Search for X-rays characteristic of element with Z=120

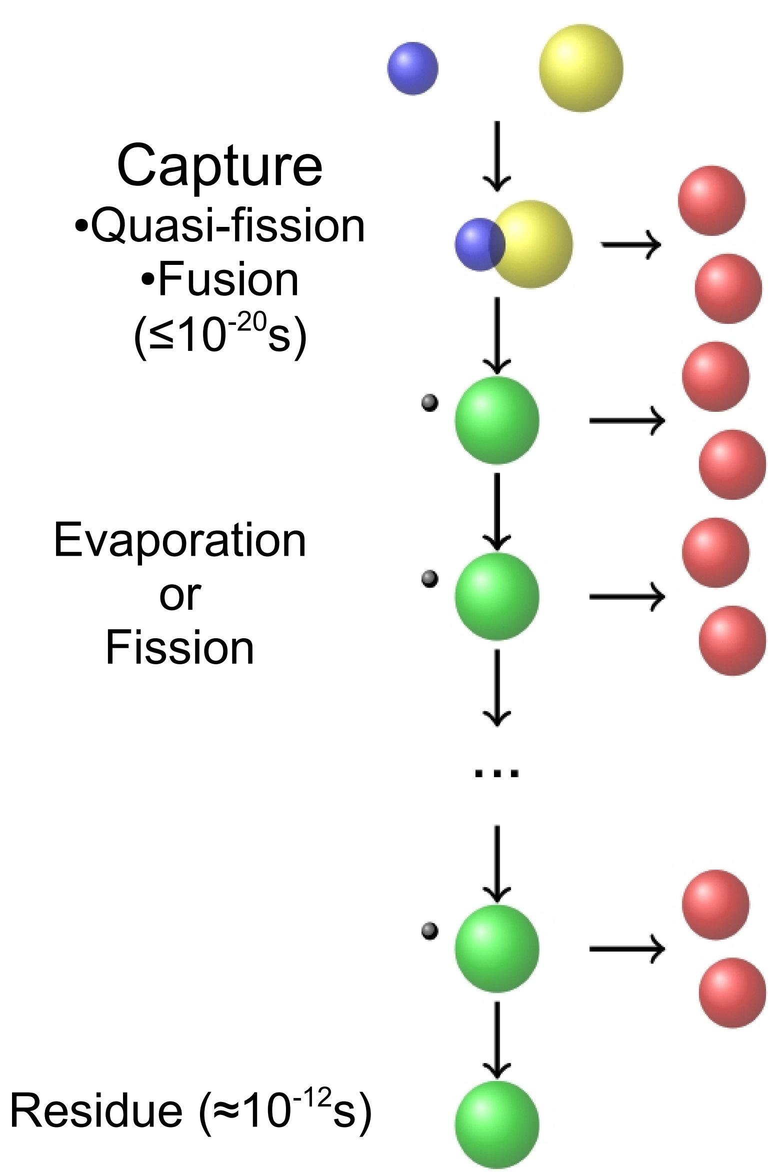
For super-heavy elements, different theoretical predictions for the maximum of stability (Z=114,120,126,etc.)**.**

Tiny probability to detect evaporation residues with Z>110 after fusion

- Fusion followed by fission.
- Quasi-Fission process :
  - Direct time measurements from angular distributions indicate characteristic times for quasi-fission $t_{qf} \leq 10^{-21}$s (J.Töke et al. NPA,440,1985,327)

Evidence for fusion-fission from very long fission times ($t_{fiss} \gg 10^{-20}$)

Fission time



At each decay step:

$$\tau_i = \frac{\hbar}{\Gamma_f + \Gamma_n}$$

The lifetime τ_i is strongly increased at each decay step before fission

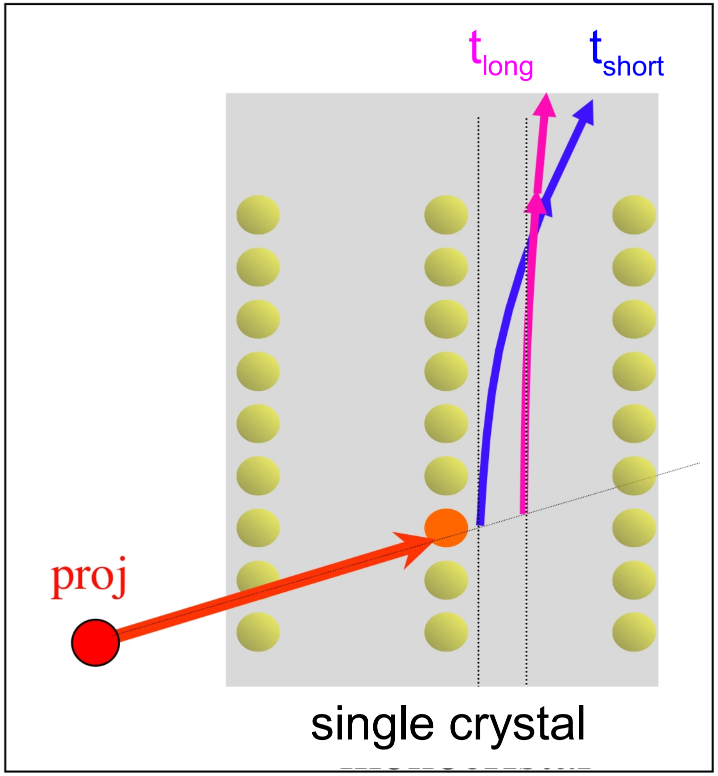
Transient time (≤10^{-21}s) strongly favors particle emission at the beginning of the reaction

Very large distribution that might reach times as long as 10^{-12}s for very fissile nuclei.

Measurement of long fission times (>>10^{-20}s) provides us with evidence for fusion-fission

Fission time measurement by crystal blocking

t_{short} / t_{long} : few /many ions
In crystal axis direction



Evidences for long fission times (t_f>10^{-18}s) by crystal blocking :

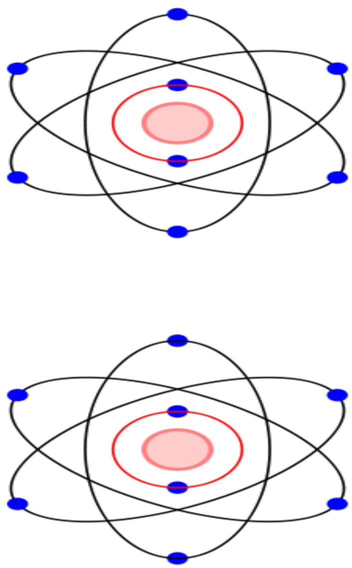
(Morjean et al, PRL,101,072701,2008)

- ^{238}U+Ge 6,1MeV/u :More than 10% of the capture events at 20° for Z=124
- ^{238}U+Ni 6,6 MeV/u :More 10% of the capture events at 20° for Z=120
- ^{208}Pb+Ge 6,2 MeV/u: Not detected for Z=114

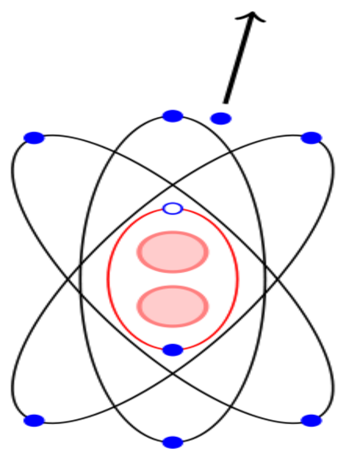
Crystal blocking requires high quality single crystals. It is hardly possible to study other systems with this technique within the super-heavy region.

