Probing the decay mechanism of hot nuclei by Coulomb chronometry

Diego Gruyer for the INDRA Collaboration

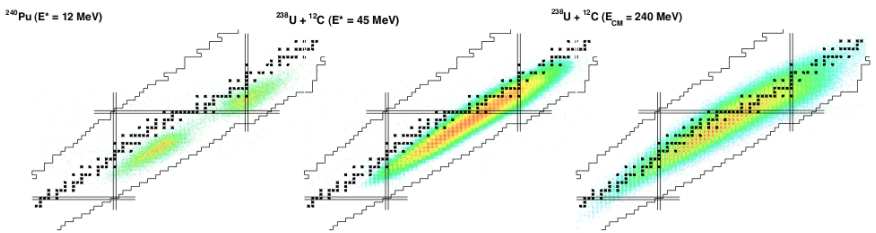
Grand Accélérateur National d'Ions Lourds, and
Université de Caen Basse-Normandie

Collisions between Coulomb and Fermi energies

Collisions between Coulomb and Fermi energies

Coulomb barrier → Fermi energies

Fission/Evaporation → Available energy

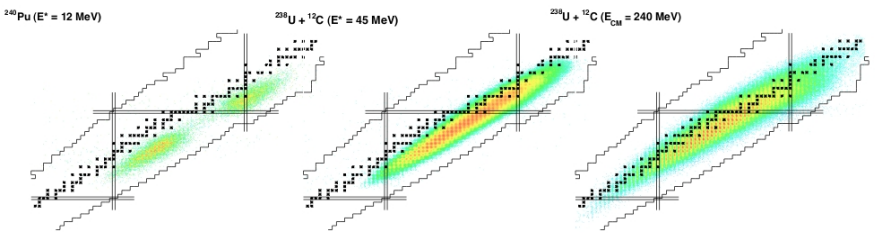


O.Delaune, PhD Thesis (2012)

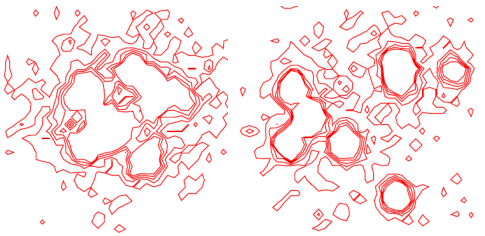
Collisions between Coulomb and Fermi energies

Coulomb barrier → Fermi energies

Fission/Evaporation → Multifragmentation → Available energy



O.Delaune, PhD Thesis (2012)

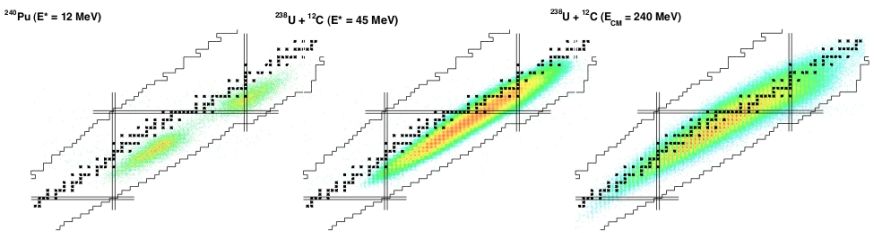


adapted from M. Colonna et al.
Phys. Rev. C **82**, 054613 (2010)

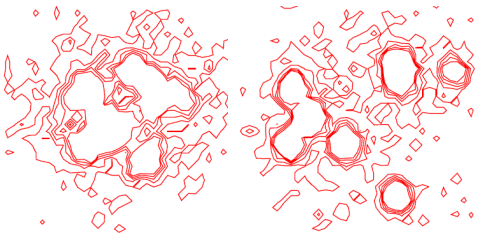
Collisions between Coulomb and Fermi energies

Coulomb barrier —This work→ Fermi energies

Fission/Evaporation — Multifragmentation — Available energy

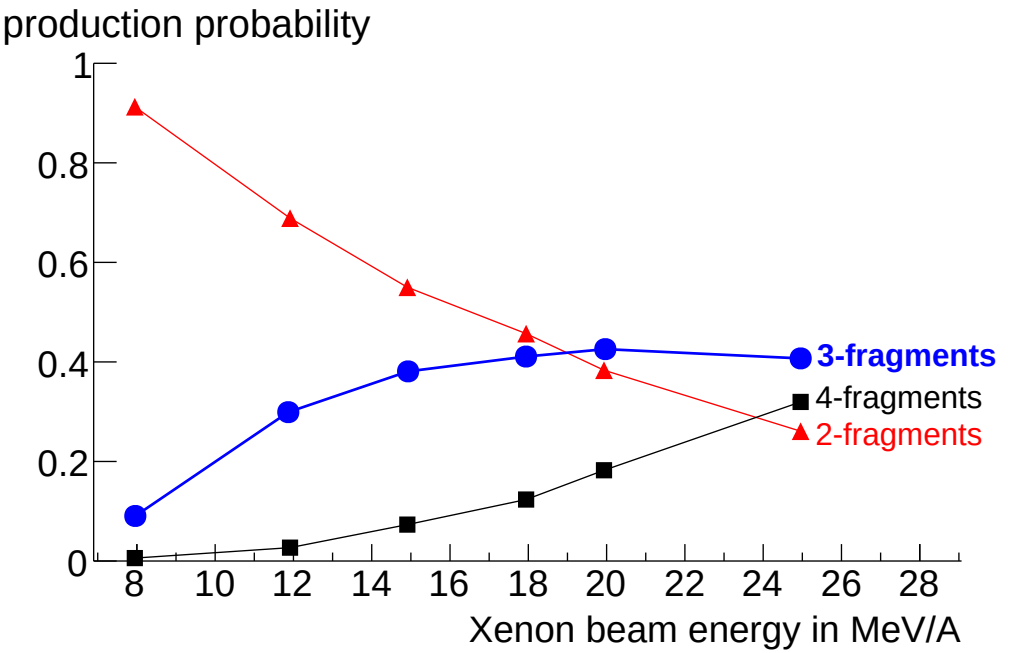


O.Delaune, PhD Thesis (2012)



adapted from M. Colonna et al.
Phys. Rev. C **82**, 054613 (2010)

Multifragment production in Xe+Sn central collisions

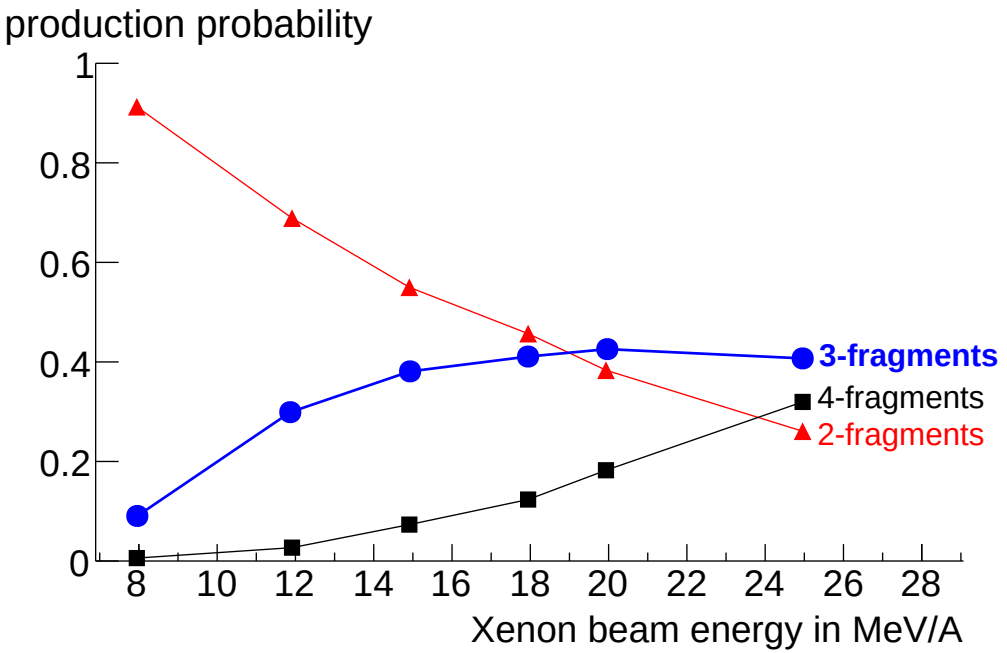


A.Chbihi et al. J.Phys. : Conf.Ser. **420**, 012099 (2012)

Multifragment production in Xe+Sn central collisions

Exit channel probabilities

- 8 MeV/A : two fragments

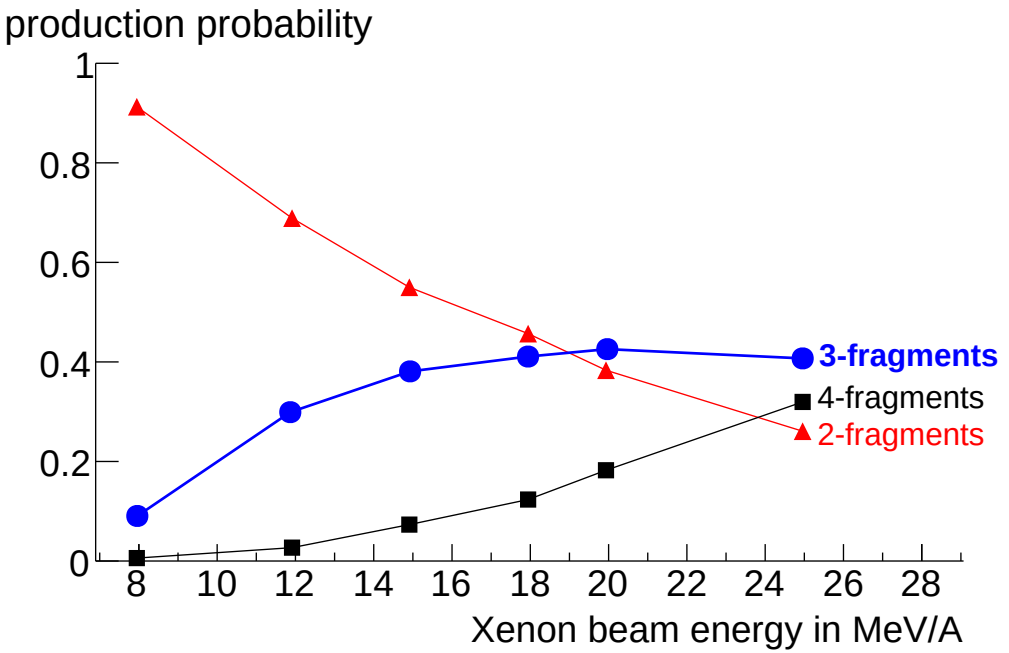


A.Chbihi et al. J.Phys. : Conf.Ser. **420**, 012099 (2012)

Multifragment production in Xe+Sn central collisions

Exit channel probabilities

- 8 MeV/A : two fragments
- Three fragment exit channel significant above 12 MeV/A

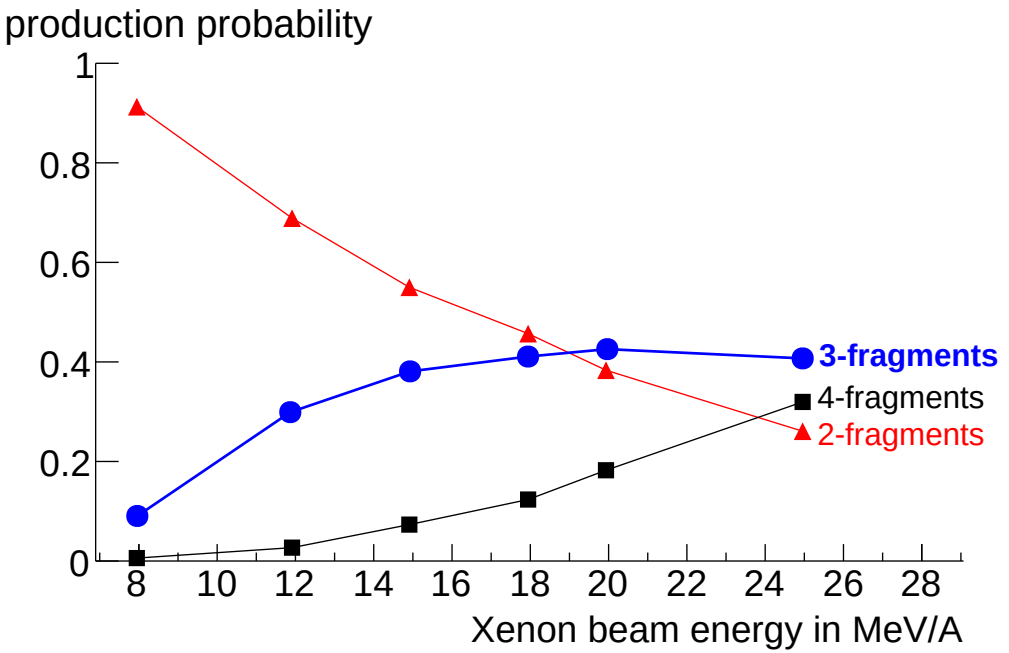


A.Chbihi et al. J.Phys. : Conf.Ser. **420**, 012099 (2012)

Multifragment production in Xe+Sn central collisions

Exit channel probabilities

- 8 MeV/A : two fragments
- Three fragment exit channel significant above 12 MeV/A



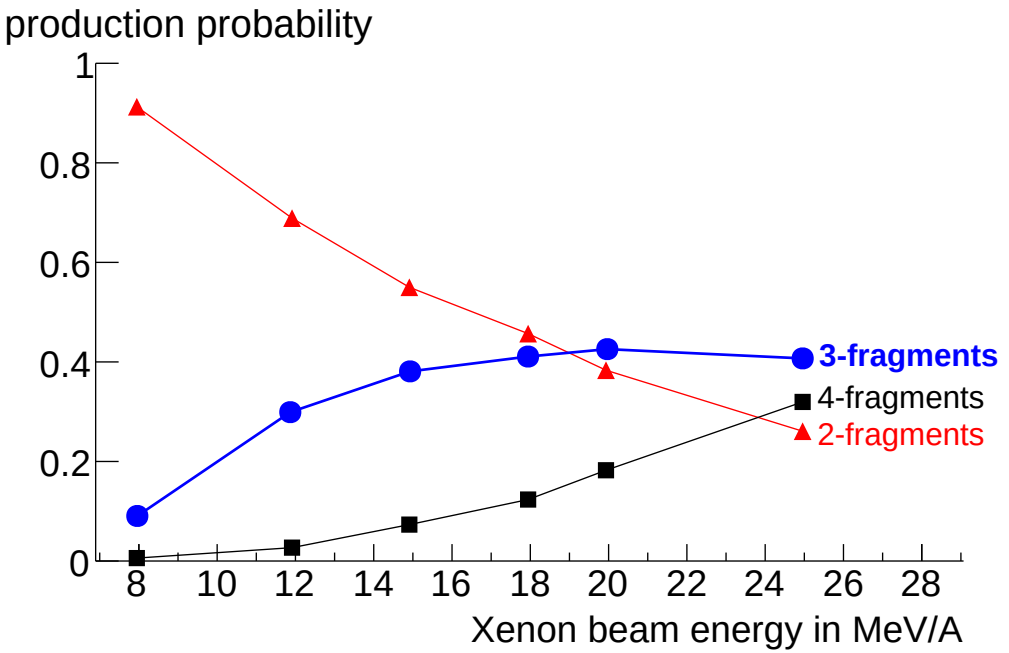
A.Chbihi et al. J.Phys. : Conf.Ser. **420**, 012099 (2012)

Mechanism of three-fragment production

Multifragment production in Xe+Sn central collisions

Exit channel probabilities

- 8 MeV/A : two fragments
- Three fragment exit channel significant above 12 MeV/A



A.Chbihi et al. J.Phys. : Conf.Ser. **420**, 012099 (2012)

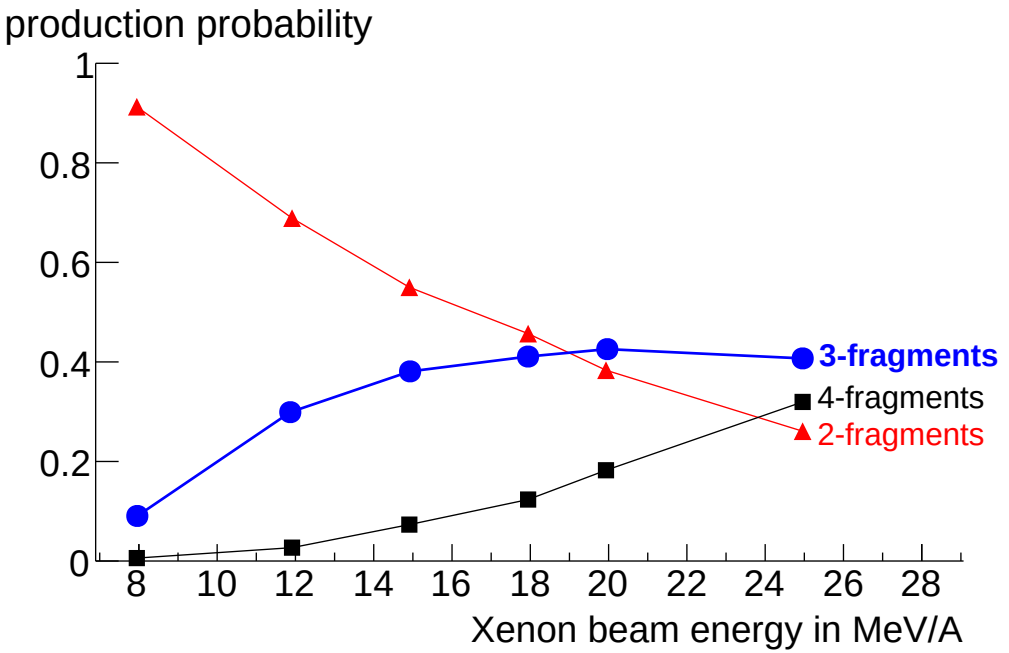
Mechanism of three-fragment production

- Is it the continuation of low energy fission or the precursor of high energy simultaneous fragmentation ?

Multifragment production in Xe+Sn central collisions

Exit channel probabilities

- 8 MeV/A : two fragments
- Three fragment exit channel significant above 12 MeV/A



A.Chbihi et al. J.Phys. : Conf.Ser. **420**, 012099 (2012)

Mechanism of three-fragment production

- Is it the continuation of low energy fission or the precursor of high energy simultaneous fragmentation ?
- Estimation of the time scale can distinguish different mechanisms.

