Development of a Gas Filled Magnet spectrometer coupled with the Lohengrin spectrometer for fission study

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Isomeric population ratio measurements for the fission of $^{233}U(n,f)$ on the Lohengrin spectrometer

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Context of the fission yield studies

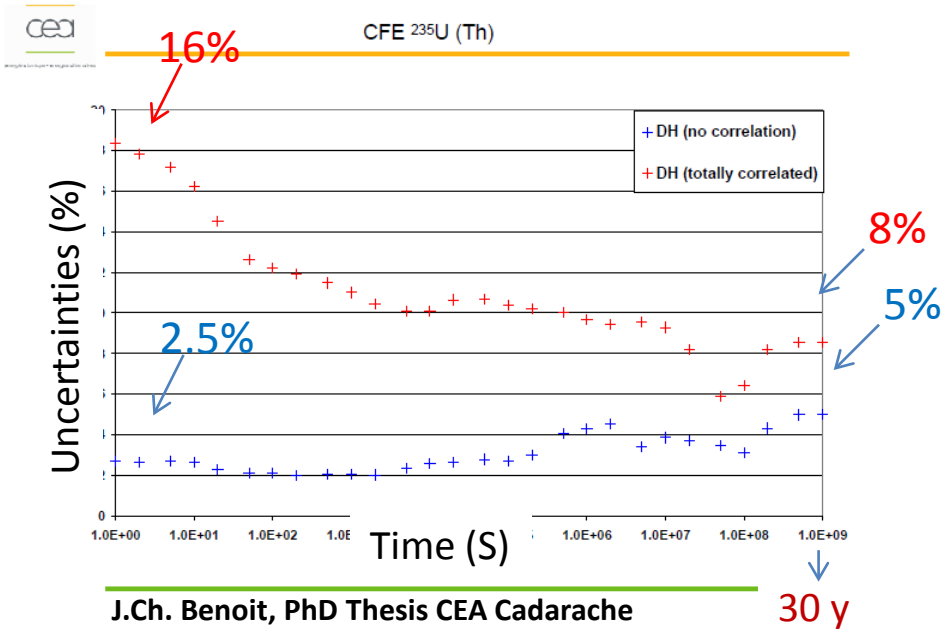
- Impact of fission yields in the actual and innovative fuel cycles
  - → Inventory of used fuel : isotopic composition
  - → Residual power : minor actinides and fission products
  - → Radiotoxicity of used fuel
  - → Experimental fuel studies : reaction cross sections and isotope yields are needed to comparison Calculation/ Experiment (C/E)
  - → Calculation of prompt γ rays emitted per fissile nucleus

- Sensitivities to residual power

→ Independent measurements : uncertainties from 2.5% to 5%

→ Total correlations in data uncertainties from 8% to 16%

→Uncertainties due to the fission yields are greater than the mean β/γ energy released or the periods with a factor 2.5 to 800.



J.Ch. Benoit, PhD Thesis CEA Cadarache
J.Ch. Benoit, O.Serot et al., Physor 2012.

Context of fission yield studies

- Measurements for fission process study

  - Fission models are necessary for the evaluations but poor prediction power (eg :Wilkins (scission point), Wahl (A_p/Z_p), Microscopic approach (Bruyères Le Châtels) …)

  - Incoherence between Models or evaluations and Experiments for heavy fragments and symmetric region

- Needs of new measurements

- Structure in mass and nuclear charge distributions (e.g. Fifrelin, neutron emission, γ prompt)

- Isotopic distributions near symmetric region ➤ Nuclear charge polarization

- Spin distributions of the fission fragments as a function of the excitation energy
  - ➢ e.g. modeling des prompt γ emission

Development of a Gas Filled Magnet spectrometer@ Lohengrin

- Progression
  - Development of a Gas Filled Magnet (GFM) coupled to the Lohengrin spectrometer → Goal : Isobaric beam

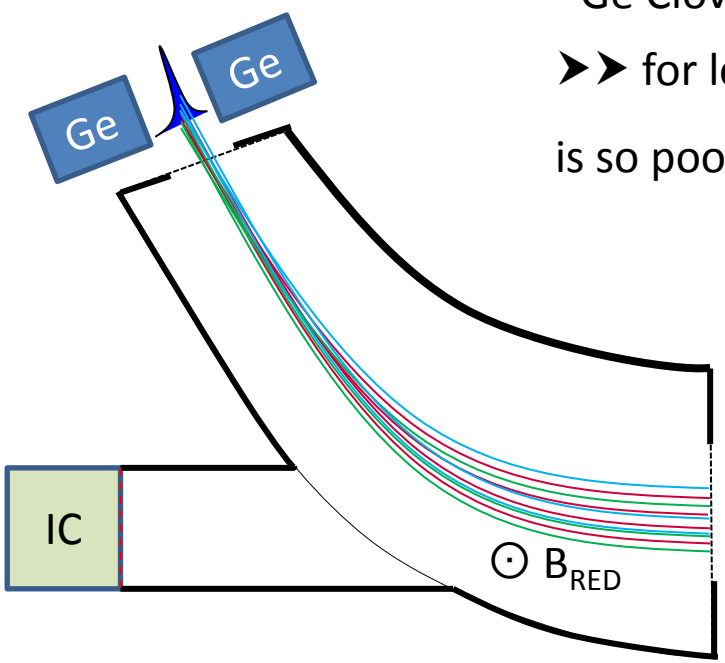
Lohengrin : selection with the mass on ionic charge ratios A/q and Kinetic energy on Ionic charge E/q

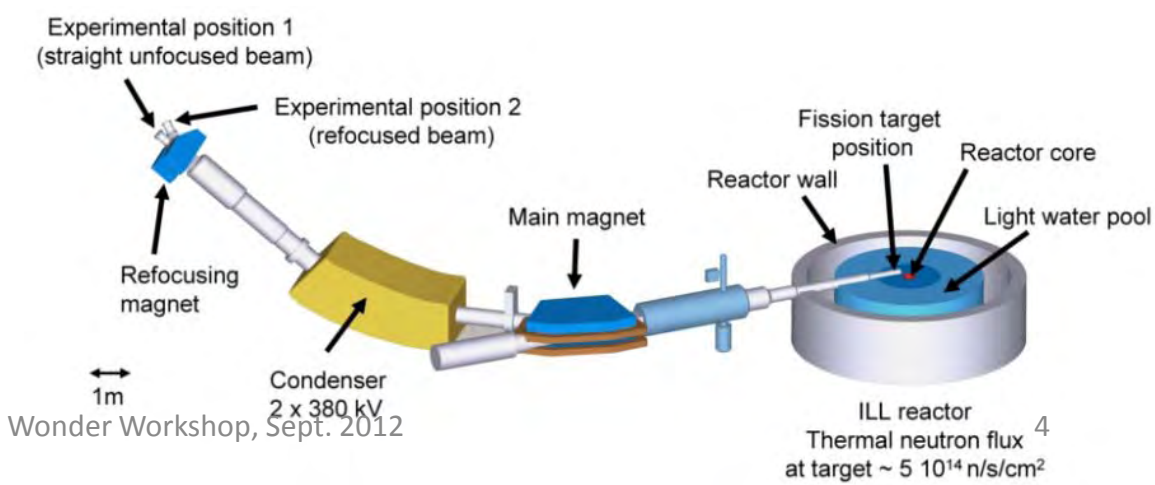
$$(A_1,E_1,q_1) \equiv (A_2,E_2,q_2) \equiv (A_3,E_3,q_3)$$

