Experimental studies of mesic nuclei at J-PARC

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The property of a pseudoscalar meson at finite density may be extracted by investigating mesic nuclei in detail. The existence of mesic nuclei is predicted theoretically, based on the understanding of the meson-nucleon interaction. Experimental programs to search for mesic nuclei at J-PARC are reviewed.

1 Introduction

Meson-nucleus bound states, a new kind of bound systems in strong interaction, will provide us unique information on hadron properties at finite density. In particular, $\overline{K}$-nuclear bound states (kaonic nuclei) and η-nuclear bound states (η mesic nuclei) attract a lot of attention from both experimentalists and theorists nowadays.

In this article, I would like to review related experimental programs at J-PARC briefly. Figure 1 is a schematic view of the J-PARC hadron experimental facility. Proton beam, accerelated to 30 GeV by the main ring, is delivered from the lower left to the production target. There are two beamlines for charged particles (K1.8 and K1.1) and one beamline for neutral kaons. The experiments described below will be performed in either the K1.8 beamline or the K1.8BR beamline (branch line of K1.8).

2 Kaonic nuclei

Because of the strong attraction between $I = 0$ $\overline{K}N$ pairs, an antikaon-nucleus system may exist as a quasi-bound state. For example, the existence of $\Lambda(1405)$ below the $\overline{K}N$ threshold can be regarded as a consequence of such a strong attractive interaction. It is a natural extension to consider $\overline{K}NN$ systems.

Theoretically, a variety of calculations of the $\overline{K}NN$ system have been carried out [1], supporting the existence of a bound state. The binding energy varies from ~ 10 MeV to ~ 100 MeV, and the decay width is moderately large. The difference mainly comes from the calculation method (Faddeev approach or variational approach) and the treatment of $\pi\Sigma N$ channel.

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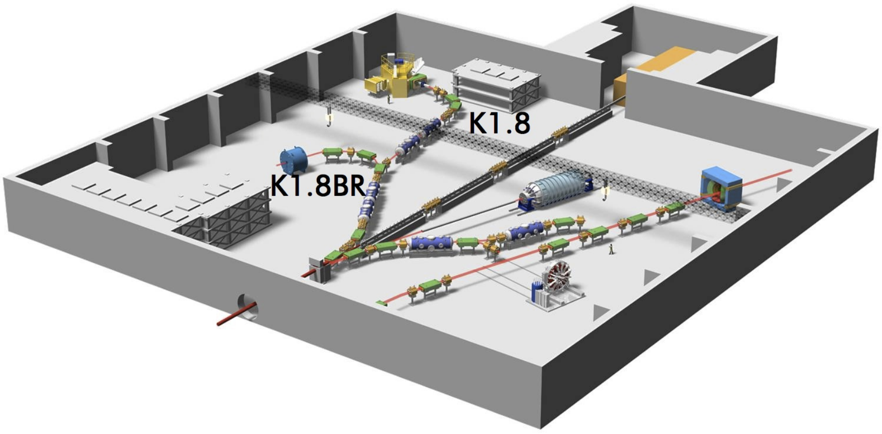


Figure 1: Layout of J-PARC hadron experimental facility.

From an experimental point of view, non-mesonic decay of $K^- pp$ states into $\Lambda + p$ is a clean signal in searching for such an exotic state. Many experiments in the past and in the near future make use of this channel.

The first observation was reported by the FINUDA collaboration [2]. They detected a pair of Λ and proton in back-to-back from K^- absorption at rest. A slow K^- beam was supplied by the ϕ-factory DAΦNE. The invariant mass of the Λp pairs was far below the $K^- + 2p$ threshold, which is in contradiction with an assumption that they originated from a two-nucleon absorption process $K^- +$ "pp" $\rightarrow \Lambda + p$. They interpreted Λp pairs may be originated from non-mesonic decay of $K^- pp$ states, whose binding energy from the $K^- + 2p$ threshold is ~ 115 MeV and decay width is ~ 67 MeV. However, this interpretation is criticized by Magas *et al.* [3] and Pandejee *et al.* [4], both of which stress the importance of final state interaction after two-nucleon absorption.

Another indication was obtained by a reanalysis of the DISTO experiment, which performed an exclusive measurement of the $p + p \rightarrow p + \Lambda + K^+$ reaction [5]. A broad distinct peak was found in the K^+ missing-mass spectrum and the $p\Lambda$ invariant-mass spectrum, when they select events with a large-p_T proton and K^+. If the peak corresponds to a $K^- pp$ state, its binding energy and decay width are ~ 105 MeV and ~ 118 MeV, respectively.

