Nuclear Physics with Great Fun

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Abstract
I have studied mainly five interesting subjects in about 50 years from 1961 to the present; these are [I] Gamow-Teller giant resonances with isobaric analog states (1961 - 1967), [II] cluster structure in nuclei (1965 - 1980), [III] hypernuclei (1980 - 1995), [IV] unstable nuclei (1987 - present), and [V] roles of pion (tensor force) in nuclei (2001 - present). The intension of these studies and their key points are summarized briefly.

1 Gamow-Teller Giant Resonances with Isobaric Analog States (1961 - 1967)

About 50 years ago (1961), I came to Tokyo from Kyoto for getting a job at the Department of Physics in Nihon University. At that time, the Nuclear Theory Group in the department was consisted of three members: Dr. J.I. Fujita and Dr. S. Fujii including myself. We were very young and had a strong ambitious to make our group world famous.

At that time, Fujita, Fujii and myself made theoretical studies covering the following fields of nuclear structure, theory of beta decays and photo-reactions, and microscopic description of nuclear collective motions. We were discussing on our research project which we wanted to develop through collaboration. From April 1962, we concentrated on the study of an interesting subject which was known as the following puzzle on the quenching of the beta transition. The puzzle is why the beta decays in heavier nuclei with N-Z$\gg$1 are delayed so much in comparison with those of the single particle estimate in the shell model. This problem was proposed by Dr. Fujita. We started to collect existing experimental data of log ft values for all the nuclear systems as shown in Fig.1. We confirmed surely the quenching effect for allowed transition strength in nuclei with N-Z$\gg$1, which is one order of magnitude smaller than those of the super-allowed transition in light nuclei (N-Z=1), where the theoretical curve shown was obtained after our theoretical studies.

One day in June 1962, Dr. Fujii reported a newly received paper in Nuclear Physics, which is entitled "Neutron emitted at 0° from nuclei bombarded by 143 MeV protons" written by P. H. Bowen et al. (AERE, Harwell) [1]. At the beginning of the paper it was written as follows: A neutron time-of-flight spectrometer has been used to measure the energy spectra of neutrons emitted in the forward direction when various nuclei are bombarded by 143 MeV protons. The nuclear elements studied are D, Li, Be, C, Al, Cu, Pb and U. At the end of this paper, they concluded as follows: For Al and heavier elements a much broader single peak is observed at mean energy about 120 MeV, corresponding to excitations of the residual nuclei between 10 and 20 MeV.

We were very excited by seeing this data and made long discussions on a new kind of charge exchange collective states with probably zero angular momentum which could be excited by the (p,n) reaction in forward direction. In a short time, we could show theoretically that in heavier nuclei with N-Z $\gg$1 the charge exchange collective states, which exhaust almost all the Fermi and the Gamow-Teller transition strengths could be obtained by using the schematic model of G. E. Brown and M. Bolsterli [2], who discussed on dipole states in nuclei. Our studies on the charge exchange collective states responsible to operators $T_\pm = \sum_i \tau_{\pm i}$ and $Y_\pm = \sum_i \tau_{\pm i}\sigma_i$ and their effects on the β decay were gradually developed and the results were presented in the following three papers by Ikeda, Fujii and Fujita [3–5]:
1) On Resonance Peaks in the (p, n) Reaction [3].
2) The (p, n) Reactions and Beta Decays [4].
3) Nuclear Core Polarization Effect on Beta Decay [5].

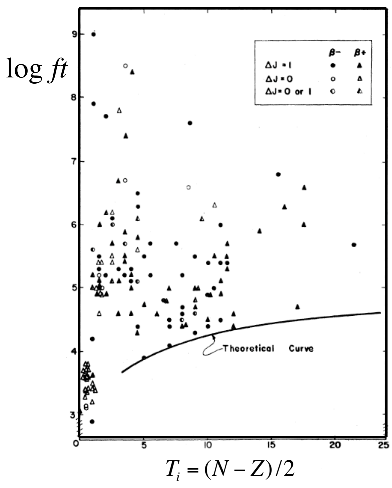

Fig. 1: The log ft values of all the existing data. The solid curve is the theoretical results. The log ft values for N-Z=1 (left corner) are close to 3.5, while those for N-Z$\gg$ 1 are hindered largely; namely $\sim$ 4.5. Taken from the paper of Fujita et al. [5].

