Letter of Intent for J-PARC 50 GeV Synchrotron

Search for tetraneutron by pion double charge exchange reaction on ^{4}He

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Candidates of a tetraneutron resonance state, composed of four neutrons, have been observed in a heavy-ion double charge exchange reaction at RIBF. We would like to investigate this exotic state by a pion double charge exchange reaction at the High-Intensity High-Resolution beamline in an extended Hadron Experimental Facility, which is currently in a planning stage.

I. INTRODUCTION

The investigation of the extremes in the nuclear chart, such as the vicinity of the proton/neutron drip line and superheavy elements, is one of the frontiers in nuclear physics. A tetraneutron state (^{4}n), composed of four neutrons, has received renewed attention in response to the observation of four candidates with the SHARAQ spectrometer at the RI Beam Factory, RIKEN [1], whose significance is 4.9σ.

The binding energy relative to the $4n$ threshold was hitherto constrained to be less than $+3.1$ MeV [2], due to the absence of the decay of $^8\mathrm{He} \to {}^4\mathrm{He} + {}^4\mathrm{n}$. Furthermore, the existence of a tetraneutron bound state is unlikely, since any isospin-2 state is not observed in other $A = 4$ systems [2]. Recent few-body calculations cannot reproduce a bound state as well [3, 4]. According to Ref. [3] which adopted realistic AV18 $2N$ and Illinois-IL2 $3N$ forces, a resonance near $+2$ MeV with a very broad width may exist [3].

The energy of the tetraneutron state observed at SHARAQ/RIBF [1], $0.83 \pm 0.65(\mathrm{stat}) \pm 1.25(\mathrm{syst})$ MeV, is centered above the threshold, but a possibility of a bound tetraneutron is not excluded from this measurement alone. A very recent calculation with the complex scaling method could not reproduce this result, unless a remarkably strong $3N$ attraction in the $I = 3/2$ channel was introduced [4]. $3N$ (and $4N$) forces will affect the nuclear Equation of State, which constrains the mass-radius relation of neutron stars. Therefore, neutron-rich nuclei, as well as neutron-rich hypernuclei, are important playgrounds for the investigation of such a many-body force which does not play a role in ordinary (hyper)nuclei.

In such a circumstance, it would be intriguing to examine the tetraneutron by means of a reaction different from the heavy-ion double charge exchange reaction utilized at SHARAQ/RIBF. We propose a new measurement of pion double charge exchange (pion DCX), i.e. the (π^-, π^+) reaction, on a ^{4}He target.

A brief history of tetraneutron is outlined in Section II, focusing on past pion DCX experiments carried out at LAMPF and TRIUMF, and the latest experiment at SHARAQ/RIBF [1]. Section III is devoted to a short summary of the proposed experiment, emphasizing the novelty of a pion-beam experiment at J-PARC.

II. BRIEF HISTORY OF TETRANEUTRON

In 1960's, a particle-stable tetraneutron was searched for in fission products from uranium, making use of a "hypothetical" secondary reaction, such as $(^4\mathrm{n}, \mathrm{n})$ [5, 6]. Non-observation of the product of this exotic reaction implies non-existence of a bound tetraneutron. Similar attempts with different kinds of reaction on heavy nuclear targets [7–9] followed thereafter, resulting in negative results.

Because these two-step reactions are only sensitive to a particle-stable state which would cause a secondary reaction in a massive target, a direct reaction to populate either a bound or resonance state of a four-neutron system is more preferred. (Please refer to Ref. [2] for a compilation up to 1991.) A variety of multinucleon transfer reactions, $^7\mathrm{Li}(^7\mathrm{Li}, {}^{10}\mathrm{C})$, $^7\mathrm{Li}(^{11}\mathrm{B}, {}^{14}\mathrm{O})$, $^7\mathrm{Li}(^9\mathrm{Be}, {}^{12}\mathrm{N})$, $^9\mathrm{Be}(^9\mathrm{Be}, {}^{14}\mathrm{O})$, and $\mathrm{d}(^8\mathrm{He}, {}^6\mathrm{Li})$ were also investigated [10–13]. In each measurement, no bound state was found below the threshold, and the spectrum above the threshold was consistent with the five-body phase space distribution[1]. Another type of the direct

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[1] The excitation energy spectrum in $\mathrm{d}(^8\mathrm{He}, {}^6\mathrm{Li})$ was reproduced better when the final state interaction between two dineutrons were incorporated [13].

reaction is a double charge exchange (DCX) reaction, which will be discussed more in detail below.

