NEW SIDES OF THE COLLINEAR CLUSTER TRI-PARTITION SCENARIO

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Experimental background
Our experimental background: FOBOS setup and its modifications

Mtt & Mte, Neutrons & Nuclear charge

"Ni-bump"
Our experimental background: family of COMETA spectrometers

neutron belt

mosaics of PIN diodes

Mtt & Mte, neutrons

COMETA (COrrelation Mosaic E-T Array)
New modified experimental methodic
Experimental approach: fast flash-ADC & modified data processing

\[ E = E_{\text{det}} + R(M, E), \]  
\[ R(M, E) = \frac{\lambda \cdot E}{1 + \varphi \cdot \frac{E}{M^2}} + \alpha \cdot ME + \beta \cdot E, \]  
\[ E = \frac{M \cdot V^2}{1.9297 \lambda} \]

Combining equation (1), (2) and (3), we obtain:
\[ G(\lambda, \varphi, \alpha, \beta, M, V) = 0 \]
\[ G = \frac{MV^2}{k} - [E_{\text{det}} + \frac{\lambda \cdot MV^2}{k} + \alpha \cdot \frac{M^2V^2}{k} + \beta \cdot \frac{MV^2}{k}] = 0, \]
where \( k = 1.9297 \).

\[ \min F = [(<ML_T> - <ML>)^2 + (<MH_T> - <MH>)^2] + \mu \sum_{M_T} \frac{(Y(M_T) - Y_T(M_T))^2}{Y(M_T)} \]

PD: \[ \Delta t_p = \gamma \frac{M^{1/6} E^{1/2}}{} \] (used in Ex2)

A new off-line method of time-pickoff “sewing-parabola”
New results
Comparison of the results from Ex1 (new) and Ex2
Specific structure which is beyond the consideration in the present talk

in our opinion this structure deserves the following mark:

“nuclear rose”

\[ M_1 + M_2 = \text{const} \]

\[ M_1 - M_2 = \text{const} \]
Comparison of the results from Ex1 (new) and Ex2

### Table I. Results of the model calculations. Ternary partitions close to the experimental ones and based on magic constituents (marked in bold) are shown in square brackets. See the text for details.

<table>
<thead>
<tr>
<th>No.</th>
<th>Locus</th>
<th>Nucl. configuration</th>
<th>$R_{12}$, fm</th>
<th>$E_{12}$, MeV</th>
<th>$E_{22}$, MeV</th>
<th>$V_{1}$, cm/ns</th>
<th>$V_{2}$, cm/ns</th>
<th>$V_{t}$, cm/ns</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>w1b</td>
<td>$^{78}$Ni-$^{41}$S-$^{139}$Xe</td>
<td>≤30</td>
<td>69.5 ± 2.6</td>
<td>0.68 ± 0.06</td>
<td>2.19 ± 0.13</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>w1c</td>
<td>$^{78}$Ni-$^{39}$Si-$^{144}$Ba</td>
<td>≤30</td>
<td>69.5 ± 2.6</td>
<td>0.68 ± 0.06</td>
<td>2.19 ± 0.13</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>w2b</td>
<td>$^{78}$Ni-$^{57}$Ar-$^{139}$Te</td>
<td>≤35</td>
<td>91.4 ± 3.1</td>
<td>1.30 ± 0.06</td>
<td>1.34</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>w2c</td>
<td>$^{78}$Ni-$^{57}$Ar-$^{139}$Te</td>
<td>≤35</td>
<td>91.4 ± 3.1</td>
<td>1.30 ± 0.06</td>
<td>1.34</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>w3b</td>
<td>$^{78}$Ni-$^{57}$Al-$^{139}$La</td>
<td>≤32</td>
<td>76.6 ± 3.1</td>
<td>1.62 ± 0.04</td>
<td>0.78 ± 0.08</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>w3c</td>
<td>$^{78}$Ni-$^{57}$Al-$^{139}$La</td>
<td>≤32</td>
<td>76.6 ± 3.1</td>
<td>1.62 ± 0.04</td>
<td>0.78 ± 0.08</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>bin. fiss.</td>
<td>$^{78}$Ni-$^{57}$Al-$^{139}$La</td>
<td>TKE 141 MeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$E_{12}$ = 102 MeV

