Nonstatistical Cooling of the Highly Excited ^{161}Dy Nucleus

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Gamma rays following the reaction ^{162}Dy(^{3}He, α) have been studied as a function of excitation energies in ^{161}Dy. For excitation energies above ~3 MeV a (2.2 ± 0.2)-MeV bump appears in the γ-ray spectra. It is suggested that the bump originates from enhanced $\Delta\Omega = 1$ single-quasiparticle transitions.

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The decay pattern of highly excited nuclei is to some extent governed by statistical laws. The average level density[1] and γ-ray multiplicity[2] are in general accounted for by the Fermi gas model. However, the statistical behavior of the nucleus might be perturbed by shell effects or structural changes such as pairing collapse and a possible transition into chaotic single-particle motion. Thus, the γ-radiation from highly excited states may be a source of information about nonstatistical cooling mechanisms of the heated nucleus.

Recently,[3] Chen and Leander suggested that unstretched $M1$ transitions may compete with the statistical cooling process and appear as high-energy bumps in the continuum γ-ray spectrum. The present Letter reports on the first observation of a ~2.2-MeV bump in ^{161}Dy which most likely has this origin.

We have used the reaction ^{162}Dy(^{3}He, $\alpha\gamma$)^{161}Dy which populates states with high-j one-hole components.[4] The α-γ coincidence technique of Ref. 5 was used to study the cooling process as a function of excitation energy. Recently,[6] a ~1.2-MeV bump was identified in the γ decay following the (^{3}He, α) transfer reaction for deformed even-even rare-earth nuclei employing this technique. The present experiment was performed by bombarding a self-supporting Dy foil (0.8 mg/cm^2), enriched to 96% in ^{162}Dy, with a 26-MeV ^{3}He-ion beam from the Oslo University cyclotron. Four surface-barrier detectors were placed at 50 deg with respect to the beam direction. A 12.5-cm × 12.5-cm-diam NaI(Tl) detector and a 19% Ge(Li) detector were placed at 135 deg. The measurements included α-particle singles and α-γ coincidences. In order to avoid summing effects in the α spectra from the intense ^{3}He elastic scattering, a fast pileup rejection circuit was used. The experiment was run over a period of one week with low beam current (~0.5 nA).

Figure 1 shows the singles α spectrum (upper part) and the α spectrum obtained in coincidence with γ rays detected in the NaI counter (lower part). The singles spectrum exhibits a rather constant pickup strength function except for the particle group found at low excitation energy. Its intensity is known[4] to depend on the Coriolis coupling of high-j states close to the Fermi surface. The coincidence α spectrum displays a drop in intensity for excitation energies around the neutron

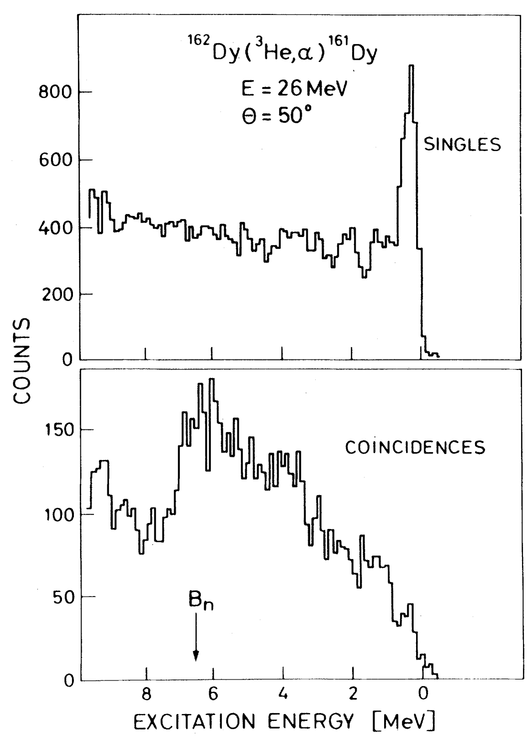

FIG. 1. Singles α spectrum and α projection spectrum obtained in coincidence with the NaI counter.

binding energy of $B_n = 6.45$ MeV. Above this energy the neutron evaporation is much more favored than the γ emission. Therefore, the neighboring ^{160}Dy isotope is populated at low excitation energy and the decay includes a few γ rays only.

