2.4 Hadron Physics at J-PARC

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Abstract

One of the main goals for the hadron physics is to understand the effective degrees of freedom (EDoF) in hadron and reveal their interactions. Spectroscopy of ground and excited states of baryons will give us hints to understand the EDoF of hadron. In addition, testing properties of known mesons/baryons, such as masses and decay widths, inside nuclear matter, will give us unique information on the interaction between EDoF and QCD vacuum.

In this paper, I will discuss the goal of the hadron physics and summarize experimental programs performed and planned at J-PARC. Finally, I will briefly discuss a future project at J-PARC, which is now under discussion.

1. **Introduction**

The strong interaction between elementary particles has been described very well by the quantum chromo dynamics (QCD). The missing element of a standard model of elementary particles, *i.e.*, the Higgs boson, has been discovered at CERN/LHC in 2012. Therefore the theory of known elementary particles, including the strong interaction, is now completed. There are many varieties of matter created by QCD, such as hadrons, nuclei and very high-density nuclear matter, such as neutron stars. Those type of matter must be interpreted by the QCD. However, due to the complexity of the QCD theory, it is very difficult to solve all problems and to understand the connection between elementary particles like quarks and gluons and hadrons or extremely high-density matter. It should be noted that not even the first step, how the hadrons and their excited states are created, is clearly understood. Therefore, not only more experimental efforts to understand hadron phenomena, but also strong theoretical supports for the hadron/nuclear physics are still mandatory to understand the matter created by QCD.

Some of the goals of hadron physics could be summarized as in the following two questions. First, how the hadrons are created via QCD? In other words, what are the effective degrees of freedom to describe hadron and excited hadrons? Second, hadrons are understood as excitations of QCD vacuum. Therefore, a change of vacuum condition should affect directly to the properties of hadron, such as mass and width. Thus, we need to know how hadron properties change when environmental condition changed, *i.e.*, vacuum inside nuclear matter.

In normal conditions, the world consists only from light quarks, *i.e.*, u and d quarks. However, inside the compressed QCD matter, creation of hadrons with strangeness is expected, theoretically. For such condition, hadrons with strangeness cannot be ignored to understand high-density matter. For example, anti-Kaon in nucleus is a hot subject in the hadron physics, which may give us hints toward physics in high-density nuclear matter. One the other hand, baryons with strangeness themselves are also a very important subject. According to the quark model, color magnetic interaction between constituent quarks can be expressed as follows.

$$V_{CMI} \sim \frac{\alpha_s}{m_i m_j}(\lambda_i \cdot \lambda_j)(\vec{\sigma_i} \cdot \vec{\sigma_j}), \tag{1}$$

where, m, λ and $\vec{\sigma}$ are mass, color and spin of constituent quarks, respectively. The equation tells us that if we choose heavy quarks as constituents for hadrons, color-magnetic interaction between a light quark and heavy quark is going to be zero.

Therefore, the interaction between light quarks will be dominant. In the case of baryons, strong correlation between di-quark will be realized. Hints for this type of correlation are expected to appear in the excited baryon spectra/decay pattern of hadron. Since the strange quark mass is heavier that u and d are, we may expect signal for such di-quark correlation in the S=-1 baryon system. In addition, S=-2 baryon can be treated as an analogy of baryon with two heavy quarks. It should be noted that baryon with two heavy quarks, such as Ξ_{cc} for example, have not been observed. Therefore, S=-2 baryon spectroscopy will be a unique doorway to understand the structure of baryons with heavy quarks, in other words, the investigation will give us an insight to the effective degrees of freedom to describe hadrons. Therefore, hadron with strangeness, *i.e.*, baryon with strangeness (Λ/Ξ/Ω) and/or Kaon, will be a key ingredient to understand the questions mentioned above.

2. J-PARC

The Japan Proton accelerator Research Complex (J-PARC) is one of the key machines to perform hadron physics. Proton beam accelerated up to 30 GeV by J-PARC Main Ring Synchrotron (MR) is delivered to Hadron experimental facility (HD) and shoot onto the production target, which is made by gold, to produce secondary hadron beams, such as $\pi^{\pm}$, $K^{\pm}$ and $p, \bar{p}$. Typical beam intensity of the primary proton beam is 4.8×10^{13} proton per spill (pps), where the spill length is 2 seconds with a 5.52 seconds repetition cycle. Inside HD, four beamlines are designed, two (K1.8, K1.8BR) are in operation and two (K1.1 and High-p) are under construction. The typical beam intensities for secondary particle for each beam lines are summarized in Table 2. As one can see, particle separated beams can be available up to 2 GeV/c and unseparated beam is available up to 20 GeV/c. In addition, a primary proton beam is also available for the experiment. A more detailed description can be found elsewhere [1].