Important papers which are intimately related to our problems were the following papers.
1) Persistence of Isobaric Correspondence Between Nuclear States in Mass Regions where Isospin is not a Good Quantum Number by A. M. Lane and J. M. Soper [6].
2) Isobaric States in Non-mirror Nuclei by J. D. Anderson, C. Wong, and J. W. McClure [7].
3) Interpretation of Groups observed in the Neutron Specta of Direct (p,n) Reaction by A. M. Lane and J. M. Soper [8].

This experience of the collaboration with J.I. Fujita and S. Fujii was really valuable for me. This style of the collaborations has been often (or correctly always) used for the collaboration with young researchers, hereafter.

Finally I would like to point out that the first observation of Giant Gamow-Teller Resonance state was done in 1975 by the Michigan State University group and after this experiment, Indiana group developed (p,n) reaction facility with beam swinger to get systematic data at forward direction on many nuclei from 1980 and the systematic experimental studies had been performed by Holen, Gaarde, Sakai, Fujita and many others by using the facilities of Indiana University, MSU and RCNP.

2 Cluster structure in nuclei (1965 - 1980)

I moved the working place to Tokyo Univ. (Dep. of. Phys.) from June 1964, where Arima-san started his laboratory of the theoretical nuclear physics. At that time, many researchers were interested in the problem of mysterious 0^+ states, especially of the first excited 0^+ state with 6.05 MeV in ^{16}O, because in the early 1960, it was known experimentally that this first excited 0_2^+ state is the band head state with $K^\pi = 0^+$ constituted of $J^\pi = 0^+, 2^+, 4^+, 6^+$ states. It was a very hard task to explain the rotational band states built upon the first excited states in the framework with the shell model and also the mean field models. Corresponding to the experimental knowledge, two different kinds of the idea were presented.

One of them is often used for these states as the strong coupling picture of deformed mean field model with 4-particle and 4-hole configuration by researchers like G. E. Brown and A. M. Green [9], and W. H. Bassichis and G. Ripka [10]. The other idea is the weak coupling model with the particles and holes in the sd shell nuclei, which was proposed by A. Arima, H. Horiuchi and T. Sebe [11]. In this model 4-particles are assumed to be in the 1s and 0d orbits and 4-holes to be in the 0p orbit and

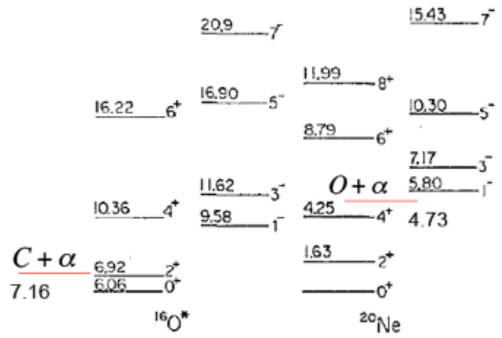

Fig. 2: The energy spectra of $K^\pi = 0^+$ and 0^- bands in ^{16}O and ^{20}Ne in unit of MeV. We show the threshold energy of ^{12}C+α and that of ^{16}O+α. Taken from Ref. [14].

they are weekly coupled from each other. The underlying concepts in weak coupling model are similar to those of the ^{12}C+α cluster coupling model by which Wildermuth and his collaborators had already suggested that first excited 0_2^+ state can be assigned to have the higher nodal states for the relative motion between ^{12}C(0_1^+) and α [12]. We wondered that this weak coupling shell model was really successful in explaining the energy spectra and E2 transitions in the energy region (Ex > 6.05 MeV) above the excitation energy of the first 0_2^+ state.

I started to continue open discussions about this problem with young researchers in our laboratory. When I discussed this problem with H. Horiuchi in one day, he showed me an experimental report presented by H. Davis at the 3rd Conference on the heavy-ion reactions [13]. Davis and his coworkers observed and analyzed α particle resonant scattering with ^{12}C and ^{16}O. They found that their observed α-reduced widths of rotational member states with J$^\pi$=1^-, 3^-, 5^-, 7^- are large to be compared with the Wigner limit values, that means the staying probability of alpha particle in near surface region for these states is about 1. We show the energy spectra for ^{16}O* and ^{20}Ne in Fig.2. We understand that this fact gave us an important evidence of spatially localized ^{12}C+α(^{16}O+α) cluster intrinsic structure in the negative parity rotational states with $K^\pi = 0^-$ band for ^{16}O (^{20}Ne).

