Correlated transitions in TKE and mass distributions of fission fragments described by 4-D Langevin equation

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M. Usang et al., Scientific Reports 9, 1525 (2019)
Background: Anomalies in FFMDs and TKEs

Anomaly in fission fragment masses and that in averaged TKE were experimentally discovered.

1. Sudden change in FFMD from asymmetric to symmetric.
2. High \( \langle TKE \rangle \) far from Viola/Unik systematics

\( \Rightarrow \) No theory can explain these anomalies SIMULTANEOUSLY.

Some models can predict FFMDs, while few models can provide precise TKEs.
Today’s Topic:
Correlated transition between FFMDs and TKEs
M. D. Usang et al., Scientific Reports9, 1525 (2019)

➢ **Aim**
  • To understand the sudden FFMD/TKE transitions in Fm-isotopes

➢ **Model**
  • 4D-Langevin model with two-center model, which can provide both FFMD and TKE(A) of $^{236}\text{U}$ precisely

➢ **Calculations**
  • From actinides to trans-actinides (from $^{236}\text{U}$ to $^{259}\text{Lr}$)

➢ **Analysis**
  • Obtained TKEs following the Brosa fission model
  • Comparison between the TKEs and FFMDs

➢ **What we found twin transition in**
1. Symmetric modes from super-long to super-short mode
2. Dominant modes from asymmetric mode to symmetric mode at Fm, Md
4-dimensional Langevin model

C. Ishizuka et al, Phys. Rev. C 96, 064616 (2017)

\[ \frac{dq_i}{dt} = \left( m^{-1} \right)_{ij} p_j \]

\[ \frac{dp_i}{dt} = -\frac{\partial F}{\partial q_i} - \frac{1}{2} \frac{\partial}{\partial q_i} (m^{-1})_{jk} p_j p_k - \gamma_{ij} (m^{-1})_{jk} p_k + \rho_{ij} R_j(t) \]

Shell corrections to the free energy \( F \) derived from their formal definitions without any additional approximations. [Ref] F. A. Ivanyuk, et al, Phys. Rev. C 97, 054331 (2018)

Macroscopic transport coefficients:
Collective inertia tensor \( m_{\mu\nu} \):
The Werner-Wheeler approx. of the liquid drop mass tensor
The friction tensor \( \gamma_{\mu\nu} \):
The wall-window friction formulation.

Shape parametrization in the two-center model proposed by Maruhn & Greiner 1972
\( q_i = (z_{\vartheta}, \delta_1, \delta_2, \alpha) \) in 4D or \( q_i = (z_{\vartheta}, \delta, \alpha) \) in 3D (\( \delta_1 = \delta_2 \))

Fixed parameters
- Neck parameter \( \varepsilon = E/E_0 \)
- The local frequency of collective motion \( \omega \)
Brosa Fission model
Brosa et al., Z. Naturforsch 41(a), 1341–1346 (1986)

Brosa calculated the average TKE of the fission mode for given possible shapes of the nuclei.

Super-short Fission Modes
➢ Average TKE bigger than standard fission modes
➢ Both fragments are oblate

Standard Fission Modes
➢ Average TKE that scales with Coulomb repulsion systematics of Viola and Unik.
➢ One fragment is oblate and the other fragment is prolate.

Super-long Fission Modes
➢ Average TKE smaller than standard fission modes
➢ Both fragments are prolate
Results

M. Usang et al., Scientific Reports 9, 1525 (2019)
Systematics

M. Usang et al.,
*Scientific Reports* 9, 1525 (2019)  \( \frac{Z^2}{A^{1/3}} \)
Systematics

Dominant modes
@TKE anomalies
Standard mode
Super-short mode
Standard mode

Symmetric modes
@TKE anomalies
Super-long mode
Super-short mode

M. Usang et al.,
Scientific Reports 9, 1525 (2019)
Results

M. Usang et al., *Scientific Reports* 9, 1525 (2019)
Results

\[ \delta_H = \delta_L \]

Dominant component

\[ \delta_H \neq \delta_L \]

sub-component

M. Usang et al., *Scientific Reports* 9, 1525 (2019)
Results

\[ \delta_H = \delta_L \]

(3D)

M. Usang et al., *Scientific Reports* 9, 1525 (2019)
Two-center model parametrization, 4D-Langevin model, Finite-depth Woods-Saxon type (mean-field) potential to calculate single-particle energy and shell corr.

Shell corr. calculated exactly starting from their definitions Without any approximation.
Ivanyuk et al. (2018) Phys. Rev. C 97, 054331

|                | <TKE>          |
|----------------|----------------|
| Present (with Ivanyuk+2018) | 137.92 MeV     |
| Nishio+2015, $^{180}$Hg*    | 131.7(10) MeV  |
| $\beta$DF study of $^{180}$Tl, $^{180}$Hg | 133.2(14) MeV  |
| Viola systematics         | 142.1 MeV      |
Conclusion and way forward

➢ Our 4-D Langevin calculations reveals that
  • the standard fission modes are dominant except $^{258}$Fm, $^{259}$Fm and $^{260}$Md
  • the symmetric component switches from super-long to super-short fission mode from Es to larger fissioning system.
  • when the fragments of $^{258}$Fm, $^{259}$Fm and $^{260}$Md prefers double magic configuration, the only channel available in the symmetric component is super-short

➢ 4-D Langevin equation allows natural transition from $^{256}$Fm to $^{258}$Fm.

➢ 3D Langevin is not sufficient to describe all possible fission path.

➢ Shell correction factor approximates higher temperature potential energy surfaces by moderating the contribution of shell correction.

➢ However, we noticed that careless applications of shell correction may give misleading conclusions. Thus we suggest either judicious choice of shell corrections depending on experimental situations
  • Ivanyuk et al. (2018) [Phys. Rev. C 97, 054331] shell correction factors for various fissioning systems
  • calculate shell corrections for a given temperature.
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Thank you for your attention.