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RECOLLECTION ESSAY

How have they started? – A brief guide for pedestrians

Takaharu Otsuka[1,2,3,4]

[1] *Department of Physics, University of Tokyo, Hongo, Bunkyo-ku, Tokyo 113-0033, Japan*
[2] *Center for Nuclear Study, University of Tokyo, Hongo, Bunkyo-ku, Tokyo 113-0033, Japan*
[3] *RIKEN Nishina Center, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan*
[4] *Instituut voor Kern- en Stralingsfysica, KU Leuven, B-3001 Leuven, Belgium*
E-mail: otsuka@phys.s.u-tokyo.ac.jp
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I shall present a very brief summary of subjects selected from what Prof. Akito Arima has done in the past years. I will focus on the initial works on the *configuration mixing* and on the *Interacting Boson Model*. Since there are many literatures on these subjects, I shall concentrate what have been done at the initial or at the pre-history stages. By doing this, we shall see how Prof. Akito Arima started from the scratch.

Keywords shell model, configuration mixing, magnetic moment, interacting boson model

1 Introduction

Professor Akito Arima has devoted his intellectual activities to the development of nuclear physics for more than half a century. In fact, his scientific career seems to have started around the year 1954, when the *configuration mixing* theory has been proposed by him with Prof. Hisashi Horie. In this year, he was only 24 years old. The idea and some results of this work were published in two papers in 1954 [1, 2]. Not only Prof. Arima was young, but also nuclear physics was young in this year, in the sense that the idea of the "independent particle model" or "shell model" by Mayer [3] and Jensen [4] was published in 1949, only five years earlier. Considering that the communications were made mainly by the conventional mail, i.e., the letter by papers, we realize that Arima–Horie's work was made in a really initial stage of the history of nuclear structure physics.

I shall try, in this article, to recall some of major contributions by Prof. Arima, while I do not attempt to present a comprehensive overview of all his works. I further focus on (i) the configuration mixing theory and the development of the shell model and also (ii) the Interacting Boson Model, particularly its very initial introduction from scratch. This article is intended to be very pedagogical so that those who are not familiar with concepts or terminology of nuclear physics can understand to a certain extent. I would like to concentrate on original initial ideas and their outcome, leaving many things untouched. In fact, Prof. Arima has presented many exciting and important studies with his collaborators, but such works are not covered by this article, expecting that most of them are discussed extensively in the other articles.

*Special Topic: Simplicity, Symmetry, and Beauty of Atomic Nuclei (Eds. Jie Meng, Takaharu Otsuka & Yu-Min Zhao).

2 Configuration mixing

The shell model proposed by Mayer and Jensen was basically the independent particle model (IPM) describing nucleons moving in the nuclear potential [3–5]. The Harmonic Oscillator potential was taken, and the one-body spin-orbit interaction (i.e., $\boldsymbol{\ell}\cdot\boldsymbol{s}$) and the so-called $\boldsymbol{\ell}\cdot\boldsymbol{\ell}$ term were included. The introduction of the spin-orbit interaction generates the spin-orbit splitting, which was crucial for the shell structure and magic numbers, 2, 8, 20, 28, 50, 82, 126. This empirical introduction is appreciated, partly because the full explanation of the spin-orbit interaction is still to come. Since its introduction up to now, the Mayer–Jensen's IPM or shell model has been solid starting basis for the studies of nuclear structure.

The IPM indeed explained well as to which proton number, Z, and neutron number, N, produce the closed shell; if Z (N) is equal to one of the magic numbers listed above, a closed shell arises for protons (neutrons). If both Z and N are magic numbers, for instance, like ${}^{16}{}_{8}\mathrm{O}_{8}$, the ground state is composed of a doubly closed shell. The nuclei with the doubly closed shell can also be called

