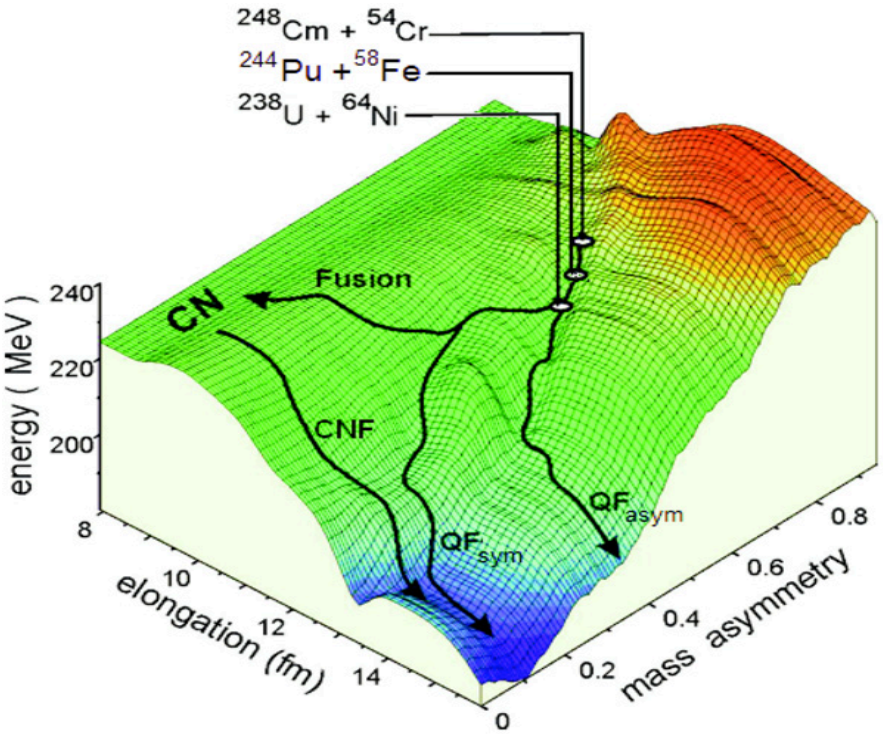
Dynamical evolution of super-heavy systems studied using the X-ray fluorescence technique



Multi-dimensional Langevin-type equations
From V. Zagrebaev et al.

POTENTIAL LANDSCAPE

An essential role in the dynamical evolution of super-heavy systems

- Pocket(s) for compound nucleus formation (fission barrier height)
- Fusion barrier height and position
- Trajectories for asymmetric and/or symmetric quasi-fission
- Trajectories for symmetric and/or asymmetric fission

X-RAY FLUORESCENCE TECHNIQUE APPLIED TO SUPER-HEAVY SYSTEMS WITH Z > 110

Reaction time

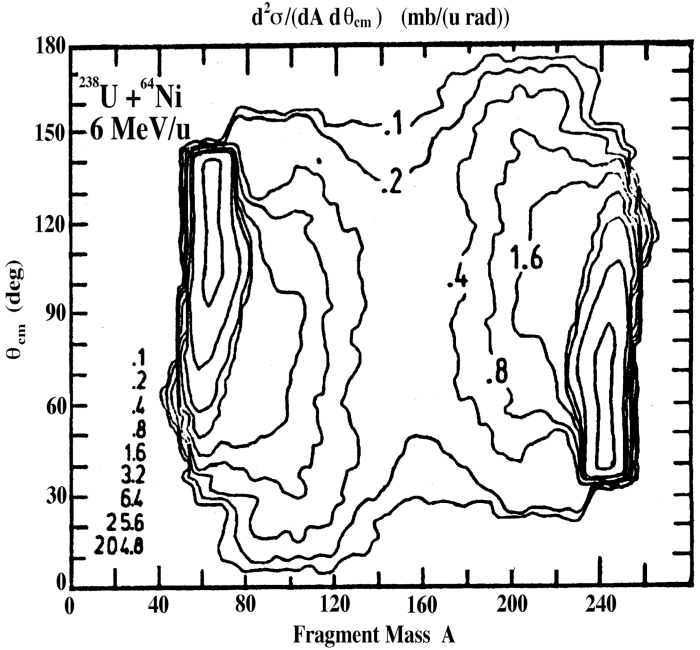
- Information on the trajectories followed (fusion-fission or quasi-fission)
- Height of the fission and fusion barriers