At present, the existence of $K^- pp$ bound states whose binding energy is as large as 100 MeV is not established. Accordingly, it is vitally important to search for $K^- pp$ states with various reactions. The $p + p \rightarrow p + \Lambda + K^+$ reaction with higher incident energy was measured at GSI in 2009, and the analysis is in progress [6]. The stopped K^- absorption reaction in ^{3}He and ^{4}He will be studied by the AMADEUS experiment at DAΦNE [7]. In J-PARC, two experiments with the ^{3}He(K^-, n) reaction (J-PARC E15 experiment) and the D(π^+, K^+) reaction (J-PARC E27 experiment) have been approved, and the preparation is in progress.

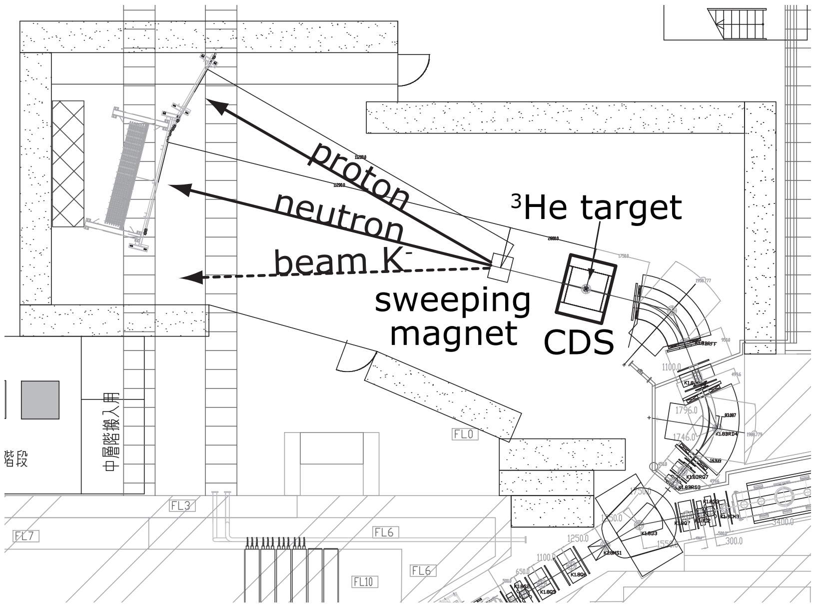


Figure 2: Setup for the J-PARC E15 experiment.

2.1 J-PARC E15 experiment

The J-PARC E15 experiment [8] will be performed at the K1.8BR beamline. 1.0 GeV/c K^- beam will be injected into liquid ^{3}He target. Figure 2 shows the experimental setup. Outgoing neutrons by the (K^-, n) reactions will be detected by a neutron counter about 15 m downstream of the target. The beam K^- will be swept away by a sweeping magnet in order not to hit the neutron counter, and as a by-product, scattered protons by the (K^-, p) reaction can be detected by installing an additional proton counter. The decay particles of K^-pp states into $\Lambda + p$ or $\Sigma^0 + p$ can be detected by a cylindrical detector system (CDS) which consist of a GEM-TPC tracker, a cylindrical drift chamber, and hodoscopes inside a solenoid magnet. Thereby, both missing-mass spectroscopy and invariant-mass spectroscopy will be enabled.

A CDS commissioning run with π^+ and K^- beam was carried out last autumn, and distinct peaks of Λ and K_S were observed by reconstructing the invariant mass of $p\pi^-$ and $\pi^+\pi^-$ pairs, respectively. The analysis for improving the resolution and the particle identification is under way.

2.2 J-PARC E27 experiment

The J-PARC E27 experiment will make use of the D(π^+, K^+) reaction [9]. K^-pp states will be produced by sticking a $\Lambda(1405)$, produced by the $n(\pi^+, K^+)$ reaction, on the spectator proton. The experiment will use 1.5–1.6 GeV/c π^+ beam at the K1.8 beamline, and the scattered K^+ will be detected by the Superconducting Kaon Spectrometer (SKS).

It is essentially important to reduce background from quasi-free processes ($\pi^+ + $"$N$"$\rightarrow Y^{(*)} + K^+$). Tagging two protons from K^-pp decay will help to eliminate these contributions; a proton from $Y^{(*)}$ decay tends to have a small emission angle, and the spectator proton is too slow to be detected experimentally. Thus, two sets of range counter arrays will be installed on the left and right sides of the deuterium target for detection of fast protons.