X-ray fluorescence technique developed in order to scan SHE region

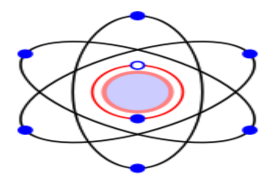
Principle of fission time measurement by fluorescence technique



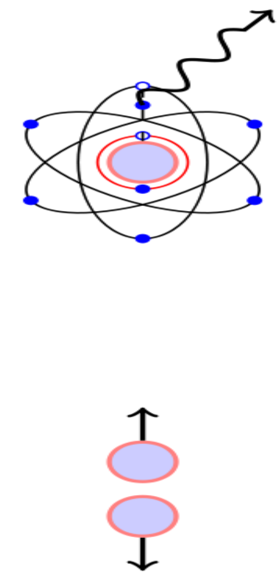
Collision



Adiabatic adjustment of the orbitals to the molecular system



For very asymmetric systems, transfer of the K vacancies from the heavier partner to the compound nucleus



X-Ray emission with energies characteristic of the compound nucleus
or
fission

Vacancy creation during the collision

X-Ray emission probability depends on the vacancy lifetime and fission time.

Principle of fission time measurement by fluorescence technique

$$P_X = P_{vac} \frac{\tau_f}{\tau_f + \tau_{vac}} \omega(E_X)$$

P_x = X-ray emission probability

·**P_{vac}** = Vacancy creation probability

·**ω(x)** fluorescence yield (=1) is a good approximation for very heavy ions

Hypotheses :

- Vacancy filling and fission follow independent exponential decay laws
- A single fission time τ_f
- Vacancy lifetime τ_{vac}

To determine fission times, we need:

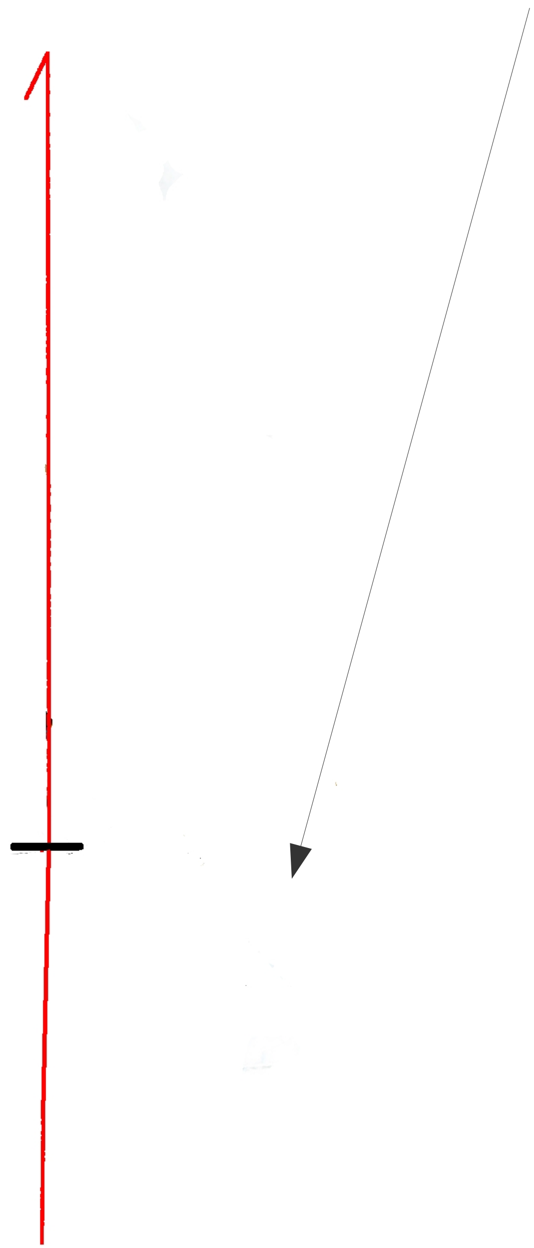
P_x : Measured through X-ray detection in coincidence with fission fragments

P_{vac} : Estimated from measured vacancy creation probability in elastic scattering

- Atomic impact parameter similar in fusion and elastic scattering reactions.
- Hypothesis P_{vac}(elastic) = 2* P_{vac}(fusion).
- The vacancies in the entrance channel of elastic reactions are totally transferred to the compound nucleus.

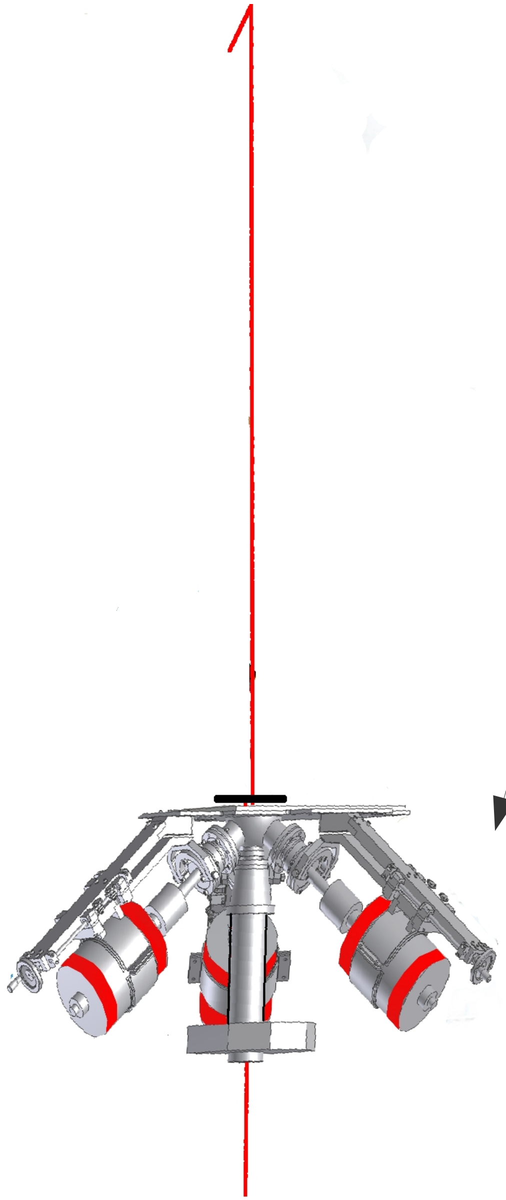
τ_{vac} : Tabulated for known nuclei; must be calculated for unknown SHEs

Experimental setup



- ^{238}U beam at 6.6 MeV/A
- ^{64}Ni target (2.0 mg/cm^2)