3. Hadron Physics Performed at J-PARC

(a) Search for Penta-Quark Baryon

Only color singlet state can exist as hadrons. This is a conclusion from QCD. Therefore, hadrons which have 5 quarks ($qqqq\bar{q}$) are not forbidden by QCD. Thus, many experimental challenges have been performed to search for such exotic states. Strong evidence have been reported from photo-production experiment [2], however, also many negative results are reported (mainly from hadro-production) [3–6]. At J-PARC hadro-production of penta-quark state using high intensity pion beam is performed, by (π, K)

Table 1: J-PARC Beam line specifications.

beamline	paricle	momentum range	typical beam intensity (40 kW MR operation)
K1.8BR	$\pi^{\pm}, K^{\pm}$ and $p, \bar{p}$ (separated)	< 1.1 GeV/c	1.5×10^5 K$^-$/spill@ 1 GeV/c
K1.8	$\pi^{\pm}, K^{\pm}$ and $p, \bar{p}$ (separated)	< 2.0 GeV/c	5.0×10^5 K$^-$/spill@ 2 GeV/c
K1.1	$\pi^{\pm}, K^{\pm}$ and $p, \bar{p}$ (separated)	< 1.1 GeV/c	1.5×10^5 K$^-$/spill@ 1 GeV/c
High-p	$\pi^{\pm}, K^{\pm}$ and $p, \bar{p}$ (unseparated)	up to 20 GeV/c	$>\sim10^7\pi^-$/spill@ 20 GeV/c
			$>\sim10^6 K^-$/spill@ 7 GeV/c
	primary proton	30 GeV	$\sim 10^{11}$ proton / spill

reaction on hydrogen target [7, 8]. No signal has been observed so far. To date, still the conclusion has not been reached concerning whether a penta-quark state exists or not.

(b) **Search for Kaonic Nucleus**

Because strong attractive force exists between anti-Kaon and nucleon, the existence of the strongly bound Kaonic-nuclear state has been discussed for a long time. It is interesting to note that, theoretically, the inside of the Kaonic nucleus could turn into high density, much higher than normal nuclear matter density. Therefore, the study of Kaonic nucleus will give us some insight on QCD at high-density matter. There are many experiments to search for such exotic state, which have been performed to date, however, still not strong conclusion is made. Two new experiments have been performed at J-PARC. Both experiments are focussing on the lightest Kaonic nuclear cluster, *i.e.*, K^-pp state. One is the E27 experiment, which aims to search for K^-pp cluster via (π, K) reaction. The result shows some indication for the deeply bound K^-pp bound state [9]. The other experiment is the E15 experiment, which aims to search for the K^-pp bound state via ^{3}He(K^-, n) reaction. The first results from the E15 experiment shows [10] no clear signal found in deeply bound region, but an interesting events enhancement has been observed near the K^-pp threshold region. Recently, the E15 experiment reported new results on exclusive analysis on ^{3}He$(K^-, \Lambda p)$n reaction [11]. The result is shown in Figure 1. Figure 1(a) shows a scatter plot for the invariant mass of Λp versus neutrons emitted angle in the center of mass frame. Figure 1(b) and (c) are the projection of the plot to the axes. Expected contributions are also plotted as histogram in Figure 1(b). A clear enhancement with respect to the expected contributions are seen just bellow the $\bar{K}NN$ threshold. It is interesting to note that as shown in Figure 1(c), a clear event concentration at $\cos(\theta_{CM}) \sim 0$, where slowly moving $\bar{K}$ produced is seen. This will be a necessary condition to form $\bar{K}NN$ bound state. However, due to the small statistics, it is still hard to conclude whether $\bar{K}NN$ bound states are produced or not.

Because both experiments try to produce K^-pp cluster by different production mechanisms further detailed studies are still needed to conclude whether K^-pp cluster really exists or not, and to know its properties.

