ANNALES
UNIVERSITATIS MARIAE CURIE-SKŁODOWSKA
LUBLIN—POLONIA
VOL. XL/XLI, 2 SECTIO AAA 1985/1986

Physics Department
Nihon University, Tokyo 156

Y. AKIYAMA

Deformed Nuclei and E4 Excitations

Jądra zdeformowane i wzbudzenia E4

Деформированные ядра и E4-возбуждения

Various theories of deformed nuclei make different predictions on the low-lying $K^{\pi}=4^{+}$ band. A natural interpretation of this band in terms of the traditional Bohr-Mottelson theory [1] or its microscopic extensions [2] is that this is a double γ-excitation band. Its band-head energy is about two times that of the γ-band under a harmonic γ-vibration, and reproduction of the ratio 2.5 in ^{168}Er has been a big problem in the nuclear structure theory. On the other hand, a theory developed by Soloviev [3], which is called the quasiparticle-phonon nuclear model (QPNM), does not predict two-phonon states in low excitation energies; his two-phonon states are much higher than the harmonic-vibration prediction. On this basis, he concluded that the low-lying $K^{\pi}=4^{+}$ band consists of one-phonon or two-quasiparticle states. The prediction of the interacting boson model (IBM) with s- and d-bosons is quite similar to that of the Bohr-Mottelson theory; the lowest $K^{\pi}=4^{+}$ band belongs to the SU(3) representation $(2N-8,4)$, where N is the number of bosons, and has the nature of two-phonon excitation, its band-head energy being again about two times that of the γ-band. However, if one incorporates g-bosons in addition, a new situation arises.

By treating the s-, d- and g-bosons on the same footing, the $U(15)\supset SU(3)$ theory has been developed [4,5]. According to this theory, there are two kinds of $K^{\pi}=4^{+}$ band, both of which belong to the SU(3) representation $(4N-8,4)$ but are classified by the SU(3)-seniority quantum number $w=0$ and 1. The $w=0$ band has again the two phonon nature and corresponds to the $(2N-8,4)$ band in the sd description. In contrast, the $w=1$ band is entirely new and its theoretical investigation opens a new possibility for describing the low-lying $K^{\pi}=4^{+}$ band. It is pointed out that the $w=1$ band can be freely parametrized by virtue of the SU(3)-seniority interaction while the $w=0$ band cannot in the SU(3) limit. Although the lowest $K^{\pi}=4^{+}$ band in ^{168}Er is identified as the $w=0$ one, an appreciable amount of SU(3) mixings is needed [6] to reproduce its band-head position. On the other hand, the lowest $K^{\pi}=4^{+}$ bands in ^{178}Hf and ^{234}U are interpreted [7] as the $w=1$ ones. It is important in these applications to experimentally confirm the w-assignments.

Another feature of the sdg IBM is its prediction on the $K^{\pi}=3^{+}$ band, which belongs to the SU(3) representation $(4N-6,3)$. Its band-head energy is predicted as 1.5 times that of the γ-band in the SU(3) limit. There are many examples in the rare-earth region which have the $K^{\pi}=3^{+}$ band around the expected excitation energy. Other theories do not predict the occurrence of this band in low excitations except the QPNM. This point is crucial for them to remain competent for a comprehensive description of deformed nuclei. Recently the sdg IBM is applied [8] to the $^{166}Er(t,p)^{168}Er$ reaction [9]. The results support the sdg description [6] of ^{168}Er. The strong excitation of the $I,K^{\pi}=4,3^{+}$ state implies that this is a collective state, which point is well understood by this model. Further information valuable for elucidating the nature of the $K^{\pi}=3^{+}$ and 4^{+} bands is accumulating in E4 excitations of $I=4$ states from the ground state.

