Population of collective bands in Dy isotopes using heavy ion induced transfer reactions

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It is demonstrated that low-lying collective bands in deformed nuclei are strongly populated by quasielastic heavy ion transfer reactions at near barrier energies. The ^{161}Dy(^{61}Ni,^{62}Ni)^{160}Dy and ^{161}Dy(^{61}Ni,^{60}Ni)^{162}Dy reactions at a beam energy of 270 MeV have been studied using a particle-γ technique. Significant population of sidebands in ^{160}Dy was observed, particularly the S band built upon the $[\nu(i_{13/2})]^2$ configuration and the $K^\pi=1^-$, 2^-, and γ bands. For ^{162}Dy the only sideband significantly populated was the γ band.

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I. INTRODUCTION

There is empirical evidence from inclusive [1] and exclusive [2] measurements of γ emission that heavy ion induced transfer reactions (HITR's) predominantly populate excited quasiparticle states in the residual nucleus. In particular, the transfer of a single nucleon will populate collective bands built upon particle-hole states in the residual nucleus and the accompanying Coulomb excitation by the heavy projectile will populate states having an average spin of around 10–12 $\hbar$ for rare-earth nuclei. Light ion induced reactions have populated bands in ^{160}Dy built on two quasiparticle states either directly by (^{3}He,α) [3] or by compound nucleus reactions [4]. In contrast to compound nucleus reactions, which populate such states nonselectively, the direct reaction will favor two quasineutron excitations involving the $i_{13/2}$, $\Omega=\frac{5}{2}$ orbital, which is the ground state of ^{161}Dy. In the experiment reported here, excited states in ^{160}Dy were populated using the ^{161}Dy(^{61}Ni,^{62}Ni)^{160}Dy (Q_{gg}=4.15 MeV) reaction. The deexcitation γ rays in coincidence with scattered ions were measured to investigate the population of the low-lying collective bands. Some data from the ^{161}Dy(^{61}Ni,^{60}Ni)^{162}Dy (Q_{gg}=0.38 MeV) stripping reaction were also collected.

II. EXPERIMENTAL DETAILS

The experiment was conducted at the Daresbury Nuclear Structure Facility using a position-sensitive parallel-plate avalanche counter inside the EUROGAM phase-I array [5,6]. The PPAC used to detect backscattered heavy ions was an annular detector, covering angles $117° < \theta < 149°$ in strips of $2°$, with six ϕ sections covering 50° each. The polar angle (θ) of scattering was obtained from the time difference of pulses from the ends of a delay line connected to isolated sections on the cathode plane. Each isolated segment of the anode plane was connected to separate amplifiers, thus giving information on the azimuth angle (ϕ) of scattering. Knowledge of the polar and azimuthal angles of the backscattered Ni particle detected in the PPAC allowed the coincident γ-rays detected in the EUROGAM array to be corrected for their Doppler shift, assuming they were emitted by the recoiling Dy. The EUROGAM phase-I array consists of 45 escape suppressed Ge detectors in rings at $\theta=72°$, 86°, 94°, 108°, 134°, and 158°. Of these detectors, the 30 in the four rings closest to 90° were fitted with slits to reduce the opening angle (from $\theta=\pm 10°$ to $\pm 5°$) and hence reduce the Doppler broadening of the γ rays. In this experiment, the recoil velocity $v/c=5\%$ and the broadening due mostly to the Ge detector opening angle was typically about 5 keV for 1 MeV γ rays. A beam of 270 MeV ^{61}Ni was incident on a self-supporting 400 μg/cm^2 foil of 95.9% ^{161}Dy, whose major isotopic impurity was ^{162}Dy (2.5%) [7].

III. RESULTS

The experiment yielded 10.5 million unfolded particle-γ-γ events, which were sorted into a γ-γ matrix. Figure 1 shows the total projection of this matrix, with the ground-state band transitions in ^{160}Dy and ^{162}Dy marked. The inset shows the region in which transitions from low-lying two-quasiparticle (2QP) and collective states to the ground-state band are expected.