Yet another method of a four-neutron breakup of a neutron-rich nucleus ^{14}Be was utilized at GANIL. Marqués *et al.* concluded they observed 6 candidates of long-lived tetraneutron clusters, which deposited unusually large energies in a liquid scintillator [14]. However, they pointed out the possibility of a low-lying tetraneutron resonance in a succeeding article [15]; pileup of correlated neutrons in the scintillator may account for the data.

A. Pion DCX reaction

The pion DCX reaction was intensively explored at LAMPF, TRIUMF and PSI (former SIN) [16, 17]. One of the objectives was to populate proton-rich or neutron-rich nuclei with changing the charge by ± 2, and to measure their masses precisely. For instance, excited states as well as the ground state of ^{9}He was clearly observed [18]. A pioneering DCX experiment was carried out at CERN [19], but most probably due to a poor beam intensity and resolution, they could not observe a tetraneutron, ^{7}H, ^{9}He, or ^{12}Be. (The latter two were successfully observed in later experiments.)

Ungar *et al.* measured the $^{4}\mathrm{He}(\pi^-, \pi^+)$ reaction with 165 MeV π^- beam at LAMPF [20]. The momentum distribution of π^+ scattered at 0° is shown in Fig. 1. The cross section of a bound tetraneutron (with the binding energy between 0 and 3.1 MeV, indicated by the arrows in Fig. 1) was deduced to be 7 ± 15 nb/sr, corresponding to an upper limit of 22 nb/sr at the 1σ confidence level. Events in the bound region, is due to *"imperfect rejection of events in which the π^+ decayed inside the spectrometer"* [20].

Later on, the same reaction but with 80 MeV π^- beam was investigated at TRIUMF [21]. Scattered π^+'s between 50° and 130° were measured by a Time Projection Chamber, with the momentum resolution of $\sigma = 11\,\mathrm{MeV}/c$ for 50 MeV (128 MeV/c) π^+. Figure 2 is the π^+ momentum spectrum (a) before and (b) after the subtraction of the empty-target background. The number of remaining events in the bound region is consistent with the contribution of the continuum DCX process due to a limited resolution. The upper limit from the measurement was determined to be 13 nb/sr.

In the meantime, an inclusive DCX reaction on ^{4}He, not only (π^-, π^+) but also (π^+, π^-), had been measured for a variety of incident energies and finite scattering angles [22], aiming at a better understanding of the DCX reaction mechanism. No apparent narrow peak structure was seen near the $4n$ threshold.

In view of above-mentioned DCX measurements targeting at a possible tetraneutron state, we conclude the sensitivity achieved so far is not sufficient enough to disfavor the existence of a tetraneutron resonance or bound state. Assuming a tetraneutron resonance with a narrow width lies above a continuum background growing rapidly from the threshold, a high missing-mass resolution as well as a good PID performance is essentially important. Furthermore, a 0-degree measurement is favorable because of a small momentum transfer. We will propose a pion DCX reaction at J-PARC with a higher incident energy so as to satisfy these prerequisites. Thereby we aim to achieve an improved sensitivity down to the order of nb/sr.

