motion of quantum systems which are sometimes called dissipative quantum systems seems to have revived in recent years in connection with supercurrents in superconductors, although a large amount of work on this problem has been done.

I did not intend here to give a comprehensive review of the whole subject, but have tried to describe how I understand the problem and how I have worked on this subject. In this sense this essay is a personal reflection.

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Evolution of Meson Science in Japan

TOSHIMITSU YAMAZAKI

Forty years after Yukawa predicted the existence of mesons, experimental research activities with the use of mesons were started in Japan. Particles of the "second generation," which have nothing to do with the structure of ordinary materials, such as muons, K mesons, and other exotic particles have been exploited as unique probes to study new constituents of matter.

ABOUT 50 YEARS AGO YUKAWA PREDICTED THE EXISTENCE of a new particle mediating the nuclear force (*1*). Nowadays, this particle, called the π meson (or pion), is produced abundantly by means of high-energy accelerators. Long before pions were identified, another particle had been discovered unexpectedly in cosmic rays. That particle was called the μ meson and is now called the muon (μ^+ and μ^-), which is believed to have the same properties as the electron except for mass (207 times heavier). Muons and muon neutrinos (ν_μ, $\bar{\nu}_\mu$) are abundantly produced from the decay of charged pions: $\pi^+ \rightarrow \mu^+ + \nu_\mu$, $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$.

Because of the maximum violation of parity in the weak interaction, the muon from the pion decay is nearly 100% polarized in the pion rest frame. Furthermore, the muon decays with a 2.2-μsec lifetime by weak interaction as $\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$, $\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$, where ν_e and $\bar{\nu}_e$ are electron neutrinos, and the positron (e^+) or electron (e^-) thus produced is very asymmetrical with respect to the muon spin. This basic property permitted the study of the behavior of muon spin in matter, and this aspect of study has been growing under the name of μSR (muon-spin rotation, relaxation, and resonance) (*2*). Positive muons behave like "light protons" and probe internal fields at interstitial sites of crystals, where they are located. They hop from one site to another, and their diffusive motion shows strong quantum effects because of the small mass of the muons (*3, 4*). Negative muons are used to create atoms of pseudonuclear charge $(Z - 1)e$ and to probe electron spin densities outside the nuclear region (*5*).

Because of the unique masses and interactions of pions and muons, they constitute a rich arena of exotic objects for scientists. This study is called meson science. Around 1975 so-called meson factories with high-intensity proton accelerators were launched at Los Alamos (LAMPF), Vancouver (TRIUMF), and Zurich (SIN), and a number of interdisciplinary research programs were initiated to study not only particle and nuclear physics but also atomic and solid-state physics, chemistry, and biomedical applications.

Birth of a Pulsed-Meson Facility in Japan

Although, theoretically, mesons were discovered in Japan, this country used to be very much behind other nations in the development of medium- and high-energy physics. In 1975, however, with the birth of the National Laboratory for High Energy Physics (so-

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called KEK), a new era began. The design concept of the KEK proton synchrotron was to have two acceleration rings in cascade. The first ring, a rapid cycling booster synchrotron with a 20-Hz repetition rate, produced 500-MeV protons. Only one-fourth of its beam pulses were injected into the 12-GeV main ring so that the remainder of the booster beam could be used for other purposes.

At that time the sharply pulsed beam of such a low duty factor (10^{-6}) was regarded as useless by most physicists in particle and nuclear physics. However, the University of Tokyo group, then working abroad in collaboration with physicists at Berkeley and Vancouver to develop μSR by using continuous meson beams, realized that a sharply pulsed beam (50-nsec width and 50-msec interval) could be extremely useful. It had the following advantages:

1) One could measure μ-e decay time spectra in a much wider time range (0 to 20 μsec) than ever before without background. Thus, muon-spin relaxation functions, in particular their long-time behavior, could be determined precisely.

2) One could apply extreme external conditions pulsewise, such as pulsed radio-frequency (RF), laser, or high magnetic fields.

3) Any time-dependent transient phenomena could be studied because the time of muon arrival is uniquely defined.

4) Rare events could be selected from continuous backgrounds.

Excited by such new possibilities they decided to construct a meson facility with a powerful superconducting muon channel (*6*). This was a somewhat adventurous project, but they believed that in order for Japan as a developing country (at least in this field) to compete with the advanced nations of the world in the frontiers in science one should not follow the already established line but move in the direction of something that had not been attempted before.

