INSTITUTE FOR NUCLEAR STUDY
UNIVERSITY OF TOKYO
Tanashi, Tokyo 188
Japan

INS-Rep.-693
July 1988

Invited talk at Symposium "perspectives on Particle Physics" (March 29-30, 1988, Tokyo) in commemoration of the 60th birthday of Professor H. Miyazawa

PIONS IN NUCLEI: FROM VIRTUAL-PION EXCHANGE TO REAL-PION TRANSFER

Toshimitsu Yamazaki

Institute for Nuclear Study, University of Tokyo
Tanashi, Tokyo 188, Japan

INS-Rep.-693
July 1988

Invited talk at Symposium "perspectives on Particle Physics" (March 29-30, 1988, Tokyo) in commemoration of the 60th birthday of Professor H. Miyazawa

PIONS IN NUCLEI: FROM VIRTUAL-PION EXCHANGE TO REAL-PION TRANSFER

Toshimitsu Yamazaki

Institute for Nuclear Study, University of Tokyo
Tanashi, Tokyo 188, Japan

Tracing the work of Miyazawa on nuclear magnetic moments, we discuss possible experimetal ways to see whether a real pion exists in nuclei or not. While virtual pions are known to play an important role in nuclei, as clarified experimentally from anomalous orbital g factors of nucleons in nuclei, nearly nothing is known for the behavior of real pions in nuclei. We have shown that deeply bound hybrid states of π^- are expected to exist in heavy nuclei, which can be populated by "pion transfer" reactions.

1. INTRODUCTION

The pion was originally predicted by Yukawa as a particle mediating the nuclear force. The pion was actually discovered and is produced abundantly in large accelerators. The pion-nucleon interaction, and then the pion-nucleus interaction have been studied extensively. The understanding of nucleon-nucleon interactions in terms of pions has been developed. While pions play important roles also in nuclei, it was widely believed that their role is implicit; namely, the role of pions is burried in the nuclear force so that nuclear physics does not need pions explicitly. Miyazawa, however, put a *milestone in the development* of nuclear physics, showing that nuclear magnetic moments are affected by pions in an explicit way [1], but this aspect had been discarded for many years until a strong experimental evidence was obtained in 1970 [2].

Nowadays, the pion is believed to be a composite particle, a (u,d) quark-antiquark pair. It is also believed to be a Nambu-Goldstone boson. The question as to what is the pion does not seem to be settled down. To solve this question we want to embed pions deep inside nuclei to study their behaviors experimentally and address the following questions; how do pions keep their free identities in nuclei?

In the present paper the author would like to begin with reviewing the Miyazawa effect on nuclear magnetic moments and then to proceed to discuss a new aspect of pion bound states and a new way to study them experimentally.

2. MIYAZAWA EFFECT ON NUCLEAR MAGNETIC MOMENTS

In 1951 Miyazawa published a paper on nuclear magnetic moments [1]. It had been known that the observed magnetic moments deviate from the Schmidt lines [3], and a dedicated effort was made by Miyazawa to explain this fact in terms of meson exchange effect.

The famous Schmidt estimate is the expectation value of the magnetic moment operator

$$\vec{\mu} = (g_\ell \vec{l} + g_s \vec{s})\mu_N \tag{1}$$

assuming the following two independent assumptions:

(A) single-particle model ($\vec{j} = \vec{\ell} + \vec{s}$) for the nuclear states of interest

and

(*B1*) *free-nucleon g factors*,

$$g_s(\mathrm{p}) = +5.586,$$
$$g_s(\mathrm{n}) = -3.826,$$

together with

(B2) $$g_\ell(\mathrm{p}) = 1 \text{ and } g_\ell(\mathrm{n}) = 0.$$

Miyazawa studied how the assumptions (B1) and (B2) are modified in nuclei through the exchange of pions in nuclear environment.

The physics of nuclear moments is described in all text books of nuclear physics. For instance, one of the famous books on nuclear moments, written by Kopfermann [4], says,

"The experimentally observed μ_I values do not lie on, but between the Schmidt lines. This could be explained by assuming that the intrinsic (spin) magnetic moments of nucleons are smaller inside the nucleus than in the free state. (The g factors of the orbital momenta behave normally throughout atomic physics, so that one would not like to admit anomalies in the nucleus, such as deviations from the values $g_\ell = 1$ for protons and $g_\ell = 0$ for neutrons.)"