Outline

Experimental details

Experimental data

- Xe+Sn at 12, 15, 18, 20, 25 MeV/A

Experimental details

INDRA 4π multidetector

- High granularity with 336 cells
- Charge identification from proton to Uranium up to 250 MeV/A
- Low identification thresholds

Experimental data

- Xe+Sn at 12, 15, 18, 20, 25 MeV/A

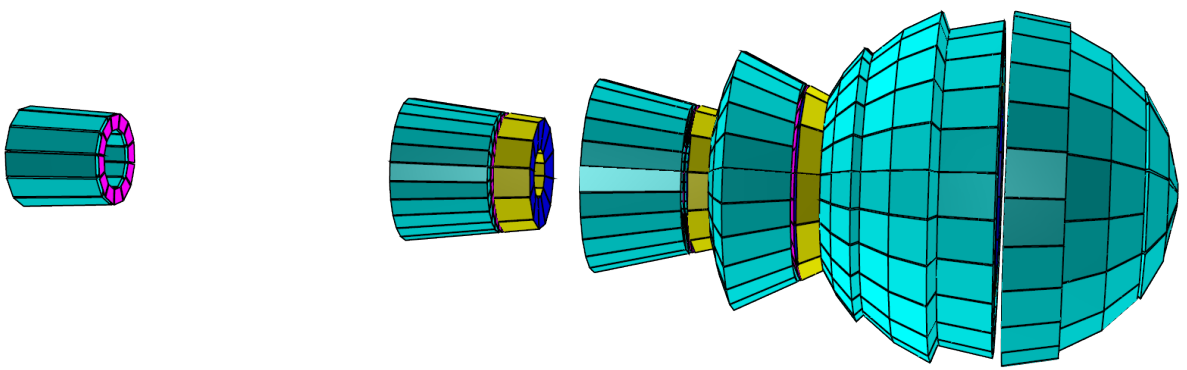
Experimental details

INDRA 4π multidetector

- High granularity with 336 cells
- Charge identification from proton to Uranium up to 250 MeV/A
- Low identification thresholds

Experimental data

- Xe+Sn at 12, 15, 18, 20, 25 MeV/A



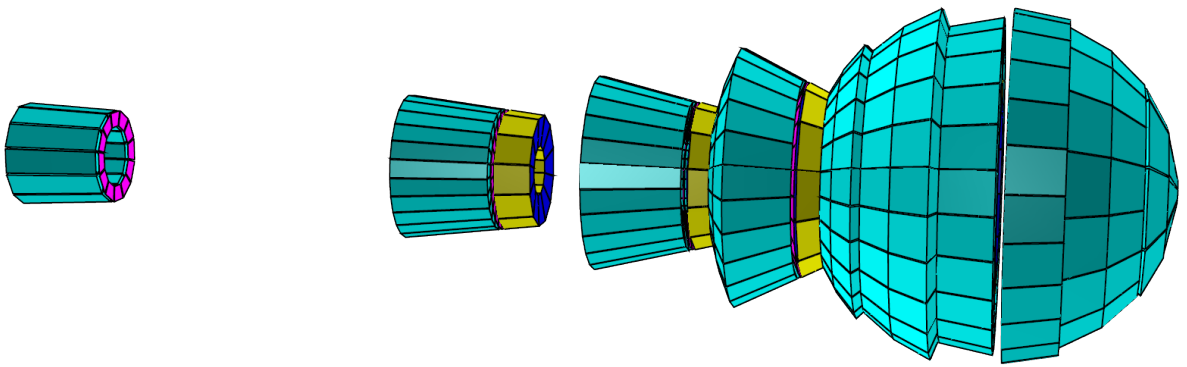
Experimental details

INDRA 4π multidetector

- High granularity with 336 cells
- Charge identification from proton to Uranium up to 250 MeV/A
- Low identification thresholds

Experimental data

- Xe+Sn at 12, 15, 18, 20, 25 MeV/A
- Most central collisions
- Three heavy fragments with Z>10 in the exit channel (Z_1>Z_2>Z_3)



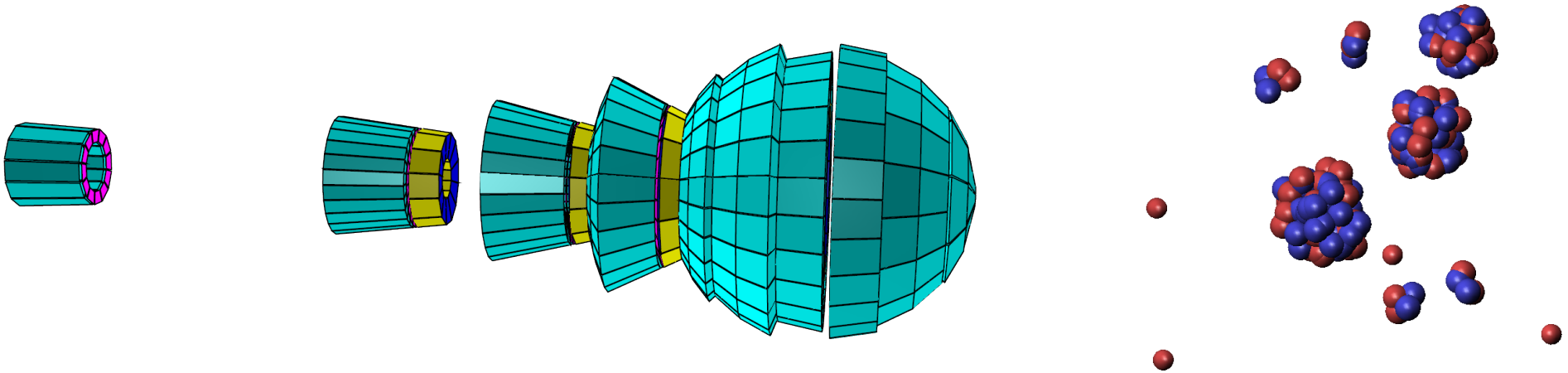
Experimental details

INDRA 4π multidetector

- High granularity with 336 cells
- Charge identification from proton to Uranium up to 250 MeV/A
- Low identification thresholds

Experimental data

- Xe+Sn at 12, 15, 18, 20, 25 MeV/A
- Most central collisions
- Three heavy fragments with Z>10 in the exit channel (Z_1>Z_2>Z_3)

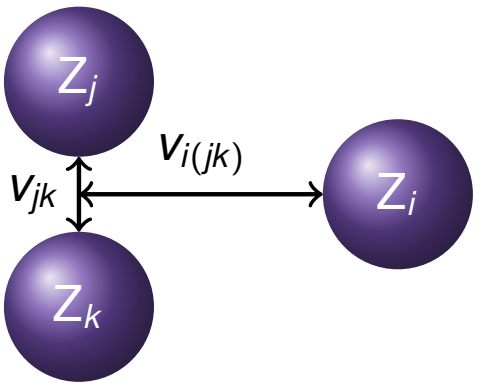


Qualitative characterization of the reaction mechanism

Qualitative characterization of the reaction mechanism

Relative velocity versus fission

- $P_i = \underbrace{(v^{exp}_{i(jk)} - v^{fission}_{i(jk)})^2}_{1^{st}\ step} + \underbrace{(v^{exp}_{jk} - v^{fission}_{jk})^2}_{2^{nd}\ step}$



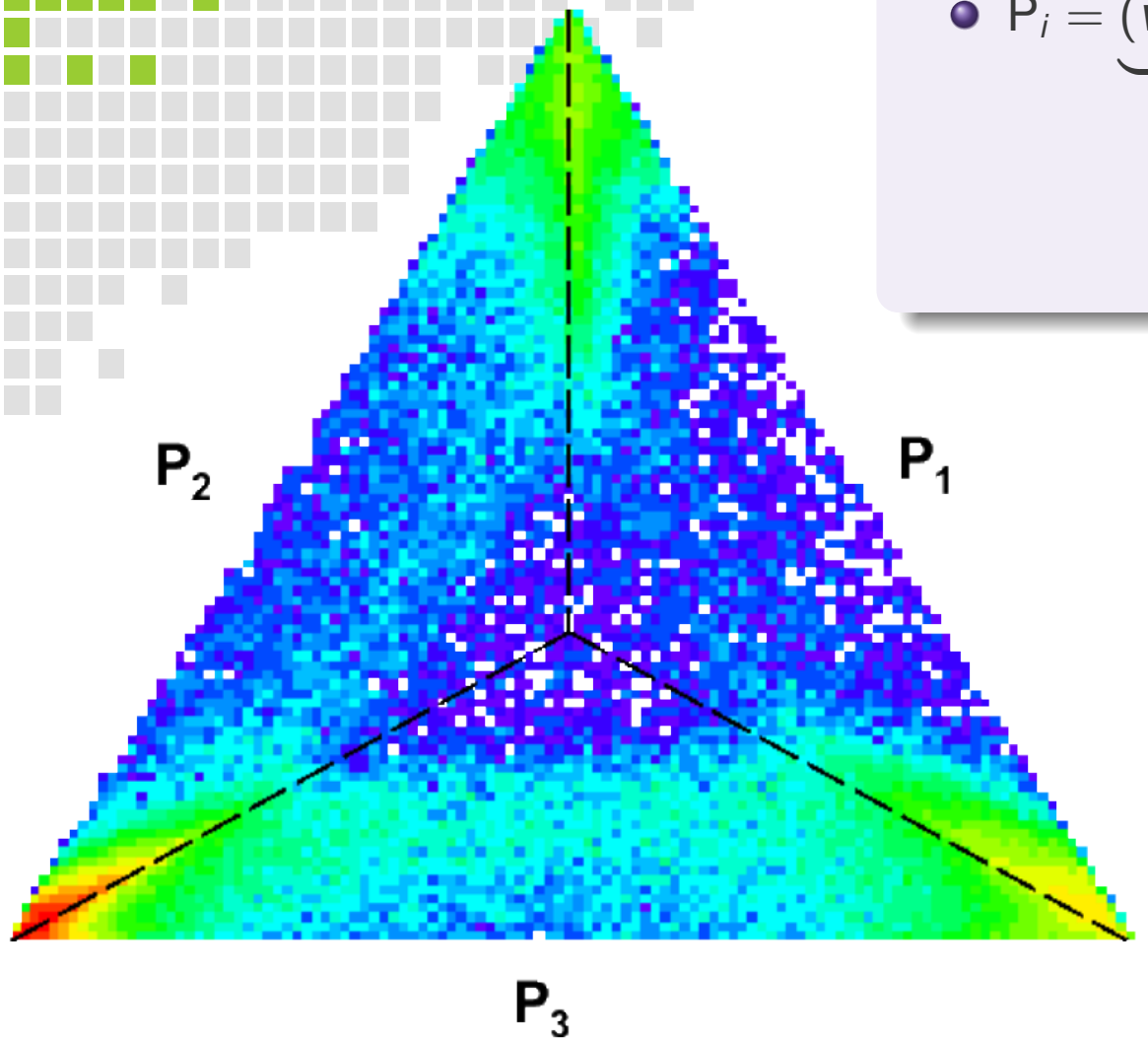
G.Bizard et al. PLB **276** (1992) 413

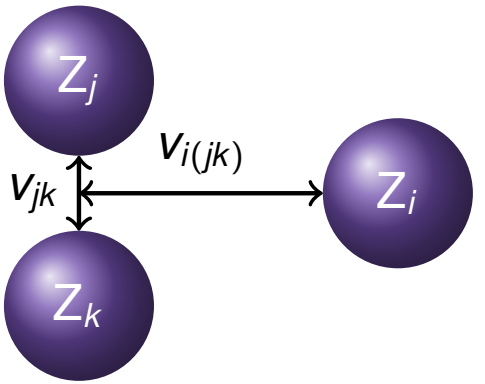
V.E.Viola et al. PRC **31** (1985) 1550

Qualitative characterization of the reaction mechanism

Relative velocity versus fission

- $P_i = \underbrace{(v^{exp}_{i(jk)} - v^{fission}_{i(jk)})^2}_{1^{st}\ step} + \underbrace{(v^{exp}_{jk} - v^{fission}_{jk})^2}_{2^{nd}\ step}$





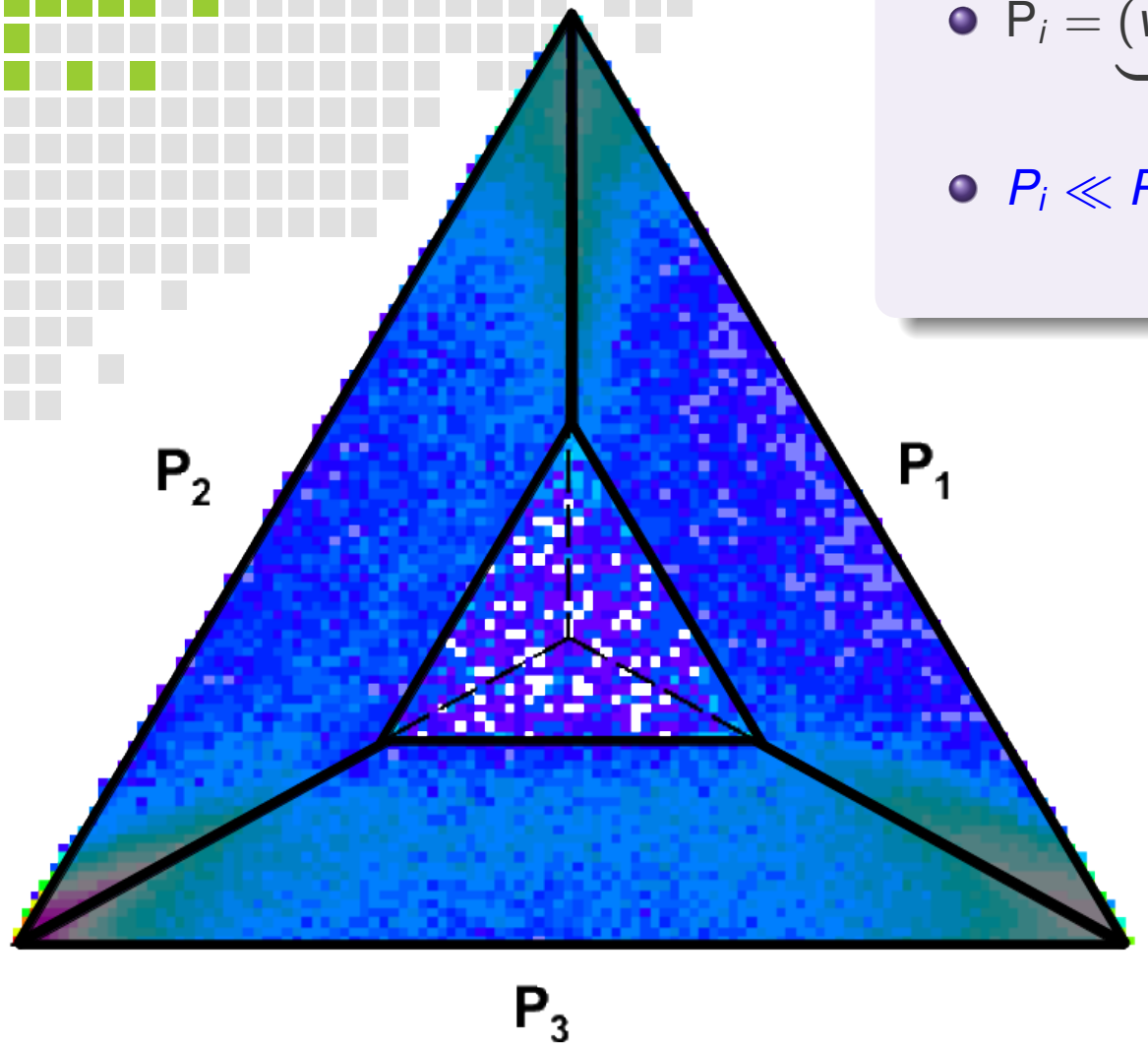
G.Bizard et al. PLB **276** (1992) 413

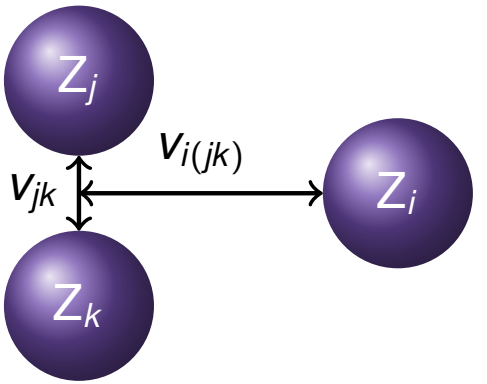
V.E.Viola et al. PRC **31** (1985) 1550

Qualitative characterization of the reaction mechanism

Relative velocity versus fission

- $P_i = \underbrace{(v_{i(jk)}^{exp} - v_{i(jk)}^{fission})^2}_{1^{st}\ \text{step}} + \underbrace{(v_{jk}^{exp} - v_{jk}^{fission})^2}_{2^{nd}\ \text{step}}$
- $P_i \ll P_j, P_k$: sequential break-up





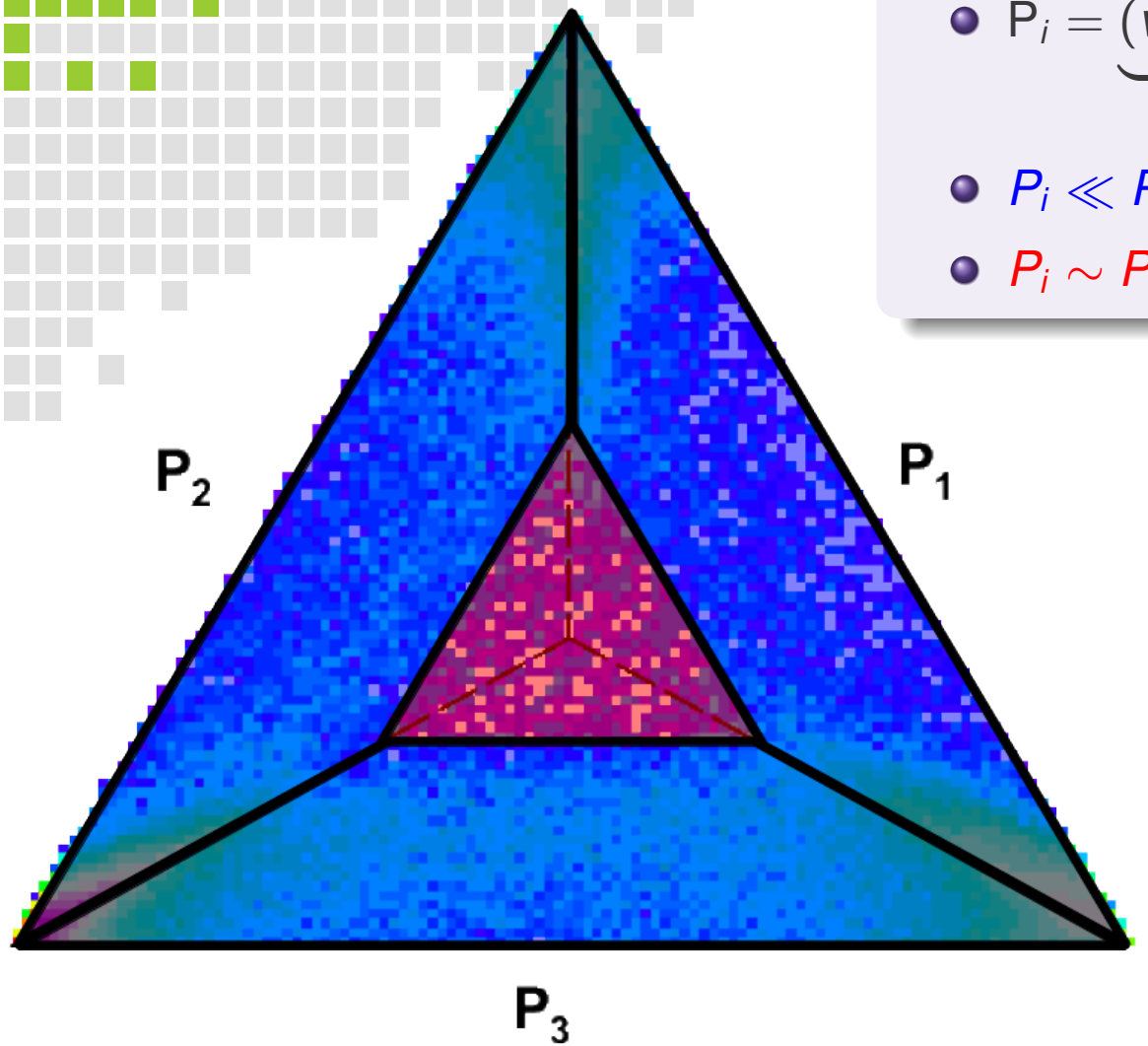
G.Bizard et al. PLB **276** (1992) 413

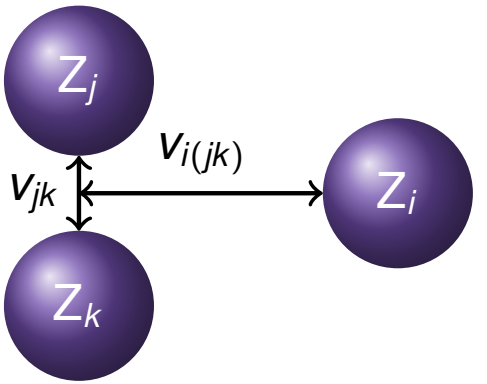
V.E.Viola et al. PRC **31** (1985) 1550

Qualitative characterization of the reaction mechanism

Relative velocity versus fission

- $P_i = \underbrace{(v^{exp}_{i(jk)} - v^{fission}_{i(jk)})^2}_{1^{st}\ step} + \underbrace{(v^{exp}_{jk} - v^{fission}_{jk})^2}_{2^{nd}\ step}$
- $P_i \ll P_j, P_k$: sequential break-up
- $P_i \sim P_j \sim P_k$: simultaneous break-up