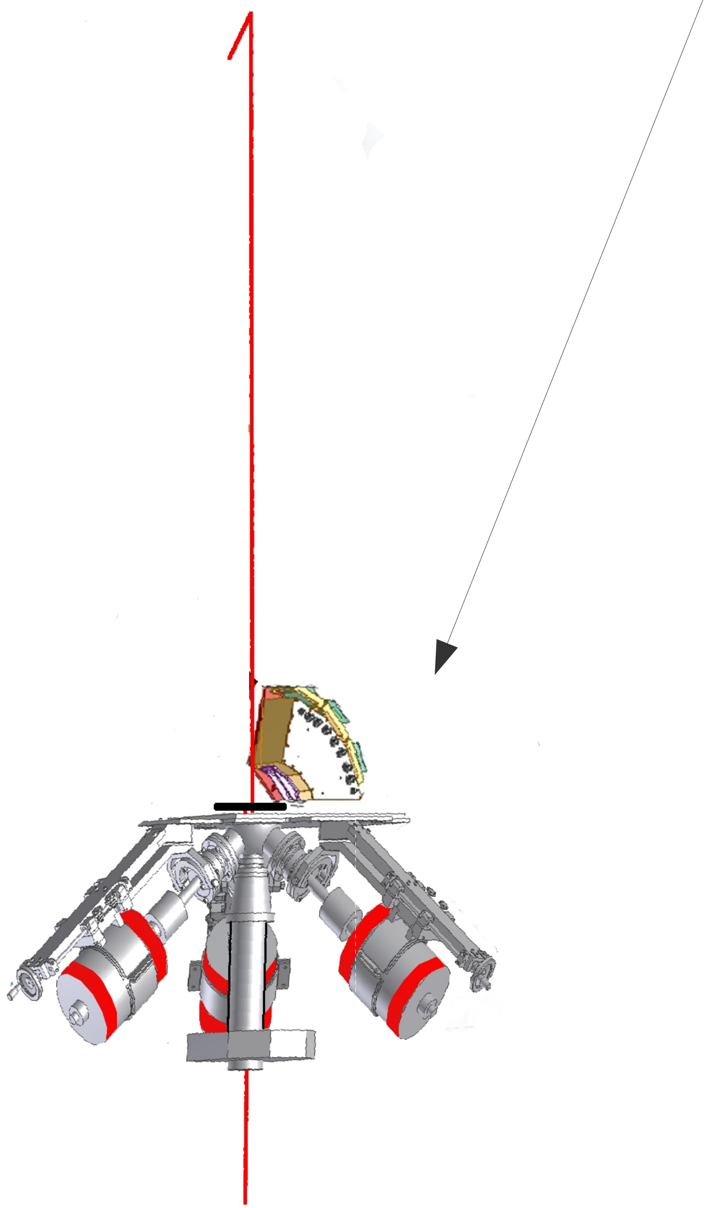
Experimental setup



3 X-ray detectors

- Planar germanium detectors
- 1 cm thick operated under vacuum
- About 6% of 4π when at 4.65 cm from target
- θ=127°
- Symmetric around the beam axis : ϕ=30°, 150° and 270°

Experimental setup



«FLUOX» Telescopes

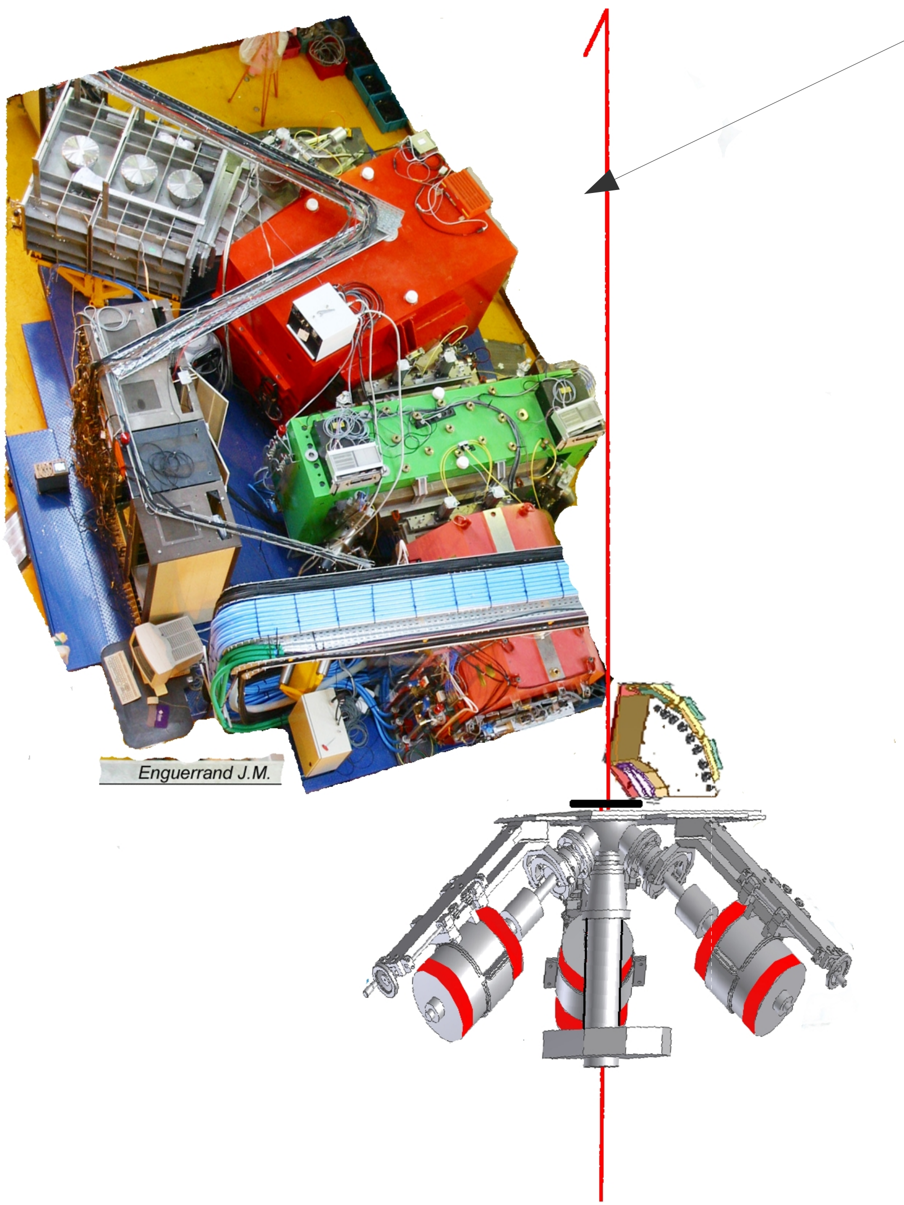
- Heavy fragment detection (Z,E,θ,φ)
- Coincidences with X-ray detectors
- Ionization chamber followed by double side silicon strip detectors (angular resolution ~ 1°)
- At 10 cm from the target

First Telescope
(16° à 28°)
- Fission fragments
- Projectile deep-inelastic scattering.
- Target inelastic scattering