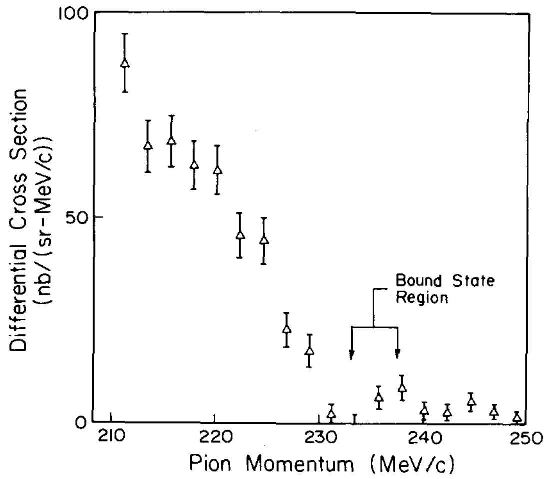

FIG. 1. π^+ momentum distribution for the $^{4}\mathrm{He}(\pi^-, \pi^+)$ reaction with the incident energy of 165 MeV. Taken from Ref. [20].

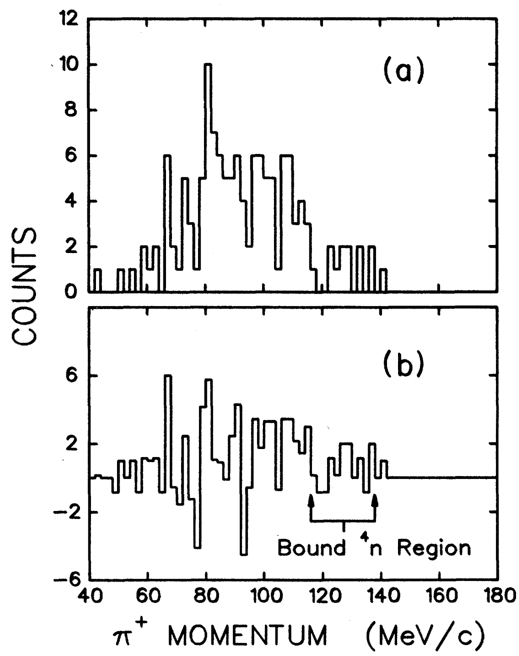

FIG. 2. π^+ momentum distribution for the $^{4}\mathrm{He}(\pi^-, \pi^+)$ reaction with the incident energy of 80 MeV. Panel (a) includes the contribution from the target flask, while it was subtracted in Panel (b). Taken from Ref. [21].

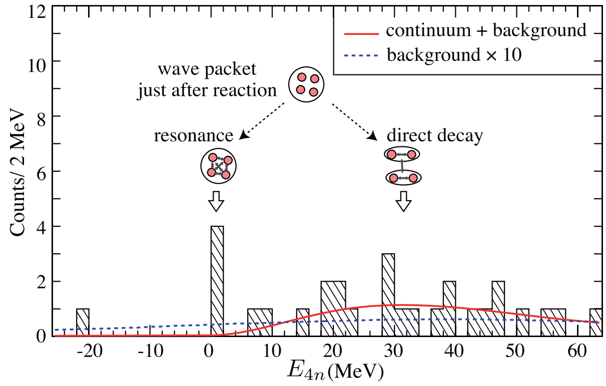

FIG. 3. Missing-mass spectrum of ^{4}He(^{8}He, ^{8}Be) reaction. The red line denotes the sum of a continuum component of a direct decay into correlated dineutron pairs and the background, which is also shown in the blue line (multiplied by 10). Taken from Ref. [1].

TABLE I. Momentum transfer (denoted as q) and Q-value for different reactions.

Reaction	q (MeV/c)	Q-value (MeV)
^{4}He(^{8}He, ^{8}Be)[a]	14.2	−3.2
^{4}He(π^-, π^+)[b]	130.7–266.3	−30.9
^{4}He(π^-, π^+)[c]	35.5	−30.9
^{4}He(π^-, π^+)[d]	32.9	−30.9
^{4}He(π^-, π^+)[e]	31.7	−30.9
^{4}He(π^-, π^+)[f]	31.3	−30.9