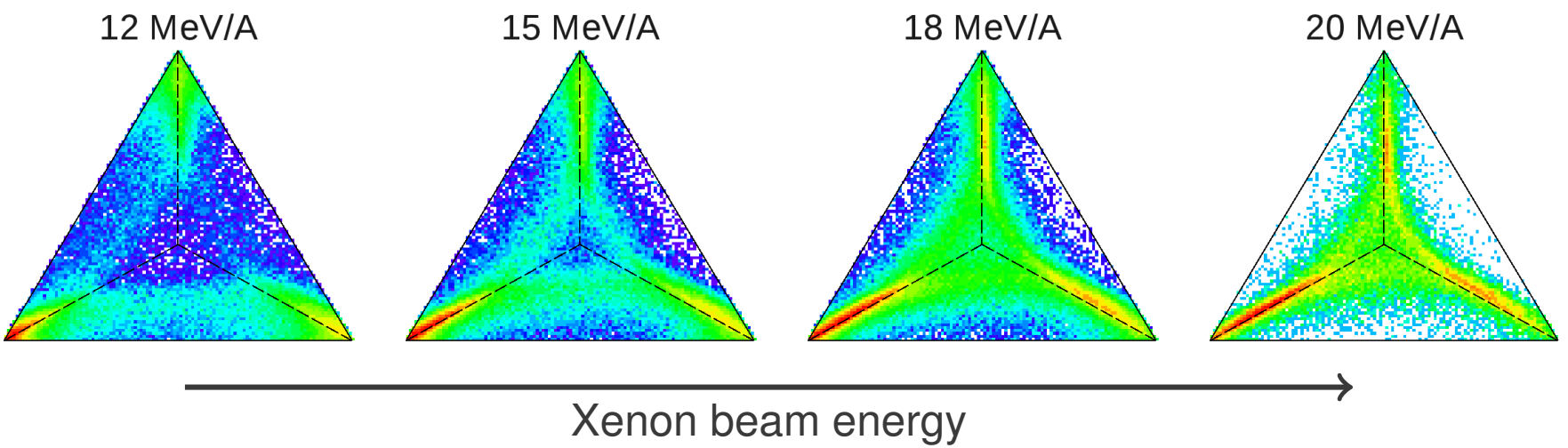




G.Bizard et al. PLB **276** (1992) 413

V.E.Viola et al. PRC **31** (1985) 1550

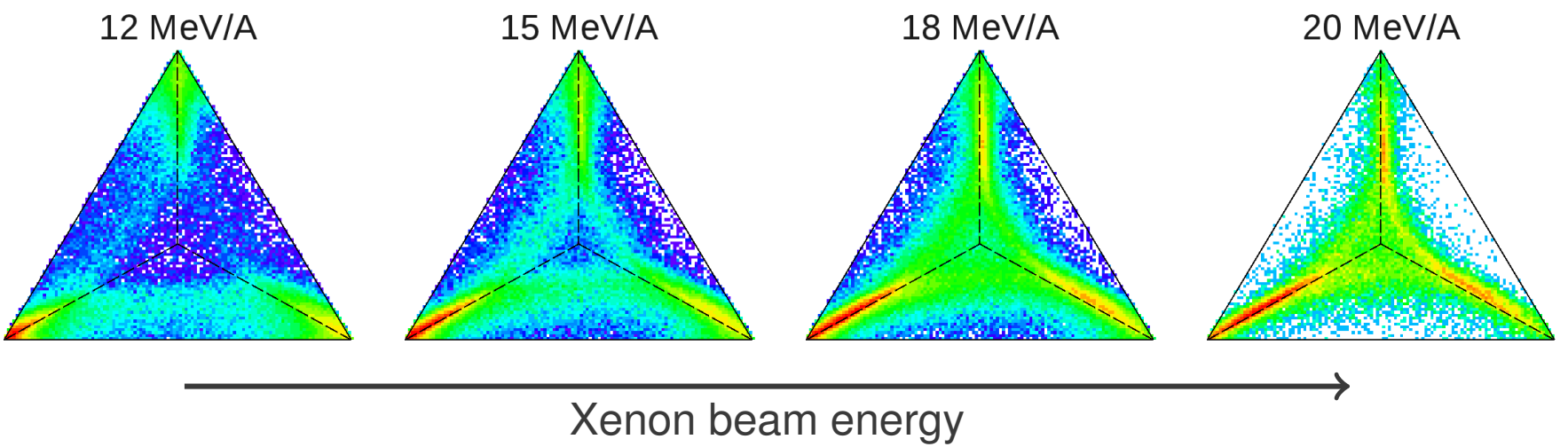
From sequential to simultaneous break-up



From sequential to simultaneous break-up

Lowest beam energy

- Three branches parallel to the edges of the Dalitz plot
- Few events close to the center
- Sequential break-up dominates



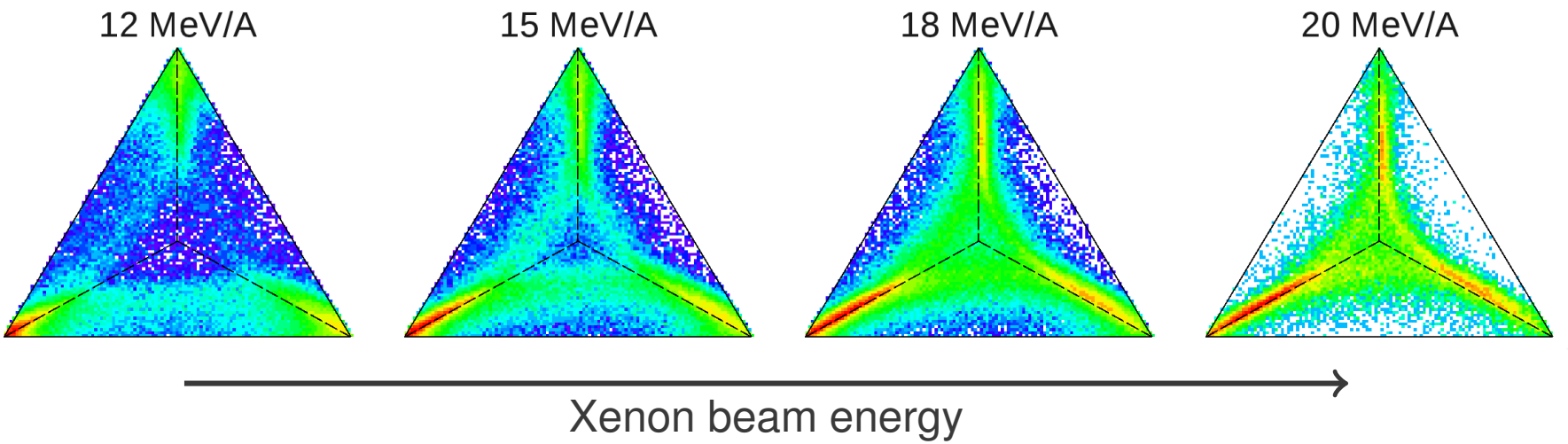
From sequential to simultaneous break-up

Lowest beam energy

- Three branches parallel to the edges of the Dalitz plot
- Few events close to the center
- Sequential break-up dominates

Increasing beam energy

- Three branches still present
- Closer and closer to the center
- Evolution from successive splittings to simultaneous fragmentation



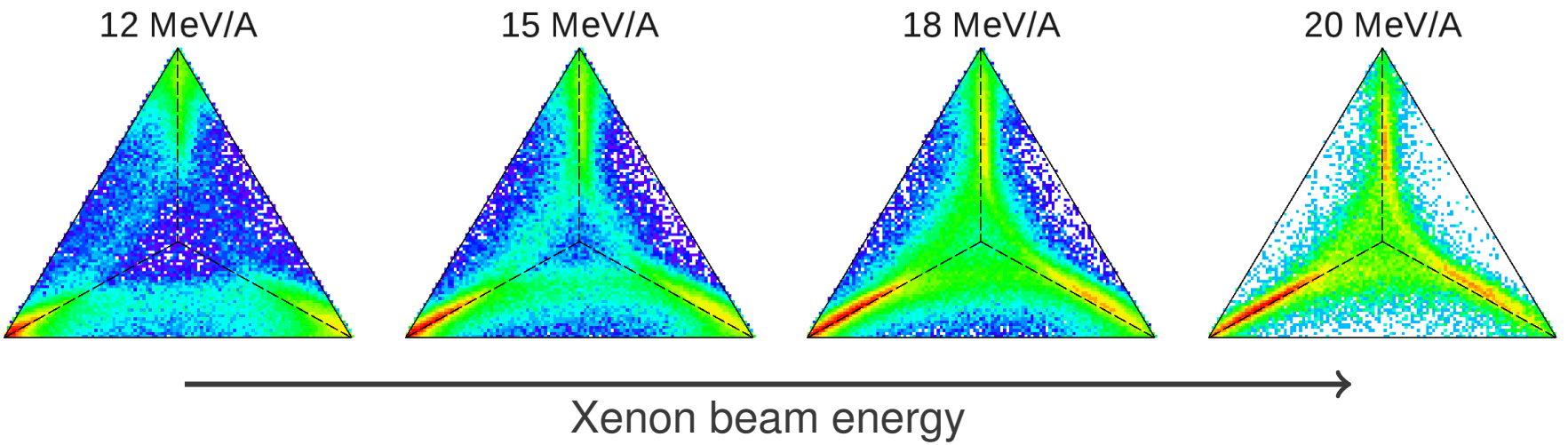
From sequential to simultaneous break-up

Lowest beam energy

- Three branches parallel to the edges of the Dalitz plot
- Few events close to the center
- Sequential break-up dominates

Increasing beam energy

- Three branches still present
- Closer and closer to the center
- Evolution from successive splittings to simultaneous fragmentation



Evolution of the involved time scale

- To estimate the time scale we must establish the sequence of splittings

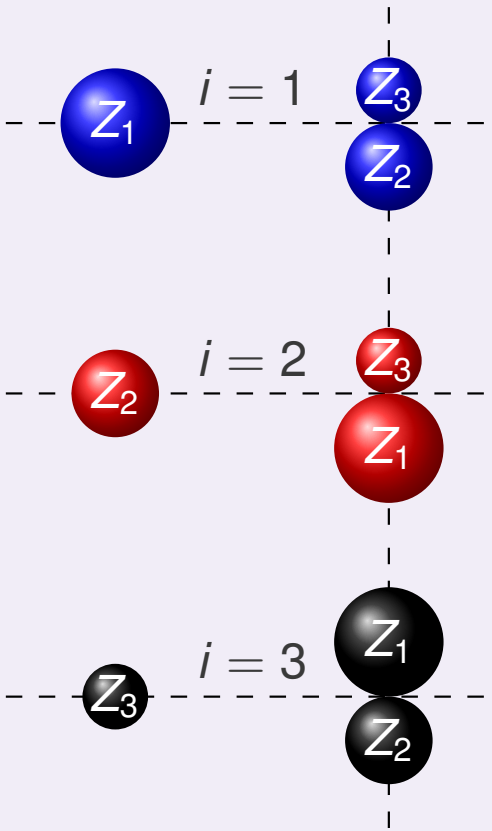
Identification of the sequence of splittings

Hypothesis

- Fragments production : 2 successive splittings

Identification of the sequence of splittings

Splitting sequences

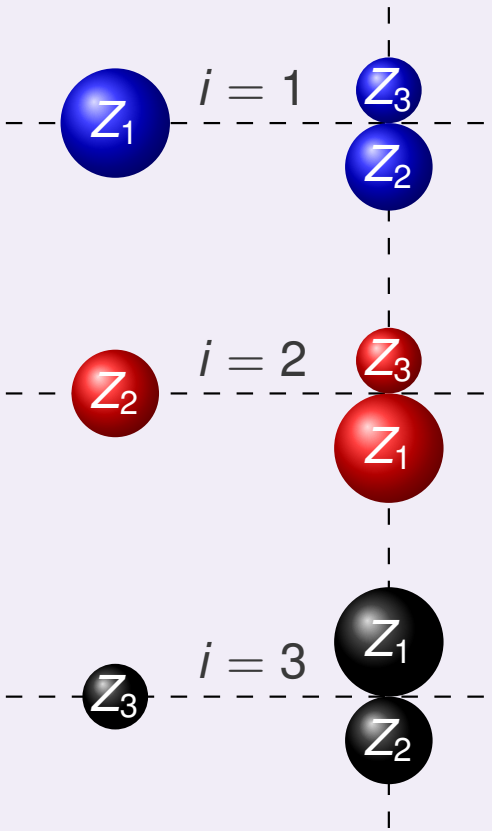


Hypothesis

- Fragments production : 2 successive splittings
- Three possible sequences of splittings

Identification of the sequence of splittings

Splitting sequences



Hypothesis

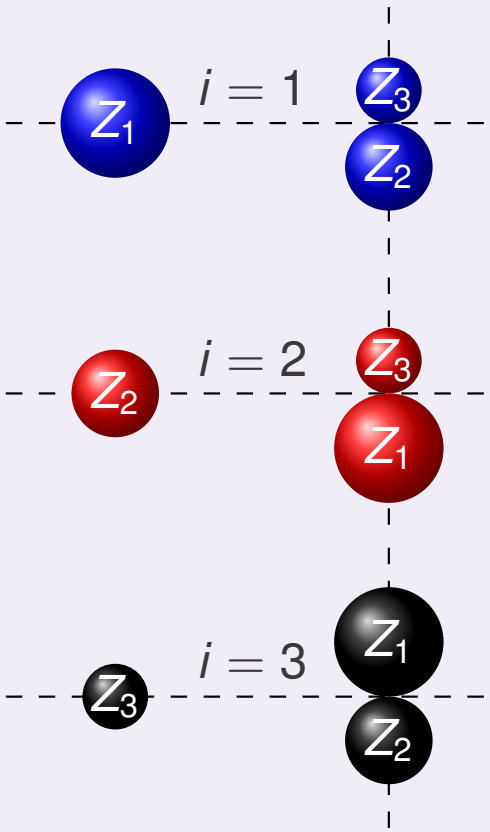
- Fragments production : 2 successive splittings
- Three possible sequences of splittings

Relative velocities versus fission

- Relative velocity of each pair of fragments compared to fission from Viola systematics

Identification of the sequence of splittings

Splitting sequences



Hypothesis

- Fragments production : 2 successive splittings
- Three possible sequences of splittings

Relative velocities versus fission

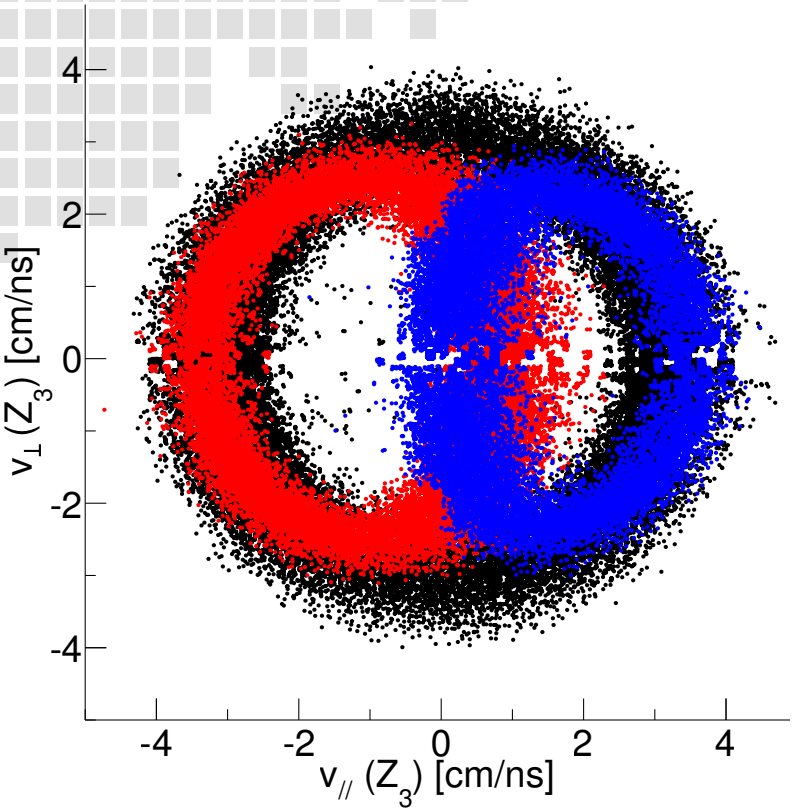
- Relative velocity of each pair of fragments compared to fission from Viola systematics

Minimization procedure

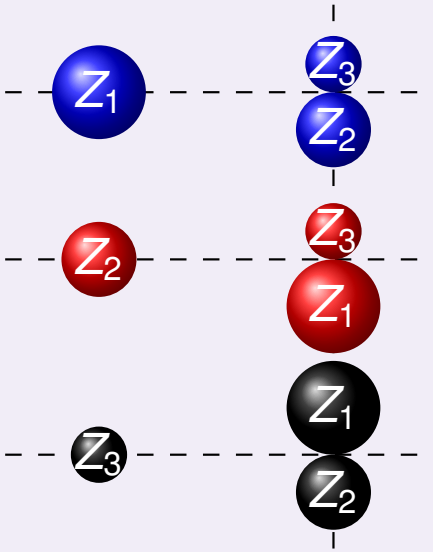
- $\chi_i = (v_{jk}^{exp} - v_{jk}^{viola})^2$: measure the compatibility of an event with the sequence i (χ_1, χ_2, χ_3)
- The smallest χ_i determines the sequence i

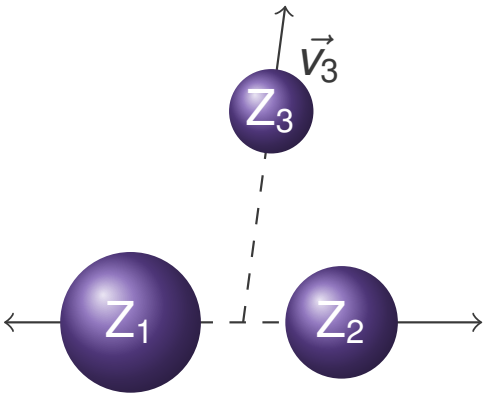
Now we know what happened event by event !

Now we know what happened event by event !