It is worthwhile to look at the sd IBM description of E4 excitations before considering the sdg one. The E4 transition operator is assumed to be a one-body operator of sd bosons. Then it is a tensor operator of rank $L_0=4$,

$$Q^{(4)}(\mathrm{sd}) = (d^{+}d)^{L_0=4}, \tag{1}$$

which has the SU(3)-tensor character (2,2). With this operator the $I,K^{\pi}=4,4^{+}$ state cannot be excited from the ground state due to the SU(3) selection rule, irrespective of its two-phonon nature. The intraband transition in the ground state band is predicted to be very strong. On the other hand, strong E4 excitations of γ-bands are reported experimentally [10,11]. The experimental ratio of B(E4) for the I=4 state excitation of the γ-band to that of the ground band is 4.2:1 [11] in ^{168}Er, which contradicts seriously the theoretical prediction of 0.05:1. Thus we conclude that the sd IBM can not reproduce the E4 excitations observed in ^{168}Er. By analyzing their experimental data, Ichihara et al. pointed out [10] importance of a hexadecapole degree of freedom in deformed nuclei. The strong γ-band excitations are recently discussed by Matsuo [12] in terms of a microscopic theory with hexadecapole forces. Nesterenko et al. [13] also introduce hexadecapole forces into the QPNM for describing hexadecapole states in deformed nuclei. In contrast, the hexadecapole degree of freedom is inherent in the sdg IBM, and no extra forces are needed.

A description of E4 excitations given by the sdg IBM is drastically changed. Here one has four parameters to specify the E4 operator;

$$Q^{(4)}(\mathrm{sdg}) = a_1\{(s^{+}g)+(g^{+}s)\}+a_2(d^{+}d)^4+a_3\{(d^{+}g)^4+(g^{+}d)^4\} + a_4(g^{+}g)^4. \tag{2}$$

For our discussion it is more convenient to decompose it according to the SU(3) tensor character. The four SU(3) components are classified as (2,2), (3,3), $(4,4)_A$ and $(4,4)_B$. The (2,2) operator is just the sdg extension of the $Q^{(4)}$(sd), which can excite only the I=4 states of the ground, β and γ bands from the ground state. The (3,3) operator can, in addition, excite the K=1 and 3 bands of the $(4N-6,3)$ representation. The K=4 bands are excited through the (4,4) operators. Although there are two (4,4) operators, essentially only one is found to give rise to the K=4 excitation. This is taken as $(4,4)_A$. Neither w=0 nor w=1 member of the K=4 states is excited by the $(4,4)_B$ operator. Thus the sdg theory predicts a definite ratio for excitation amplitudes of the w=0 and 1 states. In a 16 boson system, for example, it is about 1:6, which confirms the two-phonon interpretation of the w=0 band. A very small B(E4) value is expected for the w=0 excitation. The strong excitation of the w=1 state leads one to interprete it as a one-phonon state of a hexadecapole phonon, for which the relevant operator is just the $(4,4)_A$ operator. Strong E4 excitations of the $I,K^{\pi}=4,4^{+}$ states in Os isotopes observed in (α,α') reactions [14] suggest that these states are the hexadecapole-phonon states of w=1.

In the case of weak excitations, one has to be careful in comparing the theoretical prediction with the experimental data, because the former may be easily changed by band-mixing effects. The *weak* excitation of the $K^{\pi}=4^{+}$ band in ^{168}Er (B(E4)=0.6 spu) compared to that of the γ-band (B(E4)=16.5 spu) [11] does not contradict its w=0 interpretation. In contrast, the QPNM prediction for the $K^{\pi}=4^{+}$ band given by Nesterenko et al. [13] is 5 times stronger than the experimental value. Although a revised prediction of B(E4)=0.8 spu is reported by Soloviev [15], the accompanying energy-fit becomes poorer and the B(E4) for the γ-band is by a factor of 3 smaller than the experimental value.

The sdg IBM has an advantage of having four parameters for describing E4 transitions in a single nucleus. The three experimental B(E4)'s in ^{168}Er given by Govil et al. [11] can be reproduced without difficulty. One more datum, however, is needed to fix the parameters. Nevertheless, a tentative analysis is in progress, where the B(E4) for the $I,K^{\pi}=4,0^{+}{}_{2}$ excitation is assumed to vanish. Under this assumption a strong E4 excitation of the $K^{\pi}=3^{+}$ band, B(E4)=50 spu, is predicted. This prediction is in sharp contrast with that of the QPNM, B(E4)=0.8 spu [13]. Experimental determination of the B(E4) for this excitation would be valuable to compare these two theoretical descriptions. More details will be given in a subsequent publication.