Each of the transfer channels can be enhanced by requiring that at least one γ ray is one of the intense ground-state band transitions. The spectra for ^{160}Dy and ^{162}Dy in coincidence with any of four ground-state band transitions in each nucleus, marked with dots, are shown in Fig. 2. The transitions marked in the insets are the known [4] decays from the γ-vibrational band, an octupole vibrational-like $K^\pi=2^-$ band, and the S band to the ground-state band. The expected positions of the strongest transitions from the previously observed [8,9] 2^- band and S band to the ground-state band in ^{162}Dy are marked with arrows.

The energies and intensities of the γ rays in ^{160}Dy relative to the $4_g^+\rightarrow 2_g^+$ transition were determined and are given in

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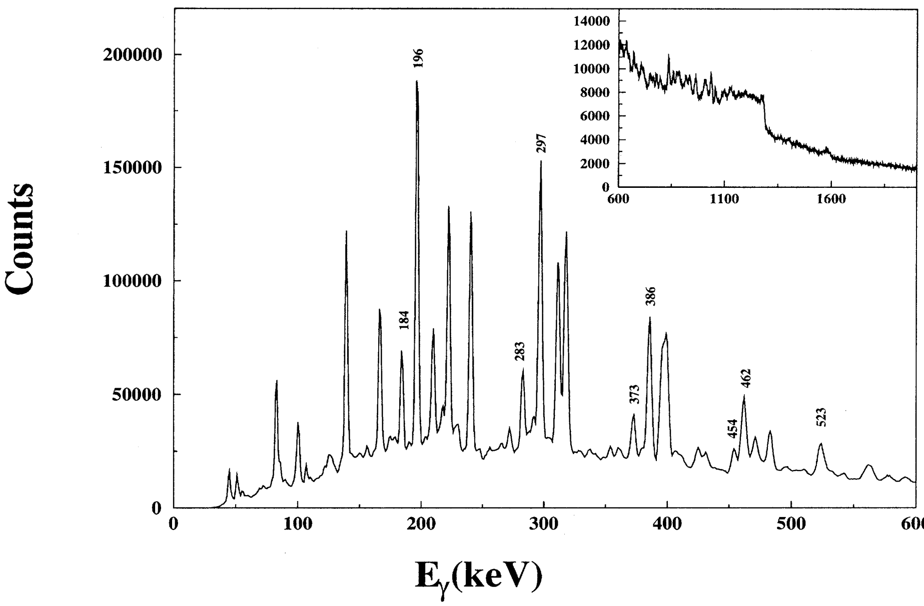

FIG. 1. The total projection of the γ-γ matrix, in coincidence with backscattered particles and corrected for Doppler shift. The transitions labeled are the ground-state band transitions in ^{160}Dy (196, 297, 386, 462, and 523 keV) and ^{162}Dy (184, 283, 373, and 454 keV). The inset is the region where transitions from two quasiparticle bands to the ground-state band would be expected. The bump from 1075 to 1290 keV is the result of the broadening of the 1173, 1163, and 1129 keV γ rays in ^{62}Ni following the procedure to correct for the Doppler shift of γ rays emitted from the Dy recoil.

Table I. The spectrum (Fig. 3) obtained by summing and binning the intensities of the observed discrete transitions in ^{160}Dy is similar to that obtained previously by unfolding NaI spectra following the reaction 270 MeV ^{161}Dy(^{58}Ni,^{59}Ni)^{160}Dy (Q_{gg}=2.55 MeV) [1]. Examination of Table I and Fig. 3 reveals that the "bump" at around 1 MeV arises from transitions from the sidebands feeding into the ground-state band. The relative populations of member states of each band, accounting for feeding from higher bands, was deduced using Table I, assuming that there is little contribution from feeding from continuum transitions. Figure 4 shows the summed population of these states for each band along with the range of states observed and the average spin and excitation energy of the bands. It can be seen that the direct population of the side bands is comparable to that of the ground state band, even though the observed intensities of transitions in the latter are 10–100 times larger. The sidebands having the largest population are the $K^\pi=2^-$ band and the γ band, $\approx$45% of the ground-state band in each case. Figure 5(a) shows the spectra given by the sum of the gates on the 288, 360, and 425 keV transitions between states in the 2^- band, and Fig. 5(b) shows the sum of the gates on the 835, 935, 1013, and 1036 keV transitions between the 2^- band and the ground-state band. In these spectra most of the transitions have been identified as either in band or arising from decays to the γ band or the ground-state band. The unassigned strong transitions have been identified as arising from ^{161}Dy. There is no evidence of strong