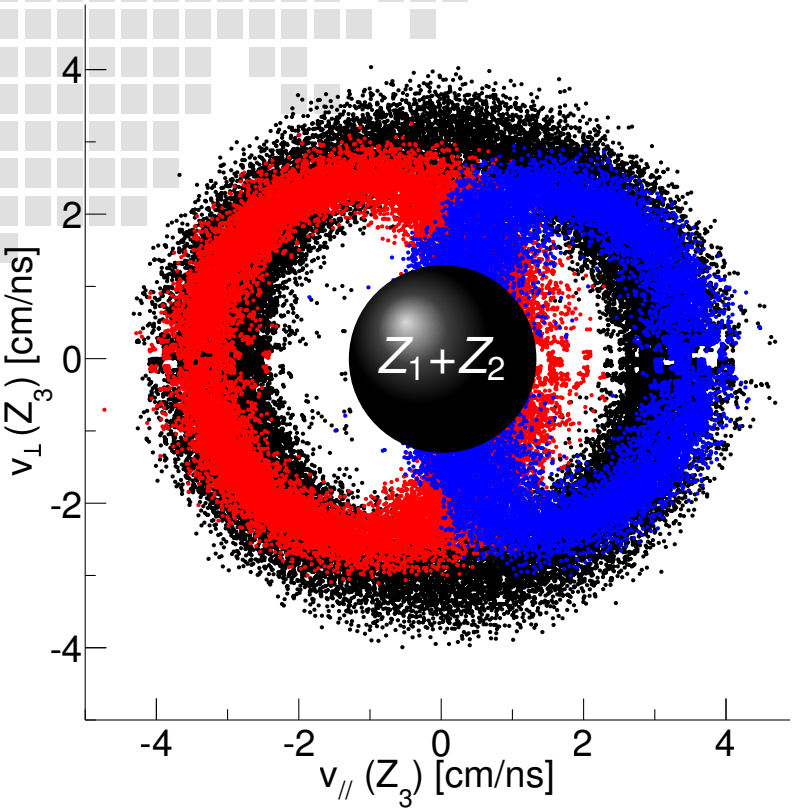


Sequences

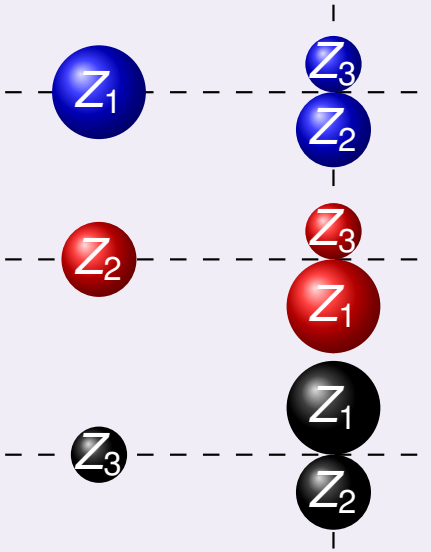


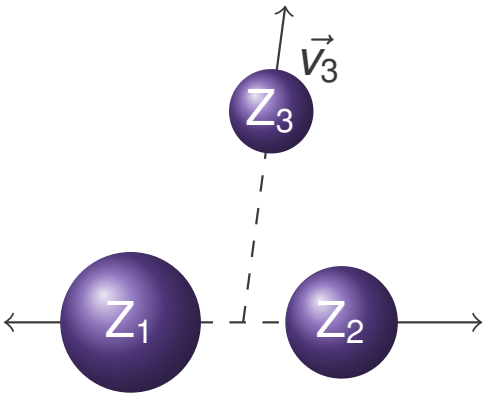


Now we know what happened event by event !

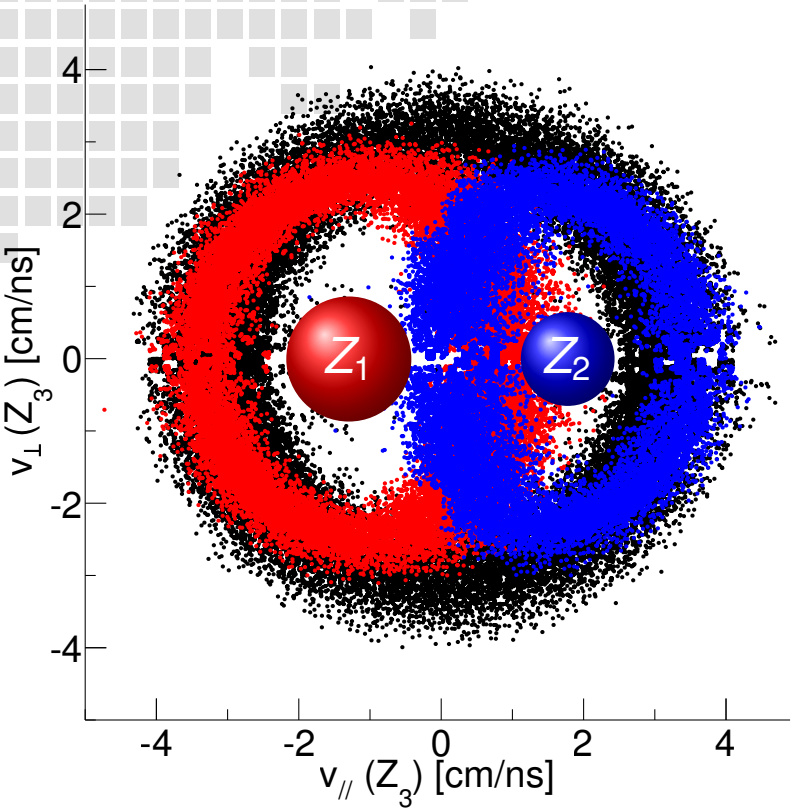


Sequences

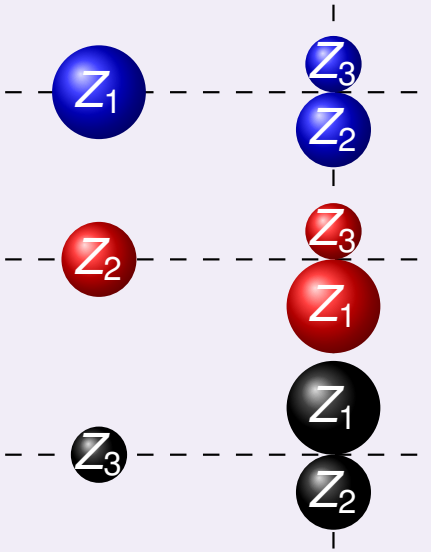


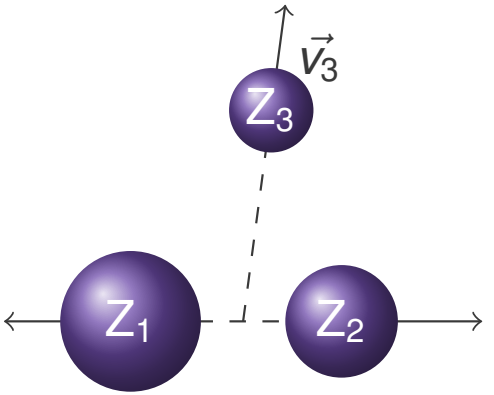


Now we know what happened event by event !



Sequences

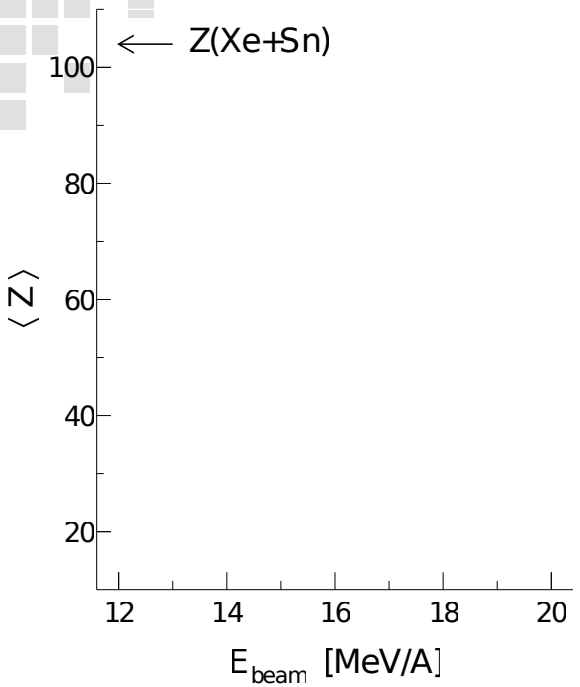


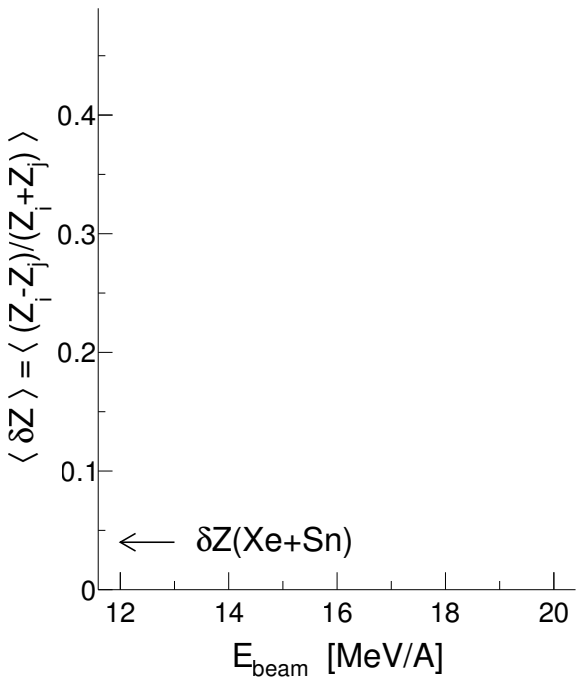


Reconstruction of the two steps

Fragment sorting and incomplete fusion

- Fragments sorted according to the sequence and the two steps are reconstructed



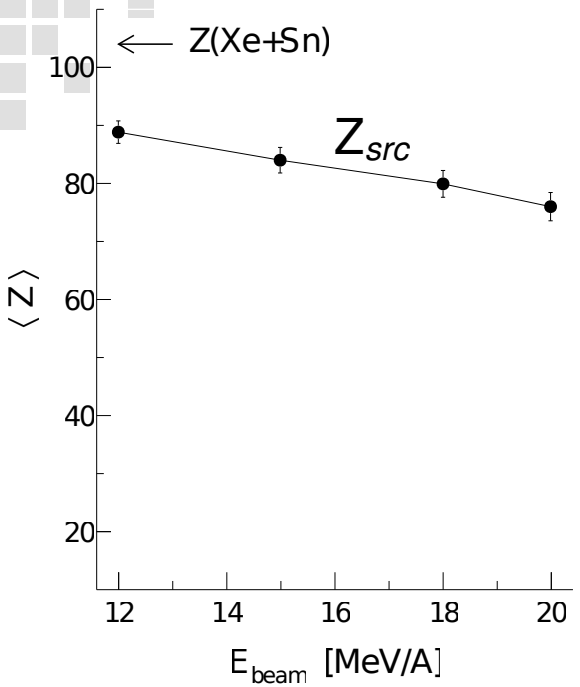


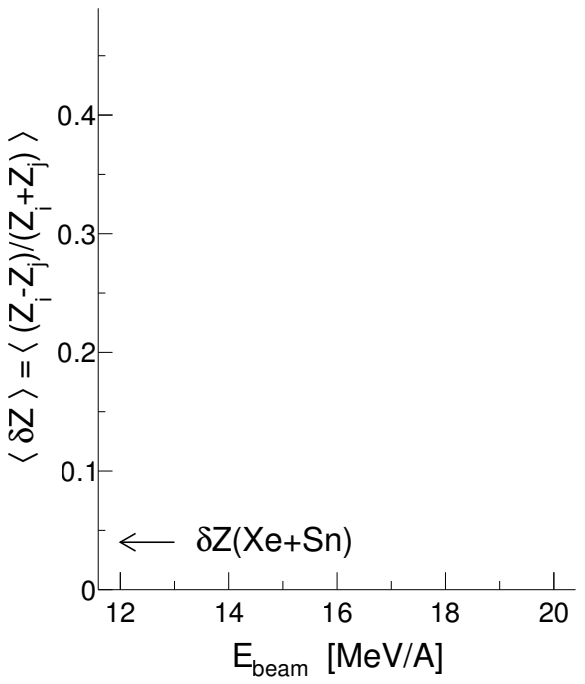
Scenario

Reconstruction of the two steps

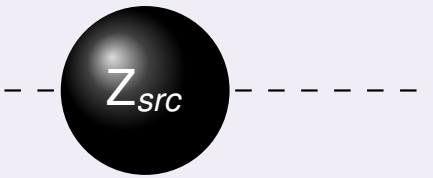
Fragment sorting and incomplete fusion

- Fragments sorted according to the sequence and the two steps are reconstructed





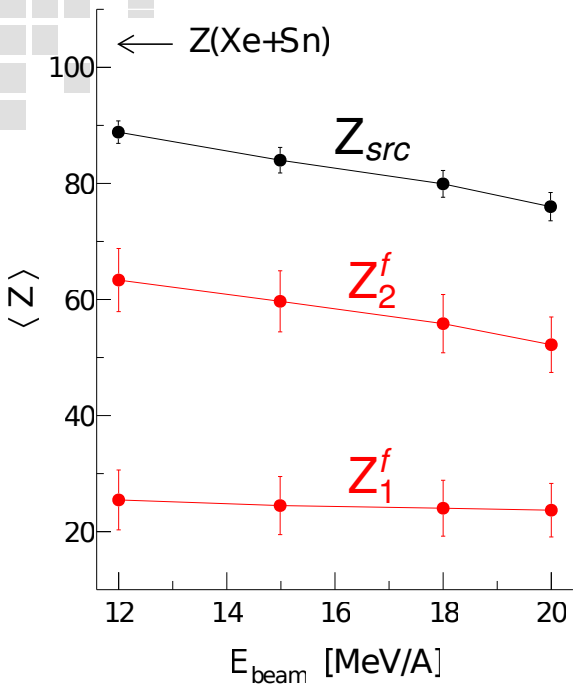
Scenario

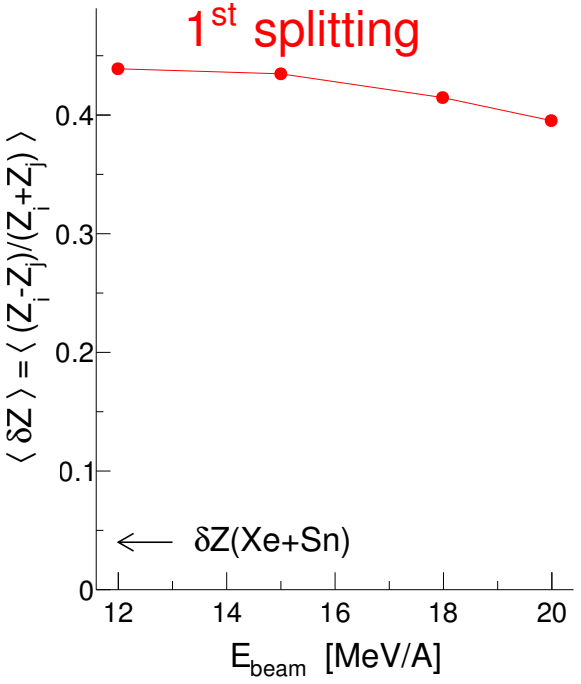


Reconstruction of the two steps

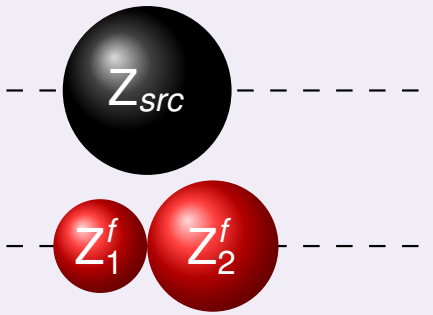
Fragment sorting and incomplete fusion

- Fragments sorted according to the sequence and the two steps are reconstructed





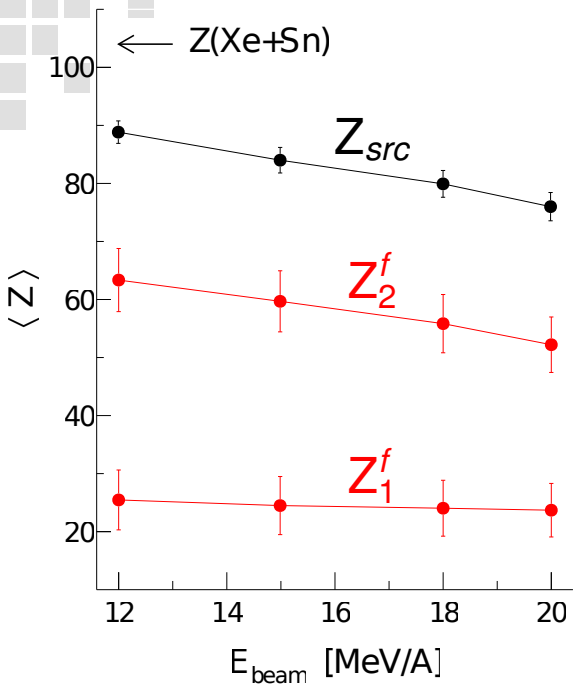
Scenario

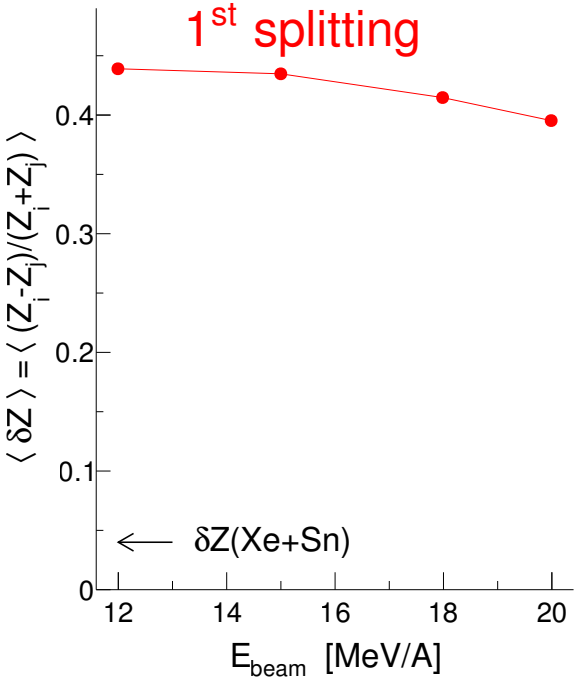


Reconstruction of the two steps

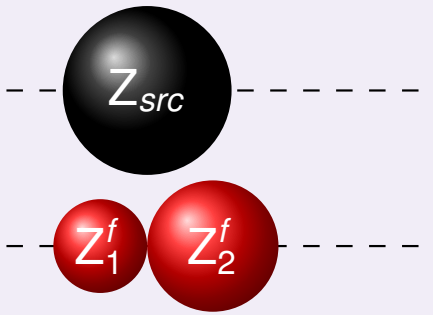
Fragment sorting and incomplete fusion

- Fragments sorted according to the sequence and the two steps are reconstructed
- First splitting very asymmetric ($\delta Z \sim 0.44 \gg \delta Z(\mathrm{Xe+Sn})$)





