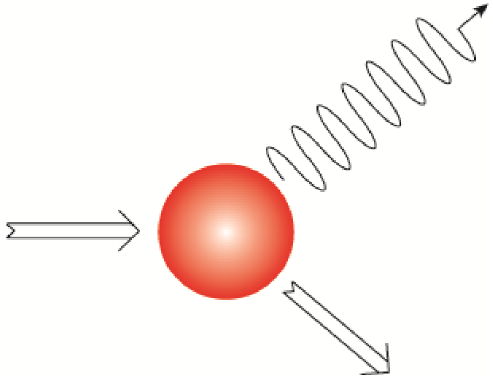
Beta-delayed neutron measurements for nuclear technologies

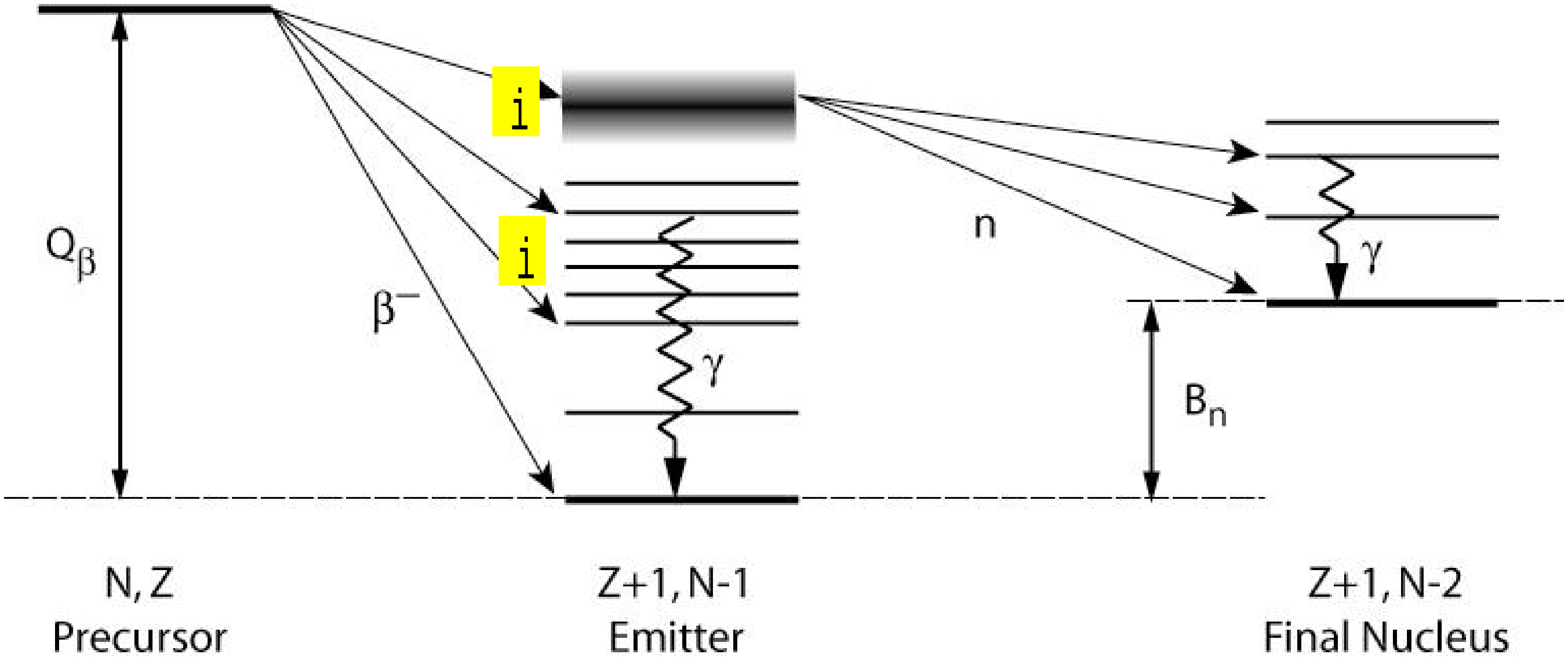


D. Cano Ott
Nuclear Innovation – Nuclear Fission Division
Dept. of Energy

CIEMAT-IFIC-UPC collaboration

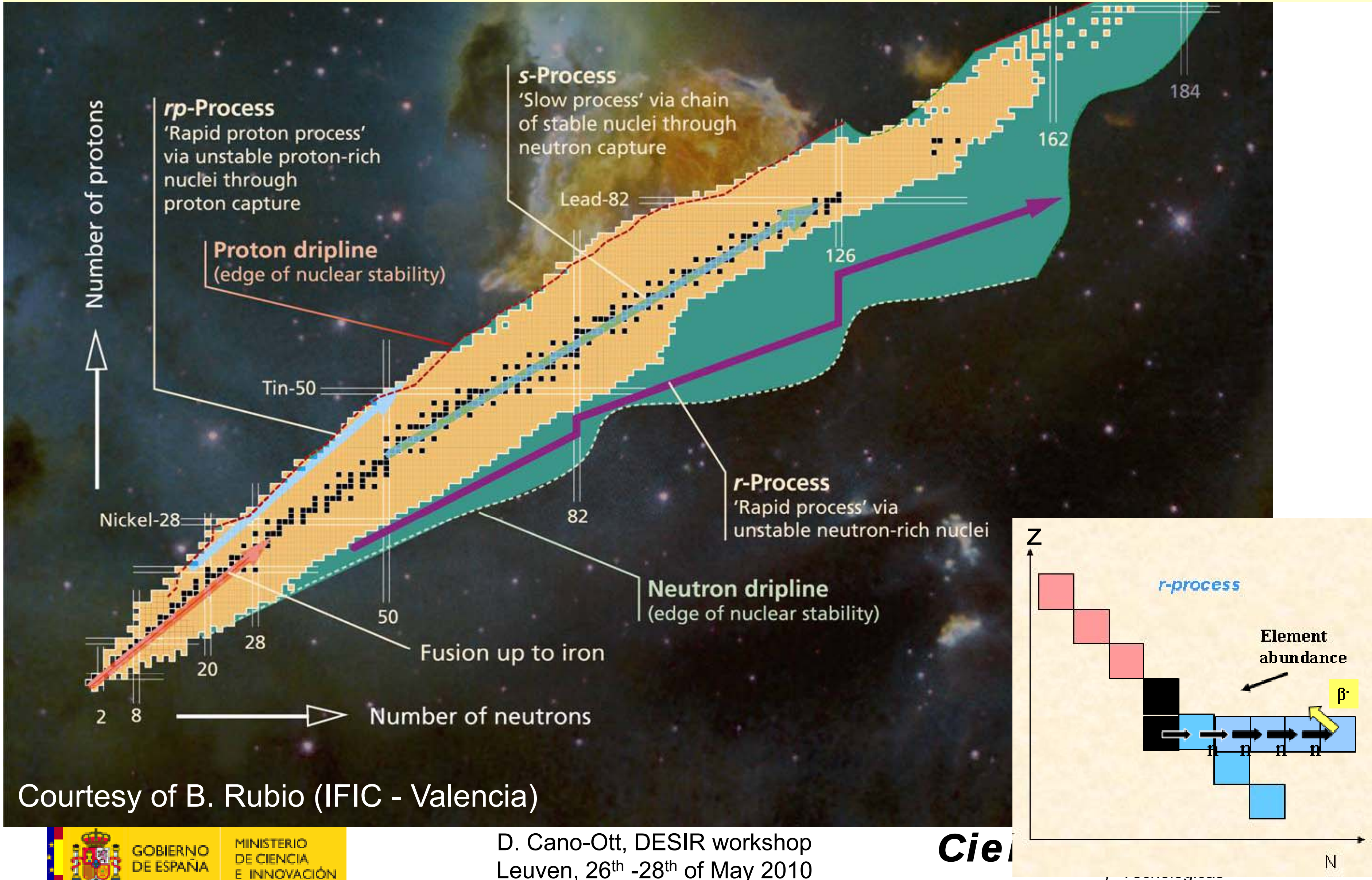
GOBIERNO DE ESPAÑA MINISTERIO DE CIENCIA E INNOVACIÓN

Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas



$$B^i{}_{GT} = K \frac{I^i{}_\beta}{f^i(Z, Q_\beta)T_{1/2}} = K \frac{1}{ft^i{}_{1/2}}$$