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doubly magic nuclei. The doubly magic nuclei play crucial roles in the description of atomic nuclei. The single-particle orbits of nucleons in the doubly closed shell are completely occupied. This means that the doubly magic nucleus should have the ground state of the spin/parity, $J^P = 0^+$. Based on this property, the IPM tells us successfully the spin/parity of the ground and some lowest levels of nuclei comprised of a doubly closed shell ± one nucleon. For instance, ${}^{17}_{8}\mathrm{O}_9$ is made by 8 protons ($Z = 8$) and 9 neutrons ($N = 9$), and the 9th neutron must be on one of the single-particle orbitals above the $N = 8$ closed shell. The lowest orbital among them is the $1d_{5/2}$ orbit, and one thus sees that the ground state should have the spin/parity $J^P = 5/2^+$ since the other nucleons form the doubly closed shell below $Z = N = 8$ with $J^P = 0^+$. Virtually all nuclear states with the appropriate doubly closed shell ± one nucleon can thus be described by the IPM of Mayer and Jensen [5].

Despite such a success, the experimentally measured magnetic moments showed substantial deviations from what can be derived from the IPM, called Schmidt values. Some empirical trends were argued on these deviations, but the origin was not clear. Arima and Horie then presented a theory, called *configuration mixing*, accounting for these deviations. This theory is what I referred to as the work began in 1954.

The magnetic moment of a given nuclear state can be expressed as the sum of the expectation values of proton spin and orbital angular momentum operators and those of neutron spin and orbital angular momentum operators, where each term is multiplied by appropriate coefficients, called spin and orbital g-factors for proton and neutron. Within the IPM, these expectation values are equal to the corresponding single-particle values, called Schmidt values:

$$\mu_{\rm sp} = j\{g_\ell \pm (g_s - g_\ell)/(2\ell + 1)\}, \quad \text{for } j = \ell \pm 1/2, \quad (1)$$

where ℓ implies the orbital angular momentum of the single-particle orbit, j is the total angular momentum coupled by ℓ and the spin 1/2, and g_ℓ and g_s denote g-factors mentioned above. This equation is valid for protons and neutrons separately. Eq. (1) indicates that there are two values corresponding to $j = \ell + 1/2$ and $j = \ell - 1/2$ for $j > 1/2$.

Experimental values of the magnetic moments are not well reproduced by either of two Schmidt values, and are lying between them. This was a major puzzle. Arima and Horie explained why the measured magnetic moments are found between two Schmidt values, apart from a very few exceptions. In the IPM, a nucleon outside the doubly-magic closed shell, or the core, is assumed to move around the core without disturbing the nucleons in the core, as shown in Fig. 1(a). This picture works for the spin/parity of the ground state and the ordering of a few lowest levels. However, as shown in Fig. 1(b), this nucleon outside the core (black circle) can interact with a nucleon in the core (white circle) through nuclear forces, and can move it into one of higher orbitals (gray circle). The occupation pattern of single-particle orbits is called *configuration* in general. Obviously, such an excited nucleon creates configurations different from the closed-shell configuration. This phenomenon was called the *configuration mixing*. The mixing of different configurations should occur more or less in general. I would like to emphasize that the configuration mixing theory by Arima and Horie has the meaning beyond such general boring remark and indeed implies some crucial effects due the mixing. They demonstrated this feature by taking the example of magnetic moment [1, 2].

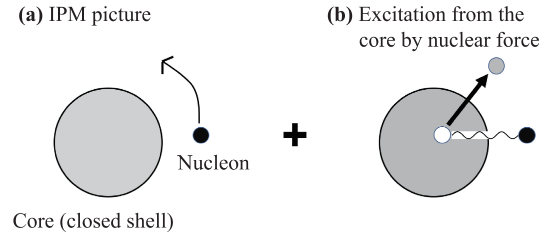

Fig. 1 Schematic picture of the extension of the IPM wave function by the configuration mixing introduced by Arima and Horie.

The magnetic moment is the response to external magnetic field. In the IPM, the magnetic field acts on the nucleon outside the core (closed shell), and the magnetic moment of the ground state, for instance, is obtained as a diagonal matrix element, as shown schematically in Fig. 2(a). Note that the core does not contribute to the magnetic moment because of its spin/parity, $J^P = 0^+$.

The magnetic field does more for wave functions produced by the configuration mixing theory. It can de-excite the excited nucleon (white circle) shown in Fig. 1(b) back to the core (gray circle) as an M1 transition between two orbitals, as shown in Fig. 2(b). Alternatively, the magnetic field can excite a nucleon in the core (white circle) to an orbital outside the core also as an M1 transition, as shown in Fig. 2(c).