Investigations, both experimental and theoretical, of E4 transitions have revealed, and will continue to reveal, detailed properties of deformed nuclei for our understanding of their structure. Experimental studies including the $K^{\pi}=3^{+}$ and 4^{+} bands are of particular importance, because they will determine the future direction of our theoretical work.

REFERENCES

1. A. Bohr and B.R. Mottelson, Nuclear Structure vol.2, Benjamin, Inc., London (1975).
2. T.S. Dumitrescu and I. Hamamoto, Nucl. Phys. A383 (1982) 205; M. Matsuo and K. Matsuyanagi, Prog. Theor. Phys. 74 (1985) 1227.
3. V.G. Soloviev and N.Yu. Shirikova, Yad. Fys.32 (1982) 1376.
4. Y. Akiyama, Nucl. Phys. A433 (1985) 369.
5. N. Yoshinaga, Nucl. Phys. A456 (1986) 21; H.C. Wu, A.E.L. Dieperink and S. Pittel, Phys. Rev. C34 (1986) 703.
6. N. Yoshinaga, Y. Akiyama and A. Arima, Phys. Rev. Lett. 56 (1986) 1116.
7. Y. Akiyama, A. Gelberg and P. von Brentano, to be published.
8. Y. Akiyama, K. Heyde, A. Arima and N. Yoshinaga, Phys. Lett. B173 (1986) 1.
9. D.G. Burke, W.F. Davidson, J.A. Cizewski, R.E. Brown, E.R. Flynn and J.W. Sunier, Can. J. Phys. 63 (1985) 1309.
10. T. Ichihara, H. Sakaguchi, M. Nakamura, T. Noro, F. Ohtani, H. Sakamoto, H. Ogawa, M. Yosoi, M. Ieiri, N. Isshiki, Y. Takeuchi and S. Kobayashi, Phys. Lett. 149B (1984) 55; T. Ichihara, H. Sakaguchi, M. Nakamura, M. Yosoi, M. Ieiri, Y. Takeuchi, H. Togawa, T. Tsutsumi and S. Kobayashi, preprint RIKEN-AF-NP-56.
11. I.M. Govil, H.W. Fulbright, D. Cline, E. Wesolowski, B. Kotlinski, A. Backlin and K. Gridnev, Phys. Rev. C33 (1986) 793.
12. M. Matsuo, preprint KUNS 845.
13. V.O. Nesterenko, V.G. Soloviev, A.V. Sushikov and N.Yu. Shirikova, JINR preprint E4-85-856, Dubna (1985).
14. D.G. Burke, M.A.M. Shahabuddin and R.N. Boyd, Phys. Lett. 78B (1978) 48.
15. V.G. Soloviev, a talk given at the Harrogate Conference, Harrogate (1986).

STRESZCZENIE

Wskazano, że dokładne badania eksperymentalne nisko leżących pasm $K^{\pi} = 3^{+}$ i 4^{+} są szczególnie ważne dla przyszłego rozwoju teorii jąder zdeformowanych. Stosunki przejść E4 dla wzbudzeń tych pasm dostarczają cennych informacji o kolektywności typu hexadekapolowego, która może okazać się bardzo interesującym problemem teorii struktury jądrowej.

Przeprowadzono wstępne rozważania dotyczące wzbudzeń E4 w modelu oddziałujących bozonów sdg. Sugerują one możliwość silnych wzbudzeń $I, K^{\pi} = 4, 3^{+}$.

Р Е З Ю М Е

Указывается, что точные экспериментальные исследования низколежащих полос с $K^{\pi} = 3^{+}$ и 4^{+} являются особенно важными для предстоящего развития теории деформированных ядер. Отношения E4-переходов при возбуждении таких полос являются источником ценной информации об коллективности гексадекапольного типа, которая может оказаться очень интересной проблемой теории ядерной структуры.

Проводились предварительные обсуждения E4-возбуждений в модели взаимодействующих бозонов sdg, откуда следует возможность сильных возбуждений состояний с $I, K^{\pi} = 4^{+}, 3^{+}$.