RAPID COMMUNICATIONS

PHYSICAL REVIEW C VOLUME 51, NUMBER 6 JUNE 1995

Fast γ-ray transitions between excited states as evidence of order in deformed nuclei

V. G. Soloviev
Joint Institute for Nuclear Research, 141 980 Dubna, Moscow region, Russia

(Received 28 February 1995)

The calculation within the quasiparticle-phonon nuclear model shows that there are fast $E1$ and $M1$ transitions with energy around 2.5 MeV between large components of wave functions differing by the octupole and quadrupole phonon. The strong 2.5 MeV peak was observed in the first-generation γ-ray spectra in the two-step cascades following thermal-neutron capture and in the ^{163}Dy(^{3}He,α) reaction at several excitation energies. These experimental data indicate relatively large many-phonon components of the wave functions and the possibility of excitation energy of less than 8 MeV order in well-deformed nuclei.

PACS number(s): 21.60.Ev, 21.60.Jz, 23.20.Lv, 27.70.+q

Based on the statement that there is order in the large components and chaos in the small components of the nuclear wave functions, the order-to-chaos transition is treated as a transition from the large to small components of the wave functions [1,2]. Therefore, it is highly desirable to find a method of experimental observation of relatively large many-phonon configurations in nuclear wave functions.

The aim of this Rapid Communication is to show that there are fast $E1$ and $M1$ transitions between large components of the wave functions of the initial and final states differing by the octupole ($K^\pi=0^-$or 1^-) or quadrupole ($K^\pi=1^+$) phonon, and to analyze experimental data on the 2.5 MeV peak in the first generation γ-ray spectra following the thermal-neutron capture and one-neutron transfer reaction.

Nonrotational states in many even-even well-deformed nuclei have been calculated within the quasiparticle-phonon nuclear model (QPNM) [3]. A two-quasiparticle state is treated in the QPNM as a specific case of a one-phonon state when the root of the RPA secular equation is very close to the relevant pole. The states below 2.3 MeV are practically one-phonon states. The $K^\pi=4^+$ double gamma vibrational states in ^{164}Dy, ^{166}Er, and ^{168}Er are the exception. Relatively large two-phonon components of the wave functions appear at energies above 2.3 MeV. As is shown in [2], two-phonon states consisting of both collective phonons are fragmented strongly. Two-phonon states consisting of the collective, and weakly collective, or both weakly collective, phonons are not so strongly fragmented. Fragmentation of two-phonon states increases with excitation energies. Three-phonon components of the wave functions appear at energies above 3.5 MeV and so on.

The γ-ray transition rates between excited states were calculated within the QPNM. $E1$- and $M1$-transition rates between one-phonon components of the wave functions of the initial and final states are small. The experimental reduced transition probabilities and the decay rates per second are the following: $B(E1;3^-1_1\rightarrow3^+2_1)=1.2\times10^{-7}$ e^2fm^2, $T(E1)=10^8$ s^{-1}; $B(E1;$ $3^-3_1\rightarrow2^+2_1)=4.1\times10^{-5}$ e^2fm^2, $T(E1)=2\times10^{10}$ s^{-1}; $B(E1;4^+4_1\rightarrow4^-4_1)=5.5\times10^{-4}$ e^2fm^2, $T(E1)=3\times10^4$ s^{-1}; $B(M1;3^-3_1\rightarrow4^-4_1)=3\times10^{-2}\mu_N^2$, $T(M1)=3\times10^{10}$ s^{-1}; and $B(M1;3^-3_3\rightarrow3^-3_1)=5.8\times10^{-4}\mu_N^2$, $T(M1)=10^9$ s^{-1} in ^{168}Er [4] and $B(E1;1^-1_1\rightarrow0^+0_1)=2\times10^{-4}$ e^2fm^2, $T(E1)=5\times10^7$ s^{-1}; $B(E1;2^+0_3\rightarrow1^-1_1)=5\times10^{-5}$ e^2fm^2, $T(E1)=8\times10^{10}$ s^{-1}; $B(E1;2^+0_3\rightarrow1^-0_1)=1.6\times10^{-4}$ e^2fm^2, $T(E1)=10^{11}$ s^{-1}, and $B(M1;2^-2_1\rightarrow2^-1_1)=8\times10^{-3}\mu_N^2$, $T(M1)=2\times10^{10}$ s^{-1} in ^{156}Gd [5]. An excited state is denoted by $I^\pi K_n$ where $n=1,2,3,\ldots$ is the number of the fixed K^π excited state. According to the calculation [6,7] within the QPNM, similar small $B(E1)$ and $B(M1)$ values and decay rates have been obtained for γ-ray transitions between one-phonon states in these and other nuclei.