As represented in this description, a possible anomaly for the spin g factors was expected, because the free-nucleon magnetic moments themselves are already anomalous *supposedly due to pion cloud (at that time this was believed* to be only one source of the anomaly; there was no concept of quark constituents), but none for the orbital g factors. Miyazawa's famous paper was often referred to as a literature in which the effect of pion exchange on the spin g factors was studied. However, the empirical g_s factors deduced by assuming (A) vary from one nucleus to another, which appeared to be in contradiction with the meson exchange picture. A few years later, Arima and Horie [5] proposed a totally different explanation based on configuration mixing in nuclear wavefunctions; in other words, the assumption (A) was questioned and modified. This theory turned out to be very successful. Although, in principle, some meson exchange effect on the g_s factors might exist, this is "eaten up" by a more pronounced "nuclear core polarization" effect. So, people believed that the global feature of nuclear maganetic moments is explained by configuration mixing without introducing meson exchange effect. However, the most striking case, the ^{209}Bi ground-state moment, remained puzzling, though the shell-model wavefunction of this state was supposed to be best known.

A new era emerged after 20 years. First, the development of experimental methods made it possible to produce high-spin nuclear excited states which are often metastable so that their magnetic moments can be measured to high precision [6]. Among them the most striking was the magnetic moment of the 11^- isomeric state of 24 nsec half life in ^{210}Po [2]. Since this state has a relatively pure configuration of $h_{9/2}i_{13/2}$ of two protons coupled to the "stretch angular momentum" ($J = j_1 + j_2 = 11$), its magnetic moment is essentially an orbital magnetic moment. Specifically,

$$g(11^-) = g_\ell + \frac{1}{121}(g_s - g_\ell). \tag{2}$$

Thus, a measured magnetic moment should yield a g_ℓ value for proton nearly independent of others. The observed value, $g(11^-) = 1.107 \pm 0.019$, showed a significant anomaly in g_ℓ.

A more surprising fact was that such an anomaly in g_ℓ,

$$g_\ell(\mathrm{p}) = 0.1 \text{ and } g_\ell(\mathrm{n}) = -0.1, \tag{3}$$

had been predicted in Miyazawa's paper of two decades ago. The anomaly in g_ℓ is a rather unique effect of pion exchange current, as depicted in Fig.1. This produces a positive anomaly, $\delta g_\ell^{\mathrm{meson}}$, for proton and a negative anomaly for neutron. Since the pion is lighter than the nucleon, it contributes to an additional magnetic moment

$$\delta\mu = \frac{M_p}{m_\pi}\mu_N = 6.7\ \mu_N \tag{4}$$

while it undergoes orbital motion. (The same enhancement is responsible for the anomalous magnetic moments of nucleons in the pion exchange model.) The g_ℓ anomaly is a genuine nuclear phenomena that involves exchange of pions among nucleons.

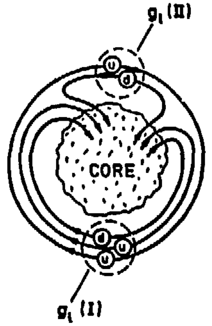

Fig.1 Quark diagram for orbital motion of proton. A proton is exchanged by a core neutron emitting a positive pion, which produces an additional δg_ℓ factor, $\delta g_\ell^{(II)}$, or $\delta g_\ell^{\mathrm{meson}}$. This diagram also shows the contribution of a possible deconfined quark cluster in a nucleus, whose electromagnetic coupling produces an effective nuclear magneton, or a correction $\delta g_\ell^{(I)}$.

One may suspect this interpretation, because nuclear states may not be described by simple shell-model wavefunctions. It was, however, shown by Nagamiya and Yamazaki [7] that higher-order impurities in the wavefunctions should contribute to decrease of "proton orbital moments" and to increase of "neutron orbital moments", thus opposite to the meson exchange effect.

