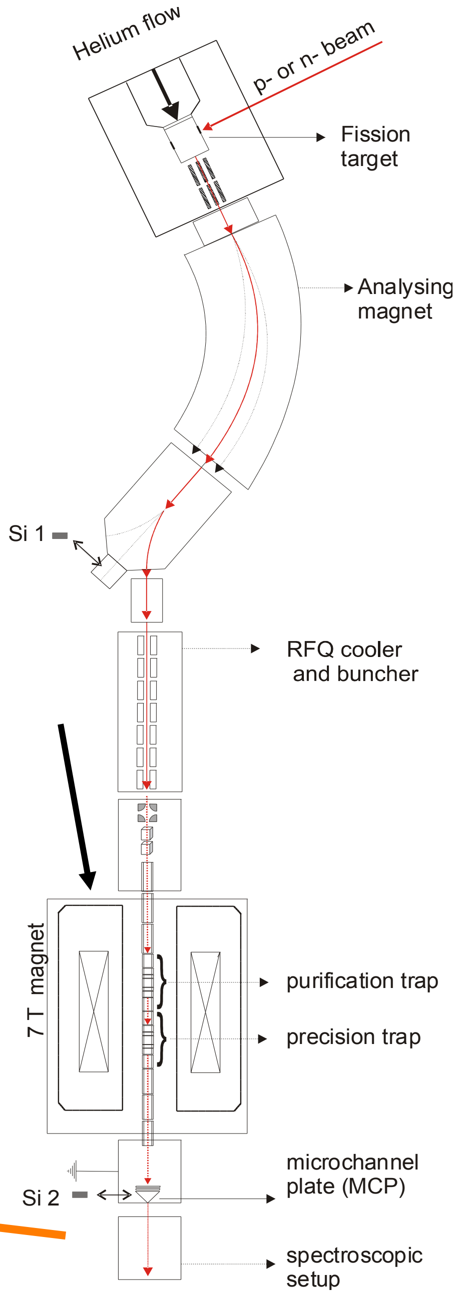
Purification trap $\Delta M/M < 10^{-5}$



