To the question of verification of collinear cluster tri-partition (CCT)

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Experiment: “Ni-bump”
Ni-bump in details

3 energy groups for Ni
Ni-bump in details

\[ \langle Q3-TKE3 \rangle \approx 30\text{MeV} \]
Theoretical background
Macroscopic part of the potential energy for fission of $^{252}\text{Cf}$ calculated for zero values of the deformation parameters $b$ and nuclear shapes $a$ depending on elongation and mass of third fragment (italic numbers).
Pre-scission configuration of the tri-nuclear system (TNS) at spontaneous ternary fission of 252Cf

Our calculations
Table 1. Pictograms illustrated scenarios of different CCT modes observed in experiments.

<table>
<thead>
<tr>
<th>row No</th>
<th>Label of the locus in fig. 3d</th>
<th>System configuration at the exit point from under the barrier</th>
<th>System configuration after first rupture</th>
<th>System configuration at the moment of the second rupture</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>w1b</td>
<td></td>
<td></td>
<td>rupture</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>w1c</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>w2b w2c</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>w3b</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>w3c</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>binary fission</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

Sequential (in time !) fission from elongated prescission configuration
### Our calculations - results

<table>
<thead>
<tr>
<th>№</th>
<th>locus</th>
<th>nucl. configuration</th>
<th>$R_{12}$, fm</th>
<th>$E_H$, MeV</th>
<th>$V_L$, cm/ns</th>
<th>$V_T$, cm/ns</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>w1b</td>
<td>$^{70}\text{Ni} - ^{39}\text{S} - ^{139}\text{Xe}$ [ $^{70}\text{Ni} - ^{38}\text{S} - ^{140}\text{Xe}$ ]</td>
<td>25</td>
<td>79 (80)</td>
<td>0.54 (0.62)</td>
<td>2.52 (2.2)</td>
</tr>
<tr>
<td>2</td>
<td>w1c</td>
<td>$^{70}\text{Ni} - ^{39}\text{Si} - ^{143}\text{Ba}$ [ $^{70}\text{Ni} - ^{38}\text{Si} - ^{144}\text{Ba}$ ]</td>
<td>26</td>
<td>70 (70)</td>
<td>0.58 (0.65)</td>
<td>2.5 (2.3)</td>
</tr>
<tr>
<td>3</td>
<td>w3b</td>
<td>$^{70}\text{Ni} - ^{35}\text{Al} - ^{147}\text{La}$ [ $^{70}\text{Ni} - ^{34}\text{Mg} - ^{148}\text{Ce}$ ]</td>
<td>25</td>
<td>78 (76)</td>
<td>1.8 (1.65)</td>
<td>0.5 (0.5)</td>
</tr>
<tr>
<td>4</td>
<td>w3c</td>
<td>$^{70}\text{Ni} - ^{26}\text{Ne} - ^{156}\text{Nd}$ [ $^{70}\text{Ni} - ^{28}\text{Ne} - ^{154}\text{Nd}$ ]</td>
<td>25</td>
<td>67 (63)</td>
<td>1.8 (1.65)</td>
<td>0.5 (0.6)</td>
</tr>
<tr>
<td>5</td>
<td>w2b*</td>
<td>$^{70}\text{Ni} - ^{47}\text{Ar} - ^{135}\text{Te}$ [ $^{70}\text{Ni} - ^{48}\text{Ar} - ^{134}\text{Te}$ ]</td>
<td>32</td>
<td>95 (93)</td>
<td>1.35 (1.35)</td>
<td>1.35 (1.35)</td>
</tr>
<tr>
<td>6</td>
<td>w2c*</td>
<td>$^{70}\text{Ni} - ^{40}\text{S} - ^{142}\text{Xe}$ [ $^{70}\text{Ni} - ^{42}\text{S} - ^{140}\text{Xe}$ ]</td>
<td>32 (bottom)</td>
<td>80 (78)</td>
<td>1.35 (1.35)</td>
<td>1.35 (1.35)</td>
</tr>
<tr>
<td>7</td>
<td>bin. fiss.</td>
<td>$^{70}\text{Ni} - ^{50}\text{Ca} / ^{132}\text{Sn}$ [ $^{182}\text{Yb}$ ]</td>
<td>24</td>
<td>TKE 141MeV</td>
<td>1.25 (1.35)</td>
<td>1.25 (1.35)</td>
</tr>
</tbody>
</table>