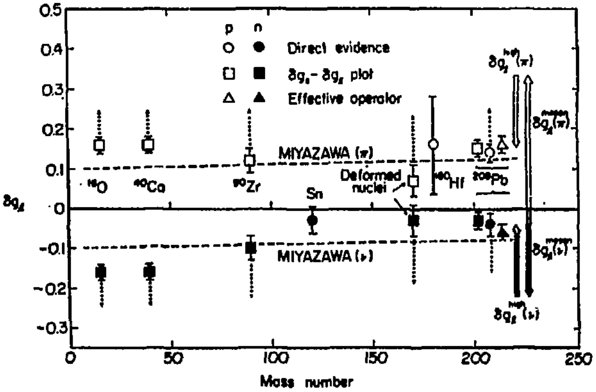

Fig.2 Empirical data of δg_ℓ versus mass number, taken from Yamazaki [8]. The deduction of δg_ℓ factors was made by three diffrent procedures; a) directly from two-particle states with dominantly orbital character (circles), b) from δg_ℓ - δg_s plots combining two or more single-particle moments (squares), and c) from fitting single-particle moments to the effective M1 operator (triangles). Detailed procedures are described in ref.[8]. The values for ^{16}O and ^{40}Ca are obtained after the higher-order correction of Shimisu *et al.* [14]. Otherwise, the directions after higher-order corrections are indicated by dotted arrows. The Miyasawa prediction after the N/Z correction is shown by broken lines.

The discovery of anomalous orbital g factors was followed by subsequent investigation of the problem by Nagamiya and Yamazaki [7], who showed that the g_ℓ anomaly is a general phenomena. They analyzed empirical data all over the nuclear mass region. The latest compilation of the experimental data [8] is presented in Fig.2. The experimental data show that the orbital g factors of proton deviate to the positive side, while those of neutron to the negative direction, which are expected from the meson exchange effect. In heavy nuclei the neutron number N exceeds the proton number Z, and the one-pion exchange current brings the following corrections,

$$\delta g_\ell(\mathrm{p}) = \frac{N}{A}\xi$$

$$\delta g_\ell(\mathrm{n}) = -\frac{Z}{A}\xi \qquad (5)$$

where ξ is a constant (Miyazawa's estimate is 0.2). These modified Miyazawa values are depicted by broken lines in Fig.2.

Another evidence for the presence of meson exchange effect was shown by Riska and Brown [9] in the enhancement of the deuteron photodisintegration cross section. Furthermore, Fujita and Hirata [10] pointed out that the hitherto known enhancement factor κ in photonuclear reaction is related to the anomalous g_ℓ factor as

$$\tau_3 \cdot \kappa = 2\delta g_\ell. \qquad (6)$$

The observed enhancement factor κ was as much as 0.5-1 [11], which in the light of the Fujita-Hirata relation (6) indicates the δg_ℓ might be larger than the Miyazawa value. What is the genuine g_ℓ^{meson} arising from meson exchange effect? To answer this we have to consider effects coming from nuclear wavefunctions.

Nagamiya and Yamazaki derived a general rule that the higher-order correction for proton is negative, while that for neutron is positive. Furthermore, Yamazaki [12] took into account the difference between the proton number and the neutron number, and gave the following expression,

$$\delta g_\ell^{high}(\mathrm{p}) = -\frac{N}{A}\zeta$$

$$\delta g_\ell^{high}(\mathrm{n}) = +\frac{Z}{A}\zeta, \qquad (7)$$

where ζ is the mixing ratio of higher-order impurities or the fraction of time in which the nucleon is combined with other nucleons [13]. This infunitive estimate is consistent with a realistic calculation given by Shimizu *et al.* [14].

