Statistical Spectroscopy

past, present & future?

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Motivation

- Discrete spectroscopy
  - Energies of discrete [2⁺, 3⁻, etc.] levels
  - Reduced transition matrix elements [B(E2)]

- Continuous spectroscopy
  - Level density, spacing \( \rho(E) \)
  - Radiative strength function
    \[
    \frac{dB(XL\uparrow)}{dE_\gamma} \propto f_{XL}(E_\gamma)
    \]
Motivation (continued)

- Nuclear structure
  - Level spacing → regularity, chaos
  - Sudden changes in LD → (phase) transitions
  - Resonances in RSF → simple excitation modes
- Applications (Hauser-Feshbach cross sections)
  - Astrophysical reactions
  - Medical isotope production
  - Reactor technology, transmutation of waste, stockpile stewardship, production of rare isotope beams
Level density measurements

- Counting of discrete levels (up to 100/MeV)
- Counting of neutron (proton) resonances
- Evaporation spectra
- Ericson fluctuation
- Fluctuation analysis of giant resonances
- Excitation-energy indexed gamma spectra
Level density (theory)

- Path-integral methods
  - Static path+random phase approximation
  - Shell Model Monte Carlo
- Moments of the Hamiltonian
- Combinatorial methods
Structures in level density

- $a-g$ (averaged around Fermi energy)

- Equidistant ~ deformed
- High $T$

- Shell gaps ~ spherical
- Low $T$

- Quasiparticles pairing
- High $T$

What about new shell structure in radioactive nuclei?
Shell structure of level density

- $a$ from neutron resonance spacings $\sim 7$ MeV
- Averaging at intermediate T (low for shell gaps, high for pairing)
- Mostly stable targets
Pairing and level densities

- Steps in level density correspond to breaking of successive Cooper pairs
The best staircase: $^{116}\text{Sn}$

- $^{117}\text{Sn} + ^3\text{He}$
- spin distribution?

![Graph showing the distribution of spin with respect to excitation energy for $^{117}\text{Sn}$ and $^{116}\text{Sn}$]
Comparison between experiments

- $^{162}$Dy only Oslo method
- $^{56}$Fe Oslo ↔ evaporation
Level density and rare isotopes

- Manifestation of new gaps in shell structure
- Low separation energy, wide continuum levels
- Need for experimental data
  - Evaporation spectra (integral/spectral method)
  - Excitation-energy indexed gamma spectra (need normalization)
- Spin and parity distribution in stable isotopes
Strength function measurements

- Photoneutron cross sections and photon absorption/scattering (real/virtual photons)
- Primary $\gamma$ intensities after neutron capture, two-step-cascade intensities
- Total $\gamma$ spectrum fitting method (hot GDRs)
- Excitation-energy indexed gamma spectra
RSF (theory)

- Nuclear response to simple electromagnetic operators (random phase approximation)
- Giant electric dipole resonance:
  - Shape fluctuation models
  - Collisional damping model
- Other effects
  - Strength fluctuations
  - Superradiance
Structures in strength functions

- Dominated by giant resonances
- GDR: $1\hbar\omega$ and $2\hbar\omega$ cross shell excitations
  shape of GDR determined mostly by deformation
- GMR: transitions between spin-orbit partners
  connected to GT strength function, single/double humped?
- Scissors mode
  single/double humped, strength temperature dependent?

Change of shell structure gives largest $B(E1)$ value in $^{11}\text{Be}$

Spin-orbit force $\sim \hat{l} \cdot \hat{s} \frac{dV(r)}{dr}$
Comparison of experiments

- $^{148}$Sm
  
  ![Graph 1: $\gamma$-ray energy vs. $\gamma$-ray strength function (MeV$^{-3}$)]

- $^{28}$Si
  
  ![Graph 2: $\gamma$-ray transmission coefficient (arb. units) vs. Gamma-ray energy $E_\gamma$ (MeV)]

- ![Graph 3: Spectra comparison for $^{27}$Si and $^{28}$Si]
Further tests and comparisons