Let us compare the decay rates between relevant one- and two-phonon components of the wave functions of the initial and final states with the decay rates between the initial and ground states. We calculated the energies and wave functions of excited states and the relevant $B(E\lambda)$ and $B(M\lambda)$ values and decay rates within the QPNM with the wave function consisting of one- and two-phonon terms. The phonons with $K^\pi=0^-$ and 1^- (denoted by $30i$ and $31i$, where $i=1,2,3,\ldots$ is the root number of the secular equation) have been calculated in the RPA with the particle-hole (ph) and particle-particle (pp) isoscalar and isovector octupole and ph isovector dipole interactions. The phonons with $K^\pi=1^+$ (denoted by $21i$) have been calculated with the ph and pp isoscalar and isovector quadrupole and spin-spin interactions with approximate exclusion of the spurious state. Other phonons (denoted by $\lambda\mu i$) have been calculated with the ph and pp isoscalar and isovector multipole interactions. Several typical cases of the $E1$ and $M1$ decay rates per second to the excited and ground states in ^{160}Gd, ^{160}Dy, ^{162}Dy, and ^{164}Dy are presented in Table I. One-phonon components $\lambda\mu i$ that are larger than 2% and the relevant two-phonon components $\{\lambda_1\mu_1 i_1,\lambda_2\mu_2 i_2\}$ of the wave functions of the initial states are also given in Table I. The final states are the one-phonon $\lambda\mu i$ or ground $0^+0_{\text{g.s.}}$ states.

As is shown in Table I, the intensities of the $E1$ and $M1$ transitions between the relevant excited states are $10-10^3$ times larger than the intensities of the $E1$ and $M1$ transitions to the ground state if the wave function of the initial state has a relatively large two-phonon term consisting of the octupole phonon with $K^\pi=0^-$ or 1^- or has a quadrupole phonon with $K^\pi=1^+$ and another phonon that is the same as the phonon of the wave function of the final state. The energies of the $E1$ and $M1$ transitions between large relevant two-

TABLE I. Calculated decay rates from the levels to the excited and ground states.

Nuclei	Initial state $I^\pi K_n$	E_n (MeV)	Structure	%	$E1$ or $M1$	E_γ (MeV)	Final state $I^\pi K_n$	$\lambda\mu i$	E_n (MeV)	Decay rate (sec)
^{160}Gd	1^-1_{10}	3.2	31 17	3	$E1$	2.2	2^+2_1	221	0.99	8×10^{13}
			31 18	10	$E1$	3.2	$0^+0_{g.s.}$		0	1×10^{12}
			{311,221}	26						
			{312,221}	45						
	1^+1_{25}	3.9	21 14	5	$M1$	2.9	2^+2_1	221	0.99	1×10^{13}
			21 15	58	$M1$	3.9	$0^+0_{g.s.}$		0	7×10^{10}
			{213,221}	10						
^{160}Dy	1^-1_{22}	3.6	31 16	62	$E1$	2.6	2^+2_1	221	0.97	4×10^{13}
			{312,221}	8	$E1$	3.6	$0^+0_{g.s.}$		0	4×10^{12}
			{313,221}	5						
	1^-0_{14}	3.7	30 10	3	$E1$	2.3	0^+0_2	202	1.44	2×10^{14}
			{301,202}	96	$E1$	3.7	$0^+0_{g.s.}$		0	2×10^{9}
^{162}Dy	1^+1_{22}	3.6	21 9	3	$E1$	2.3	1^-0_1	301	1.28	2×10^{14}
			{301,311}	87	$E1$	2.0	1^-1_1	311	1.64	3×10^{13}
					$M1$	3.6	$0^+0_{g.s.}$		0	4×10^{11}
	1^-1_{24}	3.6	31 14	7	$E1$	2.7	2^+2_1	221	0.89	2×10^{14}
			31 15	5	$E1$	3.6	$0^+0_{g.s.}$		0	7×10^{12}
			31 16	13						
			{313,221}	39						
	1^+1_{28}	3.9	21 18	19	$E1$	2.6	1^-0_1	301	1.28	1×10^{13}
			{301,313}	4	$M1$	3.9	$0^+0_{g.s.}$		0	2×10^{11}
	1^-1_{30}	4.0	31 17	6	$E1$	2.6	0^+0_1	201	1.40	7×10^{13}
			31 19	11	$E1$	4.0	$0^+0_{g.s.}$		0	4×10^{12}
			31 21	11						
			{313,201}	58						
^{164}Dy	1^-1_{20}	3.4	31 11	11	$E1$	2.6	2^+2_1	221	0.76	2×10^{13}
			31 12	13	$E1$	3.4	$0^+0_{g.s.}$		0	3×10^{9}
			31 13	34						
			{313,221}	28						
	1^-1_{21}	3.5	31 8	3	$M1$	2.5	2^-2_1	321	0.98	6×10^{13}
			31 11	3	$E1$	3.5	$0^+0_{g.s.}$		0	2×10^{11}
			31 14	4						
			{213,321}	29						