The genuine meson exchange contribution $\delta g_\ell^{meson}(\mathrm{p})$ is an observed value less the above correction, which yields $\delta g_\ell^{meson}(\mathrm{p})$ always larger than $\delta g_\ell^{obs}(\mathrm{p})$. The orbital g factors of both proton and neutron combined with a recent precise measurement of κ by Nolte *et al.* [15] are summarized in Fig.3. Yamazaki

[12] pointed out that the magnitude of $\delta g_\ell^{\rm meson}$(n) appears a little too small as compared with $\delta g_\ell^{\rm meson}$(p) in the light of the relation (5) and argued that the nuclear magneton itself, $\mu_{\rm N} = e\hbar/2Mc$, in the expression of nuclear magnetic moments may be different from the free nuclear magneton and enhanced by 10%, which can be interpreted as giving an effective "electromagnetic mass" of proton, $M = 0.9 \times M_{\rm N}^{\rm free}$. Since the nucleons have composite structure, such an *anomaly is expected*, as symbolically indicated by the $\delta g_\ell^{(\rm I)}$ in Fig.1. Whether this is ascribed to deconfinement of quarks or to relativistic effect [16] is an open problem; anyway, the effect is not very large even in the heavy nuclei.

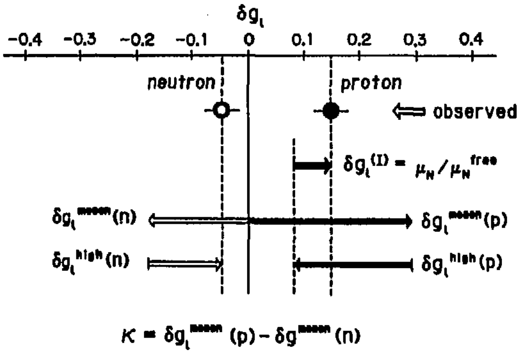

Fig.3 Summary of the δg_ℓ *anomalies in the* ^{208}Pb *region. The observed values are* decomposed into $\delta g_\ell^{\rm meson}$ and $\delta g_\ell^{\rm high}$, where the ratio between proton and neutron is assumed to follow eqs.(5) and (7), and the $\delta g_\ell^{\rm meson}$'s are adjusted so as to satisfy $\delta g_\ell^{\rm meson}({\rm p}) = (N/A)\kappa^{\rm obs}$, the latter being measured by Nolte *et al.* [15]. The resultant discrepancy, $\delta g_\ell^{\rm meson(I)} = 0.06$, is interpreted by Yamazaki [12] as an enhancement of the effective nuclear magneton.

3. REAL PIONS IN NUCLEI

The important role of pion exchange current in nuclei has thus been demonstrated. In the meson exchange vertex a virtual pion is exchanged. Could a real pion be bound and produced in nuclei? In this section we address this question. Before going into this, let us mention a very interesting case of the lightest pion-nucleus system, namely, πNN. Among the $T=2$ πNN multiplet the π^-nn and π^+pp systems would not be able to decay by the strong interaction, provided that they were bound; only the decay channel would be via the weak interaction and thus the lifetime would be as long as 10 nsec. Thus, it would be fantastic, if the system were really bound. One could determine its magnetic moment, which would show the value (5) as far as the pion keeps its identity and moves in a p orbital. A dedicated effort to find such bound states from d($\pi^\pm, \pi^\mp$) reactions is in progress at Los Alamos [17].

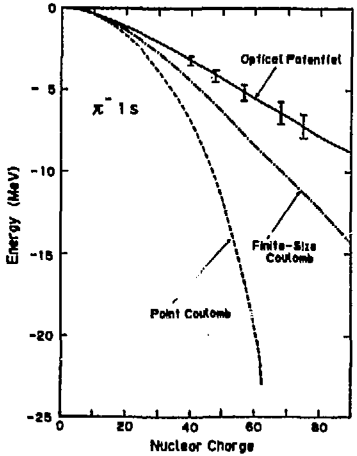

Fig.4 The Z dependence of the 1s levels of π^- calculated with the pion-nucleus optical potential (solid curve), the finite-nuclear-size Coulomb potential (dash-dotted curve) and the point Coulomb potential (dashed curve). The widths are indicated by vertical bars for representative Z. Here, $N = Z$ is assumed. From Toki and Yamazaki [19].

