Introduction

Our History and the Underlying Philosophy

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1. From static to non-static

In our report of 1956,[1] entitled 'Meson Theory III' (Nuclear Force '1956 report (Suppl.)') we presented our study on the nuclear potential as far as we could do by meson theory within the scope of its static version. There, we were able to confirm the statements described in our earlier paper. Taketani, Nakamura and Sasaki[2] (T. N. S.) of 1951 by the results of various investigations which had been made along the line given by T. N. S. In other words, the theory of nuclear forces was established as far as in the region I of our version. On this basis we then proceeded to study the non-static potential by meson theory. Just since that time the experimental informations about the scattering of protons with energy over 100 MeV on proton have been increasingly accumulated, which enabled us to explore the problem in full-scale.

2. Consistent perspecive for the dynamical region

The non-static theory of nuclear force is investigated in following various ways, and all of the works were systematically organized under the common strategy. They are investigations on;

i) the nuclear potential expressed by the momentum space variables with full recoil,

ii) the semi-phenomenological non-static potential in the coordinate space,

iii) the two-pion exchange potential calculated by the dispersion theory,

iv) the nuclear force by the one-boson exchange model,

v) phase shift analysis on the elastic scattering of nucleon-nucleon collision by taking into account the contributions from the inelastic processes (such considerations being necessary because we enter into the high energy region),

vi) hard cores in the region III,

vii) effects of the hard core and absorption on the nucleon-nucleon scattering with energy over several GeV.

By the combined results of these attacks we are now able to reach a unified view point satisfactorily. This means that the internal relationship between various ways of attacks is made clear so that we arrive at a unified understanding for the nuclear forces in the region II. Thus the present report, we expect, contains contributions comparable to that of the earlier report of 1956 in providing systematic understanding on the problem.

3. Our way of research

Here we shall briefly review history of research activities on the nuclear force in Japan which were based on tradition of the Yukawa theory. Our traditional way of research on elementary particle physics is different from that of the foreign countries in many respects. In foreign countries, main concern of publications and discussions is on works which are already accomplished. In Japan we do the same thing at the occasion of the formal meeting. However, we have organized several inter-university groups attacking the specific subjects on elementary particles in collaboration. Our group of "nuclear force" is one of the leading groups. We often hold small meeting of the group where we discuss freely on the strategical problems of the research, such as what and how we should study on the nuclear force. On such occasions a number of diverse new ideas are proposed without any restriction and at the end of discussions a certain direction can be settled to promote the research of the group. Of course, discussions are also made on how to develop necessary new techniques to explore the problem in question. Along the line given by those discussions we are able to construct the collaboration programme for the group. The results thus obtained by every member in the group are discussed in the next meeting. We have the meetings of the "Nuclear Force" group usually twice or thrice a year. After the Yukawa Hall (Institute for Fundamental Physics) was constructed in Kyoto, our meetings have been generally held there by collecting the workers coming from all over the country.

It should be noted that the Japanese works have been achieved through the discussions on the strategy of research using the philosophical and methodological considerations as guiding principles and also by systematic collaboration of inter-university character. It must be stated that even after they discuss together, there often remain a number of diverse opinions among each other. All workers of the group are not necessary to be led to the identical opinion, and there is no compulsion of opinion even in the stage when the systematic collaboration is being made. We have promoted our research works by providing each member freely ideas and outcomes of the group which were obtained through discussions. This way of attack might be compared with the so-called 'brain storming' in the foreign countries; we do it still in larger scale through the collaboration over the country and further we are equipped with the philosophical methodology.

In recent years however, fruits of research activities have been often considered in foreign countries as if they are articles of trade. This atmosphere makes free discussion and exchange of ideas very difficult.

While in Japan this was not impossible, because we were relatively isolated from such atmosphere of other countries. Only very recently, however, unfortunately it becomes difficult to retain our traditional way, since our workers have been gradually affected by strong influences of foreign countries in considering their papers to be a sort of merchandize.

4. Direction given in T.N.S. (1951)

Now it must be noted first that all statements presented by T. N. S. in 1951 are found still valid until today. The way of separating the range of nuclear forces, which was suggested then, has been effective until now. In T. N. S., we have already suggested the method of studying nuclear force by dividing into three kinds of regions.

There we have, at first, divided the nuclear forces in the two parts; one is the 'tail' which is mainly responsible for the quadrupole moment of deuteron, and the other the 'inner part' contributing to the "nucleon-nucleon interaction energy". Further in terms of the meson theory we proposed another kind of division of region. We insisted to study the outside region substantialistically, i.e. on the basis of the meson theory, and the inside region phenomenologically. It means that for the outside region we employ the second-order meson potential plus the fourth-order meson potential (non-static), and we substitute them by some suitable phenomenological potential in the inner region where the theoretical calculations break down. Let us refer to the following statement in T.N.S. §2, subsection 5:

> "In the region near the nucleon the potentials involve the effects due to the higher order perturbation, non-static forces, heavy mesons, relativistic parts, strong coupling and so on and thus the problem will become necessarily complicated".

Further we claimed there to separate the outside substantialistic region into the two parts, which was expressed in §2, subsection 11 of T.N.S. as follows:

> "The static potential due to the fourth-order calculation has not always meanings, since in the region where the fourth-order calculation has sufficient enough magnitude, other non-static effects will generally become strong, too. However, in the outer region where the static potential due to the second order perturbation is influenced by the fourth-order calculations, the spin, charge and radial dependence of the latter will be taken into consideration."

In this way, we[3] have found that pi meson is of pseudo scalar type through calculation on the quadrupole moment of the deuteron with use of the 'tail' of the one-pion exchange potential derived by the second-order perturbation.

