Prospects of the Hadron Physics at J-PARC

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Abstract. An overview of the leading subjects of hadron physics with an emphasis on those relevant to J-PARC is presented. J-PARC is a new high intensity proton beam accelerator facility built at Tokai, Japan. The subjects include (1) strangeness nuclear physics, (2) generalized nuclear force, and (3) exotic hadron spectroscopy.

1. Introduction

J-PARC, the acronym of the Japan Proton Accelerator Research Complex, located at Tokai, is a high-intensity proton accelerator jointly operated by KEK and JAEA[1]. It is composed of the proton Linac, the 3 GeV Synchrotron and the 50 GeV Main Ring. The main ring accelerates high intensity proton beam for nuclear, hadron and particle physics, where the beam is extracted for experiments at the Hadron Experimental Hall, and also for the Neutrino production beam line. In the Hadron Experimental Hall, the secondary meson beams, \( \pi \) and \( K \) of 1-2 GeV/c, are produced, which enable us to perform high precision hadron and particle physics experiments. The neutrino beam is ejected towards the Super-Kamiokande neutrino detector, located 295 km away from the J-PARC. The primary proton beam can also be used for high energy hadron physics experiments, such as studying parton distributions in the Drell-Yan processes. All the accelerators were commissioned before 2010, and the nuclear/hadron and neutrino experiments have just started.

The facility is the result of a long term effort of the Japanese nuclear physics community. Physics subjects for the hadron hall experiments range from the hadronic level to the quark level including the strange nuclear physics, hadron properties in nuclear medium, study of quark structure of hadrons and exotic hadron spectroscopy. The main research areas are summarized as follows:

- **Strangeness Nuclear Physics**
  Strong kaon (\( K \)) and anti-kaon (\( \bar{K} \)) beams (as well as pion beams) are utilized to produce various strangeness hadrons and nuclei. The main subjects there include production, structure and decays of hypernuclei, properties of generalized nuclear force, \( \text{i.e.,} \) YN and YY interactions, where \( Y \) stands for a hyperon (baryon with strangeness), and the kaon and anti-kaon interactions with the nucleon and nucleus. The generalized nuclear force seems to be the key to understand the hadronic interaction starting from the quark-ghon dynamics. J-PARC plans to carry out many hypernuclear experiments which are critically important to reveal the properties of the YN and YY forces. Searches for deep anti-kaon \( \bar{K} \) bound states in nuclear medium is a hot subject recently[2]. Such a bound state will determine how mesons interact and behave in nuclear medium. There are experiments at
J-PARC to confirm the pentaquark resonance $\Theta^+$. The $\Theta^+(1440)$ has been first reported from the photon beam facility at SPring-8 by the LEPS group\cite{3}. However, its existence is not confirmed yet. It is urgent to make the situation clear and terminate the controversy by carrying out the searches with the hadronic beam experiments at the J-PARC.

- **Hadron Properties in Nuclear Medium**
  
  One of the main goals of QCD studies is to understand the phase structure and properties of hadronic matter at finite temperature and/or finite density. Many years of researches have revealed that the phase diagram at finite baryon chemical potential may be quite complicated and show many new structures of matter\cite{4}. In particular, possibility of color superconductor phase at large baryon density with low temperature was predicted, which may be realized at the center core of the neutron stars in nature. It is, however, not possible to access such phases directly at laboratories. One possible way of probing finite density nuclear medium is by producing hadrons in nuclei. The density may not be large enough for exotic phases, but partial restoration of chiral symmetry may be manifested as mass shifts and width broadening of mesons produced inside nuclei\cite{5}.

- **Exotic Hadron Spectroscopy**
  
  Since the discovery of the pentaquark, many new approaches have been made for excited hadrons and exotic hadrons. The reaction dynamics and resonance structures are closely related and, in fact, some resonances are produced just by unitarizing scattering amplitudes of two hadrons in coupled channel systems. Such resonances may be regarded as molecular bound states of hadrons. It is quite important to identify the nature of individual excited hadrons, whether it is made of just two or three quarks, or is an exotic hadron made of extra quark or gluon components, or a hadronic molecular resonance state. In viewing the exotic multi-quark states, heavy quark may play important roles. In particular, several charmonium-like states found recently do not simply fit to the $c\bar{c}$ spectrum, and may contain tetra-quark or two-meson components.