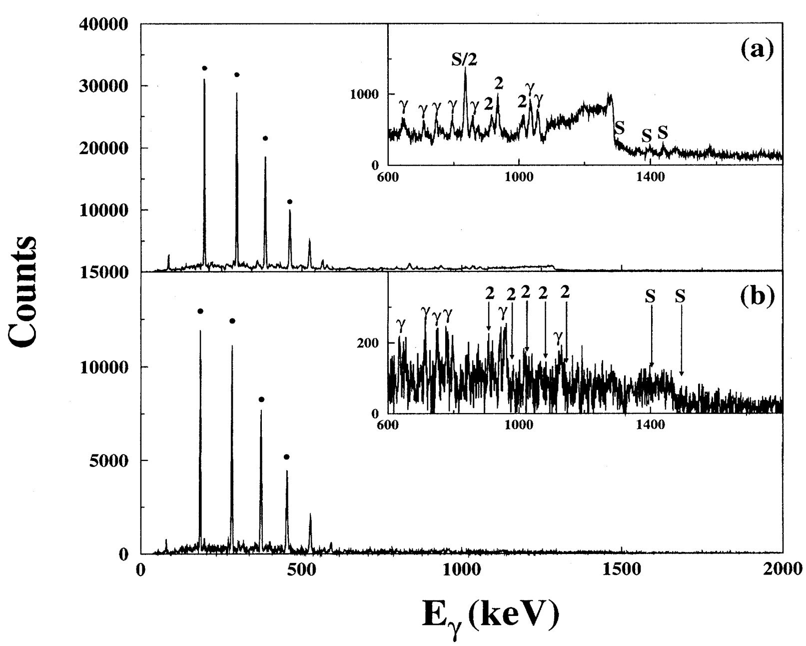

FIG. 2. Spectra in coincidence with any one of the four strongest ground-state band transitions (indicated by dots) in (a) ^{160}Dy and (b) ^{162}Dy. The insets show transitions from the γ-vibrational band and the 2^- and S bands to the ground-state band. The arrows in the spectrum for ^{162}Dy show where the most intense of the transitions from the 2^- and S bands would be expected.

TABLE I. Energies and relative intensities of ^{160}Dy transitions derived in the present work. The states labeled with the subscripts g, γ, S, 1, 2, 8 correspond to the ground-state band, γ-vibrational band, S band, 1^-, 2^- and 8^- bands, respectively. The subscript 4 refers to states in the 4^+ and 4^- bands for positive and negative parity states respectively.