From Muon-Spin Rotation to Relaxation

The conventional way to measure μSR was to measure the muon-spin precession pattern in a μ-e decay time spectrum under a transverse external or internal field. The precession pattern yields the internal field of the muon and its broadening or fluctuation. In 1978 the University of Tokyo group at TRIUMF established a new method to measure the longitudinal relaxation function $G_z(t)$ of muon spin that involves the spin-lattice relaxation time T_1 (*7*). A typical example was the study of critical phenomena in a weak itinerant magnet MnSi. As shown in Figs. 1 and 2, the longitudinal relaxation rate of a positive muon in the paramagnetic phase showed a critical divergence of type $T/(T - T_c)$, where T is temperature in kelvins, toward the Curie temperature T_c (= 29 K) of helical ordering, which was predicted by the self-consistent renormalization theory of Moriya and Kawabata (*8*).

This experiment revealed, unexpectedly, another important feature: that the longitudinal relaxation function at zero external field, $G_z^{ZF}(t)$, can be measured and is extremely useful. During this experiment they made use of an old theoretical paper by Kubo and Toyabe (*9*), who had studied the shape of the resonance line at zero and low external fields. Kubo and Toyabe had considered the case of randomly oriented local fields with a Gaussian distribution.

When the local field is static, $G_z^{ZF}(t)$ shows a Gaussian-like damping that recovers to one-third of the original value. This "one-third" tail, which is now called the Kubo-Toyabe tail, results from the local-field component along the initial spin direction and preserves the spin as long as the local field remains static. When the local field is modulated slowly so that the correlation time τ_c of the local field is longer than the Larmor period of the local field, this Kubo-Toyabe tail damps according to τ_c, whereas the transverse relaxation function in nuclear magnetic resonance (NMR) and transverse-field μSR is insensitive to slow τ_c (the line shape is not narrowed). This was a new and unique feature of the ZF relaxation function. In 1966 Kubo presented this theory at a conference on NMR, but experimenters did not respond, simply because there was no experimental access to zero-field resonance.

Ten years later the University of Tokyo group realized that μSR does provide the first and best arena for the Kubo-Toyabe theory. A precise measurement of $G_z^{ZF}(t)$ was carried out purposefully, and they found that the $G_z^{ZF}(t)$ in a MnSi magnet at room temperature is exactly represented by the Kubo-Toyabe function in the static limit. The local field in this case is the nuclear dipolar field from the surrounding manganese nuclei, and its correlation time corresponds to the hopping time of μ^+ from one interstitial site to the next in the MnSi crystal. The experimental result indicated that the μ^+ location was frozen for at least 20 μsec at room temperature. Thus, the ZF relaxation method provided sensitive detection of correlation times even in the slow modulation regime, but this required a wide time range.

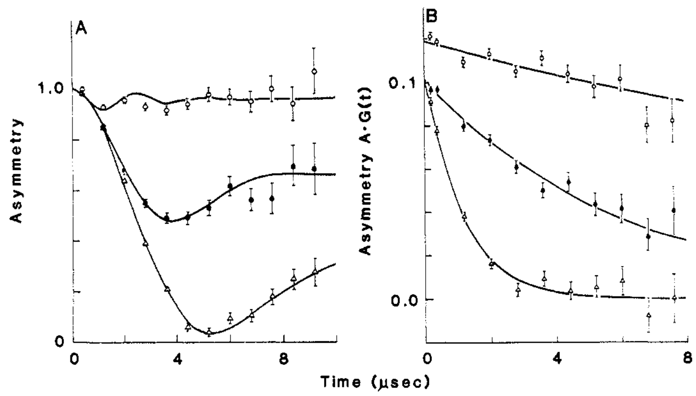


Fig. 1. Longitudinal relaxation functions of μ^+ in MnSi (*7*): (A) For zero and low external fields at temperature T = 285 K. The experimental data correspond to the Kubo-Toyabe functions in the static limit, which shows that the μ^+ hopping time in this crystal is longer than 20 μsec; ○, 30 Oe; ●, 10 Oe; △, 0 Oe. (B) In the critical temperature region above the Curie temperature 29.5 K with a longitudinal field of 700 Oe; ○, 36.2 K; ●, 30.7 K; △, 29.7 K.