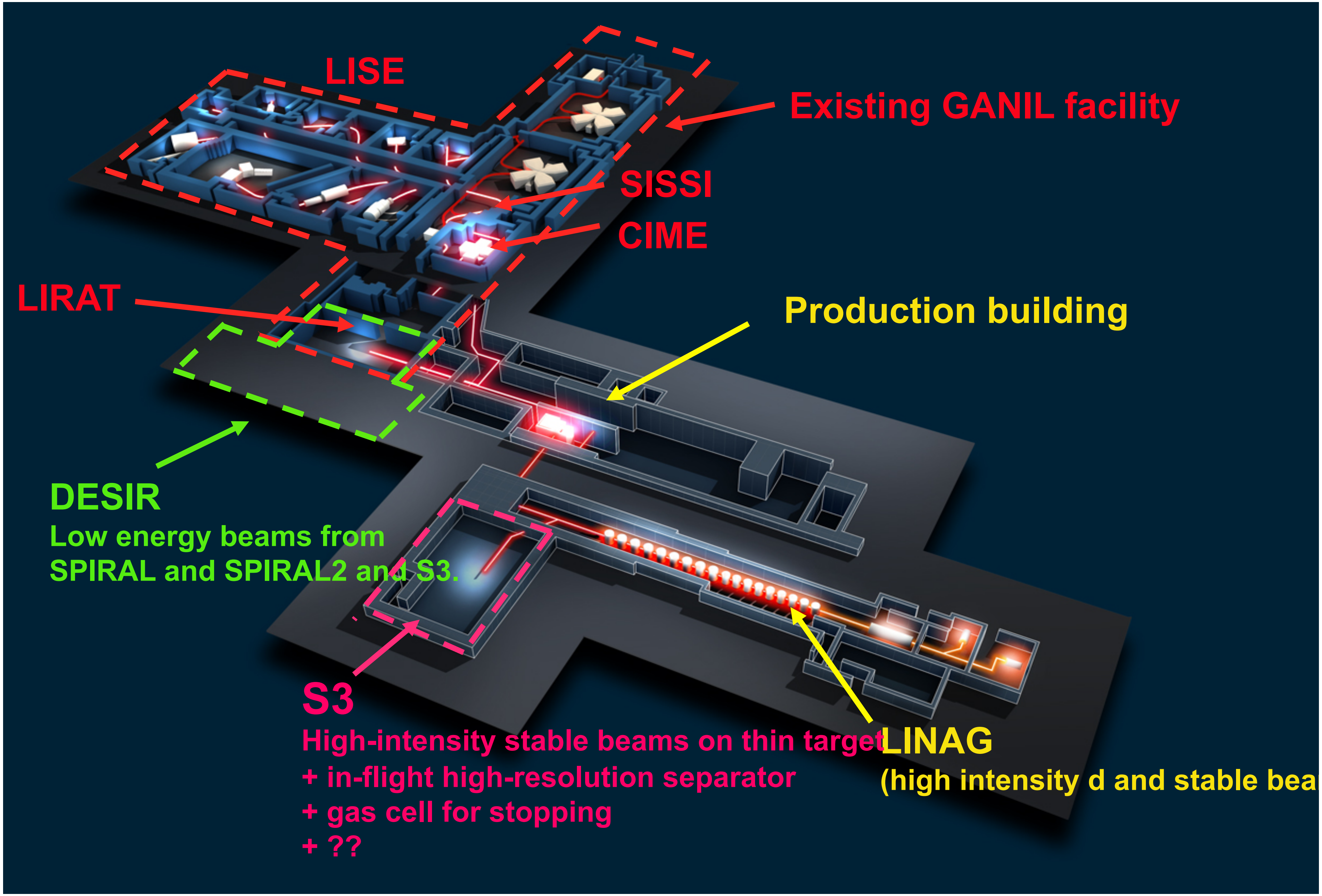
JYFLTRAP setup

Precision trap $\Delta M/M < 10^{-6}$





The French (GANIL) SPIRAL 2 project



LISE

Existing GANIL facility

SISSI

CIME

LIRAT

Production building

DESIR

Low energy beams from SPIRAL and SPIRAL2 and S3.