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**Ni &:** $^{128}$Sn, $^{134}$Te, $^{140}$Xe, $^{144}$Ba, $^{150}$Ce, $^{154}$Nd

**Z=28 & N=40**
VEGA (V-E Guide based Array) setup at the MT-25 microtrone in FLNR

Parameters used for the calculations: $V_0 = 10 \text{kV}$, $s = 0.1 \text{ mm}$, channel diameter (outer cylinder) is 56 mm, the length of one guide arm is 5 m, the target diameter is 5 mm.

According to [5] the collection efficiency $F_c$ of the guide for an extended, uniform, target of radius $b$ equal to the tube (outer cylinder) radius $R$ is estimated to be:

$$F_c = 0.153q \frac{V_0}{EFF \ln(R/s)},$$

where $V_0$ is the potential difference between the two conductors, $EFF$ – is the kinetic energy of the fission fragment, $s$ – is the radius of the central wire of the guide, $q$ – ionic charge.

Ex3: two fragments in one arm & Ni missed $\equiv$ CCT

$Y(\text{Ni}_\text{miss}) \sim 10^{-3}$

$\tau_{\text{life}} > 400\text{ns}$

for $^{68,72}\text{Ni}$ missed

$<E_1> = 63.7 \sim 64\text{MeV}$;

$<E_2> = 2.97 \sim 3\text{MeV}$;

$<V_1> = 0.96 \text{cm/ns}$;

$<V_2> = 0.43 \text{cm/ns}$

Missed $^{68,72}\text{Ni}$

delayed brake-up in the start-foil

H LL start

$^{235}\text{U}(\gamma, f)$
Discussion
What happens after 1-st rupture?

$E_3^* = Q_3 - TKE_3 \approx 30 \text{MeV}$

$V_{exp} \sim 4$ for Ni-bump:

good agreement;

H&L CCT partners are

the magic nuclei $\rightarrow$ all

$E_3^* \approx E_2^* \rightarrow$ in the deformed

neck (Ca-like nucleus).

$E_3^* \approx E_b$ (Cd-like nucl. [3])

According to Ex3 Cd undergoes

delayed brake-up in the MCP
det. foil. $\rightarrow$

Likely fission isomer state in Cd

was populated after 1 rupture

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By analogy with the shapes

for elongated Cf and Ds

elongated Cd formed after 1st rupture could evaluate to the shape “magic head +

elongated neck” – the shape typical for the 3-rd min (fission isomer state)

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Potential-energy curve (fission barrier) for $^{232}$Th calculated in the frame of the finite–temperature superfluid nuclear density functional theory [4]

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We suppose the doorway state for the CCT, at least manifested itself as the “Ni-bump”, corresponds to the differential neutron multiplicity
$Y(\nu_L/\nu_H = 4/0)$, while the $Y(\nu=4)=30\%$.
It is known as well that
$[Y(\nu_L/\nu_H = 4/0)/ Y(\nu=4)]=5.13\%$
(appreciation to Dr. A. S. Vorobyev, from Gatchina, private comm.)
Thus
$Y(\nu_L/\nu_H = 4/0) = 1.54 \times 10^{-2}$ per binary fission.

On of the fork-tooth must be missed for the correct detection of an other one.

**Table 1. Probability of the brake-up of the intermediate fragment in CCT per ($\nu_L/\nu_H = 4/0$) state**

<table>
<thead>
<tr>
<th>$L$, mm</th>
<th>PIN, mm</th>
<th>$\varphi$, grad</th>
<th>$S_{\text{green}}/S_{\text{all}}$</th>
<th>$Y_{\text{exp}}(\text{Ni})$</th>
<th>$Y_{\text{all}}(\text{Ni})$</th>
<th>$P_{\text{brak-up}}(\nu(4/0)$ state</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>18x18</td>
<td>1</td>
<td>0.5</td>
<td>$2 \times 10^4$</td>
<td>$4 \times 10^4$</td>
<td>3%</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>0.3</td>
<td>0.17</td>
<td>---</td>
<td>$10^{-3}$</td>
<td>10%</td>
</tr>
</tbody>
</table>
Summary
Summing up, the following scenario of the most populated CCT mode manifested itself as “Ni-bump” could be proposed.