Inspired by this experimental finding of the $K^\pi = 0^-$ rotational band, we further argued that if the intrinsic state of this negative parity band has the ^{12}C +α (^{16}O+α) structure with spatial localization of the clusters, the intrinsic structure has a parity asymmetric shape. This intrinsic structure generates positive-parity rotational states with $K^\pi = 0^+$ of which candidate is nothing but the rotational band built upon the first excited 0_2^+ state in ^{16}O (upon the ground 0_1^+ state in ^{20}Ne). In this way, we introduced the concept of parity doublet (inversion doublet) in nuclear structure physics. We wrote this idea in the paper entitled "A Molecule-like Structure in Atomic Nuclei of ^{16}O* and ^{20}Ne" [14].

In the course of the study of the cluster structure in the excited states in ^{16}O (^{20}Ne), we noticed an important relation between the formation of the states with well-developed cluster structure (molecule-like) and the threshold energy of the constituent clusters. For example, the excitation energies of the band head states of $K^\pi = 0^+$ and 0^- are 6.05 MeV and 9.58 MeV, respectively in ^{16}O, where the threshold energy of ^{12}C +α is 7.16 MeV as shown in Fig.2. Turning the eyes to the nucleus ^{8}Be, the ground band states of ^{8}Be (J$^\pi$=0^+, 2^+, 4^+) exist as the quasi-bound or resonant states just above $\alpha + \alpha$ breakup threshold energy. Therefore, we considered that the threshold energy of the constituent clusters is one of the most important key parameters of the structure change into the relevant well-developed cluster structure. From this finding, we obtained a general viewpoint on the aspect of systematic structure change based on the common fact that the states with well developed cluster structure realize in the energy region near the threshold energy breakup into relevant clusters. This viewpoint was presented in the following issue titled as "The Systematic Structure-Change into The Molecule-like Structures" by K. Ikeda, N.Takigawa and H. Horiuchi [15].

Using the threshold rule, we were able to draw the diagram as shown in Fig.3, which provides the

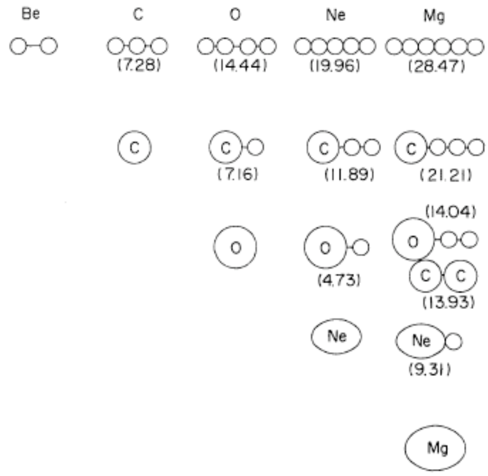

Fig. 3: The Ikeda diagram. Taken from the paper of [15].

concept of the structure change from the shell model-like structure to the molecule-like structure with a small input of energy. This viewpoint of "the Alpha-like four body correlations Molecular Aspects in light nuclei" was given as one of the most important basis of the starting point of the cluster model study under the research project of Research Institute of Fundamental Physics (Yukawa Institute) from 1968-1971. These studies were summarized in Prog. Theor. Phys. Suppl. No. 52 [16]. Hereafter, the microscopic cluster model studies in lighit nuclei had been continued up to 1980 in order to get the comprehensive understanding in light nuclei and the studies were summarized in Prog. Theor. Phys. Suppl. No. 68 (1980) [17].

This study project of the Yukawa Institute was a good play ground for collaborations, competitions and discussions among young scientists. This way of working together became a good model for Japanese nuclear theory community.

3 Hypernuclei (1980 - 1995)

After we had the experience of the study on the cluster physics under our own research Projects, I had taken a refreshment of one mouth stay at the RIFP (Yukawa institute) to start the next research project. In the institute I met Dr. H. Bando who was preparing his own research project on hypernuclei. He was a member of the cluster studies in the early stage of the cluster model project and I knew that he wished to make studies of the hypernuclear physics with inter-university collaborations.