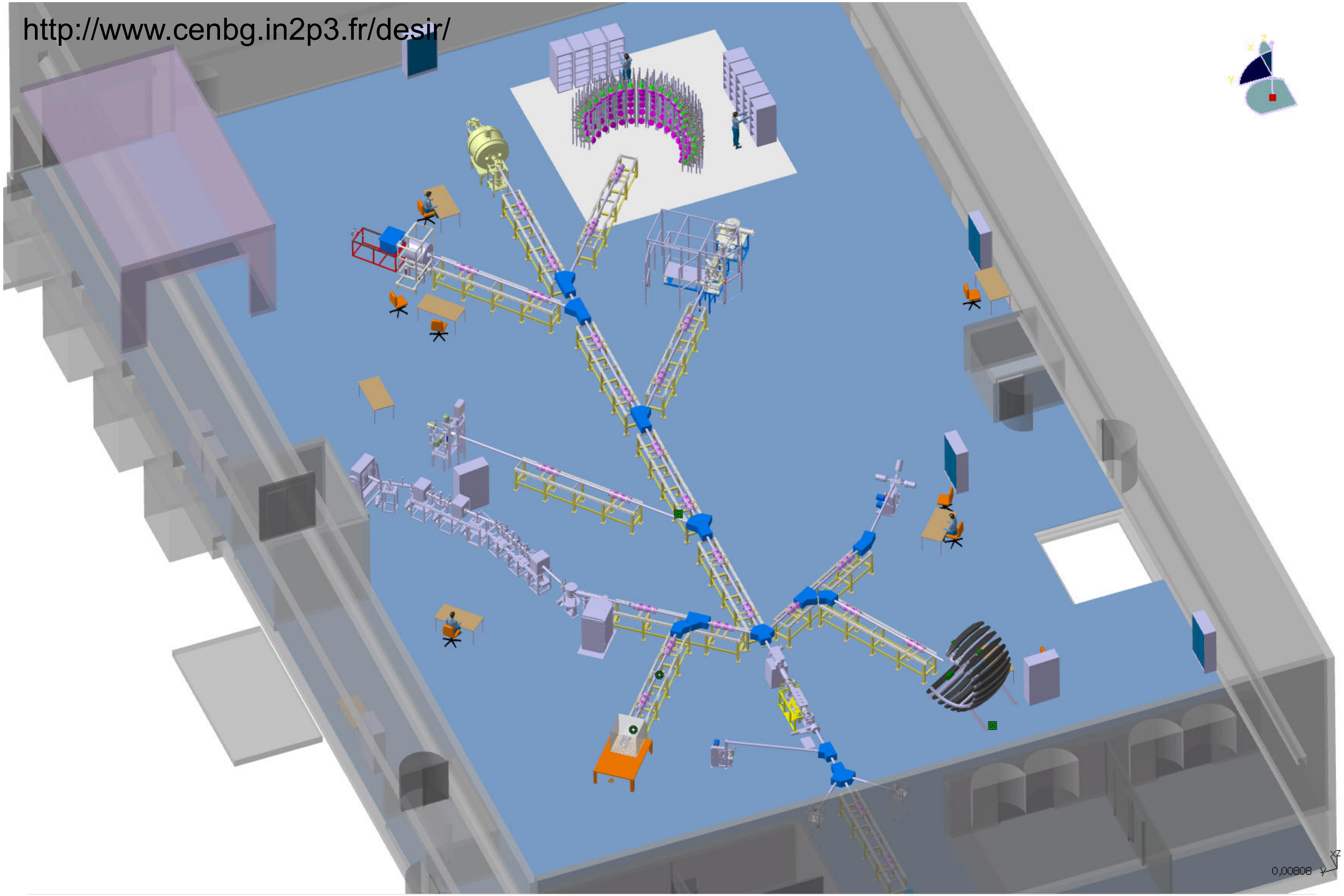
S3

High-intensity stable beams on thin target
+ in-flight high-resolution separator
+ gas cell for stopping
+ ??

LINAG

(high intensity d and stable bea

http://www.cenbg.in2p3.fr/desir/



CIEMAT's group is interested in high accuracy measurements of β-delayed neutron emitters relevant to nuclear technologies.

We are interested in both P_n values and energy spectra.

Good statistics (rates), good separation.

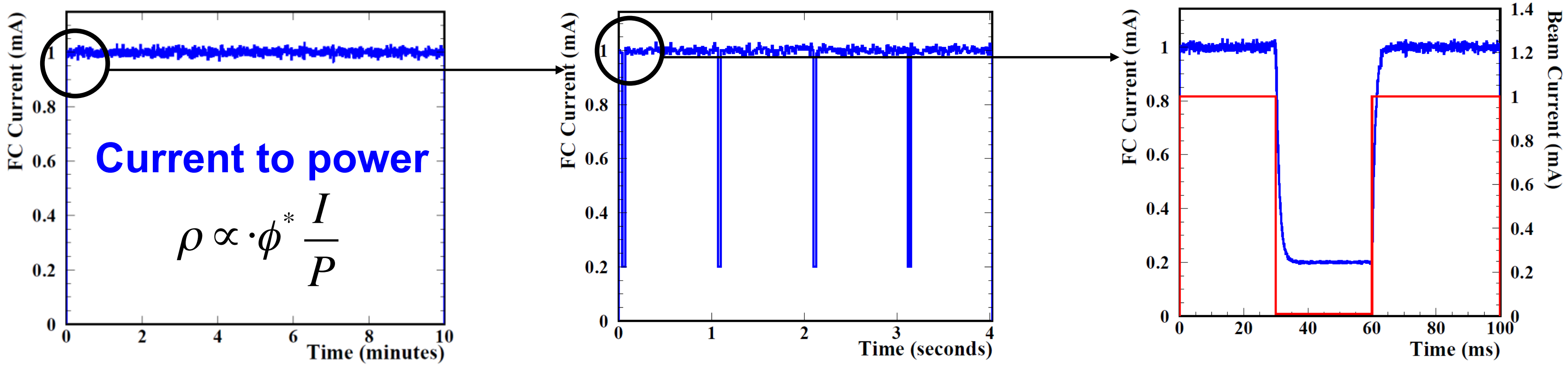
We do have 30 liquid scintillators available + 20 coming soon (< 2 years) + 40-50 at an unknown time (maybe soon, maybe not)