In all these areas of researches, the third flavor, strangeness, plays unique and important roles. In the next section, we overview the roles of the strangeness in the strong interaction of quarks in hadrons.

## 2. Roles of Strangeness in Nuclear/Hadron Physics

The basic dynamics of quarks and gluons are given by a non-Abelian gauge theory called Quantum Chromodynamics (QCD). QCD is composed of gauge invariant interactions of quarks and gluons, which are characterized by the color charge, a new internal degrees of freedom. QCD has special unprecedented properties, such as color confinement and asymptotic freedom. Namely, QCD interactions are scale dependent so that at long distances the interaction is so strong that color charges are confined, while at short distances, the color interactions are weak and can be treated perturbatively.

The QCD lagrangian,

$$\mathcal{L} = \sum_f \bar{\psi}_f(x)(i\gamma^\mu D_\mu - m_f)\psi_f(x) - \frac{1}{4} \sum_a (G_{\mu\nu}^a)^2$$  \hspace{1cm} (1)

has the exact SU($N_f$) symmetry, if the quark masses of the $N_f$ flavors are equal. In reality, the quark masses are distributed from a few MeV to 170 GeV as is shown in Fig. 1. The masses of the “light” quarks, $u$ and $d$, are much smaller than the QCD energy scale $\Lambda_{QCD}$, and their interactions are constrained by chiral symmetry that is exact for massless quarks. On the other hand, the “heavy” quarks, $c$, $b$ and $t$, are much heavier than $\Lambda_{QCD}$ and therefore heavy quark symmetry can be applied. The strange quark, $s$, has the mass just about $\Lambda_{QCD}$ and neither
the chiral symmetry nor heavy quark symmetry is good enough to neglect symmetry breaking corrections. Thus, the dynamics of the strange quark is most sensitive to the dynamics of QCD.

**Figure 1.** Quark masses and QCD scales.

The quark model with the SU(3) flavor or the SU(6) spin-flavor symmetry has played a major role in the history of hadron physics, but its limitation has become clear in the spectroscopy of excited and exotic hadrons. Indeed, accumulated evidences of new hadrons, such as $\Theta^+(1540)$, $X(3872)$, $Z^+(4430)$, and so on, have shown that there may exist “sharp” exotic resonances whose main component is not simply $qqq$ or $q\bar{q}$. It is interesting and important to reveal the dynamics of these exotic states from the QCD point of view. Beyond the quark models, many refined effective models have been proposed to describe hadron spectra and hadron structures, but the predictability of the models is limited as they involve many unknown parameters. The validity of such models will be determined by examining whether they can explain experimental data involving strange and heavier quarks.

At high density, with $\mu(u, d) > m_s$, strange matter may become stable. The strange hadrons ($K^-, \Sigma^-, \Xi^-$) with negative charges may play significant roles in the core of the neutron star, as they may override the chemical potential of electron. Especially, a strong $K - N$ attraction may drive the kaon condensation. At higher density, the quark matter with strangeness may appear in the neutron star matter, where the QCD ground state may be the color superconductor with strangeness. With $N_c = 3$ colors and $N_f = 3$ flavors, the color-flavor locking (CFL) phase with the condensate $\langle q_i^T T^a C \gamma^5 q_j \rangle = \epsilon_{abc} \epsilon_{ijc} \Delta$ may become stable.

3. Generalized Nuclear Force: Origin of Short-range Repulsion

The hadronic interaction is a major subject in the nonperturbative properties of QCD. The nuclear force, among them, is well established and is tested very well by numerous experimental data. The nuclear force consists of the longest-range one-pion exchange potential, the medium-range multi-pion and boson exchange potential and the strong short-range repulsion. The scale of each part is of 100 MeV or more, while the attraction from the medium-range part and the short-range repulsion cancel out largely and result in the small binding energy of the deuteron, 2 MeV.