Bando-san said that hypernuclear physics has entered into a new stage from middle of 1970's, since the success of the (K^-, π) counter experiments, which have been disclosing new and intriguing aspects of hypernuclear structure. I thought it is a very good chance to study the hypernuclear physics based on our experience on the cluster model studies because the new experimental data has been accumulated for the light hypernuclear systems. The shell model studies of the Λ hypernuclear structure has been continuously studied from 1970. There appeared a theoretical study based on the mean-field model. The cluster model studies, especially, for p-shell hypernuclei, are highly required for full understanding of hypernuclear structure. After some discussions, I agreed for his proposal to study the hypernuclear structure under the research project of "Cluster Structure of Hypernuclei" organized by RIFP in 1981 and 82. The core members of this project were H. Bando (Fukui Univ.), with Y. Yamamoto (Turu Univ) who worked in the field of the effective interactions with H. Bando, T. Motoba (Osaka Electro-Communication Univ.), T. Yamada (Ni-igata Univ. and Osaka Univ) and K. Ikeda (Ni-igata Univ.). They covered the research fields of the baryon-baryon(NN, NY, and YY) interactions based on the G-matrix theory, and the structure studies based on the shell model and the cluster model.

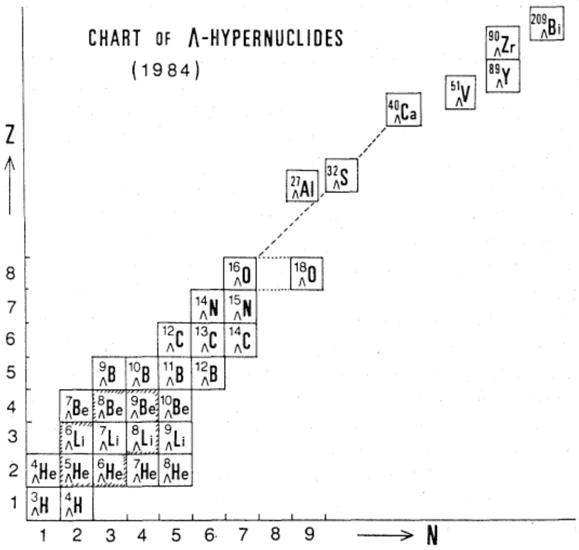

Fig. 4: Λ-hypernuclei in the Z-N plane. Taken from the paper of [18]

We have been quite enthusiastic to cultivate this new field and intensively worked together in close collaboration. The experimental situation was summarized in Fig.4. Just at that time, a project of hypernuclear experiments in KEK was started by nuclear physicists in our country. Communications with them have been so enlightening for us. Our theoretical studies carried out in three years were summarized in the following issue with a future prospect. This issue entitled "Structure of Hypernuclei" (Prog. Theor. Phys. Suppl. No. 81 (1985)) has been also helpful for the communication with experimentalists [18].

We show here briefly the content of Chapter III: Production, Structure and Decay of Light p-Shell Hypernuclei of Ref. [18]. We considered that the shell model and cluster model aspects are both crucially important to describe the light p-shell hypernuclei from the studies based on the microscopic cluster model. The incorporation of the the shell model and cluster model aspects can be achieved by the microscopic treatment of the three cluster states (α + x + Λ), where x = n, p, d, t, ^{3}He, or α. In the present model, the α and x clusters are treated to be composite and the antisymmetrization among all nucleons are property taken into account. The microscopic model can describe both the well-developed cluster wave-function and the important shell model configurations without any spurious center-of-mass excitation. This feature is desirable to the realistic estimates of physical quantities, since, for example, the (K^-, π) reaction populates the hypernuclear states up to rather high excitation energy. With this model, we make an extensive study of spectroscopic quantities with the emphases on the structure characteristics, (K^-, π) reaction population rates, electromagnetic transitions and particle decay and weak-decay strengths.

Here we illustrate only one case of $^{9}_{\Lambda}$Be in Fig.5. The calculated $^{9}_{\Lambda}$Be spectra are classified into three characteristic bands according to the underlying intrinsic structures. Our calculated results were accepted by experimentalists because the results show good agreement with a rare experimental data and includes many predictions for the spectroscopic quantities required by the experimentalists. We have enjoyed the vital roles of the microscopic cluster model to make clear the production, structure and decays of the whole life of the light hypernuclei [18]. Corresponding to the development of the experimental studies, we extended the cluster model studies up to the highly excited states. For the cases of $^{9}_{\Lambda}$Be, we show the theoretical results of the energy spectra obtained by extending the model space to