[a] Same condition as in Ref. [1]
[b] $T_{\pi^-} = 80$ MeV ($p_{\pi^-} = 170$ MeV/c) and $\theta_{\pi^+} = 50°$–$130°$. Same condition as in Ref. [21]
[c] $T_{\pi^-} = 165$ MeV ($p_{\pi^-} = 271$ MeV/c). Same condition as in Ref. [20]
[d] $T_{\pi^-} = 300$ MeV ($p_{\pi^-} = 417$ MeV/c)
[e] $T_{\pi^-} = 550$ MeV ($p_{\pi^-} = 675$ MeV/c)
[f] $T_{\pi^-} = 850$ MeV ($p_{\pi^-} = 980$ MeV/c) (to be proposed in the letter of intent)

B. ^{4}He(^{8}He, ^{8}Be) reaction

A secondary ^{8}He beam at 186 MeV/u, produced by a bombardment of primary ^{18}O beam onto a beryllium target, impinged on a liquid helium target, and an ejectile ^{8}Be, decaying into two ^{4}He's, was measured by the SHARAQ spectrometer [1]. This DCX reaction is characterized as an exothermic reaction; the internal energy of a beam ^{8}He, released when converted into ^{8}Be, is used to excite a tetraneutron from ^{4}He. As the beam was bunched with the cyclotron radio frequency of 13.7 MHz, only events with one beam particle in one bunch were analyzed so as to eliminate accidental background as much as possible. Thus, the beam intensity was limited to be $\sim 2 \times 10^6$/sec.

Figure 3 shows the obtained missing-mass spectrum for the reaction. 4 events, among 27 events in total, were concentrated near the threshold, and the significance of the peak compared with the continuum seen above 2 MeV was evaluated to be 4.9σ. The background shown in a blue line is due to a small inefficiency of a MWDC at an intermediate dispersive focal plane, which measures the beam momentum, resulting in miscounting the number of particles in a bunch.

The energy of the tetraneutron state was $0.83 \pm 0.65(\mathrm{stat}) \pm 1.25(\mathrm{syst})$ MeV, and the upper limit of the width was also estimated to be 2.6 MeV, which is mainly determined by the experimental resolution of $\sigma = 1.2$ MeV. They determined the integrated cross section $3.8^{+2.9}_{-1.8}$ nb for $\theta_{\mathrm{CM}} < 5.4°$.

They plan to carry out a new experiment in near future [23], by which the statistics is expected to be drastically improved.

C. Comparison between DCX reactions

The momentum transfer and the Q-value are compared for the two kinds of DCX reactions in Table I. While both of them are smaller for heavy-ion DCX than for pion DCX, a relatively small momentum transfer can be realized except for the case of Gorringe *et al.* [21], where large-angle π^+'s were measured. In addition, the momentum transfer rapidly converges to 31.0 MeV/c, which is almost equal to $|Q|/c$.

A comparison is made from another viewpoint. A very neutron-rich nucleus, ^{9}He, was observed by both the DCX reactions. On the one hand, a clear peak corresponding to the ground state was identified in a missing-mass spectrum for the ^{9}Be(π^-, π^+) reaction with the incident energy of 180 MeV and the scattering angle of 15° [18] (Fig. 4), and its differential cross section was determined to be 40 ± 10 nb/sr. On the other hand, the ground state was also seen in the ^{9}Be(^{14}C, ^{14}O) reaction [24] as shown in Fig. 5, whose cross section was found to be ≈ 30 nb/sr [25].

It is difficult or almost impossible to conclude which reaction is better to populate an exotic, neutron-rich nucleus. While being oversimplified, different cross sections of the two DCX reactions can be of a similar order of magnitude. In addition, the reaction mechanisms are completely different; the former can be seen as πN scattering and Δ excitation in a nucleus, while the latter is a two-proton-two-neutron exchange reaction.

In short, a state which was observed in a heavy-ion DCX reaction may be observed in a pion DCX reaction as well, and vice versa. The possible observation at SHARAQ/RIBF has motivated us to revisit the pion DCX reaction for populating a tetraneutron.

