LEVEL DENSITIES IN RARE EARTH NUCLEI * **

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An iterative procedure for simultaneous extraction of fine structure in the level density and the γ-ray strength function from a set of primary γ-ray spectra has been developed. Data from the reactions ^{163}Dy(^{3}He,$\alpha\gamma$)^{162}Dy and ^{173}Yb(^{3}He,$\alpha\gamma$)^{172}Yb reveals step like enhancements in the level density in the region below 5 MeV and peaks in the γ-ray strength function at low γ-energy ($E_\gamma \approx 2 - 3.5$ MeV). Tentative physical interpretations are presented.

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The energy distribution of primary γ-rays emitted from a well-defined initial excitation energy E_x provides a rich source of information about both the nuclear level density and the γ-ray strength function. Recent works [1, 2] explore the possibility for determination of the level density over a wide excitation region by mean of the energy spectrum of γ-rays originating from highly excited states with low spin. Analysing tools which allow an examination of the fine structure of the level density and the strength function have been developed.

The fundamental assumption behind this method [2] is that the energy distribution $\Gamma(E_x, E_\gamma)$ of primary γ-rays in the statistical regime can be expressed simply as a product of the final-state level density $\rho(U)$ (where $U = E_x - E_\gamma$), and a γ-energy dependent factor $F(E_\gamma)$:

$$\Gamma(E_x, E_\gamma) = F(E_\gamma)\rho(U)\,. \tag{1}$$

This ansatz is based on a generalized Brink–Axel hypothesis [3, 4], assuming that all possible excitation modes can be built upon any excited state, and

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that their characteristics are approximately independent of temperature. In addition, the nuclear states should be thermalized and subject to sufficient configuration mixing to contain components from a representative variety of modes.

A typical set of primary γ-spectra covers the entire initial excitation energy region from the ground state regime up to the neutron binding energy. The spectra $\Gamma(E_x, E_\gamma)$, which are approximately statistically independent, contain information about the level density $\rho(U)$ observed at various γ-energies, and about the γ-ray strength function measured at different excitation energies. Hence, sufficient information is available for extracting both factors $\rho(U)$ and $F(E_\gamma)$ simultaneously. This is done by means of the following iteration procedure: At first, trial functions $\bar{\rho}_0(U)$ and $\bar{F}_0(E_\gamma)$ are chosen. Then for iteration $\nu = 1$ a set of γ-energy dependent factors $F_\nu(E_x, E_\gamma)$ are generated, one for each primary γ-spectrum $\Gamma(E_x, E_\gamma)$, and the average $\bar{F}_\nu(E_\gamma)$ is determined:

$$F_\nu(E_x, E_\gamma) = \frac{\Gamma(E_x, E_\gamma)}{\bar{\rho}_{\nu-1}(E_x - E_\gamma)}, \quad \bar{F}_\nu(E_\gamma) = \frac{1}{N(E_\gamma)} \sum_{E_x > E_\gamma} F_\nu(E_x, E_\gamma), \quad (2)$$

where $N(E_\gamma)$ is the number of primary spectra covering the γ-energy E_γ. The improved approximation $\bar{F}_\nu(E_\gamma)$ to the γ-energy dependent factor is now used to obtain a set of level density functions $\rho_\nu(E_x, U)$ and their average, $\bar{\rho}_\nu(U)$:

$$\rho_\nu(E_x, U) = \frac{\Gamma(E_x, E_x - U)}{\bar{F}_\nu(E_x - U)}, \quad \bar{\rho}_\nu(U) = \frac{1}{N(U)} \sum_{E_x > U} \rho_\nu(E_x, U), \quad (3)$$

where $N(U)$ is the number of primary spectra covering the final-state excitation energy U. This procedure is repeated until stable solutions $\bar{F}_\nu(E_\gamma) \approx \bar{F}_{\nu-1}(E_\gamma)$ and $\bar{\rho}_\nu(U) \approx \bar{\rho}_{\nu-1}(U)$ are obtained. Convergence normally occurs after a few iterations.

The method has been applied to the primary γ-spectra extracted from the reactions ^{163}Dy(^{3}He,$\alpha\gamma$)^{162}Dy and ^{173}Yb(^{3}He,$\alpha\gamma$)^{172}Yb at a beam energy of 45 MeV. The experiments were carried out at the Cyclotron Laboratory at the University of Oslo. The reaction products were recorded by means of the multidetector array CACTUS, consisting of 8 Si particle telescopes placed in a forward angle of 45° relative to the beam axis, surrounded by 28 NaI γ-ray detectors with a total detection efficiency of $\sim 15\%$.

The trial functions for both nuclei were chosen smooth to avoid introducing any initial bias with respect to fine structure. An exponential trial level density $\bar{\rho}_0(U) = C\exp(U/T)$ with $T = 0.53$ MeV was used together with a γ-energy dependent factor $\bar{F}_0(E_\gamma) = E_\gamma^n$ with $n = 4.2$.

