Search for mesic nuclei at J-PARC

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Search for mesic nuclei at J-PARC

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Abstract. Experimental programs at J-PARC with regards to $K$- and $\eta$-nuclear systems are reviewed in this article. Both of them are theoretically expected to exist as bound states, based on the attractive nature of the meson-nucleon interaction. In-medium properties of pseudoscalar mesons may be investigated by looking into these bound states.

1. Introduction
The possibility that a meson and a nucleus may be bound and form a mesic nucleus by the strong interaction is widely discussed. In particular, several experimental observations with regard to antikaon-nuclear bound state (kaonic nuclei) and $\eta$-nuclear bound state (mesic nuclei) have been reported up to now. These mesic nuclei will provide unique information on hadron properties at finite density and hadron-nucleon interaction in the subthreshold region.

In this article, some of experimental programs at J-PARC related to mesic nuclei will be reviewed. The schematic view of the J-PARC hadron experimental facility is shown in Fig. 1. 30 GeV proton beam extracted from the main ring is delivered from the lower left to the production target, from which three secondary beamlines (K1.8, K1.1, and neutral KL beamlines) are separated. The experiments will be performed at either the K1.8 beamline or the K1.8BR beamline branched from K1.8, depending on the required beam momentum. In both the beamlines, secondary particles such as $\pi^\pm$ and $K^\pm$ are available. The maximum beam momenta are around 2.0 GeV/$c$ and 1.1 GeV/$c$, respectively.

2. Kaonic nuclei
The mass of the $\Lambda(1405)$ baryon is difficult to explain in a naive quark model, because it is the lightest baryon with $J^P = 1/2^-$, even below the non-strange $N(1535)$ baryon. One probable scenario is that it can be regarded as a $\bar{K}N$ bound state. An attractive interaction between an antikaon and a nucleon enough to form a bound state is reinforced by the $\bar{K}N$ scattering data and the X-ray measurement of kaonic hydrogen by recent experiments (KpX [1], DEAR [2], and SIDDHARTA [3]) which confirmed a repulsive shift of the 1s ground state.

If this is the case, an antikaon can attract more nucleons and antikaon-nuclear bound state may be formed [4, 5]. The $\bar{K}NN$ system is particularly important since it is the simplest system beyond $\Lambda(1405)$. Both experimental and theoretical investigations of this system have been conducted in the last decade.

A variety of calculations of the $\bar{K}NN$ system, using the Faddeev approach or the variational approach, have been performed [6]. The binding energy ranges between $\sim 10$ MeV and...
~ 100 MeV, and the decay width is moderately large. The difference mainly comes from the treatment of the $\pi\Sigma$ channel, which couples with the $\bar{K}N$ channel and affects the strength of the $\bar{K}N$ interaction.

Experimental searches for the $\bar{K}NN$ system were carried out by the FINUDA/DAΦNE and the DISTO/SATURNE collaborations. Both the analyses made use of the non-mesonic decay channel of the $\bar{K}NN$ system with the charge +1, i.e. $K^-pp$, decaying into $\Lambda + p$.

From an experimental point of view, non-mesonic decay of $K^-pp$ states into $\Lambda + p$, instead of mesonic channels, $\Sigma\pi N$ or $\Lambda\pi N$, can be a clean signal in searching for such an exotic state. Many experiments in the past and in the near future focus on this channel, because of the easiness of the detection of charged particles.

The first observation was reported by the FINUDA collaboration[7] at the $\phi$-factory DAΦNE, which is an electron-positron collider with $\sqrt{s} = 1.02$ GeV. They detected a pair of $\Lambda$ and proton from $K^-\Lambda$ absorption at rest, strongly correlated in the back-to-back direction. Slow and almost monoenergetic $K^-$ beam was produced as the decay product of $\phi$ into $K^+K^-$. The invariant mass of the $\Lambda p$ pairs is distributed far below the $K^- + 2p$ threshold ($2.370 \text{ GeV}/c^2$), and it is difficult to explain the distribution by the assumption that they originated from a two-nucleon absorption process $K^- + \text{"pp"} \rightarrow \Lambda + p$. They interpret $\Lambda p$ pairs may have originated from non-mesonic decay of $K^-pp$ bound states, whose binding energy from the $K^- + 2p$ threshold is $\sim 115$ MeV and decay width is $\sim 67$ MeV. However, the distribution may be explained by taking into account final state interaction after the two-nucleon absorption process, as discussed by Magas et al. [8] and Pandjee et al. [9].

Another indication was reported after a reanalysis of the DISTO experiment, which performed an exclusive measurement of the $p + p \rightarrow p + \Lambda + K^+$ reaction with the incident kinetic energy 2.85 GeV [10]. A broad distinct peak was found in the $K^+$ missing-mass spectrum and the $p\Lambda$ invariant-mass spectrum, when they select events with large-angle scattered proton and $K^+$. If the peak corresponds to a $K^-pp$ state, its binding energy and decay width are $\sim 105$ MeV and $\sim 118$ MeV, respectively.

At present, the existence of $K^-pp$ bound states observed by the two experiments is not
confirmed. Hence, it is important to continue searching for $K^-pp$ states with various reactions. The $p + p \rightarrow p + \Lambda + K^+$ reaction with higher incident energy was measured by the FOPI experiment at GSI in 2009, and the analysis is in progress [11]. The stopped $K^-$ absorption reaction in $^3$He and $^4$He will be studied by the AMADEUS experiment at DAΦNE [12]. In J-PARC, two experiments have been approved, the $^3$He($K^-, n$) reaction (J-PARC E15 experiment) and the D($\pi^+, K^+$) reaction (J-PARC E27 experiment).