- $^{148,149}\text{Sm}$
Results for the RSF

- Scissors mode in deformed rare-earth nuclei
  - large strength
  - mostly one humped
Is the soft resonance E1 or M1?
Two-step-cascade method

- Neutron s-capture
  - Parity of initial state
- Two steps to g.s.
  - Parity of final state
Results from experiment

- TSC intensities to four levels investigated
  - Two positive parity final states
  - Two negative parity final states
- All TSC intensities can be described by
  - Oslo level density
  - Oslo radiative strength function (+ decomposition)
  - M1 multipolarity of soft resonance
- Strength of resonance: $B(M1\uparrow)=6.5\mu_N^2$
An unexpected discovery

- Soft transitions between warm states in Fe
Support from TSC intensities

- Extraction of soft primary transitions
Experimental result

- Description of TSC intensities with Oslo results
Low-energy RSF enhancement

FIG. 1: Experimental level densities from the ($^{3}$He, $^1$H) (filled circle) and the ($^{3}$He, $^{3}$He') (open circles) reaction. The data from the new analysis is compared with previously published data [6].

SUMMARY AND CONCLUSIONS

The radiative strength function of $^{96}$Mo has been reanalyzed giving a slightly less pronounced enhancement at lower $\gamma$-ray energies. The data points at and below the 778 keV $^2+_1\rightarrow^0+_0$ transition have been omitted. Since extraction of level density is coupled to the radiative strength function, new level densities have also been presented.

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Mo radiative strength function

\[ (\gamma, n) \]

Rossendorf

Oslo

Hl_{\gamma}S

Duke University & TUNL

Impact of the $\gamma$-Ray Strength Function to Elastic and Inelastic Photon Scattering

$^98$Mo

$S_n$
Pygmy resonance in Sn isotopes

Pygmy centroids for the different nuclei is gratifying. As is seen in Fig. 12, the pygmy strengths (solid lines) are modeled as Gaussian pygmy additions to the GLO (theoretical predictions) and the measurements with the original normalization are also included as open squares.

The pygmy centroids of all the isotopes are estimated to be around 8.0(1) MeV. It is noted that an earlier experiment (Varlamov et al.) from Utsunomiya (Sn) and Varlamov et al. (Sn), the Oslo measurements, theoretical predictions describe the measurements rather well.

LEVEL DENSITIES AND TOTAL STRENGTHS (solid lines) are modeled as Gaussian pygmy additions to the GLO (theoretical predictions of Varlamov et al. and Fultz et al. [33]. (Lower left panel) Comparison of theoretical predictions of Varlamov et al. [31], [32] and Fultz et al. [33] from Utsunomiya [29], [30] with the Oslo measurements, the theoretical predictions of pygmy fits with experimental measurements for Sn with the Oslo measurements, the Oslo measurements multiplied with 1.8 (filled squares).

The arrows indicate the neutron separation energies. The pygmy centroids for Sn with the Oslo measurements, Sn to approximately 7.8 MeV, the pygmy centroids for Sn with the Oslo measurements, Sn to approximately 7.8 MeV, the pygmy centroids for Sn with the Oslo measurements, Sn to approximately 7.8 MeV, the pygmy centroids for Sn with the Oslo measurements, Sn to approximately 7.8 MeV.
Open questions

- Change of giant resonance parameters with shell structure, deformation, temperature
- Coupling to the continuum
- Astrophysical impact
Hot GDR width systematics

- Compilation of 347 hot GDR parameter sets
- All parameter sets brought on common footing
- At. Data Nucl. Data Tables 93, 549 (2007)
- $\Gamma(A,J,T)$ scaling law

$$\Gamma(A,J,T) = \left( \Gamma_0(A) + c(A) \cdot \log \left[ 1 + \frac{T}{T_0} \right] \right) \cdot L(\xi)^{4/(3+T/T_0)}$$