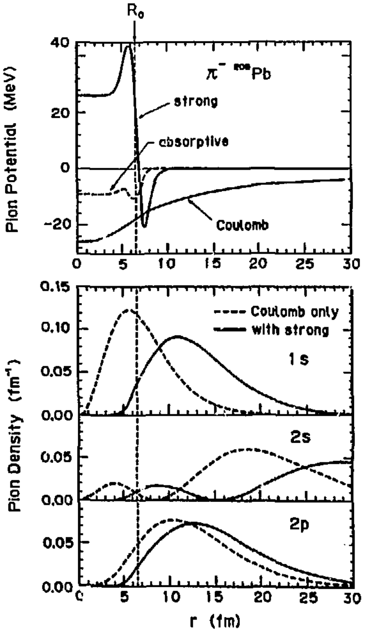

Fig.5 (Upper) The Coulomb potential and the optical potential for π^- in ^{208}Pb. (Lower) The π^- densities of the 1s, 2s and 2p states calculated by Hayano [21] are shown. The nucleus serves as a soft repulsive core, and pushes out s-state pions, thus forming narrow-width hybrid states.

Now, let us look into pion bound states in heavy nuclei. In general, a negatively-charged particle forms Coulomb bound states in nuclei, usually orbiting oustide the nucleus. In heavy nuclei, the Bohr radius is close to the nuclear radius so that the particle moves inside the nucleus. A negative hadron feels a strong-interaction potential as well. No matter whether the potential is strong or weak, the negative hadron can be bound in an orbital ($n\ell$) by the nucleus, assisted by the large Coulomb attraction. The particle resides partially outside and partially inside, thus the state formed is of "hybrid" character, lying somewhere between "atomic state and "nuclear state". Thus, the strong-interaction absorption width is somewhat attenuated,

$$\Gamma = -2\int W(\mathrm{r})\rho_{n\ell}(\mathrm{r})d\mathrm{r} = -2W_0\int_0^{R_0}\rho_{n\ell}(\mathrm{r})d\mathrm{r} \tag{8}$$

where $\rho_{n\ell}(\mathrm{r}) = 4\pi r^2|\Phi_{n\ell}(r)|^2$ is the radial density of π^- in an orbital ($n\ell$), and $W(\mathrm{r})$ is the imaginary part of the optical potential with a depth W_0. Such hybrid states are studied in connection with Σ^- hypernuclei [18].

Motivated by the above arguments Toki and Yamazaki [19] studied deeply bound pionic states theoretically. Assuming the conventional pion-nucleus potential of Ericson-Ericson type [20] they calculated bound states of inner shells in heavy nuclei. The result appears surprising. The energy and width of the 1s bound state versus Z are shown in Fig.4. Even for heaviest nuclei the width is still "narrow" compared with the level spacing, indicating that the particle undergoes orbital motion more than ten times before it dies away! Why is the width so narrow?

To understand this, let us show the density distributions of the deeply bound states in ^{208}Pb. The 1s energy level is pushed up by switching on the strong interaction, because the S-wave potential is repulsive. Namely, there is a soft repulsive core inside the nucleus. For this reason, the pion is pushed away from the center of the nucleus, as shown in Fig.5. The 1s, 2s and 2p states as shown in the figure are all "hybrid". The fraction of the pion density inside is reduced so as to yield a narrow width.

The level structure calculated is shown in Fig.6 for the cases of ^{90}Zr and ^{208}Pb. Nobody knows if these bound states be described by the known optical potential. They have to be examined experimentally. A precise determination of such a level structure, if possible, would yield entirely new information on the pion-nucleus interaction as seen from the bound states. Hitherto, the optical potential has been obtained experimentally only from pion scattering and very shallow pionic atom data. It would be much better to determine the potential directly from deeply bound states. How can we study deeply bound pionic states experimentally? This is the problem we are going to discuss in the next section.

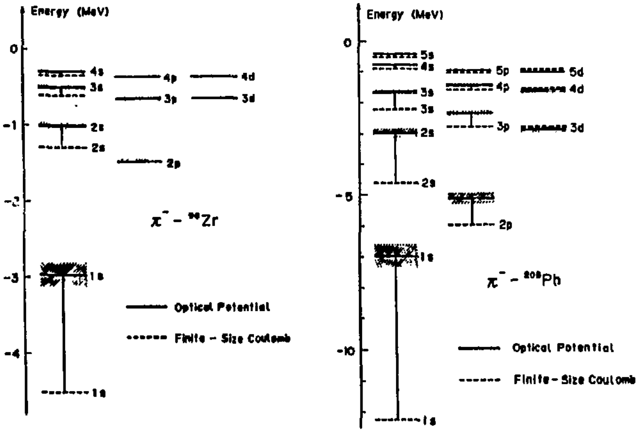

Fig.6 The calculated energy levels of $\pi^-{-}^{90}Zr$ and $\pi^-{-}^{208}Pb$ [19]. The results with the use of the optical potential are denoted by solid bars, while dashed bars are those with the finite-size Coulomb potential only. The widths are indicated by hatched areas.