D. Pion DCX above the Δ resonance

There have been measurements on analog transitions into double isobaric analog states (DIAS) with a pion

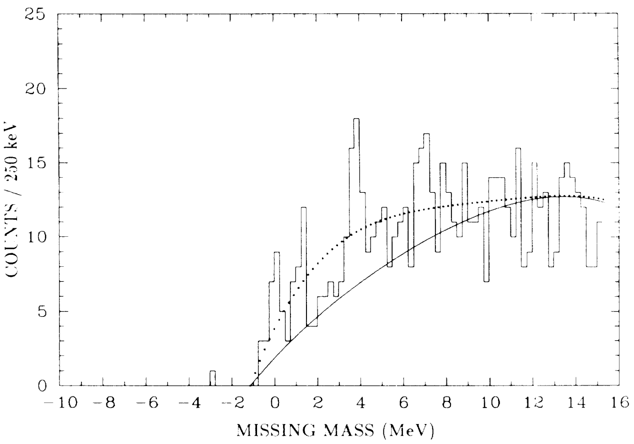

FIG. 4. Excitation energy spectrum for the ^{9}Be(π^-,π^+) reaction. Taken from Ref. [18].

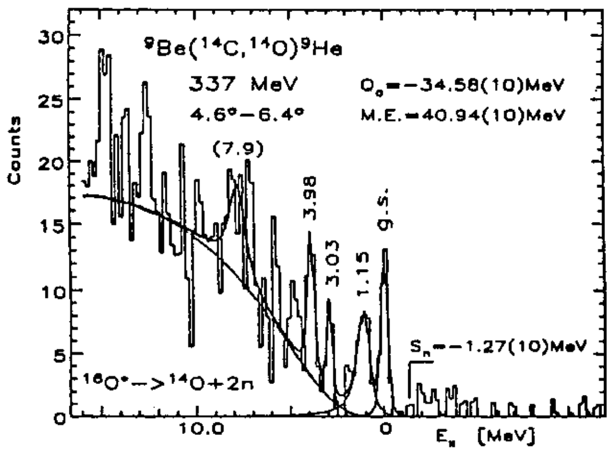

FIG. 5. Excitation energy spectrum for the ^{9}Be(^{14}C,^{14}O) reaction. Taken from Ref. [24].

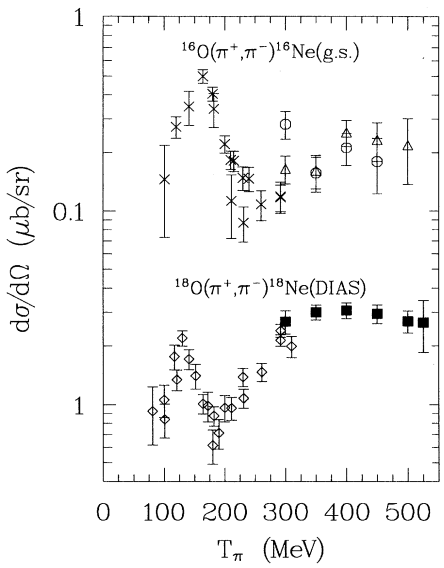

FIG. 6. Excitation functions at $\theta = 5^\circ$ for a non-analog transition of ^{16}O$(\pi^+,\pi^-)^{16}$Ne (g.s.) and an analog-transition of ^{18}O$(\pi^+,\pi^-)^{18}$Ne (DIAS). Taken from Ref. [26].