(c) **Mesons in Nuclei**

Chiral symmetry in QCD vacuum is spontaneously broken. It is now understood that

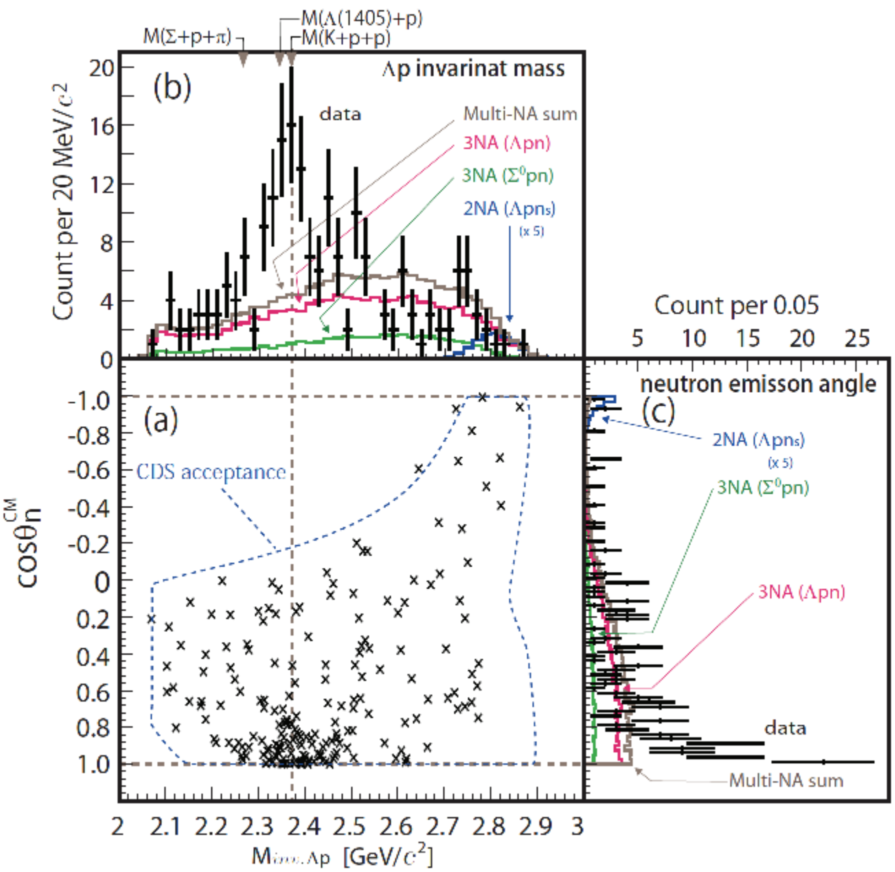

Figure 1: Results recently published by the J-PARC E15 Collaboration [11].

mass of the hadrons is generated dynamically by the broken symmetry. However, the chiral symmetry will be partially restored in high-density matter such as inside nuclei. This information can be checked through the measurement of the mass of mesons or search for the meson nuclear bound state. Because vector mesons have relatively long lifetime, therefore three experiments have been proposed to study the vector mesons in nuclear matter: E16 [12], E26 [13], and E29 [14].

The E16 experiment is aiming to measure the line shape of vector mesons via measuring $V \to e^+e^-$ decay inside a nucleus. The experiment is planed to be perform using the 30 GeV primary proton beam at the high momentum beam line.

The E26 experiment is planed to search for ω meson nuclear bound state. To maximize the formation probability of ω meson nucleus, slowly moving ω mesons are selectively produced via (π, n) reaction using the 2 GeV/c pion beam at K1.8 beamline. Signal of ω mesic nucleus is identified via missing mass spectroscopy of forward going neutron.

The E29 experiment is forccusing on the ϕ meson nuclear bound state. Very exotic elementary reaction channel, $\bar{p}p \to \phi\phi$, has been chosen to produce slowly moving ϕ meson. The experiment is planning to use the 1.1 GeV/c $\bar{p}$ beam at K1.8BR beamline. The signal is identified via missing mass analysis using the forward going ϕ meson, together with the K^+ and Λ from the target as final state particles, to ensure the double strangeness pairs are produced.