Setup:

- IC & $A/\Delta A|_{Lohengrin} = 400$ ➤ mass yields up to A = 155 (at 3σ)
- Ge Clover ➤ Isotopic yields with γ spectrometry

➤➤ for low yields or low γ intensities, signal/background ratio is so poor to obtain sufficient accuracy





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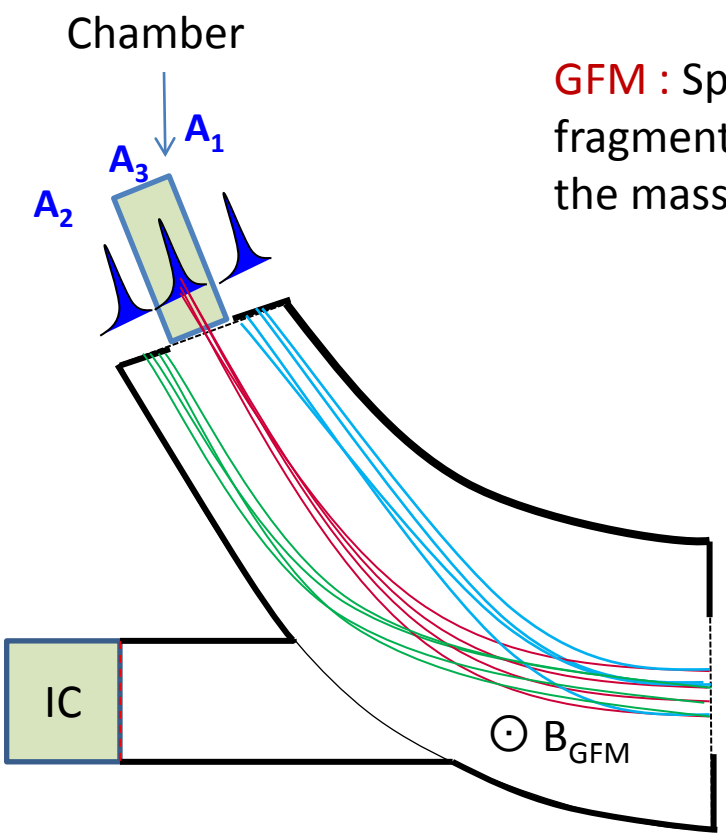
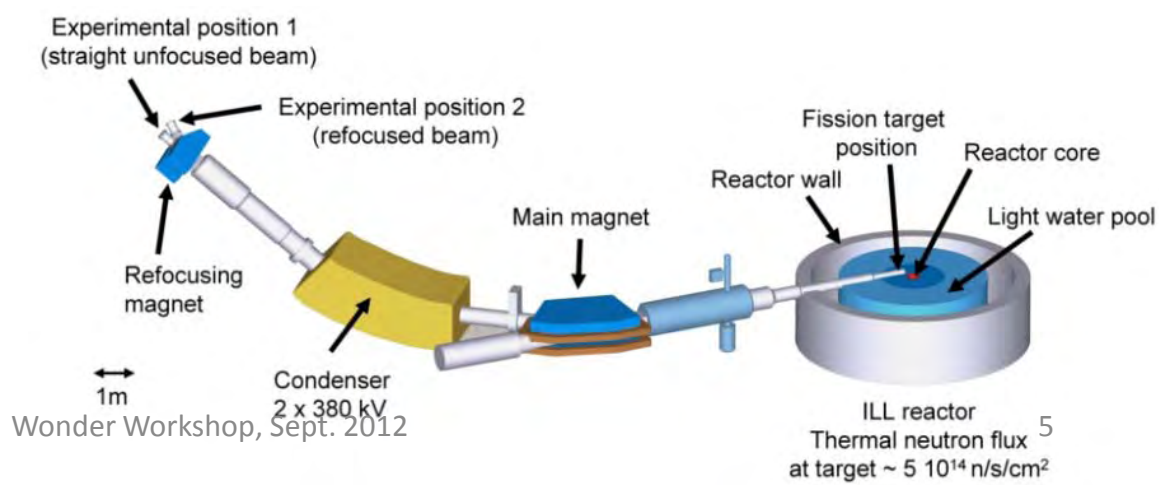
GFM : Spatial dispersion of fission fragments according to the mass A and Nuclear charge Z

$$B\cdot\rho \propto \left.\frac{A\cdot\langle v(Z)\rangle}{\langle q(Z)\rangle}\right|_{\text{Gaz},P}$$

$$B\cdot\rho \propto \frac{A}{Z^{1/3}} \qquad [1]$$





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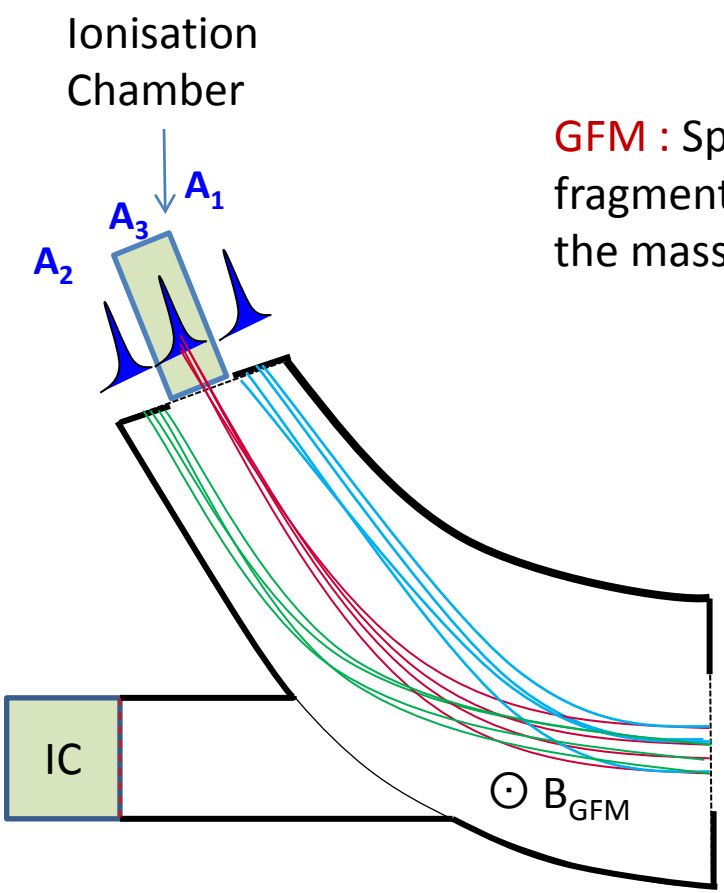


