New results in studies of the shape isomer states in fission fragments

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Fission fragments as shape isomers – hot points in treatment
Just to remind: our previous experimental results

Layout of the source module

In each ternary event: $M_1 > M_2 > M_3$

Region of elastic FF scattering

$^{63, 65}$Cu, 0.83 mkm
“true” calibr.
W: $E_3 > 9$ MeV

From C13_r2_m3_last.opj & w1: E3plz>9MeV (для устранения случ совпад с альфа)
Mass spectrum of the fragments detected in coincidence with the knocked out ions of Ti, Ni, Cu

Really:

Hypothesis: we suppose each FF, at least just after scission, looks like a di-nuclear system “magic cluster + light ion”

Due to the brake-up in the foil both constituents become free. Thus one of them should be magic nucleus.
As in the fission isomers we also expect some life-time of the isomer state in FF relative to transition to the ground state.

We have estimated experimentally the low limit for this life-time. It exceeds 1 ns.
LIS setup: Mtt & Mte & degrader

- PIN2
- TD2
- StartTD
- TD1
- PIN1

Dimensions:
- L1 = 301.0 mm
- L2 = 223.0 mm
- L3 = 150.5 mm
- L4 = 150.0 mm
- L5 = 150.5 mm
- L6 = 73.0 mm

Mass numbers:
- 124 Cd
- 128 Sn
- 134 Te
- 134 Ba
- 124 Cd
Mass spectra of the FFs crossed the foil

Comparison: $Y(M)_{lit} : \chi^2/n \sim 30$
$Y(128): 3\sigma=16, S_{above\_smooth}=18$

Magic “residuals “ only form the mass-spectrum after FF passing through the foil
Evidence of a more complicated cluster configurations in heavy fragment

Mass distributions below the loci of binary fission
Evidence of a more complicated cluster configurations in the light fragment

Preformed presumably $^{16}\text{O}$ manifests itself due to inelastic scattering of the FF in the foil
Estimation of the life time of the isomer states in FF
Estimation of the life time between the Cu foil and the Cf source, **TOF~1ns**

TOF ~ 15ns

Cu ions in frontal mosaics 2&4

- Cu foil 0.5 μm, d=0.1 mm (elastic FF scattering)
- Cu foil 0.83 μm, d=10mm (x1.25)

Counts/amu vs. (M₁+M₂)amu
Cluster configurations based on a pair of identic magic clusters
Observation of the “symmetric” CCT mode in $^{235}\text{U}(n_{\text{th}}, f)$ (IBR-2, mini-FOBOS)
Cluster configurations based on a pair of identical magic clusters.
Cluster configurations based on a pair of identical magic clusters

$^{235}\text{U}(n_{th}, f), \text{ IBR-2}$

Energies are summed up $\rightarrow$ unrealistic big MH

$^{88}\text{Se}, ^{94}\text{Kr}, ^{98}\text{Sr}, ^{106}\text{Nb}$
Now cross-talk with our results linked with the topic under discussion but obtained by an absolutely different way.
Revealing of the fine structures (FS) in the M-TKE distributions

$^{233}\text{U}(n, f)$
We assume that a trajectory in the deformation space as a continuous sequence of nuclear states in the fission valley is mapped to continuous trajectories (smooth curves) in the plane of experimentally observed variables.

Thus, the fine structure under discussion is a unique image of separate fission trajectories passed by a system.

Yu. V. Pyatkov et al., Pattern Recognition and Image Analysis, v. 21, №16 (2011) 82
“Symmetric” modes based on deformed magic clusters of $^{108}\text{Mo}$ & $^{112}\text{Ru}$

- Fine structure revealed by the “symmetry” filter; a – using $M=120\text{amu}$ as an axis of symmetry;
- b – the same for the $M=121\text{amu}$. The most pronounced structures are marked to guide the eye.
Origin of the symmetric fission mode

Studying of rare multi-body decays flashes up fundamental properties of the main process of “conventional” binary fission.