E_γ	Transition	I_γ	E_γ	Transition	I_γ
125.0	$5_2^- \rightarrow 3_2^-$	3.5(9)	(669.7)	$8_8^- \rightarrow 7_\gamma^+$	<0.8
	$4_2^- \rightarrow 2_2^-$	1.1(2)	709.3	$5_\gamma^+ \rightarrow 6_g^+$	1.3(2)
178.4	$12_2^- \rightarrow 11_\gamma^+$	0.32(4)	727.1	$4_4^+ \rightarrow 2_\gamma^+$	2.2(1)
196.4	$4_g^+ \rightarrow 2_g^+$	100.0(1)	747.5	$12_\gamma^+ \rightarrow 12_g^+$	1.5(1)
205.2	$7_2^- \rightarrow 5_2^-$	1.2(1)	754.4	$5_4^+ \rightarrow 3_\gamma^+$	0.5(3)
208.3	$6_2^- \rightarrow 4_2^-$	4.6(2)	762.5	$3_\gamma^+ \rightarrow 4_g^+$	3.2(3)
222.3	$10_2^- \rightarrow 9_\gamma^+$	0.40(6)	(772.3)	$6_4^+ \rightarrow 4_\gamma^+$	<0.7
240.4	$1529.4 \rightarrow 5_\gamma^+$	2.2(1)	795.8	$10_\gamma^+ \rightarrow 10_g^+$	1.6(1)
241.9	$11_2^- \rightarrow 9_\gamma^+$	0.40(6)	817.1	$10_2^- \rightarrow 10_\gamma^+$	0.39(8)
264.6	$8_2^- \rightarrow 7_\gamma^+$	0.44(9)		$8_\gamma^+ \rightarrow 8_g^+$	2.4(2)
273.1	$1562.1 \rightarrow 5_\gamma^+$	0.50(6)	836.6	$11_2^- \rightarrow 10_g^+$	0.3(2)
287.6	$6_\gamma^+ \rightarrow 4_\gamma^+$	1.2(5)		$10_S^+ \rightarrow 10_g^+$	3.3(2)
287.4	$9_2^- \rightarrow 7_2^-$	1.2(	857.3	$6_\gamma^+ \rightarrow 6_g^+$	1.9(3) 1)
288.0	$8_2^- \rightarrow 6_2^-$	2.1(1)	873.5	$4_\gamma^+ \rightarrow 4_g^+$	1.9(8)
294.4	$2_2^- \rightarrow 2_\gamma^+$	2.0(1)	915.1	$8_2^- \rightarrow 8_g^+$	1.5(3)
297.1	$6_g^+ \rightarrow 4_g^+$	85.0(4)	934.5	$9_2^- \rightarrow 8_g^+$	3.7(3)
305.1	$6_2^- \rightarrow 5_\gamma^+$	0.37(6)	964.4	$3_\gamma^+ \rightarrow 2_g^+$	10.1(2)
329.1	$7_\gamma^+ \rightarrow 5_\gamma^+$	0.69(10)		$2_\gamma^+ \rightarrow 0_g^+$	
336.8	$4_2^- \rightarrow 3_\gamma^+$	1.6(1)	1005.1	$5_\gamma^+ \rightarrow 4_g^+$	5.6(2)
359.8	$10_2^- \rightarrow 8_2^-$	1.2(1)	1010.6	$8_S^+ \rightarrow 8_g^+$	0.5(2)
361.1	$(1977.1 \rightarrow 7_\gamma^+)$	1.4(1)	1013.5	$6_2^- \rightarrow 6_g^+$	3.7(2)
	$(1975.9 \rightarrow 7_2^-)$		1033.7	$7_2^- \rightarrow 6_g^+$	1.5(2)
362.3	$8_\gamma^+ \rightarrow 6_\gamma^+$	0.50(10)	1035.4	$7_\gamma^+ \rightarrow 6_g^+$	5.4(3)
362.6	$11_2^- \rightarrow 9_2^-$	0.23(5)	1057.3	$9_\gamma^+ \rightarrow 8_g^+$	3.6(4)
364.5	$(4034.6 \rightarrow 18_g^+)$	0.8(2)		$11_\gamma^+ \rightarrow 10_g^+$	