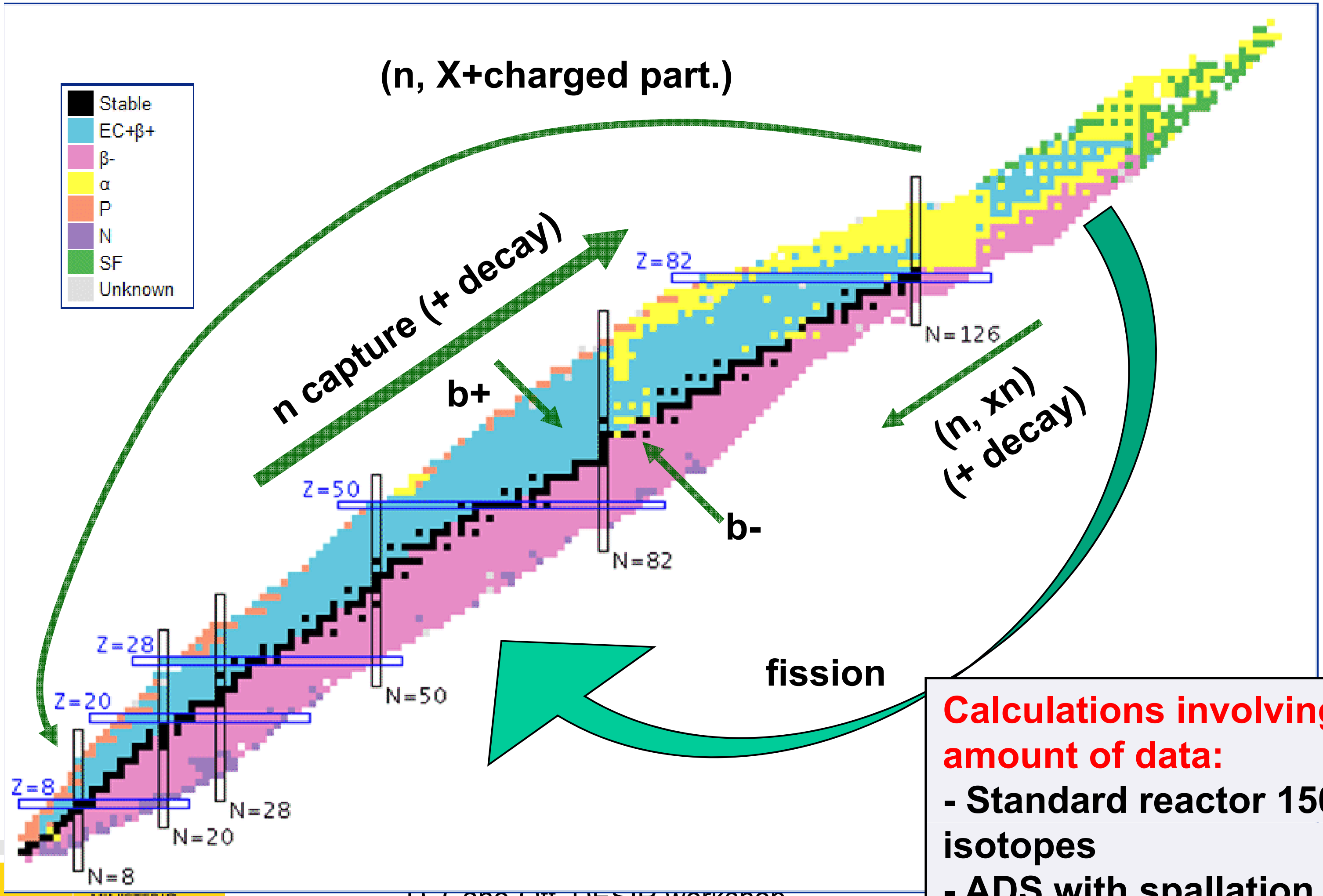
Beta decay knowledge (on neutron rich nuclei) is needed as input for nucleosynthesis calculations, and in particular for the r-process to explain the cosmological abundance of the elements.



Courtesy of B. Rubio (IFIC - Valencia)

Main reactions in a nuclear reactor (or transmutation device)

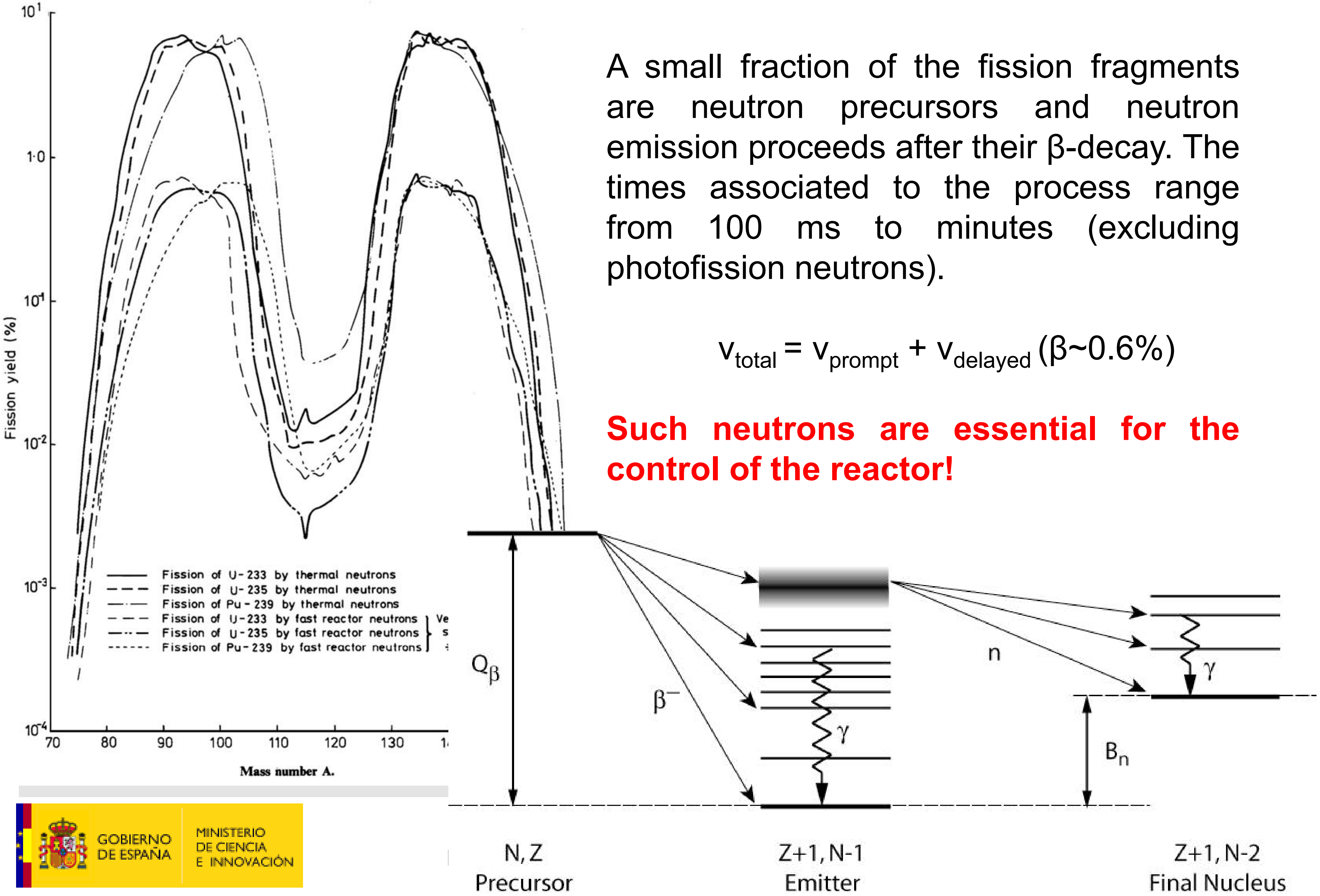
- n- induced fission (energy + waste)
- neutron capture (activation + breeding)
- elastic and inelastic neutron scattering
- radioactive decay
- (n,xn), (n, charged particle), …