The NaI γ-ray spectrum obtained with a gate on the coincidence α spectrum is displayed in Fig. 2. The α gate corresponds to an excitation region of $E_x = 2.6-6.5$ MeV in the ^{161}Dy isotope. The γ-ray spectrum reveals a bump at $E_\gamma \sim 2.2 \pm 0.2$ MeV with a width of $\sigma_\gamma = 0.9 \pm 0.3$ MeV (see shaded region). If we take into account the poor detector photoefficiency at these γ-ray energies, the bump represents an essential part of the total number of transitions in the cooling process. This becomes evident in Fig. 3 where unfolded γ-ray spectra are shown with gates on various excitation regions in ^{161}Dy. The data clearly show a ~ 2.2-MeV bump which emerges in the 2.6–3.6-MeV gate and remains present for all excitation energies up to $E_x \sim B_n$.

Besides the ~ 2.2-MeV bump our spectra reveal the γ-ray distribution from the statistical decay. This statistical component is clearly seen in the spectrum obtained with a gate on the 2.6–3.6-MeV excitation region (see Fig. 3). The distribution peaks at $E_\gamma \sim 1.2$ MeV and is expected to extend with a high-energy tail up to ~ 3.6 MeV. By taking the tail into account in the evaluation of the area of the ~ 2.2-MeV bump, we find that the bump constitutes $(34 \pm 5)\%$ of the total number of nonyrast transitions in this excitation region.

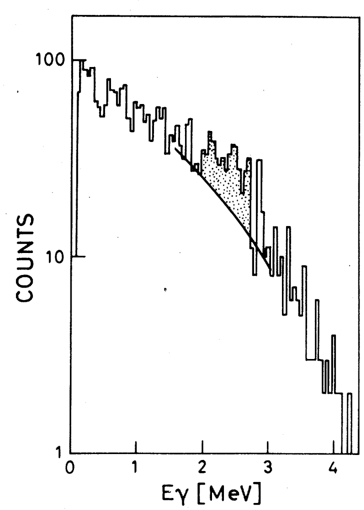

FIG. 2. Gamma-ray spectrum of ^{161}Dy measured with a NaI counter. The data are taken in coincidence with α particles depopulating levels at excitation energies of $E_x = 2.6-6.5$ MeV.

This means that roughly half the number of cascades depopulating states at $E_x \sim 3.1$ MeV contributes to the ~ 2.2-MeV bump, provided the γ-ray multiplicity is ~ 2 for the nonyrast transitions. Similar estimates at higher excitation energies are difficult since the two γ distributions are strongly overlapping.

The appearance of a large amount of nonstatistical γ rays is very surprising in a region where the Fermi-gas conditions are widely believed to govern the cooling process. A plausible explanation could be that the present reaction mechanism selects intrinsic nuclear structures with particular decay properties.

The γ-ray energy of the ~ 2.2-MeV bump coincides with the $M1$ bump predicted by Chen and Leander[3] for deformed odd-even nuclei. These authors base their calculations on the approximation[7] that for any given transition, one or zero quasiparticles are active while the rest are spectators. Gamma-ray spectra calculated from the decay of one-quasiparticle states in ^{173}Yb revealed a 2–2.5-MeV bump with large contributions from the $\frac{7}{2}^-[503] \to \frac{5}{2}^-[512]$, $\frac{7}{2}^-[503] \to \frac{5}{2}^-[523]$, $\frac{3}{2}^-[512] \to \frac{1}{2}^-[521]$, and $\frac{9}{2}^-[514] \to \frac{11}{2}^-[505]$ $\Delta\Omega = 1$ transitions.[8]

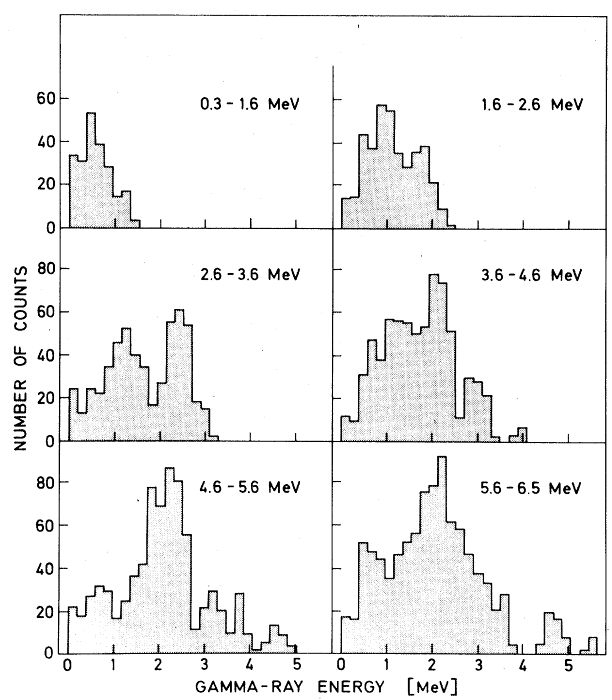

FIG. 3. Unfolded NaI γ-ray spectra coincident with α particles from the indicated excitation regions in ^{161}Dy.