	$(3457.4 \rightarrow 16_g^+)$		(1069.9)	$4_\gamma^+ \rightarrow 2_g^+$	<0.5
385.8	$8_g^+ \rightarrow 6_g^+$	54.8(4)	1097.5	$1677.8 \rightarrow 6_g^+$	0.9(2)
405.6	$9_\gamma^+ \rightarrow 7_\gamma^+$	1.9(2)	1102.2	$4_2^- \rightarrow 4_g^+$	1.4(3)
421.7	$10_\gamma^+ \rightarrow 8_\gamma^+$	1.2(1)	1117.2	$3_1^- \rightarrow 4_g^+$	0.5(3)
424.8	$12_2^- \rightarrow 10_2^-$	1.6(1)	1126.8	$5_2^- \rightarrow 4_g^+$	2.3(1)
433.3	$(13_2^-) \rightarrow 11_2^-$	1.0(1)	(1142.3)	$6_S^+ \rightarrow 6_g^+$	<0.4
461.9	$10_g^+ \rightarrow 8_g^+$	27.7(4)	1154.2	$6_\gamma^+ \rightarrow 4_g^+$	0.8(3)
465.9	$11_\gamma^+ \rightarrow 9_\gamma^+$	0.72(8)	1167.9	$2_2^- \rightarrow 2_g^+$	0.8(2)
474.0	$12_\gamma^+ \rightarrow 10_\gamma^+$	1.9(3)	1196.4	$1_1^- \rightarrow 2_g^+$	2.9(1)
482.0	$14_2^- \rightarrow 12_2^-$	0.45(3)		$3_2^- \rightarrow 2_g^+$	
482.5	$8_8^- \rightarrow 8_\gamma^+$	1.4(1)	1219.7	$8_\gamma^+ \rightarrow 6_g^+$	1.5(3)
(491.1)	$4_1^- \rightarrow 3_\gamma^+$	<1.1	1253.6	$4_1^- \rightarrow 4_g^+$	1.4(4)
(491.5)	$6_4^+ \rightarrow 6_\gamma^+$	<0.4	1273.6	$2_1^- \rightarrow 2_g^+$	3.6(6)
496.8	$8_1^- \rightarrow 7_\gamma^+$	2.6(2)	1281.3	$5_4^- \rightarrow 6_g^+$	2.5(6)
497.0	$1925.0 \rightarrow 10_g^+$	0.41(6)	1295.8	$10_S^+ \rightarrow 8_g^+$	0.46(7)
497.7	$6_1^- \rightarrow 5_\gamma^+$	1.9(1)	1311.5	$1891.8 \rightarrow 6_g^+$	1.6(3)
(513.5)	$5_4^+ \rightarrow 5_\gamma^+$	<0.7	(1313.6)	$3_1^- \rightarrow 2_g^+$	2.0(2)
523.1	$12_g^+ \rightarrow 10_g^+$	12.4(3)	1319.3	$8_8^- \rightarrow 8_g^+$	1.2(2)
(533.8)	$4_4^+ \rightarrow 4_\gamma^+$	<0.5	1366.8	$5_1^- \rightarrow 4_g^+$	1.5(3)
564.0	$14_g^+ \rightarrow 12_g^+$	3.7(2)	1396.4	$8_S^+ \rightarrow 6_g^+$	2.4(2)
577.5	$16_g^+ \rightarrow 14_g^+$	2.0(5)	1439.4	$6_S^+ \rightarrow 4_g^+$	2.0(2)
	$18_g^+ \rightarrow 16_g^+$		1479.5	$2059.8 \rightarrow 6_g^+$	2.3(2)
(636.7)	$7_4^+ \rightarrow 6_\gamma^+$	<0.6	1523.1	$4_S^+ \rightarrow 2_g^+$	0.62(8)
(640.0)	$6_4^+ \rightarrow 5_\gamma^+$	<0.4	1580.5	$5_4^- \rightarrow 4_g^+$	3.3(3)
645.8	$4_4^+ \rightarrow 3_\gamma^+$	0.75(11)	1654.3	$3082.3 \rightarrow 10_g^+$	0.7(2)
648.9	$7_\gamma^+ \rightarrow 8_g^+$	1.6(4)	1736.3	$2019.5 \rightarrow 4_g^+$	1.5(3)