Second Telescope :
(36° à 48°)
- Target inelastic scattering
- Fission fragments

Third Telescope:
(56° à 69°)
- Target elastic scattering

Experimental setup



VAMOS spectrometer

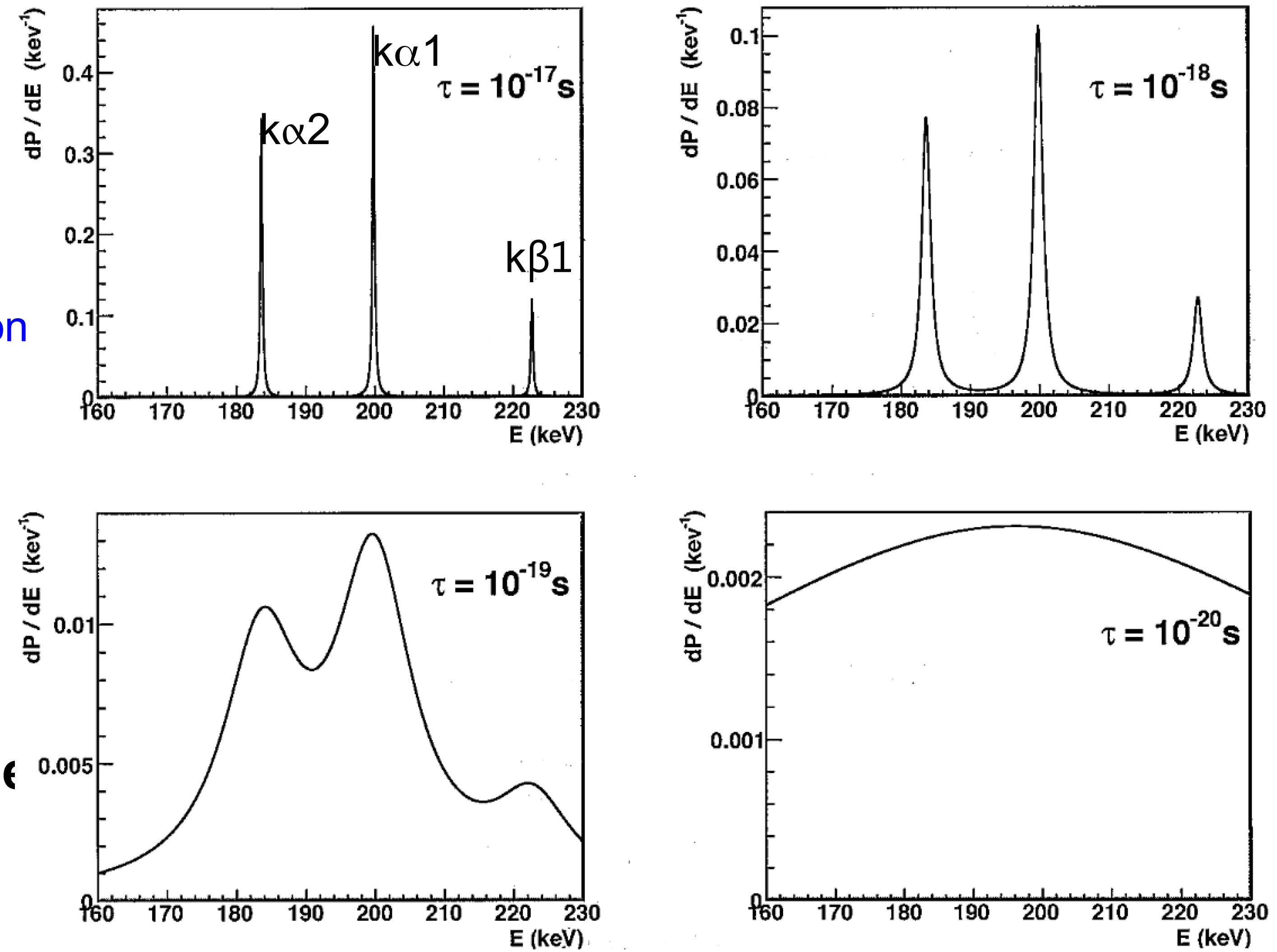
- (Z,E,A,θ,φ)
- Projectile Elastic Scattering (detection inside the grazing angle)
- Fission fragment detection in coincidence with FLUOX telescopes
- Triple coincidences with FLUOX telescopes and X-ray detectors: very low statistics.

X-ray spectrum simulations

MCDF calculations
(J. Bruno, Bruyères-le-Châtel)

coupling between all the possible electronic configurations
Dirac-Fock equation solved within mean field approximation
(atomic equivalent of Hartree-Fock equation)

Simulations



Peak broadening :

Finite fission time of the nucleus
(Weisskopf theory)

(molecular orbital emissions negligible during the fusion and fission processes due to very fast MO X energy variation with inter-atomic distance)

$$\tau_K = \frac{1}{P(K_{\alpha 1}) + P(K_{\alpha 2}) + P(K_{\beta 1}) + P(K_{\beta 3})} = 2,8 \times 10^{-18} s$$

X-ray spectrum simulation

Others broadening effects :

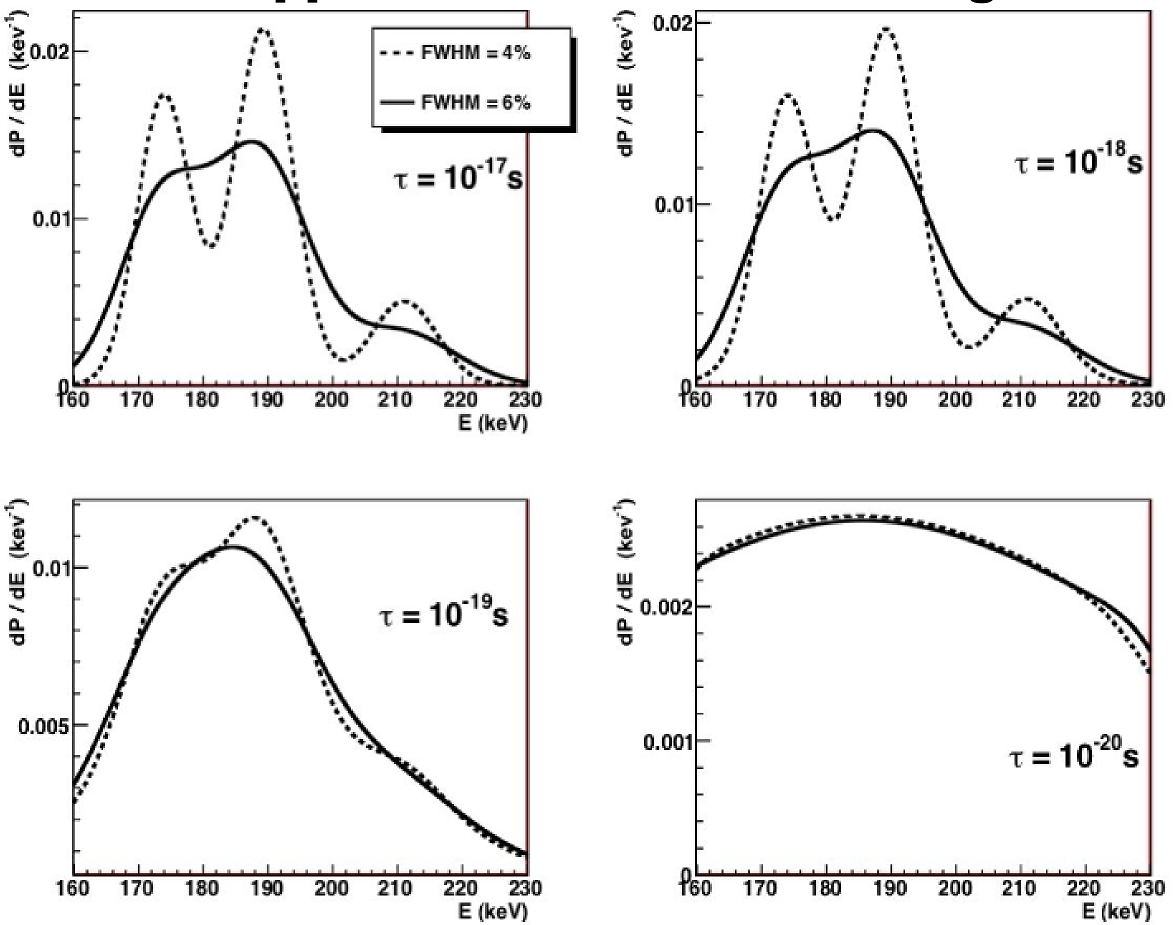
- Multiple electronic configurations (4% from MCDF)
- Low energy ray pile-up.
- Velocity distribution of the emitters
- ...

