New modelling of angular-momentum population and isomeric-yield ratios in fission

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Decay heat is determined by initial production \((A, Z, \text{isomers})\) and decay properties.

This talk:
Fission-fragment angular momenta and isomeric yields
Complex decay paths

Each nuclide, each state has different decay branching, different half live.

Figure from Nichols, Trieste 2002
Status in JEFF 3.1.1

Basic experimental data:
Measured isomeric ratios in $^{235}$U($n_{th},f$) $[1,2]$

Angular momentum after prompt-neutron emission:

$$P(J) = \text{const.} \times (2J + 1) \exp \left( -\frac{(J + 1/2)^2}{J_{rms}^2} \right)$$ $[3]$

$J_{rms} = 6.25$ $[2,4]$ (Variation with $A_{\text{fragment}}, Z_{CN}, A_{CN}, E^*_{CN}$ uncertain)

Population of isomers:
Spin distribution of nuclear levels in gamma emission, energy of isomer considered. $[4]$
(Adapted to statistical decay, may be not to yrast cascade)

Recent progress in experimental knowledge and theoretical ideas
Dependence on fragment mass

Data:
$J_{rms}$ grows with increasing fragment mass.
No direct link with prompt-neutron yield


Theory:
$J_{rms}$ depends on fragment mass and shape,
$J_{rms} > 0$ also for spherical fragments,
non-zero orbital angular momentum.

Dependence on compound nucleus

Data: $J_{rms}$ increases with $Z^2/A$

Dependence on $E^*$ of CN

Data:
(fission of $^{242}$Pu$^*$) $J_{RMS}$ grows with increasing $E^*$.

Dependence on angular momentum of CN

Data:  
\( J_{\text{rms}} \) grows with \( J \) of CN

Even-odd effect in $J_{rms}$

**Data:**
Higher $J_{rms}$ for odd-Z fragments.

**Theory:**
Orbital angular momentum of single proton.
B. S. Tomar et al., Pramana 68 (2007) 111
Preliminary calculations with GEF

Empirical variations with $A_{\text{fragment}}, Z_{CN}, Z_{CN}^{2}/A_{CN}, E^{*}_{CN}, J_{CN}$ considered.
GEF vs. Nichols (Madland/Rudstam)

GEF (preliminary parameters): slight improvement.
Possible reasons for remaining scattering:
model deficiencies, complex nuclear structure, data uncertainties.
Summary

- Many new experimental results on isomeric yields during the last decade. → General dependences established.

- Progress in theoretical understanding.

- New empirical description in GEF: Variation with $A_{\text{fragment}}$, $(Z^2 / A)_C N$, $E^*$, $J_{C N}$.

- Comprehensive comparison with available data and optimization of parameters in progress.
APPENDIX:

Bibliography

THEORETICAL:

"Problem of the conservation of the fissile-nucleus-spin projection onto the fissile-nucleus symmetry axis and quantum dynamics of the low-energy fission process"
S. G. Kadmensky, L. V. Titova
THEORY; NUCLEAR REACTIONS; nuclear fission; angular momentum; spin projection

"Coriolis interaction in the second well of deformation potential and low-energy fission"
S. G. Kadmensky, S. S. Kadmensky
THEORY; NUCLEAR REACTIONS; nuclear fission; Coriolis interaction; mixing of states with different K quantum numbers; angular distributions of fission fragments

"Quantum properties of deformation modes of fissile-nucleus motion"
S. G. Kadmensky
THEORY; NUCLEAR REACTIONS; nuclear fission; fission-fragment angular momentum; orbital angular momentum; uncertainty principle

"Scission configurations and their implication in fission-fragment angular momenta"
L. Bonneau, P. Quentin, I. N. Mikhailov
THEORY; NUCLEAR REACTIONS; fission; angular momenta of fission fragments; quantum-mechanical framework; orientation pumping due to uncertainty principle; importance of scission configuration

"A definition of scission points and consequences on some fission distribution"
L. Bonneau, P. Quentin, I. N. Mikhailov
Proc. IND (2007) 07168
THEORY; NUCLEAR REACTIONS; nuclear fission; definition of scission point; angular momentum

"Angular momentum of near-spherical fission fragments"
F. Goennenwein, I. Tsekhanovich, V. Rubchenya
NUCLEAR REACTIONS; nuclear fission; angular momentum of fission fragments; zero-point oscillations; thermal excitations; spherical and non-spherical fragments