(d) **S=-2 and S=-3 Baryon Spectroscopy**

To understand the effective degree of freedom to describe hadrons, in other words, what are the DoF to control the excited baryon spectra, it is very important to identify the complete spectra of S=-2 and/or S=-3 baryons. However, according to the PDG, only a small number of S=-2 baryons are established. In case of Ω baryon, only ground state is known. High intensity Kaon beam will improve the situation drastically. It should be noted that in case of nucleon resonances, the widths are very broad, typically more than $\sim$270 MeV, thus it is hard to identify the states easily. However, the trend of baryon with strangeness shows widths which are much narrower than of nuclear resonances, it is about $\sim$40 MeV. Therefore, we have a chance to identify those excited multi-strangeness baryon clearly. The experiment to identify Ξ baryons are in preparation at High-p beam line where high momentum K^- beam will be available. The missing mass spectroscopy via (K^-, K^+) or $(K^-, K^+\pi^+)$ is planed to establish and search for the Ξ baryons [15]. The experiment is expected to pin down the Ξ baryon spectra up to the baryons with mass $\sim$3 GeV/c^2.

(e) **Future projects: Hadron Hall Extension**

To extend the physics cases reachable at J-PARC, an extension of the HD facility is under discussion. It is true that high momentum K$^-$ is already available at High-p beamline. However, the intensity of the beam is rather low, which limits the reach of the excited Ξ search. Moreover, excited state for Ω baryon are not possible at High-p beamline, because the expected cross section is very small (sub μb). In addition, at High-p beamline, only a cocktail beam of π^-,K$^-$ and $\bar{p}$ is available, but most of it are pions. Therefore, experiments will be facing serious problems of pion interactions, which is indeed the main background for Kaon interaction studies. Therefore, high intensity and particle separated beamline is very important to enhance the physics opportunities at J-PARC.

Figure 2 shows a conceptual design for the extended hadron hall. For this extension, we will construct three new charged particle beamlines for hadron/nuclear physics and one new K_0 beam line to search the $K_L^0 \to \pi^0\nu\bar{\nu}$ decay. which has great sensitivity to the beyond the standard model. Here, we will concentrate on the K10 beamline, where high intensity and high momentum K$^-$ and $\bar{p}$ beam will be available. Figure 3 shows the expected beam intensities at K10 for K$^-$ and $\bar{p}$. As one can see in Figure 3, the expected beam intensities will be 10^7 per spill at 4 to 6 GeV/c K$^-$ and 10^7 per spill for 10 GeV/c $\bar{p}$. Utilizing those beam particles, we are planing to perform Ω baryon spectroscopy which will be possible at J-PARC once the hadron hall extension is realized. Moreover, recent lattice QCD calculation shows that tha interaction between Ω baryon and nucleon is attractive. If this is true, Ω baryon and nucleon may form Ω-N bound state. Therefore the experiment to search for the Ω-N bound state may be very important.

In addition, high intensity $\bar{p}$ beam will open new opportunity to investigate charmed meson properties in nucleus (nuclear matter). Since long time, the interaction between D meson and nucleon is believed to be attractive, based on the many theoretical predictions [16–18]. However, recent QCD sum rule calculation shows it is repulsive, in