Gas→ Ionic charge is function of ion velocity

Magnet field → spread of extracted mass from Lohengin

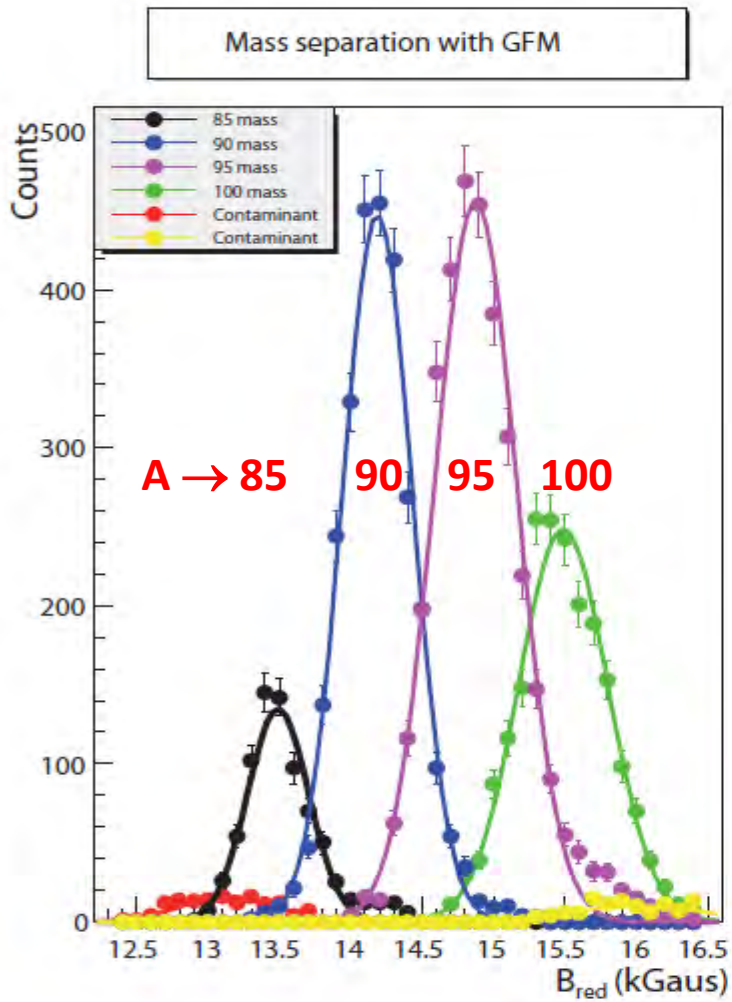
Goal of Instrument:

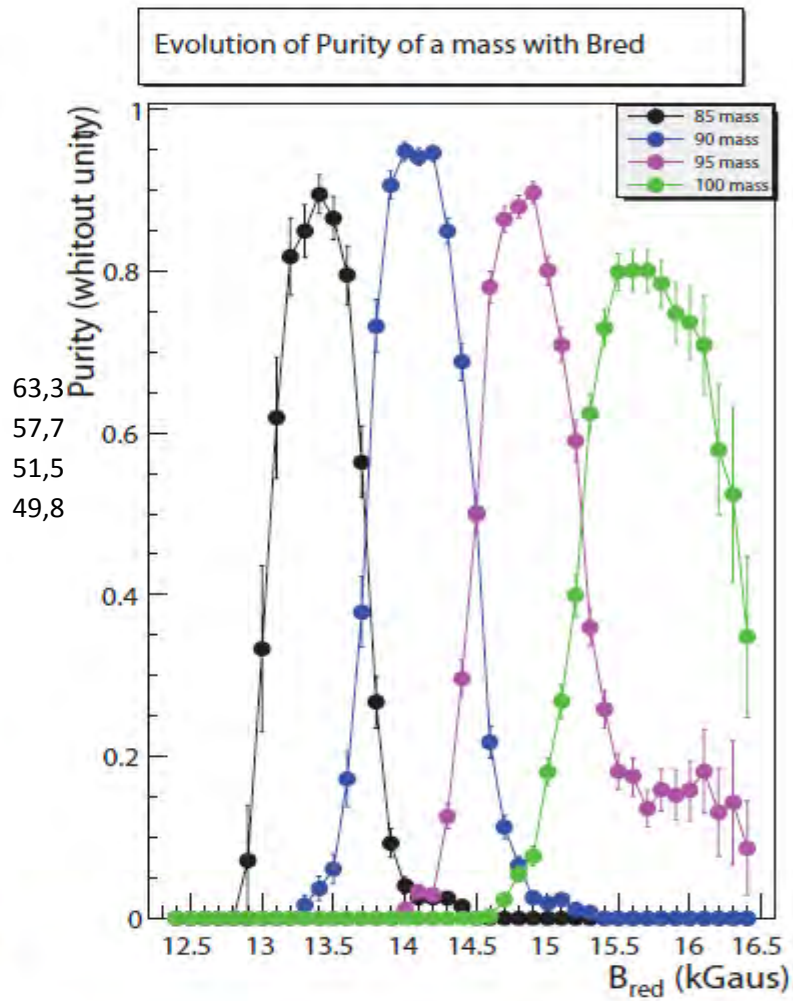
- Improve the separation power → Isobaric beam
- increase the sensitivity in symmetric region

Scope :

- fission, nuclear structure and astrophysical interest

^{4}He Gas Filled Magnet spectrometer@ Lohengrin





A/ΔA → 63 ; 58 ; 52 ; 50

exit collimator 1cm ≡ 100 Gauss

^{4}He Gas Filled Magnet spectrometer@ Lohengrin

Monte Carlo calculations :

- Initial conditions : Distributions in position, Energy and Velocity $\vec{v}$
- Effective charge distribution (q_{eff}) according to the Betz model [1]
  - motion equation step $\ell < \lambda_{q \to q'}$ $\to$ new position and velocity $\vec{v}'$
  - Bethe-Block energy loss $\to \left|\vec{v}''\right| \to \vec{v}''$
  - e^- Capture or Loss probabilities according to the Paul model [2]

    $\to$ mean free path $\lambda_{q \to q'}$ $\to$ stochastic charge
- exit condition : in/out collimator

Stochastic Trajectory Calculation

[1] H. Betz, *Reviews of Modern Physics, vol.44, n° %13, p. 373, July 1972.*

[2] M. Paul et al, *Nuclear Instruments and Methods in Physics Research A, vol. 277, pp. 418-430, 1989.*

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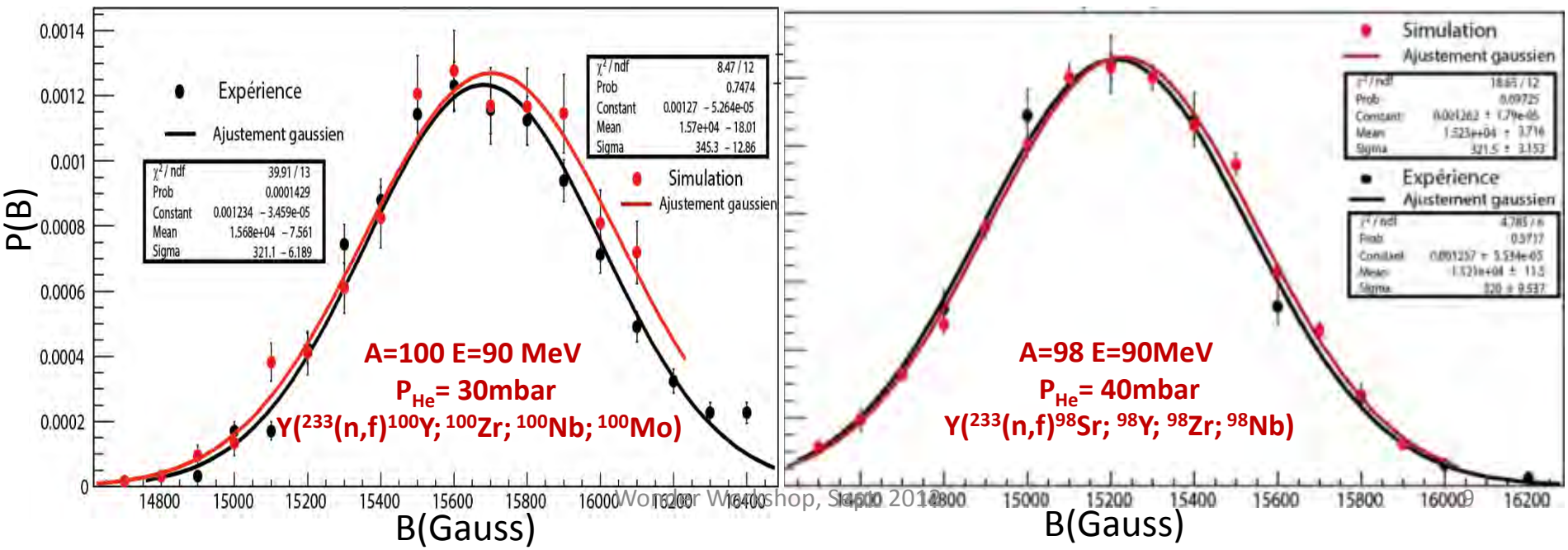