Calculations involving a large amount of data:

- **Standard reactor 1500 isotopes**
- **ADS with spallation 3000 isotopes**

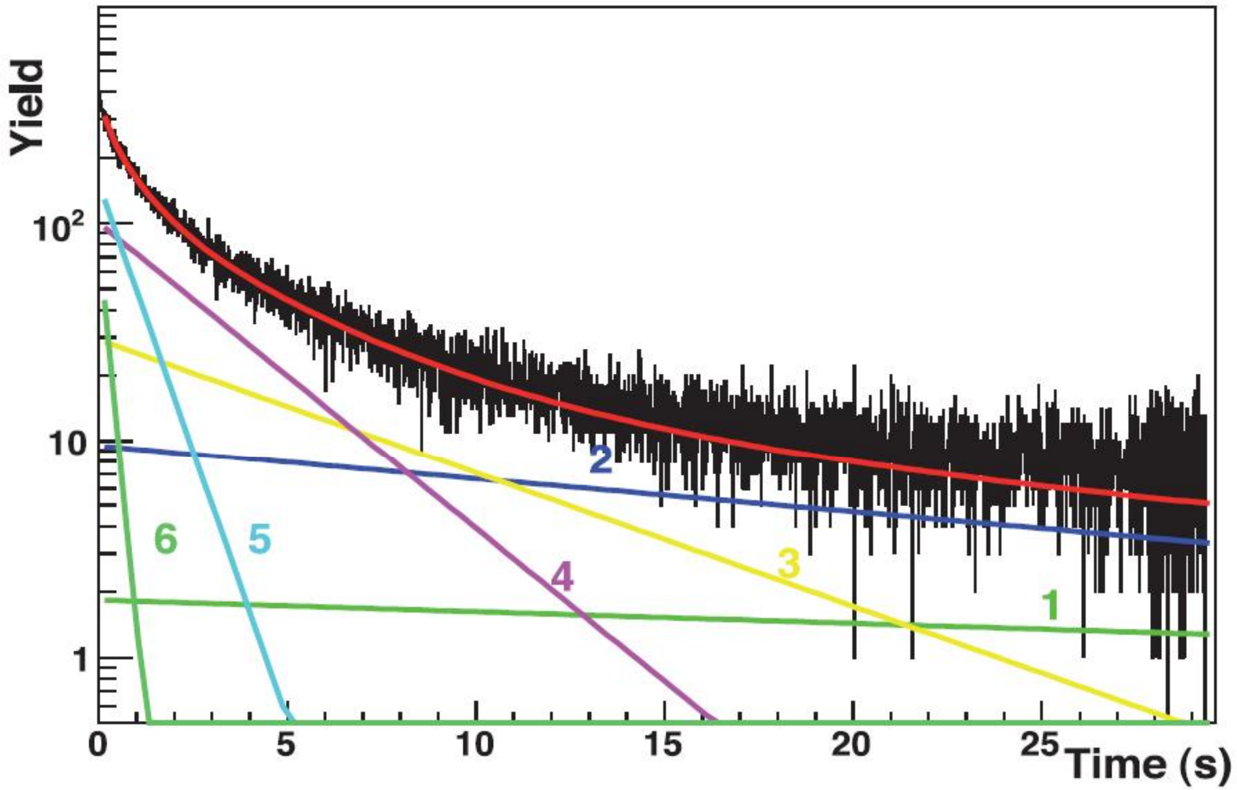
The delayed neutrons and the reactor control



A small fraction of the fission fragments are neutron precursors and neutron emission proceeds after their β-decay. The times associated to the process range from 100 ms to minutes (excluding photofission neutrons).

$$\nu_{total} = \nu_{prompt} + \nu_{delayed}\ (\beta \sim 0.6\%)$$

Such neutrons are essential for the control of the reactor!

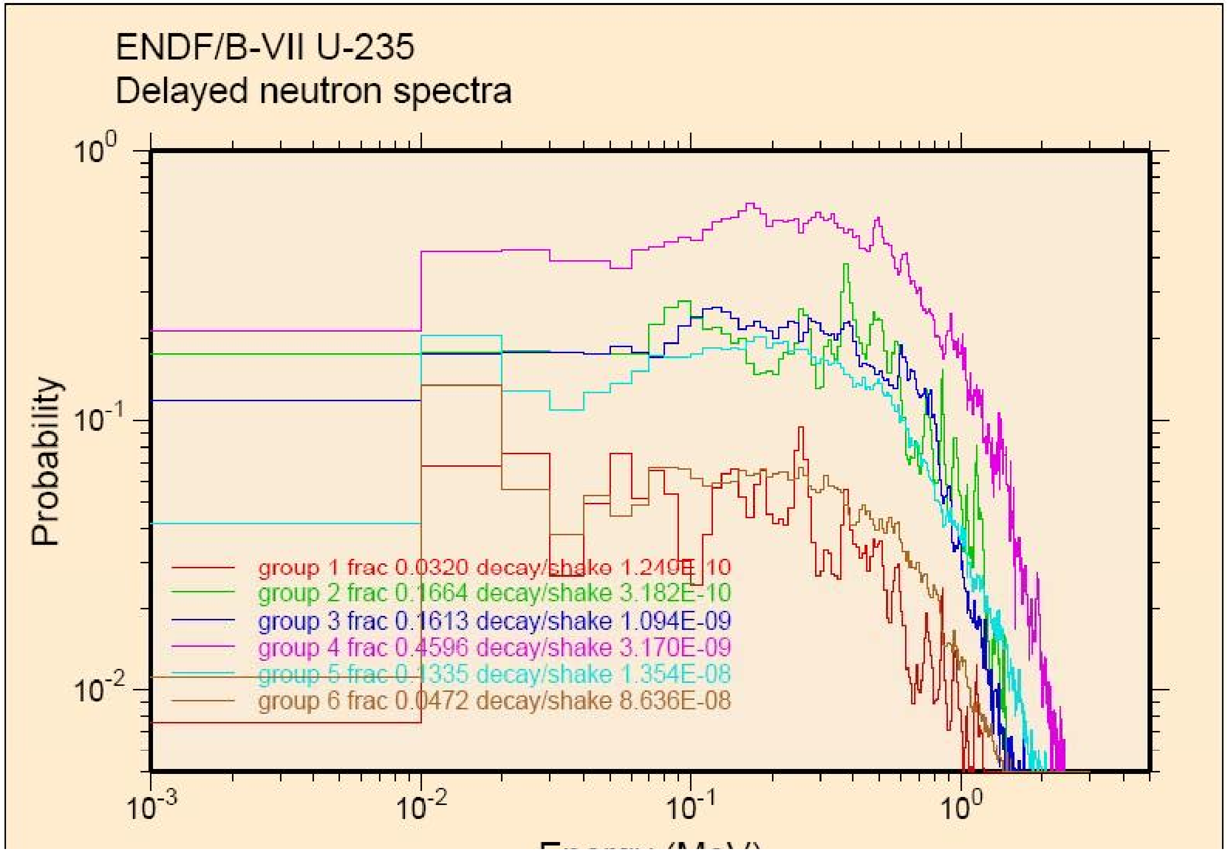


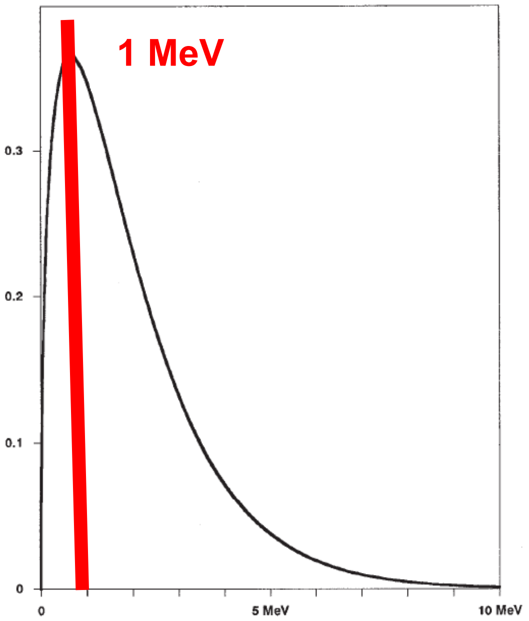
Group #→	1	2	3	4	5	6
$T_{1/2}$	54.51	21.84	6.0	2.23	0.496	0.179
λ_I	0.0127	0.031	0.1155	0.310	1.397	3.871
β_i/β	.038	0.213	0.188	0.407	0.128	0.026
β_I	0.0002641	0.00148035	0.0013066	0.00282865	0.0008896	0.0001807