5. Difference between the second and the fourth order in T.N.S.

This work was the fist to propose subdivision of the substantialistic region of the pi meson theory further into two parts: The first one is the one-pion region which can be studied quantitatively, as was demonstrated in T. N. S. in the deuteron problem treatment. The second is the region where the fourth order perturbation or the two-pion exchange potential gives serious contribution and, therefore, be treated only qualitatively.

We have to mention that some people make a mistake in understanding this point. Some of them wrote: "In T. N. S. the region of the nuclear force was divided into the two regions, the outer region consisting by the meson potential in the second order and the fourth order perturbation. And only by means of the succeeding works has the substantialistic region been divided into the two parts which are different in nature with each other".

This is obviously a misleading statement which contradicts to the fact that the work on the quadrupole moment of the dueteron with the pi meson potential was given by us at the time of T. N. S.

6. Three regions proposed by T. N. S.

The characteristic difference between the potential of the second order perturbation and that of the fourth order perturbation was rightly pointed out in T. N. S. §2, subsection 11 as referred in §4 of the present paper. The second order potential there is essentially static, while the non-static effect is strong in the region where the fourth order potential is valid. Further the following interesting consideration was already common among us at that time: the Yukawa type potential of the meson theory is essentially of classical character in the sense that it is derived as a classical solution of the Yukawa's field equation as was presented in the first paper by Yukawa (1935). The classical potential constitutes the main part of the tail of the nuclear forces in the second order perturbation approximation. On the other hand, the meson potential of the fourth order perturbation or the two-pion exchange potential cannot be deduced without referring to the field quantization, i.e. essentially quantum in nature. Thus this potential may be called 'quantum mechanical'. In view of this situation, we were led to call the region where the second (fourth) order perturbation is mainly effective by the name of the classical (quantum) region.

Thus according to T. N. S., dividing the regions of the nuclear potential, the region I, II and III were defined:

region I classical region, static main, quantitative treatment
region II quantum region, dynamical region, qualitative treatment
region III phenomenological region

7. Establishment of one-pion region

In order to explore in detail the statements given in T. N. S., a number of works have been made with various methods. The outcomes of these works may be summarized to the conclusion that the theory of nuclear force in the region I is established. The results were presented in detail in the '1956 reports (Suppl.)'. For this purpose investigations were made by the various methods of calculations on nuclear forces including the intermediate coupling theory. These works were led to diverse results with regard to the nuclear forces of two-pion exchange, but for the nuclear forces of one-pion exchange all of them were led to the identical conclusion.

Further, it was revealed that the two-pion exchange potential derived in any of methods does not affect the one-pion exchange potential at a distance greater than 2 yukawas (1 yukawa $=1\times10^{-13}$ cm). In this way, the theory of region I was established.

On the other hand, it was shown that with regard to the two-pion exchange potential the unique conclusion could not be drawn even in the static approximation. The calculated results depend on the approximation used and, therefore, should be considered only to be qualitative. Further, it was hard to have a perspective for the two-pion exchange potential because the dynamical effect is quite strong here.

By this reason no definite meaning could be attributed to the theoretical calculation in this region II at the time of 1956. Some people failed because they laid too much reliance on the theory for this region. It was clear that this region could only be treated semiphenomenologically, and even it was doubtful whether the calculation manifested really the two-pion exchange potential itself in the substantialistic sense.

8. Importance of the concept of applicability limit

The way of thinking which is characteristic for T. N. S. and its developments was to explore the problem discerning the limit of applicabilities of the theory. The philosophy of T. N. S. was originally borne from the methodological reflection on the development of the field theory, particularly on its limit of applicabilities (validities). The way of thinking presented by T.N.S. has not been accepted in foreign countries for a long time. In foreign countries, often the calculations with the meson field theory were uncritically made and the conclusions were derived beyond the limit of its applicabilities. For instance, when they found that the inner part of the nuclear force needs to be repulsive in view of the analysis with the calculation of the two-pion exchange potential, they were appreciated as if they 'proved' existence of a hard core in the nuclear forces. Recently in Japan also some people fell in an analogous pitfall in more advanced stages about the problem of hard core of the nuclear forces.

In foreign countries success of the renormalization theory was taken so impressive that the renormalizability itself was considered to be one of principles with the same quality as that of requirement of relativity. We did not follow such a line of thought in Japan. We considered that the unrenormalizable fields such as meson with pv-coupling should not be rejected from consideration, because they could have bearing to the structure of elementary particles and, therefore, they could bridge over to the future theory.

In foreign countries, some people applied the meson theory unlimitely as was mentioned above, while the other people neglected it completely because they considered it unreliable. We did in turn take the way step by step from the concrete ground by taking seriously into account the limit of applicability.

9. To limit the problem

Until 1956 our principal aim was to investigate the nuclear force by the static meson theory. We limited ourselves to the experimental informations about the total and differential cross sections of nucleon-nucleon scattering with the laboratory energy of less than 100 MeV, and about the quadrupole moment of the deuteron. We considered that the static potential gives essential contribution for the total and differential cross sections of the scattering under consideration. Of course, it may be possible that the dynamical effect could not be negligible even in this energy region. But by analyzing the experimental informations mentioned above, we were able to know nature of the static potential. In this energy region, the dynamical effect is expected to appear in other kind of the experiments such as those related to the spin effect. The other limitation we have introduced is that the S-wave of the nucleon-nucleon scattering is treated as one of the parameters to be adjusted to fit the experiment. The study of the meson potential was limited mainly on P-wave, D-wave and those with higher angular momentum. In this way, we planned to investigate mainly the tail of the one-pion exchange potential. Therefore, we considered that the problems of the binding energy of various nuclei starting from deuteron and of saturation of nuclear forces could be used to determine the phenomenological potential and not be derived from the meson theory. It is because contribution of the potential in the region II and that in the region III will be mainly responsible for these problems.