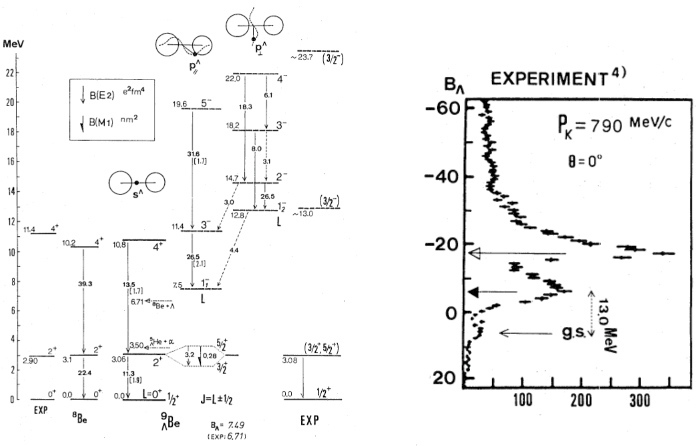

Fig. 5: In the left hand side, shown is a theoretical ${}^{9}_{\Lambda}$Be spectrum. In the right hand side, we show the experimental data. Taken from the paper of Chapter III in Ref. [18].

${}^{9}_{\Lambda}$Be = $(\alpha + \alpha^{*} + \Lambda)$ where $\alpha^{*} = 3N + N$ [19]. Experimental excitation functions for various kinds of strangeness exchange reactions are well reproduced from the low excited energy region up to the high excited energy region(Ex $\leq$ 25 MeV) as shown in Fig.5. These studies has been considered to help the development of the hyper-nuclear spectroscopic studies.

4 Unstable nuclei (1987 - present)

The first paper by the experimental group of Dr. I. Tanihata appeared in 1985, where an anomalously large radius was reported in the nucleus of ^{11}Li by using BEVALAC at LBL. This is a first triumph of the reactions by using RI-beams. I felt that the reactions by using RI-beam have opened a door to a rich field in nuclear physics, because new kinds of experiment brought always new kinds of important present to the nuclear physics community from our experience.
(p, n) reactions $\rightarrow$ (pn^{-1}) collective states like as GTRS and IAS,
Heavy-ion reactions $\rightarrow$ states with cluster (molecule-like) structure,
(K, π) reactions $\rightarrow$ Hypernuclear states,
RI-Beams $\rightarrow$ anomalous nuclear states.

I had a strong interest to the problem with a question as why such an anomalous structure can be realized in ^{11}Li. The anomalous property of ^{11}Li arises already in the separation energies of neutrons. The two neutron separation energy is extremely small, S_{2n} = 0.32 MeV, which is, moreover, much smaller than one neutron separation energy, S_n = 0.62 MeV. On the other hand, one and two neutron separation energies from ^{9}Li are S_n = 4.07 MeV and S_{2n} = 6.10 MeV, which are fairly large. These characteristics for the separation energies give a main reason why we could assume that ^{9}Li cluster is treated as the nuclear cluster with saturation properties, and also why the nucleus ^{11}Li with anomalous properties has to be properly treated in the framework of a kind of the weekly coupled three-body cluster system of ^{9}Li+n+n. The other anomalous characteristics which are known from observation of experiments are the following two: 1) so called Borromean system where two particles (^{9}Li+n and n+ n) do not form bound state, and 2) disappearance of N=8 magic effect because Halo structure needs a large amount of s-orbit contribution.

It was a long journey from 1990 to 2008 to solve the question why the halo structure appears in ^{11}Li. We went through a difficult path step by step for this problem:
(1) The microscopic studies of ^{9}Li+n and ^{9}Li+n+n systems in which ^{9}Li was treated as a frozen core with $[(0s_{1/2})^4(0p_{3/2})_{\pi}\,(0p_{3/2})^6_{\nu}]$ was performed under the bound state approximation by Tosaka et al. [20,21].