Broadening between 4% and 6%

+

Doppler effect (detectors aperture)

Simulations of X_K rays from Z=120 with Doppler effect and broadening



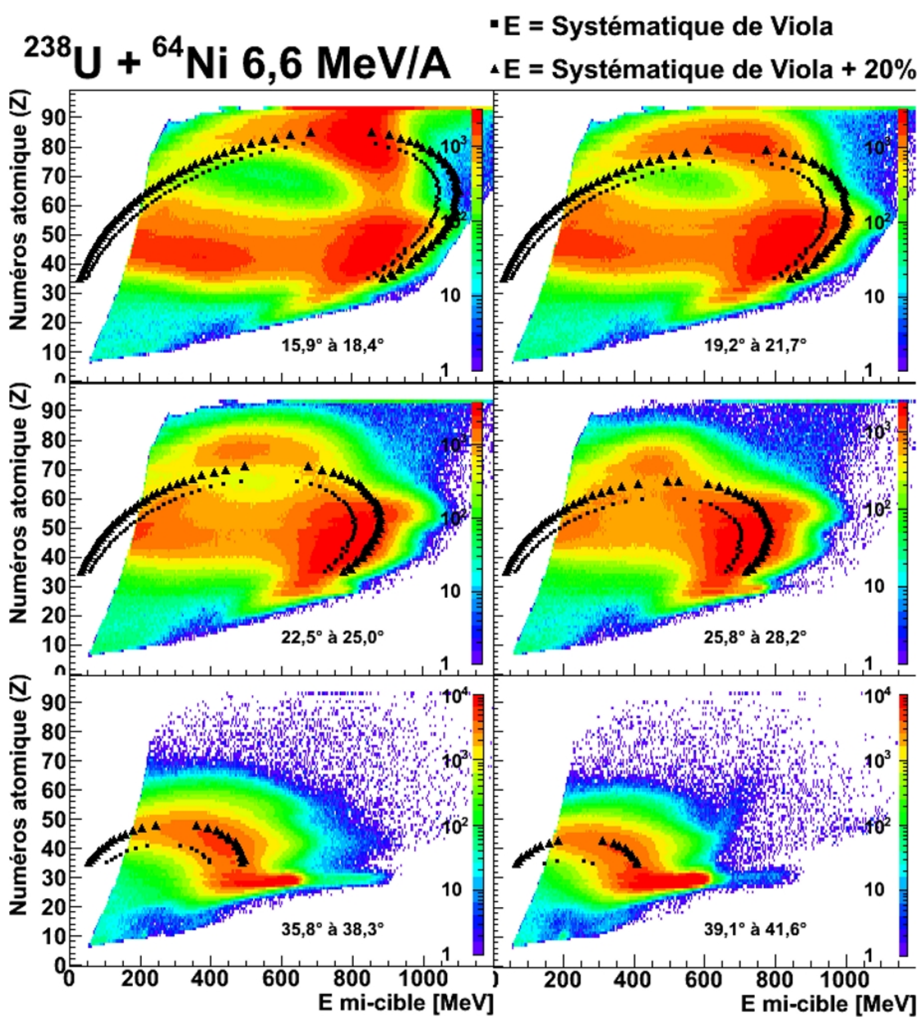
No peak for fission times shorter than 10^{-19}s

Quasi-fission ($\tau \approx 10^{-21}$ s) cannot contribute to a characteristic peak.