Further the three-body force would contribute to the saturation of the nucleus. If it exists, it is again the problem of the region III. This was another reason why we did not deal with the saturation of nucleus at that time.

10. '1953 proposal'

In February 1953 I suggested[4)] a number of research programs at the Nagoya symposium. They include:

(1) To investigate validity of the non-static meson potential obtained by the fourth order perturbation which was prevailing at that time.

(2) To determine the wave function of the deuteron by analyzing various concerned phenomena without referring to the field theory of nuclear

force. Various deuteron phenomena will disclose the wave function of the deuteron at different distances between two nucleons, so that they enable us to determine the precise behavior of the wave function of the deuteron through such analyses. At that time it was generally believed that the D-state probability of deuteron is 4%, as was given by the study of its magnetic moment. Later on Machida answered to my requirement, and he determined the D-state probability by taking into account the electron cloud in the deuterium atom.

(3) To clarify what parts of the nuclear force are effective to what kinds of the phenomena, by introducing the possible various combination of potentials of various square well. This problem was answered by Watari and others, who have determined what parts of the nuclear force will be responsible for the impact parameters of each partial wave of the nucleon-nucleon scattering.

(4) To reinvestigate the fourth-order perturbation calculation by means of the intermediate coupling theory of Tomonaga, since the fourth order perturbation calculation leaves doubtful question. Hasegawa took this problem for study.

11. Relation between the π-N scattering and the nuclear force

(5) Fujimoto and Miyazawa proposed a theory of pion-nucleon scattering through the isobar state of nucleon. In this connection, I made the following comments in the '1953 proposal':

> "The nucleon-nucleon scattering with energy more than 100 MeV will be essentially influenced by presence of the isobar state, but this will not bring about radical change for the phenomena with the energy less than 100 MeV, with the allowance being made to modify slightly the coupling constant. Since the contribution of the isobar state will depend on nature of various states of the nucleon system, we had better only to take the qualitative consideration into account and to introduce some modification."
>
> "Experimental knowledges on emission and absorption of a real π meson have been accumulated. Is it not possible to use this information phenomenologically for qualitative checking of the theory of nuclear forces without intermediation of details of meson theory? If so, we could obtain more definite knowledges."

This suggestion led to the theory of nuclear force by Konuma, Miyazawa and Otuki,[5] and also gave direction of the research with the dispersion theory.

12. Possibility of classical approximation

About the problem of approximate expansion, is it possible to give an approximate solution for the nuclear forces of the meson theory starting from the classical solution? This is meant to extend idea of the one-pion exchange potential which has a classical correspondence. I asked a question whether we can find an approximation in the field theory just like the W. K. B. method in the potential scattering. I wrote in '1953 proposal':

> "In the strong coupling theory $g^2/\hbar c$ is large, an expansion by its inverse $\hbar c/g^2$ was made. This is a sort of an expansion in power of $\hbar$, which may be considered as to evaluate the quantum correction to the classical solution."

In other words, the fact that the meson coupling g is large compared with the electromagnetic coupling e can be regarded as $\hbar$ being effectively smaller in the meson case.

Further I stated:

> "In order to look for an approximation from classical solution in true sense, the measure given by the Compton wave length should be considered. Now if we take into account the fact that $\hbar/\mu c$ (μ is the rest mass of π meson) is far smaller than $\hbar/mc$ (m is the rest mass of electron), then we have to give more fundamental meaning to the classical approximation in the meson theory. Indeed we may cite the W. K. B. approximation as an example, but we have to consider more deeply correlation (connection) between the classical theory and the quantum field theory in fundamentally systematic way. It would be the best if we could establish the general theory of approximation in which we are able to obtain any higher order term of perturbation approximation of meson theory as the first approximation."

This suggestion was fulfilled later (1961) by Ogawa, Yonezawa and their collaborators in their theory of one-boson exchange model. In this model, two-pion exchange forces are substituted by forces due to one-boson exchange which are essentially of classical character.

13. Conclusion of '1956 report (Suppl.)'. Establishment of one-pion exchange region

The results obtained in this step was presented at the International Conference on Theoretical Physics which was held at Kyoto, September 1953. Further attacks on the nuclear force by the meson theory from the various view points yielded the '1956 report (Suppl.)'.[1] At the introduction of this report entitled "Nuclear Forces and Meson Theory" I put forward the principal direction which was the basis of our research of nuclear forces by the meson theory. As a conclusion of this statement I wrote:

> "Considering these many results mentioned above, now we may be allowed to conclude that the meson potential as the outer part of the nuclear forces has been established and also that we have succeeded in establishing the meson theory in the region of the classical theory."

The succeeding works confirmed this conclusion more concretely. However, the following sentence which just preceeds the above conclusion has to be cancelled and revised by the later investigation:

"On the other hand, Otuki and his collaborators compared the meson potential with experimental results very in detail, and showed that (1) the meson potential is indispensable outside the force range, and (2) the coupling constant can be determined uniquely as $g^2/\hbar c \sim 0.08$ from only the outer part of the nuclear forces."

The statement (1) means that the existence of repulsive force in the one-pion exchange potential was proved by the analysis on the low energy proton-proton scattering in the triplet odd state. But it was revealed by the later reinvestigation that this was not necessarily so.

With regard to the statement (2), it was assumed that $g^2/\hbar c > 0.07$ for explaining the proton-proton scattering in the singlet even state with introducing the "reasonable potential" in the inner region. As soon as the knowledge on the region II became gradually clearer, the validity of this assumption was lost. Thus at present, the most precise evaluation of the coupling constant in its lower limit as well as in the upper limit is to infer the tail of the one-pion potential through the analysis of the quadrupole moment of the deuteron. In this way, we have to go back the old method of T.N.S. and T.M.O.[6] which were made at the starting step of the research. The result thus obtained was,

$$0.065 < g^2/\hbar c < 0.090.$$

Later we shall discuss this problem again in detail.