The average functions $\bar{\rho}(U)$ and $\bar{F}(E_\gamma)$ for ^{162}Dy and ^{172}Yb obtained after 5 iterations are displayed in the upper frames of Figures 1 and 2, respectively. In order to highlight the fine structure, we have transformed the two functions to a linear scale by dividing by their respective zeroth-order approximations $\bar{\rho}_0(U)$ and $\bar{F}_0(E_\gamma)$ (lower frames).

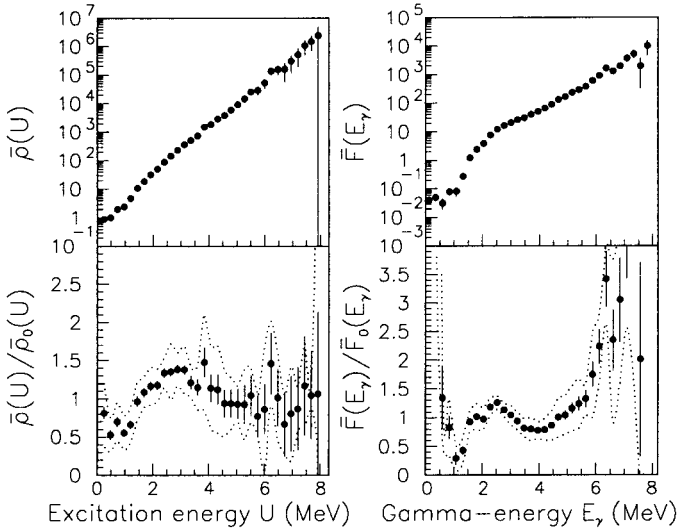

Fig. 1. Left: The final average level density $\bar{\rho}(U)$ (top) and the ratio $\bar{\rho}(U)/\bar{\rho}_0(U)$ (bottom) for ^{162}Dy. Right: The final average γ-energy dependent factor $\bar{F}(E_\gamma)$ (top) and the ratio $\bar{F}(E_\gamma)/\bar{F}_0(E_\gamma)$ (bottom). The error bars reflect statistical uncertainties for the average quantities, while the dotted lines indicate standard deviations of the fluctuations between individual E_x windows. All units are arbitrary.

The products of the average extracted functions $\bar{\rho}(U) \cdot \bar{F}(E_\gamma)$ taken at different E_x values reproduce the experimental primary γ-ray energy distributions in detail. This confirms in a convincing manner that our deconvolution method is reliable and that the ansatz of Eq. 1 to a good approximation is valid for the excitation region studied here.

The spectra $\bar{F}(E_\gamma)$ exhibit prominent peaks at $E_\gamma \approx 2.4$ MeV in ^{162}Dy and 3.3 MeV in ^{172}Yb. In this spin-temperature region, the most likely interpretation of these peaks is the decay of low-energy E1 or M1 dipole excitations, built on excited states. A number of E1 and M1 excitation modes in the region $E_\gamma = 2$–4 MeV, built on the ground state in deformed rare-earth nuclei, have been identified in recent experiments. The presence of such enhanced transitions is a signature of remaining order in terms of dominant configurations in the eigenstates of the warm nucleus [5]. Dipole

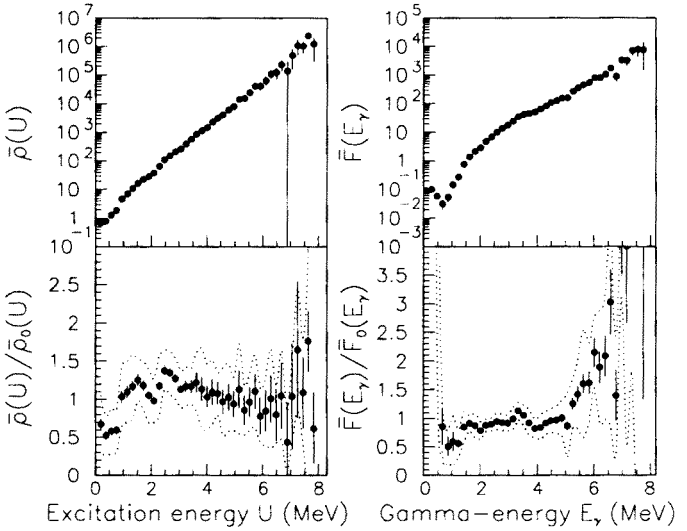

Fig. 2. Same as Fig. 1, for ^{172}Yb.

excitations built on excited states have only been sparsely investigated.

Schematic models with a finite number of particles distributed among a set of equidistant single-particle orbitals and interacting via a pairing force, produce a similar, step wise increase in the level density [6, 7]. These deviations from a smooth rise occur each time a new regime of quasiparticle states with one additional broken pair, start contributing to the total level density. In particular, a strong bunching of two-quasiparticle levels is predicted just above the energy 2Δ. This suggests the pair correlations as a likely candidate for explaining the observed irregularities.

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