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Stochastic Trajectory Calculation

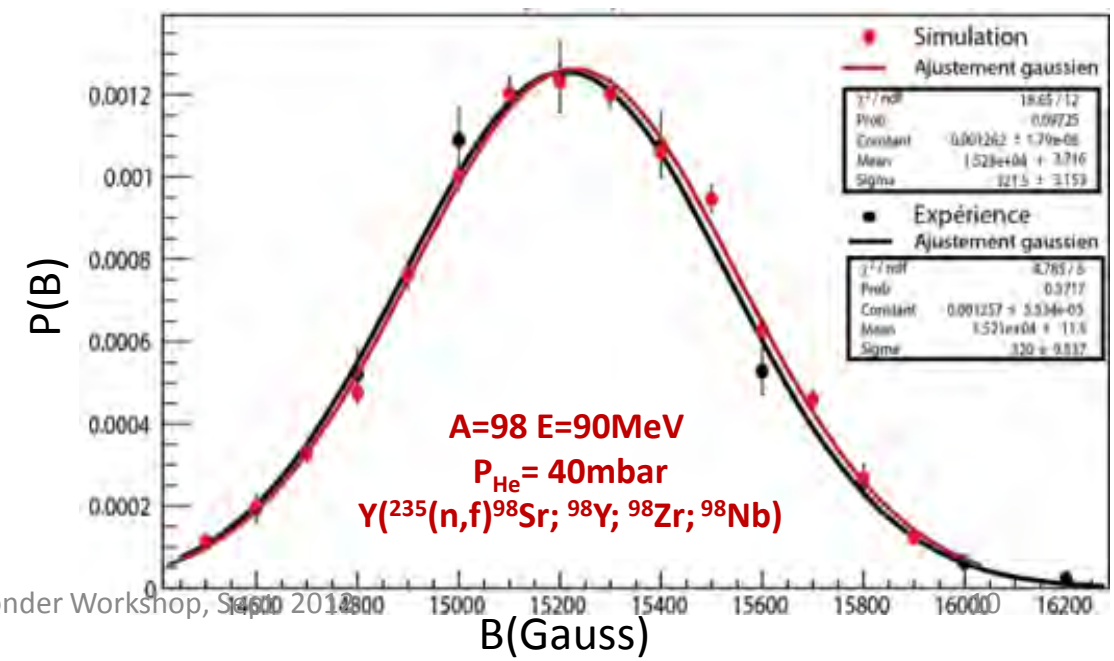
Results :

- Mass acceptance of GFM as a function of B is needed for mass and Isotopic Yield measurements

- Magnet field B(Imax) =1700G

^{4}He GFM separation up to A≈130

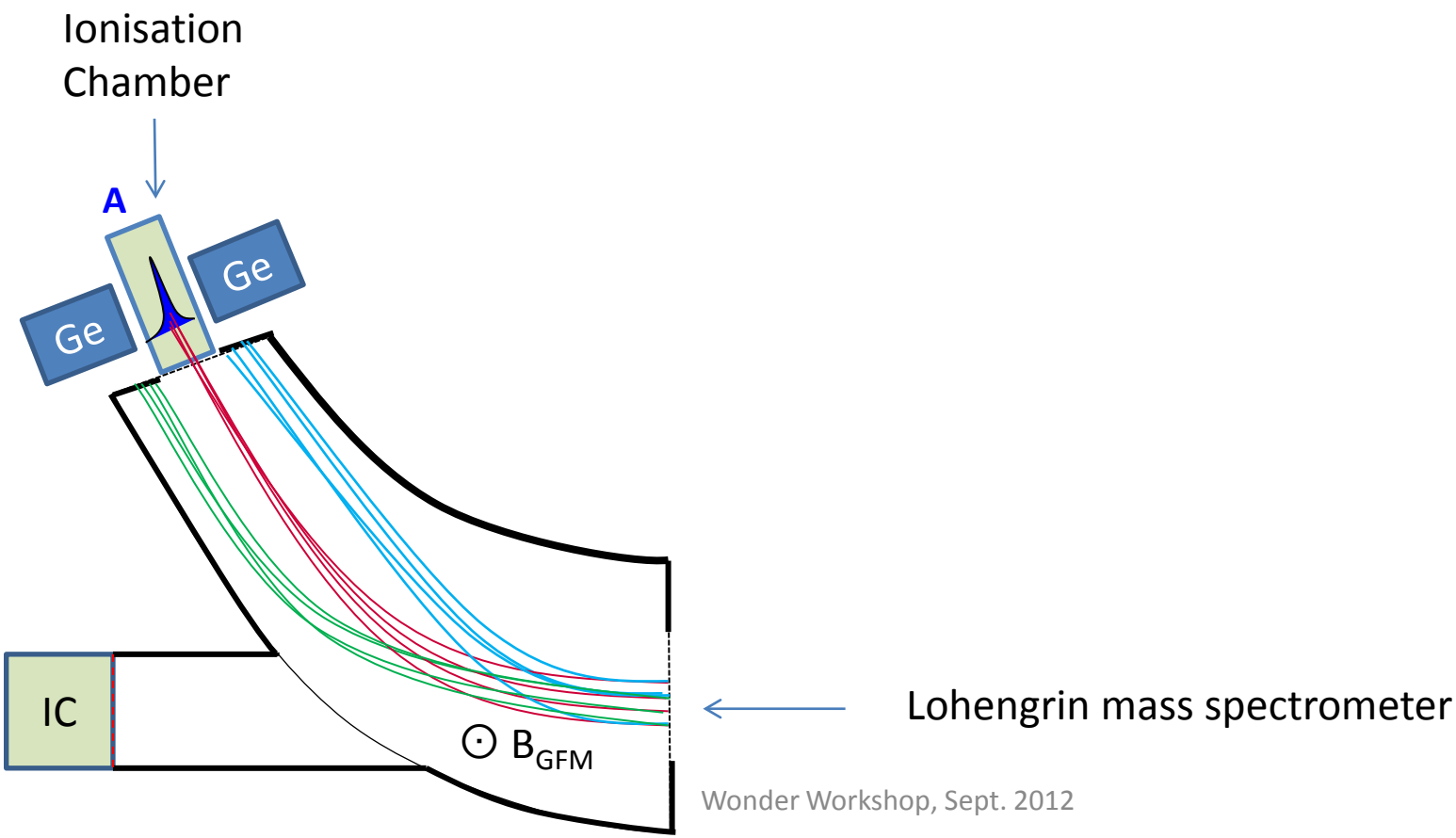
$$B\cdot\rho \propto \left.\frac{A\cdot\langle v(Z)\rangle}{\langle q(Z)\rangle}\right|_{\text{Gaz},P}$$