Arima and Horie investigated this mechanism in terms of the perturbation theory, by employing a simple δ-

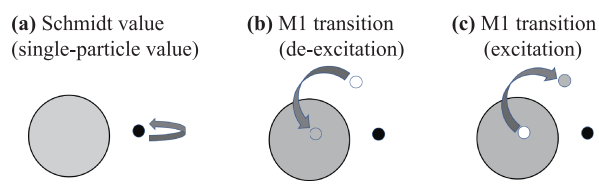

Fig. 2 Schematic picture of the contributions to the magnetic moments due to the configuration mixing introduced by Arima and Horie. The broad bent arrow indicate M1 transitions.

function interaction as the relevant nuclear force [1, 2]. Fig. 1(b) is nothing but the first-order perturbation, and the key point here is the coherence between the interaction causing this perturbation and the magnetic transition. By having rather simple interaction, the effect was studied carefully. The outcome was shown in terms of analytic formulas and also in the form of numerical results. I quote just a part of Table III from Ref. [2] in Fig. 3. One sees nice agreement with experiments. Some other aspects, for instance, the assessment of the second-order perturbation effect, were investigated. This new theory was so successful also in further developments [6].

The configuration mixing theory suggests that the nuclear forces working inside the nucleus can change nuclear properties in coherent manners with the mechanisms of physical observables to a notable extent. The outcome on the magnetic moments is quoted for instance by Bohr and Mottelson [7] together with the work of Blin-Stoyle and Perks [8]. We note that the concept of the core is extended from the doubly closed shell to a nucleus with even Z and even N assuming that those even numbers of protons and neutrons are coupled into pairs with $J^P = 0^+$.

The configuration mixing theory is a general idea, and can or should be extended from the first order to the second order. In fact, the second order process can be dominant, if all configurations in the harmonic oscillator shell are taken into account explicitly in more modern shell-model calculations. This feature will be important for the Gamow–Teller quenching issue.

The configuration mixing was applied to the quadrupole moment also [1, 2], suggesting much larger effects. However, this was not referred by Bohr and Mottelson, possibly because the Nilsson model is supposed to be used for this purpose. This is an interesting observation.

We should note that the basic idea of the configuration mixing leads us to the concept of effective nucleon-nucleon interaction including renormalization effects from 2p-2h excitations or higher.

Table III. Magnetic moments of (1/2+) nuclei

odd-proton nuclei ($\mu_{sp} = 2.79$)						
nucleus	P-configuration		N-configuration		$\mu_{\rm cal}$	$\mu_{\rm exp}$
$_9$F^{19}		$s_{1/2}$		$(d_{5/2})^2$	2.66	2.63
$_{15}$P^{31}	$(d_{5/2})^6$	$s_{1/2}$		$(d_{5/2})^6$	1.36	1.13
$_{81}$Tl^{203}	$(h_{11/2})^{12}$	$s_{1/2}$	$(i_{13/2})^{12}$	$(p_{3/2})^4$	1.44	1.61
$_{81}$Tl^{205}	$(h_{11/2})^{12}$	$s_{1/2}$	$(i_{13/2})^{14}$	$(p_{3/2})^4$	1.45	1.63
odd-neutron nuclei ($\mu_{sp} = -1.91$)						
$_{14}$Si^{29}	$(d_{5/2})^6$		$(d_{5/2})^6$	$s_{1/2}$	−0.54	−0.56
$_{48}$Cd^{111}	$(g_{9/2})^8$	$(g_{7/2})^5$	$(d_{5/2})^6$	$s_{1/2}$	−0.49	−0.59
$_{48}$Cd^{113}	$(g_{9/2})^8$		$(d_{5/2})^6$	$s_{1/2}$	−0.77	−0.62
$_{50}$Sn^{115}	$(g_{9/2})^{10}$		$(d_{5/2})^6$	$s_{1/2}$	−0.73	−0.92
$_{50}$Sn^{117}	$(g_{9/2})^{10}$	$(d_{5/2})^6$	$(h_{11/2})^2$	$s_{1/2}$	−0.50	−1.00
	”		$(d_{3/2})^2$	$s_{1/2}$	−1.25	

Fig. 3 Magnetic moments calculated by the configuration mixing theory. Taken from Table III of Ref. [2].