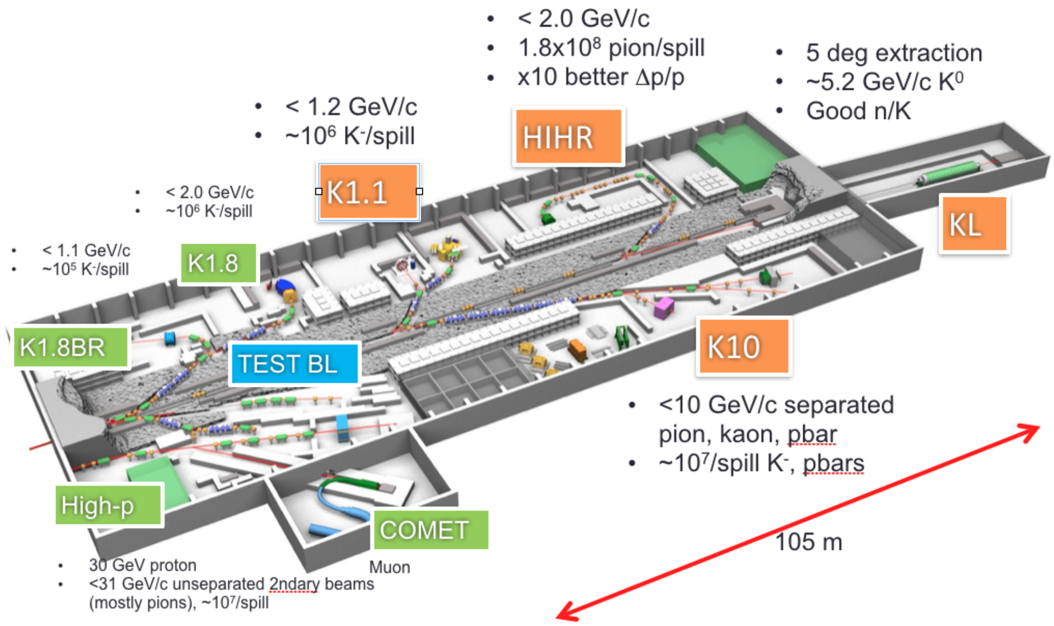

Figure 2: Conceptual design for extended Hadron Hall.

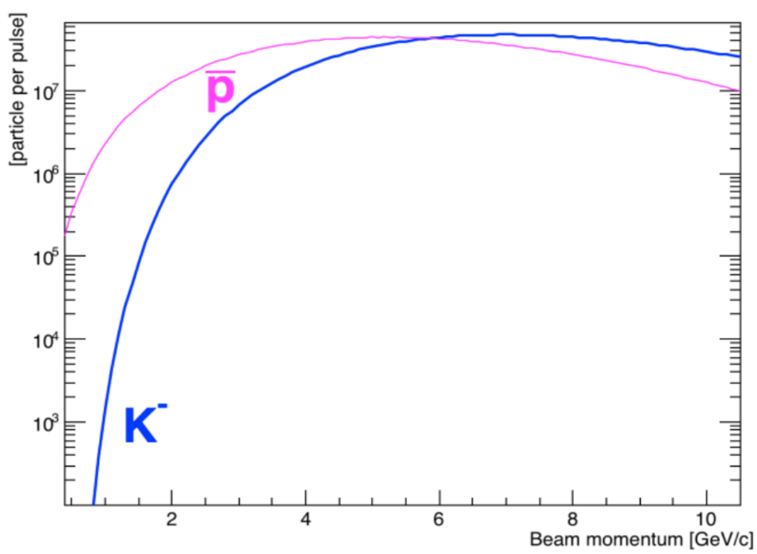

Figure 3: Expected beams intensities at K10 beamline.

other words, D meson is getting heavier in nuclear matter [19, 20]. Because no experiment was performed to investigate the D meson and nucleon interaction, no concrete information is available experimentally.

Therefore, the D meson properties in nuclear matter is one of the interesting subject to date. At K10, we plan to perform the experiment to measure $\bar{D}D$ production with $\bar{p}$ beam on proton and on nuclei, which will give us a hints for the DN interaction. It is interesting to note that recently many exotic hadrons are reported by collider experiments, such as Belle, BaBar, LHCb, BES *etc.* Those measurements provide insight into the structure of hadrons, which can be summarize as follows.

i. Charmonium spectra can be describe very well by the model of constituent quarks acting as effective degree of freedom to describe charmonium, *i.e.*, constituent quark model.

ii. Many exotic hadrons are also discovered. It is interesting that those exotic hadrons exist only above the $D\bar{D}$ production threshold.

Those phenomena indicates that the production cross section of $D\bar{D}$ near the production threshold might be sensitive whether such exotic states are really produced or not. Figure 4 shows conceptual design for the spectrometer we are planing to install K10 beamline. The detector consists of large volume solenoid detector surrounding the target together with forward dipole spectrometer.

