Vol. 40 (2009) ACTA PHYSICA POLONICA B No 3

LEVEL DENSITIES, THERMODYNAMICS AND γ-RAY STRENGTH FUNCTIONS IN ^{163,164}Dy*

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(Received October 30, 2008; revised version received December 9, 2008)

The nuclei ^{163,164}Dy have been investigated by use of the Oslo method on data from the pick-up reaction (^{3}He, α) and the inelastic scattering (^{3}He,^{3}He$'$), respectively. The experiment was conducted at the Oslo cyclotron laboratory (OCL). The γ-decay and ejectiles were measured with the CACTUS multidetector array, which consists of 28 NaI γ-detectores and 8 $\Delta E - E$ Si particle telescopes. Thermodynamic quantities have been extracted within the micro-canonical ensemble theory. The pygmy resonance found around 3 MeV in the γ-ray strength function, also referred to as the scissors mode, was studied. The question whether the width of the pygmy resonance is reaction dependent is addressed.

PACS numbers: 21.10.Ma, 24.30.Gd, 25.55.Hp, 27.70.+q

1. Introduction

Both the level density and the γ-ray strength function are indispensable when characterizing a nucleus in the quasi-continuum. The level density provides important information on nuclear structure, and it is also the starting point for extracting thermodynamic properties of the nucleus. The γ-ray strength function reflects average electromagnetic properties of the nucleus.

The Oslo group has developed a unique technique [1] which makes it possible to extract both the level density ρ and the γ-ray strength function f from one and the same experiment. Based on the Brink–Axel hypothesis [2,3] the distribution of primary γ-rays for each initial excitation energy E_i [1] is factorized in the following way: $P(E_i, E_\gamma) \propto \rho(E_i - E_\gamma)\mathcal{T}(E_\gamma)$, where the γ-transmission coefficient $\mathcal{T}(E_\gamma)$ is directly proportional to the γ-ray strength function. Through a least-squares minimization method we determine the functions ρ and $\mathcal{T}$ [1].

* Presented at the Zakopane Conference on Nuclear Physics, September 1–7, 2008, Zakopane, Poland.

2. Experimental level density and thermodynamics

The extracted level densities for both nuclei are displayed in Fig. 1. We observe an overall high level density typical for medium-heavy mid-shell nuclei. We observe a step-like structure at low energies in ^{164}Dy. This is interpreted as a fingerprint of breaking of nucleon Cooper pairs [4], where the first broken pair represent a large and abrupt step in the level density. The ^{163}Dy nucleus already has an unbound neutron in the ground state, so the first broken pair does not represent such a significant difference to the system as in the even-even nucleus, and thus the step-structure is not as pronounced.

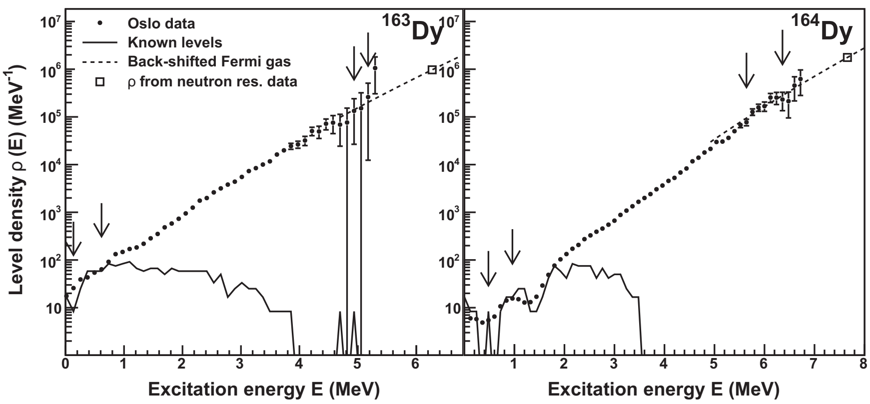

Fig. 1. Experimental level densities. The regions between the arrows are used for normalization. At low energies the level densities are normalized to known discrete levels, at high energies they are fitted to the level density $\rho(B_n)$ based on neutron resonance spacing data at the neutron binding energy B_n.

The micro-canonical entropy $S(E)$ is related to the multiplicity of states $\Omega(E)$ by $S(E) = k_{\mathrm{B}} \ln \Omega(E)$. We define a multiplicity of states which is solely dependent on the level density, $\Omega(E) = \rho(E)/\rho_0$, where ρ_0 is a normalization constant. The entropies given in Fig. 2, display a nearly constant entropy difference in the excitation region $E = 2$–5 MeV of about $\sim 2.1\ k_{\mathrm{B}}$, which is interpreted as the single particle entropy. We have assumed that the relation $T(E) = \left(\frac{\delta S}{\delta E}\right)^{-1}$ for the temperature is valid even for systems as small as nuclei.

The temperatures displayed in Fig. 2 have several negative slopes; these are interpreted as energy taken from the system in order to break Cooper pairs. The heat capacities are calculated from the relation $C_v(E) = \left(\frac{\delta T}{\delta E}\right)_V^{-1}$, and are also shown in Fig. 2. We observe negative heat capacities, which can be interpreted as a consequence of a first-order phase transition [5].