3 Shell model studies

Probably based on successful applications of the configuration mixing theory, Prof. Arima enthusiastically developed and coordinated shell-model studies with various collaborators in Japan and in US [9–13].

The subjects started with systematic calculations on light nuclei in the p and sd shells [9, 11, 12], included a challenge to identify intruder states around the $^{16}_{8}$O$_8$ nucleus [10], and were extended to an empirical determination of the effective nucleon-nucleon (NN) interaction. The last subject was made mainly during his stay in Argonne [11]. The pseudo coupling models utilizing characteristic algebraic structures are one of the favorite games of Prof. Arima, for instance, the pseudo LS coupling and the pseudo SU(3) coupling [13].

The α-particle and other clustering phenomena attracted much attention of Prof. Arima also [14], and the combination with the SU(3) scheme of the shell model was one of the subfields where Prof. Arima and his collaborators had a considerable advantage [15]. The calculation on the α-decay width was appreciated [16].

Prof. Arima has been very keen in developing and supporting shell model calculations. He was pushing such activities in Japan, keeping up with world-wide developments, see for instance, [19, 20]. He encouraged several people to create new computer codes for large-scale shell model calculations with then-advanced computers. Even the author was somewhat involved. The tradition he implanted played very important roles in the studies made later in the Tokyo group, and may have led this group eventually to the creation and developments of the Monte Carlo Shell Model [21, 22]. Although Prof. Arima has no direct relation to this research activity, his support has been present continuously, which can be appreciated by the wider community.

4 Spin-isospin mode

The shell model is a suitable theoretical framework for the studies on the spin-isospin properties, as the shell model handles different correlations on an equal footing. Prof. Arima devoted much efforts and energies to the studies on the spin-isospin modes, particularly magnetic and/or spin properties as well as Gamow–Teller transitions. The main issue was the quenching of transition strengths. This is a very important subject for him, and should be covered in other articles of this proceedings. The exchange current has been another important subject. It was studied also when he was in Stony Brook [17].

5 Interacting boson model

After working extensively with the shell model, the remaining area to be explored in nuclear structure physics was, for Prof. Arima, the collective motion and the deformation, particularly quadrupole deformation. Contrary to the present research frontline, the shell model was not able to describe heavy nuclei where the collective motion becomes more pure and visible. On the other hand, he had an ample experience of algebraic treatments of fermions and bosons. Here comes the Interacting Boson Model (IBM). Before the IBM was proposed with Prof. Francesco Iachello in 1975 [25], Prof. Arima had some ideas as to how to describe the quadrupole collective motion algebraically in terms of bosons. I quote the proceedings report of the workshop "Nuclear Collective Motion" held in May 18–20, 1967 at the Research Institute for Fundamental Physics (now Yukawa Institute for Fundamental Physics), Kyoto University. The proceedings was published in the journal Soryushiron Kenkyu [23]. But this journal is published in Japanese. Figure 4 shows the first page of the article by Arima, as well as the other pages. I display the original pages in those figures, otherwise non-Japanese would never have an opportunity to see them. Even the web site shown in Ref. [23] is in Japanese. Some parts in Chinese characters may be understandable for the readers of the present journal. The English translation can be found in Ref. [24]. Note that this article is quoted as Ref. [2] in Ref. [25].

The texts in Fig. 4 include the construction of states with a spin-2 boson, i.e., d-boson. The states with N d-bosons, depicted as d^N, are classified by totally symmetric representation $[N]$ of the SU(5), or SU_5 group. More elaborate discussions can be found in relations to the vibrational structure [26, 27] and also to the Wilet-Jean model [28]. The models with the d-boson were used in many works, for instance, [29], but Prof. Arima is, at

研　究　会　報　告　　　　　　-E47-

3　つ　の　コ　メ　ン　ト

有　馬　朗　人（東大理）

研究会では

ｉ）坂井氏のcorrespondence argumentについて

ii）吉田、大西氏のGeneralized coordinate method と池田Modelとの関連について

iii）坂東氏のeffective interactionについて

という３つのコメントをした。

ここでは(i)について記しておく。これはboson 近似におけるrotational schemeとvibrational schemeとの関係、及びvibrational state についての分類についての論である。