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% s

The delayed neutron energy spectra (left) have a mean energy of 500 keV (below the 2 MeV for the the fission spectrum)





Prompt fission spectrum

Delayed neutrons have a much lower probability of causing fast fissions than prompt neutrons because their average energy is less than the minimum required for fast fission to occur.

Delayed neutrons have a lower probability of leaking out of the core while they are at fast energies, because they are born at lower energies and subsequently travel a shorter distance as fast neutrons. Larger probability of being absorbed!

Nuclear Reactor Kinetics (without delayed neutrons)

- Average generation time" $\Lambda \equiv$ average time between the birth of two fission neutrons in successive generations
- *N(t)* = neutron population at time *t.*

$$N(t+\Lambda) = k_{eff} N(t)$$

If we identify Λ as Δt, or as *dt* in the limit, we can write

$$\frac{N(t+\Lambda)-N(t)}{\Lambda} = \frac{k_{eff}N(t)-N(t)}{\Lambda} = \frac{k_{eff}-1}{\Lambda}N(t)$$

$$\frac{dN(t)}{dt} = \frac{k_{eff}-1}{\Lambda}N(t) \quad \Rightarrow \boxed{N(t) = N(0)\exp\left(\frac{k_{eff}-1}{\Lambda}t\right)}$$

Prompt critical reactor

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

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

Thus, the neutron population (and also the power) would multiply:

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 is impossible to control such a fast power increase** with mechanical shutdown systems.

Critical reactor with delayed neutrons

For 99.4% of neutrons, take average generation time = 10^{-3} s. For the other 0.6% (the delayed neutrons) take 10^{-3} s + (say) the half-life of the precursor group (this requires a 6-term)

Using again k_{eff} =1.001, we now find in the exponential equation

$$N(t) = N(0)\exp\left(\frac{1.001-1}{0.1s}t\right) = N(0)\exp(0.01t)$$

Thus, the neutron population (and also the power) would multiply

by a factor exp(0.01) ≅ 1.01 in 1 s
by a factor exp(0.02) ≅ 1.02 in 2 s
by a factor exp(0.03) ≅ 1.03 in 3 s!

The delayed neutrons have reduced the rate of increase of fission power dramatically. It is now very achievable to control the power transient with mechanical shutdown systems.

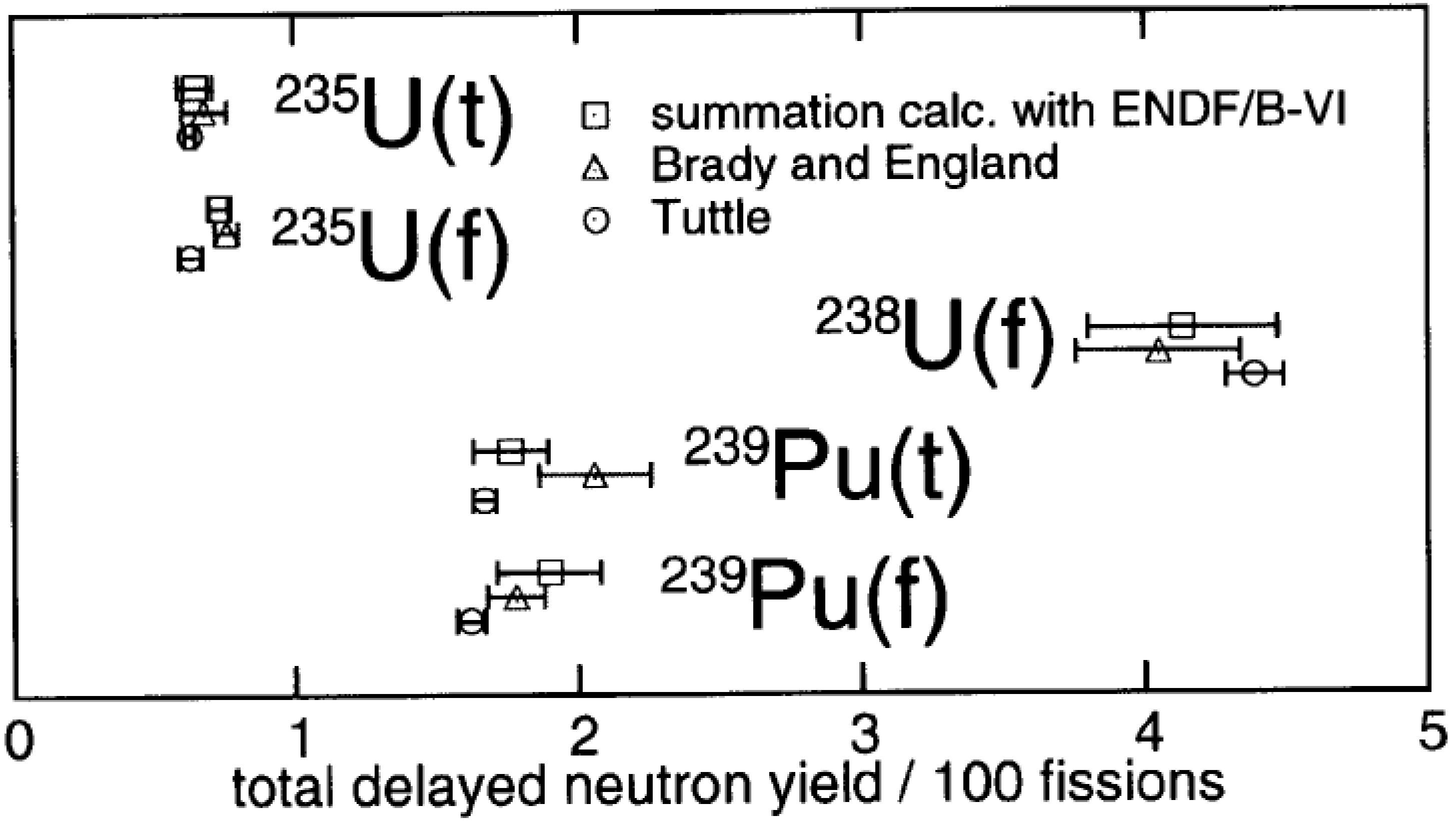
Individual precursors are responsible for a large number of the v_d