MONSTER@RIKEN? Some additional questions:

Time resolution of the implantation setup (WAS3ABi Δt= 100 – 200 ns)
We do need Δt~1 ns (CAITEN?)
Space. A typical flight path is about 3 m.
Money. Shipping 30 detectors from Spain to Finland costs ~10 k€.
Safety rules. BC501A (as any other organic liquid scintillator) is a toxic material and its use/transport is conditioned by restrictive safety rules.
Will there be sufficient beam time to justify such a big effort?

On line monitoring of the subcriticality of Accelerator Driven Systems (MYRRHA)

Beam interruption experiment



Current to power

$$\rho \propto \cdot \phi^{*} \frac{I}{P}$$

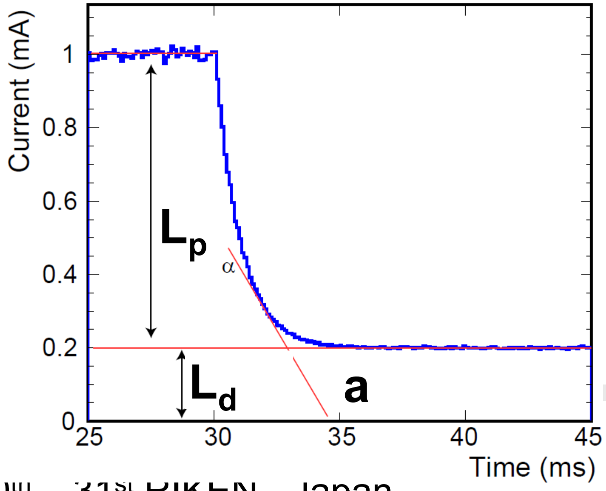
The reactivity monitoring during short beam trips (must be short in time in order to avoid thermal stress and transients). However, if the beam interruption is too short, the β-delayed neutron plateau is not reach and Monte Carlo based correction techniques need to be applied.