1. The doorway state for the forthcoming CCT represents very elongated nuclear configuration of two magic clusters connected by the long neck.
2. The first rupture occurs near the surface of one of the magic constituents, predominantly, the heavy one.
3. After first rupture the intermediate nucleus gains the deformation and the shape corresponded to its fission isomer state.
4. The life-time of the isomer state till the brake-up exceeds 400 ns.
5. The probability of the brake-up of the Cd-like fragment per one doorway state manifested itself in the binary fission via asymmetric neutron emission ($v_L/v_H = 4/0$) is estimated to be in the range 3% - 10%.
6. At the moment of the second rupture the deformation energy is concentrated mainly in the Ca-like nucleus which de-excites emitting 4 neutrons.

Just the kinematic mode where Ca stays almost at rest after the brake-up of Cd was identified by the neutron belt at the modified FOBOS spectrometer [EPJ A 2012].
Conclusions

1. Experimental results with approximately three times higher statistics obtained at the COMETA spectrometer confirmed the main features of the Ni-bump.

2. With the help of the VEGA setup reliable direct detection of two CCT partners in one spectrometer arm is achieved. The life time of the fission isomer state linked with the CCT channel observed exceeds 400 ns.
Strongly deformed prescission shapes of the $^{252}$Cf nucleus

$Y$ of $\nu_{tot} = 6$ and $\nu_L/\nu_H = 6/0$: 2.19% and 0.72% for $^{248}$Cm and $^{252}$Cf resp.


Scenarios of the CCT modes manifested in “Ni-bump”

<table>
<thead>
<tr>
<th>No</th>
<th>Label of the locus in Fig. 3(d)</th>
<th>Prescission configuration of the system</th>
<th>System configuration after the 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>$R_{12} \geq 23$ fm</td>
<td>$E_{int_2&amp;2}$</td>
<td>$R_{12} \rightarrow \infty$</td>
</tr>
<tr>
<td></td>
<td>$w1c$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>$w2b$</td>
<td></td>
<td>$E_{int_2&amp;2}$</td>
<td>$R_{12} \rightarrow \infty$</td>
</tr>
<tr>
<td></td>
<td>$w2c$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>$w3b$</td>
<td></td>
<td>$E_{int_3}$</td>
<td>under acceleration</td>
</tr>
<tr>
<td></td>
<td>$w3c$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>binary fission</td>
<td></td>
<td>$E_{int_2}$</td>
<td></td>
</tr>
</tbody>
</table>
Energies of the detected fragments in Ex1 and Ex2

similar results
Clustering in Stable and Exotic Light Nuclei

Fig. 1. Different types of clustering behavior identified in nuclei, from small clusters outside a closed shell, to complete condensation into α-particles, to halo nucleons outside of a normal core, have been discussed the last two or three decades. This figure was adapted from Ref. 13, courtesy from W. Catford.

Fig. 2. Schematic illustration of the structures of molecular shape isomers in light neutron-rich isotopes of nuclei consisting of α-particles, 16O- and 14C-clusters plus some covalently bound neutrons (Xn means X neutrons). The so-called "Extended Ikeda-Diagram" with α-particles (left panel) and 16O-cores (middle panel) can be generalized to 14C-cluster cores (right panel). The lowest line of each configuration corresponds to parts of the original Ikeda diagram. However, because of its deformation, the 12C nucleus is not included, as it was earlier. The numbers represent the threshold energy dissociating the ground state into the respective cluster configuration. Threshold energies are given in MeV. This figure has been adapted courtesy from W. von Oertzen.

(IJMPE Special Cluster, C. Beck, Clustering in Stable and Exotic Light Nuclei, 2016)
Collinear cluster tri-partition (CCT) – status quo

Prescission ternary configurations supposed to be in game

http://fobos.jinr.ru/
Ex3: different animals in the zoo but all big enough (against interferences)

almost overlapping

Time vertex ? - to be found...

one FF is missed

double-hit

FF is at the limit of the gate