N_2 Gas Filled Magnet spectrometer@ Lohengrin

isotopic resolution in the GFM spectrometer

- μs Isomer used to tag isotope



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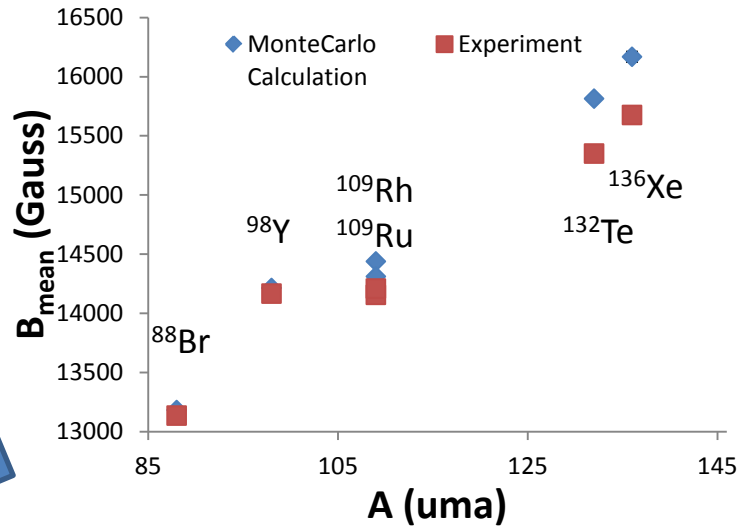