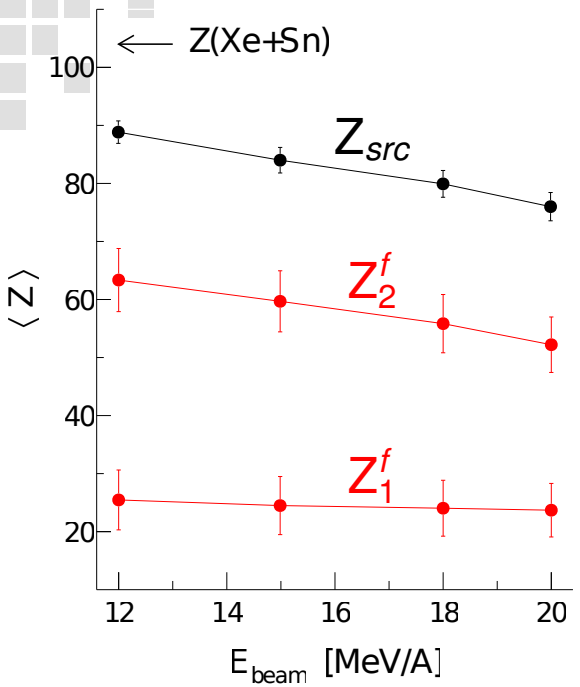
Scenario

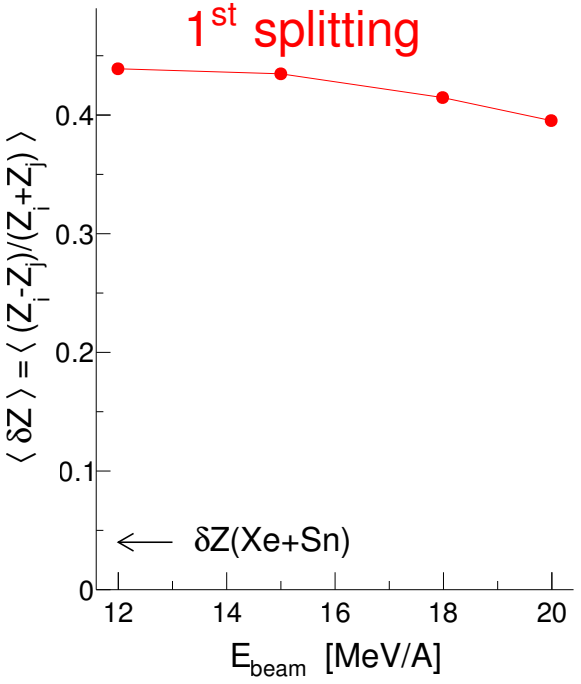


Reconstruction of the two steps

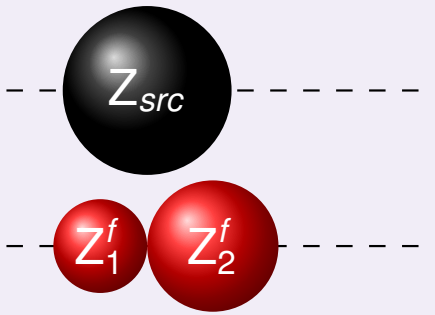
Fragment sorting and incomplete fusion

- Fragments sorted according to the sequence and the two steps are reconstructed
- First splitting very asymmetric ($\delta Z \sim 0.44 \gg \delta Z(\mathrm{Xe+Sn})$)
- The memory of the entrance channel is lost : incomplete fusion achieved





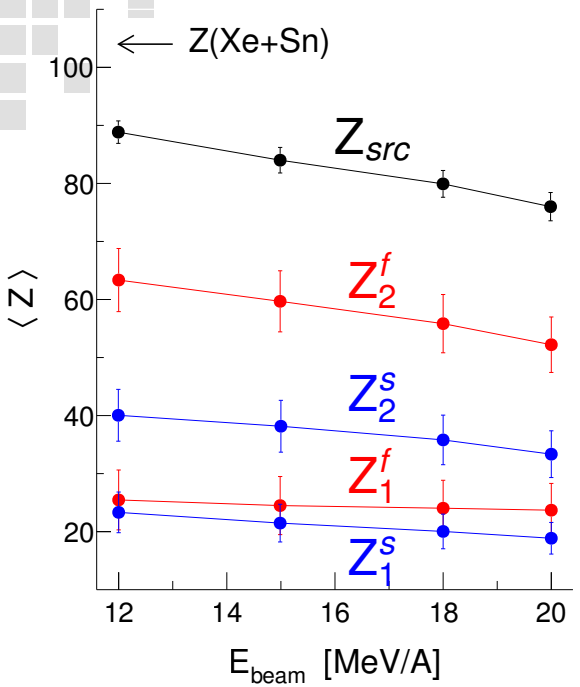
Scenario

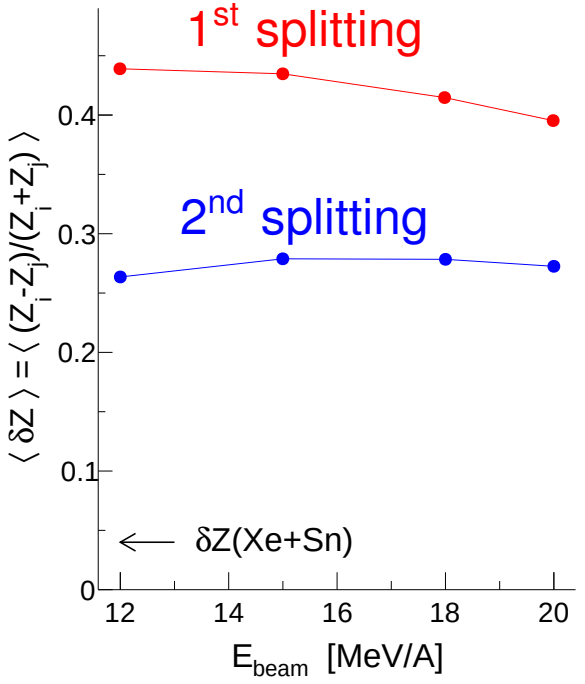


Reconstruction of the two steps

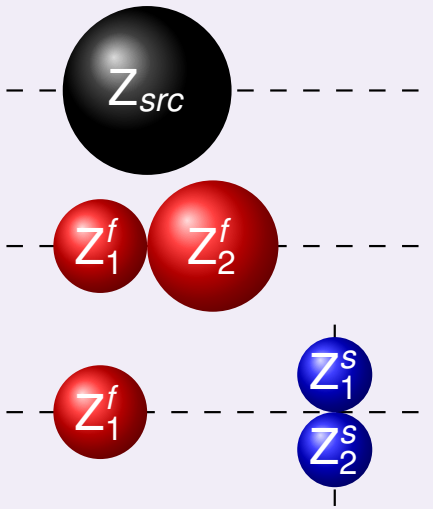
Fragment sorting and incomplete fusion

- Fragments sorted according to the sequence and the two steps are reconstructed
- First splitting very asymmetric ($\delta Z \sim 0.44 \gg \delta Z(\mathrm{Xe+Sn})$)
- The memory of the entrance channel is lost : incomplete fusion achieved

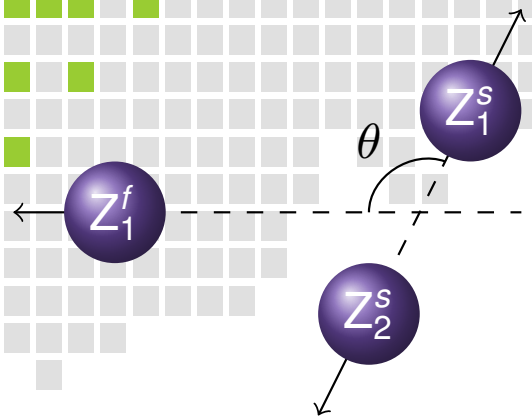




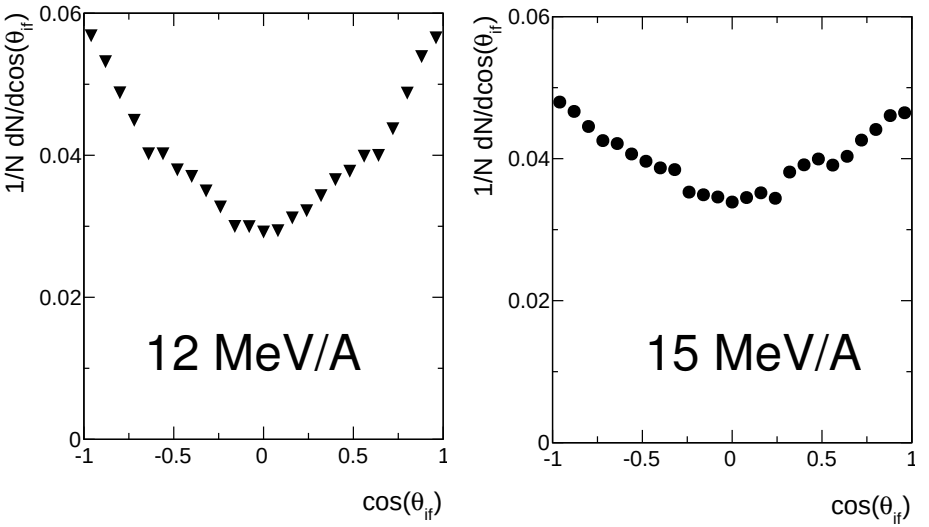
Scenario

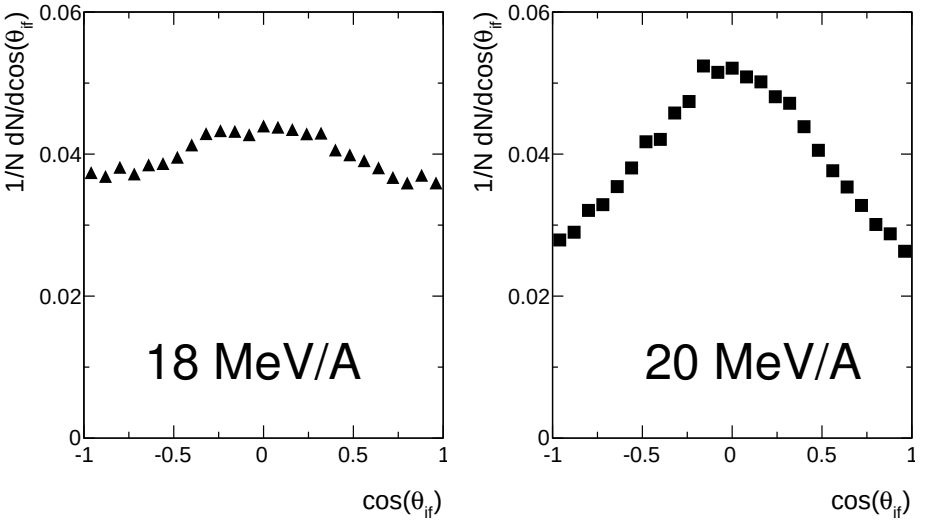


Coulomb proximity effects : angular distribution

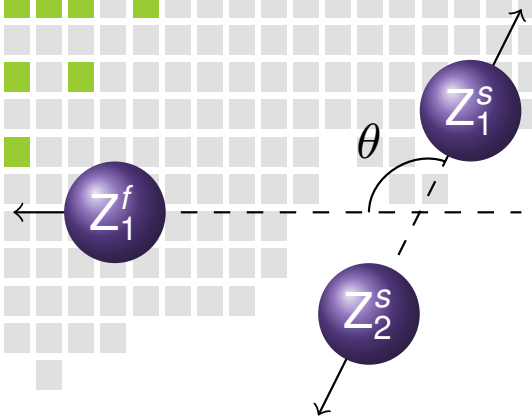


Inter-splitting angle



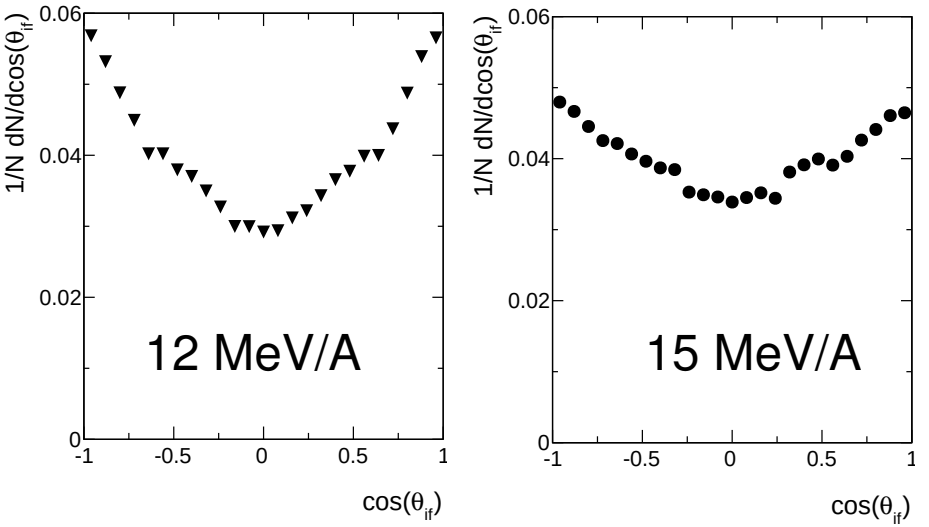


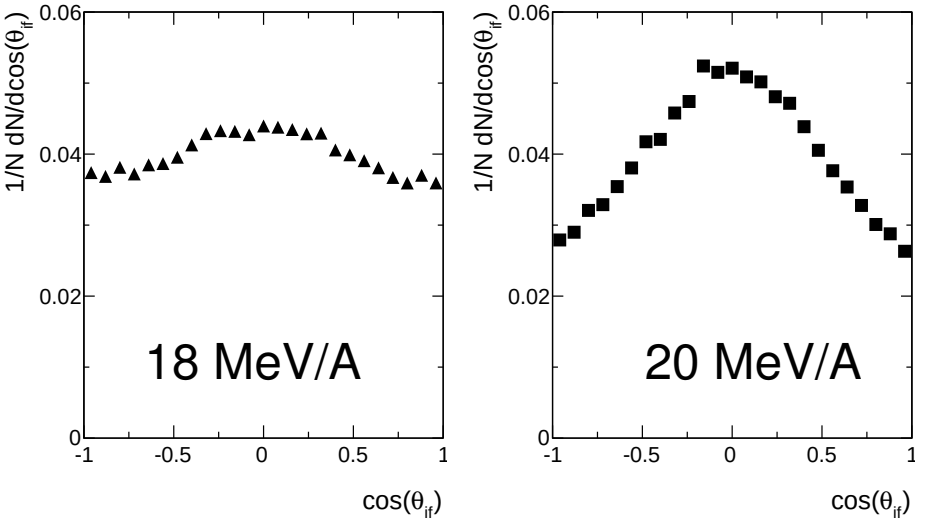
Coulomb proximity effects : angular distribution



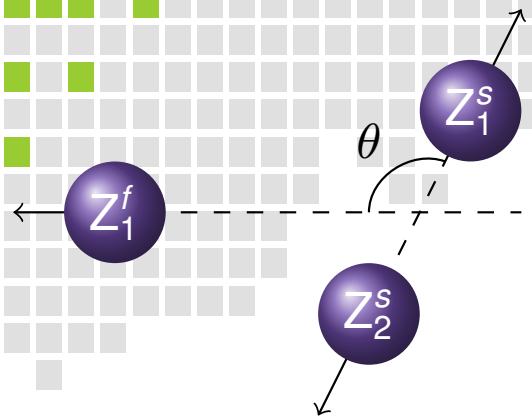
Inter-splitting angle

- 12-15 MeV/A : “U” shape characteristic of fission with angular momentum,



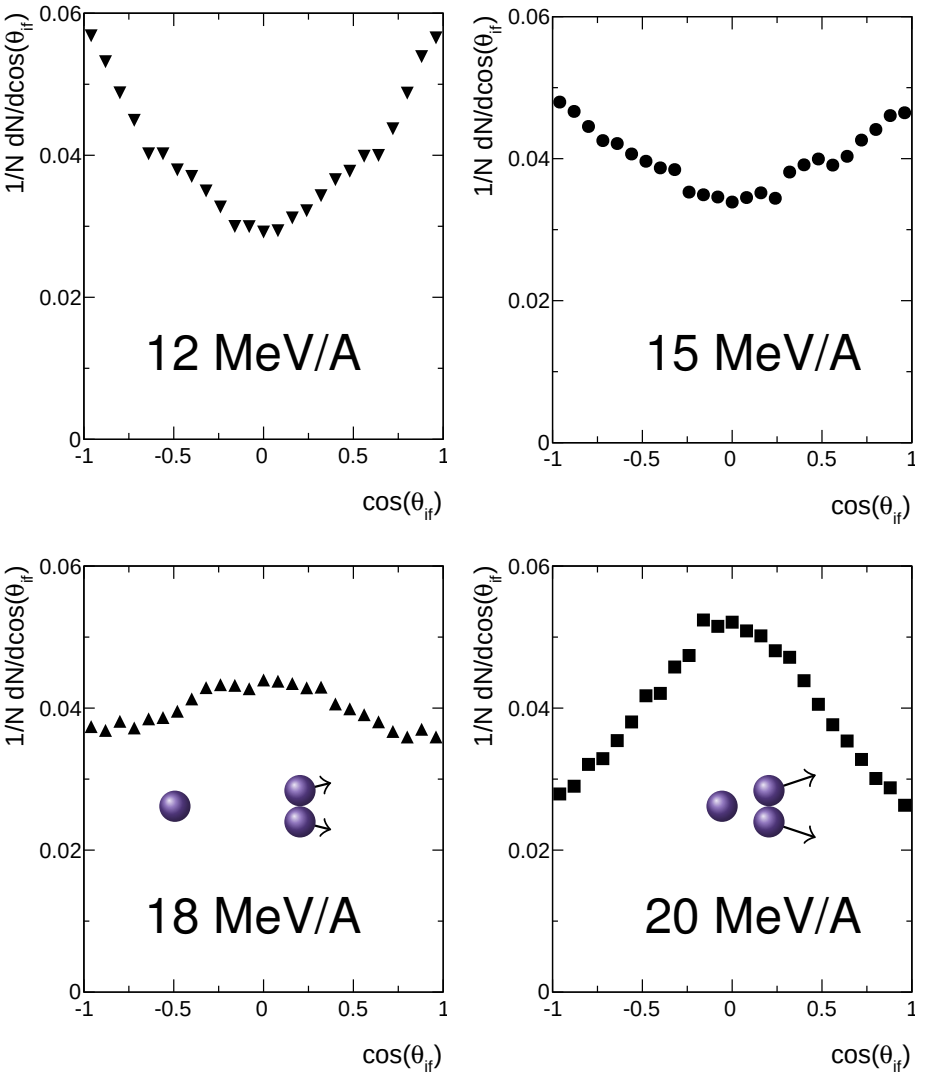


Coulomb proximity effects : angular distribution

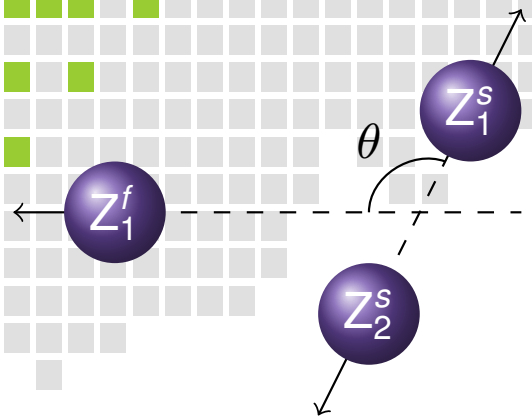


Inter-splitting angle

- 12-15 MeV/A : “U” shape characteristic of fission with angular momentum,
- 18-20 MeV/A : $\theta \sim 90°$ due to the coulomb field of Z_1^f

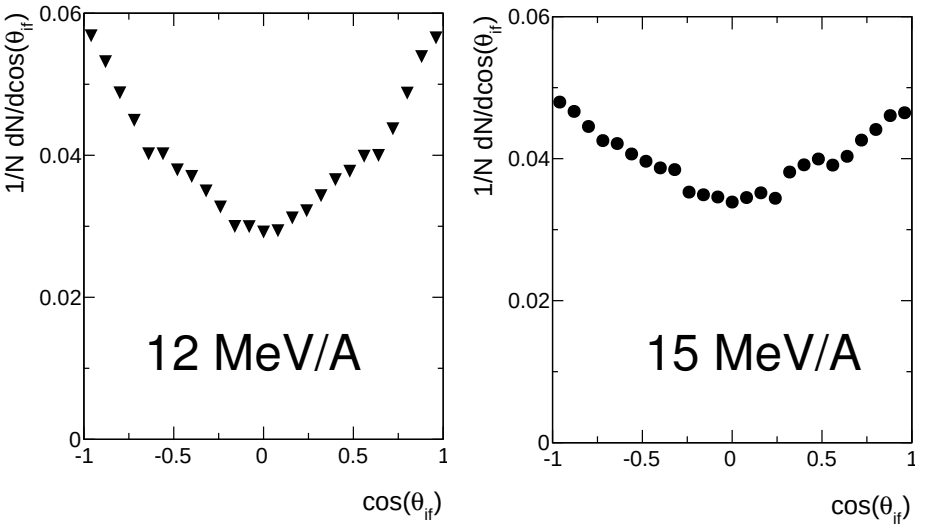


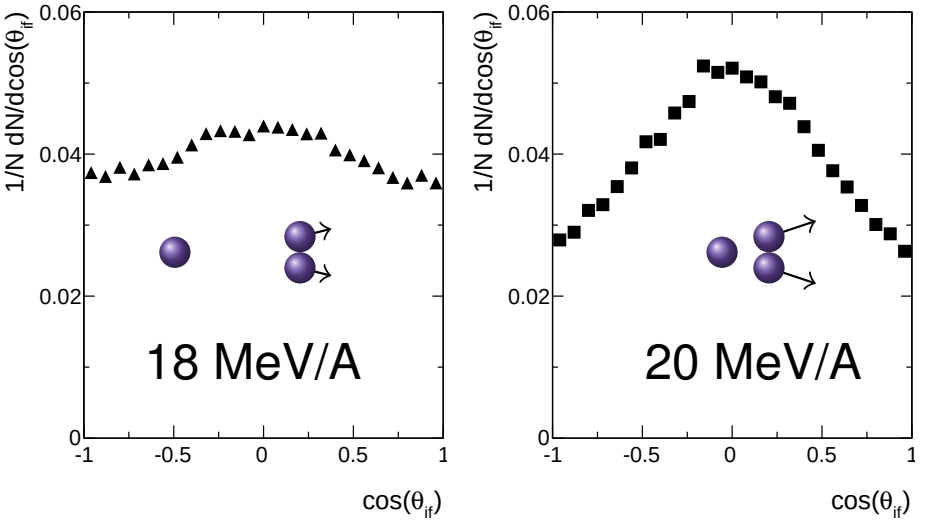
Coulomb proximity effects : angular distribution