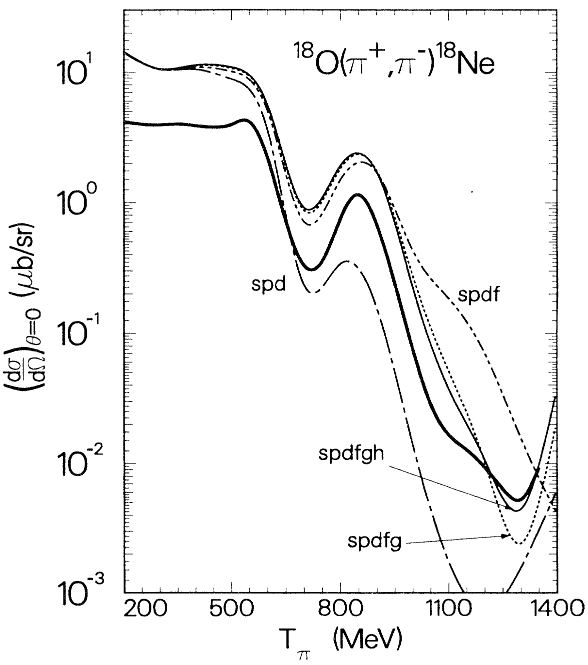

FIG. 7. Theoretical calculation of differential cross section of an analog ^{18}O$(\pi^+,\pi^-)^{18}$Ne (DIAS) transition as a function of the pion kinetic energy. The bold line is the result with the partial wave up to $l = 5$ and isovector polarization included. Taken from Ref. [27].

DCX reaction above the Δ resonance. However, as for non-analog transitions, only the measurement of the cross section of ^{16}O$(\pi^+,\pi^-)^{16}$Ne (g.s.) by Beatty *et al.* [26] covered an energy region above the Δ resonance.

Figure 6 is a comparison between a non-analog transition on ^{16}O and an analog transition on ^{18}O. The differential cross section for the non-analog transition between 350–500 MeV is 20 times smaller than that for the analog transition, but the behavior is similar to each other.

For a higher energy, only a theoretical calculation for analog transitions is available [27] (Fig. 7). A flat behavior below 500 MeV, seen in Fig. 6, was reproduced well. It is worth emphasizing that a dip at 700 MeV and a maximum around 850 MeV were found. If this behavior holds for non-analog transitions, the beam energy of 550 MeV and 850 MeV would be preferred.

From the ^{16}O data and the theoretical calculation, it can be inferred that a different cross section of the ^{4}He$(\pi^-,\pi^+)^{4}$n reaction above the Δ resonance could be one order of magnitude smaller than that in the Δ resonance, which would be less than 22 nb/sr according to Ungar *et al.* [20] This is the reason why we will set the goal of our sensitivity to be of the order of nb/sr.

TABLE II. Comparison among three DCX experiments.

	π^- energy	intensity	π^+ acceptance
LAMPF [20]	165 MeV	10^6/sec	25 msr
TRIUMF [21]	80 MeV	2×10^6/sec	$\sim 2\pi$ sr
J-PARC HIHR	850 MeV	2.7×10^7/sec[a]	~ 10 msr

[a] averaged per spill (6 sec).

III. SHORT SUMMARY OF THE PROPOSED EXPERIMENT

A plan to extend the Hadron Experimental Facility has been discussed, in which a new beam line named High-Intensity High-Resolution (HIHR) beam line is proposed. At the HIHR beam line, an intense pion beam of the order of 10^8 per spill with a very good resolution ($\Delta p/p \sim 1/10000$) will be provided. While the primary purpose of this beamline is hypernuclear spectroscopy with (π, K^+) reactions, this beamline is suited for pion DCX as well.

We will measure the ^{4}He(π^-, π^+)4n reaction. The beam energy will be 850 MeV, corresponding to the momentum of 980 MeV/c. The expected beam intensity is 1.6×10^8 per spill, according to the Sanford-Wang formula[2] [28]. If we use a 2.0 g/cm^2-thick liquid ^{4}He target, the yield of a tetraneutron state will be 97 events/(2 weeks)/(nb/sr). It indicates that the sensitivity of the order of nb/sr is within the scope, benefiting from one order of magnitude higher intensity than in past experiments. A comparison of three DCX experiments at LAMPF, TRIUMF, and J-PARC is given in Table II.

Different from the past DCX experiments, contaminant electrons in the π^- beam, which were a major source of background at LAMPF [20], will be negligible owing to an electrostatic separator along the beamline. Furthermore, π^+ decay inside the spectrometer will be suppressed because of a high momentum. Last but not least, the dispersion matching technique, to be realized in the HIHR beamline, will play an important role in improving the missing-mass resolution, which is crucial to deduce the width of a possible resonant state.

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