объединенный
институт
ядерных
исследований
дубна

S 70

E4-87-795

V.G.Soloviev

ON COLLECTIVE TWO-PHONON STATES IN DEFORMED NUCLEI

Submitted to "Romanian Journal of Physics"

1987

1. INTRODUCTION

By the conventional treatment (see. refs. [1,2]) there should exist one-, two- and three-phonon states in doubly even spherical and deformed nuclei. A large number of two-phonon collective states was observed experimentally in spherical nuclei. It has been believed for a long time [3] that scarce information on two-phonon states is caused by the difficulties in detecting two-phonon states in deformed nuclei as they should be at energies where there are many two-quasiparticle and one-phonon states apart from a large number of rotational states.

The quasiparticle-phonon nuclear model [4-6] was applied [7-10] to study the influence of the Pauli principle in the two-phonon components of the excited state wave functions. The inclusion of the Pauli principle decreases the contribution of the terms of the secular equation which are partially violated by the Pauli principle and shifts the two-phonon poles. According to the calculations of ref. [10], in spherical nuclei the inclusion of the Pauli principle in the two-phonon components of the wave functions does not lead in most of the cases to a considerable shift of energies and to the change of the structure of several first 2^+, 3^- and 4^+ states. In deformed nuclei, taking into account the Pauli principle in the two-phonon components of the wave functions leads to a large shift of two-phonon poles [7] and thus to a large increase of energy centroids of the two-phonon collective states [9]. Due to a large density of the states of doubly even deformed nuclei at energies higher than 3 MeV, the two-phonon collective state strength should be distributed (fragmented) over many nuclear levels. On this basis it has been stated [9] that collective two-phonon states cannot exist in deformed nuclei.

According to the Bohr-Mottelson model and its microscopic analog [1,11,12], dynamic deformation theory [13], self-consistent collective coordinate method [14], multiphonon method [15], interacting boson model [16] and other phenomenological models, the deformed nuclei should contain two-phonon collective states.

Such an essential difference between the statements concerning the existence or nonexistence of collective two-phonon states in deformed nuclei in different models forces to discuss this problem.

2. DESCRIPTION OF TWO-PHONON STATES

Let us consider how the two-phonon collective states in well deformed nuclei are described in various models. Phonons are defined by quantum numbers $(\lambda\mu i)$ where λ is multipolarity, μ is its projection, i=1, 2, 3,... is the secular equation root number in the random phase approximation.

According to the interacting boson model (IBM), at double or somewhat higher energies of the first $K^{\pi}_n = 2^+_1$ states, there should be states with $K^{\pi}=0^+$ and 4^+ with the dominating two-boson (or two-phonon) components in their wave functions. A further improvement of the model [16] by introducing the g boson does not change this situation essentially. Thus, by the sdg IBM [16], in ^{168}Er the first $K^{\pi}_n=4^+_1$ state has a dominating two-boson component. Obviously, an essential modification of the IBM is needed to shift the states with $K^{\pi}=0^+$ and 4^+ with the dominating two-boson components. The problem of two-phonon states is basic in comparing the IBM with the QPNM [17].

Based on the assumption that two-phonon states exist, attempts were made in refs. [12,14] to explain a large anharmonicity of γ-vibrations in ^{168}Er. The absence of two-phonon states $K^{\pi}=0^+$ and 4^+ of the type (221,221) at double energies of γ-vibrational (221) states in ^{168}Er is thought to be an exception to the general rule.

Объединенный институт ядерных исследований
БИБЛИОТЕКА

A large anharmonicity was associated with a stable γ-deformation of ^{168}Er. According to the calculations by the self-consistent collective coordinate method [14], minimum of the total ^{168}Er energy was obtained at $\gamma_0 = 13^{\circ}$ and the difference in energy in comparison with $\gamma = 0$ is equal to 1 MeV. Note that the calculations of the form of ^{168}Er by the shell correction method indicate the softness of the nucleus with respect to γ-deformation whereas the energy minimum is achieved at $\gamma_0 = 0$. According to the calculations [14], the energies of two-phonon states $K^{\pi}=4^+$ and 0^+ of the type (221,221) are equal to 2.25 MeV and 2.95 MeV. The inclusion of the mode-mode coupling reduces the energies of two-phonon states (221,221) with $K^{\pi}=4^+$ up to 2.1 MeV and with $K^{\pi}=0^+$ up to 2.27 MeV. It is to be noted that the mode-mode coupling is much simpler than the quasiparticle-phonon interaction in the QPNM.