and one-phonon terms of the wave functions of the initial and final states equal 2.0–3.0 MeV with the maximum at 2.5 MeV. The decay rates of these transitions equal $10^{13}-10^{14}$ s^{-1}; they are larger compared to the decay rates to the ground state equal to $10^{9}-10^{11}$ s^{-1} and transitions between one-phonon states equal to $10^{4}-10^{11}$ s^{-1}. According to our calculation, the intensities of the $E1$ transitions are $10^{3}-10^{10}$ times as large as the relevant $E3$ transitions.

As is shown in Table I, a contribution of the two-phonon {213,221} configuration to the normalization of the wave function of the $K_n^\pi = 1_{25}^+$ 3.9 MeV state, equal to 10%, results in the decay rate $T(M1)=10^{13}$ s^{-1} of the γ-vibrational 221 state in ^{160}Gd which is 10^2 times larger compared to the decay rate into the ground state. The contribution of the {301,311} configuration to the 1_{28}^+ 3.9 MeV state, which is only 4%, gives rise to $T(E1)=10^{13}$ s^{-1} for the transition to the octupole state in ^{162}Dy. The decay rate $T(E1)=10^{14}$ s^{-1} from the 1_{24}^- 3.6 MeV to the gamma-vibrational state in ^{162}Dy is due to the 39% contribution of the {313,221} configuration. There are many cases where a very large two-phonon configuration leads to the fast $E1$ and $M1$ transition to the excited state. There are many fast $E1$ and $M1$ transitions with energy around 2.5 MeV in all even-even well-deformed nuclei in the rare-earth region.

This means that fast $E1$ and $M1$ (2–3) MeV transitions, with maximum 2.5 MeV to low-lying vibrational states in even-even well-deformed nuclei, take place due to the contribution of the relevant two-phonon configurations to the wave functions of the states with energy 3.5–4.5 MeV. A broad peak centered at 2.5 MeV should be observed experimentally in γ-ray transitions from the levels at 3.5–4.5 MeV to the low-lying excited states in well-deformed nuclei. A strong 2.5 MeV peak is of a nonstatistical origin.

It is possible to state that the fast $E1$ or $M1$ transition with γ-ray energy around 2.5 MeV should be between large three-phonon components of the initial-state wave function consisting of the phonon with $K^{\pi}=0^-$ or 1^- or 1^+ and other two phonons containing the final-state wave function. We expect the fast $E1$ or $M1$ transition between relatively large components of the wave functions of the initial and final states differing by the operator of the octupole Q^+_{3Ki} ($K=0$ or 1) or quadrupole Q^+_{21i} phonon. The fast 2.5 MeV $E1$ and $M1$ transitions are due to the following large matrix elements:

$$\left.\begin{array}{l}\langle\Omega_1\Gamma(E1)Q^+_{30i}\Omega^+_1\rangle,\\ \langle\Omega_2\Gamma(E1)Q^+_{31i}\Omega^+_2\rangle,\end{array}\right\} \tag{1}$$

$$\langle\Omega_3\Gamma(M1)Q^+_{21i}\Omega^+_3\rangle, \tag{2}$$

where Ω_1, Ω_2, and Ω_3 consist of several phonons or quasiparticle$\otimes$several phonons.

One may expect that a broad peak centered at 2.5 MeV in γ-ray spectra should be observed independently of the excitation energy in well-deformed nuclei. This peak becomes lower and the width is broader with excitation energies. This peak should exist up to an energy limit for order-to-chaos transition.

Let us consider experimental data on the fast γ-ray transitions between excited states in well-deformed nuclei with the energy around 2.5 MeV. Neutron-resonance states can be considered as a key for studying order-to-chaos transition. As has been shown in [1,8], a large contribution of the many-quasiparticle or quasiparticle$\otimes$phonon configurations to the normalization of the neutron-resonance state wave function would enhance $E1$ and $M1$ transitions from the neutron-resonance states to the levels lying 1–3 MeV below them. The first indication of this type of enhancement of γ-ray transition rates from the thermal-neutron-capture state to the levels 2–3 MeV below it has been given in [9–11] while studying the two-step cascades in ^{156}Gd, ^{158}Gd, ^{164}Dy, and other nuclei. The peak structure located at 2.5 MeV cannot be explained within a pure statistical model like the Fermi gas model [12]. We can interpret the 2.5 MeV peak in two-step transitions as a fast primary $E1$ or $M1$ transition with the matrix element (1) or (2) between relatively large components of the wave functions of the capture and intermediate states differing by the octupole $K^{\pi}=0^-$ or 1^- phonon or by the quadrupole $K^{\pi}=1^+$ phonon. The second step is the transition from the one-phonon components of the wave functions of the intermediate states to the ground state.