4. PION TRANSFER REACTION

Deeply bound pionic states are guarded by a so called "last orbital", where the pionic atom cascades terminates because of the overwhelming pion absorption process compared with the x-ray cascade process. Here, the level width is in the region of 1-10 keV. The fact that inner bound states cannot be reached by mesic x ray cascade often misleads people who tend to believe that there are no observable states inside the last orbital. Whether a discrete state exists or not is a matter of its width, namely, whether it is smaller or larger than the level spacing (or, in other words, how many times the particle undergoes orbital motion within its lifetime.). Here, a width as much as 1 MeV can be allowed for a discrete level. This is two or three orders of magnitude larger than the width of the "last orbital", which is essentially the intervening strong absorption width in competition with the radiative width around 10 keV.

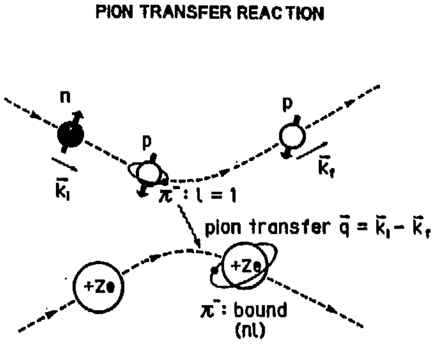

Fig.7 Diagram of the (n,p) pion-transfer reaction to populate deeply bound pionic states in heavy nuclei, where the p-wave π^- is transferred to a nuclear bound state. The intrinsic spins of the nucleons are also indicated.

In anology with the strangeness exchange reactions in the case of hypernuclei, we can populate pionic states with a "pion transfer" reaction. The best way is to use $(n,p\pi^-)$ reactions. This is just the Yukawa pion vertex, where the π^- is a real pion trapped by a target nucleus (Fig.7). In other words, the π^-cloud in the incoming neutron is transferred to a real pion bound state in a nucleus.

The cross section was given by Toki and Yamazaki [19] as follows.

$$\frac{d\sigma}{d\Omega} = \frac{M_P}{(2\pi)^2}\frac{k_f}{k_i}\left(\frac{f}{m_\pi}\right)^2\frac{q^2}{m_\pi}|\Psi_{n\ell}(q)|^2. \qquad (9)$$

where $\Psi_{n\ell}(q)$ is the Fourier transform of the pionic wave function of the $(n\ell)$ orbit, $\vec{k}$ and $\vec{k}_f$ the incoming and outgoing nucleon momenta, respectively, $f(=1)$

is the πNN coupling strength, and $\vec{q} = \vec{k}_i - \vec{k}_f$ is the momentum transfer. The cross section is proportional to the square of the Fourier transform of the pion wavefunction at the momentum transfer around $q = 200$ MeV/c which is the case in the (n,p) reaction above $T_n = 400$ MeV. This means that the cross section is larger for a more tightly bound π^-.

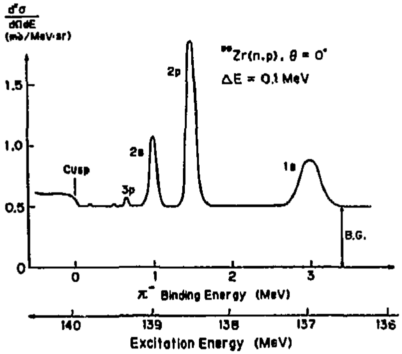

Fig.8 Expected spectrum of ^{90}Zr(n,p) reactions around the pion production threshold at $\theta = 0°$ and $E_n = 400$ MeV [19]. A background cross section of 0.5 mb/sr/MeV is assumed. The spectrum assumes an experimental resolution of $\Delta E = 0.1$ MeV.