Atomic number of the fragments

- Coupled with mass detection, provides N/Z
- Information on nucleon exchange along the different trajectories

Reaction times for systems with Z > 110

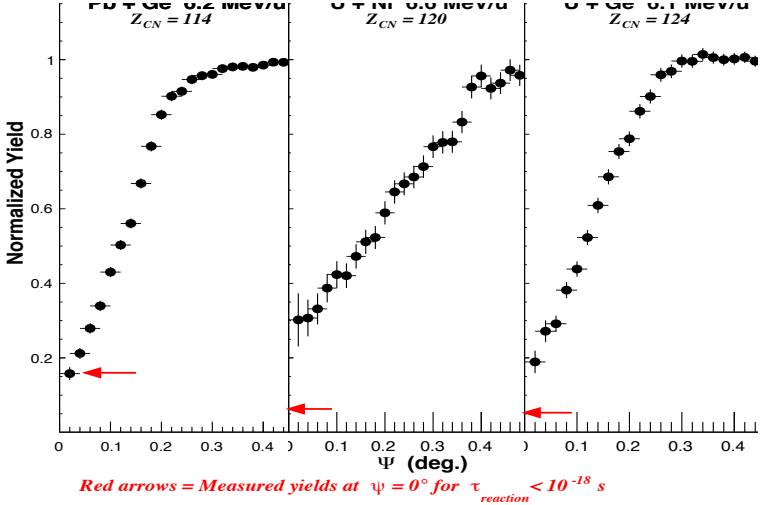
MASS-ANGLE DISTRIBUTIONS



J. Töke et al., Nucl. Phys. A440 (1985) 327

- Dominant mechanism = quasi-fission
- Most probable reaction time very short (< 10^{-20}s)
- Existence of small cross-sections of fusion followed by fission for very heavy systems?

LONG LIFETIME COMPONENTS

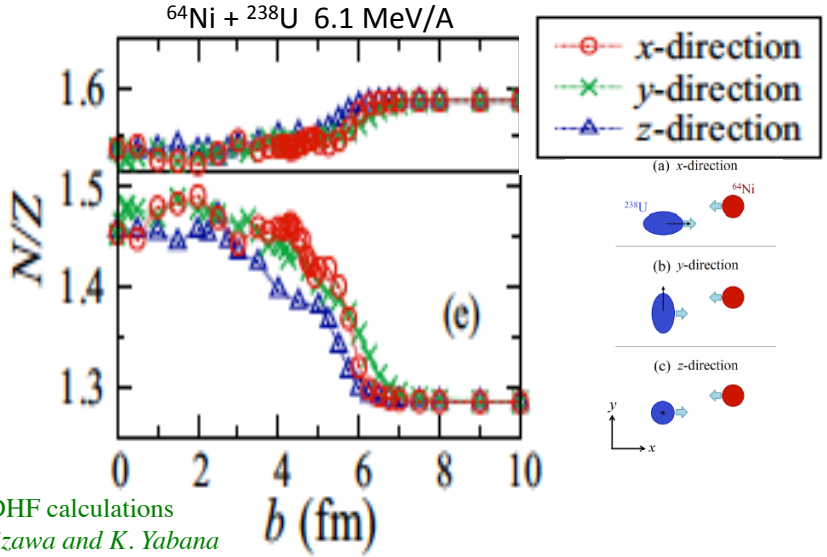


M. Morjean et al., PRL 101, 072701 (2008)

- Direct experimental evidence for long lifetime components (t > 10^{-18}s) from blocking effects in single crystals
- For Z =120 and 124, evidence for long lifetime components (t > 10^{-18}s) associated with asymmetric fissions
- Formation of Z = 120 and 124 with high fission barriers
- No evidence for long lifetime components for Z = 114 (^{284}Fl)