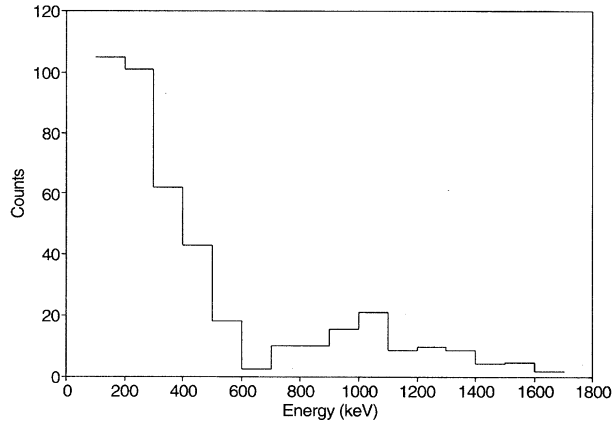

FIG. 3. Spectrum of the observed discrete transitions in ^{160}Dy in which the intensity is summed into bins 100 keV wide.

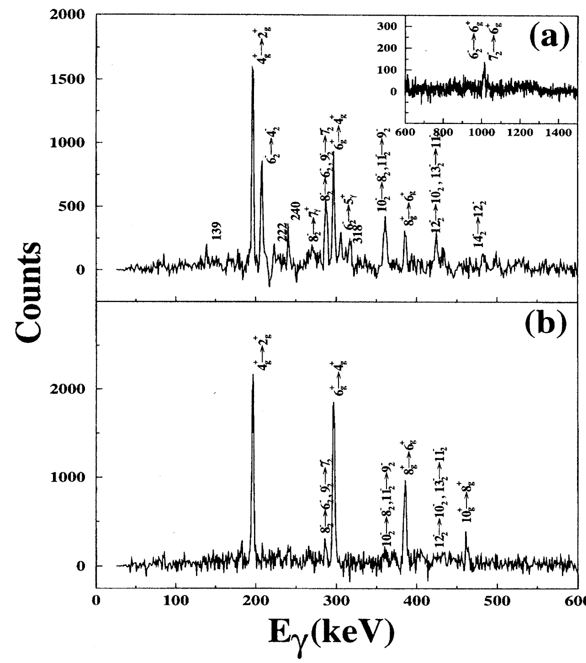

FIG. 5. γ-ray spectra for ^{160}Dy (a) in coincidence with transitions between states in the 2^- band and (b) in coincidence with transitions from the 2^- band to the ground-state band.

feeding of the 2^- band from a higher-lying band. The other strong bands observed are the S band (the 4^+, 6^+, 8^+ and 10^+ states of the S band are all observed to decay to the ground-state band) and the $K^\pi=1^-$ band (the 6^- and 8^- states are observed to decay to the γ band, while the lower levels decay to the ground-state band). The $K^\pi=4^-$ band, the $K^\pi=4^+$ band, and the $K^\pi=8^-$ bandhead are also observed in this reaction.

In the case of ^{162}Dy it is necessary to correct for the inelastic excitation of the known [7] 2.5% isotopic impurity of ^{162}Dy in the target. It was assumed that the total inelastic excitation of ^{162}Dy was 2.5% of the total inelastic excitation of ^{161}Dy. The latter was determined by measuring the intensity of the 167 keV $13/2_g^+ \rightarrow 9/2_g^+$ γ transition. The total population of ^{161}Dy was then estimated by means of a Coulomb excitation calculation [10] of the intensity of all ground-state band transitions, which assumes no contribution from nuclear excitation. For ^{162}Dy, the relative intensities of transitions in the ground-state band and γ-band populated by inelastic scattering were calculated using the Ptolemy code [11]. This procedure gave the result that 39% of the $4_g^+ \rightarrow 2_g^+$ transition strength in ^{162}Dy is due to inelastic excitation of the target impurity, and the remainder is due to transfer. For the γ band, the only side band populated with appreciable intensity in this reaction, the contribution from the impurity is about 25% averaged over the observed transitions. The relative intensities of transitions in ^{162}Dy as a result of transfer are given in Table II. No γ rays from the known two-quasiparticle states in ^{162}Dy [12] were observed.