$\Rightarrow$ plot

$$\Delta \Gamma(\text{hot - cold}) / c(A) \approx 1 \quad \text{for} \quad \xi = \frac{J}{A^{5/6}} \leq 0.6 \hbar$$
Hot GDR width scaling

- Minimal bias, 183 world data
- Power-law fit → $\Delta \Gamma / c(A) = 1.24 \cdot T^{1.91}$
Decay out of SD band

- Similar situation as in neutron capture
  - One (or few) initial levels, parity known
  - One (or few) final levels, parity known
  - Statistical $\gamma$ decay
  - Energies known
  - Gretina or Agata
  - Lifetime of SD state?
Nuclear astrophysics

- Understanding r-process in absence of \((\gamma,n) \leftrightarrow (n,\gamma)\) equilibrium
  - High entropy, fast freeze-out scenarios
  - Inhomogeneous big-bang nucleosynthesis
- Astrophysics will provide \(Y_e, S, t, n_n\), etc.
- Nuclear physics has to provide \(S_n, t_{\frac{1}{2}}, P_n, (n,\gamma)\) and \((\gamma,n)\) cross sections
General abundance patterns

- Five galactic halo stars [Cowan & Sneden, Nature, 440, 1151 (2006)]
Sensitivity to nuclear data

- $t_{1/2}$ of $^{129}\text{Ag}$, $^{130}\text{Cd}$
- Effective $t_{1/2}$!

\[
\tau_{\text{eff}} = p_1 \cdot \tau_1 + p_2 \cdot \tau_2
\]
Isomeric production and effective $t_{1/2}$

- n-capture populates 2 spins and 1 parity
- Slope of RSF determines $\gamma$ multiplicity
- Isomeric production can depend strongly on $\gamma$ multiplicity
- Similarly in branchpoint s-process nuclei
- Also important in rare isotope production facilities
RSF of radioactive nuclei

- Measure Coulomb-breakup cross section

\[
\frac{d^2 \sigma_{E_1}}{d \Omega_{\text{CM}} \, d E_{\text{rel}}} = \frac{16 \pi^3}{9 \hbar c} \cdot \frac{d N_{E_1}(\theta_{\text{CM}}, E_\gamma)}{d \Omega_{\text{CM}}} \cdot \frac{d B(E1 \uparrow)}{d E_\gamma} = 3(\pi \hbar c)^2 f_{E1}(E_\gamma) \cdot \frac{d N_{E1}(\theta_{\text{CM}}, E_\gamma)}{d \Omega_{\text{CM}}}
\]

- Calculate virtual photon flux \( N(\theta_{\text{CM}}, E_\gamma) \rightarrow \sigma(\gamma, n) \)

- Relate \( \sigma(\gamma, n) \) to \( \sigma(n, \gamma) \) by detailed balance
Coulomb breakup
Level density of radioactive nuclei

- Integral measurements
- $A$ from FMA
- Protons + gammas
  - Microball
  - Gammasphere
  - Isotopic differentiation
- Proton rich nuclei
  - Produced by $^9\text{Be}$ or $^{12}\text{C}$ capture
Level density of radioactive nuclei

- Spectral measurement
- $A$ from FMA
- Proton spectra from Microball
  - excitation energy index
  - gamma spectrum from Gammasphere
- Two proton spectra
  - TSC method for particles
- Very proton rich nuclei
  - Inverse kinematics, low Q value
Conclusion

- Statistical spectroscopy is a useful tool to investigate nuclear structure, complementary to discrete spectroscopy.
- Oslo method a success, good agreement with other methods:
  - Evaporation spectra
  - TSC, total cascade spectra, photoneutron σs
  - Probably also with (γ,γ')
Outlook

- Hot GDR width systematic, deformation dependence
- Adapt TSC method to decay out of SD well?
- Coulomb breakup $\rightarrow$ RSF of radioactive nuclei
- Astrophysical applications (r-process)
- Isomeric production cross sections
- Evaporation/$\gamma$ spectra from inverse-kinematics reactions using radioactive beams?
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Relevant publications