14. Origin of the modified phase shift analysis and the polology

Our achievement of establishing one-pion exchange potential did prepare the starting point of the following work of two new types in international scale.

(a) One was the modified phase shift analysis on the nucleon-nucleon scattering. The phase shifts analysis used to be carried out in a completely phenomenological way, so that a number of possible solutions could not be limited to less than five. However, we were able to impose further restrictions to the solutions and reduce the number to two, by introducing the one pion tail.

(b) The other was the polology of the dispersion theory. Before our report of 1956 was published, only the real meson phenomena were taken into consideration for the meson theory, particularly in foreign countries. Virtual meson phenomena were considered generally being of more complicated nature. One may cite the following sentences in the "pi-mesodynamics" by Low[7] which illustrates typically the situation:

"Clearly experiments with real mesons are a better way of trying to understand the meson-nucleon system than experiments involving virtual phenomena, such as the neutrons and protons. The virtual phenomena are difficult to understand and interpret, and the connection between the numbers that one can measure and real behavior of mesons is not as clear. So I prefer to say very little about the virtual phenomena."

Our way of thinking in Japan was contrary to those like the above. We have written this account in the introduction of the '1956 report (Suppl.)':

"We consider that the phenomena of nuclear force is a rare example which enables us to pick up the one-pion exchange phenomena purely. On the other hand, it is hard to treat the phenomena of real pion, since they are duely involved with the higher order effects of complex nature. One-pion tail of the nuclear force has a correspondence to the classical field, which makes its treatment simple. On the contrary to this, it is difficult to study the phenomena of absorption and emission of real pions, because these are involved with the big energy jump."

In 1958, the following proposal by Chew[8] was presented which accepted our point of view:

"The physical idea underlying the present proposal is an old one, although it is usually stated in a different way, namely, that the nucleon-nucleon interaction at large distances is dominated by single pion exchange, which in turn is uniquely related to g^2 and μ (see, for example, the supplement to Prog. Theor. Phys. Japan **3** (1956)). A rough correspondence of this statement to the existence of a pole at $\Delta^2=-\mu^2$ may be seen if one believes that…."

Although he attached the word 'for example' in referring our report of 1956 (indicated in the bracket), it must be noted that a priority of deducing the conclusion that the nuclear force at large distance is of the single pion exchange potential does belong to the Japanese work throughout. The work by Chew made a starting point to the polology of the dispersion theory which succeeded to become a great fashion thereafter. On the other hand, the modified analysis[9] mentioned above found its starting point by the statement of Chew who recognized the theory of one-pion tail for the nuclear forces.

15. Our new lines for the elementary particle physics

In order to prepare for the coming new development, we held a number of meetings at Kyoto, in November to December 1959, twice on the models and the structure of elementary particles and once on the nuclear force, and we made the strategical discussion. The Sakata model presented in 1955 was developed into the group theory of elementary particles by I.O.O. symmetry through work of Ogawa on the symmetry properties. Further the Hiroshima group not only treated in a unified way various baryons, mesons and a few resonances which were found at that time, but also predicted existence of many new bosons and resonance states of baryons which were not discovered at that time. And Taketani and Katayama suggested a unified theory of leptons which we call São Paulo model. Our research on the nuclear forces was making a new development toward the region II. We have discussed how we have to attempt a new development on the basis of our work mentioned above. One of the outcomes stemmed from this discussion is the Nagoya model. I wrote in 1960 the following statements on the above discussions:[10]

"As to the structure or the property of elementary particles the research work has been done from several directions. At the two meetings, which were held at the Research Institute for Fundamental Physics (Kyoto) in November and in December, 1959, separately, some possibility *to connect these directions* was disclosed and a further outlook of the future development was pointed out. Namely, *the following directions might be unified in an organic way:*

(a) To attack the problem from the outside region by making use of the meson theory of nuclear forces and nucleon structures;

(b) To clarify the electromagnetic structures of elementary particles, and to investigate the effects of weak interactions on the structure of elementary particles;

(c) To study the Sakata model, which is a composite model of mesons and heavy particles, and to develop the Nagoya, model which is a theory to relate baryons to leptons;

(d) To explore non-local theories and non-linear theories."

16. Start for attacking the region II

Thus we started with the problem of unifying a), b), c) and d) in an organic way. For study of the nuclear forces we always considered its relationship with works in the above fields for constructing the fundamental strategy. At the meeting on the nuclear force, November 1959, I put forward new lines of attack which we shall call the '1959-report'. This was published in the Japanese mimeographed circular Soryūshiron-Kenkyu in April, 1960.[11] First I mentioned there that the research on nuclear forces was the first which succeeded in performing quantitative study on the meson theory. This was obviously in contradiction with current opinions which were illustrated by the statement of Low referred above. In fact, we were able to conclude that meson is of pseudoscalar type from the analysis of the nuclear forces at the same time when the conclusion was reached by the experiments on the real meson. Also, we were able to determine value of the coupling constant, i.e., $g^2/\hbar c \sim 0.08$ by study of the nuclear forces. Then, a new step was started in the experimental study of the nuclear forces, particularly on the polarization phenomena of the nucleon-nucleon scattering and high energy nucleon-nucleon scattering over 100 MeV.

These opened up a step where the dynamical nature in the nuclear forces in the region II would be investigated.