N/Z of the fragments for systems with Z > 110

Many data for A or Z
Almost no data with a simultaneous measurement of A and Z

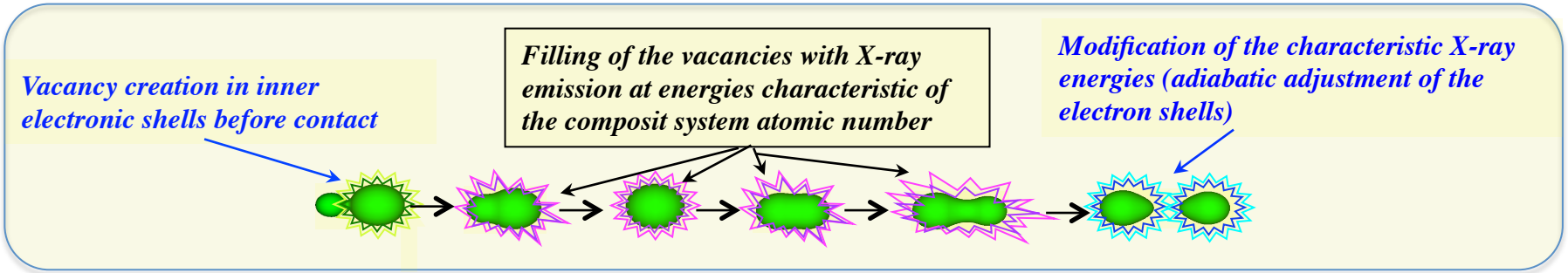


TDHF calculations
K. Sekizawa and K. Yabana
PRC 93 (2016) 054616

EXPERIMENTAL INFORMATION EXPECTED

- Full N/Z equilibrium reached for the fragments?
- Difference between fusion/fission and quasi-fission?
- Evolution with the reaction time?
- Effect of magic numbers in the exit channels?

X-ray fluorescence technique applied to super-heavy reactions



EVIDENCE FOR COMPOUND NUCLEUS FORMATION

Lifetime of a K-vacancy of the composite system ~ 10^{-18}s

⇒

Detection of characteristic X-ray from the composite system = Evidence for CN formation

REACTION TIME

No correlation between fission lifetime and vacancy lifetime

⇒

the X_K multiplicity is a clock for the nucleus lifetime before fission

N/Z EQUILIBRIUM

Precise atomic number identification of the (quasi-)fission products

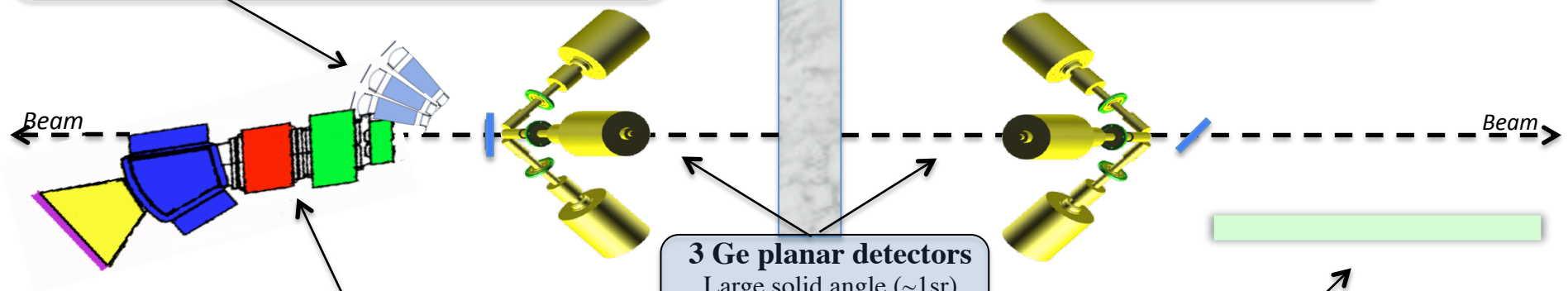
Experimental set-ups

^{238}U + ^{64}Ni 6.6 MeV/A (Ganil)

