Nuclear Level Densities from an Experimental Point of View

Magne Guttormsen
Department of Physics
University of Oslo, Norway
Energy regimes of the nucleus

Level spacing $D$ and width $\Gamma$

Related to the lifetime by $\mu \frac{1}{\ldots}$
Energy regimes of the nucleus

Level spacing $D$ and width $\Gamma$

Related to the lifetime by $\mu \frac{1}{D}$
Energy regimes of the nucleus

Level spacing $D$ and width $\Gamma$

Related to the lifetime by $\mu \frac{1}{\Gamma}$

$D \gg \Gamma$ Quasi-continuum

$D \ll \Gamma$ Discrete

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Energy regimes of the nucleus

Level spacing $D$ and width $\Gamma$

Related to the lifetime by $\mu \frac{1}{\mu}$

$D \rightarrow$ Continuum

$D \rightarrow$ Quasi-continuum

$<< D \rightarrow$ Discrete
Techniques to measure level density

- Discrete levels (Ex < 2 - 3 MeV or < 50 - 100 levels/MeV)
- Neutron/proton resonances (Ex = Sn or Sp)
- Particle evaporation spectra (Ex = 4 - 15 MeV)
- Spin/parity resolved level densities from \((p,p')\) or \((e,e')\)
- Ericsson fluctuations (Ex ~ 15 MeV)
- Primary \(\gamma\) spectra with the Oslo method (Ex < Sn)

![Graphs showing level density vs. excitation energy]

M. Guttormsen et al., PRC, (2014), in press

Kalmykov et al., PRL 99, 202502 (2007)

A.C. Larsen et al., PRL 111, 242504 (2013)
Th and U experiments at OCL

12 MeV $^d$ on $^{232}$Th
24 MeV $^3$He on $^{232}$Th
15 MeV $^d$ on $^{238}$U

Backwards: $\vartheta = 126^\circ - 140^\circ$

$^3$He beam

$^3$He, $\alpha, d, t$

$\Delta E-E$

$5''x5''$ NaI

M. Guttormsen, A. Bürger, T.E. Hansen, N. Lietaer,

NIM A648(2011)168
The Oslo method
Simultaneous extraction of NLD and $\gamma$SF

T.G. Torny et al., PRC 89, 044323, (2014)

Oslo method:
M. Guttormsen et al., NIM A374 (1996) 371
M. Guttormsen et al., NIM A255 (1987) 518
A. Schiller et al., NIM A447 (2000) 498
A.C. Larsen et al., PRC 83, 034315 (2011)
Assumption for the extraction of primary $\gamma$-spectra

The same $\gamma$-energy distribution

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From total to primary $\gamma$-ray matrix

$^{232}\text{Th}(d,p)\ ^{233}\text{Th}$
From total to primary $\gamma$-ray matrix

$^{232}\text{Th}(d,p)\ ^{233}\text{Th}$
Primary $\gamma$-ray matrix

$P(E_x, E_\gamma)$

Level density $\rho(E_f)$

Fermi’s golden rule

Trans. coeff. $T(E_\gamma)$

Brink hypothesis
\( \rho(E_f) \) and \( T(E_\gamma) \)
\[ P(E, E_\gamma) = \rho(E_f) \cdot T(E_\gamma) \]
Constant-temperature level densities

\[ T = \frac{\Delta}{1.77} = \frac{12A^{-1/2}}{1.77} \]

Moretto et al.,


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**Scissors mode**

\[ E_\gamma \approx 2.4 \text{ MeV} \]

\[ B(\text{M1}) \approx 9 - 11 \, \mu_N^2 \]
NLD + $\gamma$SF + OMP = true

(a) $^{230}$Th(n, $^{231}$Th

(b) $^{231}$Th(n, $^{232}$Th

(c) $^{232}$Th(n, $^{233}$Th

(d) $^{231}$Pa(n, $^{232}$Pa

(e) $^{232}$Pa(n, $^{233}$Pa

(f) $^{236}$U(n, $^{237}$U

(g) $^{237}$U(n, $^{238}$U

(h) $^{238}$U(n, $^{239}$U

cross section (mb)

neutron energy $E_n$ (MeV)
NLD + $\gamma$SF + OMP = true
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Experimental level densities with the Oslo method
Level densities and entropy

\[ S(E) = k_B \ln W(E) \propto k_B \ln (E) \]

\[ S(E) \xrightarrow{E \to 0} 0 \]
Temperature and heat capacity

\[ T(E) = \left( \frac{S}{E} \right)^{-1} \]

\[ C_V(E) = \left( \frac{T}{E} \right)^{-1} \]

M. Guttormsen et al.,
PRC 88, 024307 (2014)
Modeling level density in $^{196}$Pt

F. Giacoppo et al., arXiv:1408.6173 (2014) and private communication

S. Goriely et al., PRC 78, 064307 (2008)

S. Hilaire et al., PRC 86, 064317 (2012)
Predictions
Summary

- Scissors mode in rare earth and actinide region
- Experimental data support the CT level density model
- Neighboring nuclei have the same temperature
- Single quasiparticle entropy of $S_1 = 1.5 - 2.0 \ k_B$
- Two anchor points for predictions:
  - discrete levels at low excitation energy
  - neutron/proton resonance spacings at Sn/Sp
Thanks to all coworkers


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5th Workshop on Nuclear Level Density and Gamma Strength
Oslo, May 18 - 23, 2015

Scientific Program
The scientific program will include invited talks, selected oral contributions from submitted abstracts, and poster presentations, covering the following topics:

- Nuclear level density
- Gamma-strength function
- Phase transitions in mesoscopic systems
- Applications in astrophysics and reactor physics
- Other related topics

As in previous Oslo Workshops, the program will allow ample time for discussions.

Abstracts
Abstracts should be less than one page long and must be submitted in PDF format. The deadline for the submission of abstracts is March 1, 2015.

Venue
The workshop will be held at the Department of Physics on the Blindern Campus of the University of Oslo. The scientific sessions will be held at Helga Engs Hus, opposite from the Department of Physics.