"The quantum and thermodynamical characteristics of fission taking into account adiabatic and nonadiabatic modes of motion"
S. G. Kadmensky
THEORY; NUCLEAR REACTIONS; nuclear fission; spontaneous and low-energy fission; quantum and thermodynamical properties; adiabatic and nonadiabatic modes; Coriolis interaction; nonequilibrium states; pairing correlations; orbital angular momentum, spin of fission fragments
"Investigation of the reaction 208Pb(18O,f): Fragment spins and phenomenological analysis of the angular anisotropy of fission fragments"
EXPERIMENT; THEORY; NUCLEAR REACTIONS; nuclear fission; 18O + 208Pb, Elab = 78 to 198.5 MeV; gamma-ray multiplicity; spins of fragments; angular distributions; Langevin calculations; linear response theory

"Odd-even effect in fragment angular momentum in low-energy fission of actinides"
B. S. Tomar, R. Tripathi, A. Goswami
Pramana 68 (2007) 111-116
THEORY; NUCLEAR REACTIONS; nuclear fission; fragment angular momentum; scission point model; fragment deformation; low-energy fission of actinides

"Quantum and thermodynamical aspects of binary and ternary fission"
V. E. Bunakov, S. G. Kadmensky
THEORY; NUCLEAR REACTIONS; nuclear fission; low-energy fission; quantum theory; angular anisotropy; angular correlations; thermalization

"Quantum mechanical method of fragment's angular and energy distribution calculation for binary and ternary fission"
S. G. Kadmensky, L. V. Titova, N. V. Pen'kov
THEORY; NUCLEAR REACTIONS; nuclear fission; quantum mechanics; strong channel coupling; angular and energy distribution; binary and ternary fission

"The quantum and thermodynamical characteristics of fission taking into account adiabatic and nonadiabatic modes of motion"
S. G. Kadmensky
THEORY; NUCLEAR REACTIONS; nuclear fission; quantum and thermodynamic properties of the fissioning system; Coriolis interaction; pairing correlations; spins of fission fragments; binary and ternary fission; angular distributions

"Subthreshold photofission of even-even nuclei"
S. G. Kadmensky, L. V. Rodionova
Phys. At. Nucl. 68 (2005) 1421-1432
THEORY; NUCLEAR REACTIONS; nuclear fission; photofission; angular distribution and angular momentum of fission fragments; orbital angular momentum

"Quantum and thermodynamic properties of spontaneous and low-energy induced fission of nuclei"
S. G. Kadmensky
THEORY; NUCLEAR REACTIONS; nuclear fission; binary and ternary fission; superfluidity; fission-fragment angular momentum; nonadiabatic character of nuclear collective deformation motion

"Mechanisms of binary and ternary low-energy fission of nuclei with allowance for nonsphericity effects"
S. G. Kadmensky
THEORY; NUCLEAR REACTIONS; nuclear fission; binary and ternary fission; spin and orbital angular momentum of fragments

"Double fine structure in binary cold fission"
D. S. Delion, A. Sandulescu, S. Misicu, F. Carstoiu, W. Greiner
THEORY; NUCLEAR PROPERTIES; fission; binary cold fission of 252Cf; stationary scattering formalism; quasi-molecular potential pocket; angular oscillations transforming into rotation

"Ternary fission of nuclei in the adiabatic approximation"
S. G. Kadmensky
THEORY; NUCLEAR REACTIONS; nuclear fission; ternary fission adiabatic approximation; angular momentum of ternary particle

"Role of bending mode in generation of angular momentum of fission fragments"
THEORY; NUCLEAR REACTION; fission; angular momentum; bending mode; dinuclear-system concept; comparison with experimental data

"Angular momentum of fission fragments"
I. N. Mikhailov, P. Quentin, Ch. Briancon
Phys. At. Nucl. 64 (2001) 1110-1115
THEORY; NUCLEAR REACTIONS; nuclear fission; fission-fragment angular momentum

"On the spin of fission fragments, an orientation pumping mechanism"
I. N. Mikhailov, P. Quentin
THEORY; NUCLEAR REACTIONS; nuclear fission; angular momentum of fission fragments; uncertainty principle

"Angular momenta of even-even fragments in the neutronless fission of 252Cf"
S. Misicu, A. Sandulescu, G. M. Ter-Akopian, W. Greiner
Phys. Rev. C 60 (1999) 034613 (6 pages)
THEORY; NUCLEAR REACTIONS; nuclear fission; 252Cf(sf); fission-fragment angular momentum; angular momentum acquired in post-scission motion

"Statistical prescission point model of fission fragment angular distributions"
B. John, S. K. Kataria
THEORY; NUCLEAR REACTIONS; fission; statistical pre-scission point model; fission-fragment angular distributions; fragment spin distributions