Further I wrote in the '1959 report' that T. N. S. had already pointed out basis of the dynamical problem in the region II. In the §2, subsection 11 of T.N.S., as was already written in §4 of the present paper, we stated that, for the region where the fourth-order terms contribute with appreciable order of magnitude, other non-static effects will also in general become stronger, and especially for the outer part of the region of region II spin-, charge- and radial-dependence of the fourth-order terms should be taken into account.

17. Origin of *L-S* coupling force

In the '1959 report', we have pointed out that the *L-S* coupling suggested in §2, subsection 14 of T.N.S. should be noticed. Here I suggested:

> "Heisenberg[12] has emphasized to introduce vector π-meson to have strong *L-S* coupling in the nuclear forces. However, it seems probable that the fourth order perturbations will give *L-S* coupling from the pseudo scalar meson theory as its non-static part, and, therefore, we could not conclude that vector π-meson is indispensable."

Recently Furuichi and others worked out correspondence between the two-pion exchange potential and OBEM (the one-boson exchange model) in the nuclear force and further proved that the *L-S* coupling can be deduced from the two-pion exchange potential. It may be said that this point was already expected in T. N. S..

18. Tensor force and *L-S* force

I criticized in the '1959 report' current opinions on the dynamical potential prevailing up to that time:

> "A number of works on the dynamical potential have been performed in Japan as well as in foreign countries. As far as I know, no one ever succeeded to work out a reliable method of approximation. Since the dynamical effects are very delicate in nature, the results obtained depend on the methods used, and the various terms are not clearly investigated in their characteristics. In view of these situations, I was not led to draw my conclusion on the results of the various calculations on the dynamical effects. I reserved my conclusion to this problem. It must be said that no progressive results could be obtained since the time of T. N. S. in 1951."

On this basis I made the following criticism in the same paper:

> "But some people in Japanese group working on the nuclear force were apt to fall into thinking of easy going. They did not take seriously the dynamical effects into account and did depend essentially on the static potential even in analysis for the high energy processes where the nuclear

forces in the region II play the fundamental role. For instance, when the opinion was put forward that the L-S force in the nucleus can be deduced from the (static) tensor term in the nuclear forces, optimistic understanding that the L-S force is not important for the nuclear forces was prevailing among them.

Until spring of 1959 experiments on the depolarization had been performed for the high energy proton-proton scattering, but the results were not unique, two diverse results being reported. At that time, the general climate in the Japanese working group was inclined to the tensor force hypothesis as the theoretical origin of the polarization. Machida calculated the depolarization on the assumption of the tensor force, the result of which was in favor of the experimental information given by the Hawell group in England but was at variances with that given by the Harvard group in U. S. America. The latter experimental result was indeed explained with introduction of the L-S force such as the Gammel-Thaler potential. Response of the Japanese working group at that time to this situation was inclined to believe in the Hawell experiment and to reject the result of the Harvard experiment. This attitude, I thought, was dangerous. Therefore, I wrote a letter promptly from São Paulo (I stayed in São Paulo from May 1958 until September 1959), telling them that it is not advisable at this time to have a prejudice for one of them without deep reasoning. In this letter I insisted strongly that both of the possible ways of attacks should be taken, one consistent with the Hawell experiment and the other with the Harvard experiment, by introducing the phenomenological potential (including the L-S force) applicable to the region II. Further I hoped them to keep this attitude in attending the International Conference on the Nuclear Force at London (1959). My proposal was, however, neglected completely by the Japanese group who took an easy going way thereafter.[*] In the meeting on the nuclear force at November 1959, I also insisted my opinion strongly but the response was rather negative. People were interested still in success of the tensor force theory which led to explain the L-S force in the nucleus. However, it was dangerous to forget possibilities that the L-S force might be deduced from various origins other than the tensor force. In this way the precious time of a half year was lost in vain."

19. Partial wave dispersion theory

The advent of the dispersion theory was in prevailing at that time. The status of the research works on the nuclear forces around those days was reviewed in the summarizing report by Moravcsik and Noyes[13] (April

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[*] I refer this sentence of my '1959 report', because this point led misunderstanding, for example, Weisskopf said "But does it contain (L-S)-force? We do not know. In the western world people say "yes", and in Japan "no"." (Prog. Theor. Phys, Suppl. No. 11 (1959), p. 53)

1961) in detail. As the dispersion theoretical approaches in Japan we may cite a number of works, which started with the determination of the coupling constant for the pion-nucleon interaction by Matuyama and Miyazawa (1957). The results obtained by the dispersion theory in the world remained to the point of showing consistency check. They only confirmed the statements given in our '1956 report (Suppl.)' in the limited scope, so that they could not be attributed with any constructive meaning.

In the '1959 report' my evaluation on the dispersion theory and my attitude toward the dispersion theory were expressed in the following sentences:

> "Although the dispersion theory seems to be successful fairly and to be prevailing, it is still in the step of solving the excersise as far as the nuclear forces are concerned. In fact, nothing progressive could be obtained more than those from the traditional approaches. We must develop it in the direction which is more suited to understand the nuclear forces."

Furuichi and Machida (1961), replying my requirement, developed the partial wave dispersion theory so as to reflect the calssification of regions in the study of nuclear forces. Later this line of attack was further developed by our group, mainly by Furuichi, developing the dispersion theory into a very useful tool for attacking the nuclear forces. A similar application of the partial wave dispersion theory to the nucleon-nucleon scattering was also made by Noyes (1960) who used it as the starting formula for an energy dependent phase shift analysis.

