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THE ROLE OF BROKEN COOPER PAIRS IN WARM NUCLEI*

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In order to understand warm nuclei and describe the underlying microscopic structure, entropy is measured for several even–even and odd-mass nuclei. Mid-shell nuclei show significant odd–even entropy differences interpreted as the single-particle entropy introduced by the valence nucleon. A method to extract critical temperatures for the pair breaking process is demonstrated.

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1. Introduction

Entropy is a measure of the number of ways a system can be arranged at a given excitation energy. At low excitation energies, nuclei are characterized by the motion of pairs of nucleons moving in time reversed orbitals, which gives only one way of arrangement. With increasing excitation energy, these so-called Cooper pairs are broken by collective (Coriolis force) and/or intrinsic (temperature) excitations. The excited quasiparticles can then occupy several sets of single-particle orbitals for one and the same excitation energy and thereby create more entropy.

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In order to investigate the pair breaking process, experiments were conducted at the Oslo Cyclotron Laboratory (OCL) using 38 to 45 MeV ^{3}He beams in the (^{3}He, ^{3}He'γ) and (^{3}He, $\alpha\gamma$) reactions on self-supported targets. Particle-γ coincidences were detected with an array of 28 collimated NaI γ-ray detectors and eight Si particle telescopes placed at 45° with respect to the beam. By applying the Brink–Axel hypothesis, level densities and radiative strength functions can be simultaneously extracted from one and the same data set. Details on the experimental set-up and data analysis are given elsewhere [1].

2. Level density and entropy

Figure 1 shows the extracted level density of ^{160}Dy as function of excitation energy. Previously, the level densities were known in the excitation region $E = 0$–1.5 MeV and at the neutron binding energy B_n from neutron resonance spacing data. In Fig. 1 (right) the level density is transformed into entropy[1] by $S(E) = \ln \Omega(E)$, where $\Omega(E) = \rho(E)/\rho_0$ is the number of ways (multiplicity) to arrange the system. The constant ρ_0 is adjusted to give $S \sim 0$ in the ground band of ^{160}Dy. The odd ^{161}Dy system reveals more entropy than ^{160}Dy, and we interprete the difference $\Delta S = S(^{161}\mathrm{Dy}) - S(^{160}\mathrm{Dy}) \sim 2$ as the entropy carried by the valence neutron outside the warm even–even core [2]. The fact that this value is approximately constant as function of excitation energy E indicates that ΔS is independent of the number of excited particles in the underlying core.

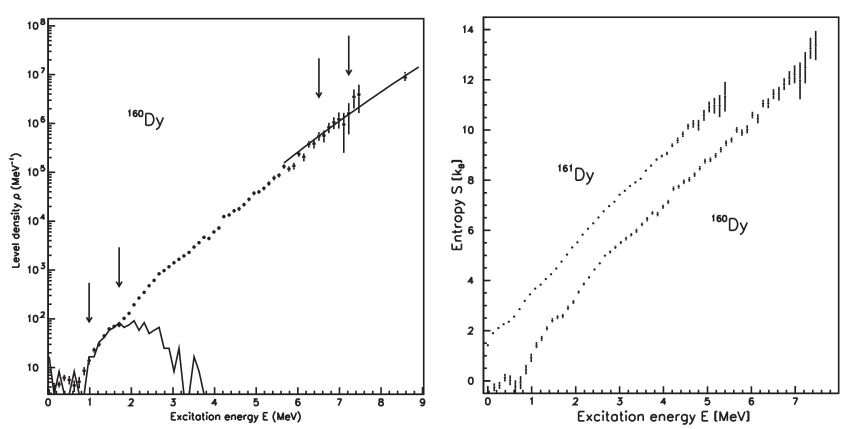

Fig. 1. Left: Experimental level density (filled circles) and extrapolation (line) to the level density based on neutron resonance data at the neutron binding energy B_n. The jagged line is based on counting known discrete levels. Right: Extracted entropies for ^{160,161}Dy.

[1] This entropy is based on level density and not state density.

With the assumption that the valence particle carries an extensive (additive) quantity of entropy, the number of excited quasiparticles can be evaluated as $N_{\rm qp}(E) = S(E)/\Delta S$. In the case of ^{160}Dy, we find that $N_{\rm qp}(E)$ increases from 0 to about six quasiparticles at $E = 6$ MeV.

Several other experiments in the rare earth nuclei have all given $\Delta S \sim 2$, and we therefore introduce the concept of thermal quasiparticles carrying an entropy that is approximatelly extensive. The thermal quasiparticles are not BCS quasiparticles with given parity and spin projection, but have the average properties of valence nucleons found in the ensemble of microstates at a given excitation energy.

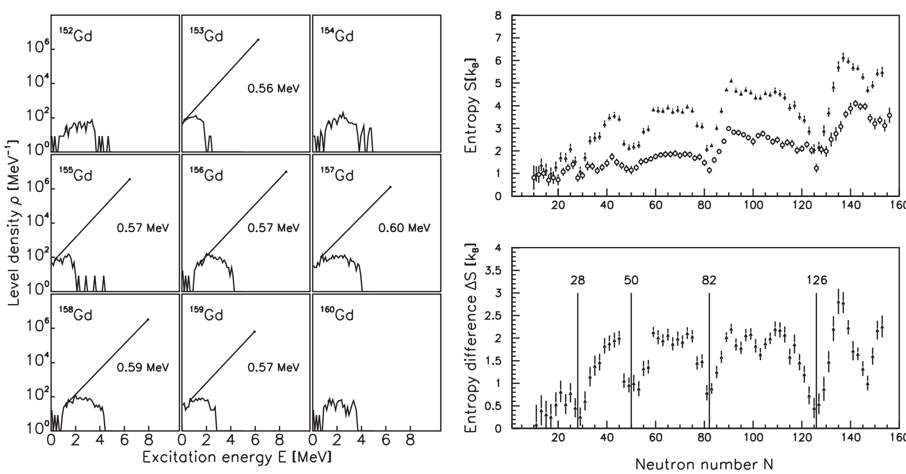

Fig. 2. Left: Level densities extracted at $E = 7$ MeV for gadolinium isotopes by interpolation with the constant teperature model up to $\rho(B_n)$. Right: Entropy and difference in entropy between even–odd (filled triangles) and even–even (open circles) nuclei as a function of neutron number at $E = 7$ MeV.