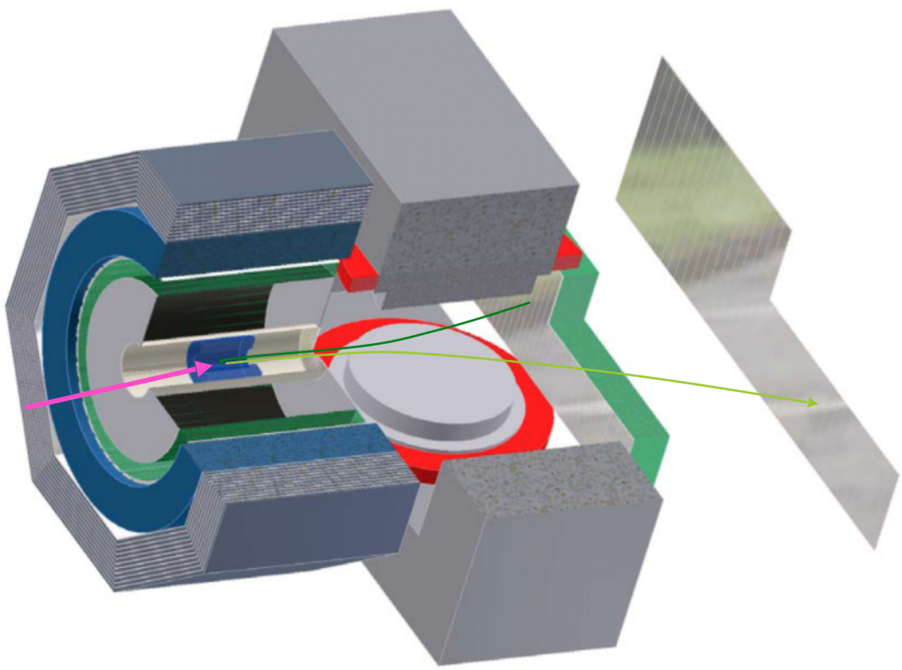

Figure 4: Conceptual design for Detector at K10.

4. **Summary**

In this paper, physics programs currently performed at J-PARC are reviewed. Baryon spectroscopy and mesons in nucleus using high intensity pion and Kaons beams are main topics for experimental programs at the current J-PARC hadron hall. Many new results are coming out.

At present, investigation for $\bar{K}N$ interaction is performed using high intensity low momentum K$^-$. Recently available new data from E15 shows strong hint about $\bar{K}NN$ cluster. However, to make strong conclusion, we need to wait the completion of the analysis with large data sample. Data have already been taken and data analysis is under the way.

A new project at J-PARC, *i.e.*, Hadron hall extension, was introduced. Three separated charged secondary beamlines will be constructed. In particular high intensity and high momentum particle separated beamline(K10) is very important for the hadron physics. High momentum Kaons beam at K10 will allow to perform multi-strangeness baryons spectroscopy. Moreover, the high intensity anti-proton beam will open the door to a new physics subject, *i.e.*, charmed mesons in nuclei.

References

[1] Prog. Theor. Exp. Phys. (2012) 02B011.

[2] T. Nakano *et al.*, Phys. Rev. C **79**, 025210 (2009).

[3] M.J. Longo *et al.*, Phys. Rev. D **70**, 111101(R) (2004).

[4] I. Abt *et al.*, Phys. Rev. Lett. **93**, 212003 (2004).

[5] S. Schael *et al.*, Phys. Lett. B **599**, 1 (2004).

[6] J.Z. Bai *et al.*, Phys. Rev. D **70**, 012004 (2004).

[7] K. Shirotori *et al.*, Phys. Rev. Lett. **109**, 132002 (2012).

[8] M. Moritsu *et al.*, Phys. Rev. C **90**, 035205 (2014).

[9] Y. Ichikawa *et al.*, Prog. Theor. Exp. Phys. (2015) 021D01.

[10] T. Hashimoto *et al.*, Prog. Theor. Exp. Phys. (2015) 061D01.

[11] Y. Sada *et al.*, arXiv:1601.06876 .

[12] S. Yokkaichi *et al.*, J-PARC E16 proposal, `http://j-parc.jp/researcher/Hadron/en/pac_0606/pdf/p16-Yokkaichi$_2.pdf` .

[13] K. Ozawa *et al.*, J-PARC E26 proposal, `http://j-parc.jp/researcher/Hadron/en/pac_0903/pdf/\Ozawa.pdf` .

[14] H. Ohnishi*et al.*, J-PARC E29 proposal, `http://j-parc.jp/researcher/Hadron/en/pac_0907/pdf/\Ohnishi.pdf` .

[15] M. Naruki and K. Shirotori, Letter of Intent, `http://j-parc.jp/researcher/Hadron/en/pac_1405/pdf/\LoI_2014-4.pdf` .

[16] A. Sibirtsev, K. Tsushima, and A.W. Thomas, Eur. Phys. J. A **6**, 351 (1999).

[17] A. Mishra and A. Mazumdar, Phys. Rev. C **79**, 024908 (2009).

[18] A. Hayashigaki, Phys. Lett. B **487**, 96 (2000).

[19] T. Hilger, R. Thomas, and B. Kämpfer, Phys. Rev. C **79**, 025202 (2009)

[20] K. Suzuki, P. Gubler, and M. Oka, arXiv:1511.04513 [hep–ph].