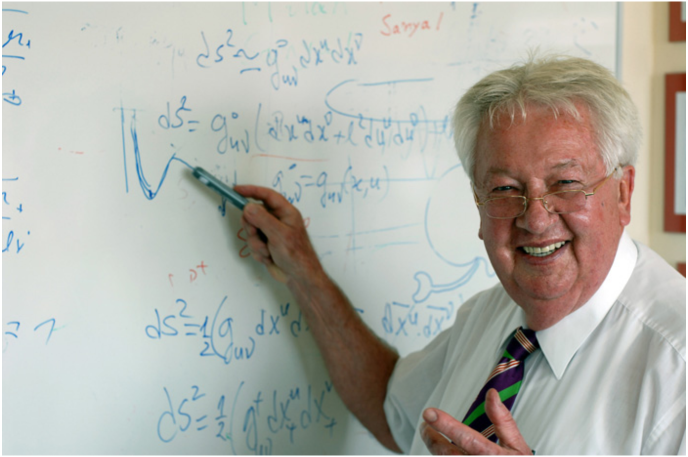
ECT-Trento Workshop on Fission of Super-Heavy Elements, Trento, Italy, April 9-13, 2018
Theory of spontaneous fission of superheavy nuclei and its competitor decay modes.

D.N. Poenaru   R.A. Gherghescu

Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest-Magurele, Romania
and
Frankfurt Institute for Advanced Studies (FIAS), J W Goethe University, Frankfurt am Main, Germany

DEDICATED TO WALTER GREINER



Prof Dr DrHCmult Walter Greiner (Courtesy J.H. Hamilton, Vanderbilt Uni)
See J.H. Hamilton and D.N. Poenaru, Walter Greiner Obituary, in *Physics Today in People and History* 24 May 2017.

OUTLINE

Cluster preformation

Cold Fission; Macroscopic-microscopic model; Asymmetric two-center shell model. Example for fission of ^{286}Fl.

Fission dynamics:

Cranking inertia
The least action trajectory.

Competition of α- and cluster- decay

Possible Chains of Heaviest SHs

CLUSTER PREFORMATION

In 1928 Gamow and Condon & Gurney explained α decay as a quantum tunneling of a preformed particle at the nuclear surface. After discovery in 1984 by Rose and Jones of cluster radioactivity (CR), confirming 1980 predictions by Sandulescu, Poenaru and Greiner http://www.britannica.com/EBchecked/topic/465998/, a similar explanation was extended to CR. We show for the first time that in cold fission the shell corrections give a strong argument for preformation of a light fission fragment near the nuclear surface.

Objectiv

A better understanding of the cold fission process. Examples for ^{282}Cn, ^{252}Cf and ^{240}Pu.

Solution

Using macroscopic-microscopic method with the radius of the light fragment, R_2, linearly increasing with the separation distance, R.

COLD FISSION

$$^{Z}A \rightarrow ^{Z_1}A_1 + ^{Z_2}A_2$$

Parent nucleus $\rightarrow$ heavy fragment + light fragment

Spontaneous fission was discovered in 1940 by G.N. Flerov and K.A. Petrzhak.
Usually the fission fragments are deformed and excited; they decay by neutron emission and/or γ rays, so that the total kinetic energy (TKE) of the fragments is smaller by about 25-35 MeV than the released energy, or Q-value.

In 1981 C. Signarbieux *et al.* (Journal de Physique (Paris) Lettres **42**, L437 (1981)) discovered the cold fission — a rare process in which TKE almost exhausts the Q-value (the fragments are not excited).