The shape of the distinct path gives an idea concerning the origin of so called "symmetric fission mode"
Conclusions

1. In the frame of the new methodic approach some basic results concerning the shape isomer states in the FF were confirmed.
2. New cluster effects linked with “symmetric” CCT mode are revealed.
3. The low limit of the FF isomer states life time was re-estimated to be more than 15ns.
Rutherford scattering - L_FF/Ti

2 solutions are possible: the same scattering angle at two different impact parameters

\[ \sigma(\theta) = \left(\frac{1}{4\pi\varepsilon_0}\right)^2 \frac{Z^2 e^4}{M^2 v^4} \times \frac{1}{\sin^4(\theta/2)} \]

- \( Z e \) = the positive charge of the target atom,
- \( M \) = the mass of the \( \alpha \) particle,
- \( v \) = incident speed of the \( \alpha \) particle,
- \( \theta \) = scattering angle,

Original Rutherford experiment

frontal impact
Low energy heavy FFs – good mass reconstruction
Conclusions presented at the previous ISINN21 meeting in 2013.

Presumably:

1. Inelastic impact, at least the frontal one, makes free the constituents of the di-nuclear system (fission fragment) formed in the binary fission.

2. Bearing in mind the distance between the Cf source and the generating foil (~1mm) the lower limit of the life-time of this di-nuclear system (shape isomer) is about 0.1ns.

3. Relative probability of elastic Rutherford scattering of fission fragments i.e. taking place without missing mass is much less then those in the inelastic channel. In other words, the bulk of the fragments from the conventional binary fission are born as shape-isomers.
Principal question to be answered:

Are there contradictions of the experimental results obtained and model proposed with well known features of the fission process?

1. We suppose that the bulk of the fragments of conventional binary fission look like di-nuclear systems (are in shape isomeric states) just after scission.

Does it mean that the total yield of the effect is sufficient to change the macroscopical fission constants?

Our answer: **No!** The brake-up of di-nuclear system (FF) appears to occur in almost frontal inelastic collisions which takes place with relatively low probability.
Angular dependence of the brake-up yield

At the large angles of scattering of the knocked-out ions from the foil, conventional elastic Rutherford scattering takes place.
There is no such peak in M1+M2 spectrum FF from conventional binary fission. Likely loosely coupled (see Poenary predictions) 10Be based di-nuclear system experiences a breakdown even in tangent collisions.

**Table 1. Calculated half lives of some quasi-molecular states**

<table>
<thead>
<tr>
<th>Particle</th>
<th>Fragments</th>
<th>$Q_{exp}$ (MeV)</th>
<th>$K$</th>
<th>log $T$ (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10Be</td>
<td>$^{132}$Sn $^{110}$Ru</td>
<td>220.183</td>
<td>19.96</td>
<td>-11.87</td>
</tr>
<tr>
<td>138Te</td>
<td>$^{104}$Mo</td>
<td>209.682</td>
<td>25.23</td>
<td>-9.59</td>
</tr>
<tr>
<td>138Xe</td>
<td>$^{104}$Zr</td>
<td>209.882</td>
<td>26.04</td>
<td>-9.23</td>
</tr>
<tr>
<td>146Ba</td>
<td>$^{96}$Sr</td>
<td>201.486</td>
<td>22.98</td>
<td>-10.56</td>
</tr>
</tbody>
</table>

**ps** life times are predicted, **low barrier** against the decay.
Estimation of the life time

10mm between the Cu foil and the Cf source, TOF~1ns
Are there contradictions with known features of the fission process?