Inter-splitting angle

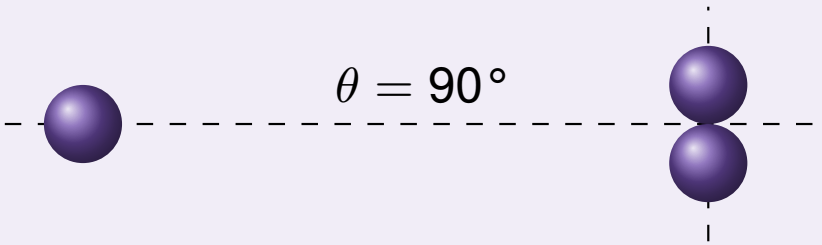
- 12-15 MeV/A : “U” shape characteristic of fission with angular momentum,
- 18-20 MeV/A : $\theta \sim 90°$ due to the coulomb field of Z_1^f
- It indicates a shortening of the inter-splitting time



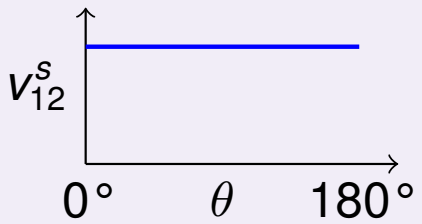


Inter-splitting time by Coulomb chronometry

Long δt

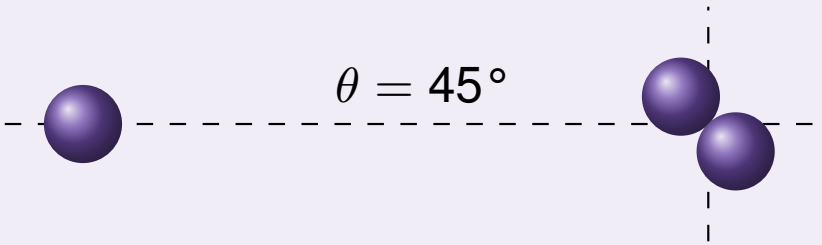


- Second splitting far away from the first emitted fragment
- Relative velocity independent of the inter-splitting angle θ

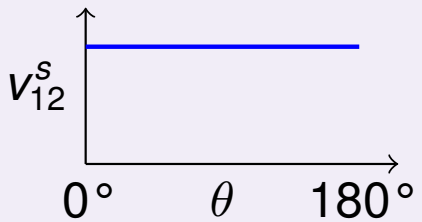


Inter-splitting time by Coulomb chronometry

Long δt

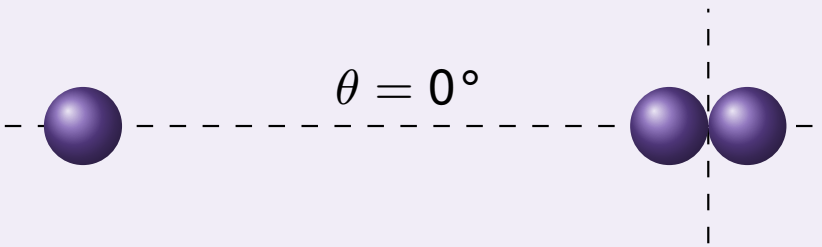


- Second splitting far away from the first emitted fragment
- Relative velocity independent of the inter-splitting angle θ

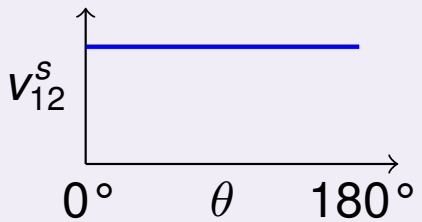


Inter-splitting time by Coulomb chronometry

Long δt



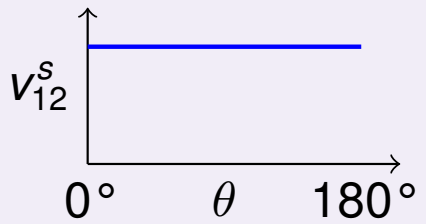
- Second splitting far away from the first emitted fragment
- Relative velocity independent of the inter-splitting angle θ



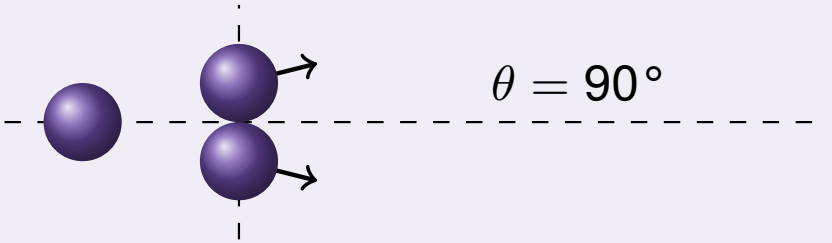
Inter-splitting time by Coulomb chronometry

Long δt

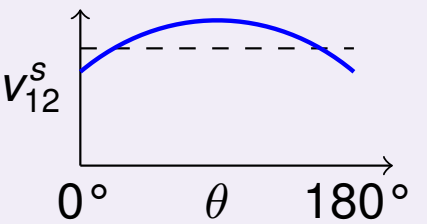
- Second splitting far away from the first emitted fragment
- Relative velocity independent of the inter-splitting angle θ



Short δt



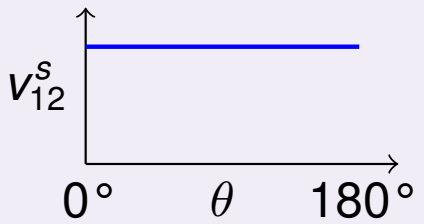
- Trajectories are modified by the Coulomb field of the first emitted fragment
- Relative velocity depend on θ



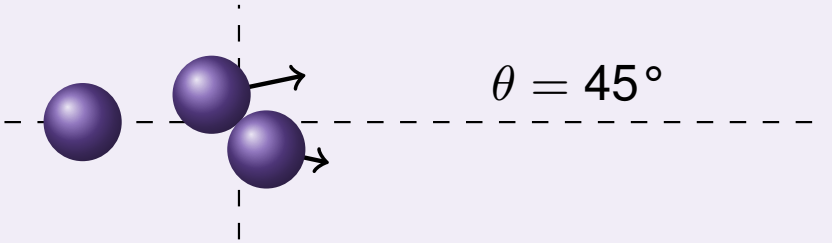
Inter-splitting time by Coulomb chronometry

Long δt

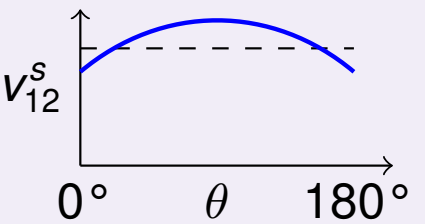
- Second splitting far away from the first emitted fragment
- Relative velocity independent of the inter-splitting angle θ



Short δt



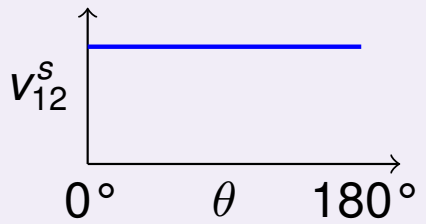
- Trajectories are modified by the Coulomb field of the first emitted fragment
- Relative velocity depend on θ



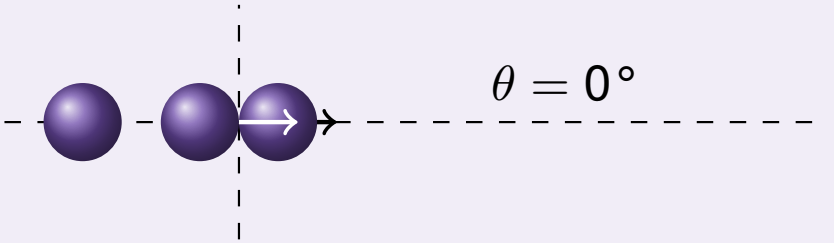
Inter-splitting time by Coulomb chronometry

Long δt

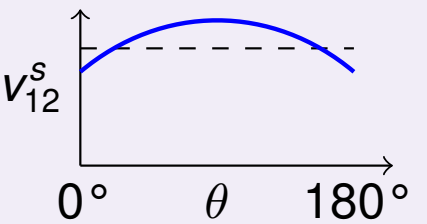
- Second splitting far away from the first emitted fragment
- Relative velocity independent of the inter-splitting angle θ



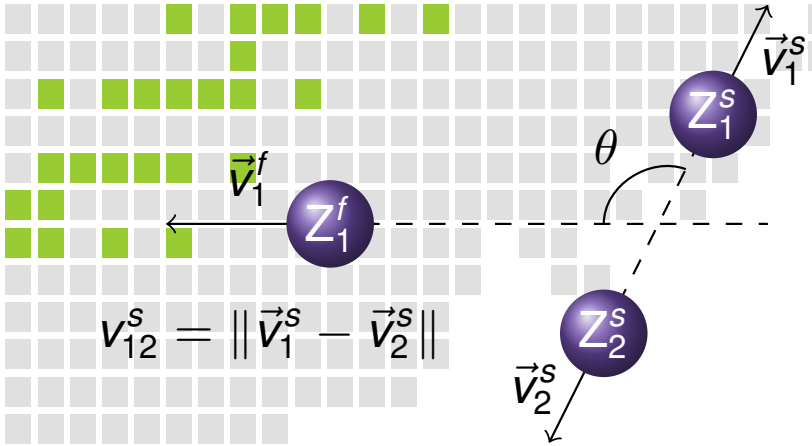
Short δt

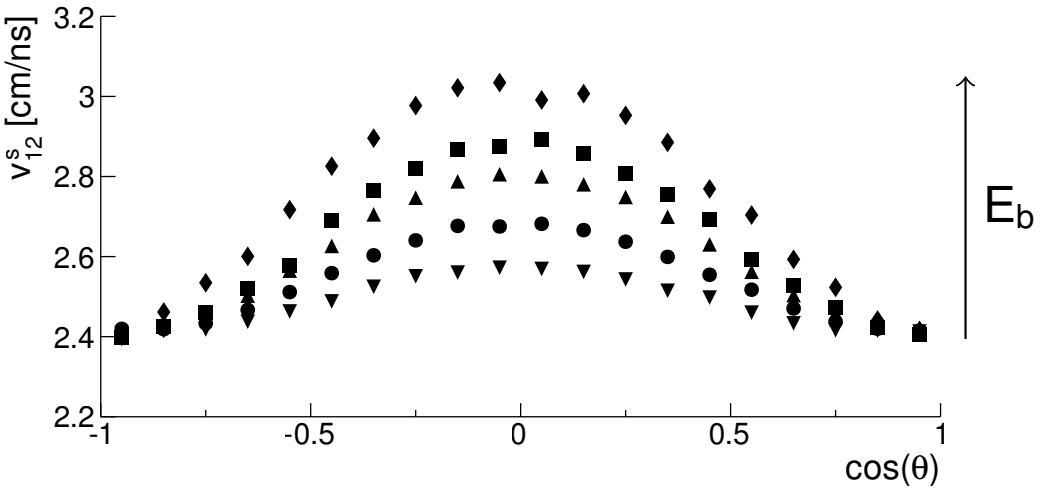


- Trajectories are modified by the Coulomb field of the first emitted fragment
- Relative velocity depend on θ



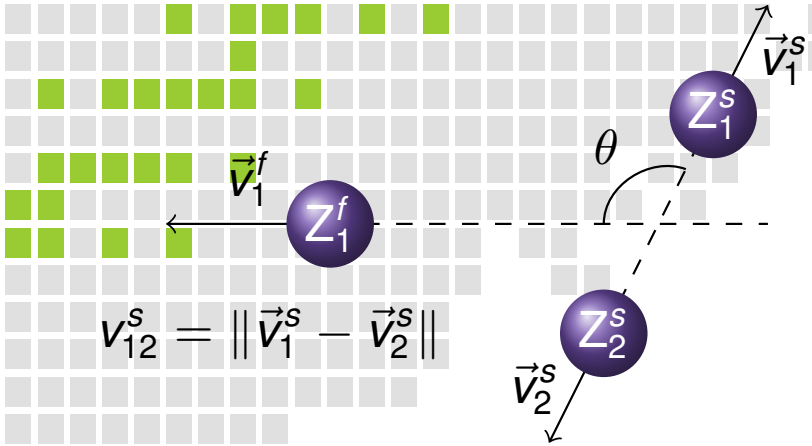
Use of the Coulomb chronometer

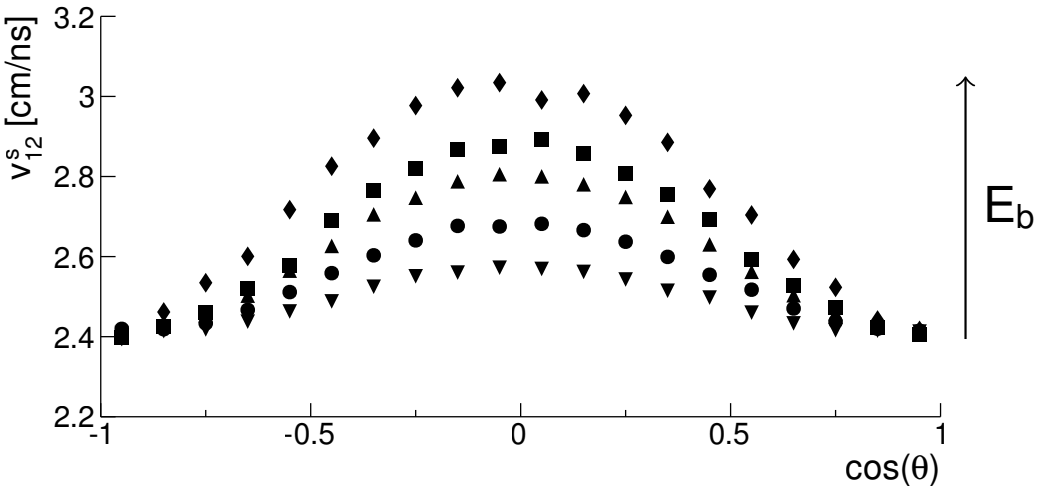




Experimental correlations

Use of the Coulomb chronometer

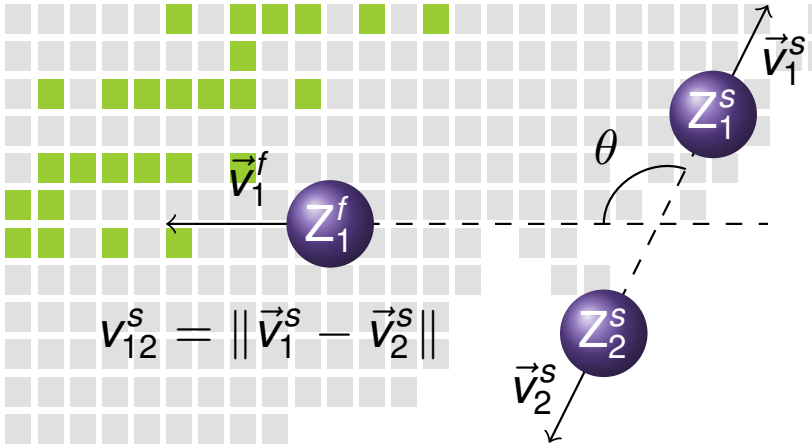


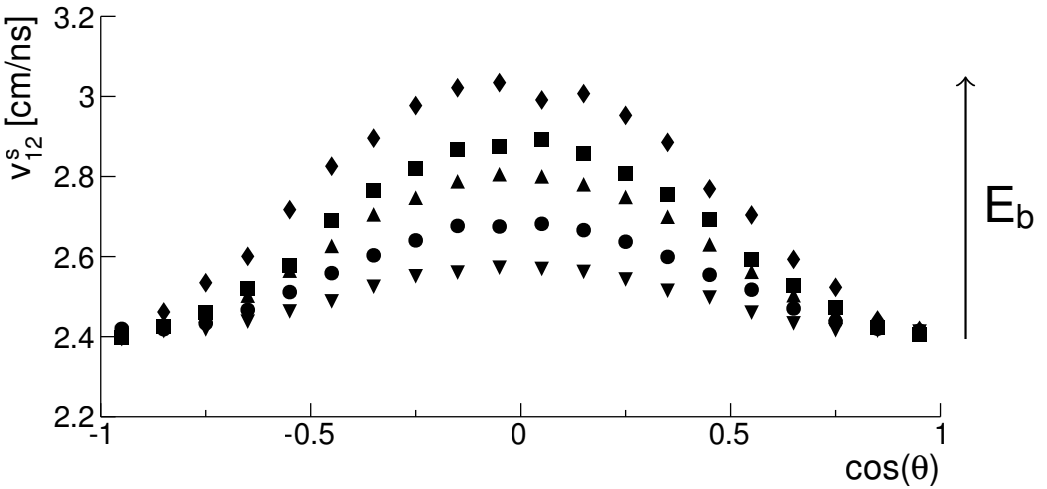


Experimental correlations

- $\langle v_{12}^s \rangle$ maximum for $\theta \sim 90°$

Use of the Coulomb chronometer

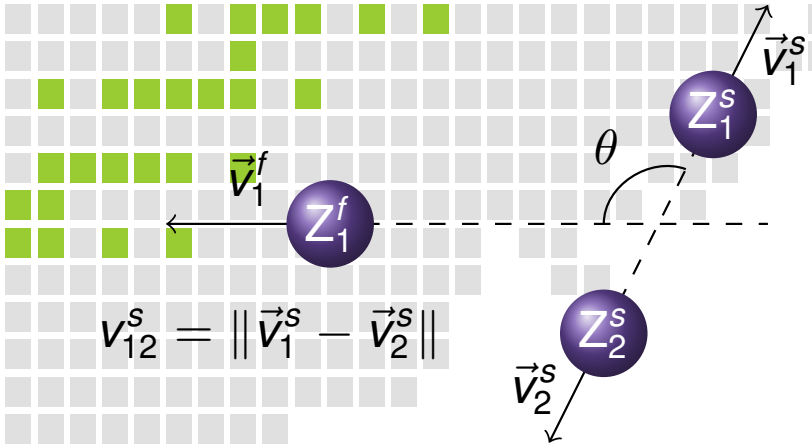




Experimental correlations

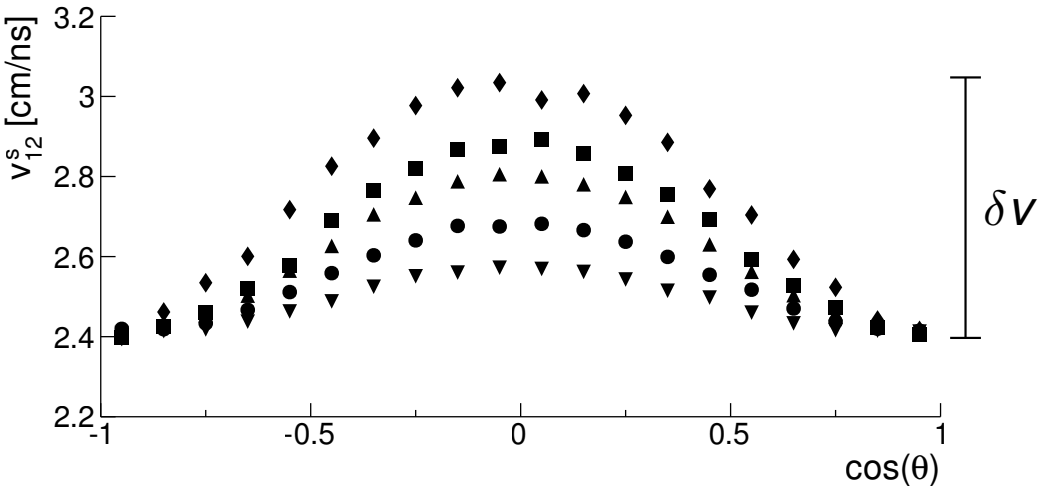
- $\langle v_{12}^s \rangle$ maximum for $\theta \sim 90°$
- This maximum increases when increasing beam energy