^{48}Ti + ^{238}U 5.75 MeV/A (Canberra)

3 telescopes
(Ionization chamber + double-sided strip silicon detector)
Identification of fission fragment #1 : Z1 , E1 , θ1 , ϕ1
Identification of elastically scattered target nuclei

Multi-wire proportional counter
Large solid angle ; large angular correlations
Identification of fission fragment #1 : A1 , v1 , θ1 , ϕ1



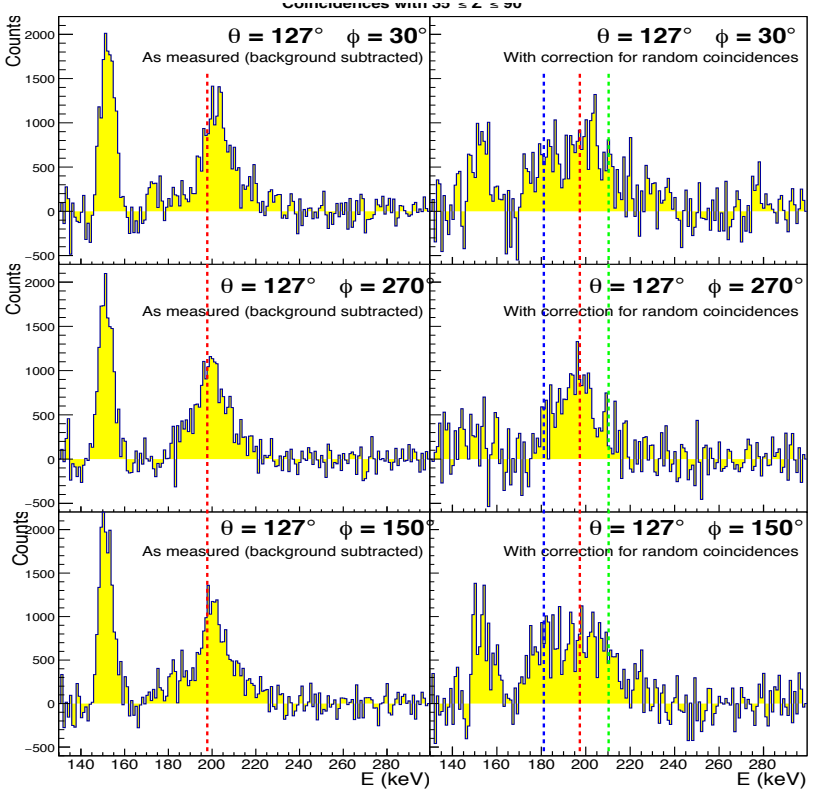
3 Ge planar detectors
Large solid angle (~1sr)
Low energy threshold

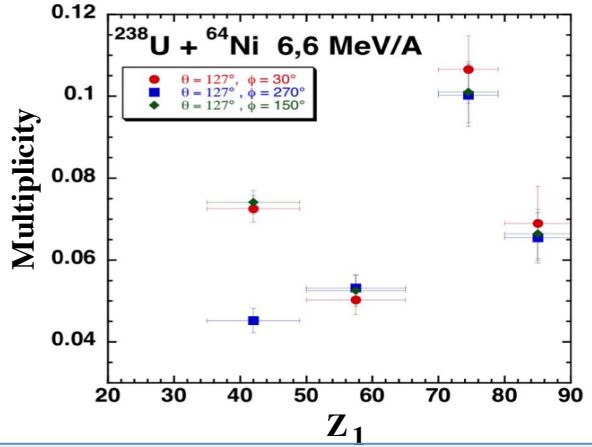
VAMOS large acceptance spectrometer
(SED + Ionization Chamber + Silicon Detectors)
Identification of fission fragment #2 : Z2 , A2 , E2 , θ2 , ϕ2
Identification of elastically scattered projectile nuclei

Multi-wire proportional counter
Large solid angle ; large angular correlations
Identification of fission fragment #2 : A2 , v2 , θ2 , ϕ2