一般にd^N 配位はSU_5で分類できる。特にboson の場合はこんな大げさなことは言わなくても、完全対称状態〔N〕が許されるだけである。SU_5 の部分群としてO_5 がある。これもboson の場合にはseniority λ を用いれば、$(\lambda, 0)$ と既約表現がきまる。Bohr のvibrational model でα_μのかわりに、$\beta, \gamma, \varphi\,\theta\,\psi$ を用いた時のβ- 振動のnode の数n_βと、$N = \lambda + 2n_\beta$の関係にある。(Wilet Jem). 所でO_5 の完全分類を行うため、O_4 をcanonical chain として入れる。O_4は$\mathrm{SU}_2 \times \mathrm{SU}_2$ と同型であるから、４つのパラメタがあればO_4の分類が出来る。今のように完全対称の場合には実はこのうちの一つは不用で、３つの量子数ですむ。従つてO_5 はλ, μ, L, M, で完全に状態の分類が出来る、この時$L = \mu, \mu+1, \cdots 2\mu-2, 2\mu$であることが証明出来る。$L = 2\mu - 1$ が飛んでいることに注意されたい。こうしてみると図のようにきれいな分類が得られる。この図をＮを一定にして横に眺めれば$n_\beta = 0$ の部分はO_5の分類になつている。そこで眼を転じて縦に眺めてみると、Ｎが一つづつふえるに従つて状態が増えて行き、Ｌも変つて行く。その変り方にきれいな法則性があり、あたかも回転レベルのように見えることがわかる。これ

Three Comments *)

Akito Arima

Department of Physics, University of Tokyo, Tokyo 113 **)

Translater's note: This article is the translated version of a proceedings report of a talk given in the workshop "Nuclear Collective Motion" held May 18-20, 1967 at the Research Institute for Fundamental Physics (now Yukawa Institute for Fundamental Physics), Kyoto University. The proceedings was published in Soryushiron Kenkyu (vol. **35** (1967), page E47-E50), in Japanese. The translation was intended to be as direct as possible. The words in the square brackets in italic (i.e., [*italic*]) are additions by the translater. Some trivial mistakes have been corrected in the translated version.

I made, in the workshop, three comments such as

- (1) on the correspondence argument of Sakai,
- (2) on the relation of the generalized coordinate method of Yoshida and Onishi to the Ikeda model,
- (3) on the effective interaction of Bando.

In this article, I shall present some notes on comment (1). Specifically, this article consists of discussions on the relation between rotational and vibrational schemes in a boson approximation, and discussions on the classification for vibrational states.

One can classify, in general, d^N configurations in terms of SU_5. For bosons, in particular, one does not need to make such a general statement, and, in fact, only fully symmetric states $[N]$ are allowed. There is a subgroup O_5 for the group SU_5. For bosons again, the irreducible representation is determined as $(\lambda, 0)$ by using the seniority λ. In Bohr's vibrational model, one can introduce variables β, γ, φ, θ, ψ instead of α_μ's. The seniority λ can then be related to n_β as $N = \lambda + 2n_\beta$, where n_β denotes the number of the nodes of the β-vibration. (Wilet Jean). Here, we include O_4 into the canonical chain, so as to classify O_5 completely. Since O_4 is isomorphic to $SU_2 \times SU_2$, the classification of O_4 can be made in terms of four parameters. In a fully symmetric case, as is the present one, one of these four parameters can be dropped, and we need only three quantum numbers. Hence, the states of the present O_5 system can be classified completely by λ, μ, L and M. One can then prove that $L = \mu, \mu{+}1, \cdots, 2\mu-2, 2\mu$. Note that $L = 2\mu - 1$ is missing. Thus, one obtains a beautiful classification as shown in Fig. 1. When one views this figure in the horizontal direction keeping N constant, the $n_\beta = 0$ part gives rise to the classification of O_5. We shall now look at Fig. 1 differently, sweeping from the bottom upwards. As N increases one by one, we find more states, and the values of L change. One finds a clear regularity in the pattern of these variations, which actually appear to be similar to [*the pattern of*] rotational levels. I suspect that this [*similarity*] is the "correspondence" addressed by Sakai.