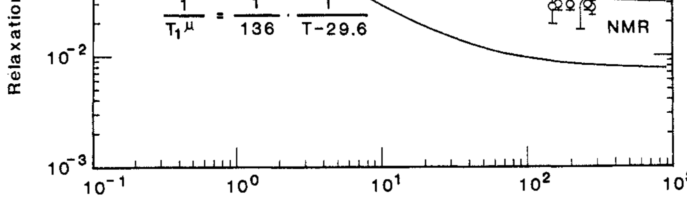
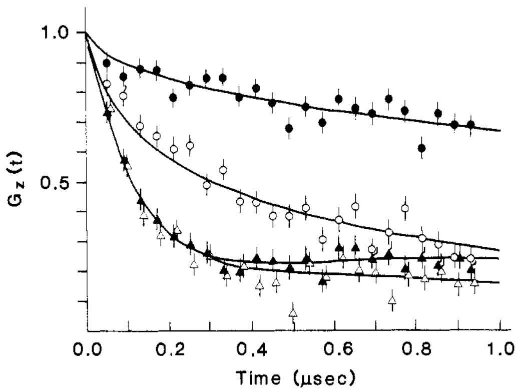


Fig. 2. Critical divergence of the μ^+ spin relaxation rates in MnSi (T_c = 29.5 K), deduced from the observed $G_z(t)$ by Hayano *et al.* (*7*). New data of the relaxation rate of manganese spin obtained from the muon-nuclear-spin double relaxation method (*33*) are also added. The experimental values correspond well to those predicted by Moriya's theory of weak itinerant magnetism (*8*).



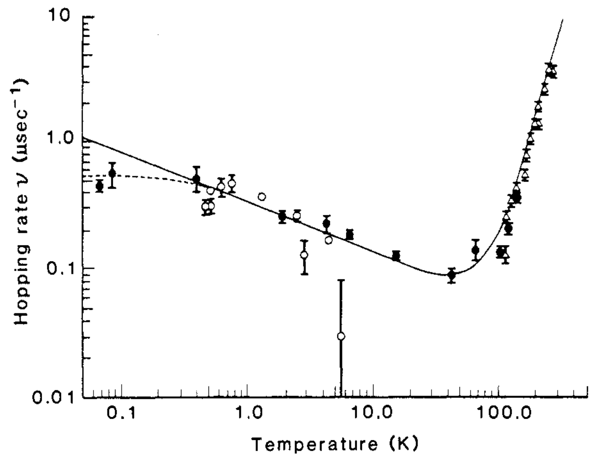


Fig. 3 (left). ZF relaxation functions of μ^+ spin in a spin-glass *Au*Fe (1 atom percent); slowing down of the iron spin fluctuation across the spin-glass temperature $T_g = 9.1$ K where $H_{ext} = 0$, is shown; ●, 10 K; ○, 9 K; ▲, 4.5 K; △, 6 K. [Reprinted from Uemura *et al.* (*13*)]. Fig. 4 (right). Hopping rate of μ^+ in pure copper deduced from ZF relaxation functions, which shows a striking quantum effect. The experimental points correspond well to those predicted by Kondo's theory. ●, Present data; ○, Clawson *et al.*, and △, Grebinnick *et al.* reported in (*4*). [Reprinted from (*4*)].

Various interesting aspects of ZF relaxation were studied both experimentally and theoretically (*10*). It was shown that the nuclear dipolar field, which is usually truncated by the external field as considered by Van Vleck (*11*), is restored to the full value at zero external field. In the zero-field case, this effect is directly observed as a static width, which is five times more than in the high-field case.

The capability of detecting slow modulation in a dynamic system is the unique feature of ZF μSR. This aspect was further developed in the application to spin-glass systems, in which dilute atomic spins are ordered in random directions at low temperatures (*12, 13*). Here, the local field follows a Lorentzian distribution, and its correlation time comes from spin fluctuation. The experiment showed that the spin fluctuation changes rapidly across the spin-glass transition temperature (Fig. 3). The dynamic and static components were separated by measuring $G_z(t)$ values at various longitudinal fields.