M. Morjean, INPC2016

Z = 120 characteristic X-rays





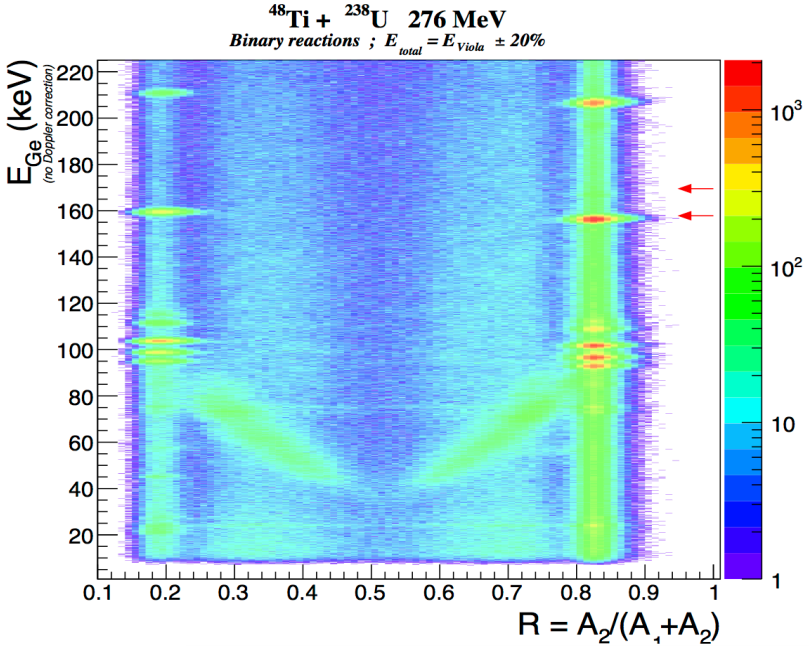
EVIDENCE FOR K X-RAY DETECTION FROM Z_{CN} = 120

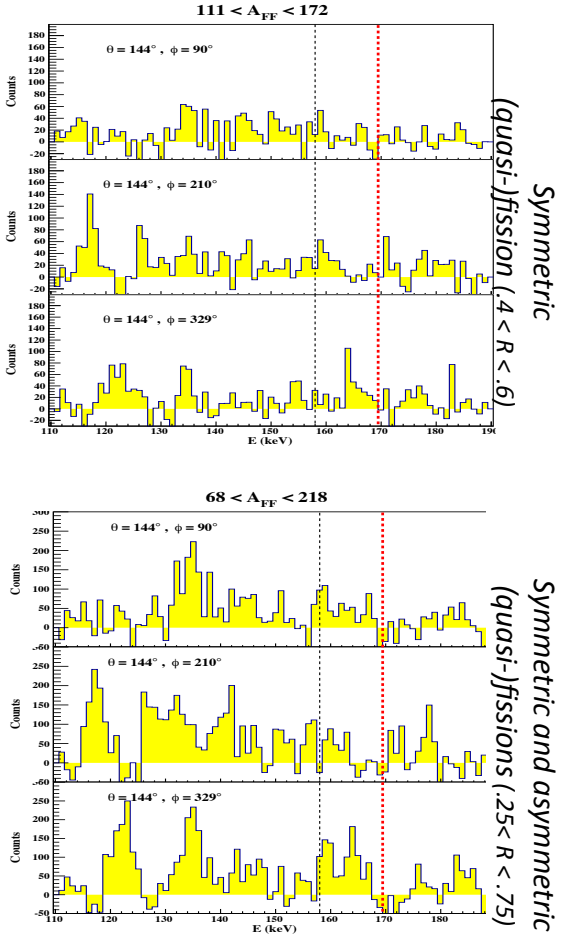
- Peak at the energy predicted by Multi-Configuration-Dirac-Fock calculations for the $K_{\alpha 1}$ ray from Z = 120
- Emission from a system moving at O°
- Maximum multiplicity in the Z domain exclusively populated by asymmetric fission and asymmetric quasi-fission of the composite system

Compound nucleus fission time > 10^{-18} s

See: M.O. Frégeau et al., PRL 108, 122701 (2012)