MACROSCOPIC-MICROSCOPIC MODEL

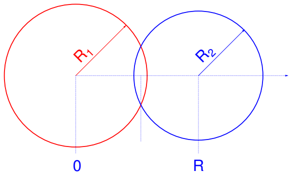
The asymmetric mass distributions of fission fragments and the spontaneously fissioning shape isomers, discovered by S.M. Polikanov *et al.* in 1962, could not be explained until 1967, when V.M. Strutinsky reported his macroscopic-microscopic method. He obtained a two hump potential barrier for heavy nuclei. Shape isomers occupied the second minimum.
He added to the phenomenological deformation energy, E_{def}, the shell plus pairing correction energy,

$$\delta E = \delta U + \delta P = (\delta U + \delta P)_p + (\delta U + \delta P)_n$$

$$E_{def} = E_{LD} + \delta E$$

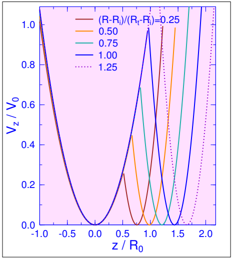
We use the Yukawa-plus-exponential model (Y+EM) to calculate $E_{def} = E_{Y+E}$, and R.A. Gherghescu's asymmetric two center shell model (ATCSM) to calculate δE. The BCS (Bardeen, Cooper, Schrieffer) system of two eqs. allows us to find the Fermi energy, λ, and the gap parameter, Δ, the pairing correction and the cranking inertia tensor needed to study Dynamics and calculate the half-life along the least action trajectory.

INTERSECTED SPHERES

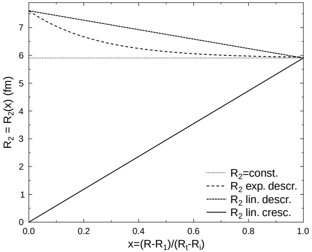


Two intersected spheres. Volume conservation and R_2 = constant or $R_2 = f(R)$. One or two deformation parameters: separation distance R and R_2. Surface equation $\rho = \rho(z)$. Initial $R_i = R_0 - R_2$. Touching point $R_t = R_1 + R_2$. Normalized variable $x = (R - R_i)/(R_t - R_i)$

Example: $^{232}U \rightarrow\ ^{24}Ne + ^{208}Pb$



TWO SHAPE COORDINATES: R and R_2



Different variation laws $R_2 = R_2(R)$:

$R_2 =$ constant

Exponentially decreasing

$$R_2 = R_{2f} + (R_{20} - R_{2f})e^{-k_2 \frac{R-R_i}{R_t-R_i}}$$

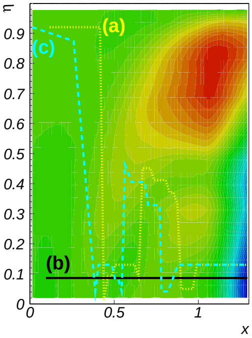
Linearly decreasing

$$R_2 = R_{2f} + (R_{20} - R_{2f})\frac{R_t-R}{R_t-R_i}$$

Linearly increasing $R_2 = R_{2f}\frac{R-R_i}{R_t-R_i}$

Only at the touching point $R_2 = R_{2f}$. This dynamical evolution produces the bunching (high quantum degeneracy) of the ATCSM single-particle levels responsible for the minimum of shell correction energy near the nuclear surface.

THREE LEAST ACTION PATHS ^{286}Fl

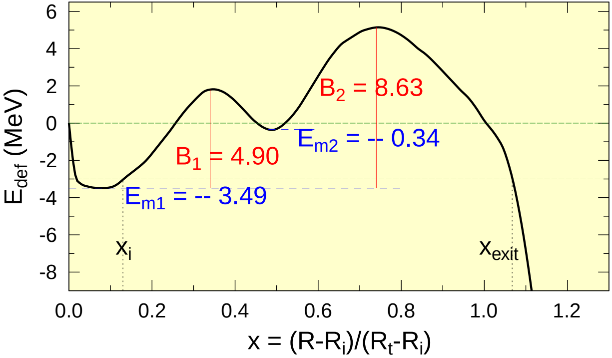


Three least action trajectories: (a) yellow dotted-line for exponentially decreasing R_2; (b) black solid line for $R_2 =$ constant, and (c) cyan dashed-line for linearly increasing R_2. $x = (R - R_i)/(R_t - R_i)$ and $\eta = (A_1 - A_2)/A$ are dimensionless quantities.

D.N. P. and R.A. G., Phys. Rev. C **94** (2016) 014309.