A test experiment with a prototype of the range counter arrays was done during the beam time for the E19 experiment, which searched for the Θ^+ pentaquark. Part of the range counter arrays were installed near hydrogen target, and scattered $\pi^{\pm}$'s and protons were stopped inside the arrays. A preliminary analysis revealed that clear p/π separation is possible by combining the energy loss in each counter, the time-of-flight between the start counter and the first layer of the array, and the range of the particle.

We plan to take the first data for the E27 experiment in early 2012, and the preparation of the detectors in the beamline and the SKS spectrometer as well as the range counter arrays is going on.

3 η mesic nuclei

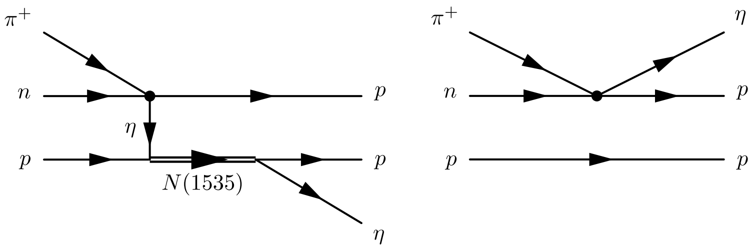
The ηN interaction is weakly attractive, because the $N(1535)$ resonance, which strongly couples to ηN, lies above the ηN threshold. However the scattering length has a large ambiguity between (0.270–1.050) + (0.190–0.399)i fm [10].

The first calculation by Haider and Liu [11] showed η mesic nuclei with the mass number $A \geqslant 12$ can be bound when the scattering length is set to $0.28 + 0.29i$ fm or $0.27 + 0.22i$ fm. If the real part of the scattering length is larger, there may be a possibility that an η meson is bound in a lighter nucleus such as ^{3}He and ^{4}He [10, 12].

Recently the COSY-GEM collaboration investigated the ^{27}Al(p, ^{3}He) reaction [13] at recoilless kinematics. By detecting back-to-back $\pi^- p$ pairs, which may originate from the decay of η mesic nuclei, they found an indication of η mesic nuclei with the binding energy of ~ 12 MeV.

Itahashi *et al.* propose to study the (π^-, n) reaction on ^{7}Li and ^{12}C target at J-PARC [14]. The advantage over a prior experiment at BNL [17] is the detection of back-to-back $\pi^- p$ pairs like the COSY-GEM experiment, and the recoilless condition by adjusting π^- momenta around 0.8–1.0 GeV/c and detecting zero-degree neutrons[2]. To achieve these conditions, the use of the E15 experimental setup is desirable. According to Ref. [15], the formation spectrum is sensitive to the in-medium property of $N(1535)$, which affects the η-nucleus

[2]The BNL experiment measured protons at scattering angle 15° from the (π^+, p) reaction, and the momentum transfer is larger than 200 MeV/c.



(a) double-scattering reaction **(b)** quasi-free reaction

Figure 3: Diagrams for the $\pi^+ d \to pp\eta$ reaction.

optical potential. While the mass difference of $N(1535)$ and N will not change largely in the chiral unitary model, the chiral doublet model leads to a decrease of the mass difference due to the partial restoration of chiral symmetry.

A pilot experiment with deuteron target is also under consideration [16] . The $\pi^+ d \to pp\eta$ reaction can be studied by detecting two protons. The dominant quasi-free process (Fig. 3b) can be eliminated because the spectator proton has a very small momentum, and we can select the double-scattering reaction (Fig. 3a). The differential cross section is sensitive to the low-energy ηN scattering amplitude because the elastic scattering $\eta N \to \eta N$ takes place near the threshold energy [18].

Lastly, the (p, ^{3}He) reaction, which was investigated by the COSY-GEM collaboration [18], may be studied at the K1.8 beamline together with the SKS spectrometer. The coincidence of decay particles will be mandatory to reduce huge background.

4 Summary

Intense $\pi^\pm$, K^-, and proton beams will allow us to investigate kaonic nuclei and η mesic nuclei. As well as the forward spectrometer, the detectors for decay particles of mesic nuclei are important to make the background level as small as possible. The preparation of the E15 and E27 experiments, both of which will search for $K^- pp$ bound states, is in progress. Moreover, search for η mesic nuclei will be feasible in future.

Acknowledgments

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