The most convincing experimental data on the 2.5 MeV peak have been obtained in [13]. The levels in the excitation region up to 8 MeV were populated by means of the ^{163}Dy(^{3}He,α)^{162}Dy reaction, and the first-generation γ rays in the decay of these states were isolated. The broad 2.5 MeV peak was observed in the first-generation spectra from the excitation regions of 4.9, 5.1, 5.9, 6.1, 6.8, 7.1, 7.8, and 8.0 MeV. The peak structure is located at the same energy independently of the excitation energy. A theoretical description of the first-generation γ-ray spectrum within the Fermi gas model gives good fits to the exponential tails but underestimates the main peak structure present in the experimental results. More closely the 2.5 MeV peak has been investigated in [13], where the centroid and standard deviation of the peak were evaluated by subtracting the Fermi gas curve from the experimental spectra. The centroid and standard deviation are nearly constant in the whole region. This peak cannot be the result of the level density since that would require a shift of the peak according to the shift in the excitation energy of the gate. The 2.5 MeV peak is most likely the result of the $E1$ and $M1$ transitions with the matrix elements of (1) and (2) with approximately the same strength throughout the whole excitation region. It is difficult to expect fast γ-ray transitions between one-phonon components of the wave functions of the initial and final states.

These experimental data indicate relatively large many-phonon components in the wave functions in the excitation region up to 8 MeV in well-deformed nuclei. Therefore, one may expect that the order takes place up to excitation energy where the 2.5 MeV peak exists.

The present consideration is in agreement with a study [14] of the (^{3}He,α) reaction mechanism in deformed nuclei. According to [14], the transferred spin is consistent with a pure one-neutron pickup reaction from the ground state up to around 5 MeV excitation energy. Above 20 MeV, the observed spin transfer indicates that preequilibrium processes play an important role and that the contribution from the compound reaction channel is negligible.

Experimental information on the many-phonon components of the wave function at excitation energy above 2.5 MeV in deformed nuclei is very important for understanding the nuclear structure and for studying the order-to-chaos transition.

I would like to thank J. Rekstad, M. Guttormsen, G. Lovhoiden, and L. Bergholt for stimulating discussions and sending experimental data prior to publication, and A. V. Sushkov and N. Yu. Shirikova for their help and useful discussions. This research was supported in part by the Russian Foundation of the Fundamental Research under Grant RFFR 95-02-05701 and by Grant N6N000 from the International Science Foundation.

[1] V. G. Soloviev, Nucl. Phys. **A554**, 77 (1993).
[2] V. G. Soloviev, Nucl. Phys. **A586**, 265 (1995).
[3] V. G. Soloviev, *Theory of Atomic Nuclei: Quasiparticles and Phonon* (Institute of Physics, Bristol, 1992).
[4] P. Petkov, W. Andrejtscheff, J. Copnell, and S. J. Robinson, Nucl. Phys. **A533**, 49 (1991).
[5] J. Klora *et al.*, Nucl. Phys. **A561**, 1 (1993).
[6] V. G. Soloviev, A. V. Sushkov, and N. Yu. Shirikova, J. Phys. G **20**, 113 (1994).
[7] V. G. Soloviev, A. V. Sushkov, and N. Yu. Shirikova, Nucl. Phys. **A568**, 244 (1994).
[8] V. G. Soloviev, Phys. Lett. B **42**, 409 (1972).
[9] E. V. Vasilieva *et al.*, Izv. Acad. Nauk Ser. Fiz. **57**, 98 (1993); **57**, 109 (1993).

[10] S. T. Boneva *et al.*, Z. Phys. A **346**, 35 (1993).
[11] M. A. Ali, V. A. Khitrov, Yu. V. Kholnov, A. M. Sukhovoj, and A. V. Vojnov, J. Phys. G **20**, 1943 (1994).
[12] A. V. Ignatjuk, G. N. Smirenkin, and A. S. Tshin, Yad. Fiz. **21**, 485 (1975) [Sov. J. Nucl. Phys. **21**, 255 (1975)].
[13] L. Henden, L. Bergholt, M. Guttormsen, J. Rekstad, and T. S. Tveter, Nucl. Phys. A (in press).
[14] M. Guttormsen, L. Bergholt, F. Ingebretsen, G. Lovhoiden, S. Messelt, J. Rekstad, T. S. Tveter, H. Helstrup, and T. F. Thorsteinsen, Nucl. Phys. **A573**, 130 (1994).