The multiphonon method [15] was applied to describe two-phonon states in ^{168}Er. In ref. [15] the consideration is limited by phonons of the same type, namely (221), in the Tamm-Dancoff approximation and the Pauli principle is taken into account exactly. Taking into account multiphonon components of the wave functions it was obtained that the two-phonon states (221,221) are at the energies $K^{\pi}=4^+$ 2.24 MeV and $K^{\pi}=0$ 2.815 MeV. These results are close to those obtained in ref. [14] by the self-consistent collective coordinate method. In refs. [14,15] for the two-phonon states $\mathcal{E}(4^+) < \mathcal{E}(0^+)$ whereas in the quasiparticle-phonon nuclear model the inverse inequality $\mathcal{E}(4^+) > \mathcal{E}(0^+)$ takes place for the energy centroids since the effect of the Pauli principle for the sum of K-values is much larger than for the difference. The main shortcoming of the methods [14,15] in describing ^{168}Er is the restriction of the consideration to γ-vibrations without coupling to other degrees of freedom. Therefore, they cannot describe properly the fragmentation of two-phonon states.

Within the multiphonon method [15] it was attempted to explain the absence of two-phonon octupole states $K^{\pi}=0^+(301,301)$ and others in the actinide region. Thus, ß-vibrational (201) and octupole (301) phonons were taken into account; the energies of the two-phonon $K^{\pi}=0^-(301,201)$, $0^+(301,301)$ states and the probabilities of E1 and E2 transitions to the ground and one-phonon (301) and (201) states were calculated. The two-phonon states were obtained at 1.78, 1.80 and 1.91 MeV, i.e. at energies larger than the sum of two-phonon energies. In these calculations γ-vibrational (221) and octupole (311) and (321) phonons as well as other degrees of freedom were neglected. Therefore, the assertion about the existence of two-phonon states is groundless.

It is now well understood that to describe the structure of states of deformed nuclei with the excitation energy 2-3 MeV (or 1.7-3.0 MeV in the actinide region) one should take into account a large number of degrees of freedom, i.e. the coupling of many one-, two- and three-phonon states.

In describing low-lying nonrotational states of deformed nuclei in the quasiparticle-phonon nuclear model, the wave function is taken as a sum of one-phonon components

$$\Psi_n(K_0^{\pi_0}) = \Big\{ \sum_{i_0} R_{i_0}^{n} Q^+_{\lambda_0\mu_0 i_0} + \sum_{\substack{\lambda_1\mu_1 i_1 \\ \lambda_2\mu_2 i_2}} P^{\lambda_1\mu_1 i_1}_{\lambda_2\mu_2 i_2}(n)\, Q^+_{\lambda_1\mu_1 i_1} Q^+_{\lambda_2\mu_2 i_2} \Big\} \Psi_0 , \qquad (1)$$

where $Q^+_{\lambda\mu i}$ is the phonon creation operator and Ψ_0 is the ground state wave function. Usually 10 one-phonon and 100-200 two-phonon terms are used. According to the calculations [9], the energy centroids of the two-phonon states $0^+(201,201)$, $0^+(221,221)$, $0^+(301,301)$, $4^+(221,221)$ and others are in the interval (2.5-4.5) MeV. Thus, according to ref. [18] the wave functions of the states with $K^{\pi}=4^+$ with an energy up to 2 MeV in the rare-earth region have one dominating one-phonon hexadecapole (441 or 442) component and the two-phonon admixture (221,221) not exceeding 10%.

Obviously, the centroid energies of the two-phonon states are somewhat overestimated in the calculations [9] . If the calculations are performed in a large space of single-particle states, then a correct description of the $K^{\pi}_{n}=2^{+}_{1}$, 0^{+}_{1} and 0^{-}_{1} energies provides somewhat overestimated B(E2)- and B(E3)-values, but not so overestimated B(E2)-values as in ref. [12] . Taking into account the interaction in the particle-particle channel, under a proper choice of the constant one can obtain a good description of the energies and B(Eλ)-values for the first 2^{+}_{1}, 0^{+}_{1} and 0^{-}_{1} states. In this case, the energy centroids of the two-phonon collective states decrease. The position of the energy centroids of two-phonon states is expected to be not very much influenced by the three-phonon terms of the wave functions.

The fragmentation of two-phonon states has not yet been calculated within the quasiparticle-phonon nuclear model. By the calculations [9] the concentration of the two-phonon strength on one level is (50-80)%. To describe the fragmentation of two-phonon states the wave function (1) should be added by three-phonon terms and a far larger number of one-phonon states should be taken into account. It is obvious that the inclusion of three-phonon states and the extention of the space of one-phonon states will enhance the fragmentation of two-phonon states. Therefore, the conclusion on the absence of two-phonon collective states remains valid.