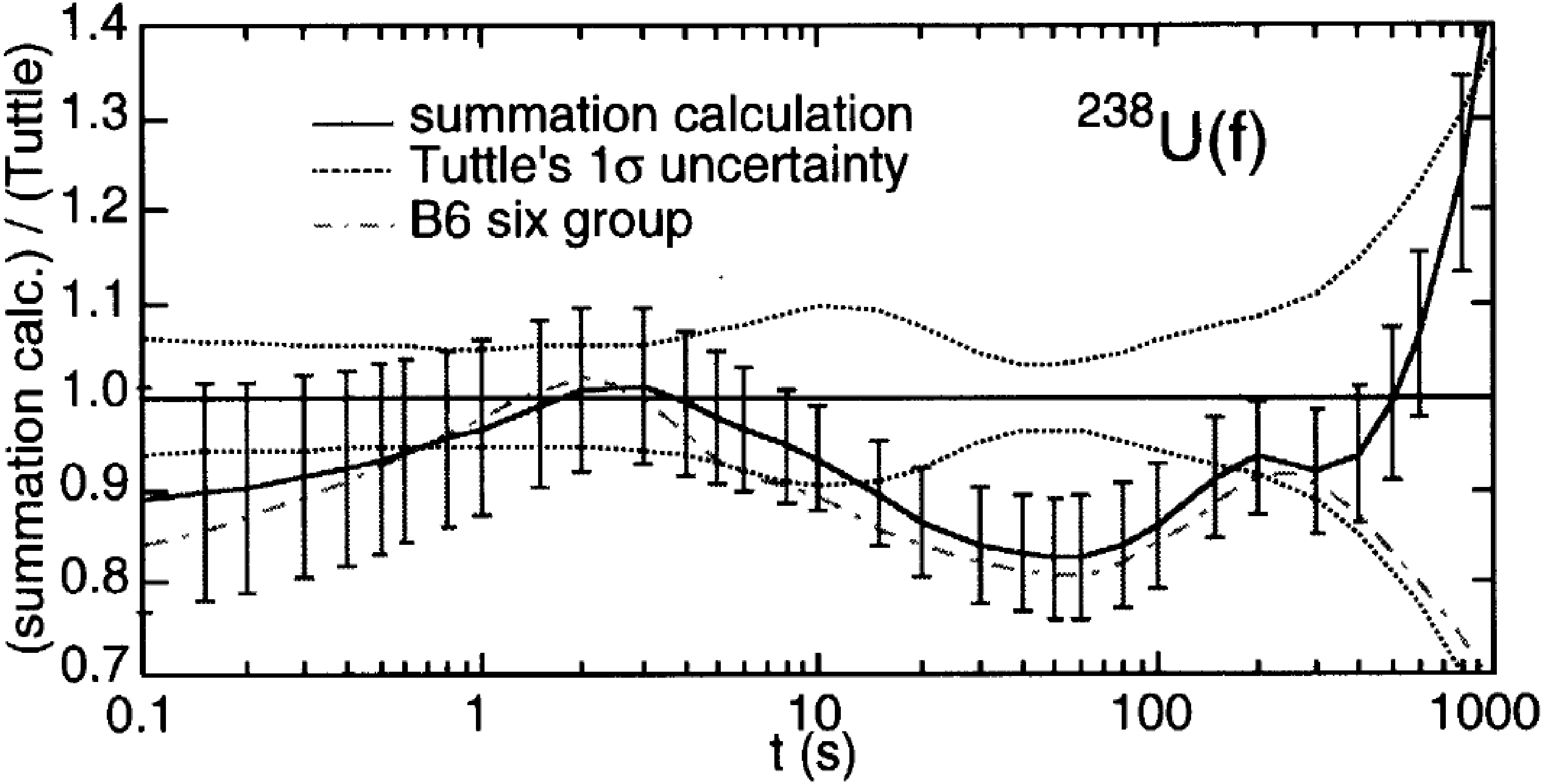
Iodine model		Precursor	Half-life, s	Bromine model	
N_{gr}	Group period, s			N_{gr}	Group period, s
1	55.69	^{87}Br	55.69	1	55.69
2	24.50	^{137}I	24.50	2	24.50
3	16.30	^{88}Br	16.30	3	16.30
4	6.46	^{138}I	6.46	4	6.37
5	4.67	^{93}Rb	5.93		
		^{89}Br	4.38	5	4.38
6	2.76	^{94}Rb	2.76	6	2.76
7	2.30	^{139}I	2.30	7	2.09
8	2.056	^{85}As	2.08		
		^{98m}Y	2.00		
9	1.119	^{93}Kr	1.289	8	1.289
		^{144}Cs	1.002	9	0.942
10	0.860	^{140}I	0.860		
11	0.443	^{91}Br	0.542	10	0.542
		^{95}Rb	0.384	11	0.384
12	0.195	^{96}Rb	0.203	12	0.195
		^{97}Rb	0.170		

Status of the delayed neutron data

The delayed neutron precursor groups seem to work reasonably well for a wide set of calculations. There are however significant discrepancies between the “evaluated/experimental results” and the results from summation calculations starting from microscopic data.

$$\overline{\nu}_d = \sum_i C_i \cdot P_n^i$$

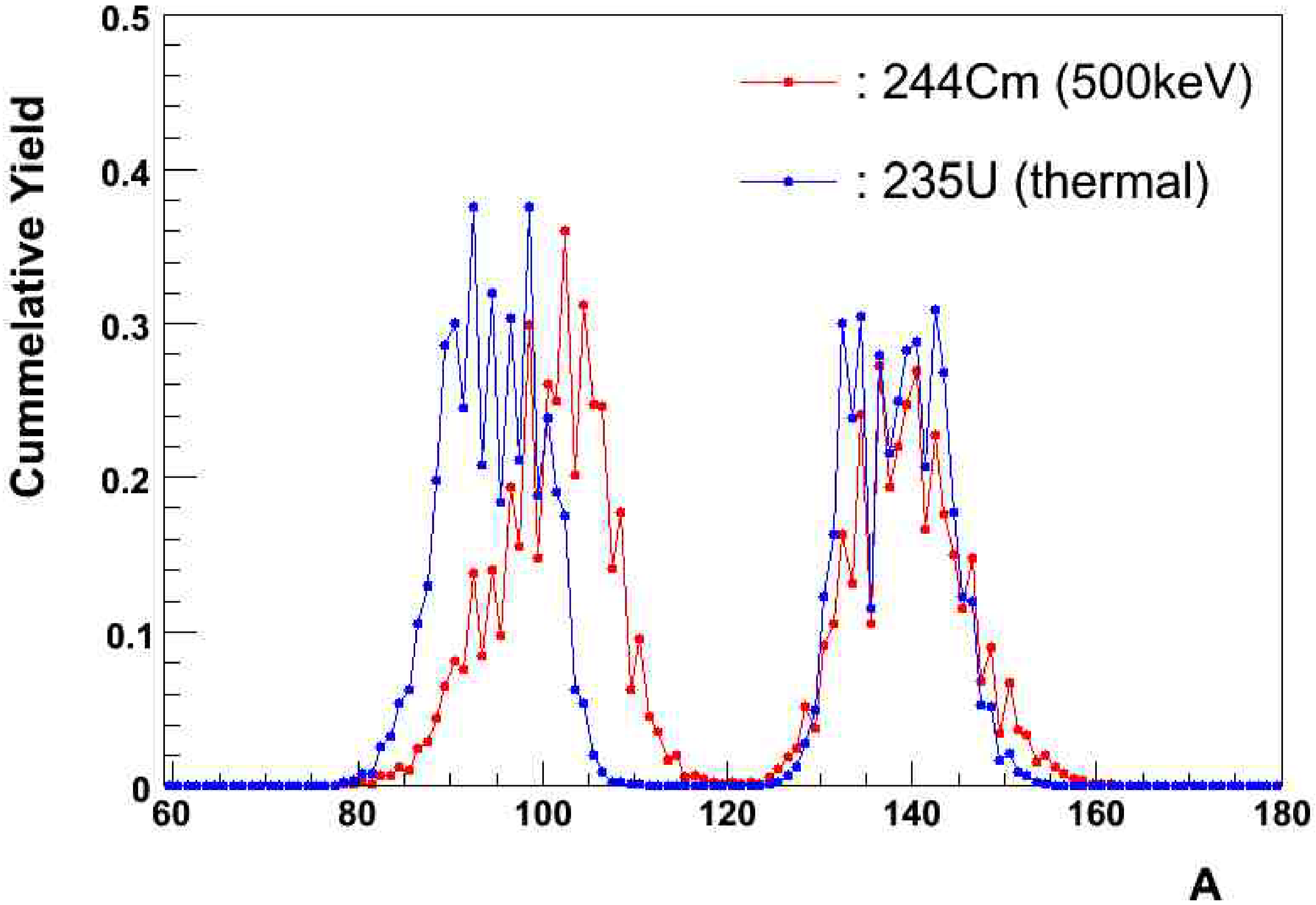




(summation calc.) / (Tuttle)
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.1
1
10
100
1000
t (s)
summation calculation
Tuttle's 1σ uncertainty
B6 six group
238U(f)