Search for a broad characteristic peak for Z=120 around 200 keV

Detected fragments in FLUOX

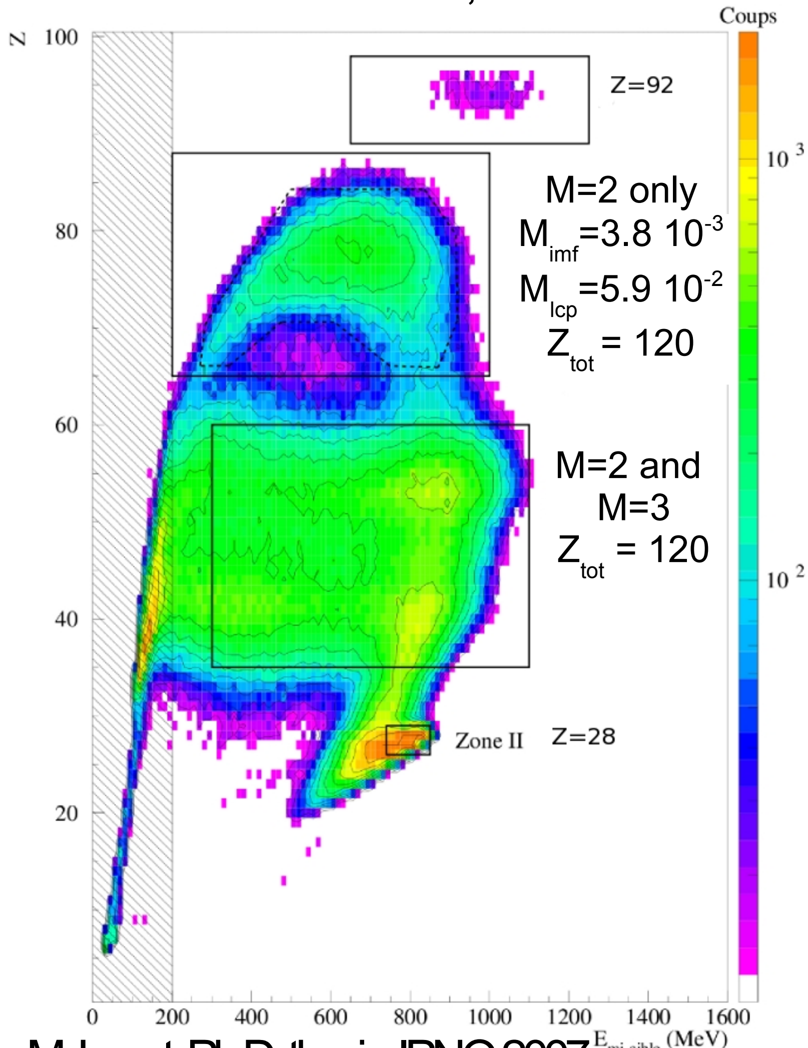
FLUOX telescope



Fragments detected between θ=16° and θ=42°

Blocking telescope (20°) + INDRA

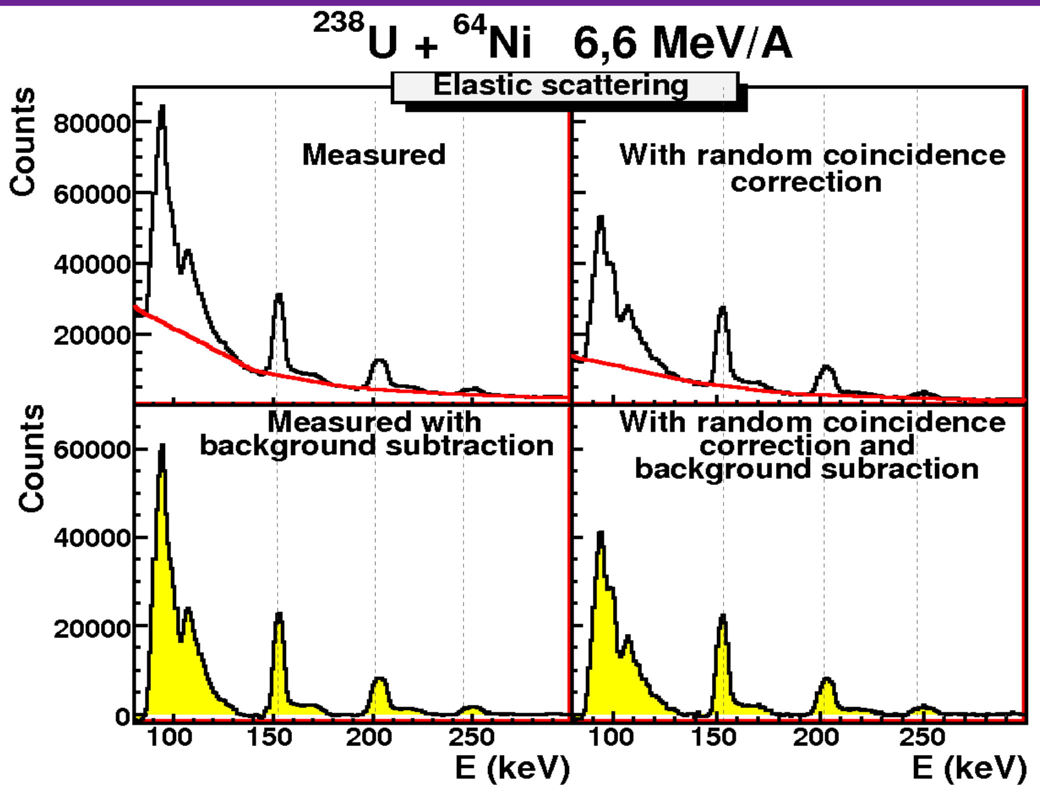
^{238}U + Ni at 6,6 MeV/A



M. Laget, Ph.D. thesis, IPNO,2007

Fragments with 70 ≤ Z ≤ 90 arise only from quasi-fission of from Z=120 fission.

Double Coincidences, FLUOX-Germanium



Elastic scattering:

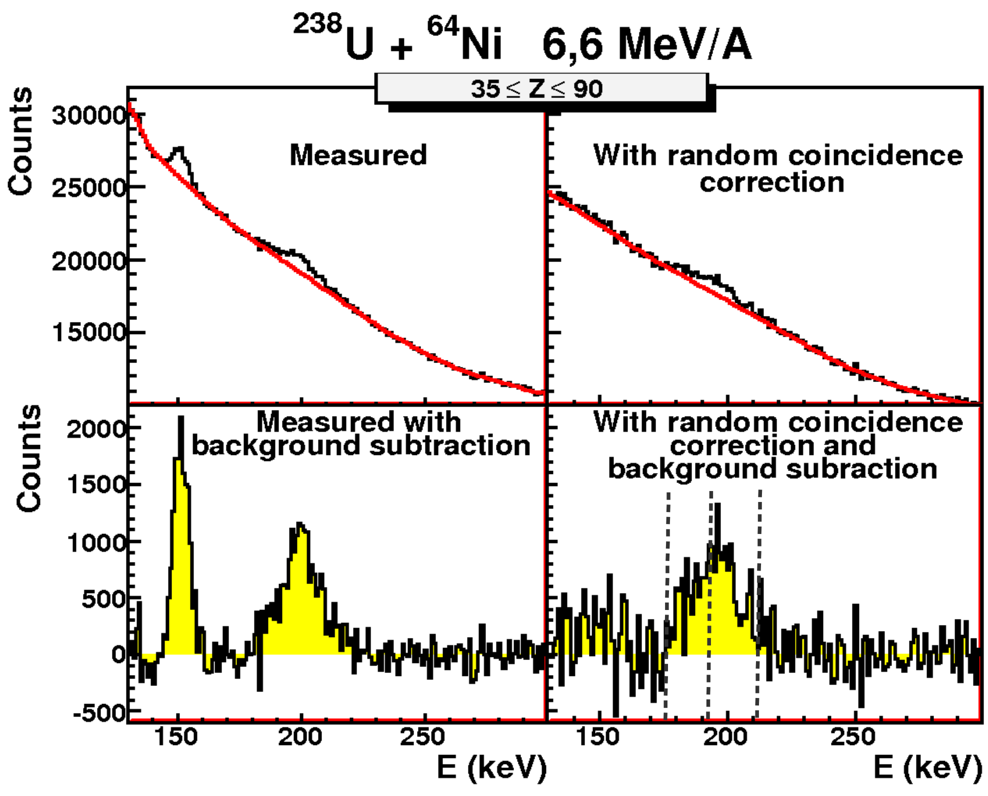
- Peaks at expected energies taking into account Doppler shift for elastically scattered projectile
- Overall spectrum shape is not affected by random coincidence correction.