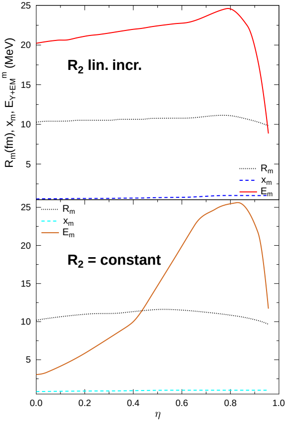
TWO HUMP FISSION BARRIER

A typical shape of the potential barrier for heavy and superheavy nuclei has two humps

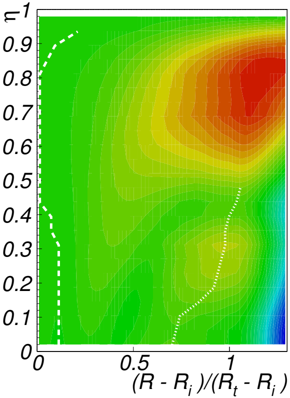


The two minima are E_{m1}, E_{m2} and the barrier heights B_1, B_2. x_i, x_{exit} are the turning points. Penetration is made via quantum tunelling effect.

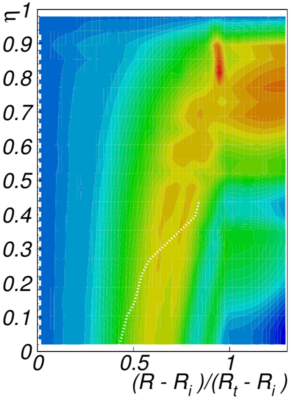
^{282}Cn POSITIONS



Position and value of maximum Y+EM model deformation energy versus mass asymmetry, η, for fission of ^{282}Cn with linearly increasing R_2 (top) and constant R_2 (bottom).



R_2 CONSTANT



R_2 LIN. INCR.

The first and second minima of deformation energy at every value of mass asymmetry are plotted with dashed and dotted white lines.

SPONTANEOUS FISSION — DYNAMICS

The potential energy of deformation, E_{def}, in hyperspace of deformation parameters $\beta_1, \beta_2, ...\beta_n$ determines generalized forces acting on a nucleus. The nuclear inertia tensor with components B_{ij}, conteins information concerning the system reaction to these forces. Unlike E_{def} which depends only on the nuclear shape, the kinetic energy

$$E_k = \frac{1}{2} \sum_{i,j=1}^{n} B_{ij} \frac{d\beta_i}{dt} \frac{d\beta_j}{dt}$$

depends on the way of the shape variation.

The nuclear half-life, T, is determined by E_{def} and B via action integral, K

$$T = \frac{h \ln 2}{2E_v exp(K)} \; ; \quad K = \frac{2\sqrt{2m}}{\hbar} \int_{R_a}^{R_b} \{ \frac{B(R)}{m} [E_{def}(R) - E_{def}(R_a)] \}^{1/2} dR$$

where E_v is the zero point vibration energy, m is the nucleon mass, R_a, R_b — turning points, $E_{def}(R_a) = E_{def}(R_b)$.

CRANKING INERTIA TENSOR

$$B_{ij} = 2\hbar^2 \sum_{\nu\mu} \frac{\langle \nu | \partial H/\partial \beta_i | \mu \rangle \langle \mu | \partial H/\partial \beta_j | \nu \rangle}{(E_\nu + E_\mu)^3} (u_\nu v_\mu + u_\mu v_\nu)^2$$

H is the single-particle Hamiltonian
E_ν is the quasiparticle energy $E_\nu = \sqrt{(\epsilon_\nu - \lambda)^2 + \Delta^2}$
$|\nu\rangle$ is the wave function ; $u_k^2 = 1 - v_k^2$
u_ν^2, v_ν^2 are the BCS occupation probabilities $v_k^2 = \left[1 - (\epsilon_k - \lambda)/E_k\right]/2$
$\{\beta_i\}$ — multidimensional hyperspace of deformation
$2\hbar^2/m = 82.94\ MeV \cdot fm^2$.
For spherical shapes we choose 2 independent deformation parameters R, η or R, R_2:

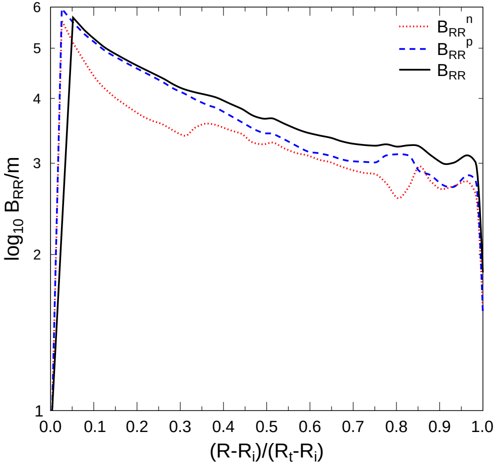
$$B(R) = B_{RR}(R, R_2) + 2B_{RR_2}\frac{dR_2}{dR} + B_{R_2R_2}\left(\frac{dR_2}{dR}\right)^2 = B_{11} + B_{12} + B_{22}$$

TECHNICAL DETAILS

- FORTRAN PROGRAMS
  - Radu: two center shell model; cranking inertia tensor and least action trajectory
  - Dorin: macroscopic deformation energy (Coulomb plus Y+EM) and shell plus BCS pairing corrections
- Graphics
  - Two dimensions: GLE
  - Three dimensions: PAW

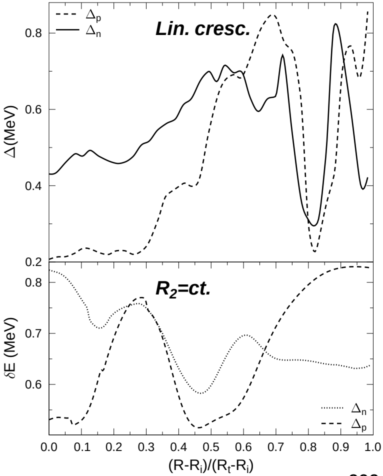
R.A. Gherghescu, Phys. Rev. C **67** (2003) 014309.
D.N. Poenaru, M. Ivaşcu, D. Mazilu, Computer Phys. Communic. **19** (1980) 205.

NUCLEAR INERTIA B_{RR} ^{282}Cn



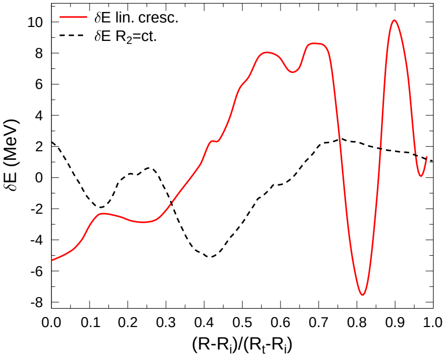
Decimal logarithm of the dimensionles RR component of nuclear inertia tensor for symmetrical fission of ^{282}Cn with linearly increasing R_2. Proton contribution is more important.

SOLUTIONS Δ_p, Δ_n OF BCS EQS. ^{282}Cn



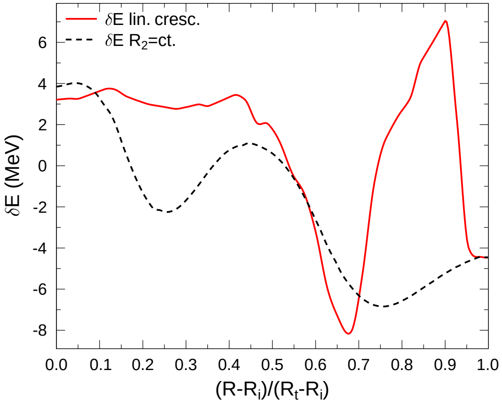
Solution of BCS equations for symmetrical fission of ^{282}Cn with R_2 constant (bottom) and linearly increasing (top): the gap for protons and neutrons.