Fig. 4 The first page of the "Three comments" paper. The left panel displays the original paper as taken from p. E47 of Ref. [23], while the right panel exhibits its English translation, as taken from Ref. [24].

least, one of the first physicists (the first to the author's best knowledge) who had shown the complete classification of all the states and the formula for the energy eigenvalues with three quantum numbers as displayed in Fig. 6.

Figure 5 is the next page of the same article and indicates a completely different and even more important messages. First, the s-boson, a spin-0 boson, was introduced. Secondly, the total number of the s-boson and d-boson is conserved in a given nucleus, or at least for a given set of its states. By denoting this total boson number as N_0, the states we have to deal with are written, besides other quantum numbers, as

$$s^{N_0-N}d^N. \tag{2}$$

This is nothing but the IBM state. It was further stated that the (Q–Q) type boson–boson interaction gives us eigenstates in terms of the SU_3 group, of which the state-classification scheme is shown in the lower part of Fig. 5. Here, the Q operator stands for the quadrupole moment operator. This is similar to the fermionic SU3) case in the shell model by Elliott [30], and is essentially equal to the SU(3) (or SU_3) limit of the IBM [25, 32, 33]. The resulting level scheme is shown in the left panel of Fig. 7, where the beautiful appearance of rotational bands can be seen. The right panel of Fig. 7 exhibits the levels given by the SU(3) limit of the IBM [25]. As the total boson number is 4 and 8 in the left and right panels, respectively, differences arise. However, the overall pattern resembles between the two. The proceedings paper was so short and somewhat incomplete: some degeneracies are not exactly practiced (maybe due to drawing). Thus, many extensive studies were needed on top of the initial idea and have indeed been carried out to great details later [32, 33].

The O(6) limit was not mentioned explicitly in the

I now present the following discussions in order to clarify the relation of the level structure mentioned above to the rotational one. Assuming that the quantity N_0 [*,which is to be defined,*] has an upper limit, I introduce a hypothetical s-boson so that the total number of bosons is conserved. Then, the above arguments can be applied to the classification of the states, $s^{N_0-N}d^N$. I introduce further a boson-boson interaction of the Q-Q type between bosons, and then diagonalize it. It turns out that the classification in terms of the SU_3 group is more convenient, producing [*the level scheme shown in*] Fig. 2. In this figure, $N_0 = 4$ is taken. In general, for fully symmetric states in the $(s,d)^{N_0}$ configuration, the following sets of the SU_3 irreducible representations emerge;

(1) $(2N_0, 0)$, $(2N_0-4, 2)$, $(2N_0-8, 4)$, $\cdots$,

(2) $(2N_0-6, 0)$, $(2N_0-10, 2)$, $(2N_0-14, 4)$, $\cdots$,

(3) $(2N_0-12, 0)$, $(2N_0-16, 2)$, $\cdots$,

etc. The values of L belonging to these (λ, μ) irreducible representations are given, accordingly to Elliott, by

$$K = \min(\lambda,\mu),\ \min(\lambda,\mu)-2,\ \cdots,\ 0 \text{ or } 1$$

$$L = K,\ K+1,\ K+2,\ \cdots,\ K+\max(\lambda,\mu),$$

where $L = 0, 2, 4, \cdots, \max(\lambda,\mu)$ for $K = 0$.*) Therefore, if $N_0 = 4$ (the total number of states is certainly the same between Figs. 1 and 2),

	(λ, μ)	K	L
(1)	(8, 0)	0	0 0 2 4 6 8
	(4, 2)*	0	0 0 2 4
		2	2 2 3 4 5 6
	(0, 4)	0	0 0 2 4
(2)	(2, 0)	0	0 0 2

Since the eigenvalue of $(Q \cdot Q)$ is $\frac{\lambda^2+\lambda\mu+\mu^2}{9} + \frac{\lambda+\mu}{3} - \frac{1}{12}L(L+1)$, one ends up with [*the level scheme in*] Fig. 2. A remarkable correspondence between Figs. 1 and 2 is noticed in the region of low excitation energy. A model with s and d bosons has also been discussed by Taruishi of the Tokyo University of Education [*now Tsukuba University*].