20. π-π interaction

Now that pion belongs to the strongly interacting particles, we have to take into consideration that the strong interaction should work between π-π. Before that time, some people attempted this line of attack but they did not studied in the systematic way and their results were not to be fruitful. In the '1959 report', I have stated about the π-π interaction in the following way:

> "The π-π interaction has been considered for instance, in the S-wave problem of the π-N scattering. So long as we limit our attention only to this aspect of the problem we could not draw any clear answer, because we would be involved with various intricated effects. In this respect, we would be lost only by adding one more parameter adjusting it to the experiments. In order to know the π-π interaction itself, we had better select the phenomena to which the effects of the π-π interaction would be more explicit. In this respect, the current method of studying the π-π interaction could not make sense. If the π-π interaction would be cleared up, the role of the nuclear forces in the region II should be also known."

In this way I have suggested to evaluate effect of the π-π interaction in the nuclear forces in the region II. This again reflects a part of our principle of performing unified attacks on the fundamental problems on the theory of elementary particles considering the internal relationship between different approaches. I have repeatedly stressed importance of making correct evaluation on the role of the π-π interaction.

Thus on one hand, Machida and his collaborators studied the static potential of the order $g^4\lambda$ due to the interaction Hamiltonian $\lambda\phi^4$. On the other hand, Fujii and Miyamoto started to carry out evaluation of the contribution of the 2π-system with $I=J=1$ (I is the total isospin, and J is the total angular momentum) by using a phenomenological form factor of a nucleon for the vector current determined by the electron scattering experiment by nucleon.

21. One pion tail and vacuum polarization

Now we come back to a point which should be corrected in the '1956-report (Suppl.)'. T. Ohmura pointed out that if we take into account effect of the electromagnetic vacuum polarization, we would cancel out effect of the one-pion repulsive tail in the triplet odd state of the low energy proton-proton scattering. In the '1956 report (Suppl.)' it had been stated that the one-pion repulsive tail is "indispensable" in view of the experimental analysis. Then is became to have to withdraw the conclusion and to state as, "we are not inconsistent with the experiments even if we introduce the one-pion repulsive tail". The difference between the old statement and the revised one is decisive. The working groups in Japan who were on this problem did not, however, take this point seriously. I wrote letters to them several times from São Paulo in order to call their attentions to this point. They accepted my suggestion the first time at the meeting of November 1959, and we decided to reinvèstigate the point. We could not, however, make any progress beyond the retreated conclusion: With the meson potential for the triplet odd state one would not be led to inconsistency with the experimental data.

22. Dynamical potential

From those days, Machida and his collaborators started to study the dynamical potential by the meson theory with full recoil expressed in the momentum space. Machida's theory gave a standard form to study the dynamical potential which had been treated in the confusing fashion before. Also they were able to make distinction between the effects from pseudoscalar coupling and those from pseudovector coupling in the meson-nucleon interaction which enabled us to hope to determine the coupling type in view of the experiments. The distinction cannot be deduced in terms of the dispersion theory which does not use the potential off the energy shell.

My '1959 report,' together with these attacks on the dynamical effects provided basis for exploring the nuclear forces in the region II. The article by Taketani and Machida[14] was published in 1960 summarizing these results mentioned above. In this way, a road was opened to investigate substantialistically, or by the meson theory, the dynamical region which had up to that time been studied only phenomenologically.

The experiments on the scattering of several hundreds MeV proton on proton were vigorously made, and they gave necessary information for studying the region II. Also from those days importance of the complete experiments began to be recognized. In fact, there had been confusion in theory of the dynamical properties of the nuclear forces in the region II, so that the complete experiments were felt necessary in order to solve the problem. By means of the proton-proton scattering with the energy greater than 100 MeV we cannot separately know the effects of the region II and those of the region III. We need to make the precise experiments on various spin effects for the proton-proton scattering with the energy less than 50 MeV, in order to bring the effects of the region II as the main contribution. Fortunately, at that time preparation of the precision experiments on the various factors of the proton-proton scattering with the energy 50 MeV began to be available with the cyclotron in the Institute for Nuclear Studies of the University of Tokyo. The experimental group of Japan took part in discussion of the nuclear force group, which created active atmosphere. The discussions were given about the question of what is the most effective experiment, and the results were useful in fixing planning of the experiments.

23. The meaning of the complete experiment

There was some erroneous attitude in the group that nothing could be known unless the complete experiments were available. Of course, the complete experiments are important but it is not always indispensable. If we want to draw some definite statement when we have no reliable theory, we would need the complete experiments. But if we have a theory and want to test it, we need not always have the complete experiments. Especially a theory can be excluded when it meets with experiment which contradicts it. But, when a certain experimental result is consistent with the theory, this does not mean that the theory is confirmed by the experiment. It is because there could be other theories which will give the same consistency.

In fact, we know some cases where the fruitful results were obtained without using the complete experiments. For instance, as was treated in the '1956 report (Suppl.)', the static nuclear forces in the one-pion tail were determined limiting the analyses to the low energy phenomena. In this case, the theory contains no logical jump and an extrapolation from the firm knowledges are possible through some reliable approximation. In cases of discontinuous development of the theory, some qualitatively new results will be predicted which cannot be expected without the theory considered. One of the typical examples is introduction of the quantum theory and also discovery of meson itself. We have also some improper examples, such as the case where some people believed that the theoretical speculation on the hard core of the nuclear forces was proved by the analysis of the experiments. It is, of course, advisable to make various speculation freely, but it must be borne in mind that its 'experimental proof' will suffer many times too much ambiguities. The most optimum case may be that any speculation leads to no inconsistency with the experiments a available to date.