The calculated cross section for the 1s state is 0.12 mb/sr for ^{90}Zr and 0.8 mb/sr for ^{208}Pb. An expected spectrum for ^{90}Zr(n,p) is shown in Fig.8. Recently, a medium-resolution (n,p) reaction spectroscopy has been established at TRIUMF using the 200-460 MeV proton beam for the purpose to study Gamow-Teller nuclear resonance states [22]. Though the excitation region around 140 MeV has not been exploited, the background cross section seems to be below 0.5 mb/sr. Therefore, detection of the 1s state in ^{208}Pb appears quite feasible. In the future, high-resolution spectroscopy ($\Delta E = 100$ keV) will also be possible at the forthcoming new cyclotron at the Research Center for Nuclear Physics of Osaka University.

So, we expect a "clean" pion-nucleus spectroscopy to come in the near future, which will yield rich information on the behavior of real pions in nuclei. In the future, based on experimental grounds, we hope to answer hitherto unsolved questions such as: "what is pion?", "does pion keep its free identify in nuclei?,.......

Acknowledgement

This article is dedicated to the 60th birth day of Professor H. Miyazawa. The authors would like to thank Professor Miyazawa for the stimulating discussions and encouragement over 20 years. The author is indebted to Professors H. Toki and R.S. Hayano for the collaborative work on the pion bound states.

References

[1] H. Miyazawa, Prog. Theor. Phys. 6 (1951) 801.
[2] T. Yamazaki, T. Nomura, S. Nagamiya and T. Katou, Phys. Rev. Letters 25 (1970) 547.
[3] T. Schmidt, Z. Phys. 106 (1937) 358.
[4] H. Kopfermann, "Nuclear Moments" (Academic Press, 1958)
[5] A. Arima and H. Horie, Prog. Theor. Phys. 12 (1954) 623.
[6] T. Yamazaki and E. Matthias, Phys. Rev. 175 (1968) 1476;
T. Yamazaki, Int. School of Physics "Enrico Fermi", Course XL (ed. M. Jean and R. Ricci, Academic Press, New York, 1969) p.791.
[7] S. Nagamiya and T. Yamazaki, Phys. Rev. C4 (1971) 1961.
[8] T. Yamazaki, in "Mesons in Nuclei" (ed. M. Rho and D. Wilkinson, North-Holland Pub. Co., Amsterdam, 1979) Vol.II, Ch.16.
[9] D.O. Riska and G.E. Brown, Phys. Letters 32B (1970) 662.
[10] J.I. Fujita and M. Hirata, Phys. Letters 37B (1971) 237.
[11] J. Ahrens, H. Borhert, H.B. Eppler, H. Cimm, H. Gudrun, P. Richn, G. Sita Ram, A. Ziegler, M. Kröning and B. Ziegler, Proc. Int. Conf. on Nuclear Structure Studies using Election Scattering and Photoreaction (ed. K. Shoda and H. Ui, Sendai, 1972) p.213.
[12] T. Yamazaki, Phys. Letters 160B (1985) 227.
[13] G.F. Bertsch, Phys. Letters 28B (1968) 302
[14] K. Shimizu, M. Ichimura and A. Arima, Nucl. Phys. A226 (1974) 282.
[15] R. Nolte, A. Baumann, K.W. Rose and M. Schumacher, Phys. Letters 173B (1986) 388.
[16] B. Serot and J.D. Walecka, "Advances in Nuclear Physics" (Plenum

Press, New York, 1986) Vol.16, p.1.
[17] D. Ashery *et al.*, private comm. (1988).
[18] T. Yamazaki, R.H. Hayano, O. Morimatsu and K. Yazaki, Phys. Letters 207B (1988) 393.
[19] H. Toki and T. Yamazaki, Phys. Letters B, to be published.
[20] M. Ericson and T.E.O. Ericson, Ann. Phys. 36 (1966) 496.
[21] R.S. Hayano, private communication (1988).
[22] M.C. Vetterli *et al.*, Phys. Rev. Letters 59 (1987) 439.