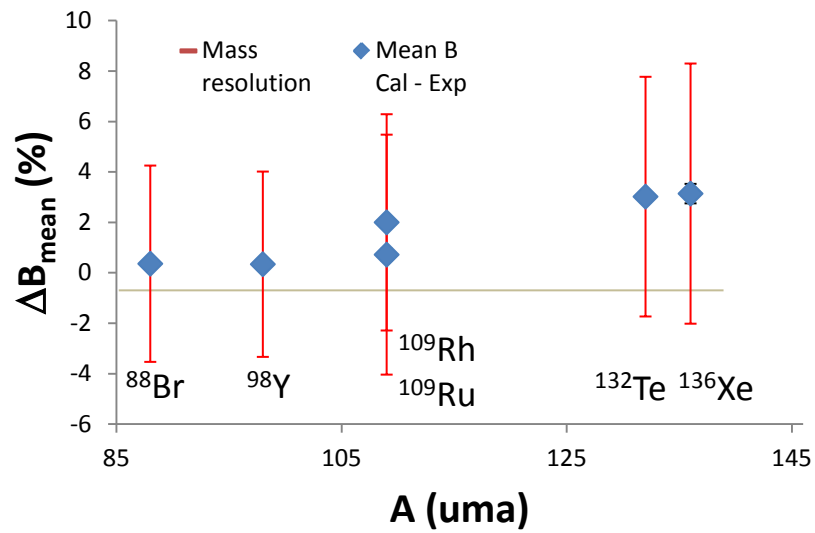

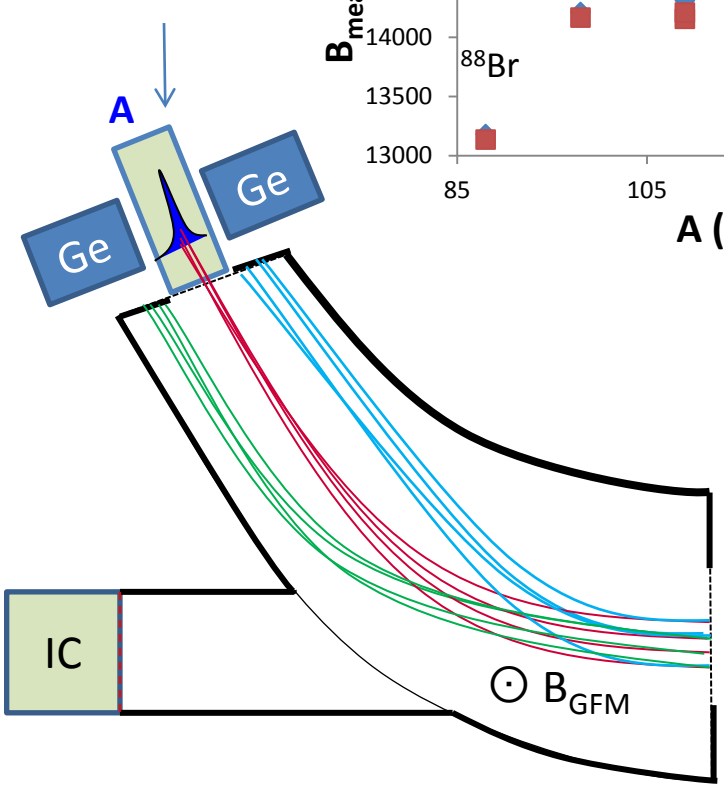

Lohengrin mass spectrometer

N_2 Gas Filled Magnet spectrometer@ Lohengrin

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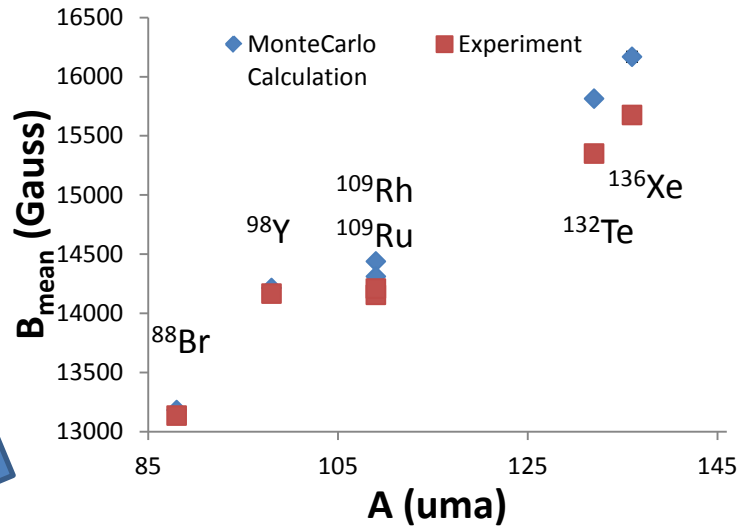
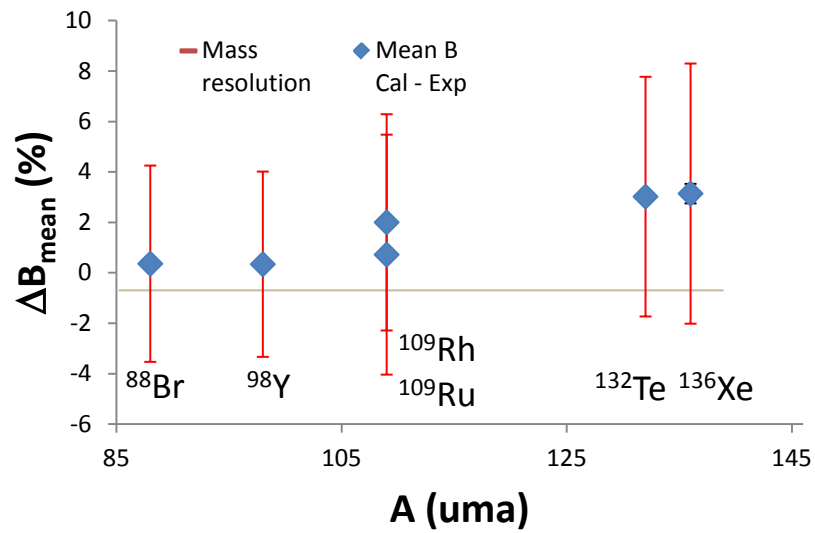
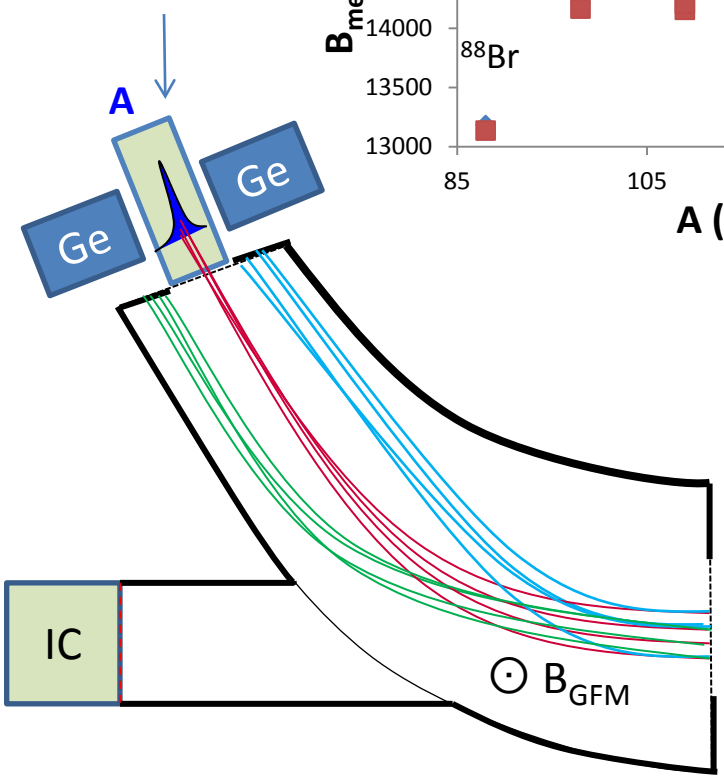






- According to Betz and unlike M.Paul et al., multi electron loss cross section have to be considered in N_2 : $\sigma_{2e^-} = 70\% \ \sigma_{e^-}$

- Validity of Betz assumptions ? Gaussian distribution of ionic charge is not correct for heavy masses $q_{exp} > q_{cal}$

- ns Isomer states in heavy region mass can disturb the ionic charge due to the internal conversion effect

GFM perspectives

• Nowadays, the instrument allows to change quickly the setup; then comparison between vacuum magnet and Gas Filled Magnet will allow to determine the energy loss in the gas. This parameter is the last constraint to compare Experiment to Monte Carlo calculation.

• The GFM will be test with heavy noble gases (Ar, Kr, Xe) to determine the mass and isotopic resolution and then the mass/Isotope acceptance

- Heavy gas > electronic density increases > q(Z) increases > magnet rigidity Bρ decreases > heavy mass
- pressure > change the electronic density > maximum of resolution i.e. minimum of ΔBρ / Bρ = *f(Gas, P, E_{ion})* > Best resolution for loss Energy in the gas ~70% E_{ion}
- For heavy mass, nowadays calculations are not sufficient to extract precisely the mass or isotopic acceptance > Description of the ionic charge distributions in heavy mass region have to be improved

• The GFM coupled to the Lohengrin spectrometer could limit the γ ray contaminants for the isotopic yield measurements

$$Y(A,Z) = Y(A) \cdot P(Z|A)$$

$$P(Z|A) = \frac{N(A,Z)/A_C(A,Z)}{\sum_Z N(A,Z)/A_C(A,Z)} \longrightarrow$$

- γ Spectrometry after β decay
- Relative measurements

Isomeric population ratio measurements for the fission of $^{233}U(n,f)$ on the Lohengrin spectrometer

Isomeric ratio with γ spectrometry method

$$Y(A,Z,Isomer) = Y(A)\cdot P(Z|A)$$

$$\times \frac{R(m/GS;\overline{E_k})}{1+R(m/GS;\overline{E_k})} \longrightarrow Y({}^{A}_{Z}X^{m})$$

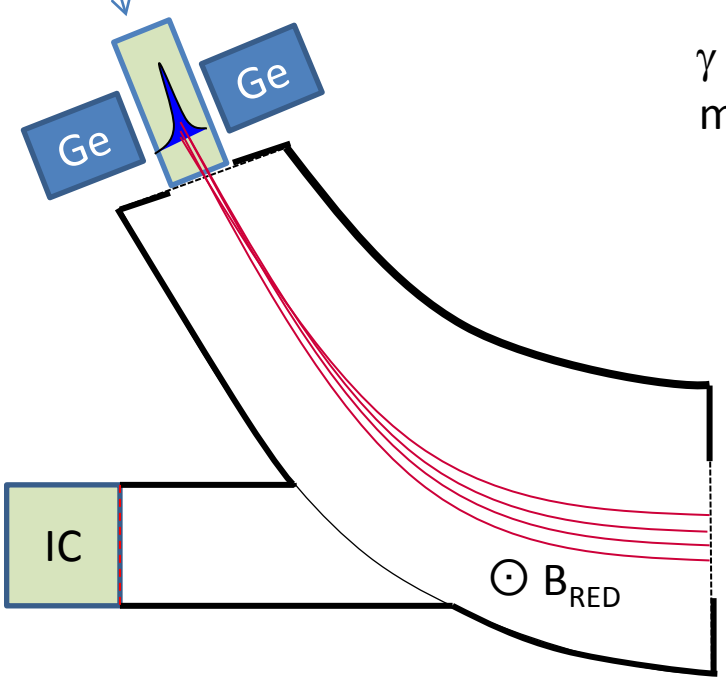
$$\times \frac{1}{1+R(m/GS;\overline{E_k})} \longrightarrow Y({}^{A}_{Z}X^{Gs})$$