2. According to our experiments fission fragments in the shape isomeric states show life time at least more than 1ns. What about the neutrons emitted from the fission fragments orders of magnitude faster?
Observation of new microsecond isomers among fission products from in-flight fission of 345 MeV/nucleon $^{238}$U


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Abstract

A search for isomeric $\gamma$ decays among fission fragments from 345 MeV/nucleon $^{238}$U has been performed at the RIKEN Nishina Center RI Beam Factory. Fission fragments were selected and identified using the superconducting in-flight separator BigRIPS and were implanted in an aluminum stopper. Delayed $\gamma$ rays were detected using three clover-type high-purity germanium detectors located at the focal plane within a time window of 20 $\mu$s following the implantation. We identified a total of 54 microsecond isomers with half-lives of $\sim 0.1-10$ $\mu$s, including the discovery of 18 new isomers in very neutron-rich nuclei: $^{59}$Ti, $^{90}$As, $^{92}$Se, $^{93}$Se, $^{94}$Br, $^{95}$Br, $^{96}$Br, $^{97}$Rb, $^{108}$Nb, $^{109}$Mo, $^{117}$Ru, $^{119}$Ru, $^{120}$Rh, $^{122}$Rh, $^{121}$Pd, $^{124}$Pd, $^{124}$Ag, and $^{126}$Ag, and...

The fast isotopic separation and identification of reaction products, which take place in several hundred nanoseconds, allow event-by-event detection of isomeric $\gamma$ rays at the focal plane of the separator with small decay losses in flight. The $\gamma$ decays are observed under low-background conditions after ion implantation. ...

In-flight fission of a uranium beam have been used as production reactions to populate isomers. In-flight fission is known to be an excellent mechanism for producing neutron-rich exotic nuclei...
Nuclear shape isomers

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We calculate potential-energy surfaces as functions of spheroidal (ε2), hexadecapole (ε4), and axial asymmetry (γ) shape coordinates for 7206 nuclei from $A = 31$ to $A = 290$. We tabulate the deformations and energies of all minima deeper than 0.2 MeV and of the saddles between all pairs of minima. The tabulation is terminated at $N = 160$. We also present potential-energy contour plots versus $ε2$ and $γ$ for 1224 even–even nuclei in the region studied. We can identify nuclei for which a necessary condition for shape isomers occurs, namely multiple minima in the calculated potential-energy surface.
Apparently, we and RIKEN group deal with the same shape isomers and they observe the de-excitation of isomeric states by detecting of delayed $\gamma$-quanta. We fill the presence of di-nuclear system (shape isomer) via brake-up.

FIG. 5 (color). Number of minima found with deformation $\epsilon_2 < 0.45$. Only the ground-state and isomer minima that are deeper than 0.2 MeV and with energies relative to the ground state of less than 2.0 MeV are counted.
Within the *two-center shell model* (TCSM) for a given nuclear configuration, we may determine the two deformed cores $a_1$ and $a_2$ surrounded with a certain number of shared nucleons: $A = ACN - a_1 - a_2$. During binary fission, these valence nucleons gradually spread between the two cores with the formation of two final fragments, $A_1$ and $A_2$.

Our case of almost complete fusion of two nuclei constituting initial di-nuclear system.

I’d like to stress once more: basing on our data we suppose each FF to be a di-nuclear system at least just after scission.
The bottoms of the fission valleys as a function of parameter $Q$ (proportional to the quadrupole moment) for $^{234}$U.

Shape isomer state (SIS) in the second potential well. De-excitation is possible via gamma channel.

Treating of our case

Some kind of memory about initial configuration: 2 distinct nuclei.

Almost complete fusion.

Actually it is a low excited state of the resultant $a_1+a_2$ nucleus. The main part of the initial $E^*$ is already exhausted by emitted neutrons.

The fusion process is stopped at the final stage reaching gamma-isomeric state. The residual $E^*$ will be carried away by gammas through time to be characteristic for this channel of de-excitation. (some $\mu$s presumably)
The last intriguing question to be discussed:

Whether all structures assigned to the CCT actually are resulted from the brake-up process discussed above?
Effect is seen in the arm from the side of scattering foil only. Thus, it is due to scattering in any sense.