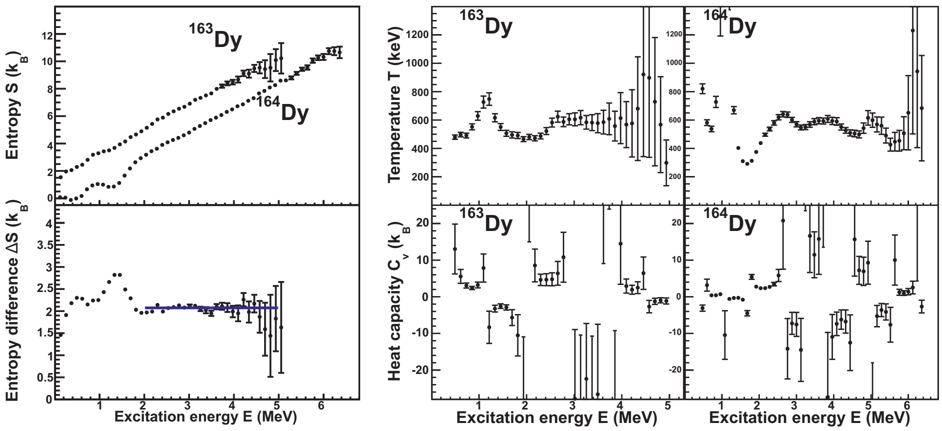

Fig. 2. Left: The entropies and the entropy differences. The solid line (lower panel) represents the average entropy difference for E_i = 2–5 MeV. Right: The microcanonical temperatures and heat capacities.

3. Experimental γ-ray strength function

The γ-ray strength functions can be viewed in Fig. 3. We observe a pygmy resonance at around 3 MeV, which has been observed in the γ-ray strength functions of several rare earth isotopes. It has been shown to be of M1 multipolarity [6, 7]. Neighboring Dy nuclei have been investigated previously with the Oslo method and a width of the pygmy resonance has been measured to lie in the interval 1.26–1.57 MeV [8]. However, these results contradict results found by the Prague group, where ^{163}Dy was evaluated by use of the two-step cascade method [7], on data from the reaction $^{162}\mathrm{Dy}(n, 2\gamma)^{163}\mathrm{Dy}$. A significantly smaller width of $\Gamma_{\mathrm{py}} = 0.6$ MeV was measured [7]. The widths found in the current experiment are $\Gamma_{\mathrm{py}}^{163\mathrm{Dy}} = 0.8(2)$ MeV and $\Gamma_{\mathrm{py}}^{164\mathrm{Dy}} = 0.8(1)$ MeV, which is less than what is observed previously in Oslo [8]. However, the slope of the strength function varies somewhat with the model used for calculating $\rho(B_n)$, and the width of the pygmy resonance is also sensitive to this. The model used in the present work is the Fermi gas model with the parameterization proposed by Gilbert and Cameron [9]. By applying the parameterization developed by Egidy and Bucurescu [10] one obtains a steeper slope. To further investigate if the width of the 3 MeV pygmy resonance is reaction dependent, $^{163}\mathrm{Dy}(p, p')$ will be analyzed.

The high strength observed for high γ-ray energies in ^{164}Dy is not predicted, it may originate from the so-called skin oscillation.

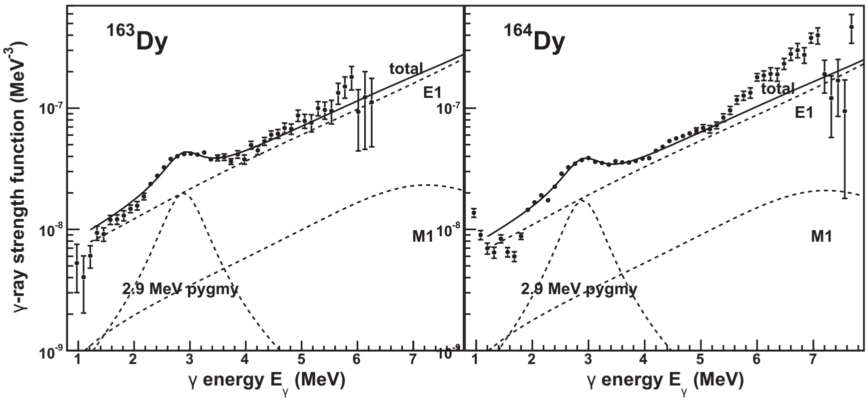

Fig. 3. Experimental γ-ray strength functions. The dashed lines represent the giant M1, the M1 pygmy resonance and the extrapolated tail of the giant E1. The solid line makes up the sum of the giant dipole resonances and the pygmy resonance. The fit to the experimental datapoints in ^{164}Dy is performed up to γ-energy 5.3 MeV.

4. Summary and conclusions

Level densities, thermodynamic quantities and the γ-ray strength functions have been extracted for ^{163,164}Dy. The level density and thermodynamic quantities display characteristic features seen in various rare earth nuclei. The width of the 3 MeV pygmy resonance is found to lie in a region between what has been measured in Oslo previously and what has been measured in Prague. Further analysis is needed to investigate if the width of the 3 MeV pygmy resonance is reaction dependent.

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