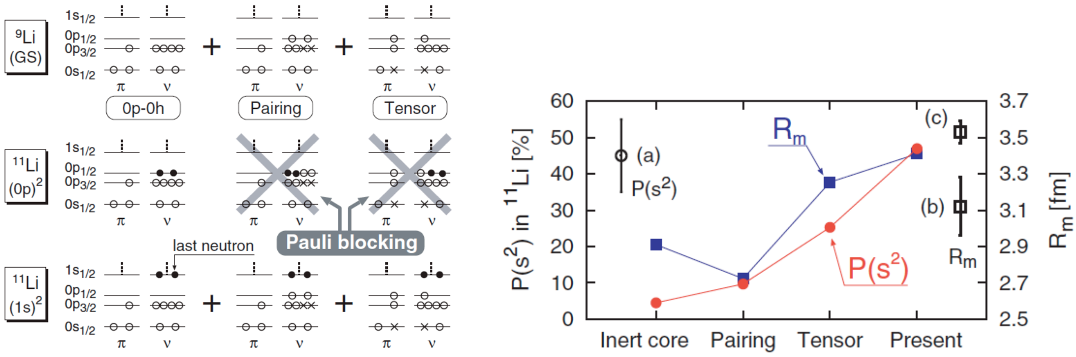

Fig. 6: Blocking effects due to the tensor and pairing correlations for ^{9}Li and ^{11}Li. In the right hand figure, we show the results on the s-wave probability and the matter radius for the inert core, with the pairing effect, with the tensor effect and with both the pairing and tensor effects (present). Taken from Ref. [26].

(2) The studies of ^{9}Li+n and ^{9}Li+n+n systems were solved with proper boundary conditions of two- and three-body systems with Kato-san, by adopting the complex scaling method which treats for bound, resonant and non-resonant states simultaneously [22].
(3) Frozen core approximation for ^{9}Li was loosened with pairing correlations, by which Pauli blocking effect was taken into account for the studies of the ^{9}Li+n and ^{9}Li+n+n states by Kato and his collaborators and Yamada-san [23, 24].
(4) Frozen core approximation for ^{9}Li was loosened not only with pairing correlation, but also with tensor correlation, by which the Pauli blocking effects caused by both correlations were taken into account for the studies of the ^{9}Li+n and ^{9}Li+n+n states. This study was connected with the next subject on the role of pion. The whole project was studied together with Myo-san from 2003 [25, 26].

Two figures are shown here in Fig.6. One is a schematic illustration of the Pauli-blocking effect in ^{11}Li. When two neutrons occupy the $0p_{1/2}$-orbit, 2p-2h excitations of the tensor and pairing correlations in ^{9}Li are blocked simultaneously. In particular, the blocking effect of the tensor correlation in ^{11}Li is expected to work strongly due to the presence of the last neutrons in the $0p_{1/2}$-orbit. For the presence of the last two neutrons in $1s_{1/2}$ orbit, $(1s_{1/2})^2$, the Pauli blocking does not occur. Consequently, the relative energy distance between $(0p_{1/2})^2$ and $(1s_{1/2})^2$ configurations in ^{11}Li becomes small enough to break the magicity and the coupling between $(0p_{1/2})^2$ and $(1s_{1/2})^2$ make the ground state to be a bound state with a small amount of the binding energy ($\sim$ 300 keV) for the case of the tensor and pairing correlations taken into account. As the result, we can naturally obtain the almost equal mixing of $(0p_{1/2})^2 : (1s_{1/2})^2$ = 1:1 as shown in Fig.6.

5 Role of Pion (Tensor force) in Nuclei (2001 - present)

I had been working on various aspects of nuclear structure; shell structure, cluster structure and nuclear structure with hyperons. In the course of these studies I strongly felt the importance of the pion in nuclear structure. The binding energy of the α nucleus is very large. On the other hand, the α-α interaction is extremely small. It should be related with the fact that the neutron-α interaction is also very small. All these facts seem to indicate that the pion in particular the tensor interaction is responsible for these facts.

With this idea, I started to talk with many physicists on the importance of the pion in nuclear structure around the year 2000. It was Toki-san, who picked up the idea and started to work together the role of the pion in nuclear structure. We went through many stages to understand the role of the pion starting with our first publication on the role of the pion in nuclear structure [27]. At the beginning we have been working in the RMF model under the spherical ansatz. In the recent years, we have realized how to describe the tensor interaction in the shell model basis. We are now very confident to treat nuclei in the tensor optimized shell model (TOSM) by using the bare nucleon-nucleon interaction [26, 28]. All these details are presented in this conference by Toki and Myo [29, 30].

Acknowledgment

I would like to thank all the collaborators of these exciting subjects presented in this talk. My life was truly fruitful through the enjoyable study of nuclear physics. I would also appreciate the efforts of the organizers of this conference and also the organizers of the Ikeda-day symposium. I thank also the speakers of the Ikeda-day symposium for the preparation of the materials and their presentation, in particular Prof. Brink and Prof. Siemssen.

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