In order to further investigate the concept of thermal quasiparticles, a systematic review of nuclei with known resonance spacing data has been performed [3]. Figure 2 (left) demonstrates how the level density at *e.g.* 7 MeV can be extracted for $^{153-159}$Gd by interpolating between the low excitation region and the level density at $E = B_n$. In the upper right panel the corresponding entropies S for even–odd and even–even nuclei are displayed. The lower right panel shows that the odd neutron (or neutron hole) of mid-shell nuclei carries an entropy of ~ 2. Around closed shells, the energy gaps reduce the density of available single-particle orbitals in the vicinity of the Fermi surface. The strongest effect is seen when a shell is filled. Then, more configurations can only be produced by crossing the shell gap. The most dramatic reduction is found for the double magic ^{208}Pb nucleus, which has about 100 times fewer levels than the lighter ^{202}Hg.

3. Pair breaking and critical temperatures

The tin isotopes have the $Z = 50$ protons shell gap filled. Thus, one expects that only the breaking of neutron Cooper pairs will contribute to the level density at lower excitation energy. Indeed, the *preliminary* level density in Fig. 3 (left) shows pronounced step structures at the two and four quasiparticle excitation regimes. The surprisingly clear step structure is due to the fact that the breaking of proton pairs is prevented and do not smooth out the entropy steps from the neutron pair breaking process.

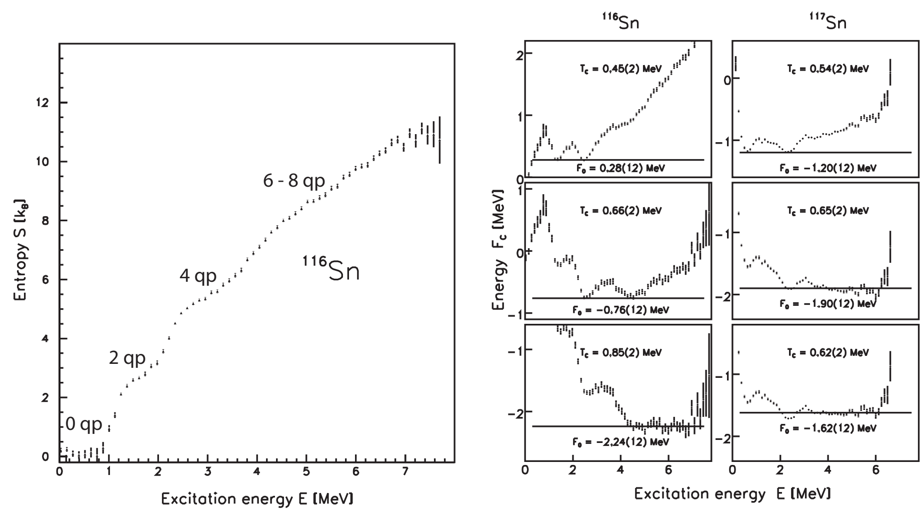

Fig. 3. Entropy and free energy extracted from preliminary data on ^{116,117}Sn.

In order to analyze the criticality of these low temperature transitions, we investigate the probability

$$P(E,T) = \Omega(E)\exp\left(-E/T\right) / \int_0^\infty \Omega(E')\exp\left(-E'/T\right)\, dE' \tag{1}$$

that the system at the fixed temperature T has the excitation energy E. Lee and Kosterlitz showed [4] that the function $A(E,T) = -\ln P(E,T)$ exhibits a characteristic double-minimum structure in the vicinity of a structural transition, *i.e.* for the critical temperature T_c, one finds $A(E_1,T_\mathrm{c}) = A(E_2,T_\mathrm{c})$. It can easily be shown that A is closely connected to the Helmholtz free energy, where we define the linearized free energy at the critical temperature T_c as $F_\mathrm{c}(E) = E - T_\mathrm{c}S(E)$. Thus, the previous condition is equivalent to $F_\mathrm{c}(E_1) = F_\mathrm{c}(E_2)$, a condition which can be evaluated directly from our experimental data.

Linearized free energies $F_{\rm c}$ for certain temperatures $T_{\rm c}$ are displayed in Fig. 3 (right). In the two upper panels, ^{116,117}Sn reveal situations, where $F_{\rm c}(E_1) = F_{\rm c}(E_2) = F_0$. Each nucleus shows two bumps, which we interpret as the critical temperatures for breaking one and two neutron pairs. For excitation energies above $E \sim 4$ MeV (lowest right panels of Fig. 3), the free energy is rather constant. Here, a continuous minimum of $F_{\rm c}$ appears for several MeV of excitation energies indicating higher order phase transitions.

4. Conclusion

We have demonstrated that the concept of single-particle entropy works nicely for mid-shell nuclei. The tin isotopes represent excellent cases for demonstrating the breaking of Cooper pairs. Critical temperatures for the depairing process were determined.

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