Beam extraction

$$-\frac{\rho}{\beta_{eff}} = \frac{L_p}{L_d}$$

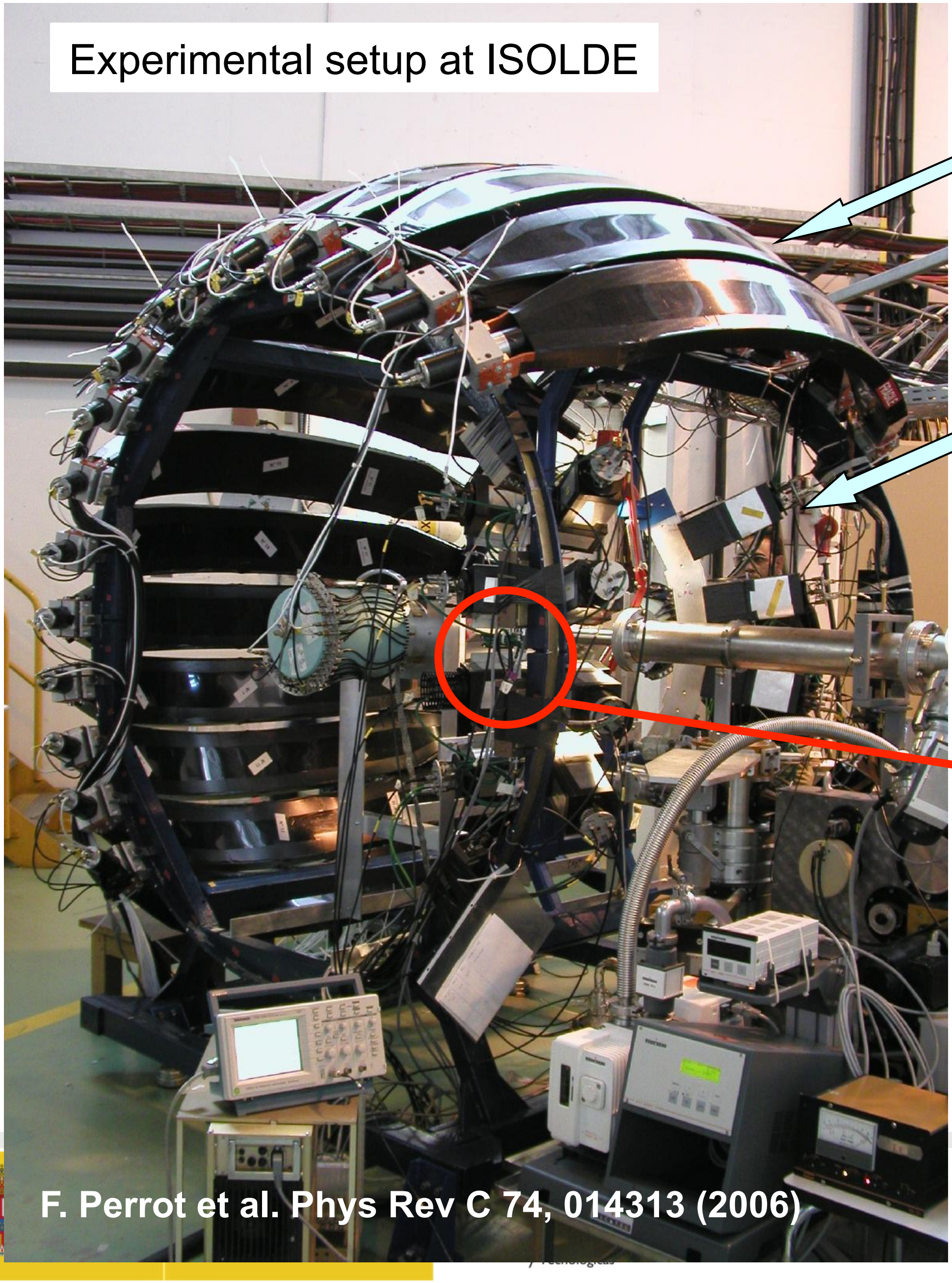
Decay shape

$$-\frac{\rho}{\beta_{eff}} = \frac{\alpha}{\beta_{eff}/\Lambda} - 1$$



The TONERRE + LEND arrays (BC400)