"Formal theory of neutron induced fission"
A. L. Barabanov, V. I. Furman
THEORY; NUCLEAR REACTIONS; nuclear fission; neutron-induced fission; angular dependence; helicity; K quantum number
"Angular - momentum - bearing modes in fission"
L. G. Moretto, G. F. Peaslee, G. J. Wozniak
THEORY; NUCLEAR REACTIONS; nuclear fission; angular momentum; thermal limit

"Systematic features of the statistical-fission model"
L. J. B. Goldfarb
THEORY; NUCLEAR REACTIONS; nuclear fission; statistical model; fusion-fission reactions; fragment angular distributions; fragment angular momentum

"Fission fragment angular distributions"
H. Rossner, J. R. Huizenga, W. U. Schroder
THEORY; NUCLEAR REACTIONS; fission; statistical scission-point model; transition-state model; fragment angular distributions; fission-fragment angular momentum

"Equilibrium statistical treatment of angular momenta associated with collective modes in fission and heavy-ion reactions"
L. G. Moretto, R. P. Schmitt
THEORY; NUCLEAR REACTIONS; fission; Studied angular momentum fractionation along mass asymmetry mode. Investigated effect of collective rotational modes on fragment spins. Equilibrium statistical treatment.

"The influence of isomeric states on independent fission product yields"
D. G. Madland, T. R. England
@ Nucl. Sci. Eng. 64 (1977) 859-865
# EVALUATION; NUCLEAR DATA; isomeric yields; fission-fragment angular momentum

"Angular momentum distribution of fission fragments as a result of bending modes at the scission point"
M. Zielinska-Pfabe, K. Dietrich
THEORY; NUCLEAR REACTIONS; nuclear fission; angular momentum of fission fragments; bending modes

"A model for calculating the angular momentum distribution of fission fragments"
J. O. Rasmussen, W. Noerenberg, H. J. Mang
THEORY; NUCLEAR REACTIONS; nuclear fission; angular momentum

"Angular momentum effects in the gamma-ray de-excitation of fission fragments"
T. Darrah Thomas, J. Robb Grover
Phys. Rev. 159 (1967) 980-984
THEORY; NUCLEAR REACTIONS; nuclear fission; angular momentum; gamma emission from fission fragments; neutron emission from fission fragments

"Interpretation of isomeric cross-section ratios for (n,gamma) and (gamma,n) reactions"
J. R. Huizenga, R. Vandenbosch
Phys. Rev. 120 (1966) 1305-1312
THEORY; NUCLEAR REACTIONS; nuclear fission; isomeric ratios; angular momentum of fission
EXPERIMENTAL:

"Single-particle spin effect on fission fragment angular momentum"
EXPERIMENT; NUCLEAR REACTIONS; isomeric yield ratios; fission-fragment angular momentum; nuclear-structure effects

"Angular momenta of fission fragments in the alpha-accompanied fission of 252Cf"
EXPERIMENT; NUCLEAR REACTIONS; nuclear fission; 252Cf(sf); ternary fission; angular momentum of fragments

"Angular momentum of fission fragments in low energy fission of actinides"
H. Naik, S. P. Dange, R. J. Singh
EXPERIMENT; NUCLEAR REACTIONS; low-energy nuclear fission; population of isomers; deduced angular-momentum distributions; odd-even and shell effects on angular momentum; global dependencies

"Microsecond isomers in the magic regions 78Ni and 132Sn"
J. A. Pinston, J. Genevey
REVIEW; EXPERIMENT; NUCLEAR REACTIONS; nuclear fission; LOHENGRIN; microsecond isomers, isomeric yields

"Fission fragment angular momentum in ODD-Z fissioning systems"
H. Naik, S. P. Dange, R. J. Singh
EXPERIMENT; NUCLEAR REACTIONS; nuclear fission of 238Np and 241Am by fast neutrons; isomeric yield ratios measured; fragment angular momenta deduced by spin-dependent statistical model analysis

"Some important aspects of fragment angular momentum in medium energy fission of 238U"
EXPERIMENT; NUCLEAR REACTIONS; fission; 238U(alph,f), 131Te/133Te/134I, E = 25-44 MeV; measured isomeric yield ratios; deduced fragment angular momentum; entrance channel parameters