Interdisciplinary Science at BOOM

At the new pulsed-muon facility, BOOM, detailed studies of dynamic systems emerged from the full utilization of the wide time range provided by the pulsed beam. One of the typical experiments is a precise study of μ^+ diffusion in copper at low temperatures (*4*). At such temperatures, where the μ^+ hopping time exceeds a few microseconds, the conventional transverse-field μSR loses its sensitivity to determine the hopping time. Precise measurements of $G_z^{ZF}(t)$ in very pure copper crystals were carried out at temperatures down to 0.05 K. This experiment revealed (Fig. 4) that the Arrhenius-type temperature dependence at higher temperatures (100 to 300 K) ceases at 100 K, and the diffusion reaches a minimum in the range of 30 to 70 K. Below this temperature region the diffusion becomes faster as a function of $T^{-0.36}$, and it levels off below 0.5 K. The hopping rate in the high-temperature region was interpreted in terms of small-polaron motion assisted by lattice vibration, but after the phonons die out at low temperatures another mechanism, bandlike diffusion, is expected to come into play, which has an inverse dependence on temperature. Recently, Kondo (*14*) and Yamada (*15*) independently pointed out that the bandlike diffusion is disturbed by conduction electrons, and they explained this observation quite well. In Fig. 4 the experimental points are fitted by means of this theory with a parameter $K = 0.32$, where the constant K represents nonadiabaticity in the tunneling matrix element modified by the presence of conduction electrons as a function of T^{2K}.

Another example is the soliton problem in *cis*- and *trans*-polyacetylene (*16*). Here, the μ^+ behaves like a neutral hydrogen atom, namely muonium (Mu is μ^+e^-), and sticks to one of the carbon atoms, which produces an unpaired electron. This experiment indicated that the unpaired electron was frozen as a free radical in *cis*-polyacetylene but moved away from the μ^+ in *trans*-polyacetylene as had been conjectured by Su, Schriefer, and Heeger (*17*). The observed longitudinal relaxation rates of μ^+ spin (*16*) (Fig. 5) showed inverse-square-root dependence on the external field, which is typical for one-dimensional motion of an unpaired electron as a soliton. There were other experimental data from NMR and electron spin resonance experiments, but their interpretation was somewhat controversial, whereas this μSR experiment gave solid evidence for the soliton.

The BOOM provides the best place for magnetic resonance of muon spins because a high RF power for μSR can be realized only pulsewise. Thus, great efforts have been made to realize and apply the muon-spin resonance technique. The first realization was of a 40-MHz resonance with an external field of 3 kG (*18*). This was applied not only to solid-state problems [for example, to identify muonium chemical reactions in alkali halides (*19*)], but also to study nuclear physics problems [precise measurement of the average polarization of ^{12}B after μ^- capture by ^{12}C to determine the induced pseudoscalar coupling constant in the weak interaction (*20*)]. Recently, a 500-MHz cavity resonance installed with a 40-kG superconducting Helmholtz coil was achieved. Its use will permit precise determination of Knight and chemical shifts of μ^+ in various materials.

Recently, the emission of thermal muonium (0.2 eV) from a hot tungsten surface in high vacuum was discovered at BOOM (*21*). Here again, the pulsed muon beam at BOOM was extremely helpful in identifying the thermal muonium. The thermal muonium production in a vacuum will be used to search for muonium to antimuonium conversion (a test case of lepton number violation) but also to study μSR in solid surfaces.

Particle Physics Studied with K Mesons

Like muons, strange particles (K mesons and hyperons) have nothing to do with the structure of our world but serve as creators and probes of exotic states. They are characterized by a "strange quark" (s quark) as one of their constituents. The 12-GeV proton synchrotron at KEK provides K^- meson beams of high quality. The recent development of particle physics at its high-energy frontier triggered and stimulated renewed interest in low-energy precision experiments. This may be called the "low-energy frontier" of particle physics. Strange particles were expected to play an important role, and the KEK proton synchrotron became increasingly important. Furthermore, new light can be shed on nuclear physics by studying the reactions of strange particles, so physicists connected with the Meson Science Laboratory have concentrated their efforts on this new domain of physics.

In 1980, stimulated by Shrock's ideas (*22*), scientists at KEK began to search for heavy neutrinos in K^+ decay. This problem was related to the mass and mixing of neutrinos (ν_e, ν_μ, ν_τ, . . .) and was beyond the standard model of electroweak interaction. With the great enthusiasm of those looking for an unknown world, the University of Tokyo group attacked this problem (*23*). They measured spectra of π^+, μ^+, and e^+ with high resolution as well as high suppression of background from the decay of stopped K^+. The spectra observed, however, exhibited no anomalous peak due to heavy neutrino emission. This experiment gave very small upper limits of about 10^{-6} on the mixing ratios of a hypothetical heavy neutrino with the muon and the electron neutrinos in its mass range of 30 to 300 MeV.