IC measurements

γ Spectrometry measurements

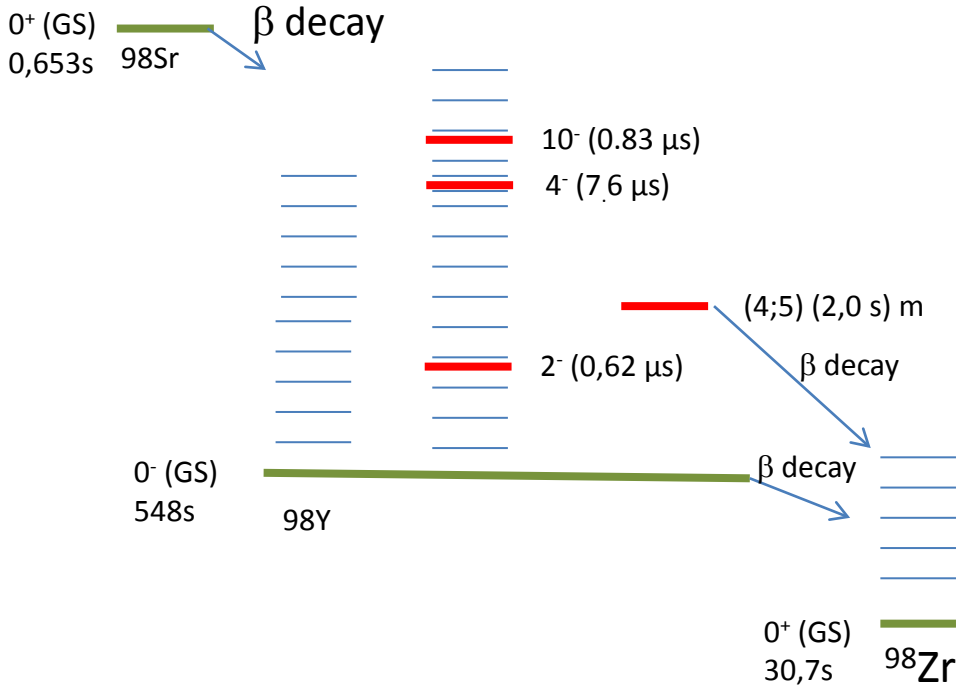
Mean isomeric ratio on energy kinetic distribution

Ionisation Chamber



Lohengrin
^{233}U(n,f)

^{98}Y Isomeric populations : GS – m states



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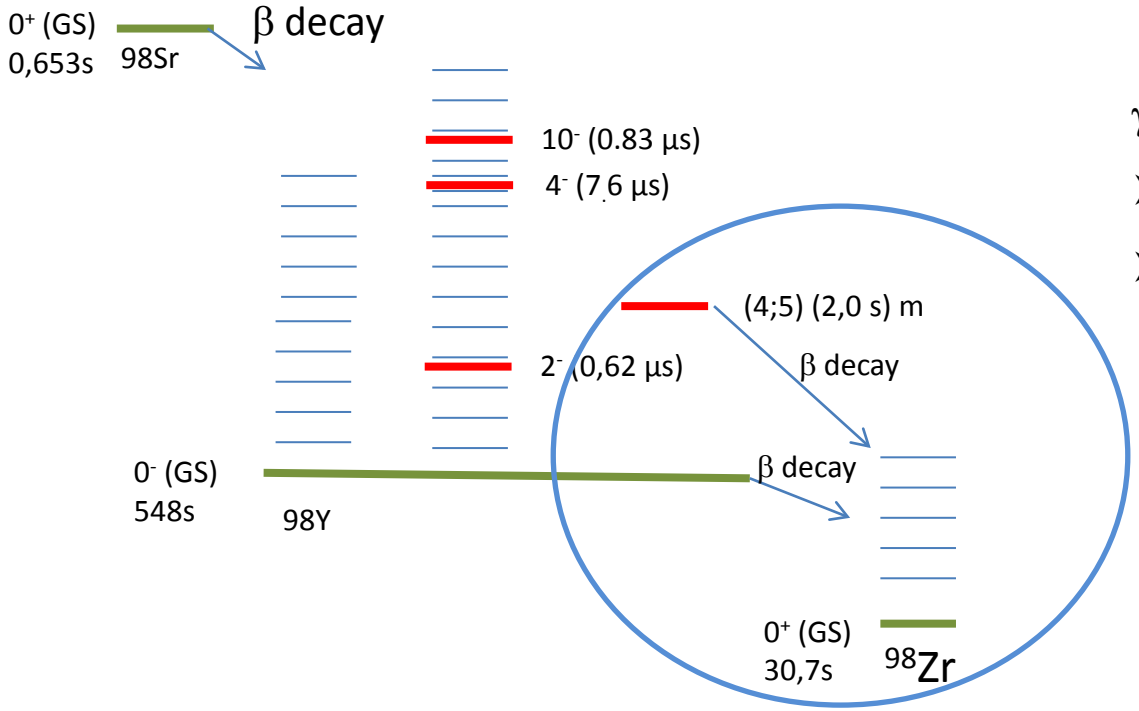


γ raies after β decay of $^{98}Y^{GS}$ & $^{98}Y^{m}$:

- 1590 keV & 1223 kev → Y^{GS} & Y^{m}
- 621 keV et 648 keV → Y^{m}

Measurements without time coincidence between IC and Ge clovers

T_{exp}= 120 mn for each kinetic energy

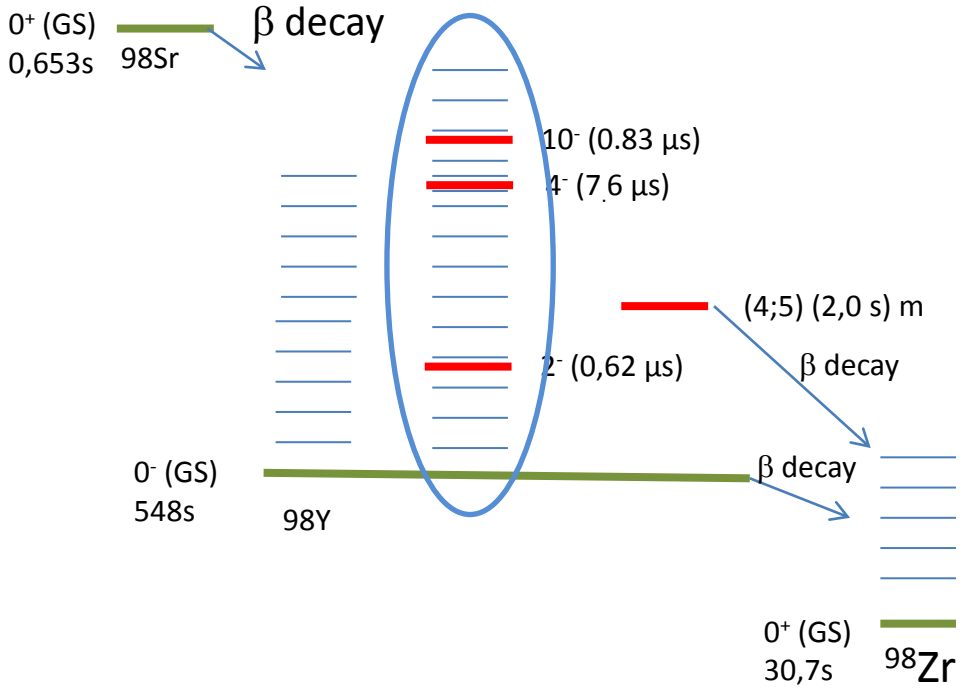
$$N(^{GS}Y)\Big|^{Fission} = N(^{GS}Y)\Big|^{tot}_{\gamma,^{98}Zr} - N(Sr \xrightarrow[\beta]{} Y^{GS})$$

γ Event from Sr

γ Raies from ^{98}Zr

$$N(^{m}Y)\Big|^{fission} = N(^{m}Y)\Big|^{tot}_{\gamma,^{98}Zr} - \underbrace{\cancel{N(Sr \xrightarrow[\beta]{} Y^{m})}}_{\text{No event from Sr}}$$