"FRAGMENT YIELDS FROM THE FISSION OF 238U BY FAST NEUTRONS"
EXPERIMENT; NUCLEAR REACTIONS; nuclear fission; independent yields; gamma-gamma coincidence data, angular momentum
"Emission angle dependence of fission fragment spin in 12C, 16O, and 19F + 232Th reactions"
EXPERIMENT; NUCLEAR REACTIONS; fission; average total spins of fission fragments; angular dependence; tilting mode

"Yields of correlated fragment pairs in spontaneous fission of 252Cf"
EXPERIMENT; NUCLEAR REACTIONS; nuclear fission; 252Cf(sf); gamma spectroscopy; fission-fragment yields; prompt neutron yields; angular momentum of fragments

"Systematics of fragment angular momentum in low-energy fission of actinides"
H. Naik, S. P. Dange, R. J. Singh, T. Datta
EXPERIMENT; NUCLEAR REACTIONS; nuclear fission; fission-fragment angular momentum; 229Th, 235,233U, 239,241Pu, 245Cm(n,F), En = thermal; measured fission fragment independent isomeric yield ratio for Sb, Te, I, Xe, Cs isotopes. Radiochemical, gamma-spectroscopic techniques RADIOACTIVITY 252Cf(SF); measured fission fragment independent isomeric yield ratio for Sb, Te, I, Xe, Cs isotopes. Radiochemical, gamma-spectroscopic techniques

"Effect of entrance channel parameters on fission fragment angular momentum in medium energy fission"
EXPERIMENT; NUCLEAR REACTIONS; fission; fission-fragment angular momentum; isomeric yield ratios of 132I; statistical model

"Gamma-ray multiplicity measurements for the determination of the initial angular momentum ranges in normal and fast fission processes"
EXPERIMENT; NUCLEAR REACTIONS; fission; gamma multiplicity; angular momentum of fission fragments; fast fission

"Correlations of fission fragment angular momentum with collective and intrinsic degrees of freedom"
H. Naik, T. Datta, S. P. Dange, P. K. Pujari, Satya Prakash, M. V. Ramaniah
EXPERIMENT; NUCLEAR REACTIONS; nuclear fission; fission-fragment angular momentum

"Effect of shell closure proximity on fragment angular momenta in 241Pu(nth,f)"
S. P. Dange, H. Naik, T. Datta, R. Guin, Satya Prakash, M. V. Ramaniah
EXPERIMENT; NUCLEAR REACTIONS; nuclear fission; isomeric yield ratios; fragment angular momentum
"Influence of fission fragment nuclear structure on scission configuration in 252Cf (S.F.)"
T. Datta, S. P. Dange, S. K. Das, Satya Prakash, M. V. Ramaniah
EXPERIMENT; NUCLEAR REACTIONS; nuclear fission; 252Cf(sf); isomeric yield ratios; influence of fragment nuclear structure; fragment angular momenta

"Angular momentum partition in HI induced fission and the effects of shells on gamma-ray multiplicities"
EXPERIMENT; NUCLEAR REACTIONS; nuclear fission; gamma emission; angular momentum of fission fragments

"Angular distributions in quasi-fission reactions: evidence for incomplete relaxation of the tilting mode"
EXPERIMENT; NUCLEAR REACTIONS; nuclear fission; quasifission; tilting mode

"Independent isomeric yield ratios and primary angular momenta in the photofission of 235,238U with 12-30-MeV bremsstrahlung"
D. De Frenne, B. Proot, H. Thierens, P. De Gelder, E. Jacobs, A. De Clercq
EXPERIMENT; NUCLEAR REACTIONS; nuclear fission; fission-fragment angular momentum; isomeric yields

"Independent yields of the isomers of 133Xe and 135Xe for neutron-induced fission of 233U, 235U, 238U, and 242Amm"
G. P. Ford, K. Wolfsberg, B. R. Erdal
EXPERIMENT; NUCLEAR REACTIONS; nuclear fission; fractional independent yields; isomeric yields; angular momentum of fission fragments

"Fission fragment angular momentum: Ratios of independent yields of isomers of 95Nb and 132I in thermal-neutron-induced fission of 233U"
T. Datta, S. P. Dange, A. G. C. Nair, Satya Prakash, M. V. Ramaniah
EXPERIMENT; NUCLEAR REACTIONS; nuclear fission; 233U(nth,f); measured independent isomeric yield ratios of 95Nb and 132I; estimated fragment angular momenta using statistical model, effect of deformation, prompt neutron number.

"Independent isomeric yield ratio of 148Pm in fission of the moderately excited 236U compound nucleus as a measure of fragment angular momentum"
D. C. Aumann, W. Gueckel, E. Nirschl, H. Zeising
EXPERIMENT; NUCLEAR REACTIONS; nuclear fission; 233,235U(n,f), E=thermal, 232Th(4He,f), E=25.8-41.4 MeV; measured 148Pm independent isomer yields; deduced primary angular momenta.