Fission-like fragments

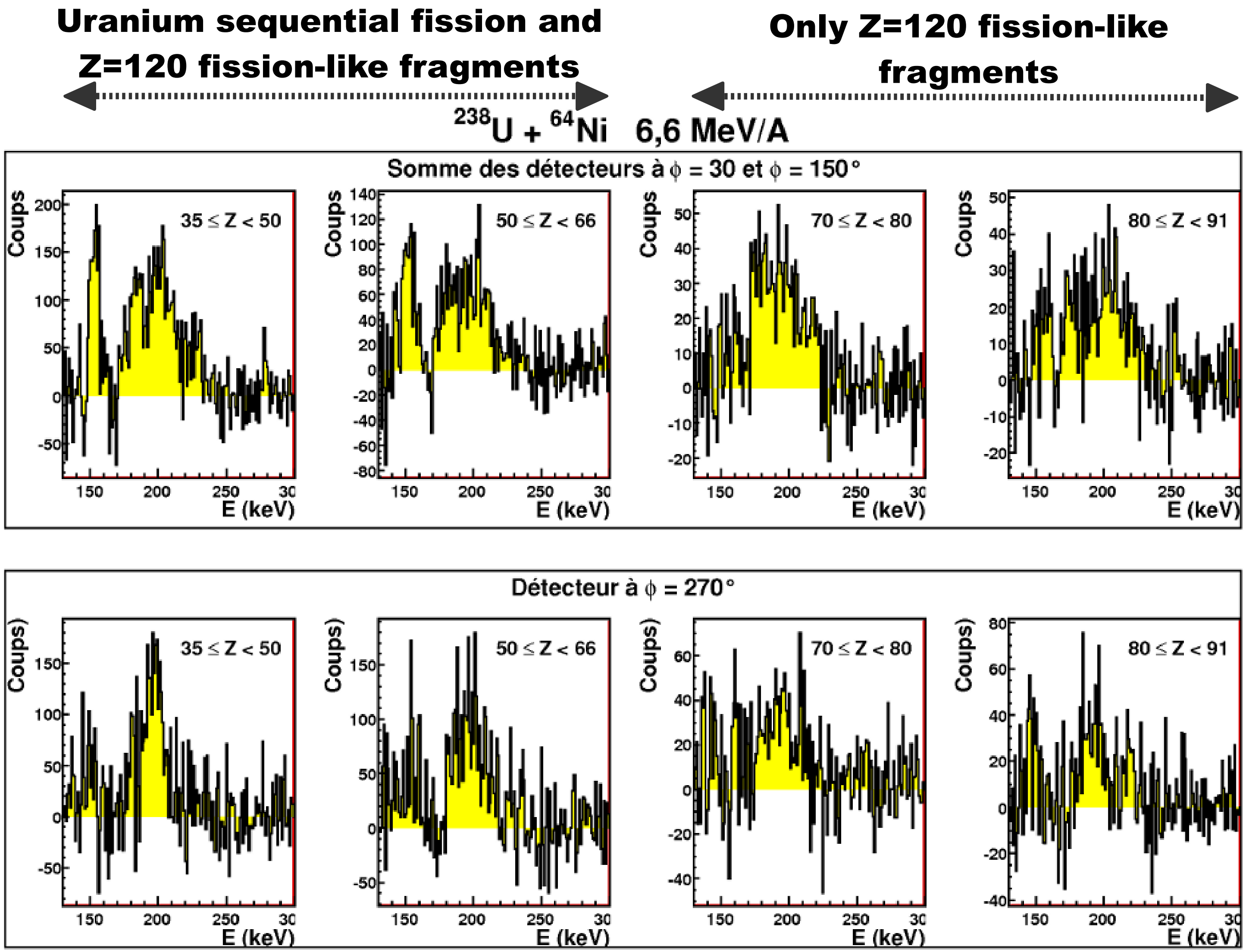
- Peaks at 150 keV and 200 keV

  Random coincidences?
- Very broad peak (50 keV) at ≈200 keV

  (only 15 keV in coincidence with elastic scattering)
- Peak at 150 keV vanishes with random coincidence correction
- Peak at 200 keV hardly affected by random coincidence correction
- Doppler shifted energies expected from MCDF for X_K rays from Z=120 in agreement with the position of the 200 keV peak



Spectrum evolution with atomic number

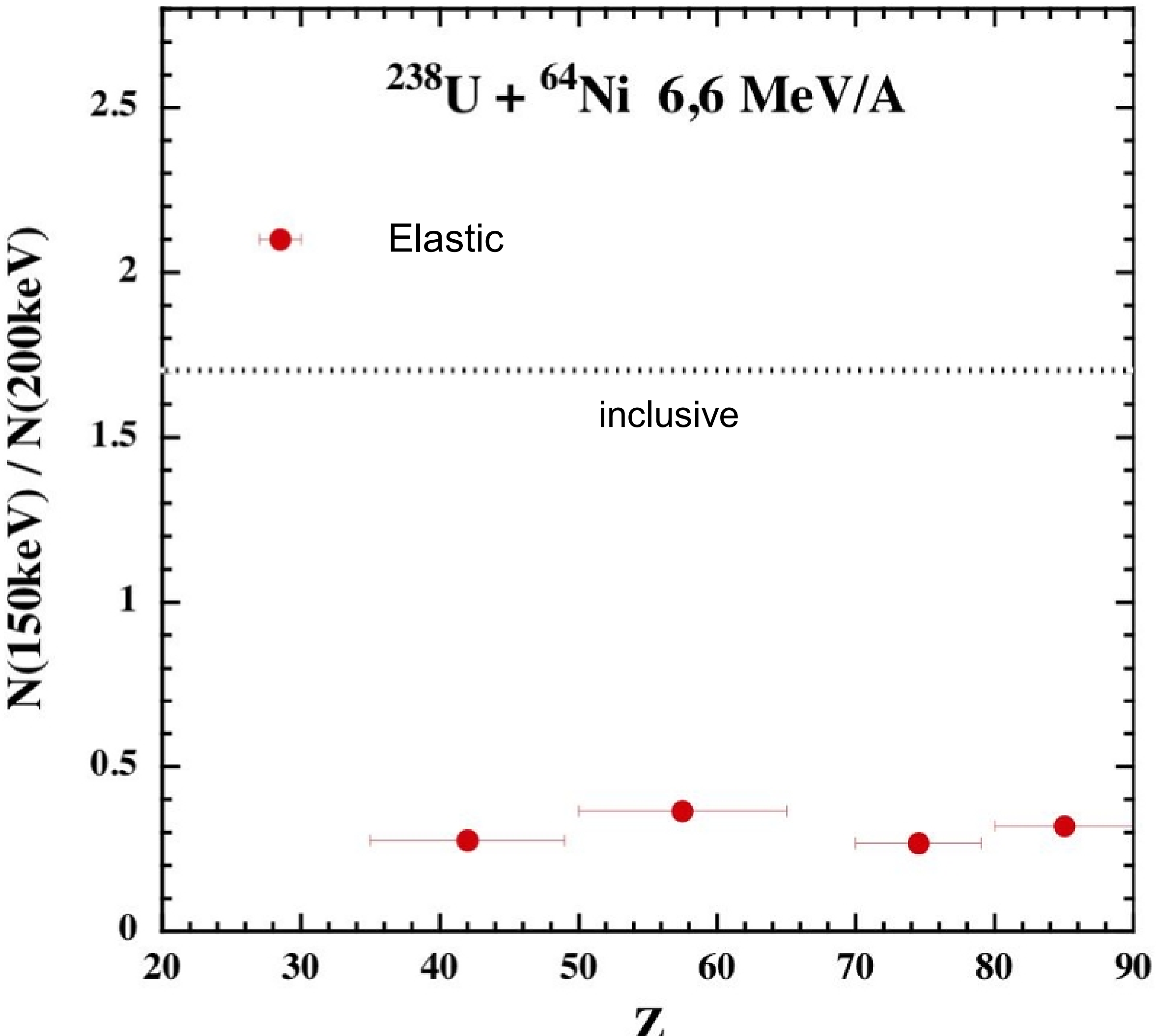


- 200 keV peak observed for any Z selection.

  (fission fragments from Z=120 expected in each selection)
- Low statistics: spectrum comparison very difficult
- Small residual peak at 150 keV observed for a few Z selections. (randoms ?)