The amount and energy of the delayed neutrons depends on the fissioning system

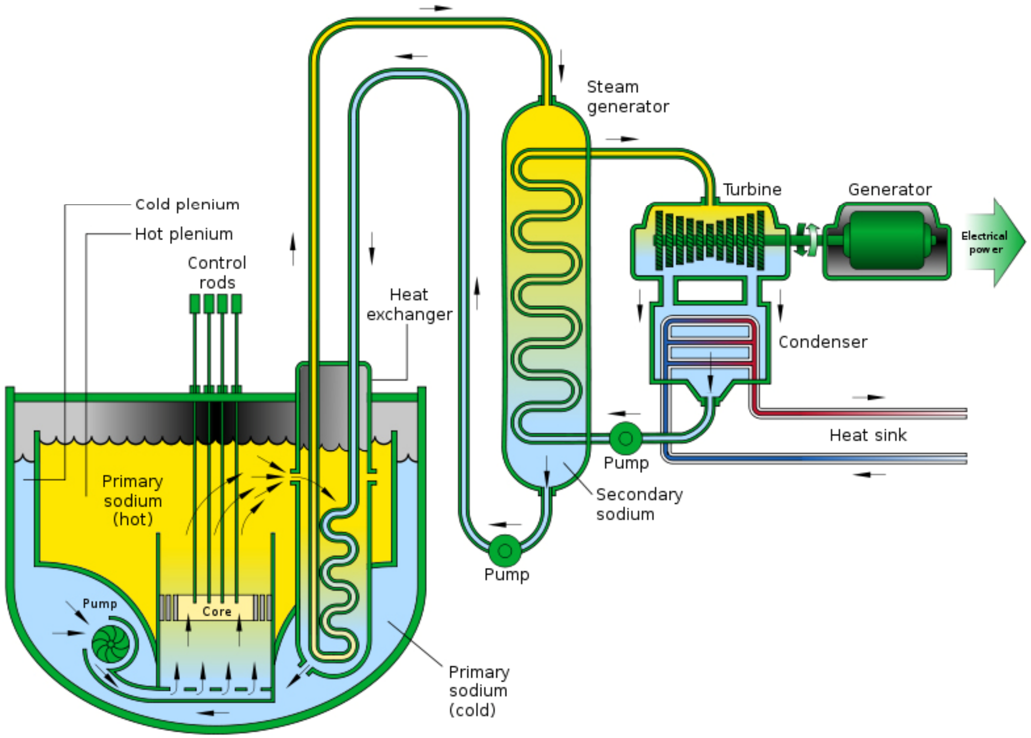
Fissioning Nuclide	Fractional Group Yield	Decay Constant λ (s^{-1})	Direct Delayed Neutron Yield (ν_d) and Fraction (β)
^{235}U Thermal Fission	0.0380 0.1918 0.1638 0.3431 0.1744 0.0890	0.0133 0.0325 0.1219 0.3169 0.9886 2.9544	$\nu_d = 0.0166 \pm 3\%$ $\boldsymbol{\beta = 0.00682 \pm 3\%}$
^{238}U Fast Fission	0.0139 0.1128 0.1310 0.3851 0.2540 0.1031	0.0136 0.0313 0.1233 0.3237 0.9060 3.0487	$\nu_d = 0.0450 \pm 4.4\%$ $\boldsymbol{\beta = 0.01584 \pm 4.4\%}$


Cummelative Yield
0.5
0.4
0.3
0.2
0.1
0
60
80
100
120
140
160
180
A
: 244Cm (500keV)
: 235U (thermal)

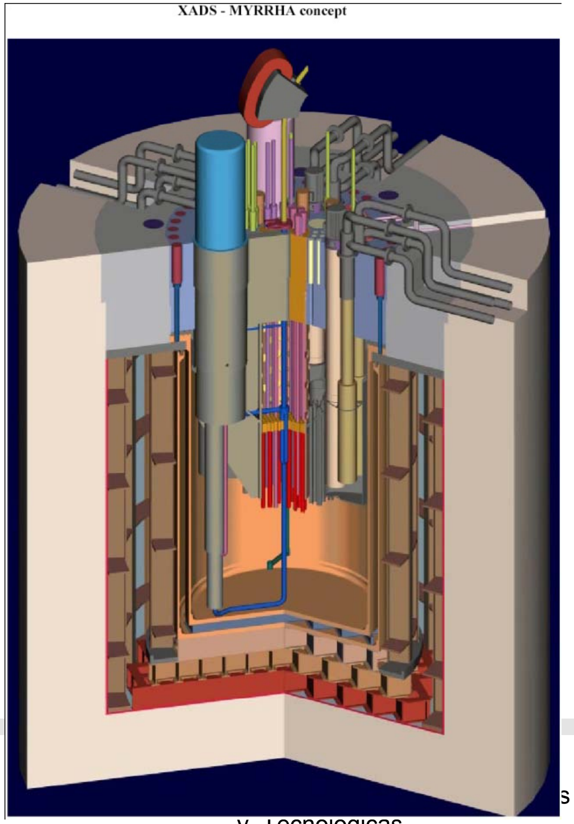
New nuclear data are necessary for the innovative nuclear technologies

Nuclear data are also necessary for the design of nuclear systems. Hot topics in the field are:

-Higher burnup
-New critical reactors (Gen IV): liquid metal Na-cooled reactor, Pb-cooled reactor and gas cooled reactor.
-Accelerator Driven Systems (ADS) for the transmutation of the nuclear waste (MYRRHA project)



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). **It is designed for burning Minor Actinides.**



s
y Tecnologicas

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

$$\beta_{eff}=4.5\cdot 10^{-3} \text{ vs } \beta_{eff}=6.8\cdot 10^{-3} \text{ for a } ^{235}\text{U LWR}$$

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

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

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

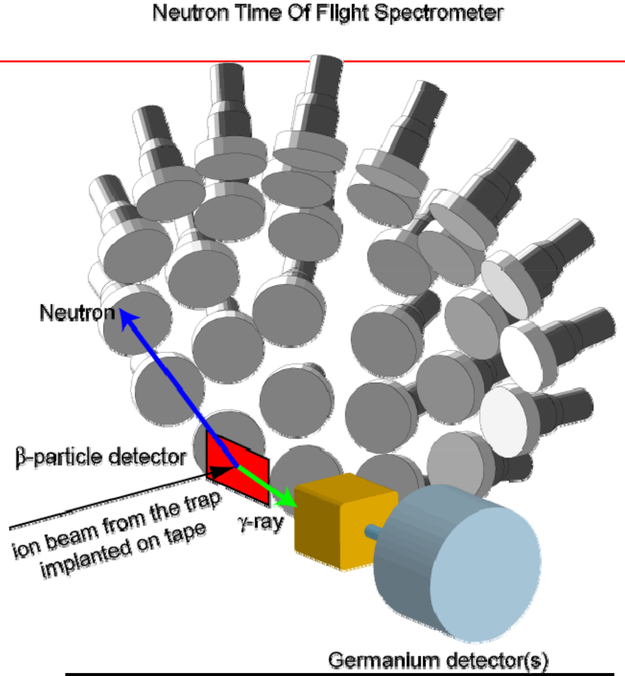
How to measure microscopic data on delayed neutrons?