2.1. J-PARC E15 experiment
The J-PARC E15 experiment [13] will be performed at the K1.8BR beamline (Fig. 2). $K^-$ beam at 1.0 GeV/c will be made to impinge on a liquid $^3$He target. Outgoing neutrons by the ($K^-, n$) reactions will be detected by a neutron counter, located at 15 m downstream from the target. The $K^-$ beam will be swept away by a sweeping magnet in order not to hit the neutron counter. Furthermore, scattered protons by the ($K^-, p$) reaction can be detected by installing an additional proton counter next to the neutron 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 consists of a GEM-TPC tracker, a cylindrical drift chamber, and hodoscopes inside a solenoid magnet. Both the missing-mass and invariant-mass techniques will be applied to suppress the background.

The commissioning run of the beamline at 1.0 GeV/c and the CDS has been performed. For example, $\Lambda$ and $K_S$ are observed by reconstructing the invariant mass of $p\pi^-$ and $\pi^+\pi^-$ pairs, respectively, which were detected by the CDS. The analysis for improving the resolution and the particle identification is under way.

The construction of the neutron counter and the installation of the sweeping magnet will start soon. We expect the first data taking to begin in 2012.

2.2. J-PARC E27 experiment
The J-PARC E27 experiment will investigate the D($\pi^+, K^+$) reaction [14]. $K^-pp$ states will be produced by sticking a $\Lambda(1405)$, produced by the elementary reaction $n(\pi^+, K^+)$, on the
spectator proton. The experiment will use 1.7 GeV/c $\pi^+$ beam at the K1.8 beamline, and the scattered $K^+$ will be detected by the Superconducting Kaon Spectrometer (SKS).

The main background in the inclusive measurement will come from quasi-free processes ($\pi^+ + "N" \rightarrow Y^{(*)} + K^+$). Since these processes have a spectator nucleon almost at rest, the tagging of two protons by a detector system surrounding the deuterium target will be useful to eliminate their contribution. Thus, two sets of range counter arrays for detection of fast protons will be installed on the left and right sides of the target.

A test experiment with a prototype of the range counter arrays was done during the beam time for the E19 experiment in 2010, which searched for the $\Theta^+$ pentaquark. A part of the range counter arrays was installed near a hydrogen target, and some of scattered $\pi^\pm$'s and protons were stopped inside the arrays. The analysis verified the feasibility of clear $p/\pi$ separation 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 the middle of 2012. The detectors in the beamline and the SKS spectrometer as well as the range counter arrays are almost ready.

3. $\eta$ mesic nuclei

The $\eta N$ interaction is known to be weakly attractive, because the $\eta N$ channel strongly couples with the $N(1535)$ resonance, which is above the $\eta N$ threshold. However, its scattering length has a large ambiguity with the real part varying between (0.270–1.050) fm and the imaginary part between (0.190–0.399) fm [15]. Haider and Liu [16] showed $\eta$ mesic nuclei with the mass number $A \geq 12$ 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, an $\eta$ meson may be bound in an even lighter nucleus such as $^3$He and $^4$He [15, 17].

Recently the COSY-GEM collaboration investigated the $^{27}$Al($p$, $^3$He) reaction [18] with the recoilless condition. By detecting back-to-back $\pi^- p$ pairs, which may originate from the decay of $\eta$ mesic nuclei, they found an indication of $\eta$ mesic nuclei with the binding energy of $\sim 12$ MeV. Studies with the ($p$, $^3$He) reaction may be continued at J-PARC at the K1.8 beamline together with the SKS or S-2S (under construction) spectrometer.

Itahashi et al. propose to study the ($\pi^-$, $n$) reaction on $^7$Li and $^{12}$C target at J-PARC [19]. There are two advantages over a prior experiment at BNL [20]: one is the detection of back-to-back $\pi^- p$ pairs like the COSY-GEM experiment, and the other one is the recoilless condition by adjusting $\pi^-$ momenta around 0.8–1.0 GeV/c and detecting zero-degree neutrons, while the BNL experiment measured protons at scattering angle 15° from the ($\pi^+$, $p$) reaction, so that the momentum transfer is larger than 200 MeV/c. To achieve these conditions, the use of the E15 experimental setup is desirable. According to Ref. [21], the formation spectrum is sensitive to the in-medium property of $N(1535)$, which affects the $\eta$-nucleus 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. The missing-mass spectrum will help to understand the in-medium behavior of $N(1535)$.

A pilot experiment with deuteron target ($\pi^+ d \rightarrow p p \eta$) is also under consideration [22]. The double-scattering reaction (Fig. 3(a)) can be distinguished from the dominant quasi-free process (Fig. 3(b)) by detecting two outgoing protons, since the spectator proton in the latter process has a very small momentum. The differential cross section is sensitive to the low-energy $\eta N$ scattering amplitude as the elastic scattering $\eta N \rightarrow \eta N$ will play an important role near the threshold energy [23].
4. Summary
Meson-nuclear bound systems, such as kaonic nuclei and η mesic nuclei can be investigated at J-PARC by using intense $\pi^\pm$, $K^-$, and proton beams. In addition to the forward spectrometer for the missing-mass spectroscopy, the detectors for decay particles of mesic nuclei are also important to reduce the background level. The E15 and E27 experiments, both of which will search for $K^-pp$ bound states but with different reactions, will start in 2012. Moreover, search for η mesic nuclei will be also feasible in future.

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