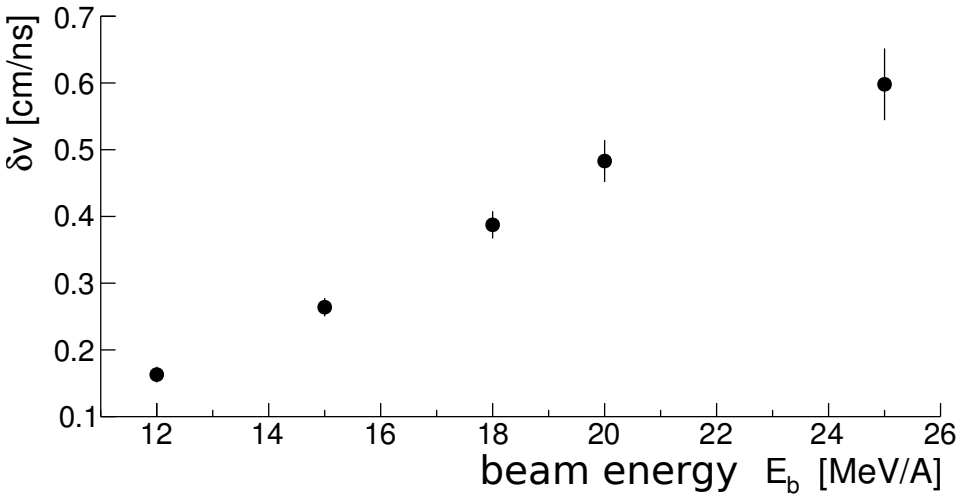
Use of the Coulomb chronometer



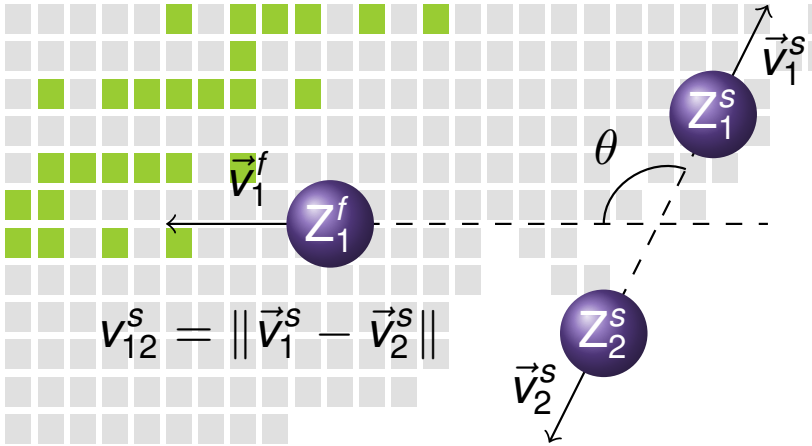
Experimental correlations

- $\langle v_{12}^s \rangle$ maximum for $\theta \sim 90°$
- This maximum increases when increasing beam energy
- Coulomb distortion parameter : $\delta v = v_{12}^s(90°) - v_{12}^s(0°)$



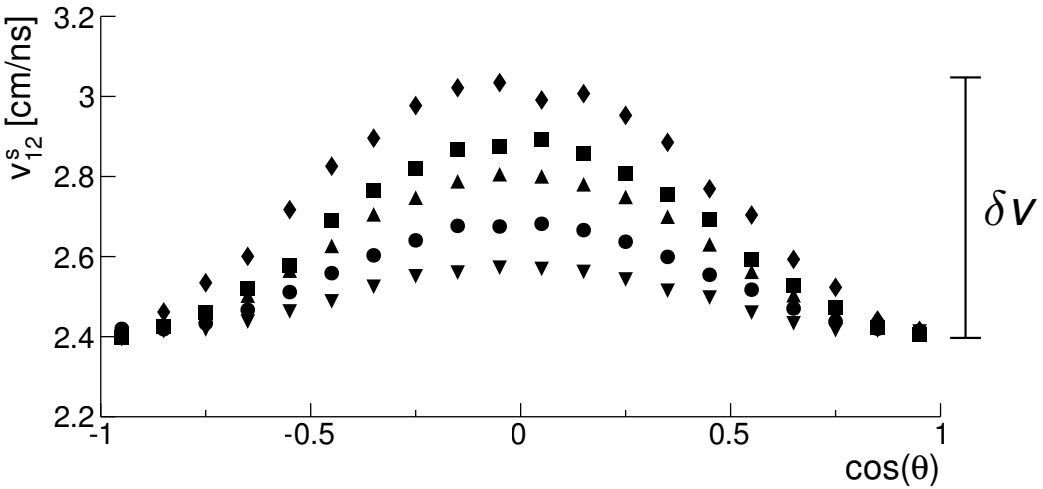


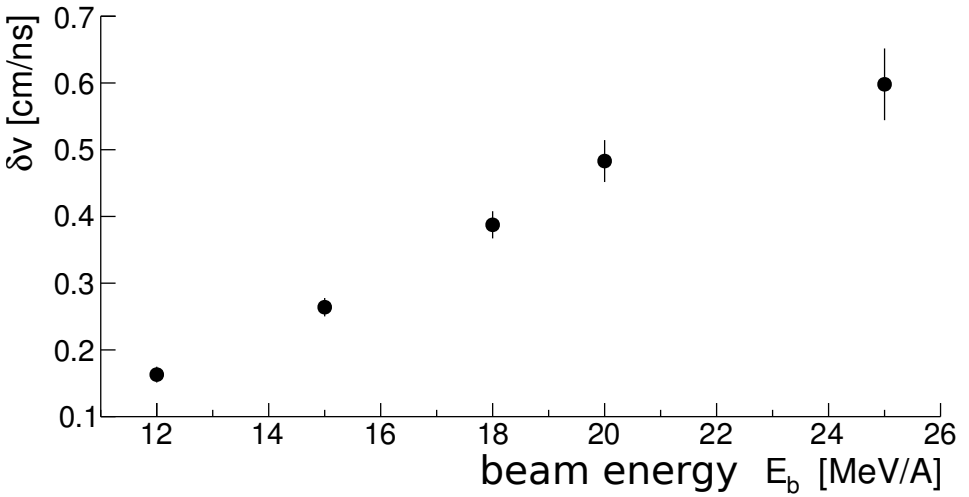
Use of the Coulomb chronometer



Experimental correlations

- $\langle v_{12}^s \rangle$ maximum for $\theta \sim 90°$
- This maximum increases when increasing beam energy
- Coulomb distortion parameter : $\delta v = v_{12}^s(90°) - v_{12}^s(0°)$
- δv and δt can be related with Coulomb trajectory calculation

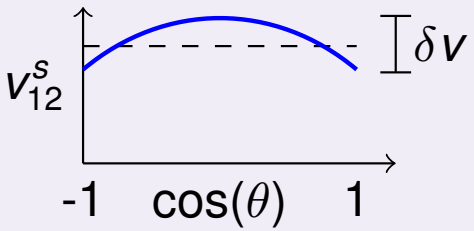


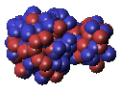


Calibration of the inter-splitting time

Coulomb trajectory calculations

- We calculate δv for different values of the inter-splitting time δt.

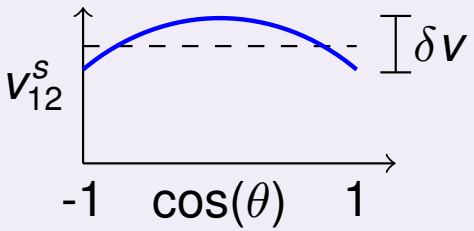


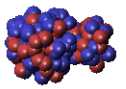


Calibration of the inter-splitting time

Coulomb trajectory calculations

- We calculate δv for different values of the inter-splitting time δt.

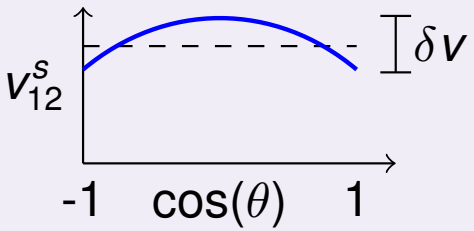


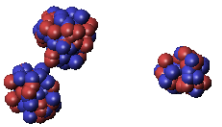


Calibration of the inter-splitting time

Coulomb trajectory calculations

- We calculate δv for different values of the inter-splitting time δt.

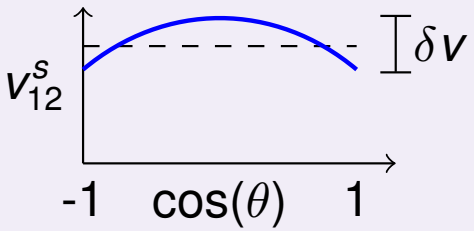


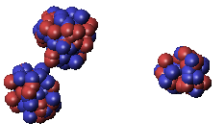


Calibration of the inter-splitting time

Coulomb trajectory calculations

- We calculate δv for different values of the inter-splitting time δt.

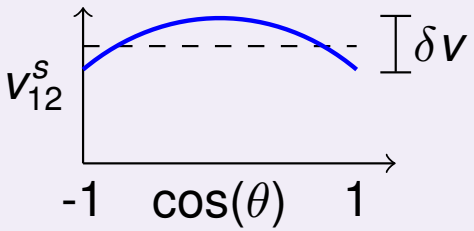


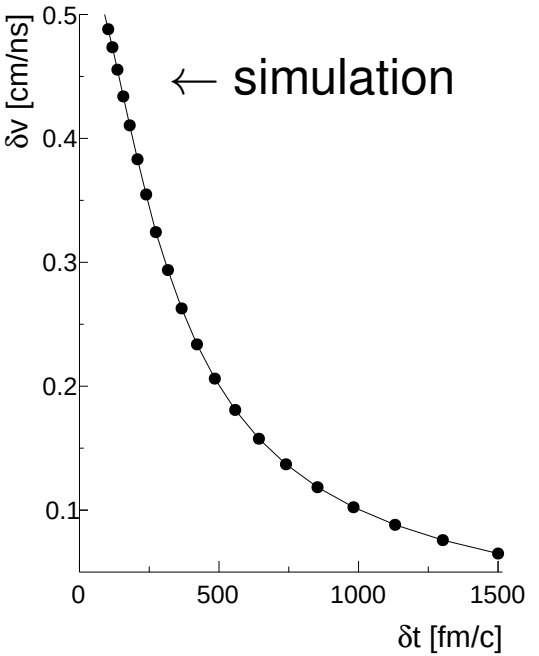


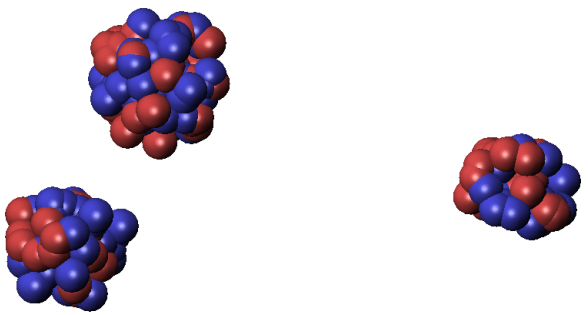
Calibration of the inter-splitting time

Coulomb trajectory calculations

- We calculate δv for different values of the inter-splitting time δt.



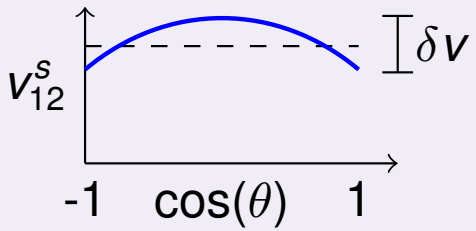


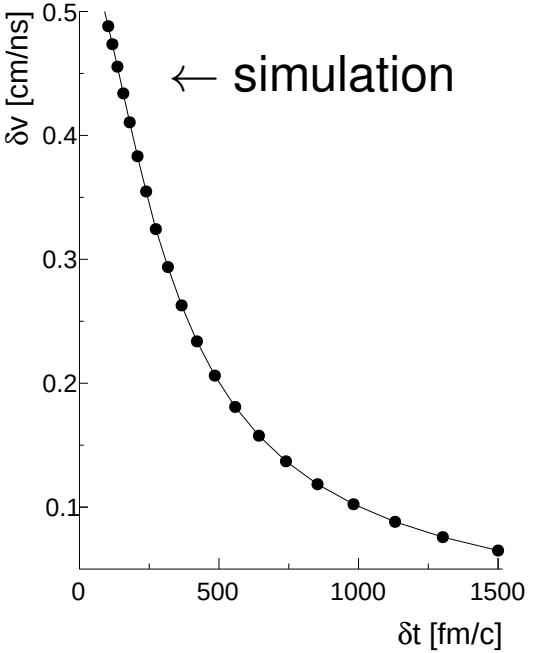


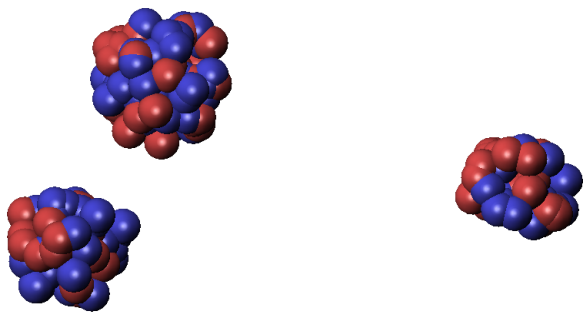
Calibration of the inter-splitting time

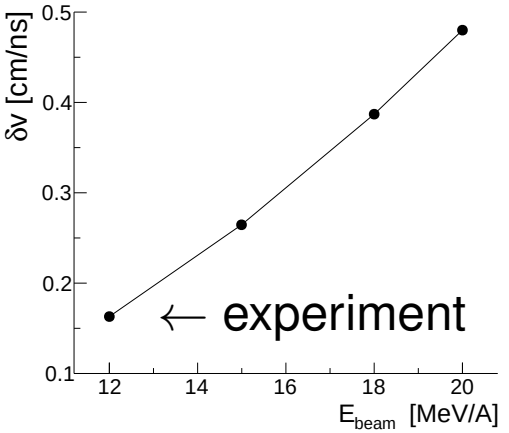
Coulomb trajectory calculations

- We calculate δv for different values of the inter-splitting time δt.





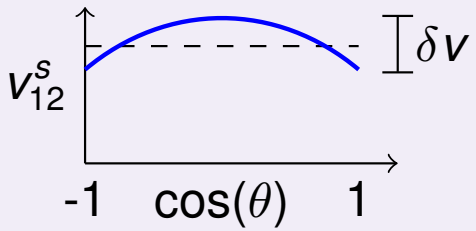


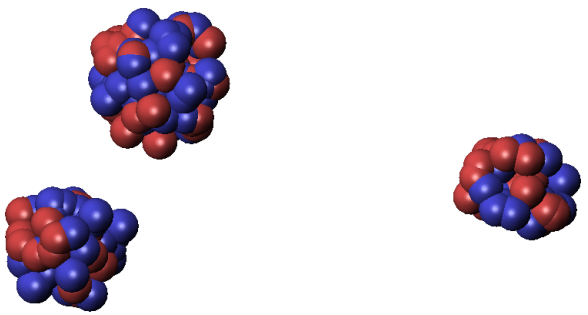


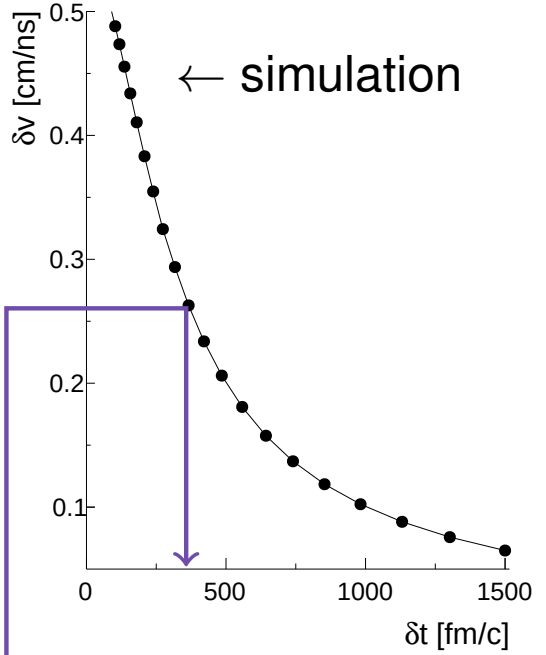
Calibration of the inter-splitting time

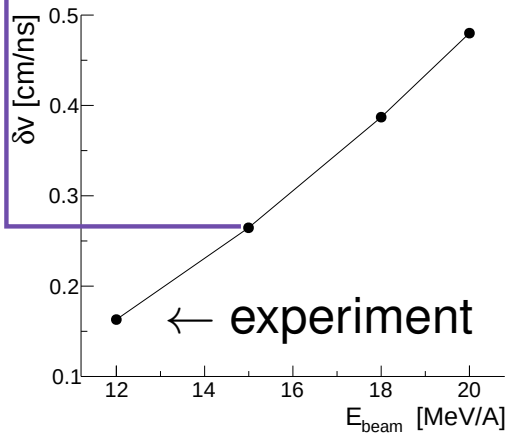
Coulomb trajectory calculations

- We calculate δv for different values of the inter-splitting time δt.

