Determination of the freeze-out temperature in the fragmentation of relativistic $^{238}$U projectiles by means of the isospin thermometer

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GLOSSARY

Isospin
Just an expression for N/Z

Freeze-out temperature
When “something” decouples from the hot source in the cooling process

Isospin thermometer
A specific thermometer based on the measurement of the N/Z
The liquid-gas phase transition in a nucleus

Exploring the nuclear-matter phase-diagram and identifying the different phases of nuclear matter is one of the main challenges of modern nuclear physics.

Up to now: Information gained with the observation of light (A<20) fragments

Temperature → isotopic ratio

High-resolution magnetic spectrometer --> Mass identification is achievable for all residues
1 Experiments: $^{238}\text{U} \to \text{Pb}$ at 1 A·GeV at FRS
   $^{238}\text{U} \to \text{Ti}$ at 1 A·GeV at FRS

2 Comparison of the experimental data with the EPAX prediction -> $\text{N/Z}$ is sensitive to the temperature

3 Exploiting the new information: the isospin thermometer

4 Possible scenario of mid-peripheral high-energy nucleus-nucleus collisions
THE EXPERIMENT AT THE FRS AT GSI

$1 \text{ A}\cdot\text{GeV}^{238}\text{U} \rightarrow \text{Ti}$

$Z \text{ from IC: } \Delta E \propto Z^2$

$A/Z \text{ from time and position: } \frac{A}{Z} = \frac{e}{m_0} \frac{B\rho}{c\beta\gamma}$
1 A GeV $^{238}$U on titanium

![Graph of A/Z vs Z showing a distribution of counts.](image-url)
velocity is calculated from $B\rho$:

$$\gamma v = B\rho \frac{Z \cdot e}{A \cdot m_0}$$

very precise evaluation!

DISCRIMINATION OF FISSION EVENTS

![Diagram showing the relationship between the laboratory frame and the beam frame in the context of fission and fragmentation events.](image)

For the element $^{94}\text{Zr}$, the histogram shows the distribution of velocities ($v$) in units of cm/ns, with a maximum count of 60. The orange line represents the trend or expected distribution based on the theoretical calculations.
From electromagnetic-induced fission to fragmentation of $^{238}\text{U}$

- Fission from low and high excitation energies
- Fragmentation in high-energy nuclear collisions

Neutron excess reflects excitation energy induced. Evaporation leaves traces which can be exploited!
**EXPERIMENTAL RESULTS**
(fission discharged)

Isotopic cross sections for $Z = 40$

![Graph showing isotopic cross sections for $Z = 40$.](image)

**EPAX**: a *systematics* of isotopic cross sections in projectile fragmentation


**EPAX** is based on the hypothesis of *limiting fragmentation*
Mean N/Z of fragments (fission discharged)

- stability line
- EPAX, projectile = Au
- EPAX, projectile = Fe
- 800 A·MeV Au + p - F.Rejmund NPA 683 (2001)
- 1000 A·MeV U + Pb - T. Enqvist NPA 658 (1999)
- 1000 A·MeV U + Ti - this work

Why do some data agree with EPAX and some deviate?
ABRASION + EVAPORATION

$E^* = \Delta A \cdot 27 \text{ MeV}$

$\langle N \rangle / Z = \text{constant}$

$E^* \propto \text{abraded mass}$

evaporation cascade
SEQUENTIAL DECAY
(EVAPORATION)

\( \Gamma_p \gg \Gamma_n \)
\( \Gamma_p \approx \Gamma_n \)
\( \Gamma_p < \Gamma_n \)
\( \Gamma_p \ll \Gamma_n \)

"evaporation corridor"
or"attractor line"
In more violent collisions the evaporation strats at lower excitation energies!
PRINCIPLE OF THE ISOSPIN THERMOMETER

Simplifying hypotheses:
- only n-evaporation
- 15 MeV consumed for every evaporated n
- the evaporation stops when \( \frac{N_{\text{final}}}{Z} = 1.25 \)

\[
E^* = 15 \text{ MeV} \cdot \frac{N_i - N_f}{Z} \\
\frac{N_i - N_f}{Z} \sim 0.34
\]

\[
E^* = a \ T^2 \\
a \sim A/10 \text{ MeV}
\]

\[
E^*/A = 0.1 \ T^2
\]

All pre-fragments start the evaporation cascade at a constant temperature!!!
ABRASION + SIMULTANEOUS BREAK-UP + EVAPORATION

\[ \langle N \rangle / Z = \text{constant} \]
\[ E^* \propto \text{abraded mass} \]

\[ E^* = \Delta A \cdot 27 \text{ MeV} \]

\[ \langle N \rangle / Z = \text{constant} \]
\[ T = \text{constant} \]
\[ \rightarrow E^* \text{ larger for larger pre-fragments} \]

evaporation cascade
COMPARISON WITH A THREE-STAGE MODEL

ABRASION / (BREAK-UP) / EVAPORATION
COMPARISON WITH SMM CALCULATIONS

![Graph showing comparison with SMM calculations. The graph plots the ratio \( \langle N \rangle / Z \) against atomic number \( Z \). Different lines represent calculations with temperatures \( T \) of 3.1 MeV, 3.9 MeV, 4.4 MeV, 4.9 MeV, and 7 MeV. There are also data points for reactions involving \(^{238}\text{U} + ^{208}\text{Pb} \) and \(^{238}\text{U} \) on \(^{197}\text{Ti} \) at 1 GeV.](image-url)
A SHARP CONSTANT TEMPERATURE?

Experimental data
Three-stage model
SMM (arbitrary normalised)

- no indications for important fluctuations in temperature
POSSIBLE SCENARIO OF MID-PERIPHERAL HIGH-ENERGY NUCLEUS-NUCLEUS COLLISIONS

\[ E^* = A T_F \Omega^2 \]

\[ E^* = 27 \Delta A \text{ MeV} \]

\[ \langle E^*_{\text{initial}} \rangle / \text{MeV} \]

\[ Z_{\text{initial}} \]

IMFs

“attractor line”

abrasion

break-up

evaporation

experimental data

N

Z
CONCLUSIONS

★ Heavy residues produced in collisions of $^{238}$U with titanium and lead at $1 \cdot A$ GeV are unexpectedly neutron-rich

★ The $\langle N \rangle/Z$-ratio is an interesting quantity also for heavy masses produced in fragmentation

★ Isotopic distributions of residual elements from neutron-rich projectile are sensitive to a simultaneous-emission phase

★ The mean $N/Z$-ratio of the final elements can be used in combination with statistical-model codes in order to deduce the freeze-out temperature after break up ("isospin thermometer")

★ The average temperature of the break-up configuration at freeze out is $T \approx 5 \text{ MeV}$

★ consequence: an equilibrated compound nucleus cannot exist above a limiting temperature of 5 MeV (EPAX is valid for $T < 5 \text{MeV}$)