Z = 114 characteristic X-rays





PRELIMINARY CONCLUSIONS

Very low statistics

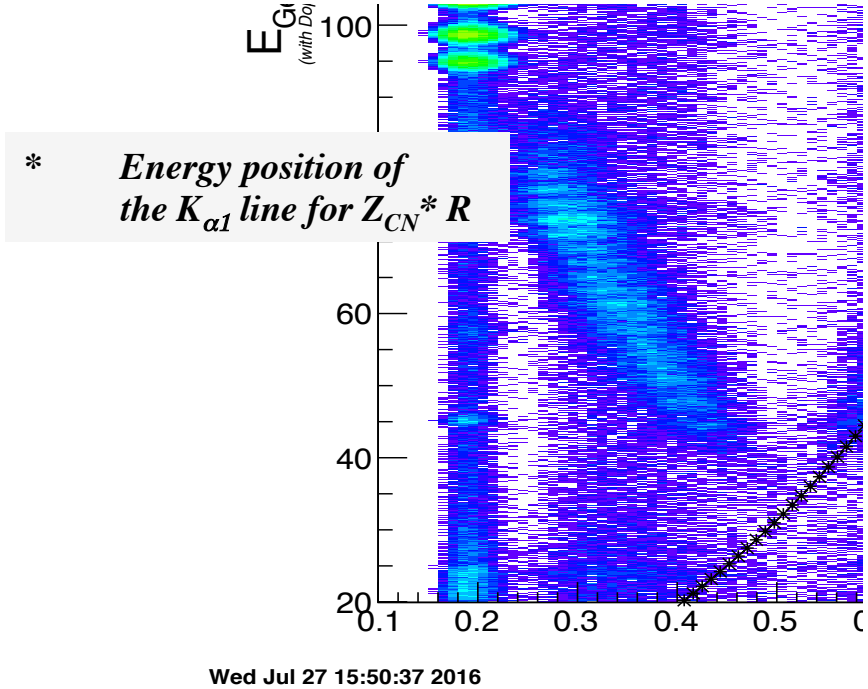
No characteristic X-ray visible for Z = 114

$\tau_{reaction} << 10^{-18}$ s *(assuming similar K-vacancy creation probability than for U+Ni)*

In agreement with the blocking experiment conclusions for ^{284}Fl :

$\tau_{capture}(Z=114) < \tau_{capture}(Z=120 \text{ or } 124)$

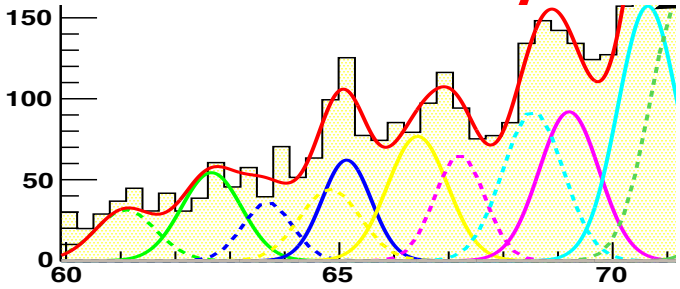
Quasi-fission fragment characteristic X-rays