^{282}Cn SHELL & PAIRING CORR. δE



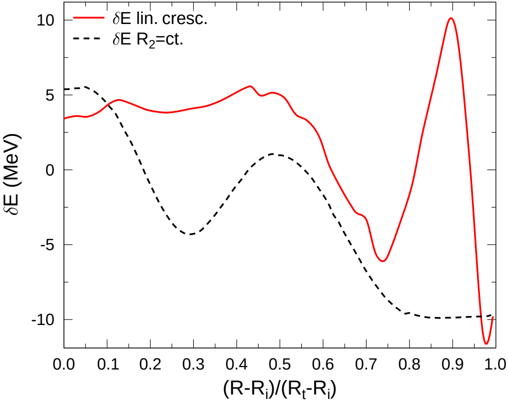
Comparison of absolute values of shell and pairing correction energies for symmetrical fission of ^{282}Cn with R_2 constant (dashed line) and linearly increasing R_2 (solid line)

^{240}Pu δE



Comparison of shell plus pairing effects for fission of ^{240}Pu with linearly increasing R_2 and constant R_2.

^{252}Cf δE



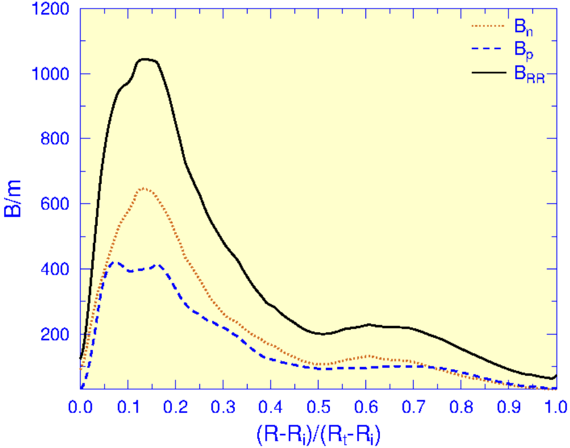
Comparison of shell plus pairing effects for fission of ^{252}Cf with linearly increasing R_2 and constant R_2.

EXPERIMENT

An interesting experiment performed by Astier et al. at the Strasbourg Vivitron with EUROBALL IV γ multidetector array proved experimentally for the first time the existence of cluster states, more exactly of $\alpha + {}^{208}$Pb structure in ^{212}Po, whose excited states have been populated by α transfer using the $^{208}Pb(^{18}O,^{14}C)$ reaction at 85 MeV beam energy.

A. Astier, P. Petkov, M.-G. Porquet, D. Delion, P. Schuck, Phys. Rev. Lett. **104** (2010) 042701; Europ. Phys. J. A **46** (2010) 165-185.

EXAMPLE of INERTIA for $^{296}120$



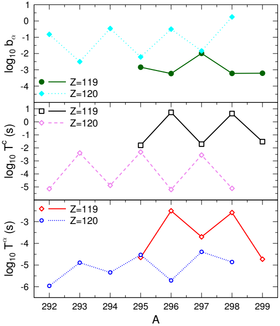
$$^{296}120 \rightarrow ^{134}Xe + ^{162}Dy$$

Prediction of heavy ion radioactivity

The New Encyclopaedia Britannica: "**Heavy-ion radioactivity.** *In 1980 A. Sandulescu, D.N. Poenaru, and W. Greiner described calculations indicating the possibility of a new type of decay of heavy nuclei intermediate between alpha decay and spontaneous fission. The first observation of heavy-ion radioactivity was that of a 30-MeV carbon-14 emission from radium-223 by H.J. Rose and G.A. Jones in 1984.*" The following cluster decay modes have been experimentally confirmed: ^{14}C, ^{20}O, ^{23}F, $^{22,24-26}$Ne, ^{28,30}Mg, ^{32,34}Si with half-lives in good agreement with predicted values within our analytical superasymmetric fission model.

http://www.britannica.com/EBchecked/topic/465998/

In figure and table we compare the half-lives for αD and CR, and the branching ratio relative to α decay
$b_\alpha = \log_{10} T_\alpha(s) - \log_{10} T_c(s)$ for the examples we took.