- **Calculations:** ~ 10% difference with exp. values

- Far asymmetric binary fission

- w2b, c* – see Table 1 of pictograms
Areas of attainable final kinetic energies of the fission fragments versus the total excitation energy of all the fragments, in the true ternary decays $^{252}$Cf (sf) $\rightarrow$ Sn + Ca + Ni. Each figure is a specific element, and the different areas indicate the choice of $x_r$ as indicated in the upper part of the figure.
Lohengrin mass-separator

Fig. 2. Left: absolute fragment-mass yields for the $^{245}$Cm(n$_{th}$, f) and $^{249}$Cf(n$_{th}$, f) measured at Lohengrin (< A < 78) and Ref. [21] (A > 77), from the JEF bars for Wahl’s data and JEF2 data (positive and negative, the figure).


M.L. Muga et al. & “DIOGENIS”

M&E are similar to those observed in CCT

A. A. Goverdovsky et al., Jadernaja Fizika 58, 1546 (1995) → 236U*

Binary fission, only

$Y_{Ni} \sim 10^{-5}$
Our answers to the critical questions, namely:

1. “Fantastic” total yield of the effect in comparison with the conventional ternary fission

2. Stability of the collinearity

3. Independent experimental verification
1. Comparison of the yields: conventional ternary fission (CTF)

Table 3  Experimental yields of light clusters in ternary fission $Y_{\text{exp}}^z(Xz)$ normalized to yield $Y_{\text{exp}}^z(4\text{He})$ of alpha-particles in comparison with the ratio of spectroscopic factors of clusters $S_x(T)$ and $\alpha$-particle $S_{\alpha}(T)$

<table>
<thead>
<tr>
<th>$^AX_z$</th>
<th>$Y_{\text{exp}}^z(^AX_z)/Y_{\text{exp}}^z(4\text{He})$</th>
<th>$S_x(T)/S_{\alpha}(T)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^4\text{He}$</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$^7\text{Li}$</td>
<td>$5 \times 10^{-3}$</td>
<td>$4.2 \times 10^{-3}$</td>
</tr>
<tr>
<td>$^{10}\text{Be}$</td>
<td>$1.3 \times 10^{-2}$</td>
<td>$5 \times 10^{-2}$</td>
</tr>
<tr>
<td>$^{11}\text{B}$</td>
<td>$6 \times 10^{-4}$</td>
<td>$2.1 \times 10^{-4}$</td>
</tr>
<tr>
<td>$^{14}\text{C}$</td>
<td>$5 \times 10^{-3}$</td>
<td>$2.5 \times 10^{-3}$</td>
</tr>
<tr>
<td>$^{20}\text{O}$</td>
<td></td>
<td>$1.3 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

$Y_{\text{CTF}} \sim$ spectroscopic factor $S_x$

$S_{\alpha} >> S_{\text{Ne, O, S}}$

&

LCP is emitted in relatively compact scission configuration
2. Comparison of the yields

**CCT**: two ruptures in *elongated* prescission configuration. What is known about the yield of such configurations?

Ek, MeV

![Graph showing neutron-emission probabilities](image)