* *Energy position of the $K_{\alpha 1}$ line for Z_{CN}* R*

Measurement of A and Z at the scission

Quasi-fission fragment characteristic X-rays



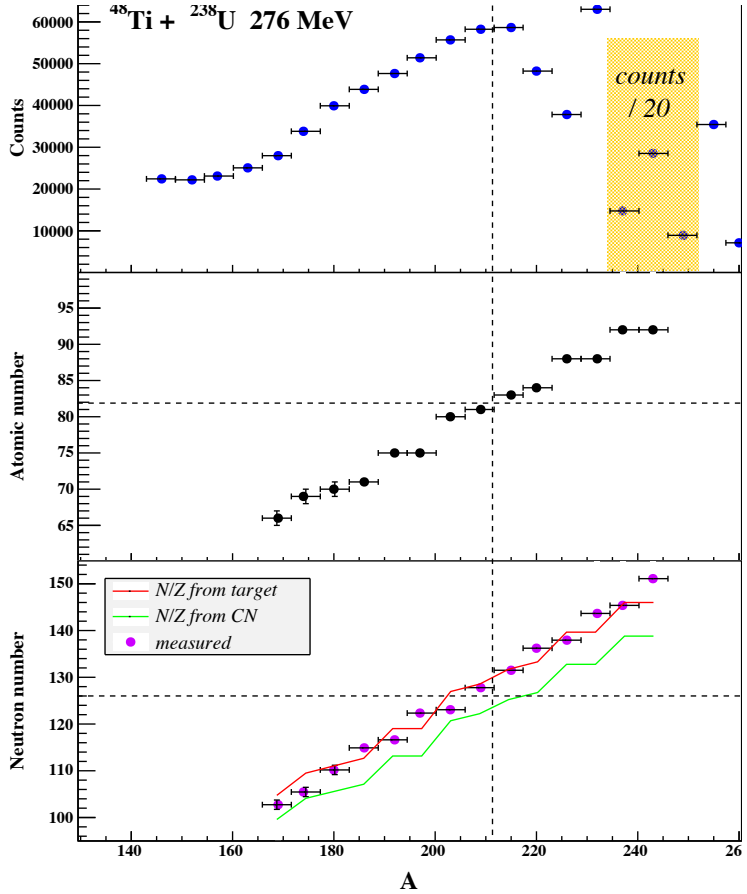
Fit (red continuous line) performed assuming:

- Only $K_{\alpha 1}$ and $K_{\alpha 2}$ transitions
- Energy of the transitions = energy from tables for ions with charge state 1+
- Intensity ratio between $K_{\alpha 1}$ and $K_{\alpha 2}$ fixed from tables for 1+ ions

Unambiguous determination of the most probable atomic number

M. Morjean, INPC2016

N/Z equilibrium of quasi-fission fragments



Maximum cross-section for $Z_{fragment} \simeq 82$

- Effect of magic number in the dynamical evolution?
- Effect of sequential fission?

Weaker effect for N = 126

N/Z of the target conserved for asymmetric fissions

Slow evolution towards N/Z of the compound nucleus for symmetric fissions?

Conclusions

X-ray fluorescence technique = powerful tool to probe the potential landscape for very heavy systems (Z > 110)

Evidence for compound nucleus formation for Z = 120

- **Average fission time:** $\tau_{fission} \gtrsim 10^{-18}$ s

No evidence for Z = 114 (^{286}Fl)

- $\tau_{capture}$ (Z=114) < $\tau_{capture}$ (Z=120) *Preliminary result*

Maximum of quasi-fission cross-section in ^{48}Ti + ^{238}U for Z = 82

- **Effect of Z magic number in the exit channel?**

Strong memory of the target (projectile) N/Z for quasi-fission fragments

- **Possible evolution towards the N/Z ratio of the composite system for symmetric quasi-fission**

Collaborations

Experience $^{238}U + ^{64}Ni$
(Ganil)

GANIL
IPN Orsay
SPhN Saclay
LPC Caen
NIPNE Bucharest
INFN Legnaro and Padova

M. O. Frégeau
M. Morjean
A. Chbihi
M. F. Rivet
F. Dechery
L. Nalpas
M. Parlog
D. Dumitriu
M. Gugiu
V. L. Kravchuk
D. Fabris
S. Barlini
D. Jacquet
E. Bonnet
J. D. Frankland
L. Tassan-Got
A. Drouart
X. Ledoux
C. Ciortea
D. Fluerasu
F. Gramegna
T. Marchi
A. Corsi

Experience $^{48}Ti + ^{238}U$
(Canberra)

GANIL
ANU Canberra
IPN Orsay
SPhN Saclay

A. Drouart
M. Morjean
D. J. Hinde
E. C. Simpson
C. Simenel
E. Prasad
D. Rafferty
K. Vo-Phuoc
D. Jacquet
L. Tassan-Got
M. Dasgupta
K. J. Cook
S. Kalkal
C. S. Palshetkar
D. Y. Jeung
N. Lobanov