Fig. 5 A part of the second page of the "Three comments" paper translated into English [24].

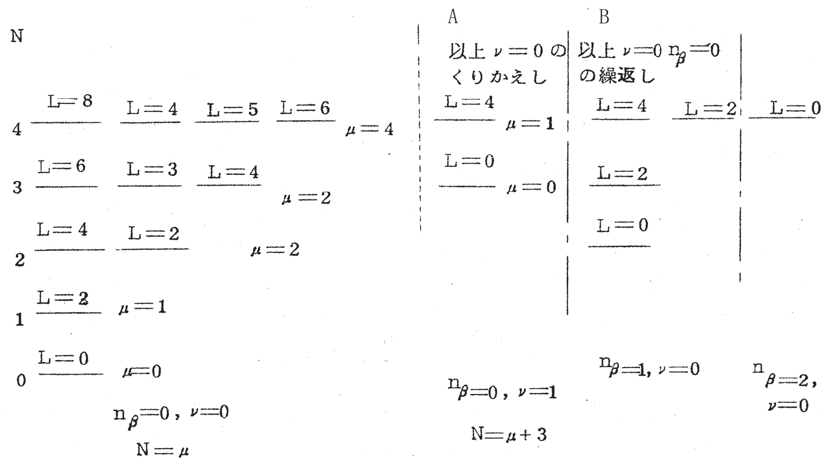

Fig. 6 A part of the third page of the "Three comments" paper [23]. The phrase marked by A (B) means "repetition of $\nu = 0$" ("repetition of $\nu = 0$, $n_\beta = 0$").

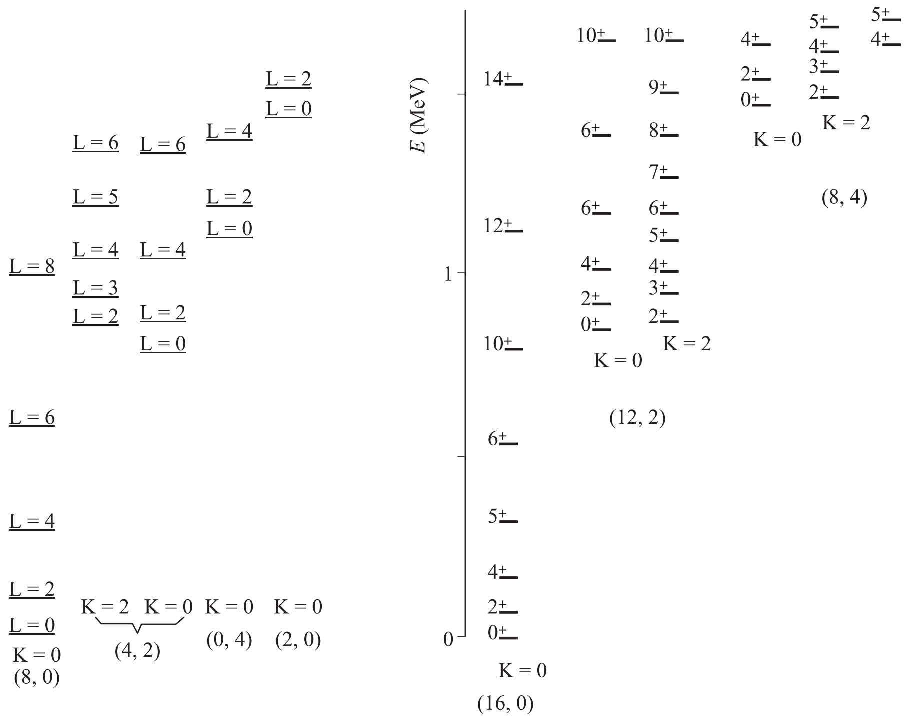

Fig. 7 Left: Fourth page of the "Three comments" paper, showing a rotational spectrum. Taken from p. E50 of Ref. [23]. See the text. Right: Level scheme of the SU(3) limit. A part of Fig. 1 of Ref. [25].

proceedings paper, but the classification shown in Fig. 6 has a close relation to the O(6) limit. Figure 8 displays the energy levels obtained by the O(6) limit, and one sees that the basic classification scheme in the O(6) limit stems from the O(5) structure of the SU(5) limit of the IBM. Physical consequences of the O(6) limit was introduced and discussed in detail in Refs. [33–35].