Individual modes / structures with equal velocity/momentum window

Structures symmetric to the arms

Vice versa: structures symmetric to the arms are independent from the scattering
Structures symmetric to the arms

$^{252}\text{Cf, FOBOS}$

$\text{FOBOS}$
$n=1$
&
momentum
box
Structures symmetric to the arms

COMETA, Cu foil, n=1

Missing mass ~50 amu

$M_1 = M_2$
Conclusions

1. Now we have not find any contradictions between all our experimental data obtained and known features of conventional fission process.
2. Studying of rare multi-body decays flashes up fundamental properties of the main process of “conventional” binary fission.
In each ternary event:

\[ M_1 > M_2 > M_3 \]

1: missing mass

2: expecting scattered events

E(Ti) = 22-57 MeV

E(Ti) = 12-40 MeV
Experimental results_2

**Ex2:**

- Ti, 2.2 mkm
- 3-point calibr.
- $E(Ti) = 25-70$ MeV
- $S = 342$ events

C12_r5 w1: n3_p3<30 (t.e. M3_3p in mos1&2) s=342 3p_calibr
Previous experiments at the COMETA setup - only thin AL₂O₃ backing was in game

Similar structure of the M₁-M₂ plot for ternary events
Both the experimental geometry and energies of the knocked-out ions give evidence that we deal with this branch of the scattering process.
FF as a di-nuclear system – possible scenario of forming

Double-magic-cluster structure of the fissioning system:

V.V. Vladimirski, JETP (USSR) 5 (1957) 673

S.L. Whetstone, Phys. Rev. 114 (1959) 581

I. Tsekanovich,
H.-O. Denschlag, M. Davi,
Z. Büyükmumcu,
F. Gönennenwein, S. Oberstedt,
H.R. Faust

Yu.V. Pyatkov, V.V. Pashkevich, Yu.E. Penionzhkevich et al.,
Two magic clusters namely, light & heavy give rise to fission mode while the neck is also clusterised consisting of LCP.

Initial configuration
Of the fission mode
Based on Sn & Ge clusters

Yu.V. Pyatkov, G.G. Adamian,
N.V. Antonenko et al.,
A possible way of decaying of di-nuclear system

Different inertia of the partners in the frontal impact could be the reason of their scission.

naive illustration of an inertial effect likely to be decisive for decaying of a nuclear molecule
S. Ćwiok et al.,

Fig. 1. Potential energy curve for $^{232}$Th as a function of quadrupole deformation $\beta_2$ along the shorter static fission path of fig. 2.

density distribution at the third minimum looks like a di-nucleus consisting of a nearly-spherical heavier fragment (around doubly-magic $^{132}$Sn) and a well-deformed lighter fragment (from the neutron-rich $A \sim 100$ region).

Fig. 2. The Woods–Saxon–Strutinsky total potential energy (relative to the spherical macroscopic energy) for $^{220}$Rn, $^{222}$Ra, $^{232}$Th, and $^{234}$U, as a function of $\beta_2$ and $\beta_3$. At each $(\beta_2, \beta_3)$ point the energy was minimized with respect to $\beta_4$–$\beta_7$. The distance between the solid contour lines is 0.5
Three-humped barrier calculated along the fission path of $^{296}_{116}$Lv (Livermorium).

“These intermediate minima correspond to the shape isomer states. From analysis of the driving potential we may definitely conclude that these isomeric states are nothing else but the two-cluster configurations with magic or semi-magic cores surrounded with a certain amount of shared nucleons.”
Calculated Fission Valleys ($^{246}\text{Cm}$)

Valley of the mass-asymmetrical shapes

Valley of the mass-symmetrical shapes

V. V. Pashkevich et al.
Aligned and compact configurations for $\alpha$-accompanied and $\alpha+^6$He+$^10$Be accompanied cold fission of $^{252}$Cf.