P_n values -> 4π detector (talks by Yu. Penionzhkevich - TETRA and B. Gómez – BELEN detector)

P_n values (depending on the threshold and energy spectrum) and energy spectrum -> ToF spectrometers (this talk and F. Delaunay)

The CIEMAT ToF spectrometer
30 cells of BC501A, 20cm x 5cm

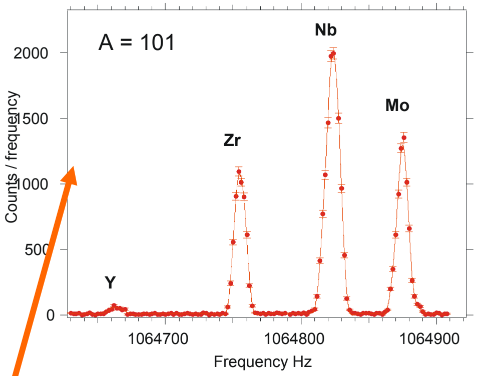
CIEMAT – Madrid
IFIC – Valencia
LPC – Caen
UPC - Pol. Univ. Barcelona
Univ. Surrey



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

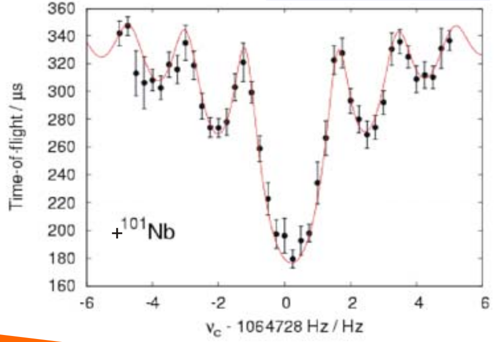
IGISOL facility

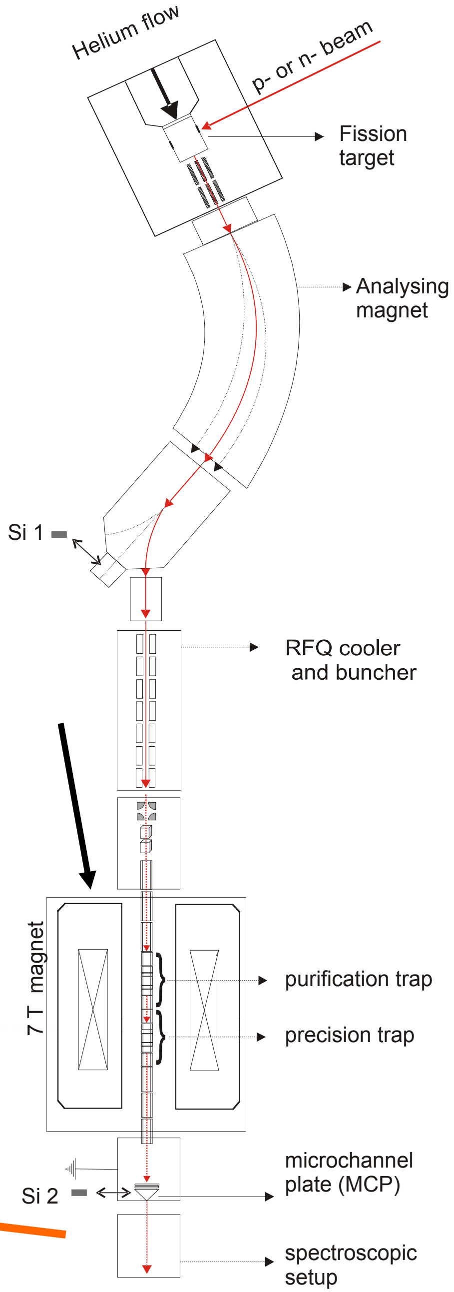
Purification trap $\Delta M/M < 10^{-5}$



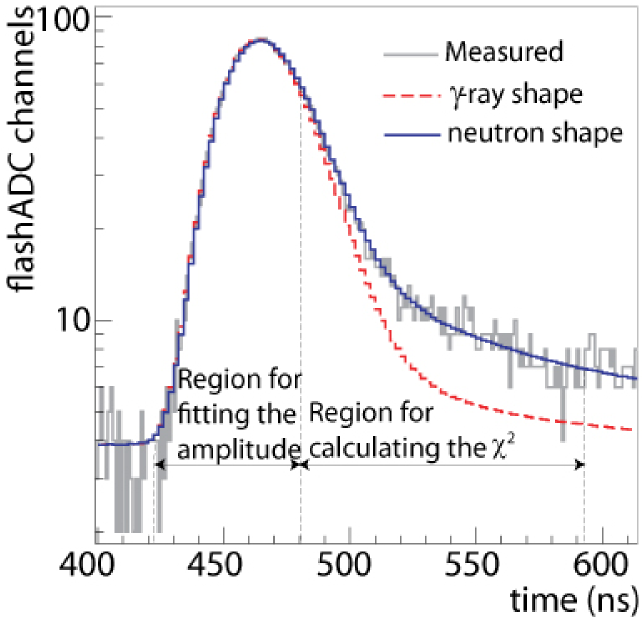
JYFLTRAP setup

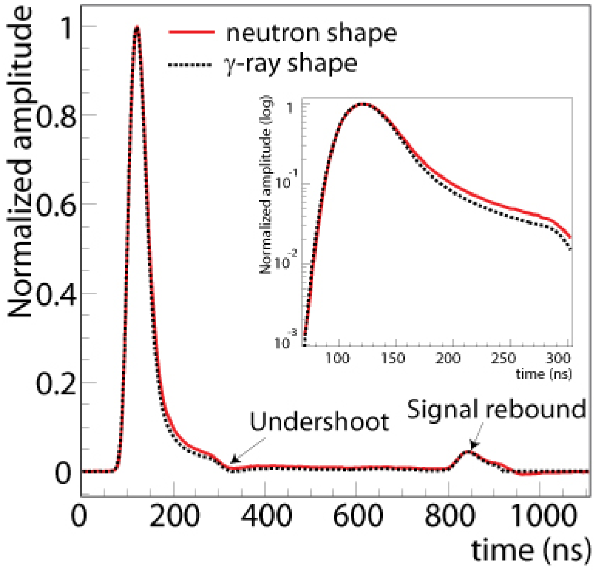
Precision trap $\Delta M/M < 10^{-6}$

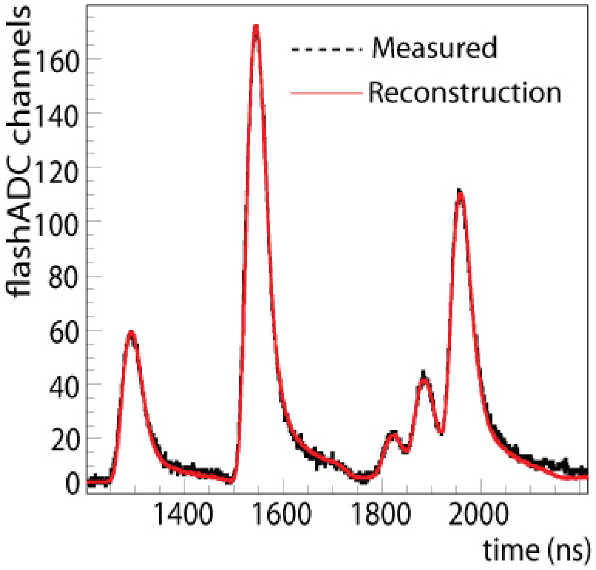




The power of digital electronics







True pulse shape from averaged signals (neutron and gamma). Fitting one param (amplitude) to both signals, calculating the $\chi 2$
Guerrero et al. NIMA 597(2008)212

Data taking with digital electronics is limited only by the scientist’s imagination.

A 12 bit (14 bit) flash ADC with 1 Gsample/s is a nearly universal digitiser:

Fast and high resolution pulse sampling.