Another experiment was performed to measure the longitudinal polarization of the monoenergetic μ^+ from the decay of $K^+ \rightarrow \mu^+ + \nu_\mu$ by using the same experimental setup (*24*). Any deviation from the maximal polarization of 100% meant a mixing of the right-handed current (RHC) in the strangeness changing process, which could be related to the mass of an unknown "right-handed" weak boson W_R as compared with that of a normal "left-handed" weak boson W_L, the mass of the puzzling "right-handed" neutrinos, and the Cabibbo angle in the right-handed sector. These were totally unknown. The present result, $P_\mu(K^+ \rightarrow \mu^+ + \nu_\mu) = -0.970 \pm 0.047$, is consistent with the absence of RHC but, if in the future one finds a significant deviation by improving the precision, that deviation will open a gateway to a world beyond standard theory.

Strange Particles: New Domain of Nuclear Physics

The atomic nucleus consists of protons and neutrons, which interact strongly with each other through mediating mesons, as Yukawa proposed (*1*). Mesons play not only an implicit role in the strong nuclear force but also an explicit role as an additional constituent of nuclei. The latter aspect is reflected most typically in nuclear magnetic moments. In 1970 the Tokyo group (*25*) discovered that the magnetic moment produced by the orbital motion of protons in heavy nuclei is greater than that expected for free protons. This anomaly was ascribed to the meson-exchange effect, which had been predicted in 1951 by Miyazawa (*26*) with the view that a single charged pion exchanged through core nucleons produces an additional magnetic moment. At the same time Riska and Brown (*27*) pointed out that the previously known enhancement of the reaction cross section of $p + n \rightarrow d + \gamma$ is due to the same pion-exchange current. These two phenomena provided clear evidence for the explicit role of pions in nuclei. In addition, Fujita and Hirata (*28*) found that the enhancement of the proton orbital magnetic moment is related to the enhancement of the total photoabsorption cross section beyond the classical estimate. Since those discoveries, the understanding of nuclear phenomena in terms of mesons has advanced.

Recently, new light was shed on nuclear structure from the viewpoint of quark structure. Since nucleons and mesons are composed of quarks and since nucleons are densely packed in a nucleus, whether the nucleons in nuclei keep their free identities (mass, size, magnetic moment, and so on) is an extremely interesting problem. The measurement of deep inelastic muon scattering on nuclei by the European Muon Collaboration (*29*) seems to indicate that the size of the nucleons is expanded by 10 to 20% in nuclei. In this connection, I reexamined the anomalous orbital magnetic moments and found (*30*) that the effective nuclear magneton, $\mu_N = e\hbar/2Mc$, was greater than the free nuclear magneton (M is the mass of the proton) by 10% in heavy nuclei.

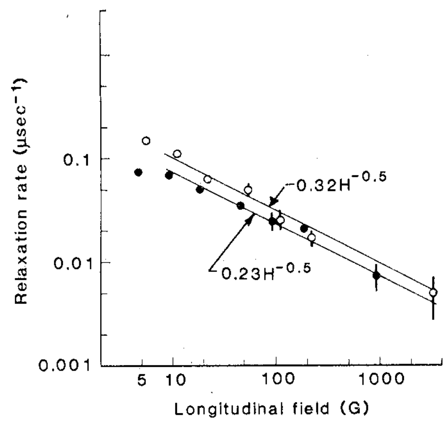


Fig. 5. Longitudinal relaxation functions of μ^+ in *trans*-polyacetylene at various external fields, indicating solitonic motion of μ^+-created unpaired electron. ○, $(CH)_x$; ●, $(CD)_x$. [Reprinted from Nagamine *et al.* (*16*)].

To study such aspects of nuclear physics, the implantation of "impurity probes" such as hyperons into normal nuclei to form exotic matter (hypernuclei) is of particular importance. The most popular hyperons are Λ and Σ hyperons, which have a quantum number "strangeness" that distinguishes them from nucleons. Thus, in a conventional picture, hyperons are totally distinguishable from nucleons and can coexist with them in a nucleus without the Pauli exclusion principle.

Like a nucleon, a hyperon in a nucleus is supposed to feel an average potential and thus move in a single-particle orbital. Hypernuclear spectroscopy on heavy nuclei may be able to prove or disprove the existence of single-particle orbitals in such a strongly interacting many-body system. This is not a trivial question at all, because baryons are composite particles, and only the subparticles (quarks) are distinguishable fermions subject to the Pauli principle. While nucleons consist of u and d quarks alone, hyperons involve "strange" quarks.