24. π-π correlation and one-boson exchange model

In §20 we stated that we treated the problem of what role the π-π interaction would play for the nuclear forces. Fujii and Miyamoto advanced the calculation by relating it to the nucleon form factor. This was an attack towards realization of promoting the research in the organic way by unifying the theme a) and b) we had followed since the year 1959 (which was accounted for in §15). Although they had no sharp intention as we did, I payed my attention to their work with great interest. They considered that the π-π interaction is correlated to existence of ρ-meson with $I=J=1$. They also suggested that this vector meson leads to the strong L-S coupling in the nuclear forces. I suggested the working group of the nuclear forces repeatedly to investigate carefully the Fujii potential.[15] On the other hand, Ogawa and his collaborators in Hiroshima put forward their consideration on various bosons as the composite systems deduced from the Sakata model. Ogawa, Yonezawa and their collaborators proposed in 1961 the one-boson exchange model as a theory treating the nuclear forces in terms of the Sakata composite model, and predicted several kinds of mesons from their analysis of nuclear forces before the identification of them.

As early as the days of T. N. S. in 1951, we noticed that the "heavy mesons' would play the role in the inner region of the nuclear forces (see T.N.S. §2, subsection 5, referred in the present paper §4). Now the time has come to confirm this prediction. Machida[16] and his collaborators calculated the dynamical potential by the various types of bosons in connection with OBEM.

25. Proposal to find the correspondence between 2πE and OBEM

At the beginning of 1963 we had a research meeting on the nuclear forces in Kyoto where I made a sequence of suggestions. One of them was about the following problem:

> "In what formulation can the effect of the meson field in the higher order perturbations be correlated to the contribution from the various heavy bosons?"

I argued this problem whenever I saw a chance.*) For instance, I gave a suggestion: In what extent can the 2π-exchange effect be replaced by the contribution of various bosons? And is it not possible to prove this point by a certain theoretical method?

The hypothesis that almost all of the 2π-exchange effects can be replaced by the contributions of bosons is the 'one-boson exchange contribution' (OBEC) model, while the assumption that a part of the 2π-exchange effects will remain not being replaced is made for the 'one-boson exchange potential' (OBEP) model. There could be another attitude to believe that the contribution from pions of higher order and that from heavier bosons exist independently.

I proposed to classify the 2π-exchange terms in view of the various degrees of freedom into the two groups, one corresponding to the boson contributions and the other not. I suggested further that the dispersion theory will be useful in making this correspondence. This proposal was answered by the endeavors of Furuichi and Yonezawa[17] (1964) who developed the dispersion theory to treat the 2π-exchange forces. Later on Furuichi group succeeded to clarify almost completely the correspondence between the 2π-exchange model and the one-boson exchange model. According to their investigation, the problem of the 2π-exchange forces is suited for being treated by the dispersion theory.

26. Philosophy of one-boson exchange model

The proposal of the one-boson exchange model in Japan was not fortuitous, but it was based on the idea of Sakata model, and also it was internally related with an idea of introducing the correlation effect by interactions acting between π-π. The basic idea of OBEM was explained in the report of Kyoto International Conference 1965. In fact, since the interaction Hamiltonian of the pion theory came out as a result of composite system of more fundamental particles, it would be meaningless to study the higher order terms by making its approximate expansion of the boson field in question. When we are going to examine the higher order approximations, we have first to come back to the so-called Hamiltonian (if it ever has the meaning of the Hamiltonian) for the fundamental forces working on the composite system and from there we have to start again. In this way we will be led to the heavy mesons.

The study of the nuclear forces can make special contribution to infer properties of many heavier mesons, because we are able to know separately the heavy boson contributions in the various states of each partial wave and thus to bring us rich informations when in the future the precision

*) Later I wrote this question in a letter memo in June 1963 to each member of the group working on the nuclear forces.

experiments will become available (its prospect is now opening). Thus the collaboration was made centered by the Hiroshima group on OBEM, particularly analyzing necessary kinds of bosons and their coupling constants between nucleon and respective mesons. Many informations were obtained from their analysis on the available experimental data at that time. In the present theory of the OBEM, however, we have to determine the coupling constants for each boson phenomenologically. The coupling constants would be given theoretically from more fundamental constants, when the theory could be completed which enables us to deduce bosons from assumption on the fundamental force.

27. Correspondence between 2πE and OBEM

As was mentioned above, Furuichi studied the detailed comparison between the OBEM and the 2π-exchange terms by the pion theory. According to him, the following results are obtained:

(a) The part in which π-π are at resonances corresponds clearly to the boson contribution. The important part is the ρ-resonance with $I=1$.

(b) The uncorrelated (unresonated) 2π-continuum part is found to be similar to the one-boson exchange term with the corresponding values of I and J for the respective 2π-system. It is to be noted that the 3-3 resonance state of πN-system makes the important contribution to this part, and its effect for the nucleon-nucleon scattering is identical with that from the scalar meson with $I=0$.

(c) The uncorrelated 2π-continuum also contributes sizable amount to the part with $I=J=1$ and that contribution lowers effectively the mass of ρ-meson as the net effect. This in turn will play an important role in explaining the electromagnetic structure of nucleon in terms of the known bosons only.[18]

(d) We have not yet confirmed the S-wave π-π resonance in terms of the experiments. From the analyses of OBEC it was pointed out that the scalar boson with $I=0$ is necessary. Then if the experiments could not allow the existence of such boson, it would mean that the boson is approximately a substitute for contribution of the 3-3 resonance in the 2π-continuum. In that case we have seen that the S-wave π-π correlation of the weak attractive force which is suggested experimentally from the analyses of $\pi N \to \pi\pi N$ process acts as a cutoff for the large exchanged mass region of the S-wave uncorrelated 2π-continuum.

(e) The dispersion theory leads us to the strong L-S coupling since it does single out the *ps-ps* coupling. It is also shown by the dispersion theory that this strong L-S force mainly comes from the $I=J=1$ 2π-continuum, whereas the pair effect in πN scattering, which has been considered troublesome for a long time, was found to be suppressed by the effect of the $I=J=0$

2π-continuum. As a result difficulties of the pair effect were solved.