Although some of the initial ideas were conceived earlier, the IBM has been developed by the collaboration with Prof. Francesco Iachello [25, 31–36]. Without this collaboration, it is very likely that no actual outcome would be obtained. In the systematic development, the general framework of the SU(6) *s*-*d* boson system is formulated [25]. The vibrational case corresponds to its U(5) limit [31], the axially-symmetric rotor case is described by its SU(3) limit [32], and the γ-soft deformation is treated by its O(6) limit [34, 35]. A variety of properties of physical observables are presented [31–33, 35, 36].

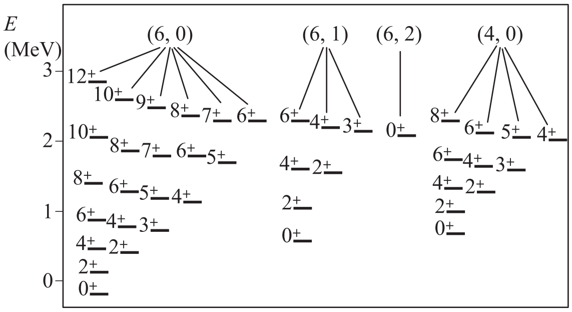

Fig. 8 Energy levels of the O(6) limit of the IBM. A part of Fig. 1 of Ref. [35].

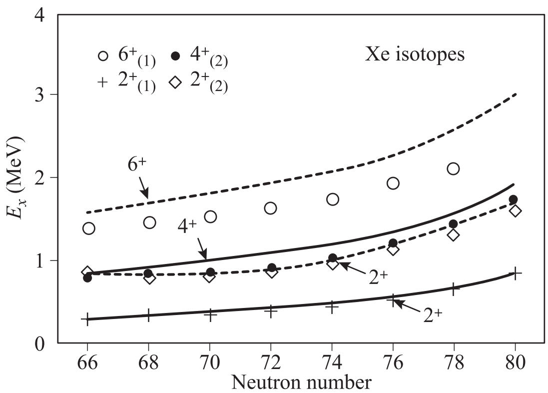

Fig. 9 Energy levels of Xe isotopes as a function of N. The symbols are experimental data, while the lines show the results of the microscopically derived IBM-2 Hamiltonian. Taken from Fig. 22 of Ref. [40].

The initial work on the relation to the shell model has been discussed in Refs. [37–39], by introducing the so-called OAI (Otsuka–Arima–Iachello) method. There have been many developments, and we have obtained a reasonable understanding of the microscopic basis of the IBM by now. Although this subject can be overviewed somewhere else, an example is depicted in Fig. 9 [40]. This figure indicates that the low-lying energy levels of O(6) nuclei can be calculated by the IBM-2 Hamiltonian derived fully microscopically within the OAI method.

6 Summary and perspectives

I have tried to present a very brief summary of some of major works by Prof. Arima. As Prof. Arima has made tremendous amount of important contributions, an overview of all of them is practically impossible. On the other hand, some initial works are so crucial to the present nuclear physics but have not been recognized widely. My attempt was to shed light on such works, which are the configuration mixing theory and the pre-historical work for the IBM. The configuration mixing theory was started for the first-order perturbation calculation of the magnetic moment. The configuration mixing has been developed and extended to second-order processes, for instance, to explain the quenching of transition strength. The configuration mixing is the key concept for the renormalization of effective nucleon-nucleon interaction, which is still a hot topic presently.

The pre-historic concepts of the IBM are introduced in this article too. They have been mentioned elsewhere several times, but have never been explained in a literature. We can see that some of the key concepts were there, while many works have been done afterwards. For the IBM, a more comprehensive microscopic derivation directly related to the mean field theory has been proposed [41], which also concludes (at least one of) my major scientific commitment to Prof. Arima.

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