Recently, various suggestions of possible hadronic molecular states, which may appear in excited hadron spectra, have appeared. There reliable prediction of the hadronic interactions is critically important. In particular, it is interesting to examine whether two baryon bound states other than the deuteron may exist or not. The origin of the short-range repulsion between two nucleons is therefore very important to determine such possibility.

In 1977, it was suggested by Neudatchin et al.\[6\] that the antisymmetrization among valence quarks may give short-range repulsion between two nucleons. In 1980, we proposed the Quark Cluster Model (QCM) of two-baryon interactions\[7\], where it was shown that the quark exchange diagrams with the help of the color-magnetic interaction (CMI) in the one-gluon exchange between quarks explains the short-range repulsion. It was also shown that the generalization of
the QCM to strange baryons gives a rich structure of two baryon interactions. Table 1 shows the classification of the S-wave ($L = 0$) two baryon interactions in terms of the spin-flavor symmetry of valence quarks[8]. From the analysis based on the quark model symmetry, we predict that the $NN$ states are moderately repulsive, which is caused mainly by the CMI. On the other hand, there are some states which have very strong repulsion at short distances caused by the Pauli exclusion principle, such as $\Sigma N$ ($I = 1/2$, $S = 0$) and $\Sigma N$ ($I = 3/2$, $S = 1$). On the other hand, no repulsion is predicted for the flavor singlet $\Lambda\Lambda - N\Xi - \Sigma\Sigma$ system, where we may have a compact di-baryon bound/resonance state. (It was first predicted by Jaffe in 1977, called H dibaryon[9].) Thus, the QCM predicts a strong state dependence of the two baryon interactions, which should be confirmed experimentally at the J-PARC.

Table 1. SU(3) × SU(2)Spin → SU(6) classification of the L = 0 two baryon systems. The SU(6) representations are given by the Young partition numbers.

| SU(3) | SU(2) | SU(6) | Baryon interactions |
|-------|-------|-------|---------------------|
| 1     | S=0   | [33]  | attractive in $\Lambda\Lambda, N\Xi, \Sigma\Sigma \rightarrow H$ dibaryon |
| 8s    | S=0   | [51]  | strong repulsion in $\Sigma N$ ($I = 1/2$, $S = 0$) |
| 27    | S=0   | [33], [51] | repulsion due to CMI, $NN^1S_0$ |
| 8a    | S=1   | [33], [51] | strong repulsion in $\Sigma N$ ($I = 3/2$, $S = 1$) |
| 10    | S=1   | [33], [51] | repulsion due to CMI, $NN^3S_1$ |

The QCM predictions have been tested by comparing them with phenomenological potential models determined by the available experimental data of hypernuclei[10]. It has been confirmed that the following properties predicted by the quark model agree very well with the phenomenological analyses.

- Suppression of the $\Lambda N$ spin-orbit interaction
- Strong short-range $\Sigma N$ repulsion with spin-isospin dependence
- Attraction in the flavor singlet $H$ dibaryon channel

Furthermore, technical development in computational QCD simulations, the lattice QCD (LQCD), now allows us to compute the baryon-baryon potential directly from the first principle. Recent LQCD calculations by the HAL QCD collaboration[11] have confirmed that the picture of the Pauli principle plus the CMI interaction for the short-range baryon-baryon interaction is consistent with QCD. In particular, Inoue et al. showed the classification given in Table 1 is indeed realized in the SU(3) limit of QCD.

Further investigations along this line, cooperation of J-PARC experiments in hypernuclear spectroscopies and lattice QCD calculations of the generalized nuclear force, should clarify the dynamical mechanism of the short-range baryon-baryon interactions and in general hadronic interactions in various hadron channels, including possible exotic hadronic molecular states.