A. Buta. NIMA 455 (2000) 412}423



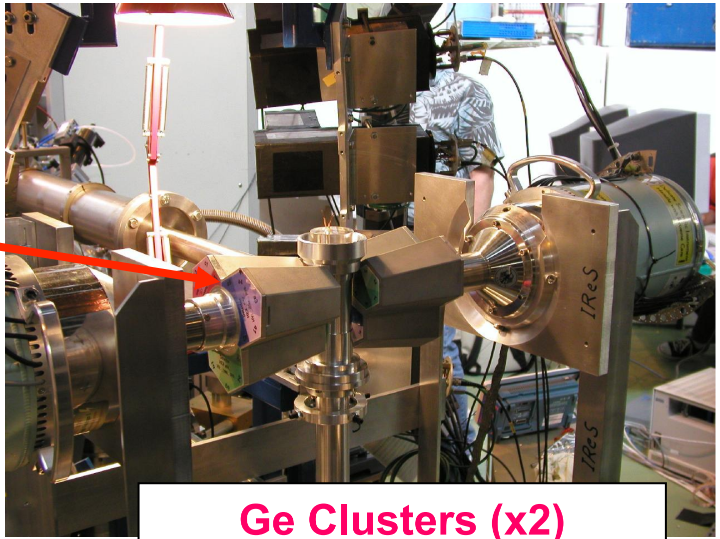
Experimental setup at ISOLDE

F. Perrot et al. Phys Rev C 74, 014313 (2006)

TONNERRE Detector
(LPC Caen, IFIN Bucarest)
E_n= 0.2-7 MeV
ε ~ 11% at 1 MeV

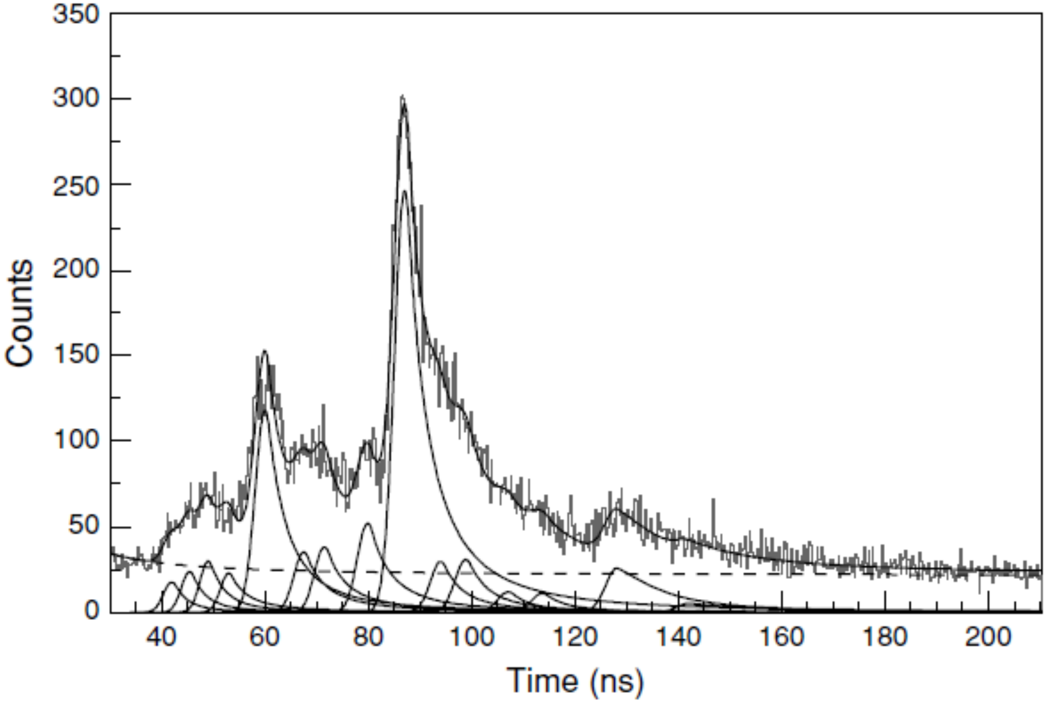
Low energy neutron detectors (x8)
(IReS - Strasbourg)