^{98}Y Isomeric populations : µs isomer



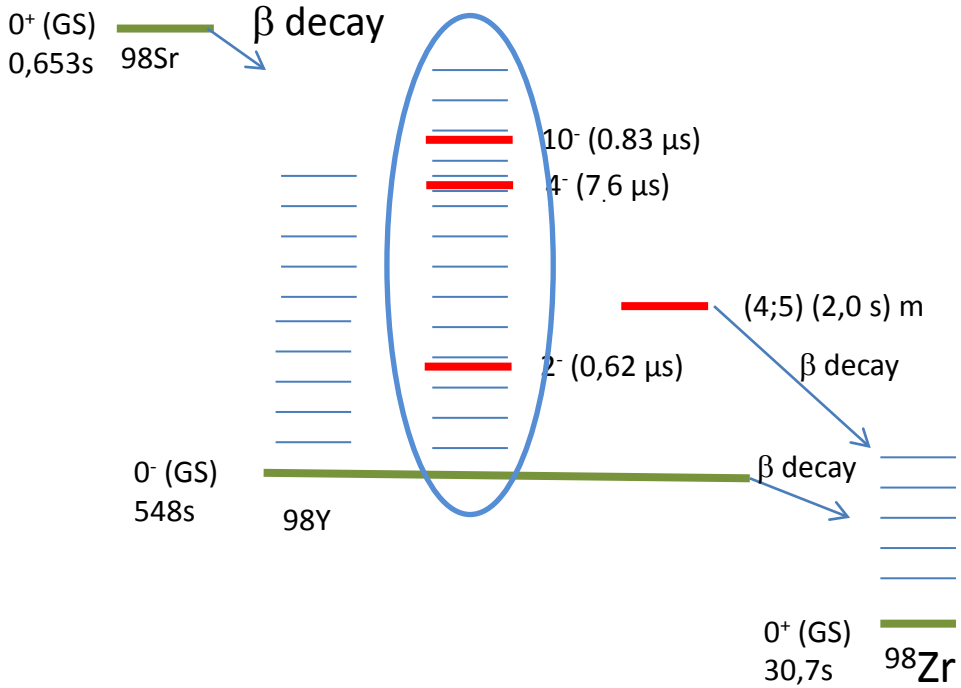
$$N(^{\mu s}Y)\Big|_{t=tof}^{f} = N(^{\mu s}Y)\Big|_{t=tof}^{tot} - \sum_{gate} N(^{\mu s}Y)\Big|_{\beta;^{98}Sr}$$

γ events from Sr
Life time Sr << T_{exp}

$$N(^{\mu s}Y)\Big|_{t=tof}^{f} = N(^{\mu s}Y)\Big|_{t=tof}^{tot} - \tau(^{98}Sr)\cdot N_{gate}\cdot \Delta t_{gate}$$

Sr decay rate : $\tau(^{98}Sr) = N(^{98}Sr)/T_{exp}$ → γ Raies after beta decay of 98Sr →444 keV and 428 keV

^{98}Y Isomeric populations : µs isomer



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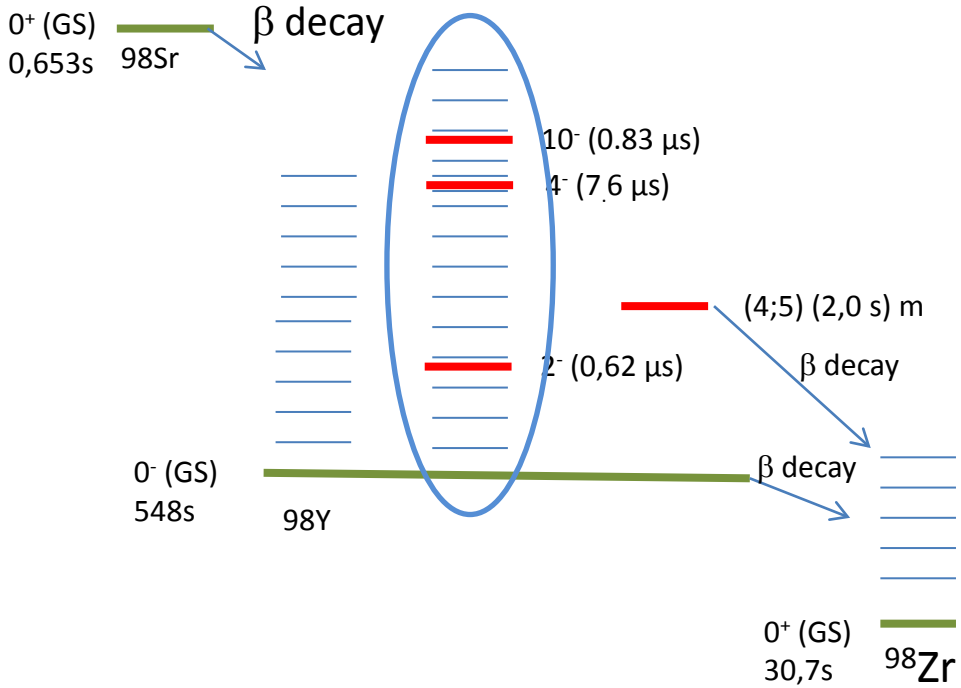

Sensitive parameters :

- Gamma Intensity per β decay
- Relative intensity
- Internal conversion coefficients [1]
- Relative gamma efficiency → ^{96}Y

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[1] IAEA data base

^{98}Y Isomeric ratios in the fission of ^{233}U(n,f)
Preliminary results

I Ratio (t=tof)	GS 0^-	m (4,5)	µ1 2^-	µ2 4^-	µ3 10^-
GS (548s)	1				
m (2s)	0,158 ±0,008	1			
µ1 (0.62µs)	0,023 ±0,011	0,146 ±0,071	1		
µ2 (7.6µs)	0,409 ±0,018	2,585 ±0,078	17,8 ±8,6	1	
µ3 (0.83µs)	0,014 ±0,001	0,087 ±0,008	0,60 ±0,29	0,034 ±0,001	1

- In fine, 10 Isomeric ratios have be determined for the mean kinetic energy of ^{98}Y
- These Isomeric Ratios depend of the spin distribution at excitation energy
- six Isomeric ratios at $\overline{E_k}$ have been measured for A =88; 94 98; 99; 129; 132 at mean kinetic energy associated

Conclusions and perspectives on the Isomeric ratio measurements for the fission of ^{233}U(n,f)

• Isomeric populations have been measured for 6 masses at different mean kinetic energy $\rightarrow$ $R\left(A, Z, \overline{E_k}\right)$

• For ^{98}Y, 10 ratios have been measured. The goal is now to interpreted these measurements as a spin probability distribution at $\overline{E_k}$: $P(J|\overline{E_k})$
The spin distribution depend of :

- ➤ level density as a function of E*
- ➤ Excitation energy repartition between the two fragments
- ➤ 10 degrees of freedom will allow to describe several momenta of the spin distribution

• Considering the isomeric ratio measurements on 6 masses at different mean kinetic energies, the spin distribution can be explored as a function of excitation energy $P(J;E^*)$

• To limit the systematic effects dues to the models, a new campaign for the same isotopes with a target of ^{235}U has been proposed to compare the spin distributions

Backup

References :

[1] H. Betz, *Reviews of Modern Physics, vol.44, n° %13, p. 373, July 1972.*
[2] M. Paul et al, «Heavy Ion Separation with a Gas-Filled Magnetic Spectrograph,» *Nuclear Instruments and Methods in Physics Research A, vol. 277, pp. 418-430, 1989.*