"Independent isomer yields of Sb and Te isotopes in thermal-neutron fission of 233U, 235U and 239Pu"
N. Imanishi, I. Fujiwara, T. Nishi
Nucl. Phys. A 263 (1976) 141-149
EXPERIMENT; NUCLEAR REACTIONS; nuclear fission; independent isomeric yields; angular momentum of fission fragments

"Formation cross sections of iodine and tellurium isomers produced in the fission of 238U by protons of energies 30-85 MeV"
M. Diksic, L. Yaffe
EXPERIMENT; NUCLEAR REACTIONS; nuclear fission; 238U(p,f), Ep = 30 to 85 MeV; isomeric yields; fission-fragment angular momentum

"Independent isomeric yield ratio of 148Pm in the thermal-neutron induced fission of 233U"
H. Umezawa
J. Inorg. Nucl. Chem. 35 (1973) 353-359
EXPERIMENT; NUCLEAR REACTIONS; nuclear fission; 233U(nth,f); fractional isomer yields; angular momentum of fragments

"Gamma-neutron competition in the de-excitation mechanism of the fission fragments of 252Cf"
H. Nifenecker, C. Signarbieux, M. Ribrag, J. Poitou, J. Matuszek
EXPERIMENT; NUCLEAR REACTIONS; nuclear fission; 252Cf(sf); prompt neutrons and gammas; TKE; fragment angular momentum

"Angular Momentum of Primary Products Formed in the Spontaneous Fission of 252Cf"
J. B. Wilhelmy, E. Cheifetz, R. C. Jared, S. G. Thompson, H. R. Bowman, J. O. Rasmussen
Phys. Rev. C 5 (1972) 2041-2060
EXPERIMENT; NUCLEAR REACTIONS; nuclear fission; 252Cf(sf); prompt gamma emission; angular momentum of fragments

"Ratios of Independent Yields of the Isomers Te131-131m and Te133-133m in Fission"
Demetrios G. Sarantites, Glen E. Gordon, Charles D. Coryell
EXPERIMENT; NUCLEAR REACTIONS; nuclear fission; 235U(nth,f); 232Th,238U(d,f), Ed=18MeV; 232Th,238U(4He,f), E=33MeV; independent yields; isomers; angular momentum of fragments

"Directional Correlation of Fission Fragments and Prompt Gamma Rays Associated With Thermal Neutron Fission"
M. M. Hoffman
Phys. Rev. 133 (1964) B714-B723
EXPERIMENT; NUCLEAR REACTIONS; fission; angular distributions of prompt fission gamma rays; thermal-neutron induced fission of 233U, 235U, 239Pu; angular momentum of fission fragments; Coulomb excitation of fragments

"Relative cross-sections for formation of the shielded isomeric pair 134mCs and 134Cs in medium energy fission"
H. Warhanek, R. Vandenbosh
J. Inorg. Nucl. Chem. 26 (1964) 669-676
EXPERIMENT; NUCLEAR REACTIONS; nuclear fission; 233,235,238U(n-alpha,f), E_alpha=27-42 MeV; 237Np(n-d,f), Ed=21 MeV; 233U(n-gamma,f), Egamma up to 16 MeV; fission fragments;
NUCLEAR DATA:

"The JEFF-3.1/-3.1.1 radioactive decay data and fission yields sub-libraries"
M. A. Kellett, O. Bersillon, R. W. Mills

"The JEFF-3.1.1 Nuclear Data Library"
A. Santamarina, D. Bernard, Y. Rugama, eds.

"Fission Product Yield Data for the Transmutation of Minor Actinide Nuclear Waste"
A. L. Nichols, ed.
IAEA report STI/PUB/1286 (2008)

"Nuclear Data Requirements for Decay Heat Calculations"
A. L. Nichols
Workshop on Nuclear Reaction Data and Nuclear Reactors: Physics, Design and Safety
Trieste, 25 February – 28 March 2002, LNS0520003, pp. 64

"Compilation and evaluation of fission yield nuclear data"
M. Lammer, ed.
IAEA-TECDOC-1168 (2000)

"Fission product yield evaluation"
R. W. Mills

"Isomeric yields in fission"
G. Rudstam
Proc. Specialists' Meeting on Fission Product Nuclear Data
Tokai, Japan, May 25-27, 1992
NEA/NSC/DOC(92)9