The γ-ray multiplicities of the one-neutron transfer channels and the inelastic channel were also determined. In this analysis the multiplicity was deduced from the ratio of the number of particle-γ-γ events to the number of particle-γ events. The measured multiplicity for the ^{162}Dy transfer channel was corrected for the contribution from inelastic scattering using the known branching ratios and internal conversion coefficients with the average excitation energy calculated using the GOSIA code [10]. The multiplicities were found to be in the ratio 2.3:1:1.4 for the ^{160}Dy channel, the ^{161}Dy channel, and the transfer contribution to ^{162}Dy, respectively. These values imply that the multiplicity of the pick-up channel is about a factor of 2 larger than for the inelastic channel, which is consistent with previous measure-

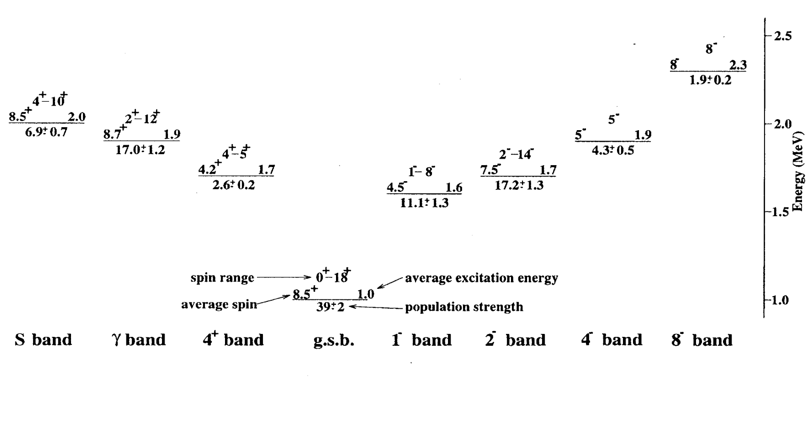

FIG. 4. The mean population for each of the bands observed in ^{160}Dy. The levels are labeled by the average spin and excitation energy of the bands, weighted to account for the population of each of the states in the band. The range of spin values of the observed states in each band is given above the average level, and the total population strength relative to the $4_g^+ \rightarrow 2_g^+$ γ-ray intensity is given below the average level.

TABLE II. Energies and relative intensities of ^{162}Dy transitions derived in present work. The intensities given are for the transfer part of the ^{162}Dy channel.

E_γ (keV)	Transition	I_γ	E_γ (keV)	Transition	I_γ
184.2	$4_g^+ \to 2_g^+$	100.0(3)	925	$8_2^- \to 8_g^+$	<0.8
282.6	$6_g^+ \to 4_g^+$	94.5(4)	943.0	$7_\gamma^+ \to 6_g^+$	2.5(3)
372.7	$8_g^+ \to 6_g^+$	79.4(3)	957.2	$9_\gamma^+ \to 8_g^+$	4.4–6.2
454.1	$10_g^+ \to 8_g^+$	45.9(1)	957	$11_2^- \to 10_g^+$	<1.8
526.8	$12_g^+ \to 10_g^+$	30.5(1)	962	$11_\gamma^+ \to 10_g^+$	
570.4	$7_\gamma^+ \to 8_g^+$	3.2(2)	980.3	$6_2^- \to 6_g^+$	<1.0
591.5	$14_g^+ \to 12_g^+$	4.2(2)	1031	$4_2^- \to 4_g^+$	<0.8
634.9	$5_\gamma^+ \to 6_g^+$	3.5(3)	1038	$9_2^- \to 8_g^+$	<0.8
652.6	$16_g^+ \to 14_g^+$	0.7(1)	1059.1	$6_\gamma^+ \to 4_g^+$	1.7(2)
698.4	$3_\gamma^+ \to 4_g^+$	2.3(2)	1089	$7_2^- \to 6_g^+$	<1.0
714.3	$10_\gamma^+ \to 10_g^+$	2.5(2)	1127.6	$8_\gamma^+ \to 6_g^+$	4.2(3)
750.0	$8_\gamma^+ \to 8_g^+$	3.2(3)	1142	$5_2^- \to 4_g^+$	<1.6
778.0	$6_\gamma^+ \to 6_g^+$	2.5(3)	1442	$8_S^+ \to 6_g^+$	<0.5
796.2	$4_\gamma^+ \to 4_g^+$	2.3(4)	1494	$6_S^+ \to 4_g^+$	<0.7

ments [2]. The much lower multiplicity for the stripping channel is consistent with the nonobservation of transitions from excited two quasiparticle states.