Recently, a new type of hypernuclear spectroscopy has emerged from KEK (*31*). K^- mesons were stopped in a nuclear target, and

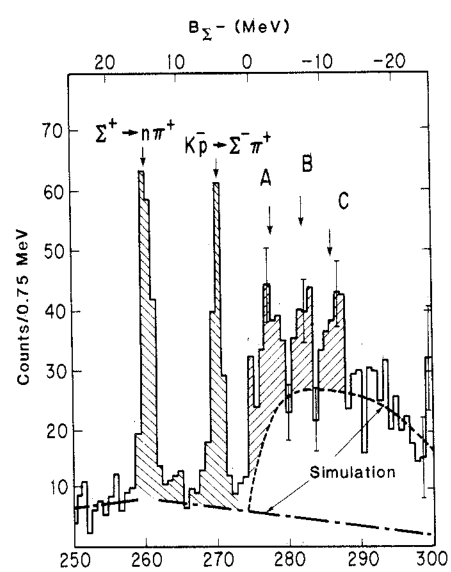


Fig. 6. Hypernuclear spectrum for Σ^- from (K^-, π^+) stopping in a plastic-counter target, $[(CH)_n]$, tagged by π^0. Three peaks (A, B, and C) seen in the unbound energy region (A at 277.4, B at 282.2, and C at 286.6) together with two elementary peaks are assigned to (proton-hole, Σ^--particle) states in ^{12}C. From a recent KEK experiment.

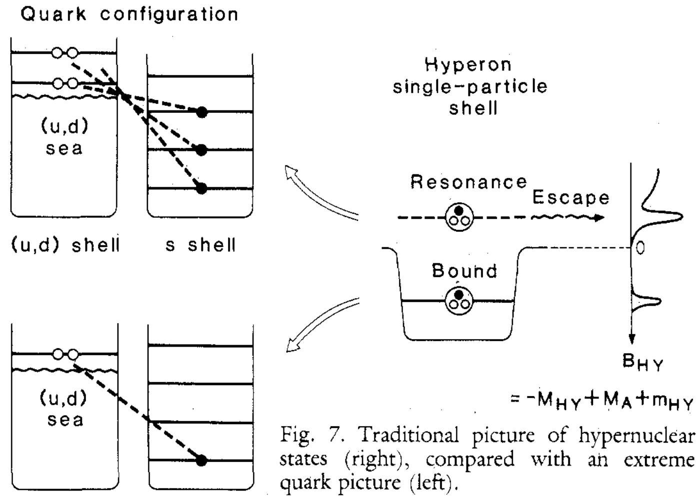


Fig. 7. Traditional picture of hypernuclear states (right), compared with an extreme quark picture (left).

both π^+ and π^- spectra were measured with the same high-resolution magnetic spectrometer used for the $K^+ \rightarrow \mu^+$ decay experiments. It was shown both theoretically and experimentally that this method efficiently produces Σ hypernuclear states. After the 1975 experiments (*32*) at CERN (the European Laboratory for Particle Physics), which employed the recoilless (K^-, π) method, there was a prevailing belief that the stopped-K^- absorption cannot produce hypernuclei because of its large momentum transfer. The KEK experiment showed that this is not true and opened a new door to the promising future. One example of the observed spectra exhibits three narrow states of Σ^- in the (stopped K^-, π^+) spectrum (Fig. 6). This spectrum is doubly astonishing. First, the states are narrow in view of the strong interaction conversion process, Σ + nucleon going to Λ + nucleon, which should make the width as broad as 20 MeV. Second, these Σ^- states lie in the unbound energy region, and the escaping of a Σ^- particle of 10-MeV energy above threshold is highly suppressed. These anomalies are not understood yet, but they could be due to a rearrangement of the inner structure of the hyperons once they are embedded in nuclei. The most interesting expectation here is that, while the s quark in a hyperon can move freely in any of its orbitals, the other two (u, d) quarks cannot; they have to float above the Fermi sea of u and d quarks (Fig. 7). Such deconfinement is not expected for nucleons in ordinary nuclei, but it is energetically favored in hypernuclei.

The University of Tokyo–KEK joint research group in collaboration with the Heidelberg group is now undertaking this type of spectroscopy at KEK with the hope of finding solid evidence for the explicit role of quarks in nuclei, which should be reflected both in energy spectra due to Pauli blocking at the quark level and in decay widths due to rearrangements in quark structure.

Future Perspectives

Meson science, as briefly traced here, is an interdisciplinary science that uses "second generation" particles (muons and K mesons) for the creation and detection of exotic states in matter. To study this interesting frontier people strongly feel the need for experimental facilities that will provide meson beams 100 times as strong as those available today plus various qualitative innovations. Planning for such facilities is under way.

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