**TABLE I. Comparison of neutron-emission probabilities for $^{252}$Cf from this work and from Ref. 8.**

<table>
<thead>
<tr>
<th>ν</th>
<th>This work</th>
<th>Reference 8</th>
</tr>
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<tbody>
<tr>
<td>0</td>
<td>0.0025±0.0004</td>
<td>0.0022±0.0001</td>
</tr>
<tr>
<td>1</td>
<td>0.0282±0.0024</td>
<td>0.0256±0.0013</td>
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<tr>
<td>2</td>
<td>0.1199±0.0081</td>
<td>0.1239±0.0014</td>
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<td>3</td>
<td>0.2681±0.0278</td>
<td>0.2715±0.0011</td>
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<td>4</td>
<td>0.3056±0.0118</td>
<td>0.3046±0.0005</td>
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<tr>
<td>5</td>
<td>0.1951±0.0217</td>
<td>0.1866±0.0006</td>
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<td>6</td>
<td>0.0674±0.0158</td>
<td>0.0681±0.0004</td>
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<tr>
<td>7</td>
<td>0.0084±0.0048</td>
<td>0.0152±0.0001</td>
</tr>
<tr>
<td>8</td>
<td>0.0045±0.0030</td>
<td>0.0021±0.0000</td>
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<tr>
<td>9</td>
<td>0.0004±0.0015</td>
<td>0.0002±0.0000</td>
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Deformed cold fission
3. Comparison of the yields
Elongated nuclear shapes based on magic clusters

Potential energy of the fissioning nucleus 252Cf corresponding to the bottoms of the potential valleys, as the function of $Q$, proportional to its quadrupole moment. (a); (b) — the contour map of the conditional mass–energy distribution $P(M|E^*)$. The panels depict the shapes of the fissioning system following from the PES calculations ascribed to the two dominant structures.

4. Comparison of the yields

CCT: 1-st rupture in elongated prescission shape $\rightarrow$ di-nuclear system (shape isomer state) $\rightarrow$ scission (CCT) or fusion (binary fission)

Yu. Pyatkov et al. ISINN-23
2. Collinearity
Collinearity

Two reasons to brake-up a collinearity:
1. Rotation of the di-nuclear system forming after 1-st rupture;
2. Focusing of a LCP (light fragment) by the Coulomb fields of the side fragments at almost right angle to the fission axis.

Answers:
1. See arguments linked with ROT effect: the reflection angle (~0.3°) is a function of spin & time of rotation. Both can differ from those in conventional binary and ternary fission.
2. According to our calculations which agree with experimental data the second rupture occurs mainly after full acceleration - “at infinity”.
   In other case kinematics can be both collinear and orthogonal.
Independent experimental verification

Problems

1. Correct measurement of TOF & E of heavy low energy ions (pulse height defect and plasma delay in PIN s).
2. Scattering of the FF simulating CCT events.
3. Precise geometry of the setup (opposite PINs must be well aligned).

Only periphery region is in game
Conclusions

1. Proposed scenarios of the CCT modes let reproduce experimental values of \( E \) and \( V \) of the CCT partners.

2. Additional arguments were put forward concerning the yield of the effect and stability of collinearity.

3. Further theoretical efforts are needed for deeper understanding of the CCT phenomenon.
Recent exp., flash-ADC, no gates
EXPERIMENTAL STUDY OF THE CORRELATION BETWEEN THE NUMBERS OF PROMPT NEUTRONS EMITTED BY THE TWO COMPLEMENTARY FRAGMENTS IN SPONTANEOUS FISSION OF $^{252}\text{Cf}$.

B. SIGNARBIEUX, R. BABINET, H. NIFENECKER, J. POITOU, IAEA-SM-174/41

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<td>0.0021±0.0000</td>
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<tr>
<td>9</td>
<td>0.0004±0.0015</td>
<td>0.0002±0.0000</td>
</tr>
<tr>
<td>Avg.</td>
<td>3.773±0.111</td>
<td>3.773±0.007</td>
</tr>
<tr>
<td>Variance</td>
<td>1.612±0.141</td>
<td>1.6155</td>
</tr>
<tr>
<td>$R_{\text{inv}}$</td>
<td>$-0.1518±0.0011$</td>
<td>$-0.1517±0.0001$</td>
</tr>
</tbody>
</table>

*The “invariant $R_i$” assumed to be independent of counter efficiency (Refs. 3, 8, and 10).