E_n = 0.05-3.0 MeV
ε ~ 0.5% at 1 MeV



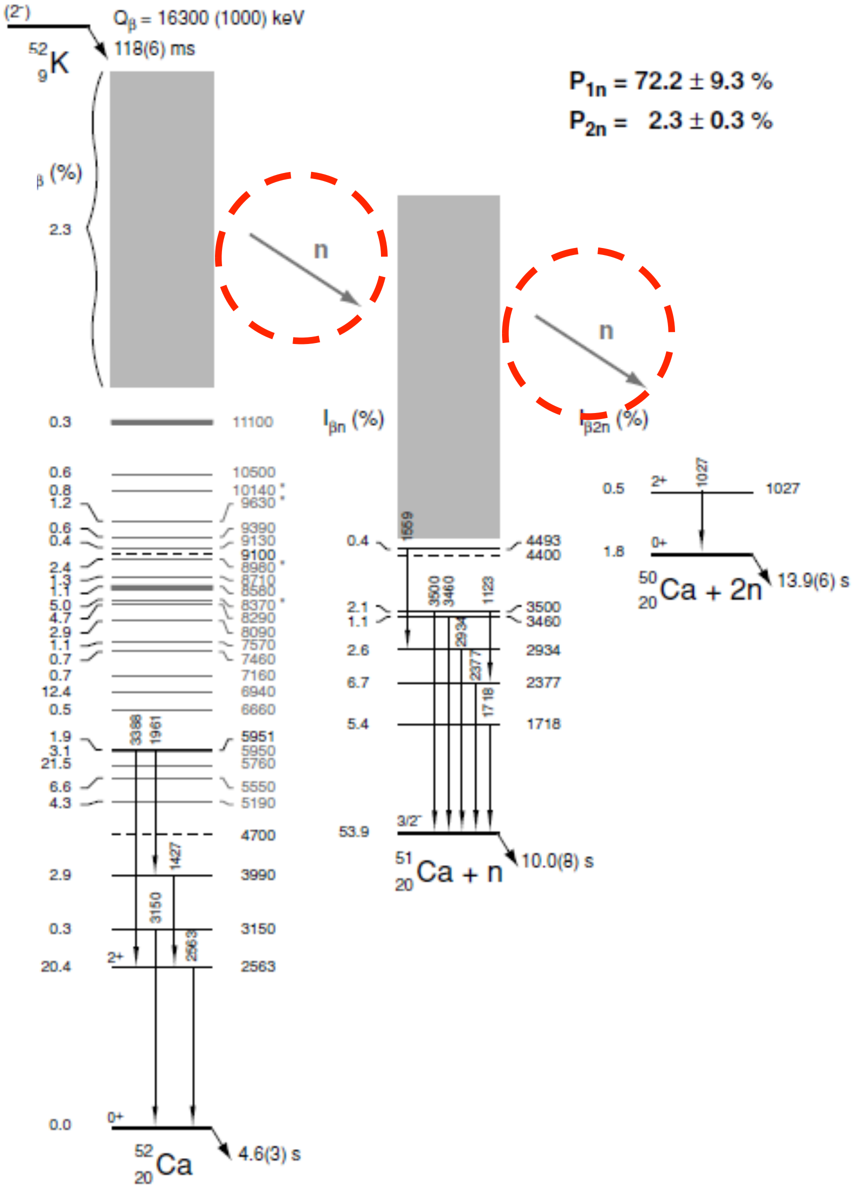
Ge Clusters (x2)
(MINIBALL collaboration)
ε ~ 5% at 1.3 MeV
and **4πβ** (start n-TOF)
ε ~ 70%

β-decay studies of neutron-rich ^{51,52,53}K isotopes:



F. Perrot et al., Physical Review C 74, 014313 (2006)

LEND 2*.0% neutron detection efficiency at 1 MeV, ΔE/E ~6% at 440 keV*
TONNERRE *neutron detection efficiency 7.7% at 1 MeV, ΔE/E ~11% at 440 keV*



I. Fast Na-cooled critical reactor

Core: 300 fuel elements of MOX: 14% - 16% ^{239}Pu + depleted U (0.25% ^{235}U)
Blanquet: a) depleted U + 10-20% Minor Actinides for waste transmutation, b) MOX

$$\beta_{eff}=4.5\cdot 10^{-2} \text{ vs } \beta_{eff}=6.8\cdot 10^{-2} \text{ for a } ^{235}\text{U LWR}$$

For the licensing of a critical reactor, it is important to determine with a good accuracy (several hundred pcms) the design parameters. Otherwise, the control mechanisms will have to be over dimensioned!

II. Accelerator Driven System

The ADS is intrinsically subcritical, even though a value close to criticality is desired for holding a sustained transmutation. For its licensing, however, one has to guarantee that the criticality will be never reached

$$\delta k_{eff} = \delta k_{prompt} + \delta k_{delayed} + \delta k_{void} + \ldots$$