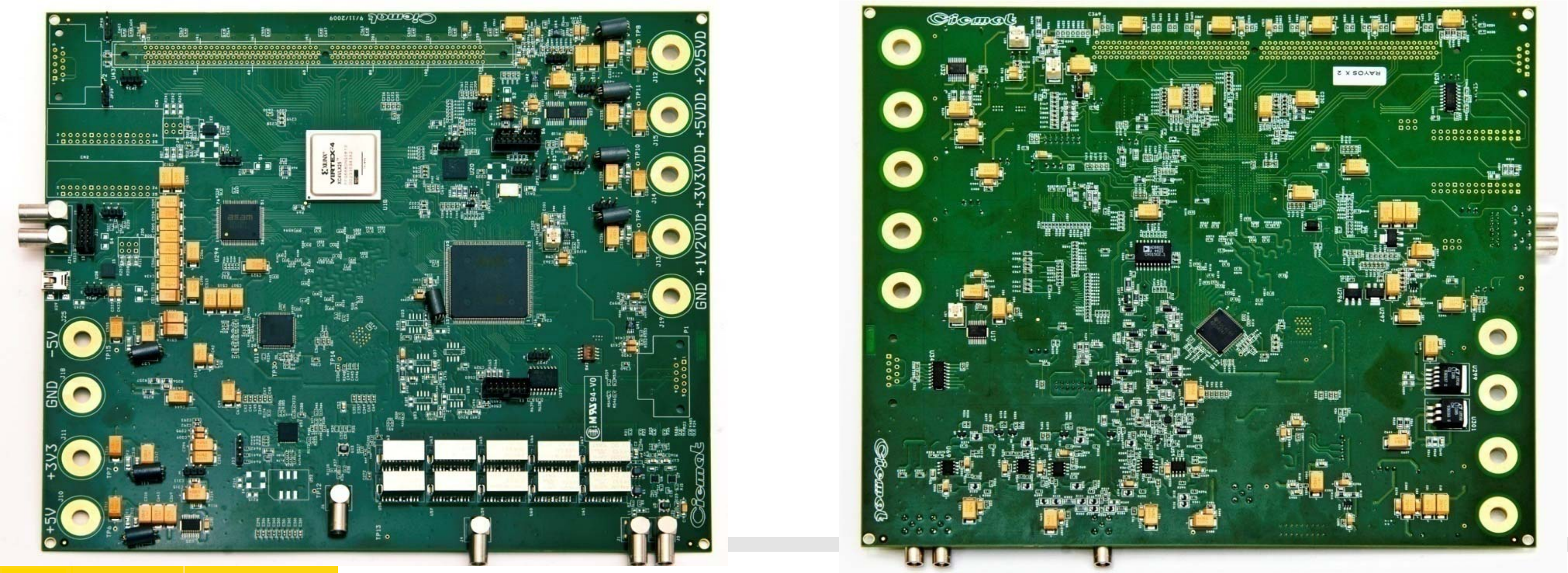
Large dynamic range.

Mounted on an FPGA ⇒ on board pulse shape analysis ⇒ data reduction.

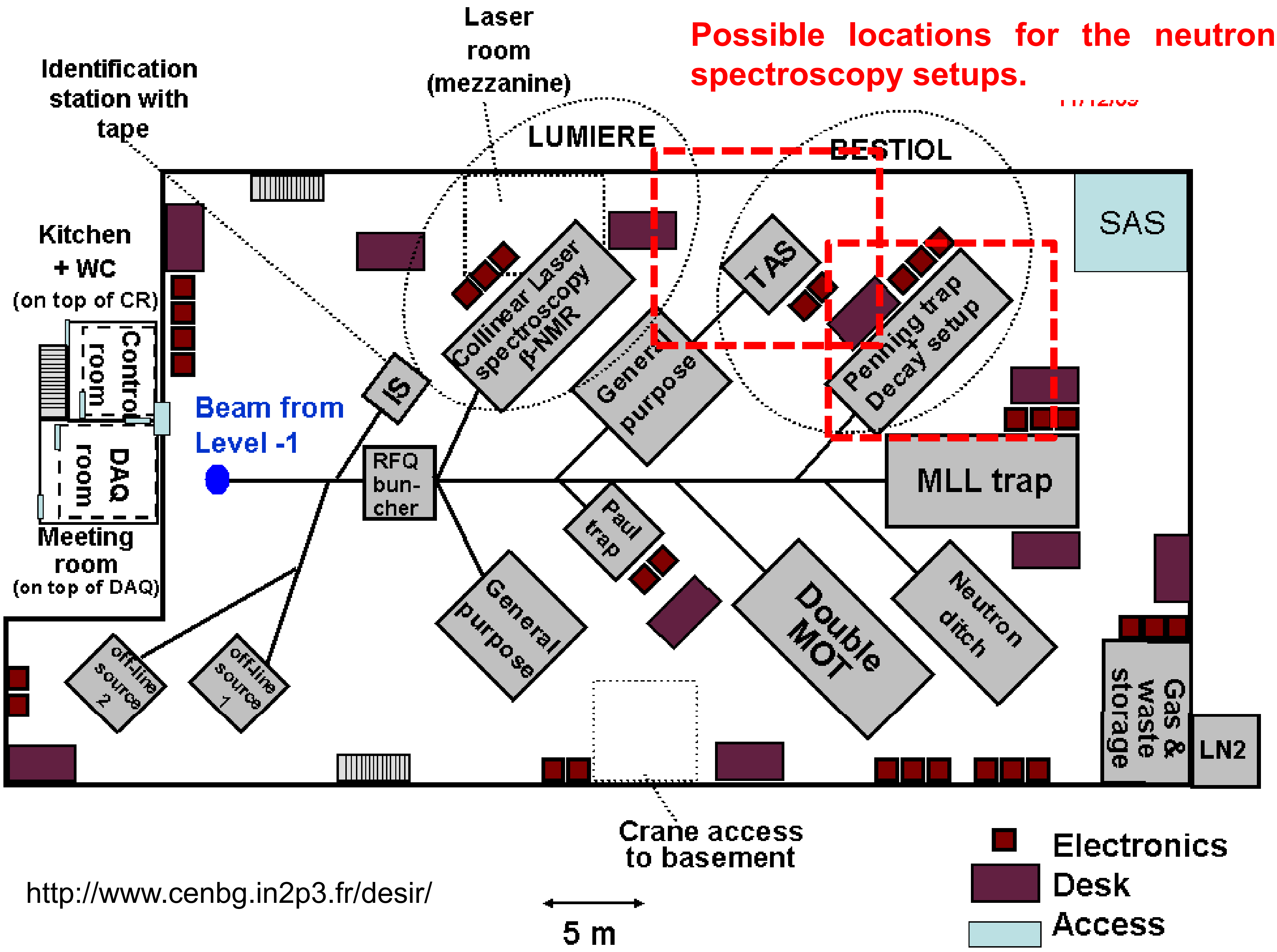
CIEMAT’s high performance flash ADC

Resolution: 12 bits @ 1 Gsample/s or 14 bits @ 800 Msamples/s (1 GHz bandwith) and 2 V p2p ADCs
FPGA for trigger decision and preprocessing.
DSP for pulse shape analysis.
2 Gbytes DDR2 for waveform storage.

Trigger in/out, external clock synchronisation, various input ranges (500 mV-1-2-5 V)



Possible locations for the neutron spectroscopy setups.



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

Summary and conclusions

Conclusions of the NEA WPEC Subgroup 6 on delayed neutron data: there is a need for a continuing effort on delayed neutron data […] mainly directed at satisfying new requirements emerging from current trends in reactor technology, such as:

-the use of high burn-up fuel
-the burning of plutonium stocks
-fuel recycling strategies
-actinide burners (ADS)

Possible **(?)** day 1 experiments: the main **Rb, I, Br, As, Ge, Y, Sb**… delayed neutron precursors should be measured with better accuracy. P_n values and neutron energy spectra.

DESIR is an excellent place for measuring several of these isotopes due to its high yields and combined instrumentation: 4π detector and ToF spectrometer.

The construction of a large ToF spectrometer with sufficient efficiency implies a significalnt financial effort that very likely will have to be shared between various partners .