3. ARE THERE COLLECTIVE TWO-PHONON STATES IN DEFORMED NUCLEI?

In 1980 the analysis of the experimental data enabled the authors of ref. [19] to make the conclusion that there were no reliable data on two-phonon collective states in deformed nuclei. Let us discuss how the situation changed since then.

Much attention was paid to ^{168}Er that was studied in detail experimentally [20-23]. In theoretical papers [11,12,15,16] it is assumed that the state with $K^{\pi}_{n}=4^{+}_{1}$ and energy 2.056 MeV is a two-phonon state of the type (221,221). However, the two-phonon structure of this state is not verified experimentally. Moreover, according to ref. [23], this state is well excited in the (α,α') reaction, B(E4)=0.6 s.p.u., which indicates a large one-phonon (441) component in its wave function. There are no experimental data on the existence of the two-phonon states $K^{\pi}=0^{+}$(221,221) or $K^{\pi}=0^{+}$(201,201). It can be stated that the existence of quadrupole two-phonon states in ^{168}Er is still an open problem.

Consider now whether two-phonon octupole states with $K^{\pi}=0^{+}$ (301,301) exist in the Th and U isotopes. Doubly even isotopes of Ra, Th and U contain low-lying states with $I^{\pi}K=1^{-}0$. Starting from ref. [24], these states are treated as octupole vibrational states (301). In recent years, the experimental measurements indicate a stable octupole deformation in the ground and low-lying states in some Ra and Pa isotopes and in the high-spin states of doubly even Ra and Th isotopes. On the other hand, it is experimentally determined that there is no octupole deformation in the ground states of ^{230}Ra [25], ^{231}Th and other nuclei. According to the calculations, there is no stable octupole deformation in nuclei with A>228. Therefore, there arises a question why the two-phonon 0^{+}(301,301) states are not observed in ^{228,230,232}Th and ^{230,232,234,238}U? By ref. [26], the two-phonon 0^{+}(301,301) state is absent in ^{228}Th. There are no indications [27] of the existence of two-phonon collective states in ^{234}U and other isotopes of Th and U [28].

The problem of absence of the two-phonon 0^{+}(301,301) states in the Th and U isotopes remains to confront the microscopic analog of the Bohr-Mottelson model, the interacting boson model and other phenomenological models. It is to be explained why the

$0^+(301,301)$ states are absent in the nuclei where there is no stable octupole deformation in the ground and low-lying states.

The multiphonon method was applied to calculate the two-phonon $0^-(301,201)$, $0^+(201,201)$ and $0^+(301,301)$ states in ^{234}U from which intensive E1 and E2 transitions should proceed to the one-phonon $0^-(301)$ and $0^+(201)$ states. However, neither in ref.[27] nor in other papers there are indications of the existence of such two-phonon states at the energies 1.7-2.0 MeV in ^{234}U.

There are no experimental data in two-phonon collective states on deformed doubly even nuclei. Thus, the experimental data do not contradict the assertion, made from the calculations within the quasiparticle-phonon nuclear model, on the absence of two-phonon collective states in deformed nuclei.

4. CONCLUSION

The existence or nonexistence of two-phonon collective states in deformed nuclei is the central problem from the point of view of elucidating the structure of low-lying states. This problem is to be solved by experimenters. Therefore, there is a great need for experiments on searching for two-phonon collective states in deformed nuclei.

REFERENCES

1. A.Bohr, B.R.Mottelson, Nuclear Structure, v. 11, W.A.Benjamin, INC. New York, 1975.
2. V.G.Soloviev, Theory of Complex Nuclei, Pergamon Press, 1976.
3. V.G.Soloviev, Yad.Fiz., 10, 296 (1969).
4. V.G.Soloviev, Particles and Nuclei 9, 810 (1978); L.A.Malov and V.G.Soloviev, Particles and Nuclei 11, 301 (1980).