4. **Exotic hadrons: $\Lambda (1405)$**
Since the report of $\Theta^+ (1440)$ discovery, the exotic multi-quark hadrons have been re-examined extensively. During analyses of various channels of excited hadrons, it becomes clear that the strangeness and heavy quarks allow multi-quark hadrons and/or hadronic molecular resonances preferably. Two main reasons for this preference are (1) suppressed kinetic energy of heavy quarks and (2) strong channel couplings to the excited states.
In the strangeness sector, the lowest energy baryon resonance with negative parity, Λ(1405), attracts much interest recently. Several first-principle calculations have been carried out. Among them, a new lattice QCD calculation[12] with three-quark interpolating field operators has revealed that there are two negative-parity Λ states around 1.65-1.8 GeV, while no trace of a state as low as 1.4 GeV is found. This result suggests that the physical Λ(1405) resonance may not be a 3-quark bound state, but may contain more quarks, or is a hadronic molecule. Indeed, a QCD sum rule analysis with mixed 3- and 5-quark interpolating field operators indicates that the lowest Λ contains the 5-quark component dominantly[13].

On the other hand, the chiral unitary approach, which describes excited hadrons as poles in the scattering amplitudes of two hadrons, has successfully reproduced the Λ(1405) peak structure using the dynamics constrained by chiral symmetry and unitarity of the amplitude[14]. Their results are consistent with and support the hadron molecule picture of Λ(1405).

It is important to clarify whether the Λ(1405) is a special case or there exist many other exotic states that are not accounted by ordinary 3-quark, or quark-antiquark pictures. In fact, several such multi-quark candidates have been proposed, which include tetra-quark resonances with heavy quarks, especially in charmonium and open charm hadrons, and dibaryon resonances. In order to study the origin and structure of such states, combinations of the first-principle QCD calculations and the hadron dynamics approaches are necessary. J-PARC may again play important roles in determining scattering amplitudes in various channels where theories suggest exotic resonances.

5. Conclusion

J-PARC is a unique facility for researches of the hadron physics and QCD. I have emphasized that the third flavor, strangeness, is a key to reveal the nonperturbative features of QCD at low energy. It is expected that new and exciting experimental data are coming out from the J-PARC experiments and our understanding of the hadron structures as well as the strong interaction dynamics will be largely developed.

References

[1] For overview of the J-PARC and its activities in particle and nuclear physics, see T. Sato, T. Takahashi and K. Yoshimura (Eds.), Particle and Nuclear Physics at J-PARC, Lecture Notes in Physics 781(Springer, Berlin Heidelberg, 2009). See also http://j-parc.jp/index-e.html.
[2] For proposed J-PARC experiments, see M. Iwasaki in ref.[1].
[3] T. Nakano et al., Phys. Rev. Lett. 91 (2003) 012002. For a recent status and proposed J-PARC experiment, see M. Naruki in ref.[1].
[4] For a recent review, see K. Fukushima, T. Hatsuda, Rept. Prog. Phys. 74 (2011) 014001.
[5] For proposed J-PARC experiments, see S. Yokkaichi in ref.[1].
[6] V. G. Neudatchin, Yu. F. Smirnov, R. Tamagaki, Prog. Theor. Phys. 58 (1977) 1072.
[7] M. Oka, K. Yazaki, Phys. Lett. 90B (1980) 41; Prog. Theor. Phys. 66 (1981) 556 and 572.
[8] M. Oka, K. Shimizu, K. Yazaki, Nucl. Phys. A464 (1987) 700.
[9] R.L. Jaffe, Phys. Rev. Lett. 38 (1977) 195.
[10] T.A. Rijken, M.M. Nagels, Y. Yamamoto, Prog. Theor. Phys. 1185 (2010) 14, and the references therein.
[11] S. Aoki, T. Hatsuda, N. Ishii, Prog. Theor. Phys. 123 (2010) 89; T. Inoue et al., Prog. Theor. Phys. 124 (2010) 591.
[12] T.T. Takahashi, M. Oka, Phys. Rev. D81 (2010) 034505.
[13] T. Nakamura, J. Sugiyama, T. Nishikawa, M. Oka, N. Ishii, Phys. Lett. B662 (2008) 132.
[14] D. Jido et al., Nucl. Phys. A725 (2003) 181; T. Hyodo, D. Jido, A. Hosaka, Phys. Rev. C78 (2008) 025203.