IV. DISCUSSION

Accurate measurements of the intrinsic excitation energy carried by the heavy partner in heavy ion induced transfer have not been performed previously to our knowledge. Measurements of excitation energy sharing in the ^{161}Dy(^{61}Ni, ^{62}Ni)^{160}Dy reaction carried out concurrently with this measurement give an average value of 2.5 MeV for the Ni-like fragment [7]. The average energy of the states populated in ^{160}Dy obtained from measurements of the intensities of the observed transitions (see Fig. 4) is about 1.5 MeV, which implies that the average intrinsic excitation energy is about 1 MeV after allowing for rotational excitations. This is to be compared with the value of ≈ 1.6 MeV expected if the total mean excitation is given by the Q value or 1.9 MeV as estimated from a distorted-wave Born approximation calculation as described in Ref. [12]. The discrepancy can be explained by the presence of unresolved or weak feeding transitions. Nevertheless, it is reasonable to assume that the more intense sidebands are populated directly following single neutron transfer between target and projectile. In the case of the pick-up reaction, several sidebands in ^{160}Dy are seen, which have previously been populated following the ^{161}Dy(^{3}He,α)^{160}Dy reaction [3]. These are the $K^\pi = 1^-$, 4^-, 8^- and S bands, which have been identified as being 2 QP bands involving the $(5/2)^+[642]$ neutron orbital: the $K^\pi = 1^-, 4^-$ bands correspond to the $(5/2)^+[642] \otimes (3/2)^-[521]$ Nilsson configuration and the $K^\pi = 8^-$ corresponds to the $(5/2)^+[642] \otimes (11/2)^-[505]$ configuration. There are no candidates for members of the S band with $I > 10$, although the calculations of Kincaid *et al.* [13] predict that the high spin ($I = 8-18$) members of this band will receive appreciable population in one-neutron transfer reactions. The $K^\pi = 2^-$ and γ bands are also observed to be strongly populated by the HITR, in contrast to the light ion reaction. In Ref. [4] a summary is given of evidence that the $K^\pi = 2^-$ band has a two-quasiproton $(3/2)^+[411] \otimes (7/2)^-[523]$ configuration, although the present measurements indicate that it is unlikely that this band contains appreciable two-proton components. Riezebos *et al.* [4] also offer evidence that this band has octupole vibrational character, an interpretation consistent with the random-phase-approximation calculations of Neergård and Vogel [14], which predict that the $K^\pi = 2^-$ band lies lowest in energy in ^{160}Dy; they additionally predict that this band has the strongest coupling to the ground state compared to the other rotational-octupole bands. If this interpretation is correct it is apparent that collective vibrational states are strongly excited following the grazing collisions, which give rise to matter transfer. These excitations should be present in inelastic scattering also, as indicated by Ptolemy calculations [15] but are more difficult to identify because of the dominant Coulomb excitation of the ground-state rotational band in the more distant trajectories and the fractionation of strength in the odd-mass target nucleus due to particle-vibrational coupling. Recently evidence has been published ([16,17,19]; see also 18) for a rather clear experimental signature of specific collective excitation of the target nucleus in sub-barrier fusion. The process whereby heavy ion induced transfer reactions excite both vibrational and rotational modes may be related to the similar mechanism observed in the sub-barrier fusion channel and may provide a selective probe of these collective degrees of freedom in nuclei.

V. SUMMARY

We have observed significant direct population of two quasiparticle side bands following the one-neutron pick-up reaction ^{161}Dy(^{61}Ni, ^{62}Ni)^{160}Dy, particularly the $K^\pi = 1^-$, 4^-, 8^- and S bands, which are also seen in the ^{161}Dy(^{3}He,α) ^{160}Dy reaction. The bands with the strongest population in heavy ion induced transfer reactions, the $K^\pi = 2^-$ and γ bands, are not observed in light ion reactions, implying the important role of collective excitations in

HITR. If the interpretation that the $K^{\pi}=2^{-}$ is a collective octupole band is correct, then it appears that the transfer reaction induced by heavy ions is capable of strongly exciting collective vibrational states as well as rotational ones and can provide a selective probe of this particular nuclear degree of freedom.

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