5. V.V.Voronov and V.G.Soloviev, Particles and Nuclei 14, 1380 (1983).
6. V.G.Soloviev, Prog.Part.Nucl.Phys. 19, 107 (1987).
7. R.V.Jolos, J.L.Molina, V.G.Soloviev. Teor.Mat.Fiz. 10, 245 (1979); Z.Phys. - Atoms and Nuclei A295, 147 (1980).
8. V.G.Soloviev, N.Yu.Shirikova, S.I.Serdyukova et al., Izv.Akad. Nauk SSSR, ser.fiz. 45, 1834 (1981).
9. V.G.Soloviev, N.Yu.Shirikova, Z.Phys. - Atoms and Nuclei A301, 263 (1981); Yad.Fiz. 36, 1376 (1982).
10. V.G.Soloviev, Ch.Stoyanov and R.Nikolaeva, Izv.Akad.Nauk SSSR, ser.fiz. 47, 2082 (1983).
11. A.Bohr, B.R.Mottelson, Physica Scripta 25, 28 (1982).
12. T.S.Dumitrescu, I.Hamamoto, Nucl.Phys. A383, 205 (1982).
13. K.Kumar, J.B.Gupta, J.H.Hamilton, Aust.J.Phys. 32, 307 (1979); J.B.Gupta, Physica Scripta 28, 21 (1983).
14. M.Matsuo, K.Matsuyanagi, Prog.Theor.Phys. 74, 1227 (1985); 76, 93 (1986).
15. R.Piepenbring, in: Capture Gamma-Ray Spectroscopy and Related Topics-1984, American Institute of Physics, New York, 1985, p. 38; Preprint Inst. des Sciences Nucleaires de Grenoble, 1987; J.Leandri, R.Piepenbring, Phys. Rev. C36, 1235 (1987).
16. N.Yoshinaga, Y.Akiyama, A.Arima. Phys.Rev.Lett. 56, 1116 (1986); Y.Akiyama, K.Heyde, A.Arima, N.Yoshinaga, Phys.Lett. B173, 1 (1986).
17. V.G.Soloviev, Pisma ZheTP 40, 1216 (1984); V.G.Soloviev, Z.Phys.- Atomic Nuclei, A324, 393 (1986); Preprint JINR E4-87-45, Dubna, 1987.
18. V.O.Nesterenko, V.G.Soloviev, A.V.Sushkov and N.Yu.Shirikova, Yad.Fiz. 44, 1443 (1986).
19. L.K.Peker, J.H.Hamilton in "Future Directions in Studies of

Nuclei far from Stability, ed. J.Hamilton, North-Holland P.C. Amsterdam, 1980, p. 323.

20. W.F.Davidson, Warner D.D., Casten R.F. et al. J.Phys.G: Nucl.Phys. 7, 455; 843 (1981).
21. D.G.Burke, B.Maddock, W.F.Davidson, Nucl.Phys. A442, 424 (1985); D.G.Burke, W.F.Davidson et al. Nucl.Phys. A445, 70 (1985).
22. W.F.Davidson, W.R.Dixon, R.S.Storey. Can.J.Phys. 62, 1538 (1984); D.G.Burke, W.F.Davidson et al. Can.J.Phys. 63, 1309 (1985).
23. I.M.Govil, H.W.Fulbright et al. Phys.Rev. C33, 793 (1986).
24. V.G.Soloviev, P.Vogel, Phys.Lett. 6, 126 (1963).
25. W.Kurcewicz, E.Ruchowska et al. Nucl.Phys. A464, 1 (1987).
26. W.Kurcewicz, N.Kaffrell et al. Nucl.Phys. A289, 1 (1977).
27. C.Ardisson, J.Dalmasso, G Ardisson, Phys.Rev. C33, 2132 (1986).
28. J.Zylicz., in "Nuclear Structure, Reactions and Symmetries", ed: R.Meyer, V.Paar, World Scientific, 1987, p. 79.

Received by Publishing Department
on December 1, 1987.

Соловьев В.Г. E4-87-795

О коллективных двухфононных состояниях в деформированных ядрах

Рассмотрены теоретические методы описания двухфононных коллективных состояний в деформированных ядрах и указано на их слабость. Проведенный анализ экспериментальных данных свидетельствует об отсутствии твердо установленных экспериментально коллективных двухфононных состояний. Утверждается, что вопрос о существовании или несуществовании коллективных двухфононных состояний является центральным для понимания структуры возбужденных состояний. Указывается на необходимость экспериментов по поиску двухфононных состояний.

Работа выполнена в Лаборатории теоретической физики ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна 1987

Soloviev V.G. E4-87-795

On Collective Two-Phonon States in Deformed Nuclei

Theoretical methods for describing two-photon collective states in deformed nuclei are treated. The analysis of the experimental data indicates that collective two-phonon states have not yet been determined experimentally. Whether collective two-phonon states exist or not is stated to be the central problem for understanding the structure of excited states. The necessity for searching two-phonon states is pointed out.

The investigation has been performed at the Laboratory of Theoretical Physics, JINR.

Preprint of the Joint Institute for Nuclear Research. Dubna 1987