Besides above, a number of corresponding relations were established between the two theories and nature of the various effects were clarified.

In OBEM the coupling constant should be determined referring to the experiments, but in the dispersion theory by Furuichi correspondence of the coupling constants to that in the pion theory could be bridged. In this way, we realize OBEM as the correct theory because the bosons actually do exist, and at the same time OBEM has a property of good approximation simple and easy of treating the 2π-exchange terms. And it also satisfies the requirement of the new classical approximation predicted in the '1953 proposal' mentioned in §12 of the present paper. This is because the one-boson exchange has essentially the classical correspondence, and, therefore, this approximation is duely very simple. And this approximation has also the meaning of reality, i.e. real bosons in almost cases.

28. Semi-phenomenological analysis for region II

In order to determine the nuclear forces in the region II, we have to introduce the phenomenological potential in the coordinate space including the dynamical effect and to infer the factors involved by the experiments. This was attacked in detail by Watari, Tamagaki and their collaborators, who brought about many results by utilizing the advantageous point of informations full of varieties on the different states of systems under the nuclear forces.

Thus we may cite a number of works (development of the theory of the dynamical effects by Machida et al., OBEM theory by the study group centered at Hiroshima, the dispersion theory by Furuichi, determination of the potential in the coordinate space by Watari-Tamagaki group). In terms of these related works, we are now able to have a full perspective on the nuclear forces in the region II.

29. To attak region III

In order to attack the nuclear forces in the region III, we have to solve problems of the nucleon-nucleon scattering in presence of the inelastic effect. Machida and Hoshizaki[19] established for the first time a method of analysis applying in the case of 660 MeV. Here they assumed that the π-production does occur exclusively through the 3-3 resonance channel. Later on the study group of Hoshizaki extended the analysis covering experiments up to several BeV. According to their analysis, it was inferred that the hard core of the nuclear forces exists up to this energy region.

Diverse opinions have been presented how the behavior of the hard core would come out in the higher energy regions. Especially, when the experiment with the energy 10 BeV $\sim$ 20 BeV was performed, various proposals were presented about interpretation of the results. It must, however, be borne in mind, that at the present stage we cannot push our way of attack relying only one of these proposals. I have insisted again and again from the year of 1963 that we have to proceed by investigating various possibilities strategically.

Special emphasis was here laid on the suggestion that the analyses of the experiments should be made in more extensive way. Unless such extensive analyses would have been made, no definite way is presented on which any conclusion is drawn. All that we can say from the results now available are that: any of proposed ideas will lead to "not inconsistent" with the experiments.[20] Before we can say what proposal is the best or which proposal should be rejected, we have to improve the experiments and their analysis more precise and more extensive.

Anyway, we are now available with the perspective of the region II, which enables us to attack the region III on its basis. Thus we may say that we are now in the stage to study the nuclear forces in terms of the more intimate connection with problems of the structure of elementay particles.

The field theory of the nuclear force expressed by the Yukawa interaction is an approximation by which the particle is inspected from large distances. Because in order to explore the region III, we have to establish a new theory by which we can look into the inner structure of the particles from short distances.

The present article is history and perspective on our study on nuclear forces viewed from my personal standpoint and does not intend to cover the whole opinions of the Japanese study group of the nuclear forces. We have to add the fact that there exists diversity in opinions among the group.

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References

1) Prog. Theor. Phys., Suppl. No. 3 (1956).
2) M. Taketani, S. Nakamura and M. Sasaki, Prog Theor. Phys. **6** (1951), 581.
3) M. Taketani, S. Ohnuma and S. Koide, Prog. Theor. Phys. **6** (1951), 635.
4) M. Taketani, Soryushironkenkyu (mimeographed circular in Japanese) Vol. 5, No. 2 (1953), 256.
5) M. Konuma, H. Miyazawa and S. Otsuki, Phys. Rev. **107** (1957), 320.
6) M. Taketani, S Machida and S. Ohnuma, Prog. Theor. Phys. **7** (1952), 45.
7) F. E. Low, Rev. Mod. Phys. **29** (1957), 216.
8) G. F. Chew, Phys. Rev. **112** (1958), 1380.
9) P. C. Ziffra, M. H. MacGregor, M. J. Moravcsik and P. Stapp, Phys. Rev. **114** (1959), 880.
10) M. Taketani, Kagaku **30** (1960), 118 (in Japanese); Prog. Theor. Phys., Suppl. No. 19 (1961), 10.
11) M. Taketani, Soryushironkenkyu (mimeographed circular in Japanese) Vol. 21, No. 2 (1960), 245.

12) W. Heisenberg, Prog. Theor. Phys. **5** (1950), 523.
13) M. J. Moravcsik and H. P. Noyes, UCRL-6388; Ann. Rev. Nucl. Sci. Vol. 11 (1961).
14) M. Taketani and S. Machida, Prog. Thor. Phys. **24** (1960), 1317.
15) Y. Fujii, Prog. Theor. Phys. **25** (1961), 441.
16) N. Hoshizaki, I. Lin and S Machida, Prog. Theor. Phys. **26** (1961), 680.
17) S. Furuichi and M. Yonezawa, Prog. Theor. Phys. **32** (1964), 804; **33** (1965), 238.
18) S. Furuichi and K. Watanabe, Prog. Theor. Phys. **35** (1966), 144.
S. Furuichi, H. Kanada and K. Watanabe, RUP 67-3 (1967).
19) N. Hoshizaki and S. Machida, Prog. Theor. Phys. **29** (1963), 44; 49.
20) M. Nagasaki, T. Hirasawa and M. Taketani, Prog. Theor. Phys. **38** (1967), No. 2.