Spectrum evolution with atomic number

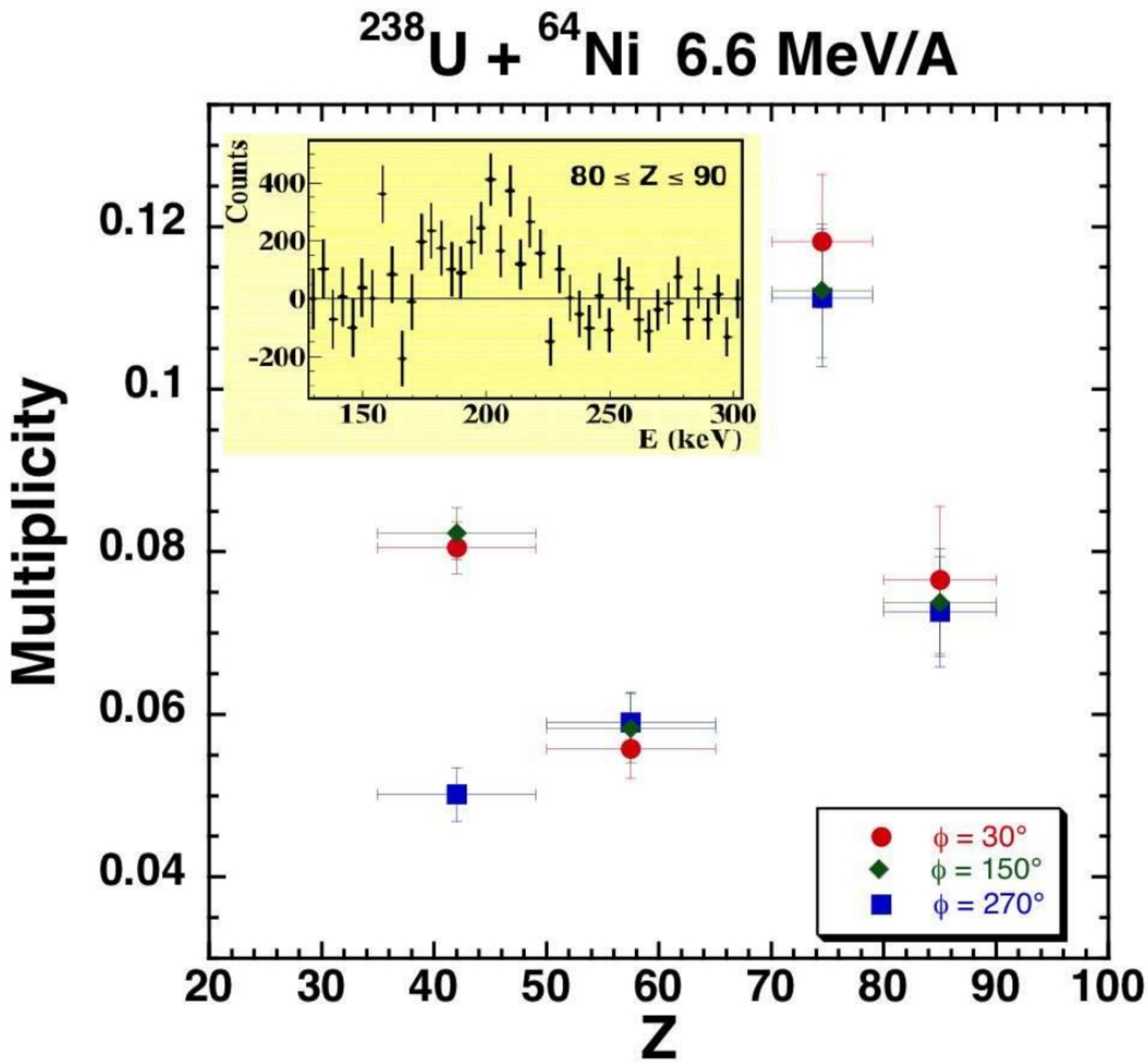
Same ratio than for inclusive measurements expected for the ratio between 150 keV and 200 keV yields if random coincidences.



•If the peak at 150 keV comes from residual random coincidences, there is at most 20% of random coincidences in the 200 keV peak.

Photon multiplicity between 175 keV and 225 keV

Multiplicity (M) = Ratio of photon number / capture event number



$$M = \frac{N_X * \epsilon(E)}{N_{inclusive}^{capture} * R}$$

Number of capture events measured during the very same time than the number of photons

- M similar for every detector except for fragment selection $35 \leq Z < 50$
  - Difference for $35 \leq Z < 50$ caused by Doppler shift.
  - Suggests presence of a γ from a fission fragment.

- Maximum multiplicity for fragment selection $70 \leq Z < 80$
  - Selection $70 \leq Z < 80$ contains only quasi-fission and fusion-fission events.
  - Selections with $Z < 65$ contains also fragments from U sequential fission
  - Selection $80 \leq Z < 90$ might contain deep inelastic events (Z resolution = ± 3 Z)

Nature of the peak at 200 keV - Summary

•Presence of a broad **peak between 175 keV and 225 keV** for all fragment selections containing **capture events**

• **Energies** very close to the ones expected for **Z=120 X_K**

•This broad peak is not observed in inclusive measurements or in coincidence with **elastic scattering**.

• **Maximum multiplicity** for fragment selection 70 ≤ Z < 80 (**capture events only**)

•For fragment selection 70 ≤ Z < 80, the peak energies at different detection angles show that the photons are mainly **emitted by a system recoiling at 0°**.

Conclusion : The region between 175 keV and 225 keV is dominantly populated by X_K emission characteristic of the element Z=120.

Fission time and fusion probability.

Lower limit for the average fission time assuming a single fission time τ:

$$\tau = \frac{\tau_{vac}}{\left(\frac{P_{K120}}{M'} - 1\right)}$$

M' = X_K multiplicity for fusion-fission reactions

τ_{vac} = (2.8 ± 0.6) × 10^{-18} s (from MCDF)

Measured quantities:

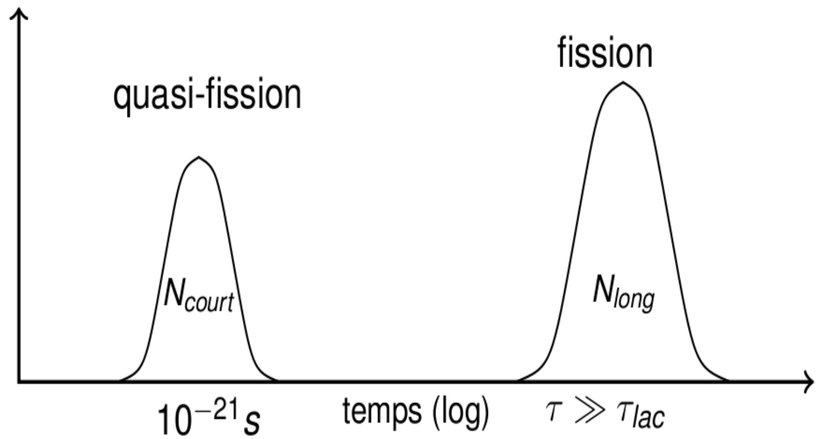
P_{el} = 0.27 ± 0.07, ionisation probability in K shell elastic scattering measurement

M = 0.11 ± 0.01 X_K multiplicity measured for capture reactions($70 \leq Z < 80$).

M is smaller than M' : we can only infer a lower limit t_{min} for the fission time of Z=120 at E*≈79 MeV :

T_{min} = 2.5 10^{-18}s

Lower limit for fusion-fission probability assuming a bimodal reaction time distribution:



With this distribution

$$M'/P_{K120} = 1$$

and

$$\frac{M}{P_{K120}} = \frac{N_{long}}{N_{long} + N_{short}}$$

At least 53% of fusion-fission events

among all the capture reactions detected at θ>16°($70 \leq Z < 80$)

Conclusions

- XK rays from the element Z=120 identified

- Very long fission time of the Z=120 formed nuclei : high fission barriers all along the decay chain

  confirmation of crystal blocking experiment results

  validation of the X-ray fluorescence technique to study SHE stability

- High ratio fusion-fission / quasi-fission : for our large detection angles

- Asymmetric fission is the dominant process.

Collaboration

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