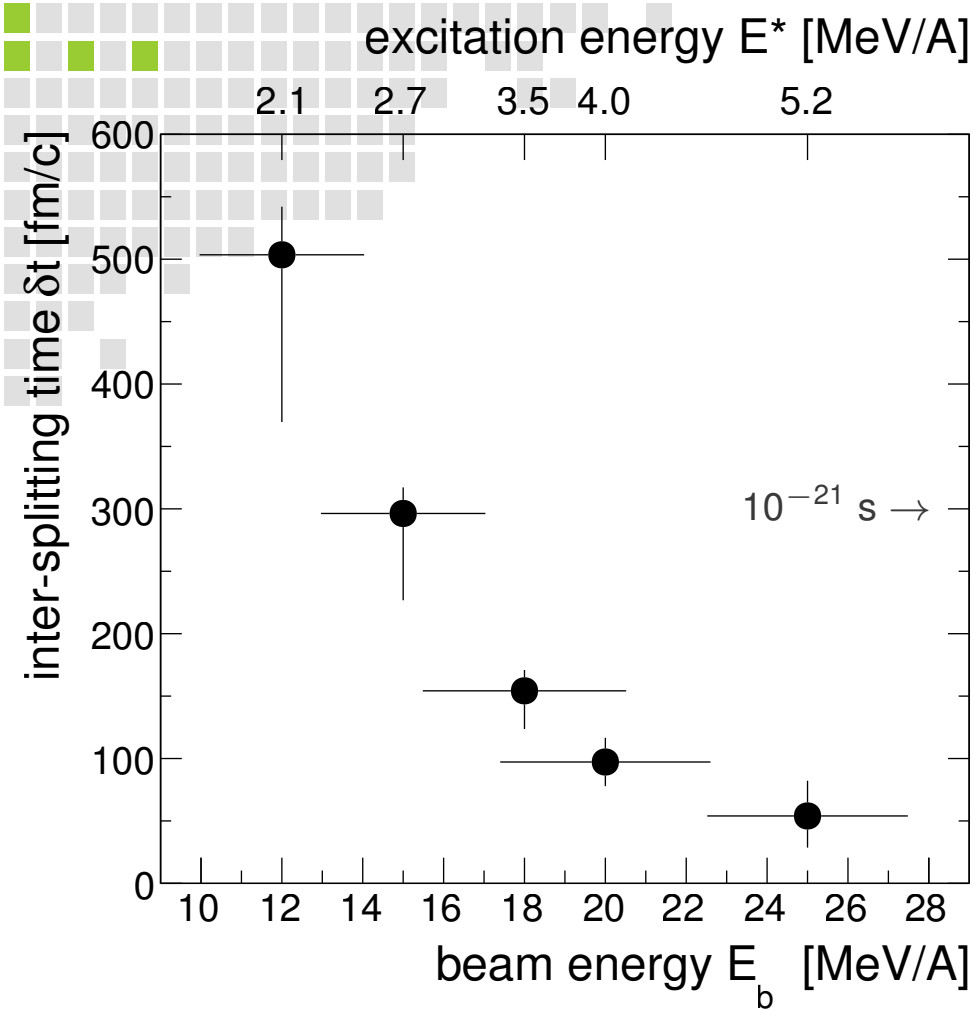








From hot sequential fission to multifragmentation

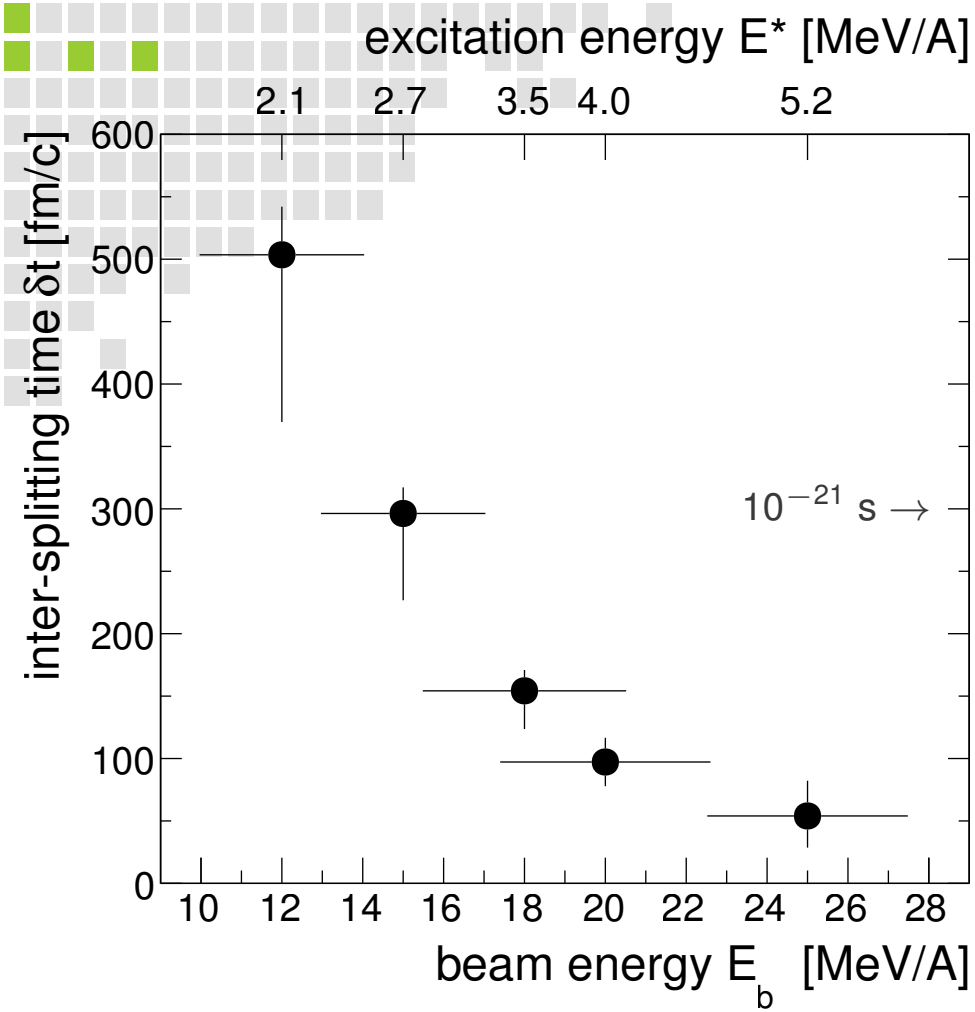


Inter-splitting time evolution

- δt decreases with increasing available or excitation energy

Reaction mechanism

From hot sequential fission to multifragmentation

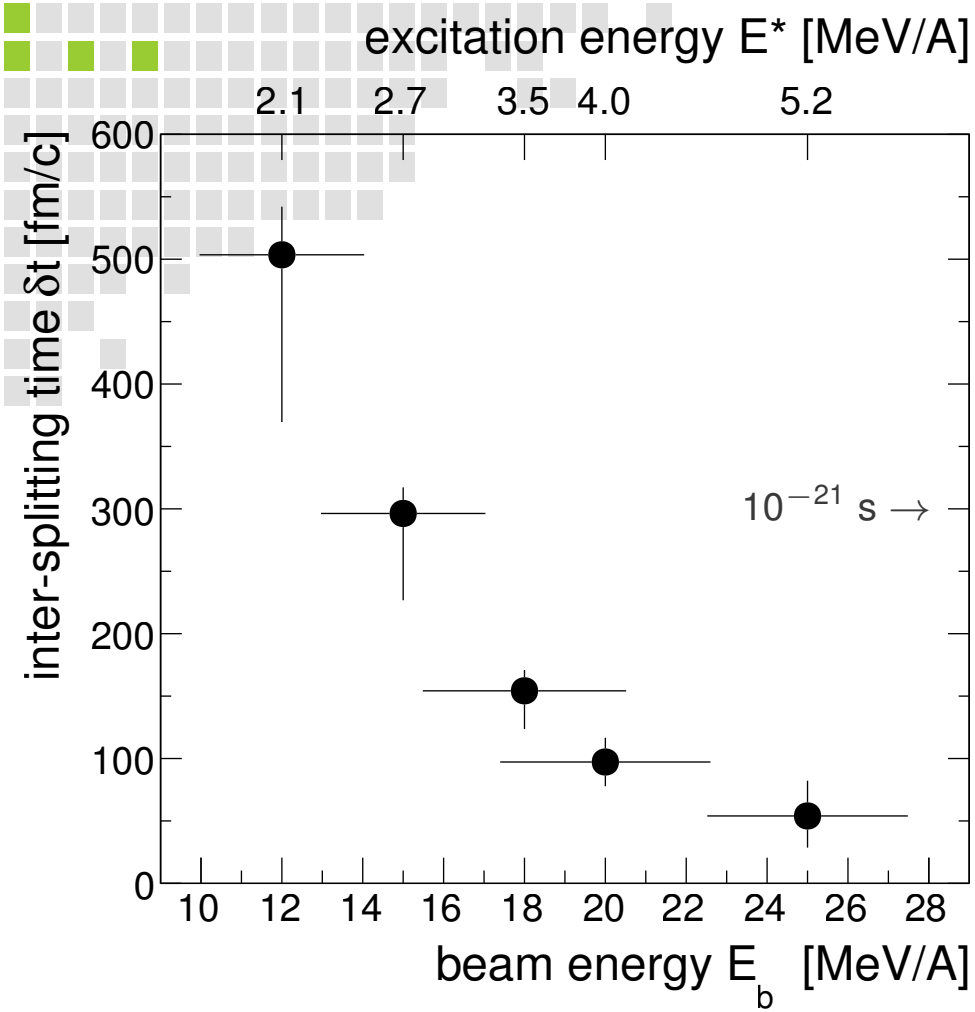


Inter-splitting time evolution

- δt decreases with increasing available or excitation energy
- For $\delta t < 100$ fm/c : no more meaningful to speak of a sequential process

Reaction mechanism

From hot sequential fission to multifragmentation



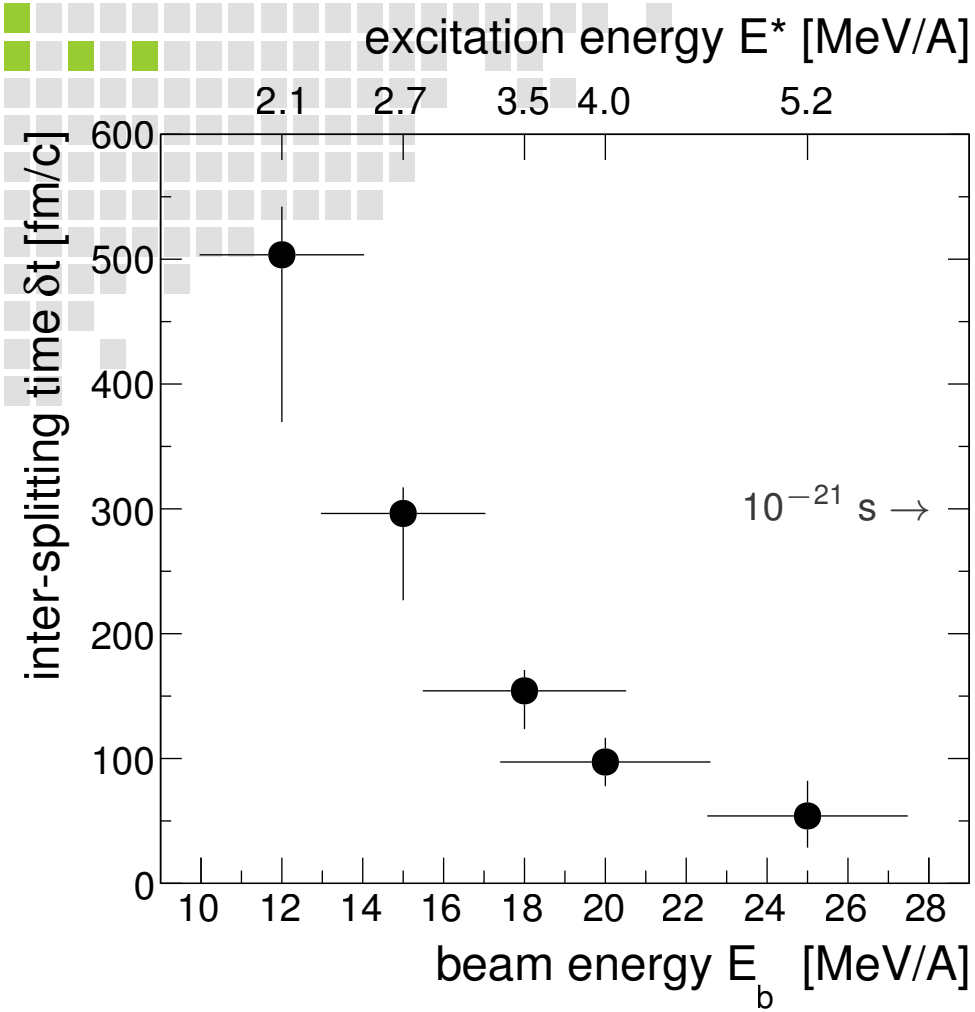
Inter-splitting time evolution

- δt decreases with increasing available or excitation energy
- For $\delta t < 100$ fm/c : no more meaningful to speak of a sequential process

Reaction mechanism

- Successive splittings occuring on shorter and shorter time scale

From hot sequential fission to multifragmentation



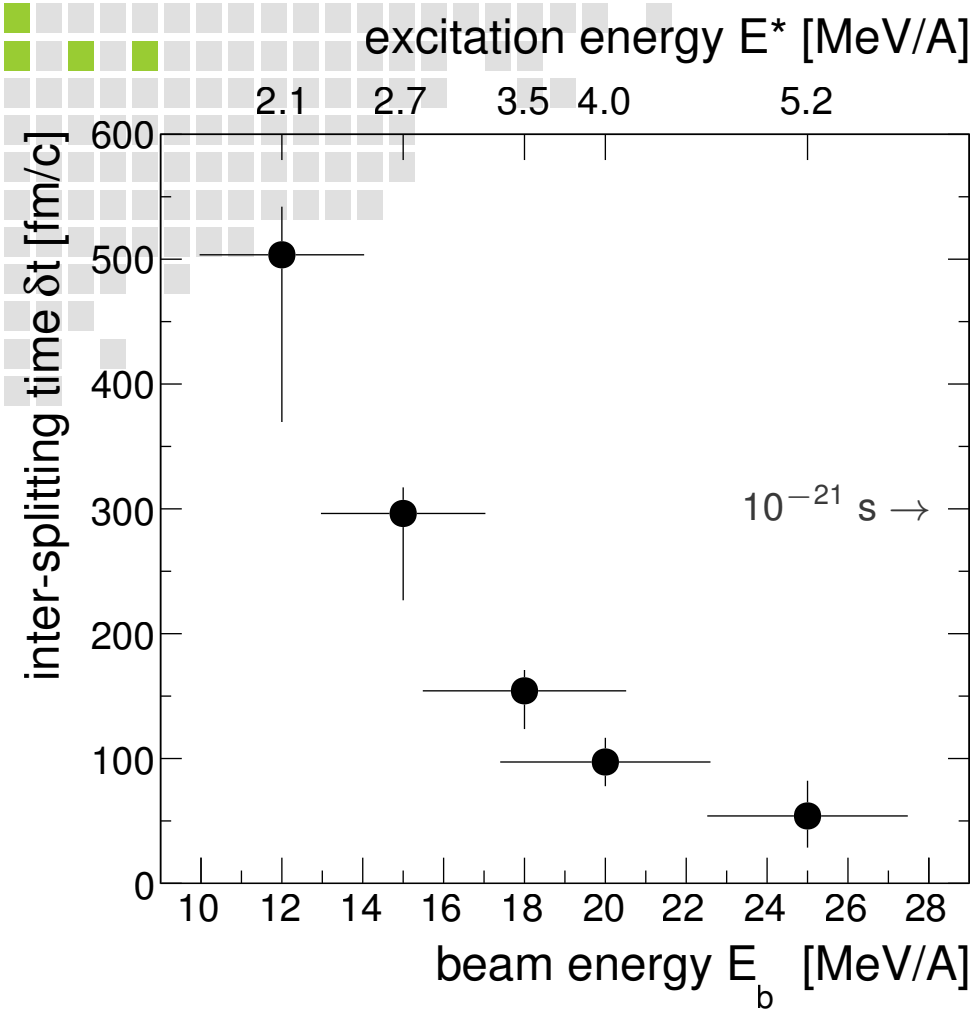
Inter-splitting time evolution

- δt decreases with increasing available or excitation energy
- For $\delta t < 100$ fm/c : no more meaningful to speak of a sequential process

Reaction mechanism

- Successive splittings occuring on shorter and shorter time scale
- Compatible with simultaneous break-up above E_b=20 MeV/A

From hot sequential fission to multifragmentation



Inter-splitting time evolution

- δt decreases with increasing available or excitation energy
- For $\delta t < 100$ fm/c : no more meaningful to speak of a sequential process

Reaction mechanism

- Successive splittings occuring on shorter and shorter time scale
- Compatible with simultaneous break-up above E_b=20 MeV/A
- Onset of multifragmentation above $E^* = 4.0 \pm 0.5$ MeV/A

Summary and prospects

Evolution of the decay mechanism : 3-fragment exit channel

- ^{129}Xe+^{nat}Sn central collisions measured with INDRA at E_{beam}=12-25 MeV/A

Summary and prospects

Evolution of the decay mechanism : 3-fragment exit channel

- ^{129}Xe+^{nat}Sn central collisions measured with INDRA at E_{beam}=12-25 MeV/A
- Two binary splittings on shorter and shorter time scale

Summary and prospects

Evolution of the decay mechanism : 3-fragment exit channel

- ^{129}Xe+^{nat}Sn central collisions measured with INDRA at E_{beam}=12-25 MeV/A
- Two binary splittings on shorter and shorter time scale
- Quasi-simultaneous above $E^* = 4.0 \pm 0.5$ MeV/A : onset of multifragmentation

Summary and prospects

Evolution of the decay mechanism : 3-fragment exit channel

- ^{129}Xe+^{nat}Sn central collisions measured with INDRA at E_{beam}=12-25 MeV/A
- Two binary splittings on shorter and shorter time scale
- Quasi-simultaneous above $E^* = 4.0 \pm 0.5$ MeV/A : onset of multifragmentation

D. Gruyer et al. (INDRA collaboration) arXiv :1309.7779 submitted to Phys. Rev. Let.

Summary and prospects

Evolution of the decay mechanism : 3-fragment exit channel

- ^{129}Xe+^{nat}Sn central collisions measured with INDRA at E_{beam}=12-25 MeV/A
- Two binary splittings on shorter and shorter time scale
- Quasi-simultaneous above $E^* = 4.0 \pm 0.5$ MeV/A : onset of multifragmentation

D. Gruyer et al. (INDRA collaboration) arXiv :1309.7779 submitted to Phys. Rev. Let.

How to go further ?

- Need of a dynamical model which describes sequential break-up

Summary and prospects

Evolution of the decay mechanism : 3-fragment exit channel

- ^{129}Xe+^{nat}Sn central collisions measured with INDRA at E_{beam}=12-25 MeV/A
- Two binary splittings on shorter and shorter time scale
- Quasi-simultaneous above $E^* = 4.0 \pm 0.5$ MeV/A : onset of multifragmentation

D. Gruyer et al. (INDRA collaboration) arXiv :1309.7779 submitted to Phys. Rev. Let.

How to go further ?

- Need of a dynamical model which describes sequential break-up
- Chronometer : transport properties of nuclear matter (isospin diffusion, etc.)

Thank you for your attention !

D.Gruyer[1], **J.D.Frankland**[1], **E.Bonnet**[1], **A.Chbihi**[1], G.Ademard[3], M.Boisjoli[1,4], B.Borderie[3], R.Bougault[5], E.Galichet[3,10], E.Gauthier[4], D.Guinet[6], P.Lautesse[6], L.Manduci[7], N.Le Neindre[5], E.Legouée[5], O.Lopez[5], P.Marini[1], K.Mazurek[8], P.N.Nadtochy[11], M.Pârlog[5], P.Pawłowski[8], M.F.Rivet[3], R.Roy[4], E.Rosato[9] G.Spadaccini[9], G.Verde[12], E.Vient[5], M.Vigilante[9], and J.P.Wieleczko[1]

(INDRA Collaboration)

[1] GANIL, Caen, France
[3] IPN, Université Paris-Sud 11, Orsay, France
[4] Université Laval, Québec, Canada
[5] LPC, Université de Caen, Caen, France
[6] IPN, Université Claude Bernard Lyon 1, Villeurbanne, France
[7] École des Applications Militaires de l'Énergie Atomique, Cherbourg, France
[8] H. Niewodniczański Institute of Nuclear Physics, Kraków, Poland
[9] INFN, Universita di Napoli "Federico II", Napoli, Italy
[10] Conservatoire National des Arts et Métiers, Paris, France
[11] Omsk State University, Omsk, Russia
[12] INFN, Sezione di Catania, Catania, Italy