Since 2011 we saw that **for $Z > 121$ cluster decay may compete with α decay: DNP, RAG, WG, Phys. Rev. Lett. 107 (2011) 062503.**

ALPHA DECAY AND CLUSTER RADIOACTIVITY 2

Parent	Emitted	Q_c(MEV)	$\log_{10} T_\alpha(s)$	b_α
$^{298}119$	^{90}Rb	311.36	-2.58	-3.22
$^{300}119$	^{92}Rb	309.74	-2.19	-3.75
$^{301}119$	^{93}Rb	308.63	-3.68	-3.51
$^{302}119$	^{94}Rb	306.98	-1.60	-5.47
$^{296}120$	^{90}Sr	322.38	-5.71	-0.50
$^{298}120$	^{90}Sr	321.73	-4.86	0.25
$^{304}120$	^{90}Sr	317.33	-4.17	-1.04
$^{306}120$	^{90}Sr	316.16	-7.16	-4.41

A half-life shorter than 1 μs, like for $^{306}120$, is not measurable.

SPONTANEOUS FISSION HALF-LIVES

Parent	WAR	STA	XU	SAN	REN
^{295}119				9.52	9.98
^{296}119				12.15	8.93
^{297}119					0.79
^{298}119					-1.75
^{299}119				6.70	-11.38
^{292}120	12.15	0.14	16.00	8.65	26.18
^{293}120				11.72	21.49
^{294}120	15.82	1.23	16.22		24.45
^{295}120					18.31
^{296}120	19.57	2.89	15.7	7.99	19.26
^{297}120				10.60	11.93
^{298}120	24.62	4.28	14.5		10.70

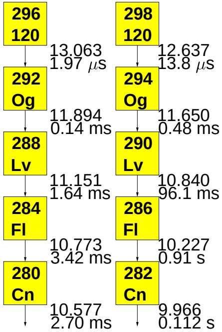
For ^{292}120 the half-lives may differ by 26 orders of magnitude!

WAR — M. Warda and J.L. Egido, Phys. Rev. C **86** (2012) 014322.
STA — A. Staszczak, A. Baran and W. Nazarewicz, Phys. Rev. C **87** (2013) 024320.
XU — Chang Xu, Zhongzhou Ren and Yanqing Guo, Phys. Rev. C **78** (2008) 044329.
SAN — K.P. Santhosh, R.K. Biju and S. Sahadevan, Nucl. Phys. A **832** (2010) 220-232.
REN — Zhongzhou Ren and Chang Xu, Nucl. Phys. A **759** (2005) 64-78.

Parent	Channel	E_b (MeV)	$\log_{10} T_f(s)$
$^{296}120$	$^{138}Ba + ^{158}Gd$	4.83	2.732
$^{296}120$	$^{136}Xe + ^{160}Dy$	4.76	1.583
$^{296}120$	$^{134}Xe + ^{162}Dy$	4.97	0.932
$^{298}120$	$^{138}Ba + ^{160}Gd$	7.22	10.76
$^{298}120$	$^{136}Xe + ^{162}Dy$	7.23	8.581
$^{298}120$	$^{134}Xe + ^{164}Dy$	5.14	1.250

TWO ALPHA DECAY CHAINS

To identify the superheavy nuclei $^{296,298}120$ one can use the decay chains from the figure, with calculated kinetic energy and half-lives



SUMMARY

- Within macroscopic-microscopic method, based on original two center shell model, we used the nuclear shape parametrization with two shape coordinates: R, R_2.
- The symmetrical cranking inertia tensor has three components, with B_{RR} — the most important one.
- A dynamical investigation for ^{282}Cn superheavy nucleus (experimental $\log_{10} T_f^{exp}(s) = -3.086$), leads to the least action along the trajectory with linearly increasing R_2.
- **BREAKING NEWS: we show for the first time that in a spontaneous cold fission process the shell plus pairing corrections calculated with Strutinsky's procedure give a strong argument for preformation of a light fission fragment near the nuclear surface.**

SUMMARY 2

- We studied alpha- and cluster decay of superheavy nuclei $^{298,300,301,302}119$, and $^{296,298,304,306}120$.
  It make sense to search for cluster decay modes: emission of ^{90}Sr from ^{296,298,304}120 with large kinetic energy, $Q > 300$ MeV and small branching ratio with respect to alpha decay (-0.50, 0.25, and -1.04, respectively).
- Spontaneous fission half-lives are longer, at least with 6 orders of magnitude larger than for α-decay.
- There is a need to improve the accuracy of calculating spontaneous fission half-lives, because one can meet large dicrepancies from model to model, e.g. **26** orders of magnitude!

THANK YOU !