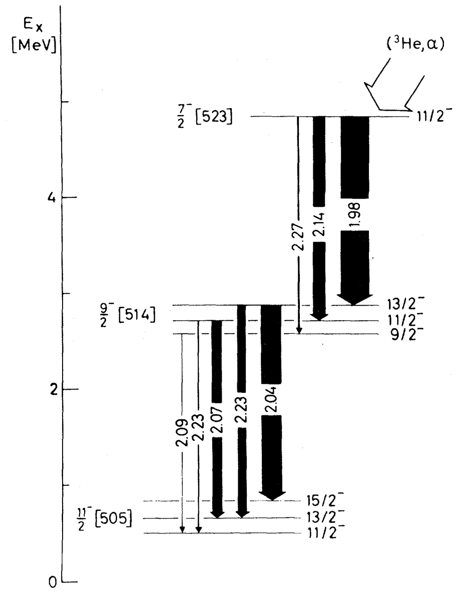

FIG. 4. Calculated single-quasiparticle $h_{11/2}$ level scheme with quadrupole deformation $\epsilon = 0.3$, pairing gap parameter $\Delta = 1$ MeV, and rotational moment of inertia parameter $\hbar^2/2\mathcal{G} = 13$ keV. The decay pattern was estimated with free neutron gyromagnetic factors and $g_R = 0.4$.

The (^{3}He, α) pickup reaction mainly populates deep-lying hole states with prominent single-quasiparticle structure. In the $A \sim 160$ mass region, around 30% of the cross section at $E_x \sim 5$ MeV is due to the $h_{11/2}$ transfer.[4] At these excitation energies the $h_{11/2}$ spectroscopic strength is heavily fragmented. However, provided that the spectator approximation is at least qualitatively valid, we expect contributions to the γ spectra from transitions between $h_{11/2}$ orbitals with a γ-ray energy spread according to the $h_{11/2}$ fragmentation.

In Fig. 4 the result of a particle-rotor model[9] calculation is shown for the $h_{11/2}$ $\frac{7}{2}^-[523]$, $\frac{9}{2}^-[514]$, and $\frac{11}{2}^-[505]$ Nilsson orbitals. The Fermi level was adjusted in order to place the $\frac{11}{2}^-[505]$ bandhead at its proper excitation energy. The calculated decay pattern for the $I^\pi = \frac{11}{2}^-$ member of the one-quasiparticle $\frac{7}{2}^-[523]$ band at $E_x \sim 5$ MeV reveals a bunch of γ rays with energies centered around 2.1 MeV. In this decay mode ~ 25% of the γ rays represent $\Delta I = 0$ $M1$ transitions. Any decay out of the $h_{11/2}$ regime is strongly hindered as a result of the high-Ω angular projection on the nuclear symmetry axis. For example we find that the branching of the $\frac{13}{2}^-$ level at $E_x \sim 3$ MeV (see Fig. 4) to the $f_{7/2}$ and $h_{9/2}$ structures is 1% and 15%, respectively.

The decay of states at high temperature probably involves the pairing of nucleons ($\Delta s = 2$ seniority change). This degree of freedom, which is not accounted for in our calculations, will influence the decay pattern and the average transition energy. Thus, it should be emphasized that the results of Fig. 4 only represent a tentative description of the decay from $h_{11/2}$ states.

In summary, γ-ray spectra of ^{161}Dy measured in coincidence with α particles from the (^{3}He, α) reaction show a prominent bump at $E_\gamma \sim 2.2$ MeV. This bunching of unresolved γ rays is proposed to originate from $\Delta\Omega = 1$ transitions between Nilsson orbitals with approximately the same angular momentum j. Calculations predict that the decay of high-Ω $h_{11/2}$ one-quasiparticle states goes with γ-ray transitions of $E_\gamma \sim 2.1$ MeV. Since the reaction favors the population of $h_{11/2}$ states, these γ rays probably contribute to the bump found here in the cooling process of ^{161}Dy.

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